Design and Management of Composting Systems

Thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

Composting is an effective method of removing a large proportion of biodegradable waste from landfill. The CO_2 produced by microbial activity demonstrates the rate of decomposition, and was measured in green waste composting in windrows, a forced aerated bay, an aerated test rig and related to the volatile solid content. The peak respiration rates were $35gCO_2kgVS^{-1}day^{-1}$ in windrows, and $290gCO_2kgVS^{-1}day^{-1}$ in the test rig. Knowing the rate of microbial activity, allows the volume of air required to supply sufficient oxygen to a composting matrix to be determined.

Recently introduced treatment regulations require 100% of the waste in a composting system to be maintained above 60 or 70°C for minimum periods. Aeration management methods were evaluated that maximise the rate of temperature increase and distribute the heat generated by microbial activity. Managing re-circulated gases between set CO_2 limits was demonstrated to an effective method of encouraging rapid temperature increase. Whilst the lowest recirculation rate of $40m^3hr^{-1}$ per m^3 of compost was required to ensure 100% of the compost matrix in the test rig was greater than 60°C.

The research presented in this thesis demonstrates methods that will aid the design and management of any composting system, especially those treating catering waste.

Acknowledgements

I would like to thank Prof. Keith Williams and Prof. Tony Griffiths for their professionalism, advice, knowledge and clarity of thought. I would also like to thank Dr David Notton for his valuable analytical approach and engineering skills.

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I would like to praise my children Rhiannon, Louisa, Grace and Rhys for their support and to apologise for the smell, and the shame of having an anorak for a dad.

I would like to dedicate this to Beth, for her infinite support and encouragement, her wise advice and the generous allowances she has made to allow me to devote time to the research.

"I have yet to see any problem, however complicated, which, when you looked at it the right way, did not become still more complicated" - Paul Alderson.

Table of Contents

Appendices

Abbreviations

ABPR	Animal by products regulations
BMW	Biodegradable municipal waste
BSI	British standards institute
C:N	Carbon to nitrogen ratio
CCWM	Climate change and waste management
CERT	Carmarthenshire environmental resources trust
cfu	Colony forming units
CH_4	Methane
CO_2	Carbon dioxide
DEFRA	Department of environment farming and rural affairs
EU	European Union
FAS	Free air space
GISS	Goddard institute for space studies
GWP	Global warming potential
H_2S	Hydrogen sulphide
IPCC	International panel on climate change
kg	Kilogram's
kPa	Kilo Pascal's
m^2	Square meters
m^3	Cubic meters
N_2O	Nitrogen dioxide
NH_3	Ammonia
O_2	Oxygen
PAS	Publicly available specification
PPMV	Parts per million by volume
RCEP	Royal commission on environmental Pollution
SOUR	Specific oxygen uptake rate
SVS	State veterinary service
TOC	Total organic carbon
UK	United Kingdom
VS	Volatile solids
WAG	Welsh assembly government

Nomenclature

A	Cross sectional area	m^2
AE_{co2}	Increase in the volume of CO_2	m^3
B	Free air space	m^3
C	Density of CO_2	gm^{-3}
CT	Core temperature	°C
D	Convert hours to days	-
E_{co2}	Concentration of carbon dioxide	%
K	Respiration rate	$kgCO_2m^{-3}day^{-1}$
M_{co2}	Mass of carbon dioxide	kg
P	Pressure	Pa
R_{co2}	Specific gas constant for carbon dioxide	Nm/kg K
Symbol	Definition	Units
td	Time	Days
T_g	Gas temperature	K
th	Time	Hours
$\overline{U}$	Average velocity	m/s
V	Total volume of compost	m^3

1 Introduction

1.1 Background

1.1.1 Global Warming

It is now generally accepted by the scientific community that global warming is occurring, and that it is due to anthropogenic influences. A proportion of the heat radiated by the sun in the form of visible and ultra violet radiation is absorbed by the Earth's surface, and a further proportion of this absorbed heat energy is emitted in the form of infra red radiation. Some of the infra red radiation emitted from the Earth's surface is retained in the atmosphere by green house gases like, water vapour, carbon dioxide (CO_2), methane and nitrous dioxide. The greater the concentration of these greenhouse gases in the atmosphere, the more of the radiation emitted from the Earth's surface is retained, leading to an overall increase in temperature.

There has been an observed temperature increase of 0.6°C over the last 100 years, and the Intergovernmental Panel on Climate Change now argues that most of the observed warming in the last 50 years is likely to have been due to the increase in greenhouse gas concentrations (IPCC, 2001). There is great debate regarding the effect and extent of global warming on weather systems, ocean currents, sea levels and in turn the effects of these world wide factors on localised climate, and how these will impact upon human populations. There is insufficient data to accurately predict the impact of these changes at the present time. But it is clear that the increasing global population and industrialisation of developing countries, especially in East Asia, will lead to total green house gas emissions increasing (Shi, 2003). If this trend is to be stabilised or reversed the reliance on fossil fuels has to addressed, as do other human activities that produce green house gases, including deforestation, agriculture and waste management.

CO_2 is the largest individual contributor to the greenhouse effect, and is thought to be responsible for 60% of the total increase in Global Warming Potential (GWP) over the period 1765 to 1999. Since the Industrial Revolution concentrations have increased from 280 parts per million by volume (ppmv) to 367ppmv in 1999. This is

higher than at any other time in the last 400,000 years. CO_2 emitted into the atmosphere today will influence its atmospheric concentration in the years to come, since the time taken for atmospheric CO_2 to adjust to changes in sources or sinks is in the order of 50-200 years. To stabilise concentrations at present day levels would require a 60% reduction of global CO_2 emissions (RCEP, 2000).

The source of the observed increase in CO_2 concentration is thought to be primarily due to the burning of fossil fuels, coal, oil and gas. Though other human activities like deforestation, intensive agricultural and cement production have also contributed. It is calculated that the developed world, which includes the UK, parts of Europe and America have not greatly increased their CO_2 emissions over the last 25 years, though the mass of CO_2 produced per person can be significantly different. America was the greatest producer of CO_2 in 2003 with a total production of 1580 million tonnes, which equalled more than 5 tonnes per person. China were the second highest producer with a total of 1131 million tonnes, but with a per person average of only 0.86 tonnes (Marland et al, 2006). France has consistently reduced their annual CO_2 emissions from fossil fuels since 1973, which has been achieved through a nuclear power generating programme rather than a reduction in energy use.

Methane is the second most important greenhouse gas after CO_2 and is estimated to have been responsible for a fifth of the enhanced greenhouse effect over the past 200 years. Although methane is nowhere near as prevalent or long-lasting as carbon dioxide, it is a far more powerful greenhouse gas with more than 20 times the heat-trapping effect (GISS, 2005). Methane is released by humans through deforestation, intensive agriculture, rice cultivation, and industrial sources. Natural decay of organic matter also produces methane. Since the 1990s the rate of increase has accelerated, largely due to increasing emissions from fossil fuel use in Asia, in particular coal burning in China. The British Antarctic Survey found that in the past 800,000 years the concentration of methane had never been greater than 750 parts per billion (ppb), but it has now increased to 1,780 ppb (Wolff et al, 2006). Reductions in major sources of methane from human activities include improved piping of natural gas and the capture of methane from landfill sites to generate electricity. Global emissions of methane are thought to total 600 million tonnes, and emissions from landfills are calculated to total 40 million tonnes, approximately 7% of the total (CCWM, 2006).

As it is suggested that the global emissions of methane need to be reduced by 15 to 20% to stabilise the atmospheric concentration increase, then reducing the emissions from landfills could play a significant role.

1.1.2 Waste Management

Both CO_2 and methane are produced by microbial decomposition of biodegradable waste in landfills, where anaerobic conditions prevail. Decomposition by microbial activity in anaerobic conditions produces both of these greenhouse gases. Bond et al (2006) demonstrated mean measures for methane and CO_2 at 4 UK landfills of between 35 and 61% volume / volume for methane, and between 24 and 39% for CO_2. But as methane has a GWP effect some 20 time greater than CO_2 its impact is far greater. It can be argued that CO_2 emissions from the decomposition of biodegradable waste under aerobic or anaerobic conditions is not a man made source of this green house gas. As the CO_2 evolved from biodegradable waste was recently fixed through photosynthesis from the atmosphere, it is in effect recycled atmospheric CO_2. Unlike that released from the burning of fossil fuels which was fixed from the atmosphere hundreds of millions of years previously. Where as methane released from landfill can be described as having a man made GWP effect as it is converting atmospheric CO_2 fixed into biomass through the photosynthetic process, into a compound which has a GWP effect more than 20 times greater.

The European Landfill Directive (European Commission, 1999) aims to reduce the quantity of biodegradable waste disposed of in landfills and therefore reduce the quantity of methane entering the atmosphere from this source. It has set out targets requiring the quantity of biodegradable municipal waste (BMW) sent to landfill in 1995, to be reduced by 25% by 2006, 50% by 2009 and 65% by 2016. As the UK sent more than 80% of its waste to landfill in 1995, it was granted a 4 year extension; therefore the targets in the UK will now apply in 2010, 2013 and 2020, respectively.

In 1995 the UK municipal waste arising's were 29 million tonnes, 60% of this waste has been determined to be biodegradable, giving a total biodegradable waste sent to landfill of 17.4 million tonnes. Though, in Wales the Welsh Assembly Government (WAG) has stated that 61% of municipal waste is biodegradable, in a national waste

strategy called Wise about Waste (WAG, 2002). In this strategy they have included targets for recycling of 15% of municipal solid waste (MSW) by 2003/4, 25% by 2006/7 and 40% by 2009/10. Unlike other UK countries this strategy includes compost specific targets, which are a minimum of 5% of MSW by 2003/4, 10% by 2006/7 and 15% by 2009/10. These are included in the total recycling proportions and are not extra to them, so approximately 30% of the total recycling targets will have to be undertaken by composting. They have also included the requirement that the composting targets can only be met using source segregated organic waste.

The quantity of MSW sent to landfill in Wales in 1995 was calculated to be 1.4 million tonnes, and with BMW calculated to be 61% of MSW, the quantity sent to landfill was approximately 0.9 million tonnes. With no growth the targets would require approximately 70,000 tonnes of composting by 3003/4, 140,000 tonnes by 2006/7 and 210,000 tonnes by 2009/10. The quantity of composting required in 2009/10 if there was a growth rate of 3% would increase to 351,000 tonnes, as shown in Figure 1.1. To demonstrate the on going impact of increasing waste arising's, projecting the growth rate of 3% to 2020 indicates that the quantity of BMW requiring diversion from landfill, would increase from 0.585 million tonne per year with no growth, to 1.6 million tonnes per year at a 3% annual growth rate, nearly 3 times greater.

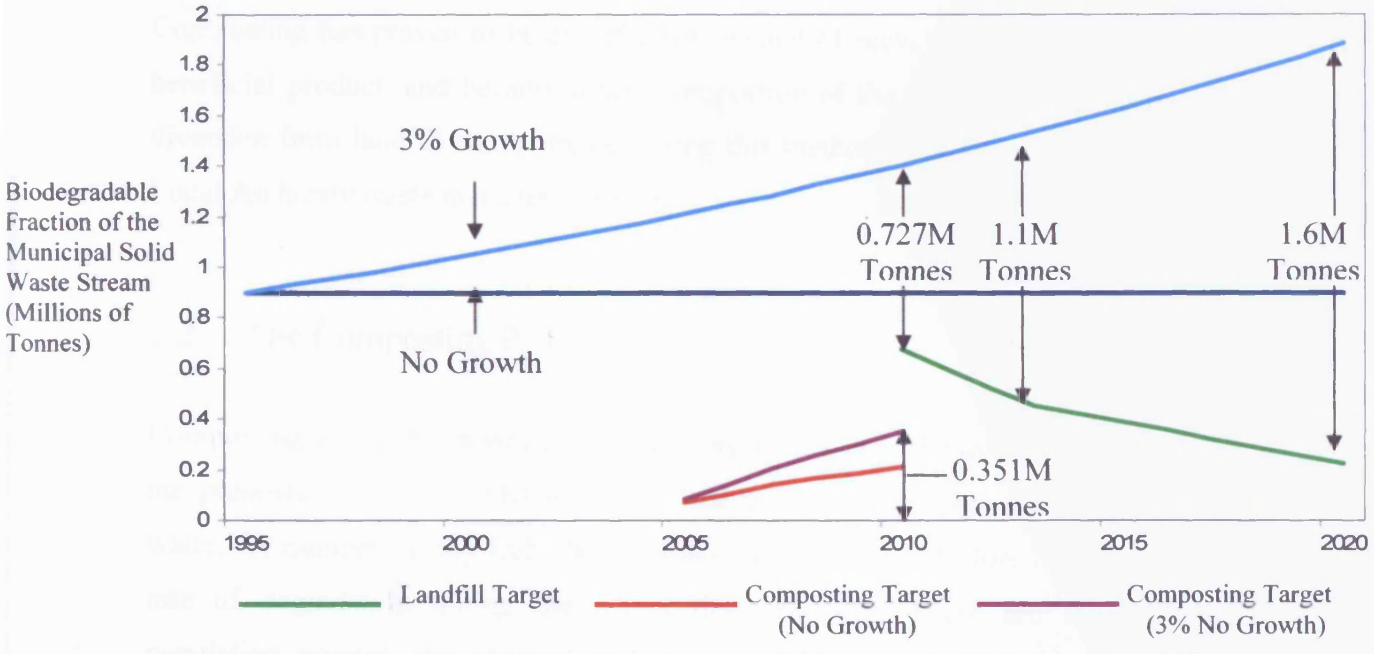

Figure 1.1 Comparison of growth of biodegradable waste in Wales and Landfill Directive and Wise about Waste targets.

The Landfill Directive has placed the burden on member states to ensure the BMW diversion targets are met, and that failure to meet these targets will result in fines being placed on those failing states. It has been suggested by WAG that they will fine Local Authorities up to £200 for every tonne of BMW sent to landfill, above their allowance values.

The UK landfill tax is a further driver, this makes recycling a more financially attractive option than the historically low cost disposal route of landfill. The rate in 2006/7 is £21 per tonne for biodegradable waste, and with landfill costs in south west Wales being in the region of £34 per tonne, the cost of sending biodegradable waste to landfill is £55 per tonne. The landfill tax is planned to increase at the rate of £3 per tonne per year until it reaches £35 per tonne, at which point there will be a review. The artificially inflated cost of landfill has resulted in the disposal of biodegradable waste to composting, at £21 to £29 per tonne for green waste and £40 to £55 per tonne for catering waste (Letsrecycle.com, 2006) a less costly option. But the extra costs of segregation and separate collection has not been factored into these costs and the convenience and simplicity of a single waste receptacle is often a large consideration for many waste producers.

Kitchen and garden waste comprises at least 50% of BMW stream, with the majority of the remainder being made up of paper and cardboard (Emery et al, 2000). Composting has proven to be an effective method of recycling organic waste into a beneficial product, and because a large proportion of the waste stream that requires diversion from landfill can be treated using this method, it is a key element of most Local Authority waste management plans.

1.2 The Composting Process

Composting is a process where by micro-organisms breakdown organic material in the presence of oxygen (O_2) into more stable organic compounds, heat, CO_2 and water. A number of physical, chemical and environmental factors impact upon the rate of degradation during the composting process. These are the microbial population present, the physical and chemical characteristics of the waste being

degraded and the environment within the waste matrix. There are a number of key environmental parameters that affect the rate of decomposition; these are temperature, O_2 and moisture availability. Changes in a single physical, chemical or environmental parameter will often have an impact on one or more other parameters. Using a different machine for shredding green waste on a windrow composting facility can result in a smaller particle size. This will reduce O_2 availability and heat loss due to reduced passive gas flow within the matrix, both of which are likely to have an adverse impact upon the rate of microbial decomposition.

There are many methods and systems employed to compost organic waste on a commercial scale, they vary widely in sophistication and technique, but all aim to manage, to a greater or lesser extent, the environment within the compost matrix,.

1.3 Commercial Composting

The vast majority of commercial composting has historically been undertaken in turned windrows systems. This method of composting is simple to undertake and has been shown to be successful in producing high quality product with relatively low capital investment and operating costs. With the introduction of the Animal By Products Regulations (ABPR) in 2003, any waste that contains or may have come into contact with animal by products is required to be treated in an enclosed composting system, and to meet a set of treatment parameters (WAG, 2003).

Windrow composting is self regulating in respect of O_2 availability and temperature, and the rate of decomposition is often governed by these 2 parameters. The shape of a windrow encourages a passive flow of air, driven by hotter air exiting the top of the windrow, and resulting in air and therefore O_2 being drawn into the sides of the windrow and heat being lost from the system. Unlike windrows, in-vessel systems not only increase the level of capital investment and operating costs associated with the composting process, they also introduce the need to actively manage key parameters.

The greater capital and operational costs associated with in-vessel composting can be partially compensated for by increasing the rate of decomposition, through managing key parameters within the reported optimums. This has the effect of decreasing the time taken to recycle an organic waste into a product suitable for its designed end market. It is also possible for the rate of decomposition when composting in-vessel to be reduced, when compared to windrow composting, if these key parameters are not managed within their optimum conditions. In-vessel composting also requires less area to process a certain tonnage of organic waste when compared to windrow composting, and commercially available in-vessel systems promote these advantages over windrows as a reason for customers to invest in the extra infrastructure required.

The proportion of the BMW that is required to be diverted from landfill by composting will demand that wastes included in the ABPR will have to be treated if the targets are to be met. This introduces a further challenge of meeting the ABPR treatment requirements. Which are technically demanding and require systems to maintain 100% of the waste being treated, at above 60 or 70°C for specified periods of time, dependent upon the particle size and category of waste being treated. The capital investment required to procure these types of systems will be large and if they do not perform to specification, especially in regards to the ABPR, considerable further expense may be incurred.

The composting industry on an international level is working towards quality standards for the products of composting. One of the long standing issues is to develop a quantative method of demonstrating when a product is stable or mature. The most wide spread methods of determining stability, is to measure the uptake of O_2 or the production of CO_2 under standardised conditions, and can accurately describe the status of the compost. If these tests are undertaken on a regular basis on a batch of compost under going treatment in a system, they can demonstrate the rate of decomposition that has occurred.

Effective management of the composting process in all systems, from simple green waste turned windrows to in-vessel composting of more difficult wastes, or wastes that are required to be treated in accordance with the ABPR, is essential if it is to occur efficiently.

The work presented in this thesis is the product of a research study into commercial scale composting that was undertaken by the Cardiff School of Engineering. The research occurred at Carmarthenshire Environmental Resources Trust Ltd's Pilot Composting Facility, located at Nantycaws Landfill Site, some 5 miles east of Carmarthen in south west Wales, UK. The facility receives green waste from Carmarthenshire County Council and windrow composts this waste in a 1500m^2 open sided building. This allowed the research conducted to examine full scale operations, and therefore improve understanding of the operational issues faced by the commercial composting community.

1.4 Aims

The aim of this thesis was to improve understanding of the composting process at a commercial scale, and to produce data that would aid the design and operation of any composting system, especially those that are required to meet the treatment requirements of the ABPR.

The aim of the composting process is promote the microbial decomposition of organic matter to convert an organic waste into a useful product. Therefore measuring the rate of microbial activity will indicate the rate of decomposition, and if this can be measured on a dynamic basis the impact of process options can be determined instantly. The use of measures of respiration to determine stability has been demonstrated to be an accurate method of measuring microbial activity. But for these methods to be effective they require the testing of small samples under standardised conditions, and therefore do not describe the rate of activity in the system in which the waste has undergone processing. One of the aims of the research presented in this thesis was to develop a method of measuring the rate of microbial activity occurring in a composting matrix that could be applied on a commercial scale. This could then be used to analyse the impact of process options.

The introduction of the ABPR in the UK has led to the requirement of enclosed composting for certain organic waste types. Enclosing the waste introduces the need to manage aeration, but before a forced aeration system can be accurately designed the volume of air required to be delivered will need to be known. The volume of air

required by a composting matrix is dependent on the rate of microbial activity and the parameter that is being controlled. Therefore a further aim was to produce data that would demonstrate the volume of air required by a compost matrix in relation to the rate of microbial activity, and therefore aid design

When the ABPR were introduced, existing in-vessel systems had not been designed to meet the treatment requirement of 100% of the compost matrix greater than 60 or 70°C. For this reason another aim was to investigate and describe methods that would maximise heat production and distribution within the composting matrix, as an aid to those designing systems to meet these requirements.

1.5 Structure

A literature review was conducted to gain background knowledge and understanding of current composting process management research, and the pertinent elements of this review are presented in Section 2.

A method of measuring the dynamic respiration rate, based on the CO_2 production from microbial activity, was developed. This method was used to monitor the dynamic respiration rate in 2 green waste windrows and 1 green waste windrow amended with chicken litter. The results of this research are presented in Chapter 3.

With the aim of producing aeration management methods that could be used to maximise heat production and distribution in the composting matrix, a forced aeration distribution system was fitted to the base of a concrete bay with a volume of approximately $90m^3$, which was then filled with green waste. A temperature probe array was then inserted into the compost matrix to examine the effect of aeration management and the direction of aeration on maximum temperature and distribution within the matrix. The methods and results from this work are presented in Chapter 4.

Following the work described in Chapters 2 and 3 a compost processing test rig with a capacity of $1m^3$ of compost was designed. This was undertaken to create and enclosed system to allow the re-circulation of gases at different rates through the

composting matrix. This was done to allow heat to be distributed from the compost matrix core to the less well insulated periphery. Thermocouples were mounted on the internal side walls of the test rig, as well as being inserted on probes into the compost matrix. It was also designed to manage CO_2 concentrations in the re-circulating gases within set levels by a computer controlled system, this also allowed the microbial respiration rate to be calculated The design of and fabrication of this test rig, along with the results of the commissioning trials are described in Chapter 5.

A number of composting trials were undertaken in the test rig to examine process management options that would maintain 100% of the compost matrix above the minimum temperature requirements of the ABPR. The trials utilised green waste and employed different gas re-circulation rates to examine temperature increase rates and distribution under different aeration regimes. The methods and results from these trials are demonstrated in Chapter 6.

Key conclusions from each Chapter are described, as well as recommendations for their application in Chapter 7. This chapter also includes recommendations for further work, based on the results found.

2 Literature Review

2.1 Background

Composting is a process where by micro-organisms breakdown organic material in the presence of oxygen (O_2) into more stable organic compounds, heat, carbon dioxide (CO_2) and water. A number of physical, chemical and environmental factors impact upon the rate of degradation during the composting process. These factors are described in this chapter, as is their reported impact on the composting process. The impact of legislation on the treatment of organic waste in the UK is also highlighted.

There are many methods and systems employed to compost organic waste on a commercial scale, they vary widely in sophistication and technique, but all aim to manage the characteristics of the waste and the environment within the waste matrix. The most widely employed methods and technologies are described, as are the major emissions from the composting process and methods devised to measure the quality of the composted product.

The rate at which organic waste degrades during the process will impact upon the design and implementation of infrastructure and operations at any facility. This rate cannot be determined by simply measuring one factor, but can be accurately described by relating the uptake of reactants or the evolution of products to the waste being treated. Methods that use these techniques are capable of demonstrating the sum effect of physical, chemical and environmental parameters on the rate of decomposition in any composting matrix.

2.2 Factors Effecting the Composting Process

2.2.1 Micro-organisms

Very little is known about the micro organisms that determine the rate of composting, affect the quality of the product and produce most of the physical and chemical changes in the waste. The study of microbial communities in the composting matrix is hindered by its heterogeneous nature and rapidly changing environmental, physical

and chemical conditions (Tiquia *et al,* 2002). Many different micro-organisms and communities of micro-organisms can be found in composting systems, these communities change rapidly as environmental factors alter within the composting system.

Bacteria are the most nutritionally diverse group of organism found in composting systems as they employ a broad range of enzymes to breakdown a variety of organic materials. They make up 80 – 90% of the billions of micro-organisms found in every gram of compost and generally range in size from 1 - 10 micrometer (μm). Bacteria are single celled and have three main shapes, which are bacilli (rods), cocci (spherical) or spirilla (spiral), as highlighted in Figure 2.1. Many bacilli survive harsh environmental conditions by forming thick walled spores which allow them to become active once environmental conditions become more favourable. Bacteria have evolved to survive in the most extreme environments and have been found to be active in temperatures up to 130°C (Jha, 2003).

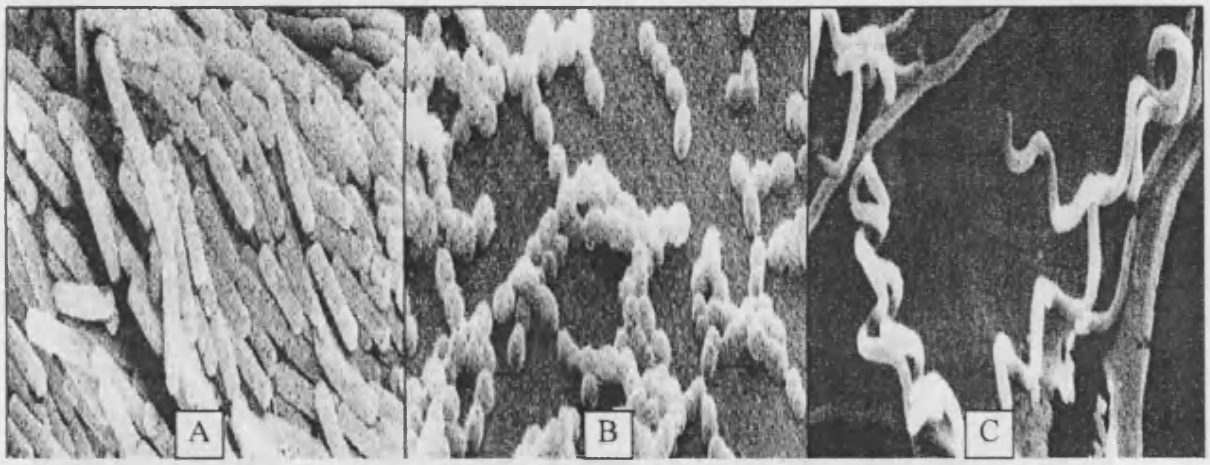

Figure 2.1. Electron micrograph images of the 3 main bacterial cell types, a colony of rod shaped bacilli (A), spherical cocci (B) and spiral spirilla (C) (Purves et al, 1995).

Actinomycetes resemble fungi by growing in multi-cellular filaments but their cell structure is the same as other bacteria. Some species are found at high composting temperatures but are more typically found in the later and cooler stages of composting. This is due to their ability to degrade complex organic compounds like lignin, chitin and proteins that other organisms have not been able to decompose earlier in the composting process. This is supported by experiments undertaken by Peters et al (2000) who found that actinomycetes diversity increased during compost maturation. They form long thread like filaments that spread throughout the

composting mass and produce chemical compounds that are responsible for the characteristic earthy smell of compost.

Fungi are another group of micro-organisms that are important in composting; this group includes the molds and yeasts. Many fungi are classified as saprophytes, meaning that they have evolved to obtain energy and nutrients from breaking down the organic matter in dead plants and animals. They are the principal degraders of dead organic matter in the biosphere and have highly developed nutrient absorption mechanisms. The body of multi cellular fungi is called a mycelium and its cells are organised into rapidly growing hyphae, which spread through out the degrading matter providing a large surface area for nutrient absorption as shown in Figure 2.2. Fungi are able to degrade organic material that is dry, acidic or low in nutrients when compared to bacteria and are normally found on the dryer, cooler outer layers. The complex lignin's found in wood are predominantly degraded by enzymes excreted by fungal hyphae.

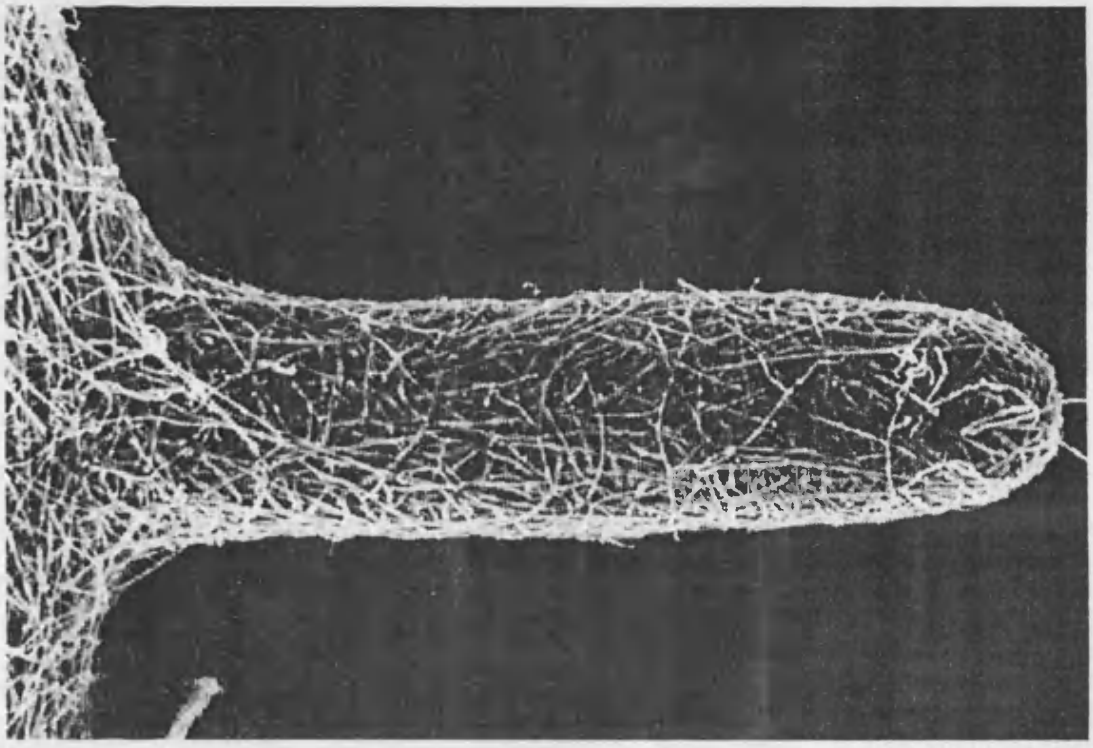

Figure 2.2. Fungal hyphae on the surface of a eucalyptus root. (Purves et al, 1995).

Waksman et al (1939) studied the effect of temperature on the microbiological population and the decomposition rate of stable manure. They found that in manure

managed at 28°C, bacteria dominated the early stages, fungal populations began to develop late in the incubation period and actinomycetes populations were very limited. At 50°C bacteria dominated for several days, and rapidly diminished as fungi and actinomycetes populations increased. At 65°C the bacteria and fungal population diminished rapidly to be replaced by actinomycetes, and at 75°C certain spore forming bacteria were the only surviving organisms. Their work also indicated that no decomposition of cellulose occurred in the manure managed at 75°C, and over the first 9 days the greatest cellulose loss was in the 65°C sample, but the sample maintained at 50°C had the greatest level of cellulose loss in samples taken on day 19, 33 and 47 respectively.

Strom (1985) studied the effect of bacterial species diversity in thermophilic solid waste composting in bench scale reactors managed at temperatures of 49°C, 50°C, 55°C, 60°C and 65°C. He found that 10 genus of bacillus dominated all samples except for the sample managed at 49°C. It was also found that species diversity decreased markedly above 60°C, but diversity was similar in the trials managed at 49°C, 50°C and 55°C. He concludes that although species diversity was greatest at 60°C it was not usually correlated with biological productivity in any direct way.

Research has been undertaken by Velikonja Bolta et al (2003) to increase the rate of composting by adding inoculants of specific micro-organisms to organic waste. This led to more rapid heat up during the initial stage and after turning when compared to non-inoculated compost in the active phase. Viable microbial biomass was also measured and during the initial phase, directly after inoculation, this was 6 times greater in the inoculated compost when compared to the non-inoculated. Tests undertaken on day 18 showed that viable microbial biomass were very similar in the test and the control samples.

The research indicates that the microbial communities involved in the composting process are very diverse over spatial and temporal parameters. It also suggests that there is a succession of organisms degrading the different elements of an organic waste over time. This is indicated by the succession and size of fungal populations degrading the pine needles beneath Scots pine (*Pinus sylvestris)* as shown in Figure 2.3.

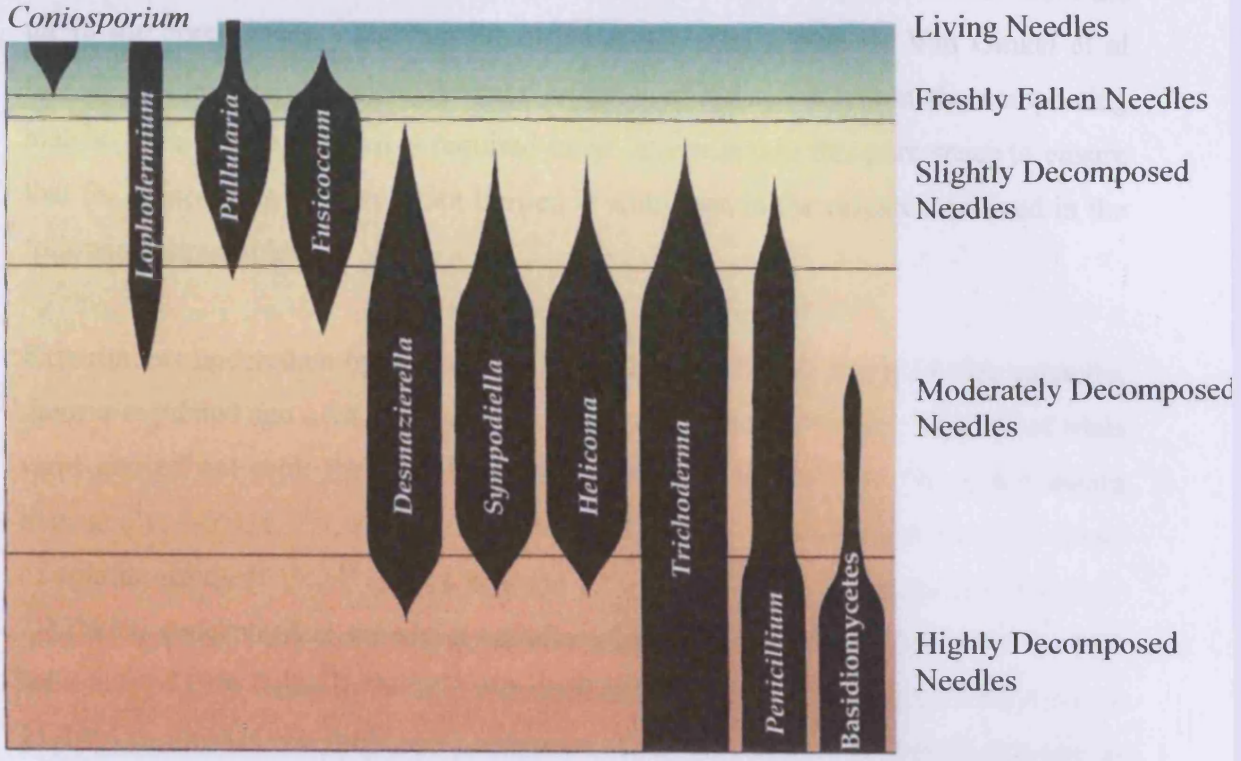

Figure 2.3. Succession of fungal populations degrading pine needles in the litter layer below Scots pine (*Pinus sylvestris*). Population size is indicated by the width of the bars. (Purves et al, 1995).

Understanding the succession of organisms degrading the organic waste may lead to increasing rates of decomposition in composting systems. If the optimal environmental variables were known for each stage of succession, process management could be used to promote optimal rates of decomposition at each stage of the composting process.

2.2.2 Oxygen Availability

Ensuring sufficient O_2 is available in the composting matrix is an important consideration at large scale composting sites. Firstly, the rate of decomposition in a composting system is affected by the availability of O_2. Secondly insufficient O_2 in the composting matrix leads to anaerobic activity, resulting in offensive odours that can have a negative impact on site operations (Cabanas-Vargas and Stentiford, 2003). The biochemical transformation of organic matter by micro-organisms in the composting matrix occurs in the water-soluble phase (Bernal et al 1998). In the composting matrix this phase occurs in the boundary layer of water on the surface of

particles. For there to be sufficient O_2 in this environment it has to diffuse from the air in the pore spaces. The rate of diffusion has been shown by Van Ginkel et al (2002) and is proportional to the total volume of air space within the composting matrix. The level of O_2 that is required to be maintained in this pore space to ensure that the composting process is not limited is addressed in the research outlined in the following paragraphs.

Experiments undertaken by Klauss and Papadimitriou (2002) using 14 litre capacity, thermo-regulated and aerated vessels show an unclear set of results. One set of trials were carried out with the vessels managed at 65°C and exhaust O_2 concentration managed at 4-6%, 6-9%, 7-12%, 11-14% and 15-16%. These trials resulted in a loss of volatile solids of 1%, 1%, 11%, 6% and 12% respectively. The trials undertaken at 7-12% O_2 concentration showed a volatile solids loss of 11%, similar to the volatile solid loss of 12% found in the trial managed at 15-16% oxygen. The trial managed at 11-14% resulted in a volatile solid reduction of just 6%, around half the loss found in trials managed with similar oxygen concentrations. O_2 consumption for the same set of trials show a different trend, the trial managed at 15-16%, uptake peaked above 8 milligrams of O_2 per gram of volatile solids per hour ($mgO_2gVS^{-1}h^{-1}$) and averaged between 4 and $5mgO_2gVS^{-1}$ h^{-1} for the majority of the trial. Those vessels managed at 6-9%, 7-12% and 11-14% averaged an uptake rate of 2-3 $mgO_2gVS^{-1}h^{-1}$ for the majority of the trial. The trials managed at 7-12% and 15-16%, have a similar loss in volatile solid content of 11% and 12% respectively, but for the same trials oxygen uptake rate in the 7-12% trial was around one half of that found in the 15-16% trial.

Similar experiments using bench scale reactors were undertaken by Beck-Friis et al (2003) managing O_2 levels at 1%, 2.5% and 16%. Higher levels of composting rate were experienced in the reactor managed at 16% when compared to those at 1% and 2.5%.

The need to supply sufficient oxygen to a system to promote composting has also been studied by Suler and Finstein (1977). They measured the effect of different concentrations of O_2 maintained in a 12 litre force aerated composting vessel on the total amount of CO_2 produced over a 96 hour period. In this instance the mass of CO_2 produced was a measure of the rate of composting in the system, as it is a direct

product of microbial degradation. The rate of CO_2 production in the vessel maintained at a target O_2 concentration of 2% was significantly lower than those vessels maintained at an O_2 concentration of 10% and 18%, over a temperature range from 48°C to 72°C. The highest CO_2 production rate for the vessel managed at 2% was 13g CO_2 per 100g of dry compost, this occurred at temperatures of 48°C, 64°C and 68°C. The highest rate of CO_2 production in the vessel maintained at 10% was 26g CO_2 per 100g of dry compost, and the peak rate experienced in the vessel maintained at 18% O_2 was 27g CO_2 per 100g of dry compost, both peaks occurred at a temperature of 56°C. This research demonstrates that there is a slight reduction in composting rate when O_2 concentration is managed at 10% rather than 18%, and is significantly reduced when O_2 was maintained at 2%.

Hewings et al (2002) measured O_2 concentrations at 92 points throughout the matrix of a green waste windrow. They used this data to produce a 2 dimensional profile of O_2 concentrations throughout a section of the windrow, as shown in Figure 2.4. They found that approximately 25% of the windrow volume was below the 10% O_2 concentration that Suler and Finstein (1977) demonstrated would reduce the composting rate.

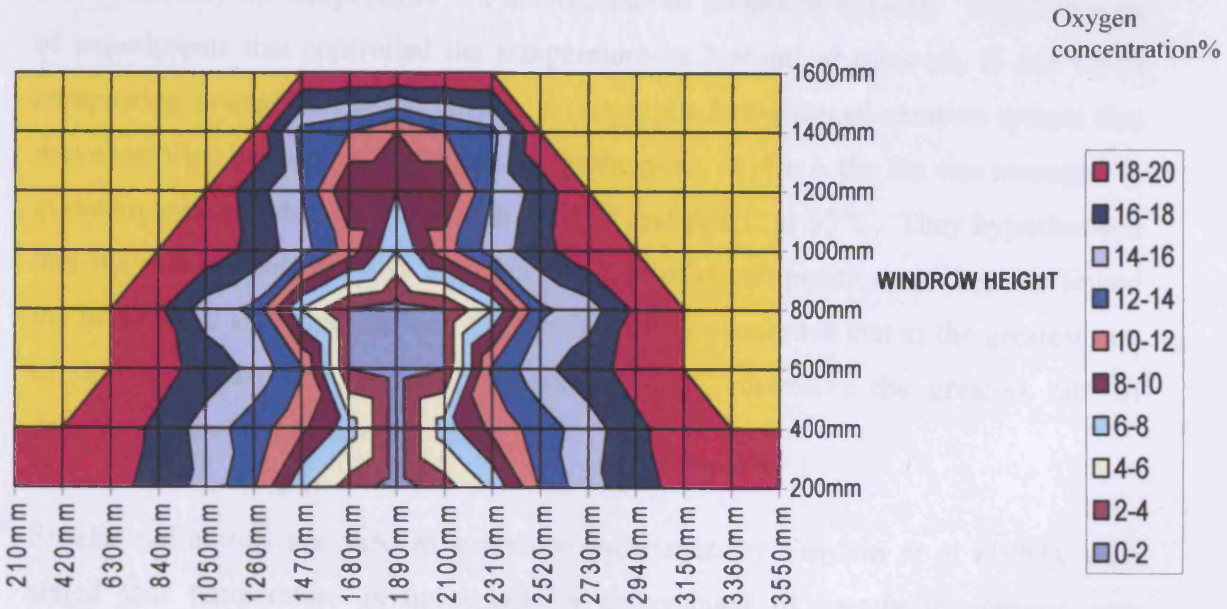

Figure 2.4. Oxygen concentration in gases sampled at 92 points throughout the composting matrix in a green waste windrow. The area in yellow represents air around the windrow. (Hewings et al, 2002).

Work undertaken to determine the forced aerated management requirements for composting systems has shown that managing oxygen concentration in the range of 5% -15% leads to temperature levels that inhibit microbial degradation (Finstein et al, 1983 and Psarianos et al, 1983). Kutzner (2000) concluded that using forced aeration to manage temperature in the composting matrix at 60°C also provides sufficient air to maintain O_2 concentrations in the optimum range.

The research demonstrates that composting rate is not significantly reduced when O_2 levels are maintained above 10% in the composting matrix, but when the temperature increases above 60°C; temperature becomes the limiting factor rather than O_2. It also demonstrates that even in a relatively small green waste windrow, 4 meters wide and 1.6 meters high, the composting rate in the core area was depressed due to reduced O_2 availability.

2.2.3 Temperature

MacGregor et al (1981) defined the temperature in a composting mass as a function of the accumulation of microbial metabolically generated heat energy and simultaneously the temperature is a determinant of metabolic activity. They ran a set of experiments that controlled the temperature in 3 identical piles (A, B and C) of composting sewage and wood chip mix. Each pile had a forced aeration system that was controlled by thermocouples placed in the piles; in pile A the fan was managed to maintain temperature at 45°C, pile B at 55°C and pile C at 65°C. They hypothesised that the rate of moisture loss indicated the rate of decomposition, as they are linked via heat output and vaporisation. On this basis they concluded that as the greatest rate of drying occurred in the pile managed at 45°C, therefore the greatest rate of decomposition had occurred in this pile.

Similar definitions are used in a review undertaken by Finstein et al (1983), who stated that temperature is universally a determinant of metabolic activity, one manifestation of such activity is heat generation. In composting systems heat generation leads to a dynamic positive and negative feedback where by rising temperatures promote higher rates of activity until a certain level is reached, at which point rising temperatures inhibit the rate of activity. The review indicated that the

temperature at which the feedback mechanism changed from positive to negative was 60°C.

Suler and Finstein (1977) ran a series of trials in bench scale reactors to determine the effect of temperature and O_2 content on the rate of decomposition of food waste by measuring the cumulative generation of CO_2 over 96 hours. They found that in trials where O_2 was maintained at 10% and 18%, CO_2 generation was at a maximum when temperature 56°C and only slightly less at 60°C.

Jeris and Regan (1973) used 2 different types of bench scale vessels to investigate the effect of temperature on CO_2 production. One method involved 3 separate horizontally rotating drums that were maintained at the target temperature with a heating element and O_2 was maintained above 10% in the exhaust gases. The other method used 500ml flasks that were contained within a temperature controlled environment, a Burrell shaker was used to agitate the flasks for 2 minutes every 2 hours. Gas samples were taken from the flasks every 3-4 hours and then completely aerated. They found that composting municipal waste with a high content of paper (60%-70%) gave a peak CO_2 production of 0.35 milli moles per day per gram of volatile matter, when the temperature was managed between 40°C and 50°C. When composting mixed refuse they found a peak CO_2 production rate of 4.5 milli mole per day per gram of volatile matter at a temperature of 60°C. The measured peak rate was more than 10 times that observed when composting mainly paper waste and it occurred some 10-20°C hotter.

Cathcart et al (1986) investigated the optimum temperature for composting crab waste in forced aerated, 200 litre insulated plastic composting vessels. These vessels were filled with shredded or un-shredded crab waste, along with chopped straw and a pH controller of ferrous Sulphate was added. The waste was then managed at a number of different maximum temperatures. They found that the maximum rate of CO_2 production occurred at 56°C for shredded and 63°C for the un-shredded crab waste.

Earlier work demonstrated that the temperature of the composting matrix also had an effect on the rate of degradation of different elements of a straw and horse manure mixture. The research by Waksman et al (1939) demonstrated that different

constituents of the composting waste were degraded more rapidly at different temperatures. The total dry matter, cellulose and hemi-cellulose content of a horse manure and straw mix was recorded and 600 grams of the mixture was then placed in 16 containers. The containers were then managed at 28°C, 50°C, 65°C and 75°C by placing in a water bath in the case of the 75°C sample and incubators for the other samples. There were four replicate samples in each trial. Cellulose content for each treatment was measured on day 9, 19, 33 and 47; the percentage of original cellulose remaining is highlighted in Figure 2.5. The samples stored at 28°C and 50°C have comparable rates of reduction, but the 50°C sample showed the greatest reduction in cellulose content of all four samples on days 19, 33 and 47, with 45%, 14% and 6% respectively, of the original content remaining. The sample stored at 60°C had the greatest reduction on day 9, at 65% of original content, but showed less reduction than the 28°C and 50°C samples on day 19, 33 and 47. There was very little reduction in cellulose content in the sample stored at 75°C. The microbial community present in the 75°C sample consisted almost entirely of spore-forming bacteria and only spores were present after a period. Therefore the lack of cellulose reduction is due to there only being non metabolising spores present.

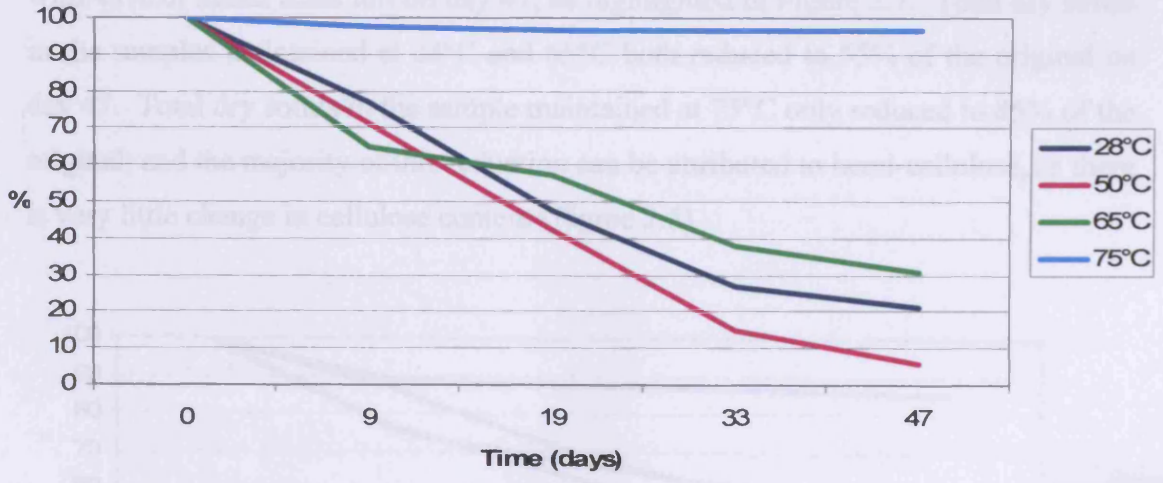

Figure 2.5. Proportion of original cellulose content of a horse manure and straw mixture stored at different temperatures, remaining after 9, 19, 33 and 47 days of composting. (Waksman et al, 1939).

Measurements of hemi-cellulose reduction for the same samples are different to that of cellulose. Reduction of hemi-cellulose is largest in the sample maintained at 65°C on day 9 and 19, whilst the sample maintained at 50°C had a slightly greater reduction on days 33 and 47. The most marked difference between cellulose and hemi-cellulose

reduction over time was that in the 75°C sample, as there was a very small loss in cellulose. But hemi-cellulose was reduced to 55% of original content by day 19, as shown in Figure 2.6.

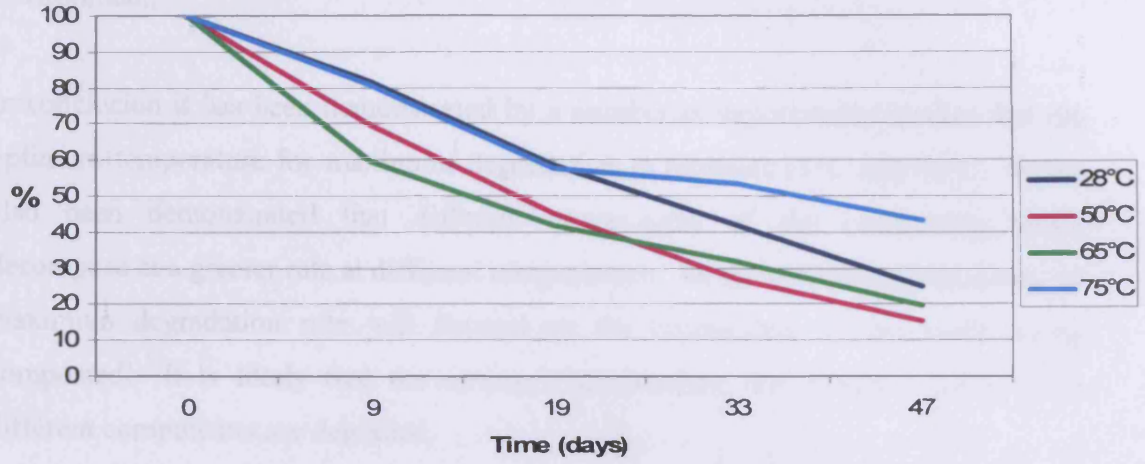

Figure 2.6. Proportion of original hemi-cellulose content of a horse manure and straw mixture stored at different temperatures, remaining after 9, 19, 33 and 47 days composting. (Waksman et al, 1939).

Reduction of total dry solids over the 47 day period was greatest in the 50°C sample, with 45% of initial mass left on day 47, as highlighted in Figure 2.7. Total dry solids in the samples maintained at 28°C and 65°C both reduced to 55% of the original on day 47. Total dry solids in the sample maintained at 75°C only reduced to 85% of the original, and the majority of this reduction can be attributed to hemi-cellulose, as there is very little change in cellulose content (Figure 2.5).

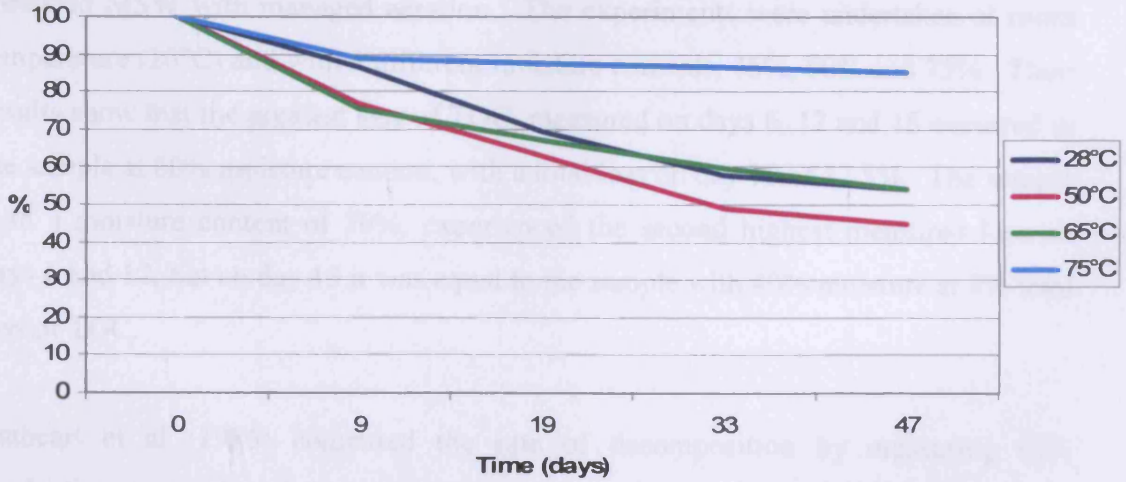

Figure 2.7. Proportion of total dry solids of a horse manure and straw mixture stored at different temperatures, remaining after 9, 19, 33 and 47 days composting. (Waksman et al, 1939).

Waksman et al (1939) do not indicate if air was added to the compost in the containers during the trial. If air was not added it was likely that the manure and straw mix did not have sufficient oxygen, therefore the results may indicate decomposition of the measured compounds in a partially or fully anaerobic environment.

In conclusion it has been demonstrated by a number of experimental studies that the optimum temperature for maximum degradation is between 55°C and 60°C. It has also been demonstrated that different components of the composting waste decompose at a greater rate at different temperatures. So the optimum temperature for maximum degradation rate will depend on the constituents of the waste being composted. It is likely that the optimum temperature will change over time as different components are degraded.

2.2.4 Moisture Content

Microbial decomposition of organic waste, occurs in thin liquid films on the surface of particles, therefore moisture is an important parameter in the composting matrix. Moisture levels can become limiting when they reduce to less than 20%, and the optimum moisture content is widely reported to be between 40% and 70% and is dependent on the characteristics of the feedstock (Jeris and Regan, 1973, Suler and Finstein, 1977 and Cathcart et al 1986). Hamoda et al (1998) examined the effect of moisture content on loss of Total Organic Carbon (TOC) in 0.5kg samples of shredded MSW with managed aeration. The experiments were undertaken at room temperature (20°C) and with 3 different moisture contents, 45%, 60% and 75%. Their results show that the greatest loss of TOC, measured on days 6, 12 and 15 occurred in the sample at 60% moisture content, with a total loss on day 15 of 12.5%. The sample with a moisture content of 70%, experienced the second highest measured loss on days 6 and 12, but on day 15 it was equal to the sample with 40% moisture at 8% total loss of TOC.

Cathcart et al (1986) compared the rate of decomposition by measuring CO_2 production in samples of shredded and un-shredded crab scrap with different moisture levels. The optimum moisture content in the shredded crab waste was 55% and in the

un-shredded samples it was 67%. This difference can be understood from the work undertaken by Barrington et al (2002) who demonstrated that the higher the moisture content of a certain feedstock, the more pressure is required to drive the same amount of air through the compost matrix. This indicates that void space in the composting waste has been reduced with higher moisture content as it has been partially filled with water. As the void spaces will be larger in the un-shredded crab waste it is able to maintain sufficient porosity with higher moisture contents. So the presence of excessive moisture is inhibiting microbial activity by decreasing oxygen distribution within the composting matrix.

Haug (1980) defined the total volume of voids within the composting matrix as free air space (FAS). He reported that a range of moisture contents have been shown as optimum for different composting wastes, this range is highlighted in Figure 2.8. He attributed these differences to the physical characteristics of the composting waste, especially bulk density and the extent of fibrous material within the waste. He hypothesised that the optimum moisture content for a particular waste was dependent on the maintenance of a minimum FAS. Therefore different wastes can maintain the minimum FAS with varying levels of moisture content.

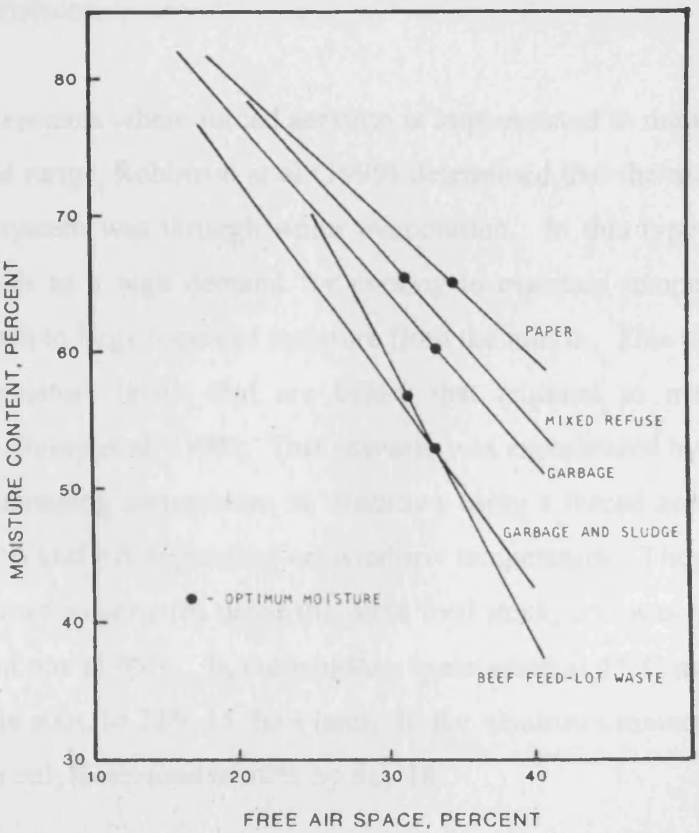

Figure 2.8. Free air space as a function of moisture content for various wastes. Reported optimum moisture contents tend to occur within a reasonably narrow range. (Haug, 1980).

The moisture content of the feedstock can impact on operations at composting facilities. If the moisture content of waste received is low, water will need to be added and if too wet it may be necessary to mix in a dryer material. Eklind and Kirchmann (2000) investigated the use of different bulking agents to improve structure, aeration, reduce overall moisture content and increase carbon content when composting organic household waste. They found that certain fractions of the household organic waste stream, mainly vegetables, had moisture contents of up to 90%. They mixed this waste with different materials, straw, leaves, hardwood chips, softwood chips, paper and peat. These mixtures were then composted, plus a control with no additions in 125 litre composting vessels. They found that the control had the greatest loss of dry matter, but this sample was determined to be partly anaerobic in the first month due to the presence of high volatile fatty acid concentrations. This effect is also demonstrated by work undertaken by Suler and Finstein (1977) who found that composting rate was very similar at moisture levels of 50% and 60% when the samples were maintained at oxygen concentrations of 2%, 10% and 18%. Composting rates with samples maintained at a moisture content of 70% were significantly less than those at 50% and 60%. Samples maintained at a moisture content of 70% showed greater composting rates with the maintenance of increased oxygen concentrations.

In composting systems where forced aeration is implemented to maintain temperature within a desired range, Robinzon et al (1999) determined that the major route of heat loss from the system was through water evaporation. In this type of system rapid composting leads to a high demand for cooling to maintain temperatures. A high cooling rate leads to large losses of moisture from the matrix. This rapid loss of water can lead to moisture levels that are below that required to maintain microbial decomposition (Sesay et al, 1998). This scenario was experienced by MacGregor et al (1981) when managing temperature in windrows using a forced aeration system that was switched on and off depending on windrow temperature. They employed three separate windrows constructed using the same feed stock, one was managed at 45°C, one at 55°C and one at 65°C. In the windrow maintained at 45°C moisture decreased from 76% at the start, to 22% 15 days later. In the windrows maintained at 55°C and 65°C, moisture only decreased to 40% by day 18.

The effect of moisture content on the permeability of composts was investigated by Das and Keener (1997). They found that large increases in pressure were required to drive air at a certain velocity through a bed of compost when moisture content approached 60%. Barrington et al (2002) found that the proportion of FAS in the waste material dropped from 0.76 at a moisture content of 60% to 0.57 at a moisture content of 75%, in a mix of pig manure and chopped hay. They then measured the pressure required to maintain an airflow rate of $0.9m^3\ hr^{-1}$ through the waste in a vessel 0.95 meters high with a diameter of 0.4 meters. The waste with a moisture content of 52% required a pressure of 56.7kPa to maintain the airflow rate, the same waste with a moisture content of 67% required a pressure of 134.2kPa.

The research in this section demonstrated that there is very little microbial activity when moisture content falls below 20%. High moisture content also has a negative impact upon microbial degradation rate by decreasing FAS as it leads to reduced oxygen transport within the composting matrix. Moisture content needs to be considered in the design and use of forced aeration systems. The higher the moisture content of an organic waste the more pressure is required to drive a certain air flow rate. Forced aeration systems can rapidly reduce the moisture content of an organic waste to a point at which microbial degradation is reduced.

2.2.5 Nutrient Availability

Organic waste is made up of three major constituents, water, organic and inorganic compounds. Moisture will usually make up around 65% of the waste, of the remaining 35% around 60% will be volatile solids and the rest will be inorganic compounds that microbes are unable to degrade (Hewings et al, 2003). Using this scenario 100 tonnes of green waste received will typically be made up of 65 tonnes of water, 21 tonnes of volatile solids and 14 tonnes of inorganic solids. As the micro-organisms only act upon the volatile solids content, even if all the volatile solids could be degraded the mass of waste would only be reduced by 20%, assuming there was no moisture loss. Reported mass loss during the composting process was around 50%; therefore the majority of mass loss was due to moisture removal.

Nutrients in organic waste fulfil two basic microbial needs, those of providing the basic elements for synthesising new microbial biomass and as an energy source for microbial activity. The heterogeneous nature of organic waste being delivered to centralised composting facilities will contain sufficient quantities of macro nutrients like carbon, sulphur, calcium, magnesium, potassium and phosphorous to ensure microbial activity and population size are not restricted, the one exception to this is nitrogen (Krogmann and Korner, 2000).

The ratio between the carbon and nitrogen content of a waste mixture is considered to be a significant parameter of composting suitability (Kutzner, 2000). It is widely reported that the optimum initial carbon to nitrogen ratio to ensure the process is not restricted is around 30:1 (Hamoda et al, 1998. Cathcart et al, 1986. Schuchardt, 2000). The importance of the carbon to nitrogen ratio is due to the microbes undertaking the composting process requiring carbon for energy and nitrogen for the production of new microbial biomass, which results in population size increases. Increases in population size provide a greater number of individual organisms to degrade the organic waste. Lower ratios of carbon to nitrogen usually result in ammonia volatilisation, causing odour issues at facilities and reducing the final nitrogen content of the compost. Nitrogen is a valuable element if the product is being applied as a fertiliser (Bertoldi, 1995). Methods used to determine the carbon to nitrogen ratio of organic wastes cannot illuminate the availability of those elements to microbial degradation. This is especially true for carbon as it is often in larger woody pieces that have a very small mass to surface area ratio, which ensures that carbon is not available to microbial action.

As highlighted in section 2.2.1, the organic compounds available in the waste, influences the structure of the microbial community (Waksman et al, 1939). In the initial stages organisms that are more able to utilise the more readily degradable compounds like carbohydrates, lipids and proteins, are present. Once these simpler compounds have been degraded, organisms that have the capacity to degrade more complex organic compounds like lingo-cellulose and chitin become more prevalent.

There are only 2 practical methods available to increase the availability of nutrients in the composting waste. The first is to add a nitrogen source to an organic waste that

has a higher than optimum carbon to nitrogen ratio. This is only financially expedient if a local source is available at no cost, but it is usually the case that lower rates of decomposition are acceptable in the winter months as waste entering the site is far less than that experienced in the summer months. The other method is to shred the incoming waste to a smaller particle size, which is more costly. Smaller particle sizes produce a larger surface area for the same amount of waste and as microbes function on the surface of particles, an increase in degradation rate can occur (Nakasaki et al, 1986). Unfortunately smaller particle sizes reduce the FAS within the composting mass (Agnew and Leonard, 2003). This leads to reduced oxygen availability, which has a negative impact upon the rate of degradation.

2.2.6 Physical Characteristics

The physical characteristics of an organic waste can be broadly defined as its bulk density, moisture content, particle size distribution and porosity. These parameters are related to each other as changes in one will normally lead to changes in at least one of the others. They have a direct influence on several key elements of compost processing such as, oxygen transport through the composting matrix, total surface area, moisture availability, aeration requirements and space required to treat a certain tonnage (Agnew and Leonard, 2003 and Keener et al, 1997).

The importance of oxygen in the composting process is highlighted in section 2.2.2, the physical characteristics of a waste affects the amount of oxygen that is required, along with how effective oxygen is transported throughout the waste matrix. The mechanism of oxygen transport in windrows is through passive airflow, as hotter air leaves through the upper surfaces of the windrow, cooler air is drawn into the sides of the windrow. Robinzon et al (2000) measured water evaporation from three different windrows, one not turned, one turned six times per week and one turned every 5 days. Moisture content in all three windrows was 50% at the start, the turned windrows were maintained at approximately 40% and the windrow that was not turned had no moisture additions over the 50 day process. They then calculated losses of water through evaporation, which was 13,988 kg for the windrow turned daily, 11,567 kg for the windrow turned every 5 days and 6,131 kg for the un-turned windrow. This demonstrates increased rates of evaporation with increased turning frequency; they

attribute the greater rate of evaporation to increased porosity and temperature in the turned windrows when compared to the un-turned one. It was concluded that the rate of degradation in the turned windrows was roughly double that of the un-turned windrow and that this was largely due to the turnings improving permeability and passive airflow.

Particle size indicates the total available surface area within the composting matrix to microbial action as this occurs in the thin liquid layer on particle surfaces (Nakasaki et al, 1986). Therefore if two wastes with identical chemical properties are shredded to different particle sizes the one with a smaller particle size will have the capability to degrade at a greater rate, due to its greater surface area. Typically in composting, reducing the particle size to increase surface area also has the effect of reducing the porosity of the composting waste. The resulting reduction in porosity will decrease O_2 transportation throughout the matrix leading to the degradation rate being adversely affected. This effect was measured by Hamoda et al (1998) who found that a waste with 40mm particle size lost 11% of total organic carbon during an 18 day process, but the same waste with a particle size of 20mm and 30mm lost 8% of total organic carbon over the same time period. They conclude that the particle size of the organic waste affected microbial activity by limiting O_2 transfer in the composting matrix. This effect is demonstrated in Figure 2.9 and 2.10. The arrows in Figure 2.9 represent airflow through a composting matrix, whilst Figure 2.10 represents the same waste with more small particles. These smaller particles have blocked the routes demonstrated by arrows in Figure 2.9.

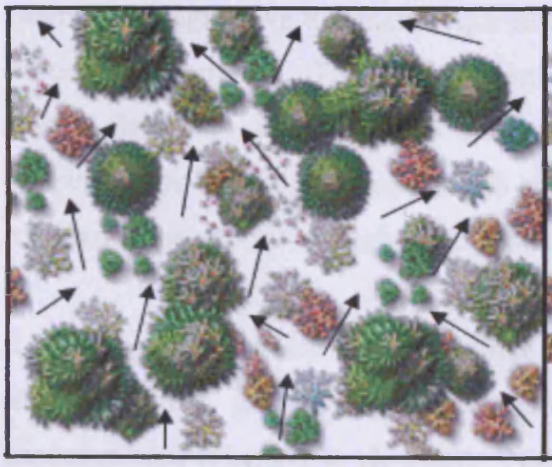

Figure 2.9 Representation of a composting matrix. Arrows demonstrate air flow routes.

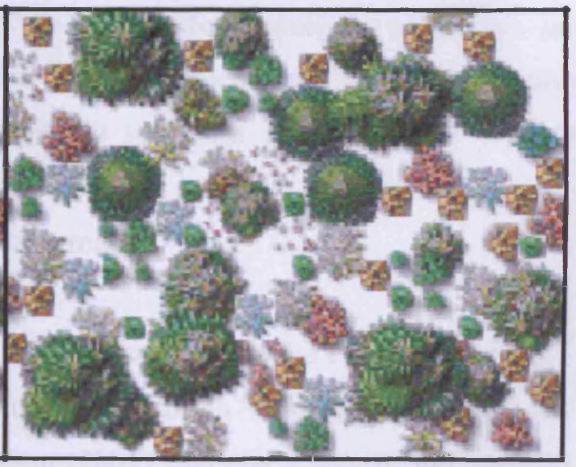

Figure 2.10 Representation of a composting matrix. The air flow routes seen in figure 2.9 are blocked by small particles.

Moisture content in the composting waste is a further key parameter, and was addressed in section 2.1.4. In brief the optimum moisture content for composting organic waste is between 40% and 70% and the particle size can have an effect on the optimum moisture content.

2.2.6.1 Impact of Physical Characteristics on System Design

The introduction of composting treatment regulations in the UK has led to the requirement of certain organic wastes being treated in enclosed systems. Composting in most enclosed systems requires the implementation of forced aeration to maintain O_2 content and temperature in the desired range. The physical characteristics of the organic waste will have to be known before an enclosed composting system can be designed as it affects several key design features. An enclosed composting system will be designed with a specific volume capacity but the density of the organic waste will have a large impact upon the tonnage that this volume can process. With reported bulk densities for shredded waste being between 370kg/m^3 (Hewings et al, 2002) and 750kg/m^3 (Compost Association, 2004), a 200m^3 vessel would have a maximum capacity of between 74 tonnes and 150 tonnes. If the upper figure was used in the design criteria and the waste delivered to site was at the lower figure after shredding, the system capacity would be less than one half of the designed capacity.

With the advent of new regulations the design of a forced aeration system could have a greater effect on plant viability as incorrect design may lead to the system not meeting the legislative treatment requirements and therefore would not be suitable for its designed purpose. There are a number of crucial elements for forced aeration system design to address, these are, providing sufficient air to manage O_2 and temperature in the desired range and to ensure there is sufficient pressure to drive the required volume of air through the composting matrix.

It has been demonstrated that the volume of air required to cool a composting matrix is significantly greater than the amount required to maintain optimum O_2 concentrations (Finstein et al, 1983). Notton (2005) suggests a significantly greater air supply rate of around 7×10^{-3} m^3 s^{-1} m^{-3} of waste to cool compost with a density of

500kg/m^3 respiring at 50gCO_2kgVS^{-1}day $^{-1}$, when compared to an air supply rate of around 0.25×10^{-3} m^3 s^{-1} m^{-3} to maintain O_2 levels.

Das and Keener (1997) demonstrated that the pressure required to drive a volume of air through a bed of compost increased with moisture content and bed depth. The volumetric flow rate divided by the area through which that air is passing is termed superficial velocity. To drive air with a superficial velocity of 0.05ms^{-1} through a 3 m deep bed of compost with a moisture content of 63% required a pressure of 1.2kPa, but with a bed depth of 2m the pressure required to create the same superficial velocity was 0.4kPa. Using the same waste and superficial velocity they replicated the experiment with a moisture content of 53.7% and found the pressure required was 0.3kPa at a bed depth of 3m and 0.2kPa for a bed depth of 2m. McGuckin et al (1999) compared the use of differently shaped and sized plastic bulking agents to pine bark as a method of increasing airflow through a raw vegetable organic waste, at different air flow rates. The difference in pressure required to maintain airflow rate through vegetable waste, and the same waste amended with pine bark is highlighted in Figure 2.11. The pressure required to maintain a superficial velocity of 0.04ms^{-1} in the vegetable waste (0.1kPa) is 2.5 times greater than that required to maintain the air flow rate in the pine bark amended waste (0.04kPa). This work demonstrates that a forced aeration system cannot be accurately designed unless the bed depth, moisture content and particle size distribution of the intended waste is known.

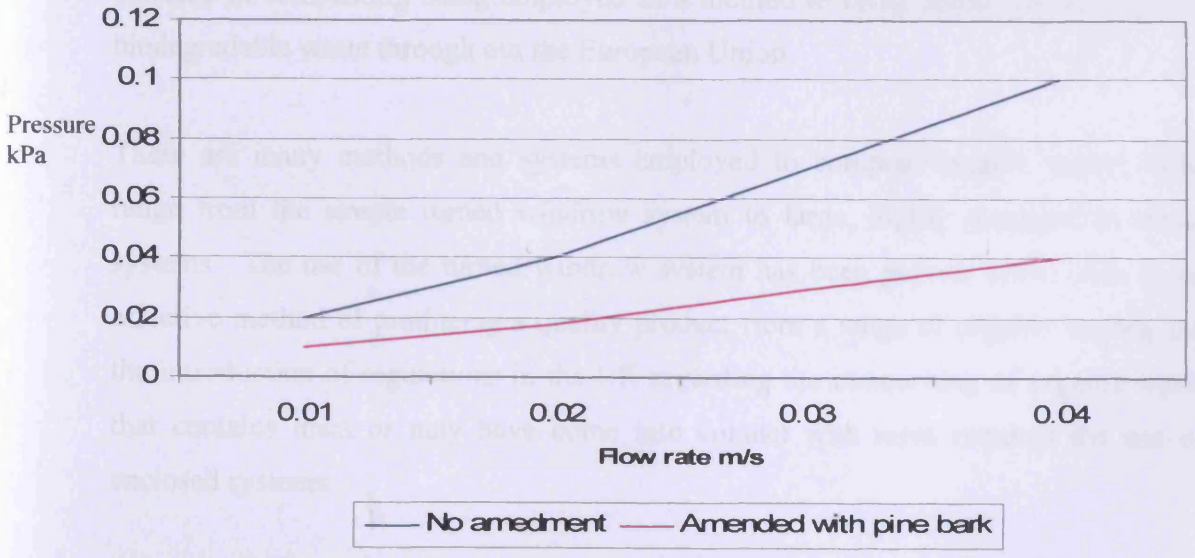

Figure 2.11. Pressure required to maintain an airflow rate through a bed of none amended vegetable waste and the same waste with an amendment of 1.25 m^3 of pine bark per tonne. (McGuckin et al, 1998).

In conclusion the physical characteristics of an organic waste have a large impact upon oxygen transport, aeration requirements and facility design, therefore knowing the characteristics of the organic waste stream being treated is essential.

2.3 Legislation Impacting on the Treatment of Organic Waste

The Animal by Products Regulations (ABPR) 2003 (Statutory Instrument 2003/1482, 2003), splits animal waste into 3 categories; Category 1 includes diseased and suspect carcases, specified high risk material and catering waste from international transport. These wastes may not be composted. Category 2 contains material like condemned meat that is not suitable for human consumption and may only be composted after rendering (133°C, 3 bar pressure). Category 3 includes catering waste from households and restaurants, former foodstuffs and some slaughterhouse waste (blood, feathers etc). EU regulations state that category 3 material must be treated in an enclosed system at over 70°C for 1 hour with a maximum particle size of 12mm (European Commission, 2002). Individual EU member states may introduce their own standards (that meet the same pathogen kill) for facilities that compost only catering waste.

The European Landfill Directive (European Commission, 1999) requires the amount of biodegradable wastes going to landfill to be drastically reduced over the coming decade, as highlighted in the introductory chapter. This requirement has driven an increase in composting being employed as a method to bring about the recycling of biodegradable waste through out the European Union.

There are many methods and systems employed to compost organic waste, these range from the simple turned windrow system to large, highly managed in-vessel systems. The use of the turned windrow system has been proven world wide as an effective method of producing a quality product from a range of organic wastes, but the introduction of regulations in the UK regarding the composting of organic waste that contains meat or may have come into contact with meat requires the use of enclosed systems.

In Wales regulations have been introduced to govern sites composting only catering waste (Statutory Instrument No.2003/2756 W.267, 2003). These regulations cover all aspects of site management but the most prescriptive elements address processing and are highlighted in Figure 2.12. There are 2 types of catering waste that will require separate treatment regimes, "meat excluded catering waste" and "non meat excluded catering waste". There is unlikely to be much difference between these 2 types, but meat excluded catering waste must have an audit system in place to ensure that householders are not putting meat in their catering waste segregated bin.

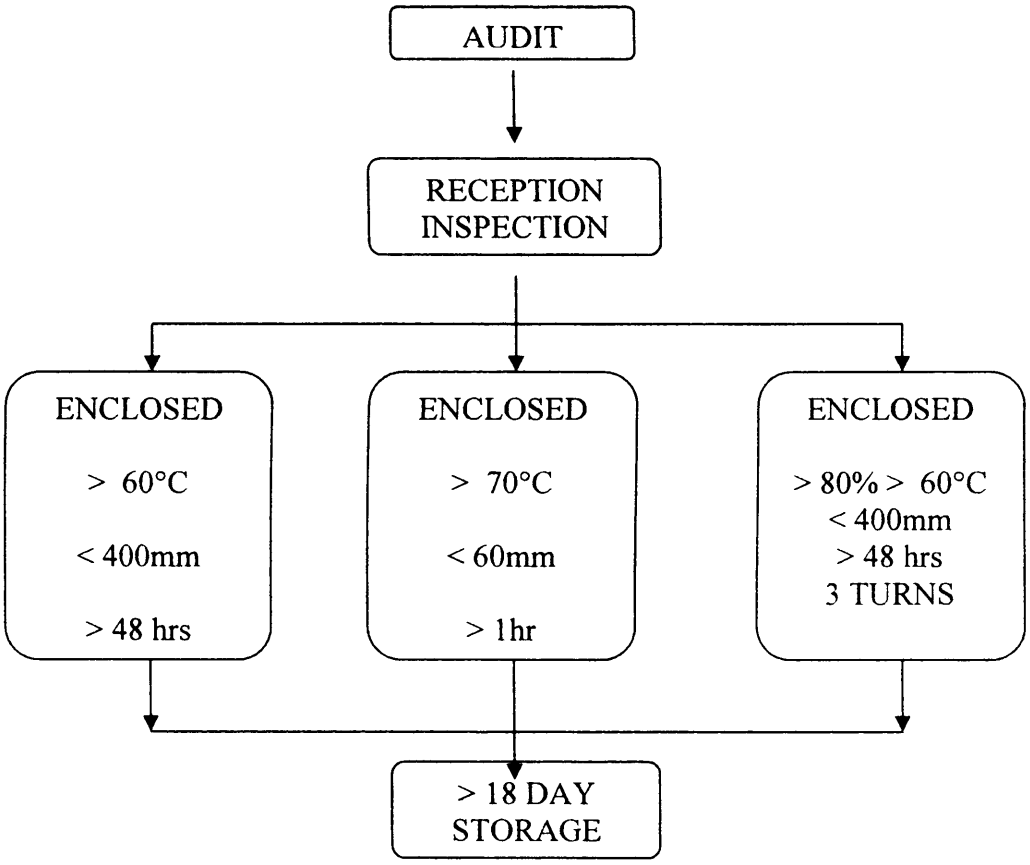

Figure 2.12 Processing requirements for sites composting meat excluded catering waste.

The treatment regime is based on the findings of a Department for the Environment Food and Rural Affairs (DEFRA) risk assessment on the composting of animal by products. The risk assessment contains an allowance for 2-3% of meat in catering waste that is being composted (Gale, 2002).

Catering waste that is designated as "non-meat excluded" does not require an audit to ensure the waste is meat excluded, but does require a higher level of treatment.

Catering waste that is classified as "non-meat excluded" will have to be primarily processed in the same way as "meat excluded" catering waste but instead of the 18-day storage requirement the waste will need to be mixed and treated again to the same parameters as the initial treatment. The only difference in the secondary treatment is that the waste does not have to be totally enclosed. It is important to note that an enclosed windrow system used for phase 1 treatment is expected to not have waste at different stages of treatment within in the same enclosure. Simply put, each batch must be separately enclosed.

For a facility to gain a licence they must provide information to the State Veterinary Service (SVS) that demonstrates the system is capable of meeting the regulations. Once they are satisfied that the system is capable of being managed in line with the requirements a time limited approval is given. This is done to allow the facility to receive and treat wastes covered by these regulations. During this period the facility will have to demonstrate that the temperature/time targets can be met and that the treated material passes microbial tests. The tests are designed to ensure that the system is capable of achieving appropriate levels of pathogen destruction. They qualify this statement by saying "The European Commission is seeking a scientific opinion on whether these organisms are appropriate marker organisms for such plants and will review this requirement if necessary" (DEFRA, 2004).

If the facility is treating catering waste, only Salmonella is required to be tested. Whereas treating category 3 wastes requires testing for Salmonella and Enterobacteriaceae. When a prescribed tonnage or number of batches has passed these tests without failure the facility will be awarded a 2 year licence. The licence will require a level of microbial testing to be undertaken during this period and will be dependant on the amount of waste or the number of batches treated.

There are many other regulations regarding site management, site operations, record keeping and monitoring equipment calibration. These include the requirement for waste to be received into a fully enclosed building, a one way flow of waste through the site to ensure material cannot by-pass the process, physical separation between processed and un processed waste and a documented pest control programme.

It has been noted by the author that on some facilities licensed to treat these types of waste the regulations have not been implemented in the way that they have been written. Two sites are known to be allowed to receive waste externally before it is enclosed. It has been noted that at least 2 others receive the waste in a reception building, where shredding takes place. The shredded waste is then transported externally to open vessels. These vessels are enclosed, by means of a sliding roof, after they have been filled. In other cases the vessels are filled and emptied from the same end, which does not constitute a one way flow of material through the system. This element of the regulations was included to reduce the risk of by-pass, which exists in the area in which vessels are being loaded and un-loaded, as treated and un-treated waste can be in the same area at the same time.

A further issue has been noted by the author whilst visiting sites is that in many cases the temperature probes are being placed in areas of the compost that are not close to, or at the periphery. Guidance published by DEFRA (2004) states that "As temperature will be lowest at the periphery, probes in the walls would be adequate". The placing of temperature probes in single treatment vessels is crucial, as simplistic systems can reach the minimum temperature in a large proportion of the waste. But reaching the target temperature in all parts of an aerated vessel is a substantial technological challenge.

2.4 Commercial Composting

2.4.1 Introduction

There are many methodologies employed to compost organic waste on a commercial scale. Every facility has slight differences in machinery, methods and management to compost organic waste but the main methodologies have been demonstrated and organised into a hierarchy of types by Gruneklee (1998), as shown in Figure 2.13.

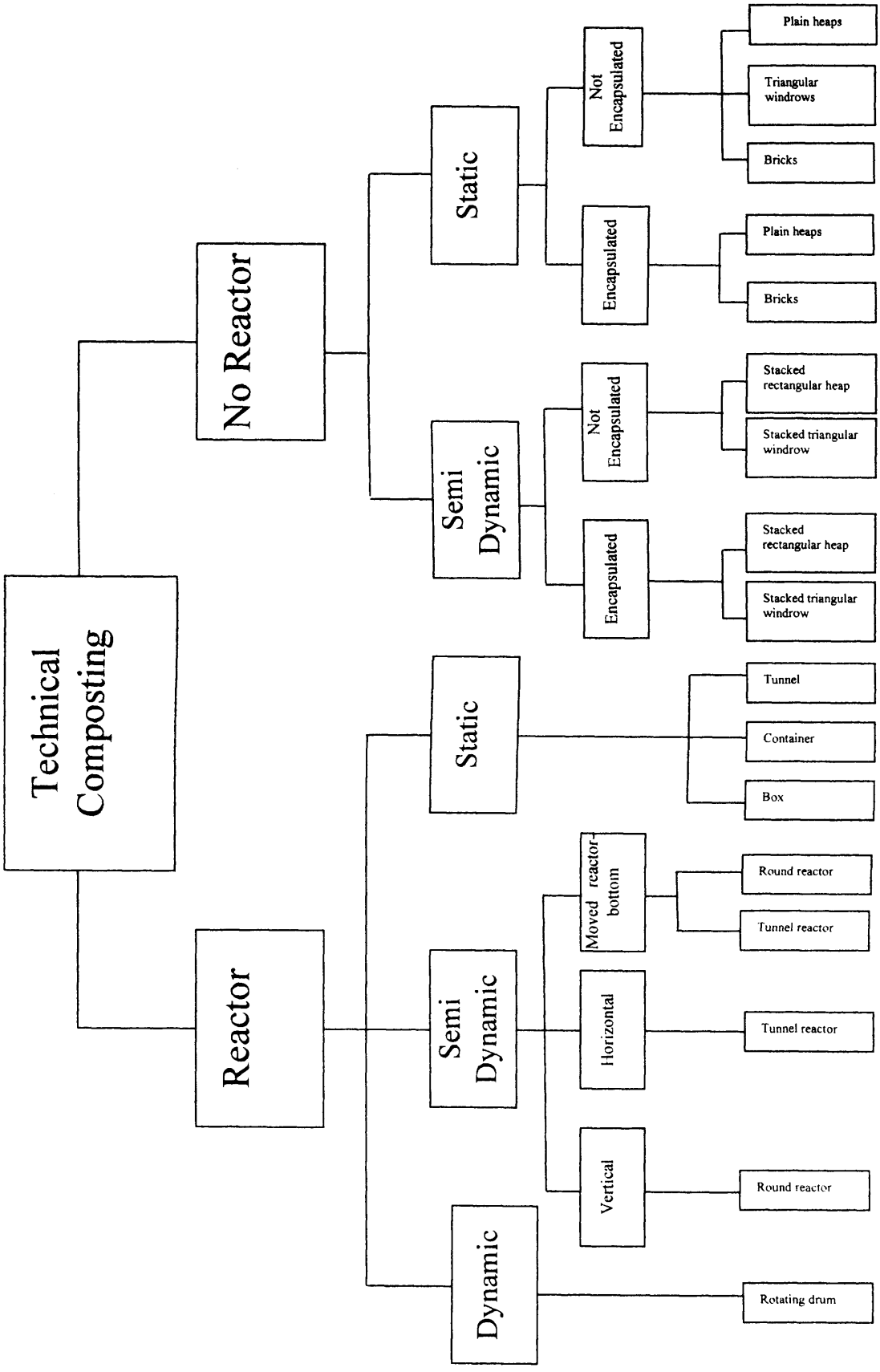

Figure 2.13. Hierarchy of composting systems (Grüneklee, 1998).

Historically the great majority of organic waste in the UK has been composted using the open windrow system. There are a number of ways to manage windrow composting depending upon the size of windrows and the machinery employed to turn them. The introduction of legislation regarding the treatment of organic waste that may contain, or have come into contact with meat products, requires this type of waste to be treated in an enclosed system. For this reason only windrow systems and fully enclosed composting technologies that are theoretically capable of meeting these regulations are described.

2.4.2 Windrow Composting

As mentioned in the introduction the vast majority of organic waste in the UK has historically been composted in windrows. A windrow is a long pile of shredded organic waste with a roughly triangular cross section. The shape of the windrow promotes passive airflow as hotter gases exit from the top of the windrow a flow of air into the sides occurs. The windrows are typically turned at frequencies ranging from a few days to weeks. Turning promotes pathogen kill by moving material from the cooler outside to the hotter core and restores permeability. Turning is undertaken by a number of methods; self propelled windrow turners either lift the material up and drop it back down behind the machine, as shown in Figure 2.14, or lift it onto an elevator that drops the material to one side, as shown in Figure 2.15.

Figure 2.14. A self propelled windrow turner, turning a green waste windrow. This machine is capable turning a windrow 4 meters wide and 2 meters high.

The lateral turn device allows a one way movement of compost from one side of the facility to the other. This promotes quality control as adjacent windrows are always at a similar state of treatment, therefore reducing the opportunities for waste to by-pass the treatment process.

Figure 2.15. A self propelled windrow turner with a lateral turn device fitted. The lateral turn device uses conveyors to transfer the waste lifted by the turner further along the composting pad. This machine is capable of turning a windrow 5.7 meters wide and 2.8 meters high.

Turners can also be towed behind tractors as shown in Figure 2.16, these machines require a gap between windrows which increases the area required to treat an equivalent amount of waste. Windrows can also be turned using bucket loaders or excavators, this method does not have the vigorous mixing effect which occurs when a dedicated turning machine is used and therefore does not result in the same level of porosity.

Figure 2.16. A tractor towed windrow turner. The turner is powered by the tractor engine and is capable of turning a windrow 4 meters wide and 2 meters high.

Larger windrows have become common place in the UK composting industry, with heights up to 5 meters high (Cabanas-Vargas and Stentiford, 2003). This has been due to operators attempting to treat more organic waste within a specified area. Expanding windrow size leads to odour problems and increased processing times, due to passive airflow being proportionally reduced. Larger windrows result in greater compression of lower layers of waste and increased distance from the core to the periphery. This increases the likelihood of anaerobic conditions developing in the larger core zone.

2.4.3 In-Vessel Composting Systems

The advent of regulations requiring catering waste to be composted in enclosed systems has led to the need for most composting facilities to invest in enclosed composting technologies.

As shown in Figure 2.13 there are a variety of in-vessel technologies types. The Composting Association divide all in vessel composting systems into 6 types (Composting Association, 2004):

- Containers,
- Tunnels,
- Agitated bays,
- Rotating drums,
- Silos or Towers,
- Enclosed halls.

Containers are generally mobile batch type vessel based on roll-on-off skip type technology, with a capacity of between 10 and 20 tonnes, with a forced air system utilising a perforated floor, an example is shown in Figure 2.17. One of the main advantages of containerised composting is the relative ease with which the system can be expanded by adding further units.

Figure 2.17. An example of a container composting system being loaded with organic waste through the hydraulically operated top door.

Gruneklee (1998) compared windrow systems to containerised systems and concluded that the containerised system was superior to windrows due to its uniform aeration and even temperature profiles combined with emission, moisture and odour control. Higher rates of degradation due to advanced aeration systems is one further reason given for the superiority of the containerised systems, though no data are given to confirm this.

Tunnels are very similar to containers but are fixed large scale vessels that usually have aerated floors where air is fed into the system. These systems are usually loaded with bucket loaders or extended elevator systems that reduce in length as the tunnel is filled, an example is shown in Figure 2.18.

Figure 2.18. An example of a concrete constructed tunnel composting system with insulated doors, in this case the tunnels are loaded and unloaded from the same end. (Composting Association, 2004).

Hoitink and Keener (1995) described the operation of a tunnel system which had a 7 day residence period followed by a 28 day maturation period in windrows. Control of the system was through monitoring of oxygen and temperature levels within the compost.

Agitated bays are similar to tunnels; retaining walls are constructed either side of the bay which allows a turner to straddle the bay and turn the waste, resulting in it being moved along the bay, as seen in Figure 2.19. Because of the retaining walls the floor area can be used more efficiently than a windrow as there is a greater volume of waste on the same area of floor. It is usual for several bays to be constructed next to each other and the turning machine shared between them. Because the waste is contained between retaining walls it cannot benefit from passive ventilation like windrows so a forced aeration system is required to ensure that decomposition rates are not reduced by lack of oxygen.

Figure 2.19. An example of an agitated bay composting system. The agitator moves along the top of the bay walls, lifting the organic waste and moving it a predetermined distance along the bay. (Composting Association, 2004).

Rotating drums are large cylinders that can be greater than 100 meters in length, mounted a few degrees from horizontal, an example is shown in Figure 2.20. They are loaded from one end and unloaded from the other, as the drum rotates the material is moved from one end to the other.

Figure 2.20. An example of a rotating drum composting system, it is approximately 30 meters long.

These can be run continuously by adding and removing an equivalent amount, or as batch processes by filling the whole drum for a period and then emptying all the waste. A comparison of several commercially available rotating drum composting systems was undertaken by Ali (2004) who calculated throughputs using data available from manufacturers. He highlighted that when analysing data provided by composting system manufacturers it is important to understand that most organic waste requires further treatment, usually in windrows, to make a product that is suitable for application to land.

Silos or tower systems, an example of which is shown in Figure 2.21, use a vertical plug flow method that operate on a continual basis, waste is loaded at the top of the vessel and an equivalent volume removed from the bottom. Elevator and auger technology is usually employed to load and unload these systems, which can be complicated and expensive. Because of the small footprint and height of this type of system, they can achieve large throughputs per unit of area, but due to the engineering can be capital intensive. Myrddin (2003) compared a variety of in-vessel composting systems using manufacturers' data for capacity, footprint and residence time within the system. She found that the highest throughput in kilograms per square metre per week was achieved by vertical composting units. However the area required for maturation of the compost, post treatment was not included in this calculation. Waste is usually loaded into the top of these vessels by auger or conveyor systems, and removed from the bottom with heavy duty augers. These systems are divided into vertical units, and aeration can be either passive or forced.

Figure 2.21. An example of a tower composting system. The conveyors that carry the waste to the top of the towers can be seen on the left of the picture and across the top of the system. (Composting Association, 2004).

Enclosed halls hold all of the material being processed in one large pile; waste is normally loaded at one end, moved across the floor using specially designed handling equipment such as large buckets and then removed at the opposite end. An example of a bucket system can be seen in Figure 2.22. These types of systems often use forced aeration to ensure that the process remains aerobic. They employ a number of conveyors to move the waste being processed from on area to another. Typically these systems have large infrastructures but operating costs can be low due to automation.

Figure 2.22. An image of the specialised equipment used in enclosed halls to turn and move waste through an enclosed hall composting system. (Composting Association, 2004).

In-vessel composting systems offer several advantages over open systems, such as odour control, reduced land requirement and improved process control (Smith and MacConell, 1992). Das and Keener (1997a) comment that large scale in-vessel composting has high operational costs and in order to optimise the economics high rates of degradation and quality end products must be achieved. This requirement for high degradation rates can only be delivered by highly developed process control and management systems. Bertoldi and Schanappinger (2001) comment that there are many sophisticated systems available, varying in complexity, but most of them do not address process control and management correctly. The higher capital costs of in-vessel systems can be partially offset by improvements to the rate of degradation and concurrent reductions in time and therefore space to produce a quality product but they will still be more expensive to build and operate than open windrow systems. It is important to note that waste on removal from in-vessel systems will usually require further treatment and maturation. The cost and extent of further treatment is rarely included in the costs of in-vessel systems and it is important to take these issues into account when planning composting systems.

The advent of legislation governing the treatment of organic waste that contains or may have come into contact with meat, along with the EU Landfill diversion targets requiring the diversion of organic waste from landfill is driving investment in compliant composting systems in the UK (European Commission, 1999). The required temperature/time treatment parameters have only been known since the regulations were published in July 2003 (European Commission, 2002); therefore systems available to treat waste to the requirements are mostly modified existing systems that were available before that date.

There are very large differences in capital and operating costs quoted for compliant systems and there is often a lack of information regarding the amount and cost of post in-vessel treatment required to produce a quality product. Until a universally accepted method of measuring rates of decomposition and stability achieved by available systems there can be no standardised method of assessing the claims of the manufacturers. Without these standardised methods of assessment it will continue to be problematical for investors in composting equipment to purchase systems with known capabilities, costs and efficiencies.

2.5 Process Products

2.5.1 Introduction

The process products from a composting system are treated waste, moisture (leachate or steam), gases and bio-aerosols. There is a reduction in the mass of waste during the composting process, and depending on the extent of processing the mass of original waste can be reduced by 50%. As indicated in section 2.2.5 the greatest proportion of mass lost is moisture, which makes up around 85% of the total. The other 15% of mass loss can be attributed to gaseous emissions and is in large part due to carbon loss in the form of CO_2.

The emissions that are of greatest concern to commercial composting facilities are addressed. These are emissions that have the potential to pollute, be a health risk or cause odour issues.

2.5.2 Emissions from the Composting Process

In the UK large scale composting facilities are required to operate on a surface impermeable to liquids, and any drainage from this surface has to be retained in a storage lagoon. This liquid waste is generally recycled back on the composting waste to maintain moisture content in the desired range, if there is an excess it can be spread on agricultural land if it is shown to provide benefit. If this route is not available it will have to be taken to a suitable treatment facility.

Other emissions from the composting process are air-borne; these emissions can be defined as moisture, dust, chemical and bio-aerosols, which are air-borne microbes. Dust can be managed by maintaining moisture content in the compost and is rarely an issue in the UK where precipitation is usually sufficient. If the material being handled is dry and dust is thought to be an issue, water sprays can be employed to remediate the problem.

Chemical compounds produced by the composting process that impact upon large scale environmental issues like global warming and ozone depletion are methane

(CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) (Yaowu et al, 2001). CO_2 is the major gaseous emission from composting as it is a direct product of aerobic microbial degradation. In fact the aim of commercial scale composting is to maximise CO_2 production as it is the mechanism by which organic matter is stabilised. The CO_2 produced from composting does not add to the total CO_2 in the atmosphere over time as it was recently assimilated by plants from the atmosphere (Hellebrand, 1998).

CH_4 is produced when micro-organisms cannot breakdown organic material to CO_2 due to O_2 not being available as an electron receptor under anaerobic conditions within the composting waste (Defoer and Langenhove, 2002). Even in forced aerated systems where there is a high percentage of O_2 in the exhaust gases there will be micro sites that are O_2 depleted. Haug (1993) indicated that during aerobic composting there are many low molecular weight odorous intermediate compounds formed, these compounds are less unpleasant to humans than their anaerobic counterparts but are still odorous.

N_2O has been shown to be produced by composting systems (Yaowu et al, 2001). They found that in the composting of food waste; significant nitrous oxide emissions started concurrently with ammonia volitisation. They also found that more than 95% of the N_2O emissions occurred during the later stages of composting, and attributed this situation to there being insufficient carbon left in the system. Studies by Beck-Friis et al (2001) found that organic waste collected from households, mixed with straw and then composted in 200 litre forced aerated vessels, resulted in $< 1\%$ of original nitrogen being lost as N_2O. Hellebrand (1998) found that windrow composting of green waste produced a relatively low level of N_2O emissions this is likely to be due to the relatively high carbon to nitrogen ratio usually experienced in green wastes. He also found that N_2O emissions were reduced with greater rates of aeration.

Of greater interest at commercial composting facilities is odour production during the composting process. As illuminated in a previous paragraph there are intermediate low molecular weight compounds formed in aerobic composting that are odorous, so even maintaining optimal conditions will not produce an odour free process. Hydrogen sulphide (H_2S) and ammonia (NH_3) are the 2 most common inorganic

causes of offending odours and organic sources generally come from sulphur and nitrogen containing compounds like methyl mercaptants, methyl sulphides and amines (Haug, 1980). There are 2 major processing parameters that are usually responsible for the production of unpleasant odours at composting facilities. These are anaerobic conditions and the volatisation of NH_3. Anaerobic conditions occur in composting systems that are inadequately aerated, in passive aerated systems like windrows the odours are only evident when turning occurs as the products of anaerobic degradation are in areas of the windrow where there is poor or no passive airflow, and therefore the odours are not transported until these areas become agitated. Even in forced aerated system it is not unusual for there to be insufficient airflow to provide the volume of air required to maintain O_2 in the desired range, or the distribution system has been inadequately designed to ensure complete distribution.

NH_3 volatisation is normally a separate issue and is due to the loss of excess nitrogen from the system. Tiquia et al (2002) found that during the composting of poultry manure more than half of the original nitrogen (58%) had been lost over a 168 day process in aerated static piles. Becks Friis et al (2001) found that more than 98% of the nitrogen lost from their forced aerated 200 litre composting vessel was in the form of NH_3. This loss of nitrogen is seen as a loss of a valuable fertiliser by some researchers and has provoked research into conserving this resource. If the nitrogen in the NH_3 can be conserved within the composting waste it can help to reduce emissions and hence decrease the problems associated with NH_3 emissions.

Jeong and Kim (2001) investigated a method to reduce the nitrogen loss from composting waste to increase its value as a fertiliser and suggested that the reduction in ammonia volatisation was a method of reducing odour issues at composting facilities. They found that the addition of water soluble salts of magnesium and phosphate reduced the loss of nitrogen from the composting system. Identical samples of food waste and wood chip were treated in similar vessels for the same amount of time. The sample with added salts lost 4.8% and the sample without lost 22% of initial nitrogen.

Eklind and Kirchmann (2000) composted household waste mixed with 6 different amendment materials with a view to measuring differences in nitrogen losses. They

found that there were differences in the loss of initial nitrogen between the different mixes, 70% for the control with no amendment, 60% for paper and softwood and around 42% for peat and straw. They concluded that initial carbon to nitrogen (C:N) ratio does not explain differences in nitrogen losses but go on to state that high nitrogen losses in the control batch was due to a low C:N ratio. The control batch had a ratio of 13 and the mixtures ranged from 22 to 34. These ratios are relatively low when compared to green waste composting facilities where NH_3 volatisation is rarely an issue.

A major objection to new facilities being built is the emissions of bio-aerosols from the composting process. The majority of concern is associated with *Aspergillus fumigatus* as it is a potential pathogen, as well as a potent agent of allergic reactions (Kutzner, 2000). This organism is not only associated with composting as it can be found where there are large amounts of degrading organic matter as is demonstrated by the disease it causes in the agricultural community i.e. farmer's lung. Breum et al (1997) studied the potential of municipal waste to generate air-born micro-organisms depending on the type of storage the waste had been under prior to collection. They concluded that the content of viable micro-organisms in the bio-aerosols generated from a waste cannot be expected to be the same as the organisms present in the waste material. They also found that waste stored in a container that allowed the access of air produced more bio-aerosols than those that were sealed. This work also highlighted that the organic waste being delivered to site is a generator of bio-aerosols before it enters the composting system.

A study of bio-aerosol dispersal of *Aspergillus fumigatus* from a green waste windrow composting site was undertaken by Kamilaki and Stentiford (2001). They found that levels adjacent to the studied windrow when no operations were occurring on site were 141colony forming units per cubic meter of air (cfu/m^3) downwind. Monitoring undertaken at the same time 25m up wind and downwind demonstrated measurements of <40cfu/m^3 and 176cfu/m^3 respectively. Monitoring undertaken whilst the windrow was being turned showed large increases, at 5 m downwind from the windrow 70×10^3cfu/m^3, at 40m down wind 33×10^3cfu/m^3 and at around 70m downwind 11×10^3cfu/m^3.

A further study of bio-aerosol dispersal from green waste windrows, during different operational activities was conducted by Taha et al (2007) at the CERT facility. This research demonstrated greater numbers of *Aspergillus fumigatus* bio-aerosols at 5 meters from a green waste windrow turning event. They peaked at 4400×10^3 cfu/m^3 of *Aspergillus fumigatus* when turning a 1 week old windrow, and 370×10^3 cfu/m^3 when turning a 4 week old windrow. In these instances the quantity of *Aspergillus fumigatus* was 5 to 63 times greater than that found by Kamilaki and Stentiford (2001).

In conclusion, emissions from composting can be categorised into three types, those that have a negative impact upon large scale environmental issues like greenhouse gases (CH_4, N_2O and CO_2), those that create odour issues (H_2S, NH_3 and nitrogen or sulphur containing organic compounds) and those that create health issues for operators and local inhabitants (dust and bio-aerosols). Odorous gases can be minimised by appropriate aeration as can CH_4 and N_2O, dust can be suppressed using water sprays but reducing bio-aerosol production in open systems is problematical. Bio-aerosols and odorous compounds from enclosed systems can be reportedly reduced by passing exhaust gases through a bio filter. A bio filter is usually made up of the coarse material remaining after the composted product has been passed through a fine screen. The exhaust gases from an enclosed composting system are passed through a bed of this material. The bio filter creates an ecosystem that is limited by nitrogen, and as the majority of odorous compounds contain nitrogen they are removed from the gases passing through this environment by micro-organisms. The effectiveness of bio-filters in reducing emissions of the bio-aerosol *Aspergillus fumigatus* was measured at 7 facilities by Sanchez-Monedero and Stentiford (2003), and found an average reduction of greater than 90%.

2.5.3 Product Quality

There are two main factors affecting the quality of a composted product, the presence of unwanted material i.e. plastic, metal, heavy metals, glass, stones, plant pathogens and propagules, and the extent of stability or maturity of the remaining organic material.

Larger unwanted materials can be removed from the composted product through size screening. There is also air separation technology that can remove light materials from the waste and other technologies that can remove metals and stones. There are no proven technologies to remove heavy metals and small particles of glass that cause safety concerns.

Plant pathogens and propagules can be destroyed by the higher temperatures (>55°C) found during the composting process. Quality control procedures are required to ensure all of the waste within a composting system remains over these temperatures for the required time period.

Stability and maturity are words often used to describe the biological quality of the end product of the composting process. Many reports use the terms interchangeably, whilst others define maturity as the condition where compost poses no adverse effects to plants and is determined empirically using bioassays (Chen and Inbar, 1993). Stability is a definable measure of the biological activity that can be sustained by the material. Therefore stability is a measure of the extent that the organic material has been degraded by microbial action and maturity is an elusive term that can mean different things depending on the view point of the commentator and use of the product (Iannotti et al, 1992).

One of the reasons composting is valuable as a solid waste management option is that the stable organic compounds present in the product are useful to plants and soils (Rynck, 1992). The degree of stability impacts upon plant response to compost application and site management issues like odour production. The time taken for a certain composting system to produce a product with a defined stability is an indication of the efficiency of that system (Stentiford, 1993).

A myriad of different methodologies have been put forward to measure compost stability and maturity, ranging from measurements of volatile organic acids, ammonium content, carbon to nitrogen ratio, infrared spectroscopy, cation exchange capacity, plant growth bio-assays, heat production, oxygen uptake and carbon dioxide production (McAdams and White, 1996). There is no universally accepted measure that accurately indicates when composted waste becomes stable enough to store

without the material becoming anaerobic and causing odour and application issues (Brewer & Sullivan, 2001 and Stentiford 2002).

There is growing acceptance that the most effective methods measure the rate of microbial activity that can be sustained by a waste material in the form of O_2 uptake, CO_2 production or heat output. A simple means of measuring stabilisation by measuring heat output is the Dewar self heating test. This method was first introduced in Europe in 1982 and was adopted as an official standard for "ripeness" by the German Department of the Environment in 1984 (Brinton et al, 1995). The Dewar self heating test consists of a 2 litre steel encased Dewar vessel with a 100mm internal diameter, a dual scale minimum-maximum inside/outside digital thermometer which has a range of 10°C-80°C and a thermocouple probe. The methodology requires the cooling of a representative sample to room temperature and amending moisture content to between 40% and 60% before placing it in the vessel. Over several days the microbial activity occurring in the sample leads to a temperature increase over ambient. The maximum temperature occurring in the vessel is used to determine the extent of stability. The scale used to determine the stability of the compost in the European system is based on 10°C increments as shown in Table 2.1.

Table 2.1 European system of compost stability classification using the Dewar self heating test. (Brinton et al, 1995).

Temperature rise above ambient (°C)	Official class of stability	Description of class	Major group
0-10	V	Very stable well aged compost	Finished compost
10-20	IV	Moderately stable; curing compost	Finished compost
20-30	III	Material still decomposing; active compost	Active compost
30-40	II	Immature, young or very active compost	Active compost
40-50	I	Fresh, raw compost, just mixed ingredients	Fresh compost

There have been a number of limitations highlighted that affect the accuracy of the self heating test, these are moisture content, low pH and heat damage (Zimmerman and Richard, 1992), and for these reasons it has not been universally accepted.

More recent research into producing a robust stability test has focused on the two parameters that are generally accepted to be the most accurate measurement of

compost stability, O_2 uptake and CO_2 evolution (Adani et al, 2002). Of these 2 gases O_2 uptake by the micro-organisms degrading the organic waste is reported to be the most accurate method of respiration rate analysis. CO_2 production does not differentiate between aerobic and anaerobic production and there is a reported difference between the O_2 uptake and CO_2 production depending on the make up of the organic waste. Notton (2005) demonstrated that when carbohydrate was being degraded by micro-organism the uptake of a mole of O_2 resulted in the production of a mole of CO_2, resulting in a CO_2:O_2 ratio of 1. This ratio changes when fat is being degraded to between 0.7 and 0.62 and when primary sludge is being degraded between 0.83 and 0.7.

There are a number of methods described in the literature to measure oxygen uptake under standardised conditions and therefore address the issue of environmental variables affecting the results. The Specific Oxygen Uptake Rate (SOUR) has been demonstrated by Stentiford (2002) to measure O_2 uptake by placing a sample of organic waste in an aqueous medium managed at a set temperature of 30°C. To ensure nutrients are not limiting microbial activity an addition of key nutrients is made. Performing the test in an aqueous solution overcomes the O_2 transfer limitations experienced in dry systems that are dependent on the physical structure of the organic material. The solution is aerated periodically and the rate of O_2 consumption is measured using a dissolved O_2 probe placed in the solution. The peak rate of O_2 consumption is expressed as milligrams O_2 g volatile solids^{-1} h^{-1}.

Methodologies that measure microbial respiration rate through O_2 uptake or CO_2 production have been demonstrated widely and have been compared by Adani et al (2002). They compared static respiration index, dynamic respiration index, Sapromat, specific O_2 uptake rate, and solvita methods. They found that all the methods analysed, apart from solvita demonstrated the extent of the stability of the organic waste. All were reproducible and ensuring O_2 diffusion through out the sample was imperative if the method was to be accurate.

Stability tests have been researched widely and there is general agreement that O_2 uptake and CO_2 production are the most accurate methods. As yet there is no universally accepted and implemented methodology, but it is likely that a method

based on microbial respiration will be accepted in the future. A respiration rate methodology based on CO_2 production has recently been included in the BSI PAS 100 (BSI, 2002) specification for composted waste products in the UK.

2.6 Measuring Rate of Decomposition

2.6.1 Introduction

The rate of decomposition in any composting system is best described by measuring the uptake of O_2 or the production of CO_2 or heat energy. The rate at which O_2 is consumed, or CO_2 and heat are generated is directly proportional to microbial activity and degradation occurring within the system (Cathcart et al, 1986, Cronje et al, 2004, Suler and Finstein, 1977, MacGregor et al 1981, Mari et al, 2003).

The majority of research into respiration rate monitoring of composting has occurred in small scale vessels (3-200 litres) managed under standardised conditions. These usually occur in controlled environments and demonstrate respiration rates under specific conditions. Commercial sized systems rarely contain homogenous waste types, temperatures or gas concentrations, therefore the efficiency of each system cannot be interpreted from simple measures of temperature, volatile solids content or gas content, as it is usual for there to be wide variation through out the composting matrix.

2.6.2 Carbon Dioxide Production

Work undertaken at Cardiff University's Composting Research Facility (Hewings et al, 2002, 2003, 2003a, 2004, 2005 and Notton, 2005) has monitored CO_2 production in relation to volatile solid content, environmental and management variables in commercial scale windrows, aerated bays, aerated vessels and in vertical plug flow and in an aerated test rig, utilising a number of different organic wastes. They found a maximum respiration rate for a green waste windrow of $30gCO_2kgVS^{-1}day^{-1}$ and an average of $14gCO_2kgVS^{-1}day^{-1}$. A trial containing a mix of green and citrus waste in a forced aerated vessel system demonstrated respiration rates ranging from 14 to $47gCO_2kgVS^{-1}day^{-1}$.

To compare the respiration rates found in small scale trials to those found in the commercial scale systems the different methods of expressing CO_2 evolution rates had to be standardised, worked examples of conversions are shown in Appendix A. Cronje et al (2004) found that a mix of pig manure and chopped straw evolved a maximum of 36mg CO_2 g total solids^{-1} over a 24 hour period at 50°C, as volatile solids were 86.8% of total solids this converts to 41.47gCO_2kgVS^{-1}day^{-1}. Jeris and Regan (1973) found a peak respiration rate of 4.3mmoles CO_2day^{-1}gVS^{-1} when composting mixed refuse at 62°C and 0.3mmole CO_2day^{-1}gVS^{-1} when composting newsprint at 40°C. These convert to 189gCO_2kgVS^{-1}day^{-1} for the mixed refuse and 13.2g CO_2kgVS^{-1}day^{-1} for composting news print. Suler and Finstein (1977) found that a 50:50 mixture of food waste and newspaper managed at 56°C with O_2 concentration at 18% had a peak respiration rate of 26g$CO_2$100g dry matter^{-1} over a 96 hour period. With a volatile solid content of 92% dry matter this converts to 70.65gCO_2kgVS^{-1}day^{-1}. The respiration rates measured were over a large range, varying between 13 and 189gCO_2kgVS^{-1}day^{-1}. The reported range of respiration rates from large scale systems was between 14 and 47gCO_2kgVS^{-1}day^{-1}, these are in the lower range of those found in bench scale trials.

A test rig was designed and built at Cardiff University's research facility with a capacity of 1m^3 to measure respiration rate under different conditions and with varying waste types. During the initial trial using green waste, respiration rates peaked at 200gCO_2kgVS^{-1}day^{-1} after 15 hours, this reduced to 131gCO_2kgVS^{-1}day^{-1} after 30 hours and to 72gCO_2kgVS^{-1}day^{-1} after 67 hours (Hewings et al, 2005a). This trial demonstrated an average respiration rate of 125gCO_2kgVS^{-1}day^{-1} over the first three days.

2.6.3 Oxygen Uptake

As mentioned in section 2.4.3, O_2 uptake by the micro-organisms degrading the organic waste is reported to be the most accurate method of respiration rate analysis. CO_2 production does not differentiate between aerobic and anaerobic production and there is a reported difference between O_2 uptake and CO_2 production, depending on the make up of the organic waste (Adani et al, 2002). Notton (2005) demonstrated

that when carbohydrate was being degraded by micro-organism the uptake of a mole of O_2 resulted in the production of a mole of CO_2, resulting in a CO_2:O_2 ratio of 1.

The reported difference in ratio between O_2 uptake and CO_2 production was demonstrated by Weppen (2001) when composting food waste amended with woodchips and chopped straw. He found that when adding fat to a batch of amended food waste the ratio was 0.87 and that for the control without added fat it was higher at 0.946. The reported difference between CO_2 evolution and O_2 uptake will need to be taken into account if a comparison of respiration rate measured by O_2 uptake in one system and CO_2 evolution from a different system is undertaken.

2.6.4 Heat Production

Heat produced during the composting process is a by-product of the chemical reactions mediated by microbes whilst degrading the organic matter. Bari et al (2000) investigated the kinetics of forced aerated composting and concluded that the extent of degradation in the composting mass could be predicted on the basis of outlet air temperature. The amount of heat produced in relation to O_2 uptake was measured by Weppen (2001) on food waste mixed with chopped straw or wood chips. He summarised that there was good correlation between O_2 uptake and direct calorimetry in the laboratory trials and found the relationship, 452 ± 29 kJ of heat energy produced for every mole of O_2 used. He also concluded that thermo-chemical estimates of specific heat of degradation from samples taken at the beginning and end of treatment were much less reliable than data obtained from on line evaluation.

Tancho et al (1995) investigated the relationship between substrate induced respiration and heat loss in contaminated soils and came to the conclusion that heat loss and CO_2 evolution were highly correlated. They also found that the detrimental effect of pollutants on soil microbes was demonstrated by either of the test methods in soil samples of only 1g. Similar work by Gustaffson and Gustaffson (1983) measured the effect of toxins on O_2 uptake, CO_2 evolution and heat production of a sediment based microbial community and also found good correlation between these three variables.

Rothbaum and Stone (1961) measured the heat production of *Escherichia Coli* (E.coli) in relation to O_2 uptake and CO_2 evolution in a liquid medium with different levels of glucose. They found that for every mole of CO_2 produced there was 581 kJ mol^{-1} of heat energy released, and for O_2 there was 467kJ mol^{-1} released. Rothbaum (1961) also investigated the heat output of thermophiles occurring on wool in relation to CO_2 evolution and found that at 60°C it was 631kJ mol^{-1} and at 70°C it was 381kJ mol^{-1}.

Notton (2005) used simple relationships to examine energy release in composting systems based on stoichiometric calculations. He demonstrated that the relationship between CO_2 evolutions, O_2 uptake and heat production changes in respect to the chemical composition of the organic waste being degraded and the production of new microbial biomass within the composting matrix. He also demonstrated that the ratio between CO_2 evolution and O_2 uptake varied between 0.72 and 1 for organic wastes that are commonly composted, with fat and oil making up the lowest ratio (0.72) and carbohydrate and bacteria making up the higher ratio (1). In a composting system some of the products of degradation will be incorporated into new microbial biomass, so measuring CO_2 evolution and O_2 uptake from gases entering and leaving a composting matrix will not be able to indicate the amount of CO_2 that has been incorporated into new microbial biomass. He went on to show that the weight of the newly formed biomass was governed by the yield coefficient (Y) and that Y was equal to the weight of new biomass formed divided by the weight of substrate used. Haug (1993) believed that values for Y derived from the composting process, was between 0.1 and 0.2.

Notton (2005) calculated the theoretical energy output per mole of O_2, with a yield coefficient of 0.1, to be between 430 and 530kJmol^{-1}. This agrees with the experiments performed by Weppen (2001) and Rothbaum and Stone (1961). He also determined that the theoretical heat output for every mole of CO_2 produced was between 430 and 630 kJmol^{-1} at a yield coefficient of 0.1. Again this correlates well with experimental measures undertaken by Rothbaum (1961) and Rothbaum and Stone (1961).

2.6.5 Conclusions

The literature demonstrates that the respiration rate of the microbial community degrading organic matter in a composting system can be accurately monitored by measuring either, O_2 uptake or CO_2 and heat production and that these three parameters are related to each other. The relationship between these parameters is affected by the chemical make up of the waste being degraded and the proportion of products incorporated into new microbial biomass (Y coefficient).

Measuring the respiration rate of composting waste in an encapsulated system, using either O_2 uptake or CO_2 production, can be simply achieved as inputs and exhausts can be easily controlled, measured and managed. Unlike measuring gas concentrations, that in a fully enclosed system will only have one inlet and one outlet point, heat will have diffuse losses through surfaces, which will be hard to define and measure.

Information on the relationship between the three measured parameters allows calculations to be made on the amount of air that needs to be added or removed from an enclosed system for a given respiration rate. This can also be said of the data on heat production as it demonstrates the amount of heat that needs to be removed from a system to maintain temperature at a required level in relation to the measured respiration rate.

Data presented in section 2.5.2 shows that CO_2 production rates in small scale laboratory trials and in a test rig peaked at up to $200gCO_2kgVS^{-1}$ day^{-1}. Which were considerably greater than those found in commercial scale systems at up to $47gCO_2kgVS^{-1}day^{-1}$. Suggesting that commercial scale systems are not managing environmental variables in their optimum.

Weppen (2001) concluded that thermo-chemical estimates of specific heat of degradation from samples taken at the beginning and end of treatment were much less reliable than data obtained from on line evaluation. This statement suggests that on-line evaluation methods are a reliable, accurate measure of degradation rates.

2.7 Summary

Measuring temperature, moisture, nutrient and O_2 availability individually does not accurately describe the rate of composting. Each of these individual parameters can have a profound impact upon the composting process, but it is the interaction between the microbial community and these environmental conditions that dictates the rate of decomposition.

Research has successfully used respiration rate measurements to describe the effect of environmental variables on composting for more than forty years. Apart from the novel work undertaken at Cardiff University's, Composting Research Facility there has been no known research that describes the respiration rate occurring in commercial scale systems.

The rate at which O_2 is consumed, or CO_2 and heat are generated is directly proportional to microbial activity and degradation occurring within the system. Measuring these parameters in relation to the volatile solid content of the composting waste effectively integrates the sum effect of environmental conditions on the activity of the microbial population. The CO_2 production rates found in small scale laboratory trials, of up to $200gCO_2kgVS^{-1}$ day^{-1}, when compared to commercial scale systems of up to $47gCO_2kgVS^{-1}day^{-1}$, suggests that the commercial scale systems are not managing environmental variables in a way that leads to optimal composting conditions. This conclusion is reinforced by Bertoldi and Schanappinger (2001) who comment that there are many sophisticated systems available, varying in complexity, but most of them do not address process control and management correctly.

The advent of legislation governing the treatment of organic waste, along with the European Union landfill targets requiring the diversion of organic waste from landfill, is driving investment in compliant composting systems. It is evident that the development of proven engineering data is required if in-vessel systems are to be managed effectively. Previous research has indicated aeration requirements for individual trials and systems, but it has not been related to a universal process parameter, which would allow the requirement to be calculated for any composting matrix. The research by Notton (2005) has demonstrated the amount of air required

to manage O_2 requirements, moisture loss and heat removal in relation to respiration rate.

The treatment requirements of the ABPR, has introduced the need for composting systems to ensure that 100% of the waste within the system is greater than a specified target temperature. The time taken for the waste to reach the target temperature will have a great impact on the extent of infrastructure required to treat a certain mass of compost. To minimise the amount of infrastructure needed to treat a certain volume of organic waste it is necessary to maximise temperature increase through process management.

It is clear that dynamic respiration rate monitoring is a valuable tool in analysing the composting process by integrating the effect of all environmental, chemical, physical and management parameters on the rate of decomposition. This monitoring technique has only been applied to commercial scale composting systems in a limited way. The effect of process control options on the rate of degradation in any system can be determined immediately by dynamic respiration rate monitoring. Developing the use of this methodology will increase composting management knowledge.

3 Measuring Dynamic Respiration Rate in Windrow Composting

3.1 Introduction

The pilot scale research facility mentioned earlier, composts green waste from Carmarthenshire County Council's Civic Amenity sites using traditional windrows. Windrow processing occurred in a 1,500m^2 building with controlled drainage. Green waste was delivered to the facility in 35m^3 roll-on-off type skips, and then loaded into a Seko 600/20 shredder/mixer using a tractor fitted with a hydraulic loader. The shredded waste was built into windrows, 4 meters wide, 2 meters high and 45 meters long. The building has a capacity for 4 of these sized windrows once space has been left to employ the tractor pulled windrow turner (Menart SP4000). Due to the windrow turner being towed behind a tractor, a 3 meter gap was required between windrows to allow the tractor access; this layout and the windrow turner are shown in Figure 3.1.

Figure 3.1. Windrows at the Composting Research Facility (A), and the windrow turner operating in the building (B).

To optimise composting in this system, methods were sought that were capable of measuring the rate of decomposition and the effect of management options on that rate. There is at present no widely used method to measure the rate of decomposition in commercial composting systems. It has been demonstrated that the most accurate methods of determining the rate of decomposition in small scale laboratory based trials is to measure the rate of activity of the microbial population (Cathcart et al, 1986, Cronje et al, 2004, Suler and Finstein, 1977, MacGregor et al 1981, Mari et al, 2003). Micro-organisms like humans consume oxygen (O_2) and evolve carbon dioxide (CO_2) and heat when undertaking activity. Measuring any of these three parameters will indicate the rate of decomposition. This rate determines the time, space and therefore costs required to compost a specific mass of organic waste.

Continuous monitoring of the rate of decomposition will immediately demonstrate the impact of management operations and different composting techniques used. Measurement of the rate of decomposition will allow changes in feedstock or management regimes to be evaluated immediately, rather than present evaluation methods that measure the stability of the composted material at the end of the composting period, which is usually months.

The majority of research associated with measuring O_2 or CO_2 in relation to composting has been undertaken by removing compost from a facility and placing it into a highly controlled laboratory environment. The need for these highly controlled conditions are justifiable when respiration rate is being measured to determine if a compost meets a standard for stability, but is less applicable when trying to maximise the rate of decomposition in a commercial environment.

The vast majority of waste composted in the UK is undertaken using the windrow system, but the recent requirement for organic waste that contains, or may have come into contact with meat, to be composted in enclosed systems to stringent treatment requirements will lead to more in-vessel systems being built (WAG, 2003). The development of a method that was capable of measuring respiration rate in open and enclosed systems was therefore required.

Measuring heat production in open and enclosed systems was thought to be problematical due to the difficulty of measuring total heat input and total heat loss as there are a number of complex routes for heat transfer. As measuring respiration rate through heat production was thought to be impractical, only O_2 uptake and CO_2 production rates remained. It was determined that O_2 uptake or CO_2 production would be suitable for enclosed systems that have controlled input and output of gases, but O_2 would be less suitable in open systems. O_2 concentration in air is relatively high at 21% by volume, and the low rate of passive air flow that was likely to be experienced in passive aerated composting systems, like windrows, would lead to small differences between ambient concentrations and those measured in gases exiting the windrow. As ambient concentration of CO_2 is in the region of 0.03% it was determined that increases in CO_2 concentration would be large when compared to back ground levels, leading to more accurate measurement of the microbial production rate. The rate of CO_2 production was then described in relation to the initial volume of green waste in m^3.

To gain understanding of respiration rate under typical commercial green waste windrow composting, 2 green waste windrows were monitored, one for a 14 day period starting 7 days after the windrow was formed and the other for a 41 day period starting 7 days after formation. The windrows were of the same dimensions as other windrows on the facility, and were managed in the same way. They were normally turned at intervals between 3 and 8 days, but windrow 2 was not turned from day 19 to 32, to examine respiration rate during periods of no turning.

The carbon to nitrogen ratio (C:N) in a green waste windrow is dependent on feedstock makeup, and is reported to be between 50 and 70:1. The optimum initial C:N ratio in a composting system is reported to be approximately 30:1 (Hamoda et al, 1998. Cathcart et al, 1986. Schuchardt, 2000). To examine the effect of increasing the nitrogen content on the respiration rate of a green waste windrow, a number of feedstocks were assessed for suitability. Dried sewage sludge pellets were thought to present a problem due to reports that re-hydration can be difficult to achieve. Inorganic fertilizers are easy to handle, homogenous and easily soluble but have a high cost, making them unsuitable as an additive in a commercial environment.

Chicken litter was chosen because it is available locally at no cost, easily handled and readily soluble but it does have the disadvantage of having odour related to it.

3.2 Methodology; Windrow Respiration Rate Monitoring

To ensure assumptions were correct regarding passive airflow rates from windrow systems and to determine the likely CO_2 concentrations that would be encountered, a temporary canopy was erected over a section of windrow as shown in Figure 3.2. The temporary canopy channelled gases leaving a section of the windrow through an exhaust pipe. Measuring the velocity of gases exiting the windrow through this pipe with a hand held hotwire anemometer and measuring the concentration of CO_2 in the exhaust, gave good indications as to the air flow rates (between 0.2 and 0.6 ms^{-1}) and CO_2 concentrations (up to 1.7%) that could be expected. This allowed the most suitable type of instrumentation to be sourced, for long term measurements in the field.

Figure 3.2. Temporary canopy channelling exhaust gases from a green waste windrow through a 110mm pipe. Hot wire anemometer used to measure velocity and infra red gas analyser to measure CO_2 concentration.

A canopy was designed to be placed directly over a windrow with minimum disturbance to the airflow over and around the windrow. The canopy was designed to cover 2400mm of the windrow length and full dimensions are shown in Figure 3.3.

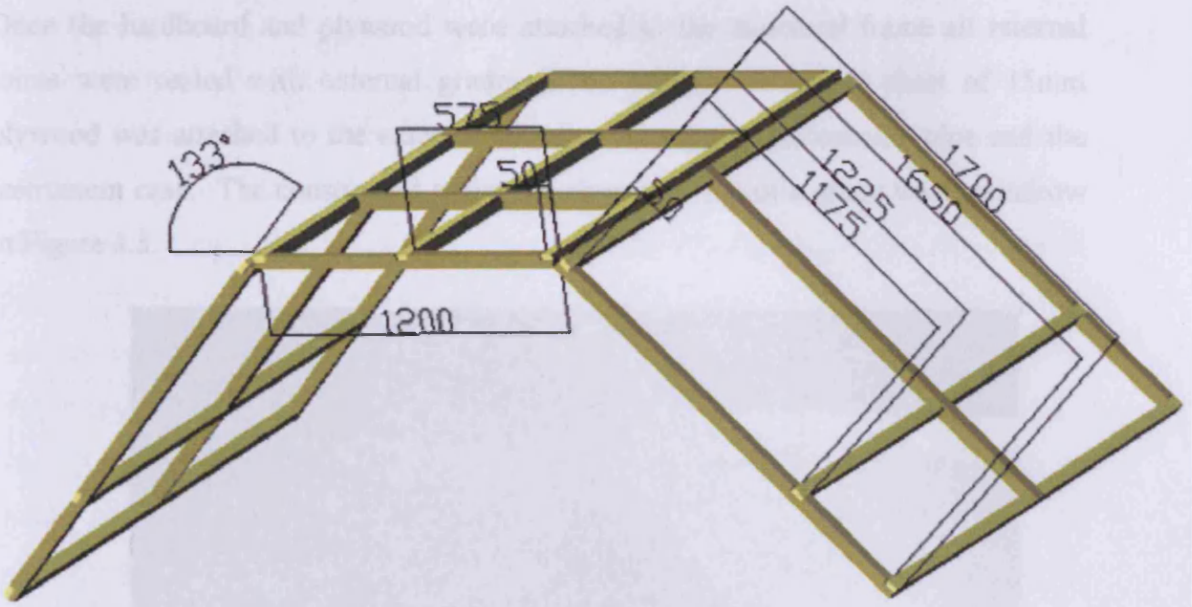

Figure 3.3. Design and dimensions (in mm) of the windrow canopy structure.

The structure was covered internally with 3mm plywood, and 15mm plywood was cut to the rough shape of the windrow and then attached to each end of the canopy. This was carried to ensure a good seal was made between the canopy and the windrow to ensure that gases exiting the windrow pass up through the 110mm exhaust pipe and could not exit from the sides of the canopy, without being measured, as shown in Figure 3.4.

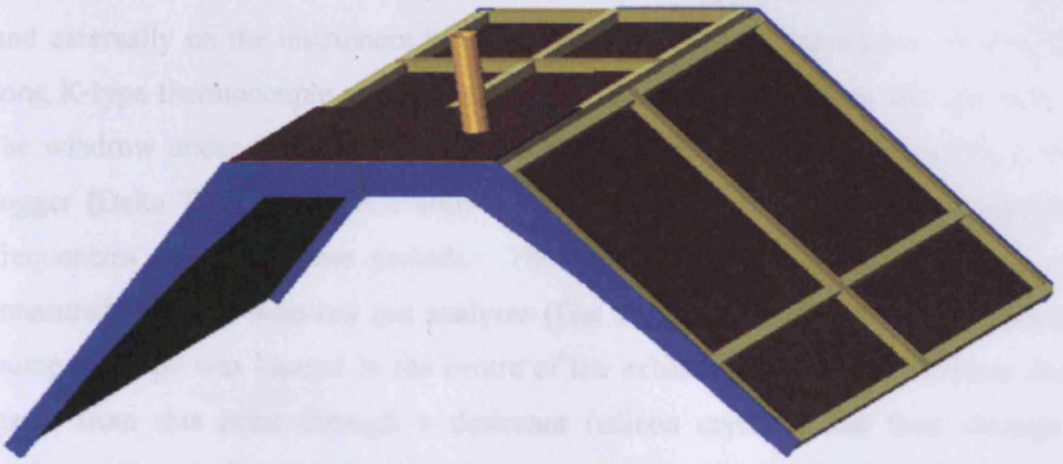

Figure 3.4. Design of the windrow canopy with hardboard attached to internal surfaces, shaped plywood end panels and 110mm exhaust pipe attached to the top surface.

Once the hardboard and plywood were attached to the structural frame all internal joints were sealed with external grade silicon sealer. A further sheet of 15mm plywood was attached to the external structure to support the exhaust pipe and the instrument case. The constructed canopy is shown on top of a green waste windrow in Figure 3.5.

Figure 3.5. Canopy constructed from wood, with 110mm pipe in the top to allow exhaust gases to exit, placed on a green waste windrow.

The velocity, temperature and CO_2 content of the gases are measured as they pass through this exhaust pipe. A hot film anemometer (E+E Electronik series EE65 or EE66) was mounted in the centre of the exhaust pipe. Thermistors (RS 813-828) were mounted into the exhaust pipe to measure the temperature of the exhaust gases and externally on the instrument box to measure ambient temperatures. A 1000mm long K-type thermocouple probe was inserted to a depth of 700mm into the core of the windrow under the canopy. These three instruments were connected to a data logger (Delta T, DL2e), which allowed the readings to be recorded at changeable frequencies over long time periods. The CO_2 concentration in the exhaust was measured using an infra-red gas analyser (Gas Data PCO_2) which had an on-board pump. A pipe was located in the centre of the exhaust pipe, the gas analyser drew gases from this point through a desiccant (silicon crystals) and then through a moisture filter, before passing into the gas analyser. The gas analyser had in-built logging capacity and was set and down loaded using a RS232 serial connection to a lap top.

The use of high resistance thermistors for the ambient and flue temperatures allows the minimisation of errors due to cable resistance. The thermistors used had a negative temperature coefficient meaning the resistance fell with increasing temperature; their resistance was 10 kΩ at 25°C with an accuracy of ±0.5°C. To measure the core temperature a type k thermocouple was used. A thermocouple gives a voltage output proportional to the difference in temperature between its hot and cold junctions and in order to ensure accuracy of this measurement a reliable cold junction is required. For these measurements the data logger's internal cold junction was used. The error of the hot film anemometer used to measure the gas velocity was ±3% of the reading; the anemometer was designed to allow for misalignment of up to 20 degrees. The thermistors, thermocouple and anemometer were all connected to the data logger for testing and calibration. The infra-red gas analyser measuring carbon dioxide concentrations was a separate unit capable of logging data, the accuracy of the meter was ±2% of full scale. This instrument set up was placed in a secure box mounted close to the exhaust pipe on the canopy, as shown in Figure 3.6.

Figure 3.6. Data logger, moisture trap, moisture filter and gas analyser shown in secure box connected to the canopy, along with laptop computer used to down load data.

The volume of shredded green waste below the canopy was measured by erecting a frame over the windrow and measuring the distance from the windrow surface to the frame every 100mm horizontally. This was done directly after the windrow was first turned following construction. The exhaust gas velocity and CO_2 concentration,

along with volume under the canopy were used to evaluate CO_2 evolution, per initial m^3 of composting waste. The resulting data can be used to describe the rate of decomposition at any point in time.

3.2.1 Green Waste Windrow 1

86 tonnes of shredded green waste with a moisture content of 60% was formed into a windrow 4 meters wide, 2 meters high and 45 meters long. The volume of green waste in the windrow was measured and found to be $4.2m^3$ per linear meter of windrow. The canopy covered 2.4 meters of the windrow, giving a total volume of green waste under the canopy of $10.1m^3$. The density of the green waste was then calculated from windrow length, mass in the windrow and total volume, giving a density of 455 kg m^{-3}. The mass of green waste under the canopy was calculated from the total mass of the windrow divided by the length and was 4586kg. With a moisture content of 60% there was 1834kg of dry compost under the canopy. The volatile solids content of the green waste received at the CERT facility was between 50 and 70% of dry matter, as demonstrated by Hewings et al (2003, 2005 and 2005a). Therefore the mass of initial volatile solids under the canopy was estimated to be between 917 and 1,284kg. The windrow was turned 3 days after formation and the canopy was placed on the centre of the windrow 4 days later. The windrow was turned 8, 14 and 18 days after formation.

3.2.2 Green Waste Windrow 2

92.8 tonnes of shredded green waste with a moisture content of 60% was formed into a windrow 4 meters wide, 2 meters high and 45 meters long. The canopy covered 2.4 meters of the windrow, and with each meter of windrow having a measured volume of $4.2m^3$, giving a total volume of green waste under the canopy of $10.1m^3$. The density of the green waste was then calculated from windrow length, mass in the windrow and total volume, giving a density of 491kg m^{-3}. The mass of green waste under the canopy was calculated from the total mass of the windrow divided by the length of windrow under the canopy and was 4949kg. With a moisture content of 60% there was 1980kg of dry compost under the canopy. The volatile solids content of the green

waste received at the CERT facility was between 50 and 70% of dry matter, as demonstrated by Hewings et al (2003, 2005 and 2005a). Therefore the mass of initial volatile solids under the canopy was estimated to be between 990 and 1,386kg. The canopy was placed on the centre of the windrow 7 days after formation, and remained in place, for the following 42 days. The windrow was turned directly prior to monitoring on day 7 and then on days 12, 19, 32, 40 and 44 days after formation.

3.2.3 Green Waste Windrow Amended with Chicken Litter

3,000 kg of pre-shredded green waste was loaded into the Seko mixer/shredder, followed by 1,500 kg of chicken manure. In total 67,085kg of green waste and 34,300kg of chicken litter were mixed in this fashion and formed into a windrow. The C:N ratio of this mixture was calculated to be 19.4:1, based on the estimated characteristics of the waste from Rynk (1992), which are detailed in Table 3.1.

Table 3.1 Estimated carbon/nitrogen ratio of the green and chicken manure windrow, based on assumed feedstock characteristics (Rynk, 1992).

Green waste	67,085 kg
60% moisture	26,834 kg dry matter
Volatile solids @ 60%	16,100 kg
Organic carbon @ 54%	8,700 kg
CN: ratio of 70:1	124 kg Nitrogen
Chicken manure	34,300 kg
40% moisture	20,580 kg dry matter
Volatile solids @ 60%	12,348 kg
Organic carbon @ 54%	6,668 kg
C:N ratio of 10:1	667 kg Nitrogen
Total Carbon	15,368 kg
Total Nitrogen	791 kg
Total C:N Ratio	19.4:1

The green waste and chicken litter was then built into a windrow approximately 2 meters high, 4 meters wide and 35 meters long, with a total mass of 101,385 kg, and 2,898 kg per linear meter of windrow. The volume of the windrow was measured using the method described in Section 3.2.1 and was again found to be 4.2 m^3 per linear meter. Density was 690 kg per m^3, simply calculated by dividing the total windrow mass by the volume per linear meter multiplied by the total length.

Samples of the mixture were taken from the formed windrow and the moisture content and carbon to nitrogen ratio of the mixture were measured. The nitrogen content was measured using the modified Kjeldahl method as specified in BS EN 13654-1:2001(BSI, 2001) and found to be 1.65% of the dry weight. The carbon content was measured using a Shimadzu SSM 5000A total organic carbon analyser and was found to be 35.12% of the dry weight, giving a carbon to nitrogen ratio of 21.3:1. The measured C:N ratio is close to that predicted in Table 3.1. The moisture content was measured gravimetrically, and was found to be 55%. Therefore the volume of green waste under the canopy was 10.1m^3, the total mass was 6955kg of which 55% was water, giving 3130kg of dry matter. The initial volatile solid content was estimated using the assumption that organic carbon was 54% of the volatile solid content (Rynk, 1992). The organic carbon content was 35.12% of the dry matter under the canopy (3130kg), which is equal to 1099kg. Dividing the total organic carbon content (1099kg) by 54% gave an estimated initial volatile solid content of 2035kg.

The canopy and associated equipment was mounted onto the windrow 3 days after completion of the windrow. Due to a number of technical problems the windrow respiration rate was only monitored from day 3 until day 20, day 44 until day 48 and day 69 until day 76.

3.3 Data Analysis

The data recorded by the carbon dioxide meter and the logger were downloaded and fed into an Excel spreadsheet. The rate of carbon dioxide release is calculated by the equation B1.

$$M_{CO2} = \frac{P \times \bar{U} \times A \times \Delta E_{CO2}}{R_{CO2} \times T_g \times 100}$$

Where

M_{CO2} is the mass of CO_2 evolved in kilograms,

P is atmospheric pressure, 101325 Pa,

$\bar{U}$ was the mean velocity of gas through the chimney in m/s,

A is the cross sectional area of the chimney $8.22 \times 10^{-3} m^2$,

ΔE_{CO2} is the change in concentration of carbon dioxide in %v/v (between inlet and outlet),

R_{CO2} is the characteristic gas constant for carbon dioxide 188.96 J/kg K,

T_g is the temperature of the gas being released in Kelvin,

Volumetric flow rate through the chimney was calculated using the cross sectional area and the mean velocity, and with a calculated Reynolds number of 6629 turbulent flow was assumed through the chimney, then the mean velocity is equal to 0.82 times the centre line velocity (Massy, 1989). This allows the volumetric flow rate of carbon dioxide to be found by multiplying the flow rate by the carbon dioxide concentration. To convert the volumetric flow rate of carbon dioxide into a mass flow rate the perfect gas equation is used to correct for temperature. Once the mass of CO_2 is known the respiration rate is calculated per cubic meter of compost, a worked example is shown in Appendix B.

3.4 Results

3.4.1 Green Waste Windrow 1

The canopy was placed on the windrow 7 days after formation. Respiration rate at this time was fluctuating between 2 and 3 $kgCO_2m^{-3}day^{-1}$ as shown in Figure 3.7. The canopy was removed directly before turning and was replaced directly after turning, and remained in place for a total of 14 days. The windrow was turned on day 8, which had little effect on the respiration rate as it remained in the same range as it had on day 7. From day 11 to 14 the respiration rate reduced to between 1.2 and 2.3 $kgCO_2m^{-3}day^{-1}$. The windrow was turned again on day 14, after which the respiration

rate increased rapidly to 3.6 $kgCO_2m^{-3}day^{-1}$ and then reduced to between 2 and 3 $kgCO_2m^{-3}day^{-1}$ on day 15 and reduced further over days 16 and 17 to 2 $kgCO_2m^{-3}day^{-1}$. The same pattern occurred after the windrow was turned on day 18, when respiration rate increased rapidly to 3.5 $kgCO_2m^{-3}day^{-1}$ and then a gradual reduction to the pre-turning rate by day 21.

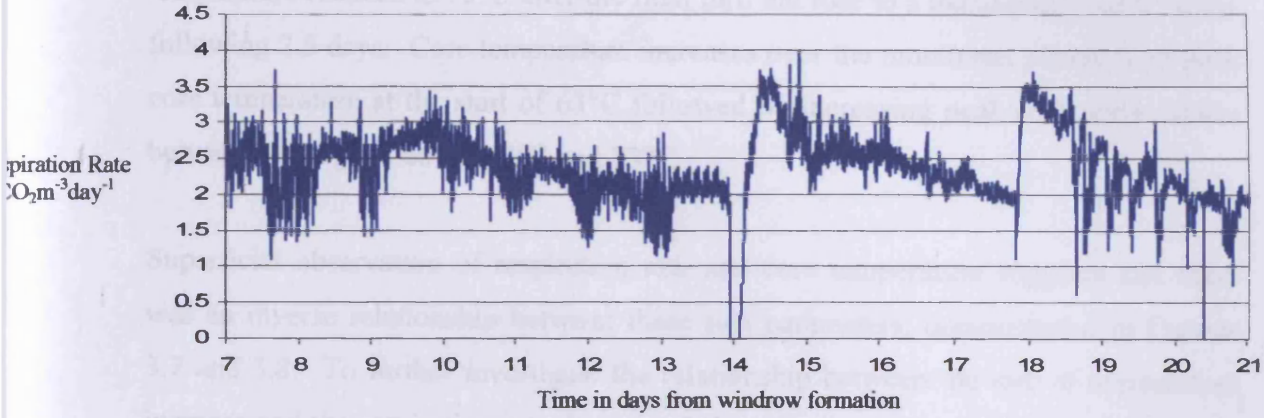

Figure 3.7. Respiration rate of a green waste windrow over a period of 14 days, starting 7 days after windrow formation.

The temperature in the core of the windrow was recorded over the same period and showed a reduction in temperature directly after turning followed by a gradual increase until the next turn, as shown in Figure 3.8.

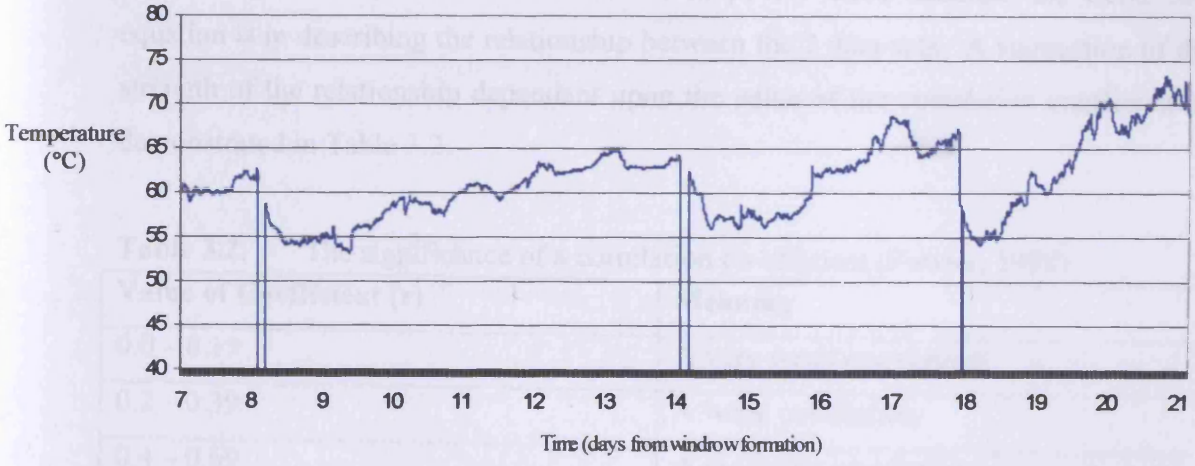

Figure 3.8. Core temperature for the period 7 days to 21 days after windrow formation. The windrow was turned on days 8, 14 and 18.

Core temperature was 60°C at the beginning of the monitored period and reduced to 55°C following the turning on day 8, after turning core temperature rose to a maximum of 65°C on day 13. Following the turning on day 14 the core temperature dropped to 57°C and rose to a maximum of 68°C on day 17. The pattern of core temperature dropping after turning followed by a gradual increase over the period between turns is demonstrated again following the turning on day 18. The core temperature reduced to 55°C after the final turn but rose to a maximum of 73°C in the following 2.5 days. Core temperature increases over the monitored period, with peak core temperature at the start of 63°C followed by increasing peak core temperatures between turnings of 65°C, 68°C and 73°C.

Superficial observation of respiration rate and core temperature suggests that there was an inverse relationship between these two parameters, demonstrated in Figures 3.7 and 3.8. To further investigate the relationship between the rate of temperature increase and the respiration rate decrease following a turning event, the data for each of these parameters during the period directly following each turning event was plotted separately. A linear trend line was fitted to the data between turning events. The trend line equation demonstrates the rate of change and the R^2 value indicates the correlation coefficient between the 2 sets of data. The correlation coefficient value is between 0 and 1 for a positive relationship and between 0 and -1 for an inverse relationship. The nearer the value of the correlation coefficient is to 1 for a positive relationship and -1 for an inverse relationship, the more accurate the trend line equation is in describing the relationship between the 2 data sets. A suggestion of the strength of the relationship dependant upon the value of the correlation coefficient is demonstrated in Table 3.2.

Table 3.2. The significance of a correlation co-efficient (Fowler, 1998)

Value of Coefficient (r)	**Meaning**
0.0 – 0.19	A very weak correlation
0.2 – 0.39	A week correlation
0.4 – 0.69	A moderate correlation
0.7 – 0.89	A strong correlation
0.9 - 1	A very strong correlation

Examples of the trend line fitted to the data for the period following the 3rd turn on day 18 to the peak temperature on day 20, for core temperature versus time, respiration rate versus time and respiration rate versus core temperature are demonstrated in Figures 3.9, 3.10 and 3.11 respectively.

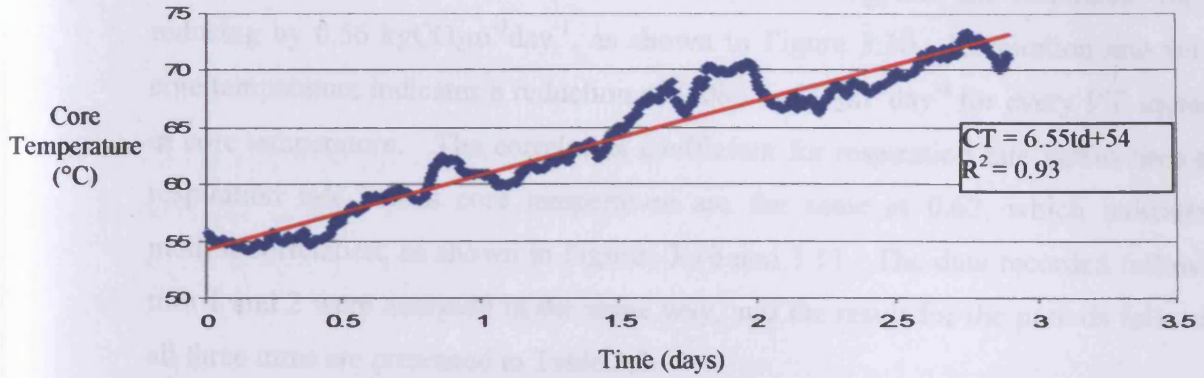

Figure 3.9. Core temperature (CT) plotted against time in days (td) with linear trend line, trend line equation and R^2 value.

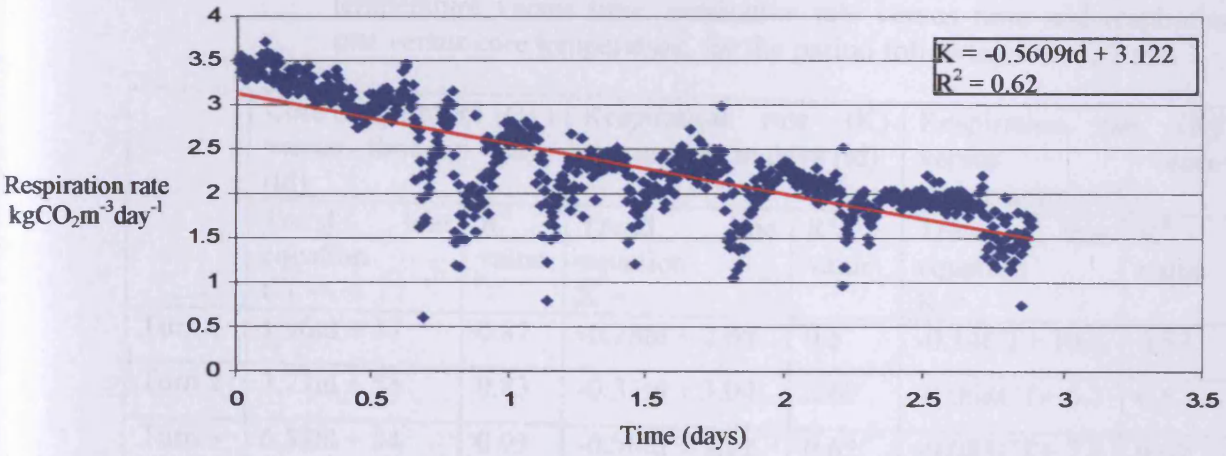

Figure 3.10. Respiration rate (K) plotted against time in days (td) with linear trend line, trend line equation and R^2 value.

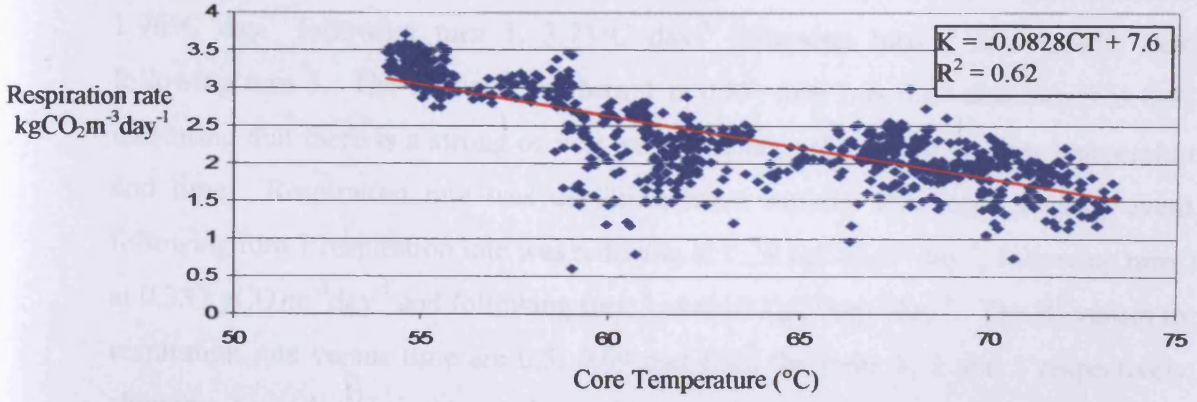

Figure 3.11. Respiration rate (K) plotted against core temperature (CT) with linear trend line, trend line equation and R^2 value.

The correlation coefficient for core temperature versus time for the period following turn 3 was 0.93, which can be described as a very strong correlation, as shown in Figure 3.9. The slope of the line is CT = 6.55td, demonstrating that the core temperature is increasing 6.55°C day^{-1} during this period. The slope of the line for respiration rate versus time is K = -0.56td, indicating that the respiration rate is reducing by 0.56 $kgCO_2m^{-3}day^{-1}$, as shown in Figure 3.10. Respiration rate versus core temperature indicates a reduction of 0.083 $kgCO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature. The correlation coefficient for respiration rate versus time and respiration rate versus core temperature are the same at 0.62, which indicates a modest correlation, as shown in Figures 3.10 and 3.11. The data recorded following turn 1 and 2 were analysed in the same way, and the result for the periods following all three turns are presented in Table 3.3.

Table 3.3. Windrow 1 trend line equation and R^2 value for compost core temperature versus time, respiration rate versus time and respiration rate versus core temperature, for the period following turn 1, 2 and 3.

	Core temperature (CT) versus time in days (td)		Respiration rate (K) versus time in days (td)		Respiration rate (K) versus core temperature (CT)	
	Trend line equation CT =	R^2 value	Trend line equation K =	R^2 value	Trend line equation K =	R^2 value
Turn 1	1.96td + 57	0.87	-0.28td + 2.68	0.5	-0.14CT+ 10.6	0.53
Turn 2	3.73td + 55	0.83	-0.33td + 3.04	0.69	-0.068CT+ 6.7	0.5
Turn 3	6.55td + 54	0.93	-0.56td + 3.12	0.62	-0.083CT+ 7.6	0.62

The rate of core temperature rise is increasing after each turn, with a growth rate of 1.96°C day^{-1} following turn 1, 3.73°C day^{-1} following turn 2 and 6.55°C day^{-1} following turn 3. The R^2 value for turn 1 is 0.87, turn 2 is 0.83 and turn 3 is 0.93, indicating that there is a strong or very strong relationship between core temperature and time. Respiration rate was declining more rapidly after each turning event, following turn 1 respiration rate was reducing at 0.28 $kgCO_2m^{-3}day^{-1}$, following turn 2 at 0.33 $kgCO_2m^{-3}day^{-1}$ and following turn 3 at 0.56 $kgCO_2m^{-3}day^{-1}$. The R^2 values for respiration rate versus time are 0.5, 0.69 and 0.62 for turns 1, 2 and 3 respectively, showing a moderate inverse relationship. Plotting respiration rate against core

temperature demonstrates an inverse relationship of between -0.068 and -0.14kg$CO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature. As the coefficient value ranges from 0.5 to 0.62 the slope of the trend line is only a moderate indication of the relationship between the 2 parameters. The average respiration rate for the monitored period was 2.33kg$CO_2m^{-3}day^{-1}$.

3.4.2 Green Waste Windrow 2

The canopy was placed on the centre of the windrow 7 days after formation, and remained in place for the following 42 days. Respiration rate for the monitored period is shown in Figure 3.12 and demonstrates a similar pattern of increased rate directly after turning events as those shown in windrow 1, occurring on days 12, 19, 32, 40 and 47. After the turning event on day 40 there was only a small increase in respiration rate, from 1.6 to 2kg$CO_2m^{-3}day^{-1}$, but following the turning event on day 47 there was a large measured increase from 0.5 to 2.5g$CO_2m^{-3}day^{-1}$.

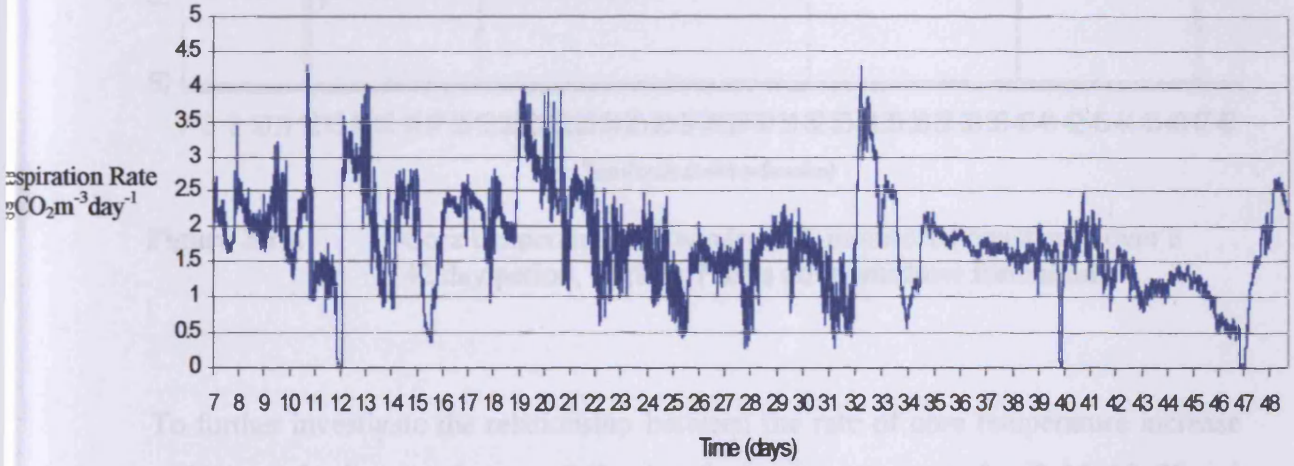

Figure 3.12. Respiration rate for windrow 2, monitored constantly over a period of 42 days, starting 7 after windrow formation.

The windrow was not turned for 13 days from day 19 to day 32, the respiration rate increased from 1kg$CO_2m^{-3}day^{-1}$ before turning, to a maximum of 4kg$CO_2m^{-3}day^{-1}$ directly after turning. Over the following 3 days the respiration rate reduced to that experienced immediately prior to turning and remained between 0.5 and 1.5 kg$CO_2m^{-3}day^{-1}$ for the following 10 days. A trough in respiration rate occurred on day 15 when the rate fell rapidly from 2.5kg$CO_2m^{-3}day^{-1}$ to 0.5kg$CO_2m^{-3}day^{-1}$ and then rapidly returned to previous levels. This pattern appears to a lesser extent on days 25,

Table 3.4. Windrow 2 trend line equations and R^2 value for core temperature versus time in days (td), respiration rate versus time and respiration rate versus core temperature, for the period following turn 1, 2, 3, 4 and 5.

	Core temperature versus time in days (td)		Respiration rate (K) versus time in days (td)		Respiration rate (K) versus core temperature (CT)	
	Trend line equation CT =	R^2 value	Trend line equation K =	R^2 value	Trend line equation K =	R^2 value
Turn 1	3td + 57	0.88	0.052td + 2	0.02	0.01CT + 1.4	0.01
Turn 2	3.86td + 56	0.87	-0.53td + 3	0.38	-0.15CT+ 11.6	0.53
Turn 3	3.52td + 56	0.9	-0.47td + 3.2	0.5	-0.13CT+ 10.6	0.54
Turn 4	7.96td + 56	0.86	-1.27td + 2.9	0.7	-0.17CT+ 12.3	0.86
Turn 5	4.43td + 62	0.88	-0.3td + 1.9	0.44	-0.07CT + 6.5	0.6

Core temperature versus time for all 5 turns demonstrates a very consistent R^2 value of between 0.86 and 0.9 which shows a strong or very strong correlation. Core temperature increases between 3 and 7.96°C day^{-1} following each turning and core temperature following turning is very closely related at between 57 and 56°C, except following turn 5 when core temperature was 62°C.

The relationship of respiration rate with time and respiration rate with core temperature for turn 1 shows no real correlation, with R^2 values of 0.02 and 0.01 respectively. Respiration rate versus time demonstrates an inverse relationship with a rate reduction of between -0.3 and $-1.27 kgCO_2 m^{-3} day^{-1}$. The slope of the trend line for respiration rate versus temperature following turns 2 -5, varies between -0.07 and -0.17, with modest R^2 values for turn 2, 3 and 5 and a strong correlation on turn 4 with a R^2 value of 0.86.

Rapid changes in respiration rate and core temperature occurred on days 15, 25, 28, 31 and 34 when no turning had been undertaken. As these changes in core temperature and respiration rate had occurred independent of a turning event, the changes on days 25 and 28 were examined in more depth.

The rapid increase in respiration rate on day 25 was investigated by examining key parameters in detail during the period from 613 to 616 hours after windrow formation.

Core temperature during the monitored period reduced from 70°C to 66.5°C and respiration rate increased from 0.8kg$CO_2m^{-3}day^{-1}$ at the start of the period to a peak rate of 1.6kg$CO_2m^{-3}day^{-1}$ near the end of the monitored period, as demonstrated in Figure 3.14.

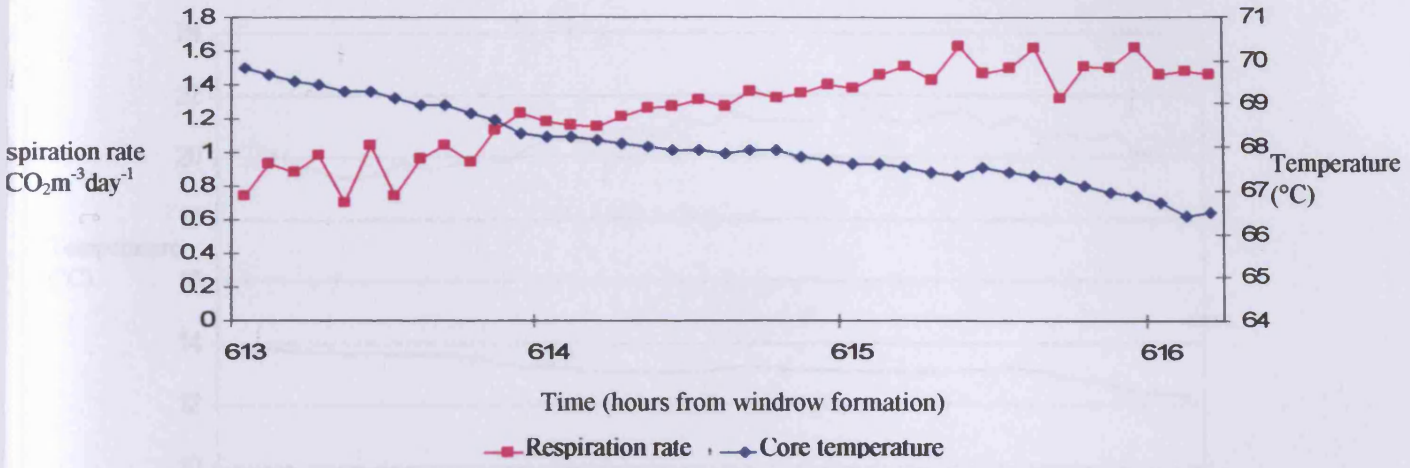

Figure 3.14. Core temperature and respiration rate recorded in windrow 2 over a three hour period, starting 613 hours after windrow formation.

During the same period CO_2 concentration measured in the canopy exhaust increased from 0.4 % to 0.8% and gas velocity measured in the exhaust averaged 1.1 ms^{-1}. Gas velocity in the exhaust was erratic, varying between 0.8 and 1.3 ms^{-1} during the first hour of the measured period when CO_2 concentration increased from 0.4 to 0.7 %, as shown in Figure 3.15.

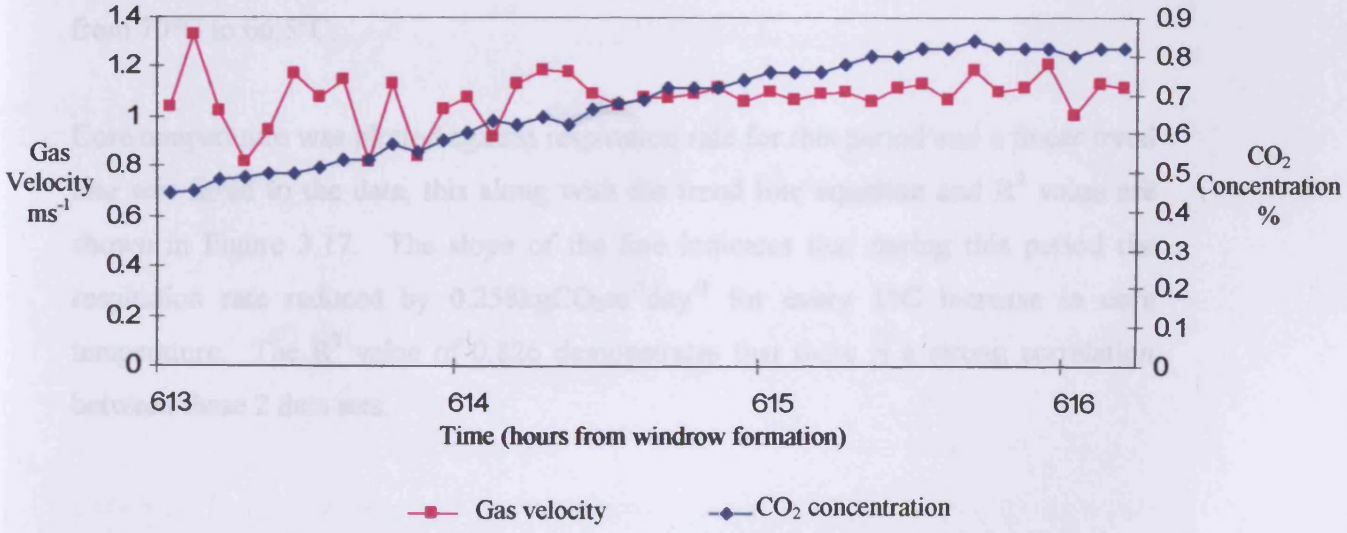

Figure 3.15. Gas velocity and CO_2 concentration in the canopy exhaust during a 3 hour period starting 613 hours after windrow formation.

Over the monitored period ambient temperature reduced from 13.8°C to 12.3°C and gas temperature measured in the canopy exhaust was 20°C at the start of the period, peaked at 21.6°C on hour 615 and reduced back to 20°C at the end of the period as demonstrated in Figure 3.16.

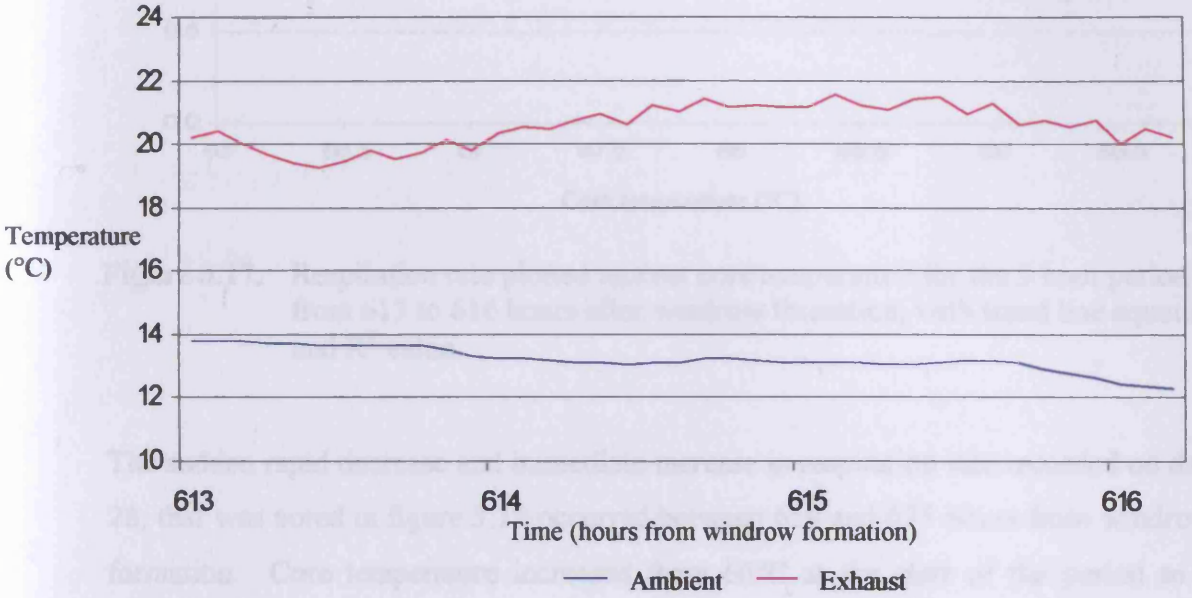

Figure 3.16. Ambient and exhaust gas temperature over a three hour period starting 613 hours from windrow formation.

Respiration rate doubled over the 3 hour monitored period, from 0.8kg$CO_2m^{-3}day^{-1}$ at the start of the period to a peak of 1.6kg$CO_2m^{-3}day^{-1}$, with core temperature reducing from 70°C to 66.5°C.

Core temperature was plotted against respiration rate for this period and a linear trend line was fitted to the data, this along with the trend line equation and R^2 value are shown in Figure 3.17. The slope of the line indicates that during this period the respiration rate reduced by 0.258kg$CO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature. The R^2 value of 0.826 demonstrates that there is a strong correlation between these 2 data sets.

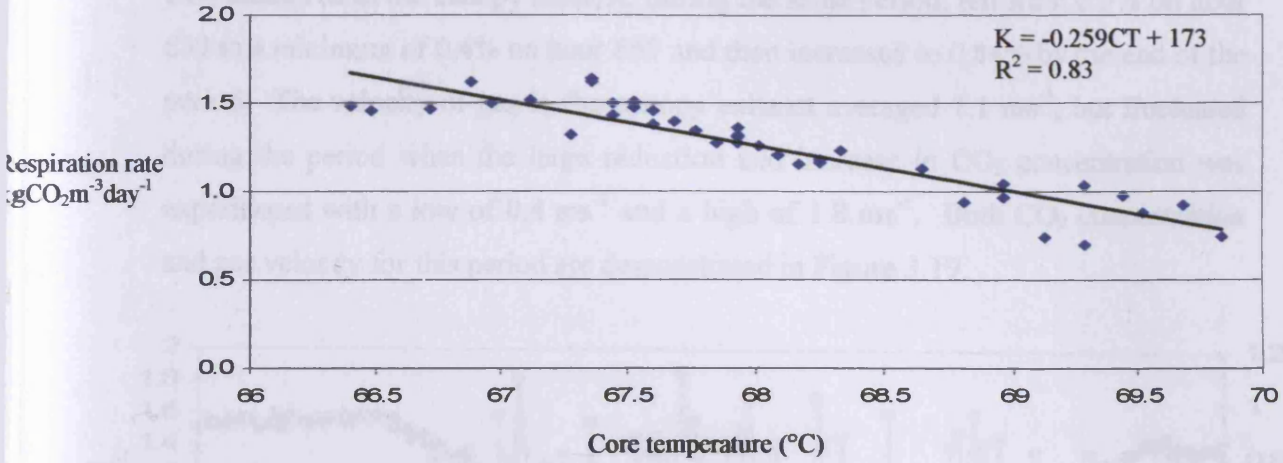

Figure 3.17. Respiration rate plotted against core temperature for the 3 hour period from 613 to 616 hours after windrow formation, with trend line equation and R^2 value.

The sudden rapid decrease and immediate increase in respiration rate recorded on day 28, that was noted in figure 3.12 occurred between 659 and 675 hours from windrow formation. Core temperature increased from 66°C at the start of the period to a maximum of 69.8°C at hour 667 and then reduced to 66.5°C at the end of the period. During the same period respiration rate decreased from 1.6$kgCO_2m^{-3}day^{-1}$ at the start to 0.7$kgCO_2m^{-3}day^{-1}$ on hour 667 and then increased to the starting rate by the end of the period, both are shown in Figure 3.18.

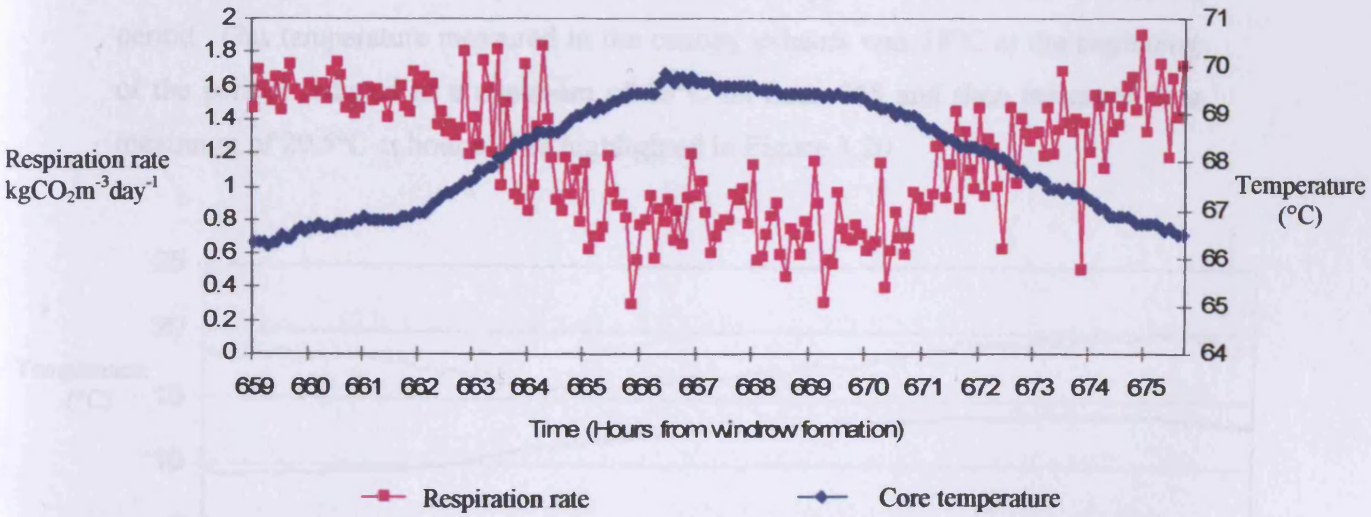

Figure 3.18. Core temperature and respiration rate recorded in windrow 2 over a sixteen hour period, starting 659 hours after windrow formation.

CO_2 measured in the canopy exhaust, during the same period, fell from 0.9% on hour 659 to a minimum of 0.4% on hour 667 and then increased to 0.84% by the end of the period. The velocity of gas in the canopy exhaust averaged 1.1 ms^{-1}, but fluctuated during the period when the large reduction and increase in CO_2 concentration was experienced with a low of 0.4 ms^{-1} and a high of 1.8 ms^{-1}. Both CO_2 concentration and gas velocity for this period are demonstrated in Figure 3.19.

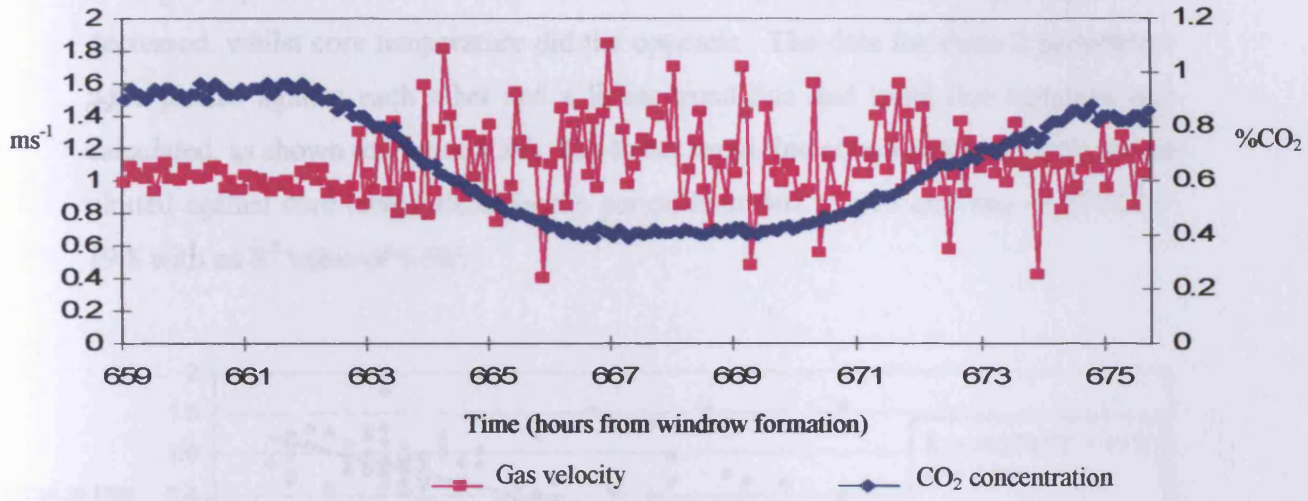

Figure 3.19. Gas velocity and CO_2 concentration measured in canopy exhaust from windrow 2 over a sixteen hour period starting 659 hours from windrow formation.

Ambient temperature remained at 9°C from hour 659 to hour 662 and then rose steadily to a peak of 13.7°C by hour 674 and then dropped to 13°C at the end of the period. Gas temperature measured in the canopy exhaust was 18°C at the beginning of the period, reduced to a minimum of 15°C on hour 665 and then increased to a maximum of 20.5°C at hour 674 as highlighted in Figure 3.20.

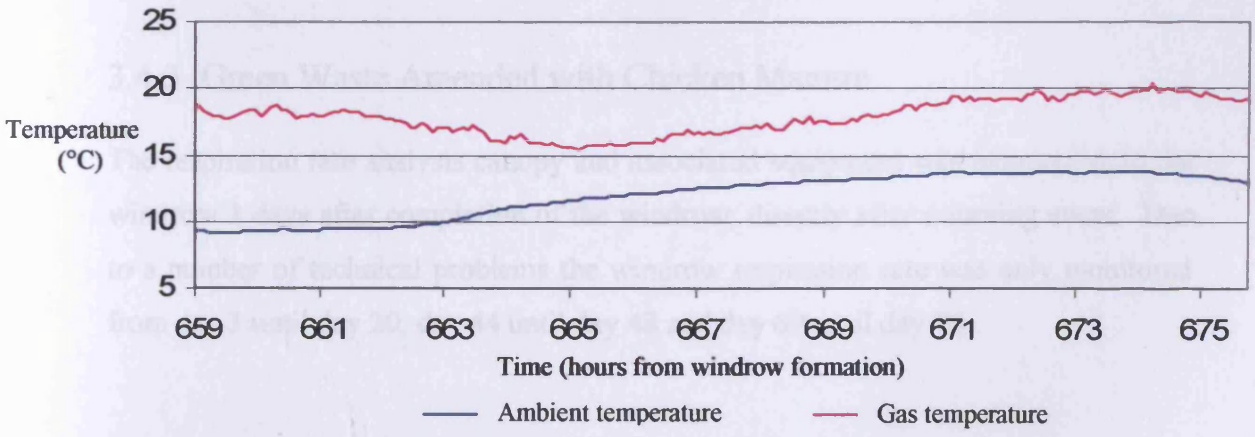

Figure 3.20. Ambient and exhaust gas temperature over a sixteen hour period starting 659 hours from windrow formation.

Core temperature increases at the same time that gas velocity becomes erratic, as shown in Figures 3.18 and 3.19. The respiration rate becomes erratic during the same period, this is because the respiration rate is calculated from CO_2 concentration and gas velocity in the canopy exhaust, and therefore an erratic velocity will impact upon the calculated respiration rate.

During the period between hours 662 and 675 respiration rate increased and then decreased, whilst core temperature did the opposite. The data for these 2 parameters were plotted against each other and a linear trend line and trend line equation was calculated, as shown in Figure 3.21. The linear trend line equation for respiration rate plotted against core temperature for the period hour 662 to 675 and was -0.274CT + 19.8 with an R^2 value of 0.685.

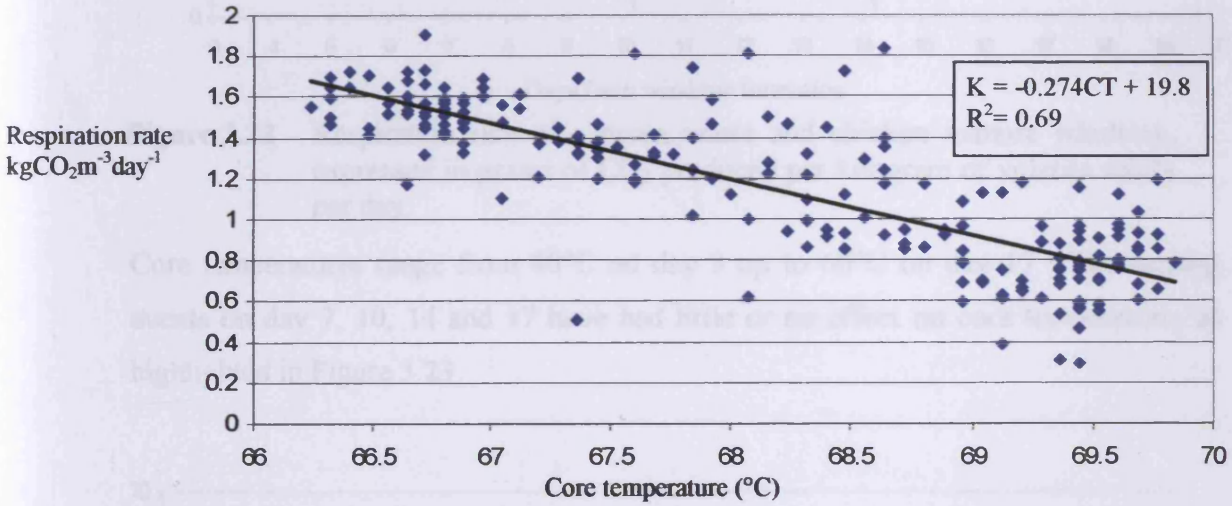

Figure 3.21. Respiration rate (K) plotted against core temperature (CT) for the 3 hour period from 662 to 675 hours after windrow formation, with trend line equation and R^2 value.

3.4.3 Green Waste Amended with Chicken Manure

The respiration rate analysis canopy and associated equipment was mounted onto the windrow 3 days after completion of the windrow, directly after a turning event. Due to a number of technical problems the windrow respiration rate was only monitored from day 3 until day 20, day 44 until day 48 and day 69 until day 76.

Respiration rate from day 3 to 20 shows 3 peaks, occurring on days 3, 7 and 14, all of which occur directly after turning, as highlighted in Figure 3.22 Respiration rate peaks at $2.6kgCO_2m^{-3}day^{-1}$ on day 3, $3.4kgCO_2m^{-3}day^{-1}$ on day 7, and $3.1kgCO_2m^{-3}day^{-1}$ on day 14. The windrow was also turned on day 10 and 17, these turnings seem to have had little or no effect on the general downwards trend of respiration rate since the previous turning.

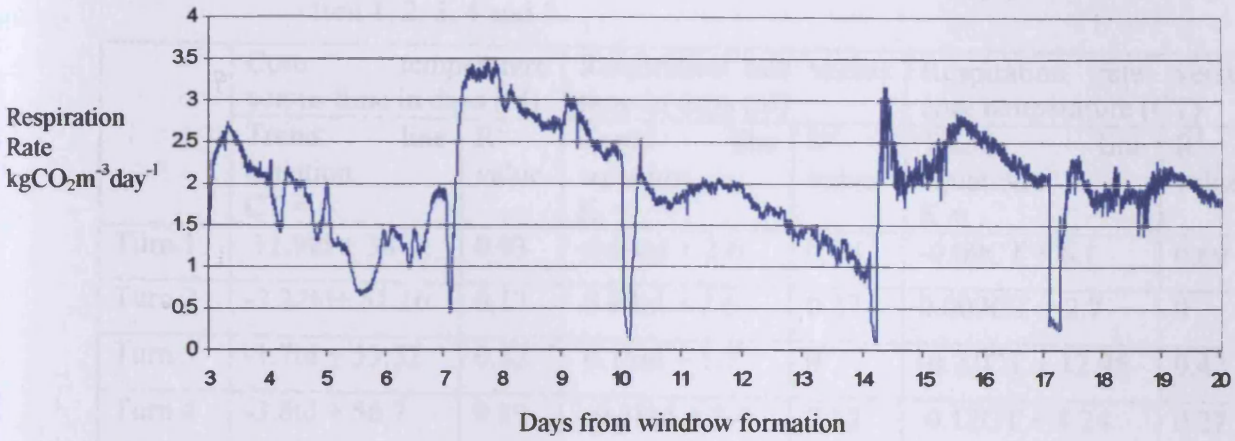

Figure 3.22 Respiration rate of a green waste and chicken manure windrow, expressed in grams of CO_2 produced per kilogram of volatile solids per day.

Core temperatures range from 40°C on day 3 up to 60°C on day 17. The turning events on day 7, 10, 14 and 17 have had little or no effect on core temperature, as highlighted in Figure 3.23

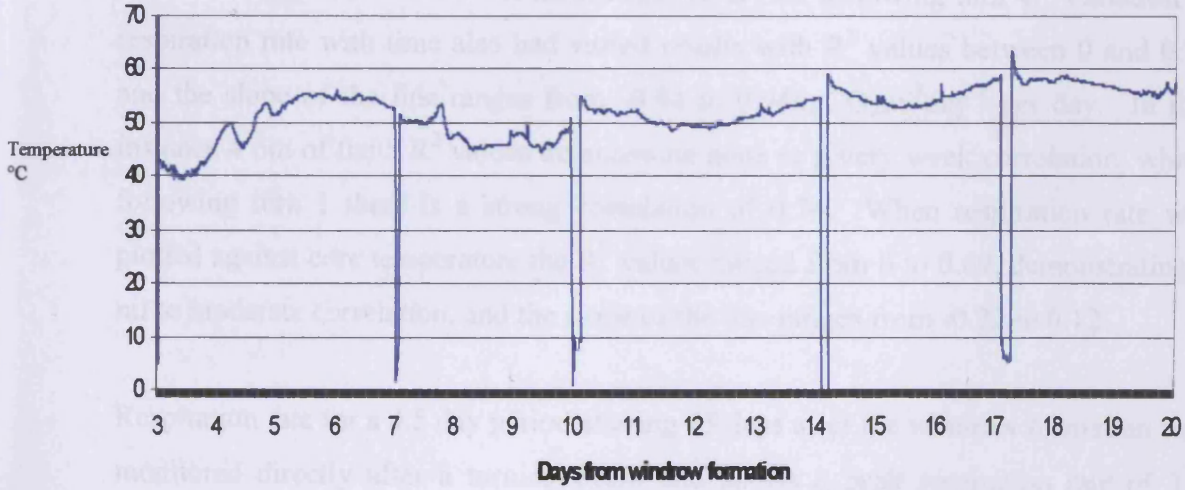

Figure 3.23 Windrow core temperature, 1m down from surface, from day 3 to day 20.

Core temperature and respiration rate for a 1 day period following each of the 5 turns from 3 to 20 days after windrow formation were plotted against time and each other, trend lines, trend line equations and R^2 values were then calculated from the resulting graphs. The results are shown in Table 3.5.

Table 3.5 Green waste and chicken manure windrow trend line equation and R^2 value for core temperature versus time, respiration rate versus time and respiration rate versus core temperature, for a 1 day period following turn 1, 2, 3, 4 and 5.

	Core temperature versus time in days (td)		Respiration rate versus time in days (td)		Respiration rate versus core temperature (CT)	
	Trend line equation CT =	R^2 value	Trend line equation K =	R^2 value	Trend line equation K =	R^2 value
Turn 1	11.9td + 38	0.93	-0.94td + 2.6	0.74	-0.09CT + 6.1	0.69
Turn 2	-2.22td+ 51.16	0.17	0.94td + 2.6	0.27	0.007CT + 2.7	0
Turn 3	-1.7td + 53.52	0.42	0.15td + 1.7	0	-0.21CT + 12.95	0.42
Turn 4	-3.8td + 56.7	0.89	-0.38td + 2.4	0.12	0.12CT + 4.24	0.27
Turn 5	-0.11td+ 58.27	0	-0.057td + 2	0	-0.22CT + 14.7	0.43

The relationship of core temperature with time had R^2 values between 0 and 0.9, and the slope of the line ranges from -3.8 to 11.9°Cday^{-1}. The 2 strongest relationships occur after turn 1 (R^2=0.93) and turn 4 (R^2=0.89) but the slope of the line is greatest at 11.9 following turn 1 and is the most negative at -3.8 following turn 4. Variation of respiration rate with time also had varied results with R^2 values between 0 and 0.74 and the slope of the line ranges from -0.94 to 0.94kg$CO_2m^{-3}day^{-1}$ per day. In this instance 4 out of the 5 R^2 values demonstrate none or a very week correlation, whilst following turn 1 there is a strong correlation of 0.74. When respiration rate was plotted against core temperature the R^2 values ranged from 0 to 0.69, demonstrating a nil to moderate correlation, and the slope of the line ranges from -0.22 to 0.12.

Respiration rate for a 4.5 day period starting 45 days after the windrow formation was monitored directly after a turning event and shows a peak respiration rate of 3.4 kg$CO_2m^{-3}day^{-1}$ at the start of the period, followed by a gradual decrease until the end of the monitored period when there is a sudden increase, as shown in Figure 3.24 A

linear trend line was fitted to the data, the trend line equation demonstrates that the respiration rate was reducing at the rate of $0.35 kgCO_2m^{-3}day^{-1}$ and the R^2 value of 0.8 indicates a strong correlation.

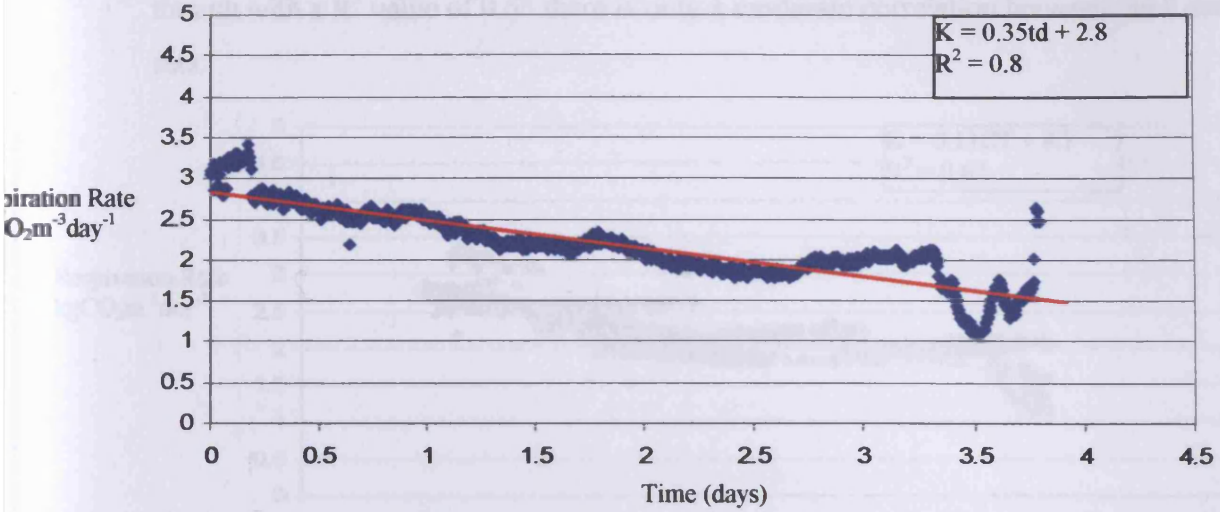

Figure 3.24 Respiration rate (K) versus time in days (td) including a linear trend line, trend line equation and the R^2 value for a 4.5 day period starting 45 days after the green waste and chicken litter windrow was formed.

Core temperature was plotted against time for this 4.5 day period starting 45 days after windrow formation. There is an increase in core temperature from 57°C at the start of the period to 68°C 4 days later, highlighted in Figure 3.25. A linear trend line was fitted to the data which demonstrated that core temperature was increasing at the rate of $2.64°Cday^{-1}$ with a R^2 value of 0.89, demonstrating a strong relationship.

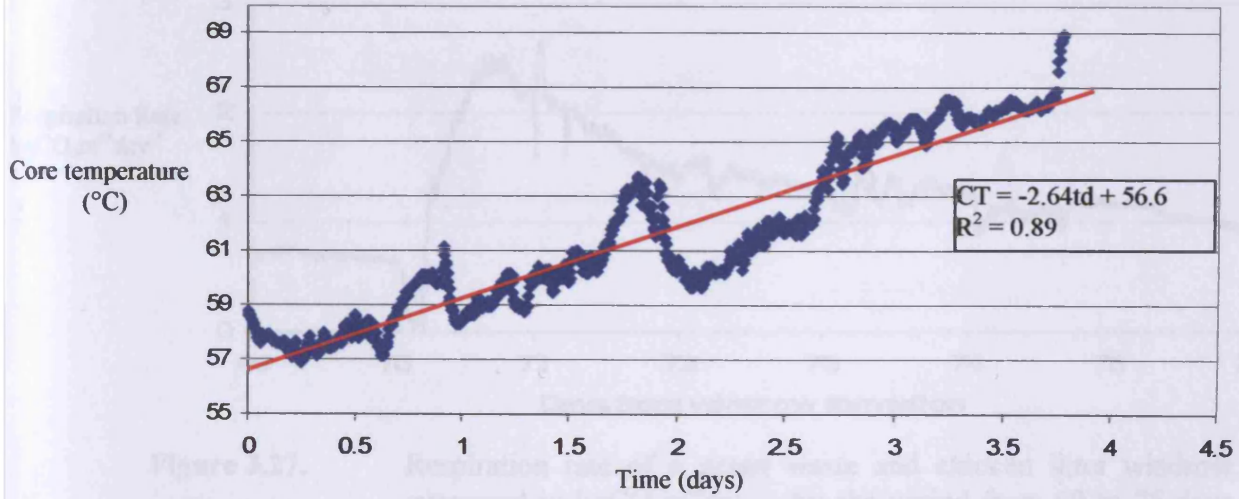

Figure 3.25 Core temperatures (CT) versus time in days (td), including a linear trend line, trend line equation and the R^2 value for a 4.5 day period starting 45 days after the green waste and chicken litter windrow was formed.

Respiration rate was plotted against core temperature and a linear trend line was fitted to the data, as shown in Figure 3.26. The trend line equation indicates a reduction in respiration rate of $0.11 kgCO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, though with a R^2 value of 0.63 there is only a moderate correlation between the 2 data sets.

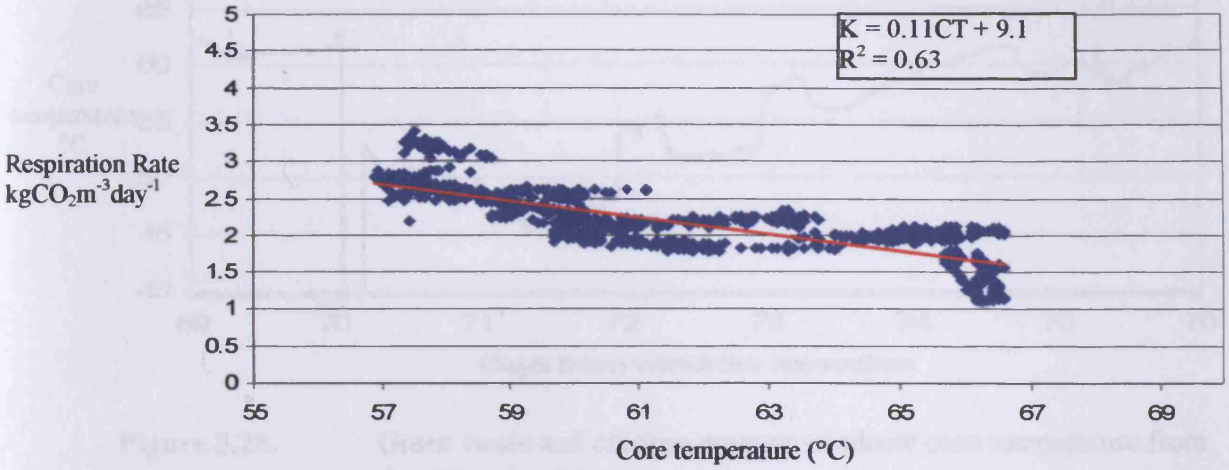

Figure 3.26 Respiration rate (K) versus core temperature (CT) including a linear trend line, trend line equation and the R^2 value for a 4.5 day period starting 45 days after the green waste and chicken litter windrow was formed.

Respiration rate from day 69 to 76 was at a minimum on day 69, at $0.7 kgCO_2m^{-3}day^{-1}$ and peaks at $2.4 kgCO_2m^{-3}day^{-1}$ directly after turning on day 70. The rate reduces to $1.5 kgCO_2m^{-3}day^{-1}$ by day 72, and more gradually to $1 kgCO_2m^{-3}day^{-1}$ by day 76, as demonstrated in Figure 3.27.

Figure 3.27. Respiration rate of a green waste and chicken litter windrow, expressed in $kgCO_2m^{-3}day^{-1}$, for the period from 69 to 76 days. The windrow was turned on day 70.

Temperatures were manually recorded in a grid pattern across one half of a section of the windrow on day 72. The resulting data was used to construct a 2 dimensional temperature profile by assuming the side of the windrow that was not surveyed was equal to side that was, as shown in Figure 3.30. This demonstrates that the maximum temperatures are not in the core, but are in saddle shape following the general outline of the windrow upper surfaces. The zone where temperatures are greatest, between 65°C and 75°C, extends down to 200mm from the windrow base at 1200mm in from the bottom edge of the windrow on each side, but in the centre of the windrow this zone is close to 800mm from the bay base. On the top of the windrow this zone extends to within 200mm of the surface. At the side walls the zone is within 200mm at the top, increasing to 400mm at 400mm above the windrow base.

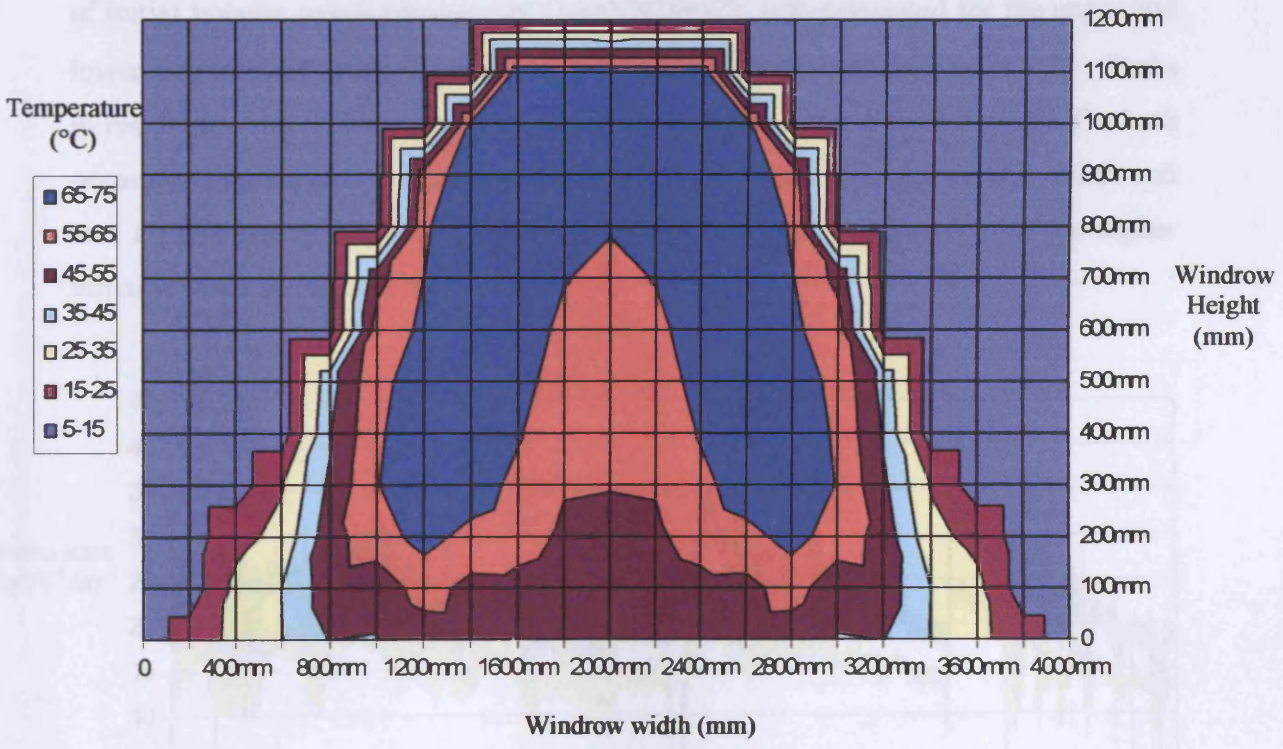

Figure 3.30 Temperature profile through a section of the green waste and chicken litter windrow, recorded 72 days after the windrow was formed. Profile constructed by measuring temperatures in one side of the windrow and assuming the other side was equivalent.

3.4.4 Carbon Dioxide Production in Relation to Estimated Initial Volatile Solids Content

The initial volatile solid content for windrow 1, 2 and the windrow amended with chicken litter are estimated in Sections 3.2.1, 3.2.2 and 3.2.3, respectively. These estimates are based on the range of volatile solid content of the green waste received at the facility of between 50 and 70% of dry matter for windrows 1 and 2. For windrow 1 the initial volatile solids content under the canopy is estimated to be between 917 and 1284kg, and for windrow 2 between 990 and 1386kg. The initial volatile solid content of the green waste and chicken litter windrow was estimated on the assumption that the measured organic carbon content made up 54% of the volatile solids (Rynk, 1992). This assumption gives an estimated volatile solid content of 2035kg.

The respiration rate in relation to the volatile solid content, in grammes of CO_2 per kg of initial volatile solids per day ($gCO_2kgVS^{-1}day^{-1}$), was calculated for the upper and lower estimates of initial volatile solids content and are shown in Figure 3.31. Peaks in respiration rate occur directly after turning events on day 14 and day 18. On both occasions the respiration rate was calculated from the lower initial volatile solids and was approximately $10gCO_2kgVS^{-1}day^{-1}$ greater than that calculated from the higher initial volatile solids content.

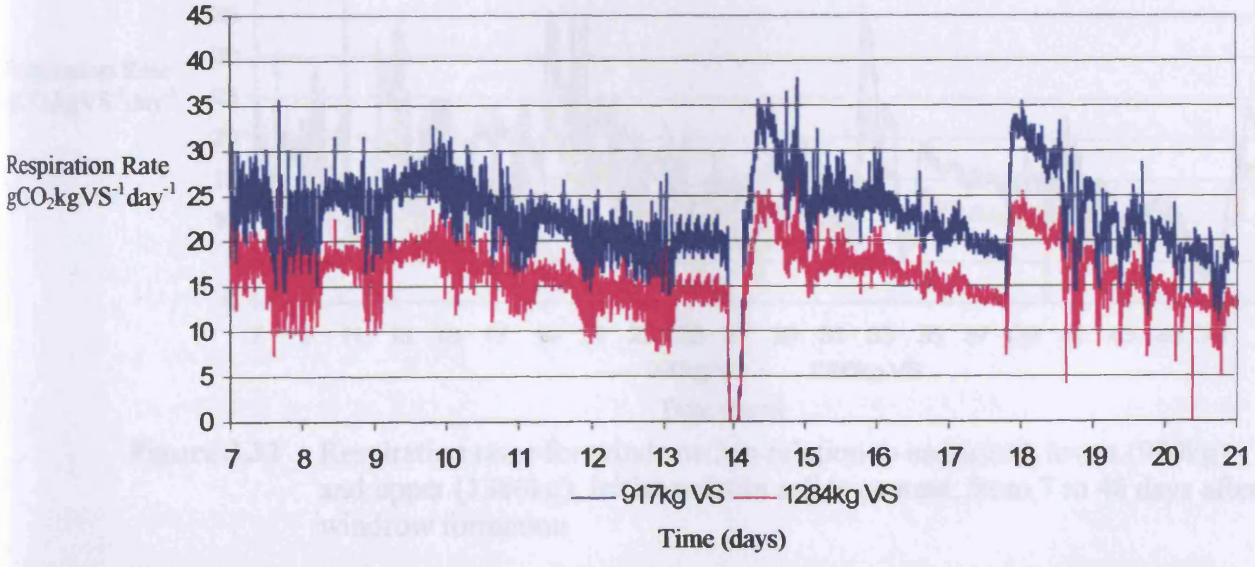

Figure 3.31 Respiration rates for windrow 1 in relation to estimated, lower (917kg) and upper (1284kg), initial volatile solids content, from 7 to 21 days after windrow formation

The average respiration rate using the higher estimated initial volatile solids content of 1284kg was 15.9gCO_2kg$VS^{-1}$$day^{-1}$. The average respiration rate when the lower estimate of initial volatile solids content (917kg) was employed was 22.3gCO_2kg$VS^{-1}$$day^{-1}$ and the average difference between the 2 different initial volatile solids content was 6.4gCO_2kg$VS^{-1}$$day^{-1}$. The mass of initial volatile solids content was calculated from the lower (50%) and upper (70%) limits of the green waste that was delivered to the facility, on a dry matter basis. If the average of 60% was used the average respiration rate would have been 19.1gCO_2kg$VS^{-1}$$day^{-1}$, and the error limit would have been ± 3.2gCO_2kg$VS^{-1}$$day^{-1}$ or 17%.

The CO_2 production rate of windrow 2 was measured from 7 to 48 days after the windrow was formed, and the respiration rate was calculated in relation to a lower (990kg) and upper (1386kg) initial volatile solids content, as shown in Figure 3.32. The average respiration rate during this period was 15.7gCO_2kg$VS^{-1}$$day^{-1}$ with the lower initial volatile solids content and 11.2gCO_2kg$VS^{-1}$$day^{-1}$ with the upper, with an average difference between the 2 of 4.5gCO_2kg$VS^{-1}$$day^{-1}$. If the average of 60% initial volatile solids was used the average respiration rate would have been 13.45gCO_2kg$VS^{-1}$$day^{-1}$, and the error limit would have been ± 2.25gCO_2kg$VS^{-1}$$day^{-1}$, which is the same as that found in windrow 1 at 17% .

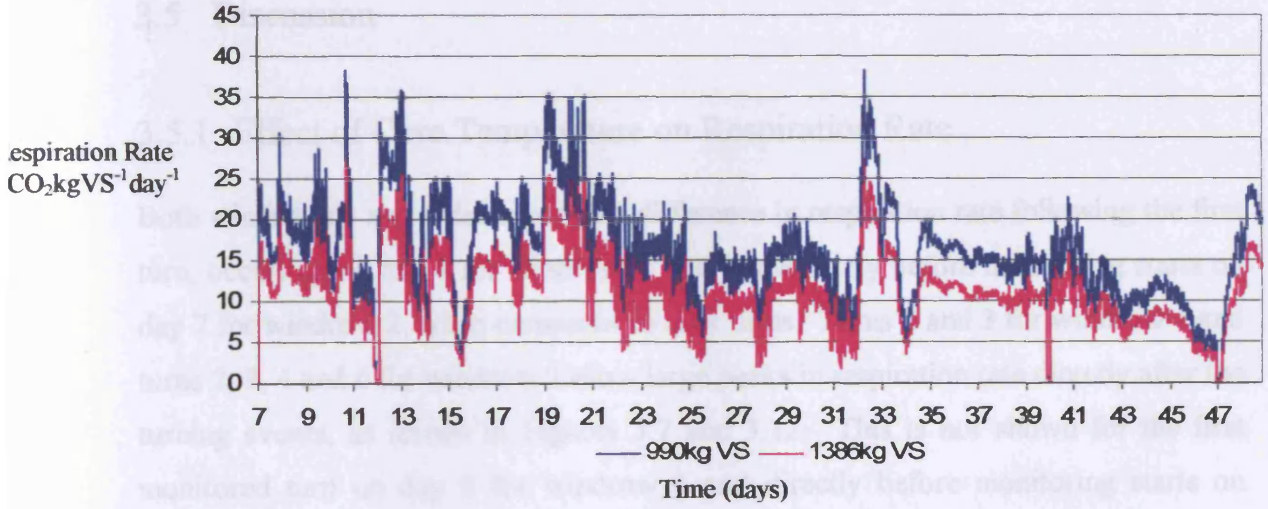

Figure 3.32 Respiration rates for windrow 2 in relation to estimated, lower (990kg) and upper (1386kg), initial volatile solids content, from 7 to 48 days after windrow formation

The respiration rate for the green waste and chicken litter windrow was monitored from 3 to 20 days after windrow formation, and was generally less than that found in windrows 1 and 2 which contained green waste only, with an average of $9.8gCO_2kgVS^{-1}day^{-1}$. Peak respiration rates occurred directly after turning events on day 7 ($17gCO_2kgVS^{-1}day^{-1}$) and 14 ($gCO_2kgVS^{-1}day^{-1}$), as shown in Figure 3.33. The turning events on days 10 and 17 had no effect on respiration rate.

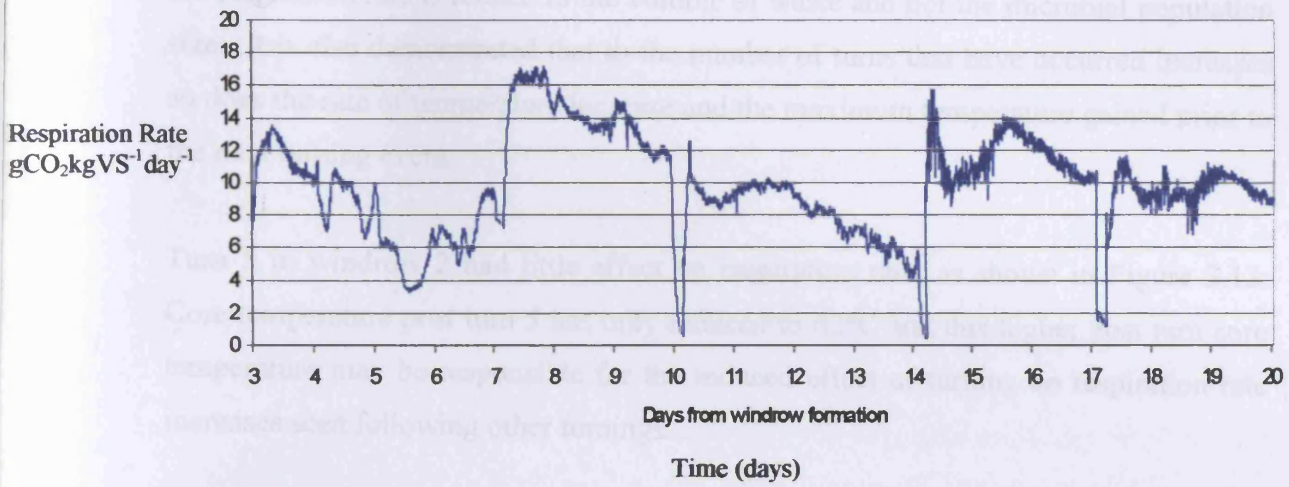

Figure 3.33 Respiration rates for the green waste windrow amended with chicken litter in relation to estimated initial volatile solids content under the canopy of 2035kg, from 3 to 20 days after windrow formation

3.5 Discussion

3.5.1 Effect of Core Temperature on Respiration Rate

Both windrows 1 and 2 demonstrate a difference in respiration rate following the first turn, occurring on day 8 for windrow 1, and immediately before monitoring starts on day 7 for windrow 2, when compared to later turns. Turns 2 and 3 for windrow 1 and turns 2, 3, 4 and 6 for windrow 2 show large peaks in respiration rate directly after the turning events, as shown in Figures 3.7 and 3.12. This is not shown for the first monitored turn on day 8 for windrow 1 and directly before monitoring starts on windrow 2 on day 7. Core temperature prior to turn 1 in windrow 1 was 62°C, and decreased to 55°C post turning and prior to turn 2 and 3 it was 64°C and 67°C and post turning 56°C and 55°C respectively, as shown in Figure 3.8. As windrow 2

monitoring started directly after the windrow had been turned core temperature prior to turning was not recorded. Core temperature was 57°C at the start of the period directly post turning and rises rapidly to 67°C 3 days later, as shown in Figure 3.13.

It is likely that the microbial population size at the time of the first turning for windrows 1 and 2 was still increasing and was not at a size great enough to deliver the respiration rate increases seen following later turns. It is important to recognise that the respiration rate is related to the volume of waste and not the microbial population size. It is also demonstrated that as the number of turns that have occurred increases so does the rate of temperature increase and the maximum temperature gained prior to the next turning event.

Turn 5 in windrow 2 had little effect on respiration rate, as shown in Figure 3.12. Core temperature post turn 5 has only reduced to 62°C and this higher post turn core temperature may be responsible for the reduced effect of turning on respiration rate increases seen following other turnings.

Superficial examination of respiration rate and core temperature suggests an inverse relationship in both green waste windrows, as core temperature increases respiration rate decreases, a seen in Figures 3.7, 3.8, 3.12 and 3.13. This apparent relationship is supported by further analysis of the data recorded for respiration rate and core temperature. Following the turning events in windrow 1 respiration rate was plotted against core temperature and a linear trend line was fitted to the resulting data, as shown in Table 3.3. The trend line equation demonstrates that for every 1°C increase in core temperature, respiration rate reduces between 0.068 and 0.14 $kgCO_2m^{-3}day^{-1}$. The R^2 values are in the range 0.5 to 0.62, indicating a moderate correlation between the 2 data sets. Following turns 2-5 for windrow 2 the same analysis was undertaken, as shown in Table 3.4. Demonstrating that for every 1°C increase in core temperature there is a reduction of between 0.07 and $0.17kgCO_2m^{-3}day^{-1}$. For 3 of the 4 turning events the R^2 value was between 0.53 and 0.6 demonstrating a moderate relationship, but following turn 4 when the greatest rate of reduction was found, the R^2 value was 0.86, demonstrating a strong relationship. Generally, the relationship between respiration rate and core temperature is increasing over time, which is likely to be due to reducing particle size and bulk density. This will result in reduced heat loss and

therefore more rapid core temperature increase, leading to temperature having a greater impact upon the rate of microbial activity.

Turning the windrow has resulted in lower core temperatures and higher respiration rates, but turning is likely to have increased porosity and may have increased substrate availability. Increased porosity will lead to improved passive airflow and therefore oxygen availability within the composting matrix and mixing may lead to increased substrate availability, either of which is likely to increase the respiration rate (Robinzon et al, 2000). As turning the windrow reduces temperature, increases oxygen availability and may increase substrate availability the modest inverse relationship between core temperature and respiration rate may be affected by changes in these other parameters.

A number of rapid decreases and increases in respiration rate recorded from windrow 2 on days 25 and 28 are not connected to turning events, as shown in Figure 3.12. These changes in respiration rate cannot be due to changes in passive airflow and increased substrate availability that are associated with a turning event, as the windrow was undisturbed during these periods. The data from these periods indicate that as core temperature rises, shown in Figures 3.14 and 3.18, CO_2 concentrations in the canopy exhaust are decreasing, shown in Figures 3.15 and 3.19.

During these periods there is no clear relationship between gas velocity measured in the canopy exhaust to core temperature or CO_2 concentration. Although gas velocity measured in the canopy exhaust does appear to become more erratic when CO_2 concentration was rising and falling, as shown in Figures 3.15 and 3.19. From these data it can be determined that, when core temperature is reducing, CO_2 production is increasing and when core temperature is increasing CO_2 production is falling. These rapid increases and decreases in respiration rates when no management operations have occurred, strongly suggest that the peaks in respiration rate following turning are predominantly due to reductions in core temperature.

The data for core temperature and respiration rate from the period on day 25 when core temperature was decreasing independently of any management operations, was

plotted against each other, as seen in Figure 3.17. During this period respiration was reducing at the rate of $0.258 kgCO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, as described by the linear trend line equation seen in Figure 3.17. The R^2 value of 0.83 indicates a strong correlation between the 2 data sets.

The data recorded from a similar event on day 28 reinforces this relationship. During a 17 hour period core temperature increased from 66°C to 70°C and then reduced back to the initial temperature. A linear trend line was fitted to a plot of core temperature against respiration rate for this period, as shown in Figure 3.21. The trend line equation demonstrates that during this period the relationship was, for every 1°C increase in core temperature there was a reduction of 0.274 $kgCO_2m^{-3}day^{-1}$ in the respiration rate. The R^2 value for this relationship was 0.69, demonstrating a moderate correlation.

The reason for the changes in core temperature during these periods is not clear but may be due to atmospheric conditions affecting the rate of passive airflow and therefore the amount of heat retained or lost from the composting matrix. This supposition is not supported by gas velocity measured in the exhaust as it does not increase whilst core temperature decreases, as demonstrated in Figure 3.15. The average exhaust gas velocity remains static as core temperature decreases and then increases from 659 to 675 hours after windrow formation, but it does become erratic during this period, as shown in Figure 3.19. The erratic gas velocity during this period is likely to be due to gusting wind conditions, which may have caused an increase in heat loss.

During the same period exhaust gas temperature decreases from 18°C to 15°C from the start of the period to hour 666, which roughly coincides with the period that core temperature is increasing, as highlighted in Figures 3.18 and 3.20. From hour 666 to the end of the measured period, exhaust gas temperature increased from 15°C to 20°C, whilst core temperature reduced from 69.5°C to 66.5°C. This suggests that respiration rate is increasing as core temperature is decreasing due to greater heat loss through the exhaust and vice versa, but this is due to the gases exiting the windrow increasing in temperature rather than the volumetric flow rate increasing.

The strong relationship between core temperature and time, indicated by the consistently high R^2 values seen in Tables 3.3 and 3.4, is likely to be due to the influence of only 2 parameters, heat production and heat loss. Where as respiration rate is influenced by microbial population size, make up and availability of substrate, O_2 availability, moisture content and temperature. The relationship between respiration rate and core temperature is greatest following turn 4 (Table 3.4) when the R^2 value is 0.86 and respiration rate is decreasing at the rate of $0.17 kgCO_2 m^{-3} day^{-1}$ for every 1°C increase in core temperature. The core temperature during these periods was in the range 55°C to 70°C, apart from following turn 4 when core temperature was in the range 62°C to 75°C. Optimum composting temperatures have been widely reported to be between 55°C and 60°C (Wiley, 1956. Rothbaum, 1961. Jeris and Regan, 1973. Suler and Finstein, 1977. Cathcart et al, 1986 and Myrddin, 2003). As the core temperature range analysed here is equal to or above the reported optimum and the respiration rate reduces as core temperatures rise, the presented data supports the argument that core temperatures greater than 55°C-60°C reduce the rate of decomposition.

3.5.2 Dynamic Respiration Rate Monitoring

Measuring respiration rate on a continuous basis on green waste windrows and a green waste windrow amended with chicken litter has proven to be a robust and reproducible method of measuring microbial activity in windrow systems.

Windrow composting systems are highly heterogeneous environments with large variations in temperature, porosity and therefore oxygen availability, moisture content, microbial community size and diversity and chemical makeup. Changes in any of these variables impacts upon the microbial community, and therefore the rate of decomposition is dictated by the interaction of a number of variables. Measuring any or a number of these variables individually does not reliably indicate the rate of degradation. Measuring the respiration rate integrates the total impact of all environmental variables upon the rate of microbial activity.

Measuring the respiration rate of the windrows has demonstrated the size and duration of the effect of turning on the respiration rate, as shown in Figures 3.7 and 3.12. It has also allowed the impact of core temperature on the rate of respiration to be calculated within certain temperature ranges, as shown in Tables 3.3 and 3.4 and in Figures 3.17 and 3.21.

The initial volatile solid content of the green waste in both windrows 1 and 2 was between 50 and 70% on a dry weight basis. If the mid point of 60% volatile solids was used as an estimate of initial volatile solids, then the respiration rate expressed in $gCO_2kgVS^{-1}day^{-1}$ would be accurate within ± 17%.

It may be possible to examine further the use of continuous respiration rate analysis to accurately predict the desired level of stability, dependent upon that required by the desired market place for the composted product. Knowing the mass of carbon lost from the system through constant monitoring of CO_2 will allow greater product consistency.

Assuming that the initial volatile solids content was 60% of dry matter, then the average respiration rate for windrow 2 was $13.45gCO_2kgVS^{-1}day^{-1}$ over a period of 41 days (Figure 3.32), and the windrow was constructed 7 days before monitoring started. Assuming the average respiration rate over the full 48 day period, then $646gCO_2kgVS^{-1}$ was evolved during the period. The carbon in the evolved CO_2 will have originated from the organic matter in the composting waste and the O_2 will have originated from the air. For every 44g of CO_2 evolved, 12g will be carbon lost from the organic matter in the composting waste and 32g will be O_2 from air. Therefore, during this period there was a total loss of carbon from the composting organic waste of $176gCkgVS^{-1}$. As approximately 50% of the mass of VS is made up of carbon, it is a reasonable to conclude that 35.2% of the original VS content has been degraded.

Kamilaki and Stentiford (2001) found that a composted product which had been processed in a windrow for a period of 125 days had a VS loss of 28%. As windrow 2 was made up of similar waste as that in the work by Kamilaki and Stentiford (2001) but was only composted for 48 days rather than 125 days, but showed a greater estimated VS loss based on carbon losses. Then it is likely that estimating total VS

loss by measuring total carbon loss may not be directly related to actual reductions in VS. To assess if there is a correlation between measured carbon loss and total VS loss both measures need to be undertaken on the same windrow, unfortunately the VS loss was not measured in windrow 2.

A further use of results from dynamic respiration rate analysis is that the production of CO_2 is proportional to O_2 uptake and heat production (Notton, 2005). Therefore knowing the likely maximum CO_2 production rate of a specific organic waste in a system will allow calculations to be made to deliver sufficient air to provide the required volume of O_2 and to remove excess heat from the system to manage temperature.

3.5.3 Chicken Litter Amended Windrow Compared to Green Waste Windrows

The green waste windrow amended with chicken manure was conducted to measure the effect of bringing the C: N ratio into the reported optimum range, on the dynamic respiration rate. The windrow was managed in the same way as previous green waste only windrows and the reduced C:N ratio was expected to increase the dynamic respiration rate. This expectation was based on previous research demonstrating that increasing nitrogen availability would increase microbial population growth and result in increased respiration rates (Hamoda et al, 1998. Cathcart et al, 1986. Schuchardt, 2000).

In practice the peak respiration rate for the amended windrow was less than that previously recorded for green waste only windrows. The windrow exhibited a peak respiration rate of $3.4kgCO_2m^{-3}day^{-1}$ on day 8 (Figure 3.22). Whilst windrow 2 contained green waste only and recorded peak respiration rates of $4kgCO_2m^{-3}day^{-1}$ on days 10, 19 and 32 (Figure 3.12).

Comparing the relationship between core temperature and respiration against time and core temperature for the green waste windrows and the chicken litter amended green waste windrow, demonstrates some fundamental differences. Following turning

events 1, 2 and 3 for windrow 1 (Table 3.3) and turning events 2, 3, 4 and 5 for windrow 2 (Table 3.4) core temperature increases and respiration rate decreases. Whilst following turning events 2, 3, 4 and 5 for the chicken litter and green waste windrow, core temperature is decreasing and respiration rate is increasing (Table 3.5). Following turning events recorded on days 45 and 70 there is an increase in core temperature and a reduction in respiration rate, similar to that seen in the green waste windrows, as shown in Figures 3.24, 3.25, 3.27 and 3.28.

The reduction in respiration rate is thought to be caused by decreased porosity within the windrow matrix due to the small size of the chicken litter particles (Hamoda et al, 1998. Cathcart et al, 1986. Beck-Friis et al, 2003), as shown in Figure 3.34. This higher proportion of smaller particle sizes is likely to have caused reduced passive gas flow due to air spaces being partially filled with these smaller particles. This theory is supported by bulk density measurements which were 688 kg m^{-3} in the nitrogen amended windrow, and 491 kg m^{-3} in windrow 2 which contained green waste only.

Figure 3.34. 34 tonnes of chicken manure with a moisture content of 20%.

The resulting higher density has reduced air pore space and resulted in reduced passive air flow, oxygen availability and heat loss from the system (Agnew and Leonard, 2003). Further more, measurement of the windrows temperature profile demonstrates that high temperatures are created and maintained in the sides of the windrow but not in the centre, highlighted in Figure 3.30. Temperature profiles measured in previous green waste windrows have indicated that the core is typically hotter than regions closer to the surface, as demonstrated in Figure 3.35 Conditions for higher activity are evident in the outer regions of the chicken litter amended windrow; therefore it is likely that the low core temperatures are caused by reduced oxygen availability caused by reductions in free air space resulting in reduced passive airflow.

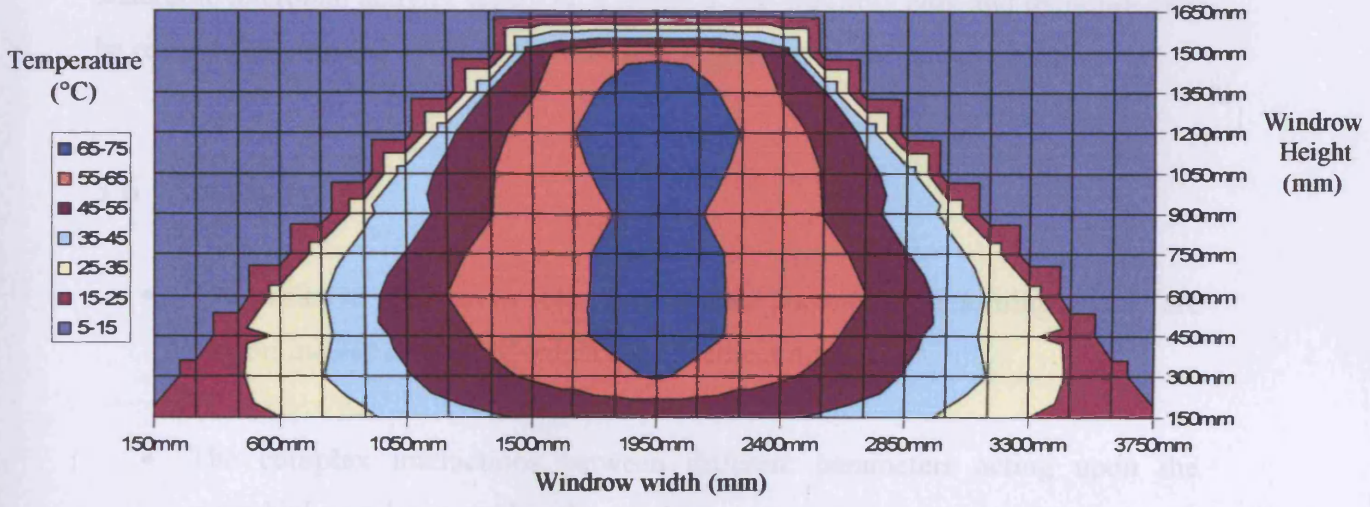

Figure 3.35 Temperature profile through a section of a green waste windrow.

Core temperatures recorded for this windrow were also lower than those of a green waste only windrow; core temperature does not reach 60°C until day 17, where in an un-amended windrow core temperature reaches 60°C within 8 days, as shown in Figures 3.8, 3.13 and 3.23. Average core temperatures in the green waste windrows were 65°C, and in the nitrogen amended windrow 55°C. In the amended windrow the core temperature is not the greatest and higher temperatures are found nearer to the external surface of the windrow, as shown in Figure 3.30.

On a facility management level the windrow did produce a noticeable level of ammonia, leading to a number of turnings causing a substantial odour issue. The

cause of nitrogen loss in the form of ammonia is due to there being more nitrogen present than is required by microbial biomass production, leading to the excess being lost from the system. The odours may have also been due to anaerobic activity in the core, again an indication that passive airflow was restricted in this windrow. Green waste composting is a system where microbial population growth is usually limited by nitrogen availability, and therefore all of the available nitrogen will be incorporated into the microbial biomass (Becks Friis et al, 2001. Tiquia et al, 2002). To see if the odour issue was partially caused by anaerobic activity the exhaust gases through the canopy were measured for methane, a common product of anaerobic conditions and no levels were found (Defoer and Langenhove, 2002). But if anaerobic conditions were occurring in the windrow core due to the lack of oxygen caused by reduced passive airflow. It is not unreasonable to assume that the gaseous products of anaerobic microbial activity would be trapped in the windrow core and therefore only be released at a turning event, and would not be present in the canopy chimney.

3.6 Summary

- The peaks in respiration rate demonstrated directly after turning events are predominantly a result of reduced core temperature.

- The complex interactions between different parameters acting upon the microbial population within the windrow composting matrix are demonstrated by the apparent failure of the green waste windrow amended with chicken litter experiment to bring about the expected result. In this case it can be reasonably concluded that reduced porosity has resulted in lower passive air flow, leading to reduced oxygen availability, and has had a greater negative effect on respiration rate than the expected positive effect of increasing the nitrogen content.

- If the proportion of VS loss required to transform an organic waste into a stabilised product is known, then the time required for that waste to experience the required proportion of VS loss in any composting system or process can be predicted by measuring its dynamic respiration rate.

- Respiration reduces at the rate of 0.258 to 0.274kg$CO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, in the range of 66°C to 70°C in green waste windrow 2. Following turning events, respiration rate in both green waste only windrows reduces at a rate of between 0.068 and 0.17kg$CO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, in the range of 55°C to 70°C.

- The methodology used to measure respiration rate in an open system is capable of illuminating the effect of management operations on the dynamic respiration rate occurring within the composting matrix of a windrow.

4 Managing Forced Aeration in a Turned Bay System

4.1 Introduction

Targets set by the Welsh Assembly Government require at least 15% of the Municipal waste stream to be composted by 2009/10 (WAG, 2002). Studies of waste composition in South Wales have shown that green waste makes up less than 15% of the waste stream (Emery et al, 2000). If this target is to be met by local authorities in Wales, source segregated kitchen waste (catering waste) will have to be collected and composted.

The composting of catering waste is governed by the Animal by Products Regulations (ABPR) which were based on a risk assessment undertaken by Gale (2002)(Statutory Instrument, N0 1999/646 and 2001/1704). Therefore, the collected catering waste will have to be treated at a facility that meets these regulations. The ABPR splits waste into 3 categories,

- Category 1 animal waste includes diseased carcases and suspect carcases, specified high risk material and catering waste from international transport, these wastes may not be composted.

- Category 2 contains material like condemned meat that is not suitable for human consumption and may only be composted after rendering (133°C, 3 bar pressure).

- Category 3 includes catering waste from households and restaurants, former foodstuffs and some slaughterhouse waste (blood, feathers etc). EU regulations state that category 3 waste material must be treated at over 70°C for 1 hour with a maximum particle size of 12mm in a fully enclosed system. Individual EU member states may introduce their own standards for facilities that compost only catering waste.

In the UK regulations have been introduced to govern sites composting only catering waste. These regulations cover all aspects of site management but the most prescriptive elements cover processing. There are 2 types of catering waste that require different treatment regimes. These are "meat excluded catering waste" and "non meat excluded catering waste". Meat excluded catering waste must have an audit system in place to ensure that householders are not putting meat in their catering waste segregated bin.

Facilities handling catering waste have a number of treatment options available. If the waste is "meat excluded" the following treatment options can apply.

- In an enclosed system with a maximum particle size less than 400mm, where 100% of the waste is maintained above 60°C for a minimum of 48 consecutive hours.
- In an enclosed system with a maximum particle size of less than 60mm, where 100% of the waste is maintained above 70°C for 1 hour
- In an enclosed windrow system with a maximum particle size of less than 400mm, where 80% of the windrow is greater than 60°C for more than 48 consecutive hours. The windrow has to meet these requirements 4 times and the windrow must be turned between each phase.

If the waste is "non meat excluded" it is required to be treated to the same standards again, although the second phase of treatment may be undertaken in external windrows.

The introduction of the ABPR places a requirement on batch in-vessel composting systems to ensure that 100% of the waste within the system is above the target temperature. Previous to the introduction of these regulations in-vessel systems were not designed to meet this technically demanding requirement. Where as meeting the treatment requirements by maintaining 80% of the material above the target temperature and turning the waste to ensure all of the material has been in the high temperature zone is less likely to require advances in technology. The time taken to reach the target temperature and the reliability of either system in achieving the target will have an impact upon operational costs and the amount of infrastructure required to treat a certain tonnage.

Further additions to the regulations came into effect in January 2007 and are an amendment to the ABPR treatment requirements that are described in European Commission (1774/2002). These amendments (EC 208/2006) allow any enclosed composting system that can demonstrate a 5 log pathogen kill to treat wastes covered by this legislation. Although these regulations are less prescriptive in achieving certain treatment parameters, it is likely that the implementation of methods that demonstrate the required level of pathogen kill will be problematical. They may allow systems that cannot meet the present requirements to demonstrate the required level of pathogen kill, and therefore increase the technology options to treat this type of waste.

The windrow treatment option requires the first phase to occur in an enclosed building. Traditionally shaped windrows promote a passive airflow, as air is drawn into the sides of the windrow due to hot gases exiting the top of the windrow. By enclosing the windrow in between concrete walls the tonnage of waste per m^2 of floor will be approximately 2 times greater than if traditional windrows are employed, leading to increases in the treatment capacity of an enclosed area. Changing the cross sectional shape of the windrow from triangular to rectangular and enclosing it between walls will greatly reduce the passive flow of air through the material. Due to this reduction in passive airflow and the desire to manage the composting process to promote high temperatures a forced aeration system is required.

To meet the ABPR treatment requirements a turned system must be capable of maintaining at least 80% of the organic waste in the system above 60°C for a minimum of 48 hours between each turn. This must be repeated at least 4 turns to statistically demonstrate that 99.8% of the waste in the system has been above the target temperature for at least 48 hours. If less than 80% of the waste in the bay is above the target temperature more turns will have to be carried out to reach the 99.8% target. If more than 80% is greater than the target temperature it may be possible to reduce the number of turns. The number of turns required to treat a specified mass of waste will impact upon the enclosed area required and the operational costs of turning. A statistical model was constructed to calculate the number of turnings that would be required to ensure that >99.8% of the material in the composting mass has met the minimum time-temperature relationship, assuming random mixing at each turn, and is demonstrated in Table 4.1.

Table 4.1 Calculated number of turnings required to ensure >99.8% of the mass has been over the target temperature, against number of turns (each turn is assumed to provide random mixing) (Notton, 2005).

Volume above target temperature	0	1	2	3	4	5	6	7
10%	10%	19.00%	27.10%	34.39%	40.95%	46.86%	52.17%	56.95%
20%	20%	36.00%	48.80%	59.04%	67.23%	73.79%	79.03%	83.22%
30%	30%	51.00%	65.70%	75.99%	83.19%	88.24%	91.76%	94.24%
40%	40%	64.00%	78.40%	87.04%	92.22%	95.33%	97.20%	98.32%
50%	50%	75.00%	87.50%	93.75%	96.88%	98.44%	99.22%	99.61%
60%	60%	84.00%	93.60%	97.44%	98.98%	99.59%	99.84%	99.93%
70%	70%	91.00%	97.30%	99.19%	99.76%	99.93%	99.98%	99.99%
80%	80%	96.00%	99.20%	99.84%	99.97%	99.99%	100.00%	100.00%
90%	90%	99.00%	99.90%	99.99%	100.00%	100.00%	100.00%	100.00%
100%	100%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

To examine the effect of forced aeration system management on the percentage of material greater than the ABPR target temperatures in a turned bay system, a trial forced aerated bay was manufactured in a 6 meter wide, 7 meter long by 2.2 meter deep concrete constructed bay. 2 separate trials were undertaken in this bay, the aim of these trials was to maximise the temperature and to maximise the rate of temperature increase. For these reasons a fan was specified that could provide sufficient air to meet oxygen demand but not to manage temperature, which can require 25 times as much air (Notton, 2005).

The first was with shredded green waste only, this was primarily undertaken to test if the aeration system was sufficient to deliver the required volume of air to supply oxygen demand. The second was with processed vegetable waste mixed with shredded green waste to examine any effects that may occur after adding catering waste type material to green waste. The second trial also examined the time taken for 80% of the compost matrix to exceed the target temperatures following each turning event, and how this would impact upon treatment time.

4.2 Green Waste Trial

4.2.1 Method

The bay was originally constructed as a green waste collection area at the adjacent Civic Amenity site. The bay is sunk into the ground to allow the public to discharge their green waste, as shown in Figure 4.1. It was surrounded by at least 2 meters of concrete and backfill, providing a substantial heat sink at the bay periphery.

Figure 4.1. Concrete constructed bay in which the composting trials were conducted, 6 meters wide, 7 meters long and 2.2 meters high.

To allow the bay to be turned with a front end loader without disturbing the aeration distribution system, 60mm diameter perforated land drainage pipes were placed on the concrete base between 75mm deep soft wood planks. Sheets of 50mm thick high density foam insulation panels were attached to the bay walls; this arrangement is shown in Figure 4.2.

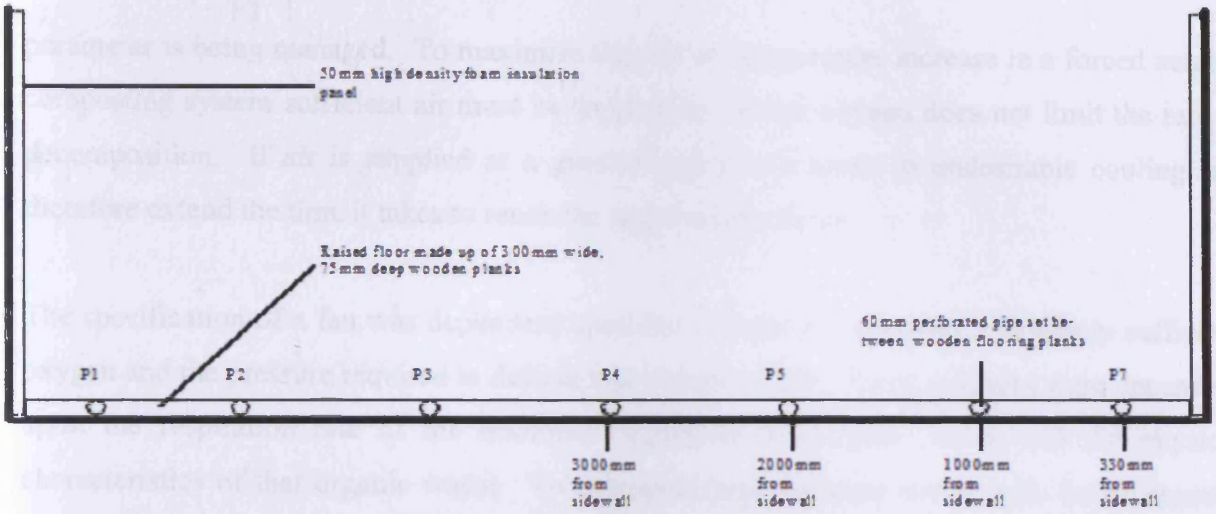

Figure 4.2. Cross section of the concrete bay with 60mm perforated land drainage pipes, between 75mm deep softwood planks to allow emptying and refilling, with 50mm insulation panels attached to back and side walls. The pipe layout was symmetrical, and their distance from the side wall is shown.

An aeration manifold was constructed that consisted of 110mm plastic piping connected directly to the perforated aeration pipes. The first 2 meters of perforated pipe were taped over so that air was unable to escape from the distribution system before the organic waste. Duct work was connected to the inlet and outlet side of the fan to easily facilitate changing aeration between negative and positive directions, the manifold and fan are shown in-situ in Figure 4.3.

Figure 4.3 Aeration fan and manifold connected to perforated distribution pipes.

To design an effective aeration system the volume of air required to manage certain variables and the pressure required to deliver that volume of air must be known. The volume of air that a composting matrix requires is highly dependent upon the rate of decomposition and what

parameter is being managed. To maximise the rate of temperature increase in a forced aerated composting system sufficient air must be supplied to ensure oxygen does not limit the rate of decomposition. If air is supplied at a greater rate it will result in undesirable cooling and therefore extend the time it takes to reach the target temperature.

The specification of a fan was dependent upon the volume of air required to supply sufficient oxygen and the pressure required to deliver that volume of air. These volumes were dependent upon the respiration rate of the microbes degrading the organic waste and the physical characteristics of that organic waste. To calculate these volumes the organic waste density, moisture content, volatile solid content and respiration rate were estimated from previous measurements of green waste composted in windrows. The calculations were made assuming a density of 500kg per m^3, moisture was 60%, volatile solid content was 60% of dry matter and the maximum respiration rate was $40gCO_2kgVS^{-1}day^{-1}$ which equates to 4.5 $kgCO_2m^{-3}day^{-1}$, which was greater than the peak measured in windrows.

The volume of air required to supply sufficient oxygen to an organic waste meeting these assumptions was calculated to be $2\times10^{-4}m^3s^{-1}$ for every m^3 of shredded green waste (Notton, 2005), and the volume of waste in the bay when filled was calculated to be $90m^3$. Therefore the volume of air required to supply sufficient oxygen to the organic waste in the bay was $0.018m^3s^{-1}$ which was equivalent to $64.8m^3hr^{-1}$. These calculations assumed that all of the oxygen in the air was utilised by the microbes degrading the waste. In practice the gases exiting the compost should have a minimum oxygen concentration of 11% to ensure the rate of decomposition was not impaired (Suler and Finstein, 1977). Therefore the volume of air required to supply sufficient oxygen was a minimum of $130m^3hr^{-1}$.

Assuming the same characteristics and conditions a supply of $5\times10^{-3}m^3s^{-1}$ for every m^3 of shredded green waste was required to remove the heat produced by microbial activity, which was equivalent to $3240m^3hr^{-1}$. The volume of air required to remove the heat produced by microbial activity is 25 times greater than that required to supply oxygen demand. These calculations are supported by Rynk (1992) who suggests the same air flow rate for temperature control of composting, though he does not relate it to the rate of microbial activity. As the aim of these trials was to maximise temperatures the system was designed to deliver sufficient air to satisfy oxygen demand only ($130m^3hr^{-1}$), but not to manage temperature ($3240m^3hr^{-1}$).

The pressure required to maintain a superficial velocity through a bed of compost was highly dependent on the physical characteristics of the waste that makes up that bed. The superficial velocity of air through a composting bed was derived from the volumetric flow rate divided by the area of the bed. The superficial velocity required in the aerated bay system to provide sufficient oxygen would be $130m^3hr^{-1}$ divided by the area of the bay that was aerated, $42m^2$. Therefore the required superficial velocity was 8.6×10^{-4} ms^{-1}. As the pressure requirement was highly dependent upon the characteristics of the waste the results from trials that evaluated the static pressure required to maintain a range of superficial velocities at a range of bed depths at the research facility were used (Hewings et al, 2003). These trials suggested that a static pressure of $10mmH_2O$ would maintain the required superficial velocity through a 2.2m deep bed of shredded green waste. To allow for pressure reductions in the pipe work, a fan was used that was capable of providing more than $130m^3hr^{-1}$ at a static pressure of 60mm H_2O. The centrifugal fan used was built by Pellcroft Engineering Ltd, model number TLV4, with a 1.1 kW motor and a specification of $800m^3/hr$ at $100mmH_2O$.

The Beltsville process management methodology aimed to maintain oxygen concentration within the composting matrix between 5 and 15%. This was accomplished by activating the aeration fan on a timer and was originally developed to reduce odour levels at sewage sludge composting facilities in the United States. The frequency and duration of fan activation could be modified in response to measuring oxygen levels within the composting matrix but the timer was typically operated for 20% of the time. This methodology led to compost matrix temperatures of 80°C and was undertaken using fans of approximately 1kW for every 90 tonnes of wet waste (Parr et al, 1978).

To ensure that the assumptions regarding aeration and management met the requirements the bay was filled with approximately 45 tonnes of shredded green waste. The aeration system was connected to induce negative pressure resulting in a top down airflow and the timer was set to operate the fan for 15 minutes every 3 hours. A k-type thermocouple probe was placed 3 meters from the back wall, 300mm from the side wall and 1000mm down into the compost matrix. This probe was connected to a Delta T DL2e data logger that recorded temperature every 10 minutes. A 1000mm long sample tube was inserted in the same place and an infra red CO_2 analyser (Gas Data PCO_2) with an on board pump was connected to the sample tube via a moisture trap. The CO_2 analyser sampled and recorded CO_2 concentration every 10 minutes.

4.2.2 Results

CO_2 recordings were down loaded 24 hours after the bay was filled. These recordings demonstrated that CO_2 concentration reduced to 4% at the end of each 15 minute aeration period, but increased to >10% 40 minutes after the aeration period. This indicated that oxygen concentration was above 10% for more than 50% of the time. To ensure low oxygen concentrations were not inhibiting microbial activity the fan timing was altered to 15 minutes every 120 minutes. After this adjustment CO_2 concentration in the composting matrix was maintained between 1 and 10% for the following 3 days, as shown in Figure 4.4.

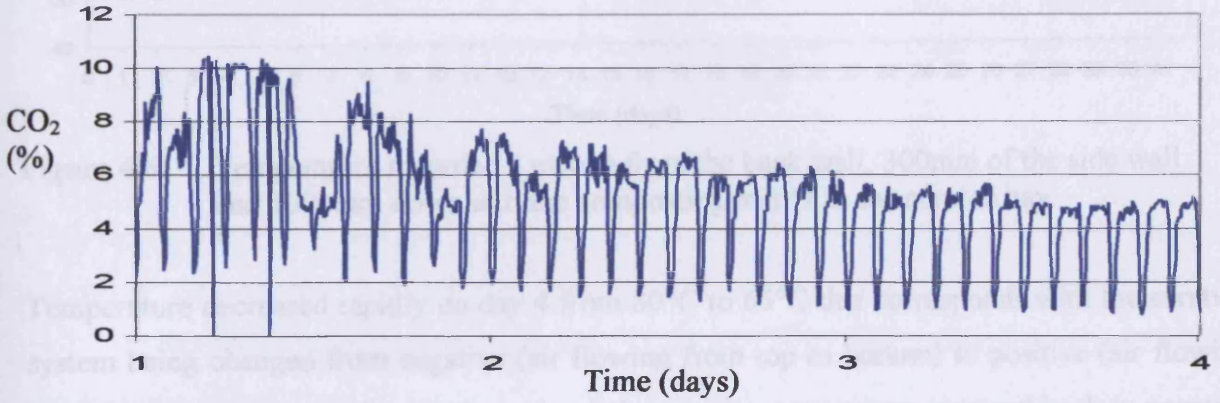

Figure 4.4. CO_2 concentration measured 1000mm down and 300mm from the side of the aerated bay over a period of 3 days.

During the same period the temperature of the compost matrix recorded at the same location increased from a low of 67°C at the start to a high of 84°C at the end of the period, as demonstrated in Figure 4.5. During the periods of fan operation recorded temperatures increased between 5 and 12°C. This was likely to be due to air being drawn down through the 1000mm of compost matrix above the probe where temperatures were greater.

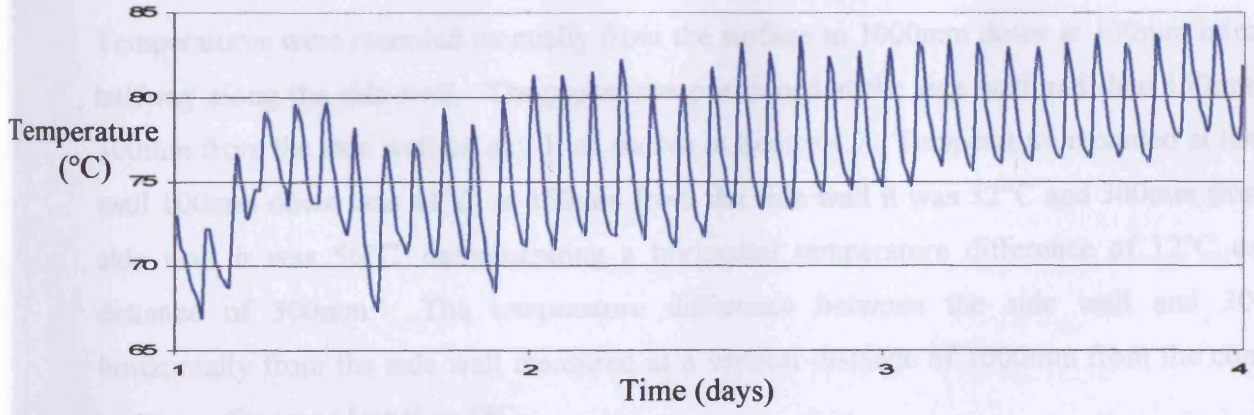

Figure 4.5. Temperature measured 1000mm down and 300mm from the side of the aerated bay over a 3 day period.

Temperature was monitored for 31 days and maximum temperature was reached on day 11 at 91°C, a minimumctemperature of 60°C occurred on day 24, as shown in Figure 4.6. Temperature at the monitored point increased to 70°C within 24 hours of filling. Temperature was maintained above 80°C between day 6 and 12.

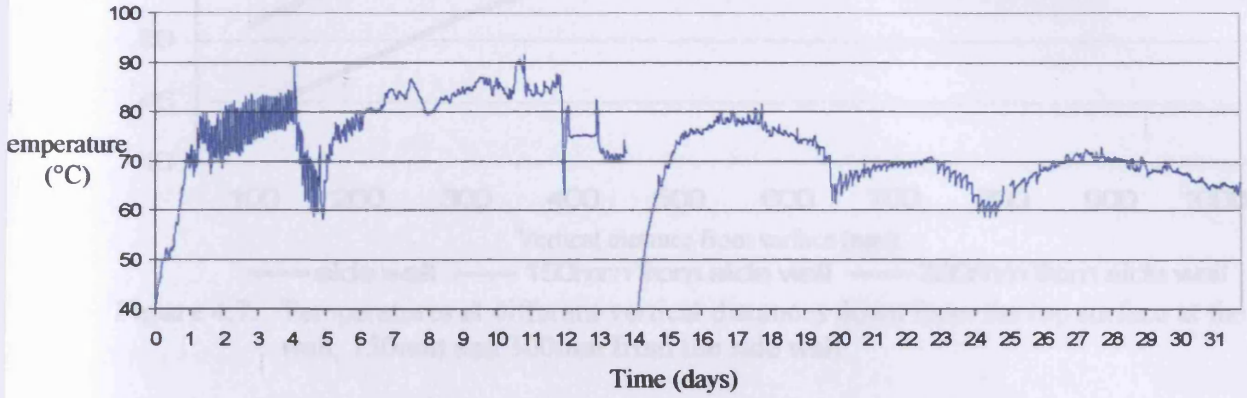

Figure 4.6. Temperature recorded 3 meters from the back wall, 300mm of the side wall and 1000mm down into the composting matrix in the aerated bay.

Temperature decreased rapidly on day 4 from 80°C to 65°C this corresponds with the aeration system being changed from negative (air flowing from top to bottom) to positive (air flowing from bottom to top) aeration. Early in day 5 the aeration system was changed back to negative aeration, leading to a rapid increase in temperature at the probe location. The fan was turned off from day 6 until day 12, corresponding with the composting mass remaining in a steady temperature range between 80°C and 90°C. On day 12 the fan was switched to constant flow, until the temperature dropped to 65°C, at which point the aeration was changed to negative aeration for 15 minutes in 3 hours. At the beginning of day 14 the bay was emptied and refilled with the same material to replicate a turning event. After turning, temperature increased to 70°C within 24 hours of turning.

Temperatures were recorded manually from the surface to 1000mm down at 100mm intervals, halfway along the side wall. The probe was positioned at the side wall and then 150mm and 300mm from the side wall on day 1, as shown in Figure 4.7. Temperature recorded at the side wall 100mm down was 44°C, at 150mm from the side wall it was 52°C and 300mm from the side wall it was 56°C, demonstrating a horizontal temperature difference of 12°C over a distance of 300mm. The temperature difference between the side wall and 300mm horizontally from the side wall measured at a vertical distance of 1000mm from the compost matrix surface was less than 5°C.

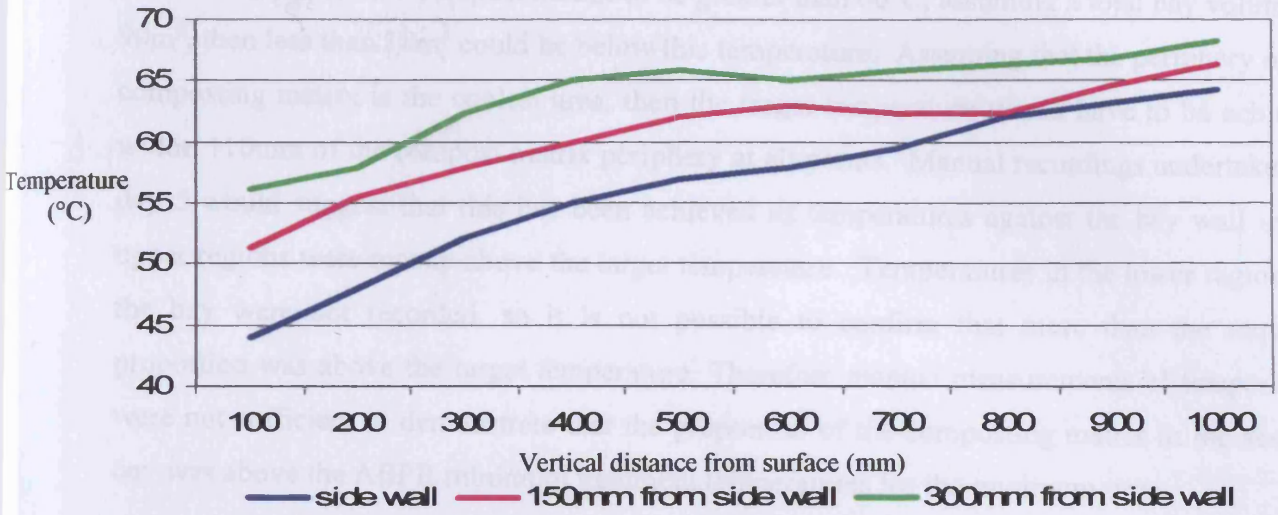

Figure 4.7. Temperatures at different vertical distances down from the top surface at the side wall, 150mm and 300mm from the side wall.

Composting matrix temperatures were also manually recorded at various depths and distances from the insulated bay wall; this was replicated at three positions around the bay 5 days after filling. Against the bay wall, 150mm down from the surface temperature ranged from 57°C to 64°C. At a depth of 300mm temperature ranged from 68°C to 74°C, and at a depth of 1000mm temperature ranged from 70°C to 72°C. Temperatures were also measured 150mm from the wall, at three different positions in the bay and at depths of 150, 300 and 1000mm. Recorded temperatures at a depth of 150mm ranged from 68°C to 71°C, at a depth of 300mm from 73°C to 76°C and at depth of 1000mm they ranged from 71°C to 75°C. The same methodology was employed to record temperatures at 300mm from the bay wall. Temperatures ranged from 70°C to 74°C at a depth of 150mm, 74°C to 75°C at a depth of 300mm and 76°C to 78°C at a depth of 1000mm.

4.2.3 Discussion

The general increase in temperature during the monitored period demonstrates that the air management regime has met its design criteria of maintaining sufficient oxygen within the mass whilst increasing compost matrix temperature, as demonstrated in Figures 4.4 and 4.5.

Temperature increases at the measured location to 70°C, 24 hours after the bay was filled, and returns to that level within 24 hours following a turning event. Indicating that the minimum time needed to complete the treatment requirement is 12 days. This assumes that 80% of the compost matrix is above the target temperature, for 48 hours, over 4 phases that includes 3

turns. For 80% of the compost matrix to be greater than 60°C, assuming a total bay volume of $90m^3$, then less than $18m^3$ could be below this temperature. Assuming that the periphery of the composting matrix is the coolest area, then the target temperature would have to be achieved within 110mm of the compost matrix periphery at all points. Manual recordings undertaken on day 5 would suggest that this has been achieved as temperatures against the bay wall in the upper regions were mostly above the target temperature. Temperatures in the lower regions of the bay were not recorded, so it is not possible to confirm that more than the required proportion was above the target temperature. Therefore manual measurements of temperature were not sufficient to demonstrate that the proportion of the composting matrix in the aerated bay was above the ABPR minimum treatment temperatures for the minimum time.

Increases in recorded temperatures during fan operation suggest that higher temperatures are being experienced in the composting material directly above the monitored point. As the fan was producing a top down air flow during operation and that heat is being distributed downwards by air movement within the composting mass, as shown in Figure 4.5.

A consistent temperature recording for 6 days when the fan was turned off suggests that once high temperatures have been produced, they can be maintained, as highlighted in Figure 4.6. It is likely that the composting rate is greatly reduced at these high temperatures due to thermal inhibition of microbial activity.

4.3 Green Waste and Processed Vegetable Waste Trial

4.3.1 Introduction

To increase understanding of composting catering waste mixed with green waste in the aerated bay system a feedstock was sourced which would mimic the main physical properties of this mixture. The main aims of the trial were to evaluate methods that would induce the highest proportion of the compost matrix above the treatment target temperatures, examine airflow within the composting matrix and ensure that the treatment target temperatures could be met following a number of turning events. The time taken for the composting waste in a commercial turned bay system to attain the minimum proportion above the minimum temperature, after initial filling and following each turning event will impact upon the volume of organic waste that can be treated by that system.

For a turned system to meet the ABPR treatment requirements it has to be demonstrated that a minimum of 80% of the composting matrix is greater than 60°C for 48 hours. To gain an understanding of the period required too achieve these requirements, following initial filling and turning events, the bay was emptied and re-filled after the required time / temperature regime had been met. The time taken to achieve the requirements was calculated for the initial filling and following the subsequent turning events.

The ABPR treatment regulations also allow catering waste to be treated by maintaining 100% of the waste undergoing treatment to be maintained above 60°C for a minimum of 48 hours with a maximum particle size of 400mm, or greater than 70°C for 1 hour with a maximum particle size of 60mm. To investigate if this could be achieved with a simple non recycling aeration system, the aeration system was managed to maximise the proportion of organic waste in the bay above the target temperature.

The temperature recordings made during the initial green waste trial (section 4.2) were not sufficient to accurately determine the proportion of the composting matrix that was greater than the target temperature. For this reason an array of temperature probes were fabricated. The array was made up of 5 separate probes, each probe contained 12 thermocouples at specified points along their length, namely 100(01), 300(02), 500(03), 700(04), 900(05), 1100(06), 1300(07), 1500(08), 1700(09), 1900(10), 2100(12) and 2200mm(12) from the inserted end of the probe. This probe array was inserted in line across one half of the bay to allow the recorded data to be constructed into a 2 dimensional representation of the temperature profile, and to allow the proportion of the bay greater than a specified temperature to be calculated, as shown in Figure 4.8. It was also though that the resulting data would improve understanding of the effect of forced aeration upon the temperature profile within the composting mass.

Figure 4.8 Thermocouple array inserted into compost at 0, 750, 1500, 2250 and 3000mm from the sidewall.

Table 4.2 Timing and details of aeration management and turning events in the aerated bay whilst filled with processed vegetable waste and shredded green waste.

Date	Day	Event	Aeration Management
16/01	0	Bay filled.	Negative; 30 minutes in every 180
20/01	3	Fan operation frequency changed to maintain CO_2 concentration between 4 and 10%.	Negative; 30 minutes in every120
21/01	4	Aeration direction changed to examine effect on temperature distribution.	Positive; 30 minutes in every 120
22/01	5	Fan turned off to examine effect on temperature distribution.	Turned off
23/01	6	Probes removed for remedial work.	Turned off
27/01	10	Bay emptied to replicate a turning event.	Turned off
28/01	11	Bay partially re-filled (due to machinery breakdown).	Turned off
29/01	12	Bay re-filled to examine effect of a turning event.	Negative; 30 minutes in every 180
3/02	17	Aeration changed from negative to positive for 2 aeration events and then switched off. This was done in the expectation that it would maximise the proportion of the bay over the target temperature.	Positive; 30 minutes in every 180. Fan switched off after 2 positive aeration events to stabilise the temperature profile
4/02	18	Aeration frequency change to manage CO_2 concentration between 4 and 10%. Temperature array moved sequentially through the whole rear quarter of the bay, to allow more complete profile construction	Positive; 15 minutes in 120 (from 16:00)
5/02	19	Aeration change to examine effect of constant aeration on temperature profile.	Positive; constant (10:30 to 16:30)
6/02	20	Bay emptied and re-filled to replicate and examine the effect of a turning event.	Negative; 15 minutes in 120 (15:00)
12/02	26	Aeration change to positive with the aim of maximising temperature profile. Fan was then switched off to examine changes to temperature profile with no aeration.	Positive; 15 minutes in 120 (9:30 to 14:00) and then switched off.
13/02	27	Bay emptied and re-filled to replicate and examine the effect of a turning event.	No aeration after turn to examine temperature profile following a turning event with no aeration.
16/02	30	Aeration change to manage CO_2 concentration between 4 and 10%.	Negative; 15 minutes in 120 (start 14:30)
17/02	31	Aeration change to manage CO_2 concentration between 4 and 10%.	Negative; 15 minutes in 180
19/02	33	Aeration changed from negative to positive for 2 aeration events and then switched off. This was done in the expectation that it would maximise the proportion of the bay over the target temperature.	Positive; 15 minutes in 180 (17:30) 3 aeration events and the turned off
23/02	37	Fan switched off to examine changes to temperature profile.	Turned off
25/02	39	Bay emptied and re-filled to replicate and examine the effect of a turning event.	No aeration after turn to examine temperature profile following a turning event with no aeration.
27/02	41	Aeration turned back on to manage CO_2 concentration between 4 and 10%.	Negative; 15 minutes in 180
10/03	52	Temperature array moved to back wall to examine periphery temperatures.	Negative; 15 minutes in 180
24/03		Trial end	

4.3.3 Temperature Measurement Accuracy

During the green waste and processed food waste trial the temperature recordings made by the data logger were down loaded onto a lap top. On day 27 the data that had been recorded over the previous 10 days was down loaded. When the recorded temperatures were analysed it was noted that un-feasibly high temperatures of >100°C had been recorded (a maximum temperature of 91°C was recorded with a calibrated probe in Figure 4.6). These unfeasibly high temperatures were first recorded on day 18 and day 26, when recorded temperatures from location E06 inserted in the centre of the bay, reached a maximum of 105°C and remained greater than 100°C for more than 10 hours, as shown in Figures 4.24 and 4.32.

To examine if there was a problem with the temperature recording system a calibrated hand held K-type thermocouple probe was attached to probe E at location E03 on day 30. Temperature measured by this hand held probe, were manually recorded at the same time as the temperature reading on the data logger at probe E03. The difference between the calibrated probe temperature (73.5°C) and the data logger (74.2°C) were within 1°C at 10am on day 30. At 3pm on day 30 the difference between the calibrated probe temperature (74.5°C) and the data logger (80.4°C) was 5.9°C. Further measurements were made in this way from day 30 until day 38 and are shown in Table 4.3.

Table 4.3 Difference in recorded temperature between a calibrated handheld thermocouple probe and probe E03 recorded on the data logger.

Day	Time	Calibrated probe (°C)	Datalogger (°C)	Difference (°C)
30	10:00	73.5	74.2	+0.7
30	15:00	74.5	80.4	+5.9
31	08:30	78.7	84.3	+5.6
31	11:30	78.6	80	+1.4
31	16:30	80.3	85.9	+5.6
32	08:45	82.4	84.6	+2.2
32	12:45	82.7	85.3	+2.6
34	08:30	74.5	74.4	-0.1
37	08:30	54.1	56.9	+2.8
38	10:45	57.5	60.9	+3.4

The difference between the temperatures recorded by the calibrated probe and the thermocouple at location E03 vary between -0.1 and +5.9°C, with an average difference of +3°C. At the end of the trial the probe array and data logging system were removed and examined in detail. This examination found that the system had been incorrectly configured. The terminals at the end of the thermocouple wires are termed the cold junction and in the configuration used the temperature at the cold junction is required by the data logger to calculate the temperature at the hot junction (inserted probe). The data logger had a built in thermocouple that was used as the reference cold junction. The thermocouple cold junctions were connected to terminal blocks in the junction box mounted on the top of each probe, and then connected to the data logger with standard wiring, as shown in Figure 4.9. Therefore the thermocouple cold junction was in the junction box on top of each probe and the reference cold junction was in the data logger located in the instrument box.

The error between the temperatures recorded on the data logger from probes A – E and the actual temperature is equal to the difference in temperature experienced at the probe cold junction in the terminal box and that experienced by the data logger reference cold junction in the instrument box. From the start of the trial until day 18 and from the turning event on day 27 until the end of the trial the instrument box was on the concrete area surrounding the bay. The instrument box was in this location when the comparison in temperature readings between a calibrated hand held probe and probe location E03, the results of which are shown in Table 4.3. The terminal box on top of each probe was approximately 600mm above the compost surface for the whole of the trial, as shown in Figure 4.8.

Based on the data in Table 4.3 the error in temperatures recorded on the data logger during these periods was a maximum of +6°C with an average of +3°C. During the period from day 18 to 27 when the unfeasibly high temperatures were recorded the instrument box was located directly on top of the compost, under the sheet covering the compost. In this location the reference cold junction in the data logger was at a higher temperature than when it was located next to the bay, which has resulted in a greater error. There was no comparison to a calibrated probe during that period as the error was not found until data had been down loaded and inspected. Therefore the temperatures recorded from day 18 to day 27 have an unknown margin of error, but examining temperatures with a known error (days 30 to 38) and comparing to later and earlier temperatures at the same locations, it may have been as much as +20°C.

Temperature data recorded from day 18 to 27 is presented from hour 29 in Figure 4.24 and the whole of Figures 4.25, 4.26 and 4.27. The temperatures presented in these figures had a substantial (up to +20°C), but unknown error associated with them. All other temperatures had a maximum error of +6°C. When temperatures were recorded and used to construct the temperature profile for the whole bay on day 19 (Figure 4.28) the cover was removed from the compost and the instrument box was moved from the compost surface to allow the probes to be moved. During this period it can be assumed that there was a maximum error of +6°C.

The central cross section temperature profiles were constructed from the temperatures recorded on the data logger, which apart from Figures 4.25, 4.26 and 4.27, had a maximum error of +6°C. Where these profiles have been used to calculate the proportion of the cross section that is greater than 60 or 70°C, a lower and upper proportion was calculated. The upper proportion was calculated from the temperatures recorded by the data logger and the lower by reducing each recorded temperature by the maximum 6°C error.

Though the absolute temperatures recorded from days 18 to 27 have a substantial but unquantifiable error associated with them, changes in temperature caused by aeration management is accurate. Therefore the data has been presented to demonstrate the impact of aeration events and to indicate the changing temperature profile within the composting mass. It is important to take into consideration these errors within the temperature recordings when examining the data.

4.3.4 Results

4.3.4.1 Initial Heat up Phase

CO_2 concentration measured 1000mm down in the compost matrix in the centre of the bay increased by approximately 6% between aeration events during the first 12 hours of the period, as highlighted in Figure 4.10. During the fan operation periods CO_2 concentration reduced by less than 6% leading to an overall increase over time. After 12 hours, peak CO_2 concentrations increased above 12%, which was the maximum concentration the monitoring equipment was capable of measuring. From 36 hours to the end of the period CO_2 concentration only reduced below 12% for very short periods at the end of the fan operation.

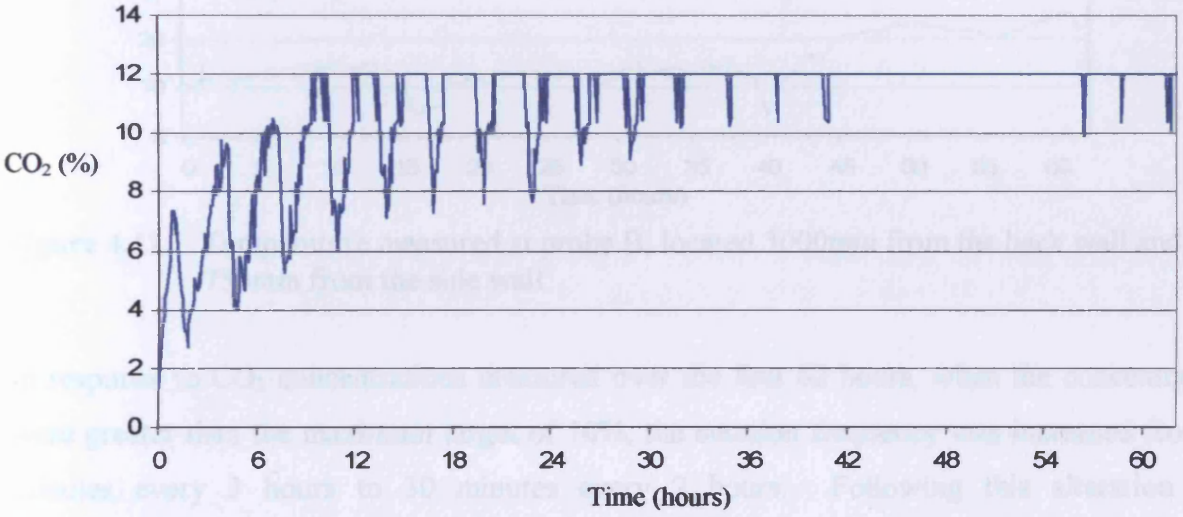

Figure 4.10. CO_2 concentration measured 1000mm down in the centre of the forced aerated bay. The equipment used had a maximum range of 12%.

Temperature readings from probe B, placed 750mm from the side wall, show a maximum temperature of 50°C after filling, the maximum-recorded temperature rose steadily over the following 48 hours to a maximum temperature of 80°C, as shown in Figure 4.11. There was a large temperature gradient from top to bottom, with surface temperatures (B12) being 40°C to 60°C cooler than that experienced at the bay base (B01). Recorded temperature when compared to the location of the thermocouple within the composting mass demonstrate that during negative aeration temperatures increase as distance from the bay base decreases. This is due to heat from higher up the composting matrix being drawn down by the gas flow stream during negative aeration phases.

Temperatures at probe B were generally increasing even though CO_2 concentration was greater than 12% from hour 36, peak temperature measured in the lower regions of the bay (B1) levelled off after 15 hours. Temperatures in the middle and upper regions of the bay (B6 and B12) continued to increase until hour 45, as shown in Figures 4.10 and 4.11.

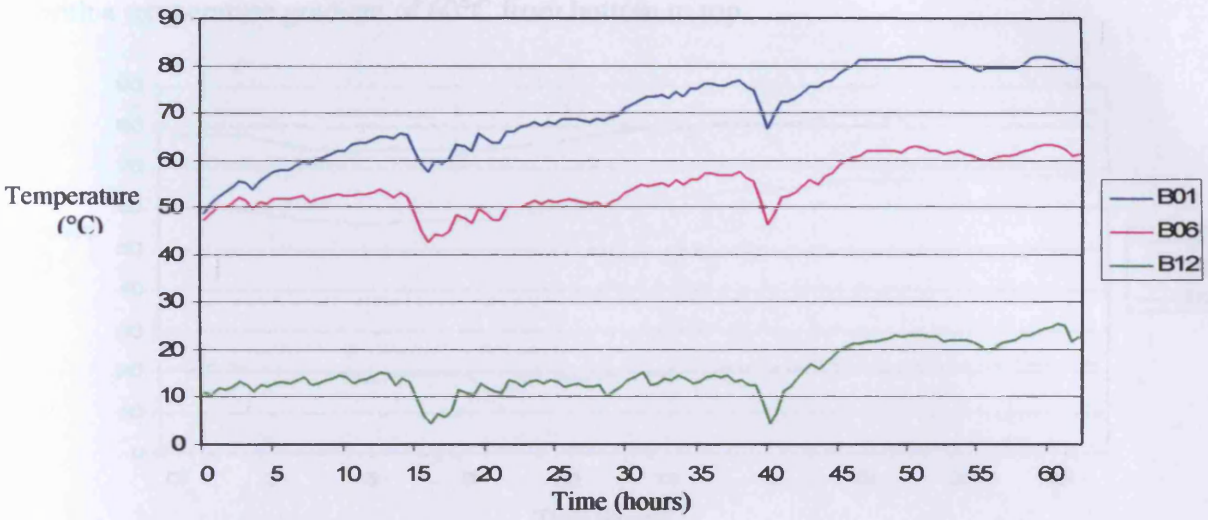

Figure 4.11. Temperature measured at probe B, located 3000mm from the back wall and 750mm from the side wall.

In response to CO_2 concentrations measured over the first 62 hours, when the concentrations were greater than the maximum target of 10%, the aeration frequency was increased from 30 minutes every 3 hours to 30 minutes every 2 hours. Following this alteration CO_2 concentration remained within the target limits of greater than 4% and less than 10%, as shown in Figure 4.12. During fan operation CO_2 concentration fell from 10% to 6% and then increased during the 90 minute period that the fan was not operating back to 10%.

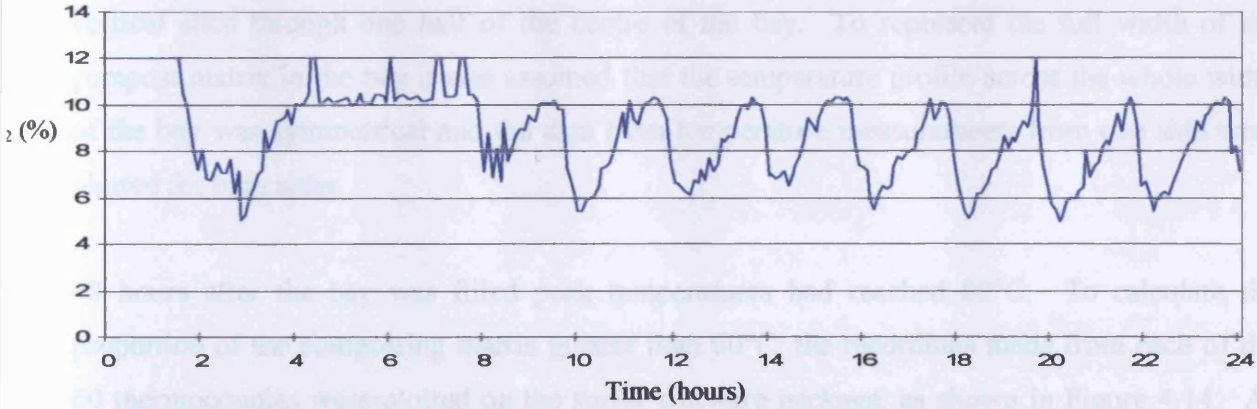

Figure 4.12 CO_2 concentration measured 1000mm down in the centre of the bay over a 24 hour period starting 3 days after the bay was filled, aeration frequency was changed on hour 2 from 30 minutes every 3 hours to 30 minutes every 2 hours.

During the same period temperatures recorded at probe B generally increased by 10°C in the 10 hour period following the change in fan operation frequency that occurred at hour 8, as shown in Figure 4.13. At location B06, which was located 1100mm above the bay base, temperature increased from 57°C at hour 8 to a maximum of 70°C by the end of the period. Recorded temperatures were generally greater the closer the probe location is to the bay base, with a temperature gradient of 60°C from bottom to top.

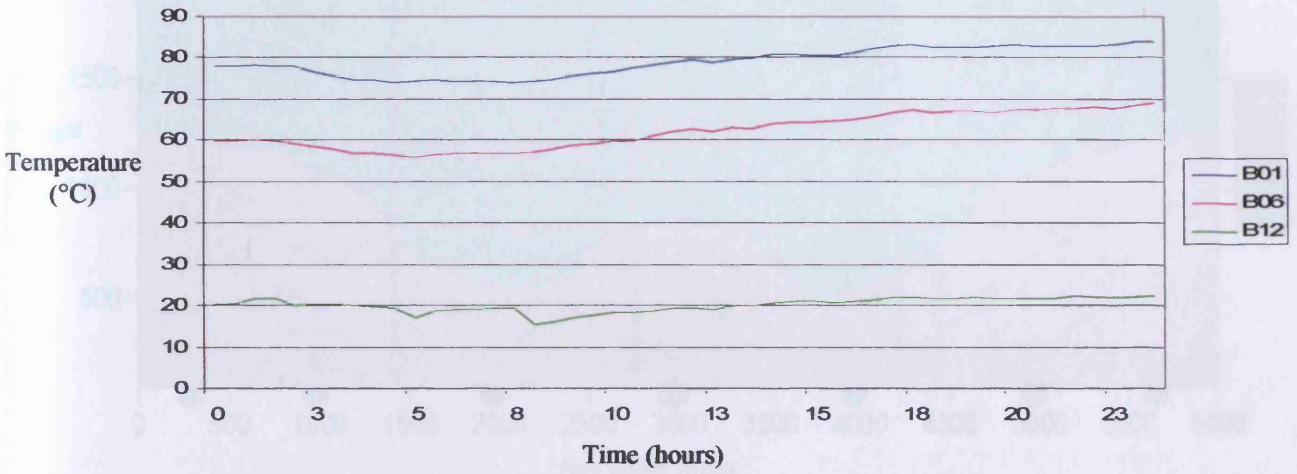

Figure 4.13 Temperatures measured at probe B, located 3000mm from the back wall and 750mm from the side wall. Over a 24 hours period starting 3 days after the bay was filled.

To enable the proportion of the composting matrix greater than 60°C to be calculated a software package was employed that was capable of plotting the temperature measured at each thermocouple on to a 2 dimensional representation of the compost matrix within the bay (Golden software, surfer package). The software was also capable of calculating the proportion of the plotted area that was above a specified temperature. Temperature measurements from the probes placed at 750mm intervals from the bay wall to the centre of the bay at a distance of 3000mm from the back wall of the bay were plotted. This represented a vertical slice through one half of the centre of the bay. To represent the full width of the compost matrix in the bay it was assumed that the temperature profile across the whole width of the bay was symmetrical and the data from temperature measurements from one side were plotted for both sides.

48 hours after the bay was filled peak temperatures had reached 80°C. To calculate the proportion of the composting matrix greater than 60°C, the recordings made from each of the 60 thermocouples were plotted on the surfer software package, as shown in Figure 4.14. As there was a known temperature recording error of up to +6°C an upper and lower range was calculated by using the recorded temperatures for the upper and reducing the recorded

temperatures by this amount for the lower. 22% to 40% of the area of this vertical profile was greater than 60°C and only 6% to 13% of the area was greater than 70°C. The process was repeated 100 hours after the bay was filled, at this time 72% to 87% of the bay was greater than 60°C and 29% to 44% was greater than 70°C, as shown in Figure 4.15.

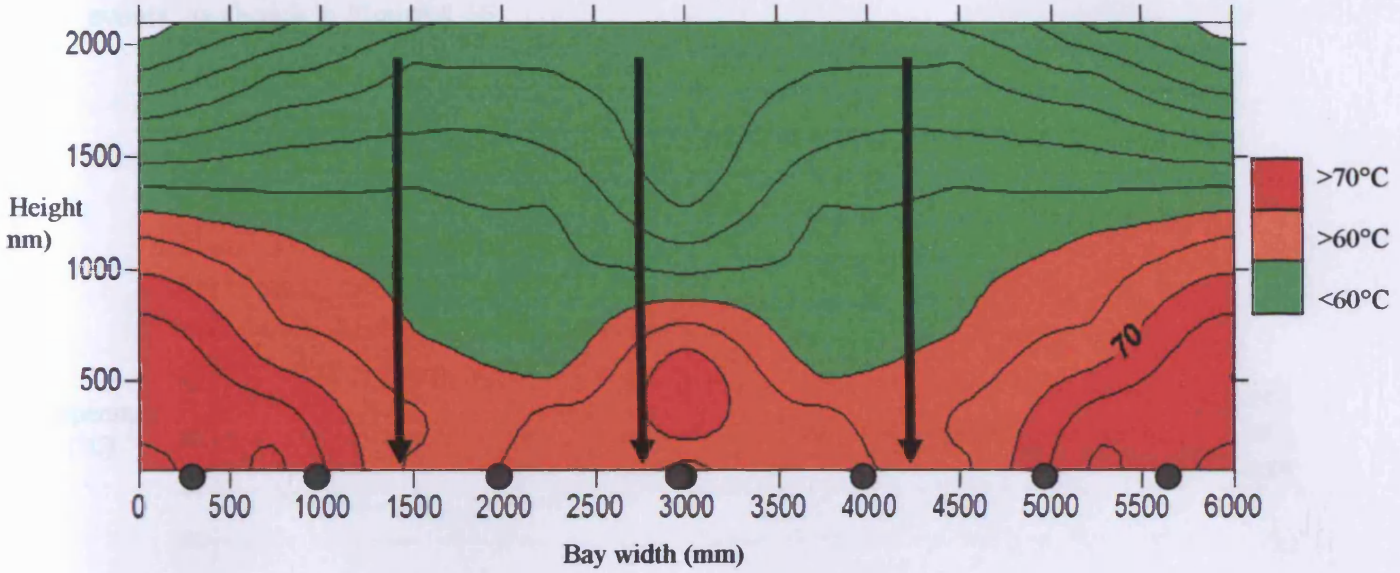

Figure 4.14. Central cross section temperature profile in the aerated bay, 48 hours after the bay was filled. Contour lines are at 5°C intervals and arrows show direction of gas flow. ● = Aeration pipe location

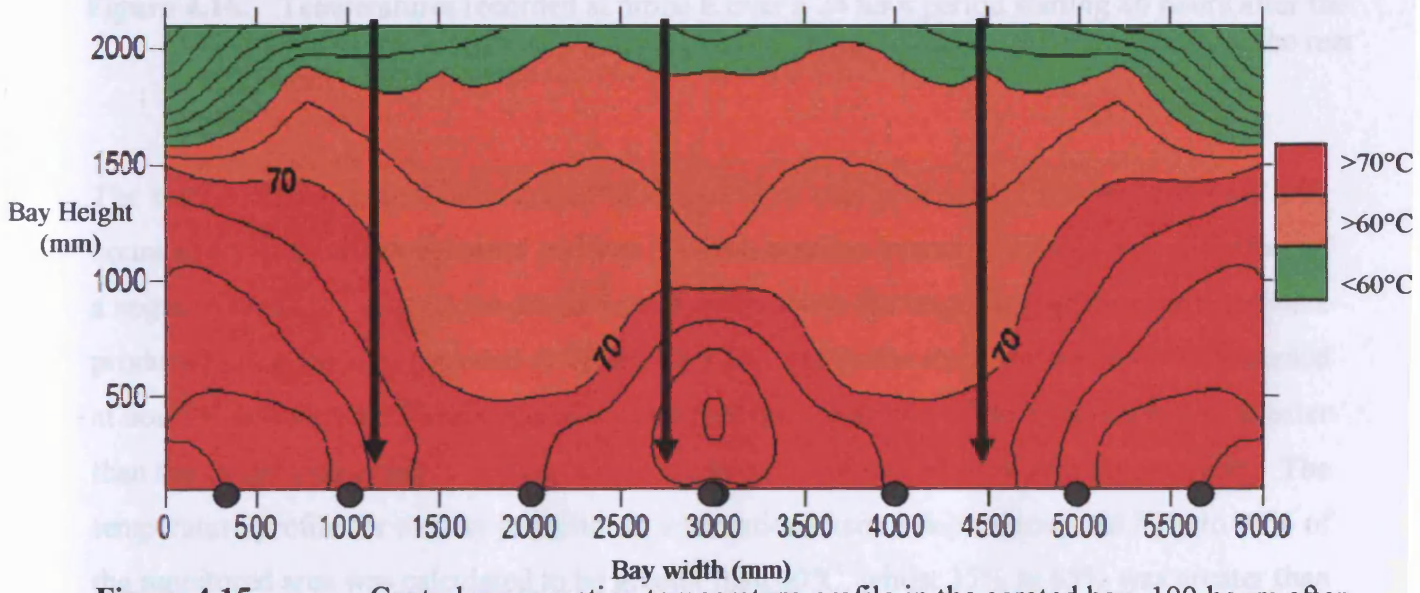

Figure 4.15. Central cross section temperature profile in the aerated bay, 100 hours after the bay was filled. Contour lines are at 5°C intervals and arrows show direction of gas flow. ● = Aeration pipe location

Temperatures recorded at probe E located at the centre of the bay, during the 24 hour period starting 80 hours after filling, indicate that at location E01, located 100 mm up from the bay base, there is an increase of more than 10°C in response to an aeration event. At location E12 (2200mm up from bay base|) there is a reduction in temperature of between 4°C and 8°C following each aeration event and at E06 there is no temperature change in response to aeration events, as shown in Figure 4.16.

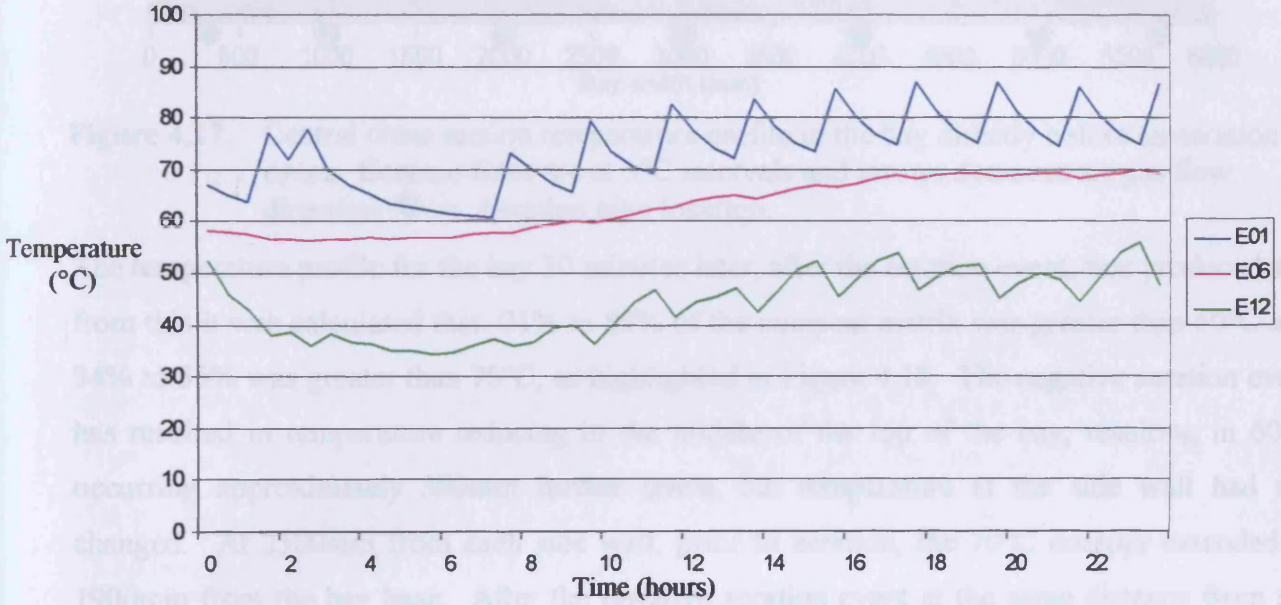

Figure 4.16. Temperatures recorded at probe E over a 24 hour period starting 80 hours after the bay was filled. Probe E was located in the centre of the bay 3000mm from the rear wall.

The temperature profile demonstrated in Figure 4.15 was produced from data recorded 100 hours after filling which occurred midway between aeration events. To determine the effect of a negative aeration event on the proportion of waste above the target temperature, profiles were produced using the data recorded at 97 and 97.5 hours from the start. An aeration event started at hour 97 and finished 30 minutes later, therefore the proportion of the compost matrix greater than the target temperatures can be calculated directly before and after an aeration event. The temperature profile for the bay just prior to an aeration event was produced and 89% to 95% of the monitored area was calculated to be greater than 60°C, whilst 35% to 65% was greater than 70°C, as demonstrated in Figure 4.17.

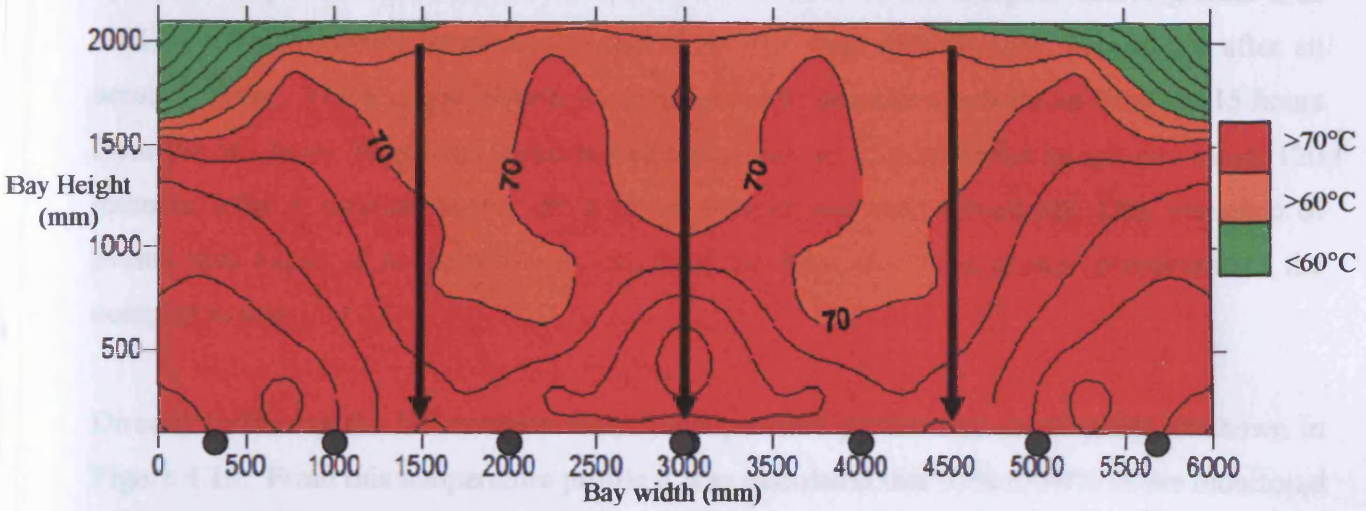

Figure 4.17. Central cross section temperature profile in the bay directly before an aeration event. Contour lines are at 5°C intervals and arrows demonstrate gas flow direction. ● = Aeration pipe location.

The temperature profile for the bay 30 minutes later, after the aeration event, was produced and from this it was calculated that 71% to 88% of the compost matrix was greater than 60°C and 34% to 55% was greater than 70°C, as highlighted in Figure 4.18. The negative aeration event has resulted in temperature reducing in the middle of the top of the bay, resulting in 60°C occurring approximately 300mm further down, but temperature at the side wall had not changed. At 2500mm from each side wall, prior to aeration, the 70°C contour extended to 1900mm from the bay base. After the negative aeration event at the same distance from the side walls the 70°C contour was approximately 900mm lower. Only 500mm across in the centre of the bay the 70°C contour did not move in response to the aeration event.

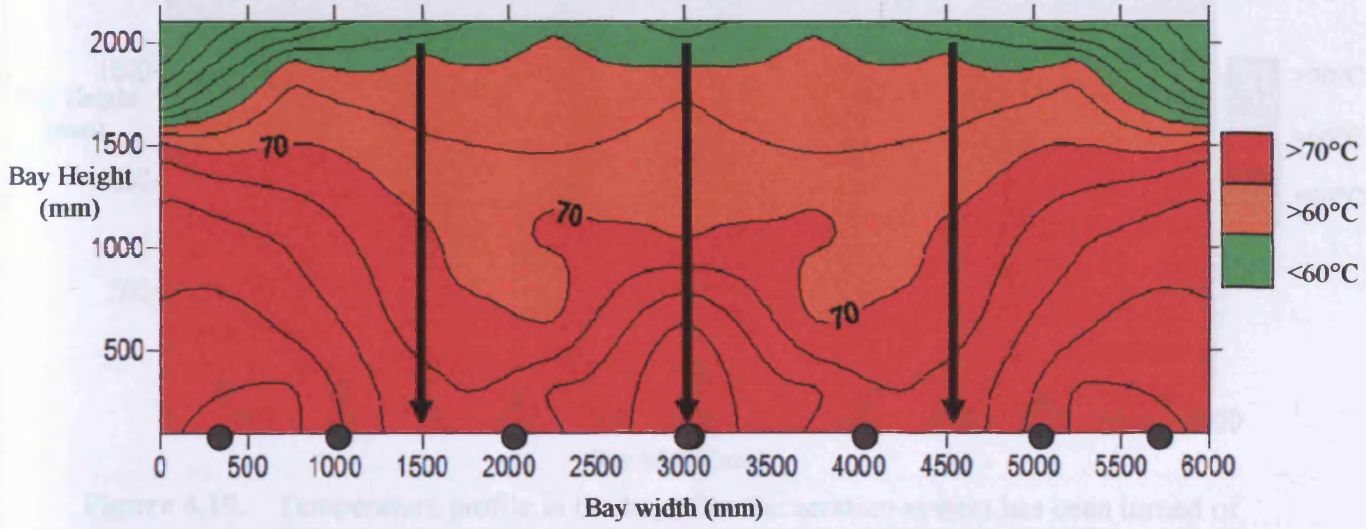

Figure 4.18. Centre cross section temperature profile in the bay, directly after a 30 minute negative aeration event. Contour lines are at 5°C intervals and arrows indicate gas flow direction. ● = Aeration pipe location.

The period up to 100 hours has resulted in 89% to 95% of the compost matrix greater than 60°C but the maximum proportion greater than 70°C was 35% to 65%, 90 minutes after an aeration event. The aeration system was configured to produce a bottom-up flow at 115 hours from the bay being filled, and aeration frequency was set to operate for 30 minutes every 120 minutes, after 4 aeration events the aeration system was then turned off. This sequence of events was expected to redistribute heat from the base area to a greater proportion of the compost matrix.

Directly following the last aeration event a temperature profile was constructed, as shown in Figure 4.19. From this temperature profile it was calculated that 97% to 99% of the monitored section of the composting matrix in the aerated bay was greater than 60°C and that 92% to 95% of the area was greater than 70°C. The upper area in the centre of the bay was the region in which temperature had increased from over 60°C to above 70°C. Prior to changing airflow direction from bottom to top, compost matrix temperature was below 70°C at a distance of approximately 700mm from the bay base at 2200mm from the side wall, following the 4 positive aeration events this distance had increased to above 2100mm from the bay base. The side wall temperature was greater than 70°C up to approximately 1800mm, some 300mm higher than that experienced prior to the change. The lower corner of the bay had reduced from above 80°C to between 60°C and 70°C.

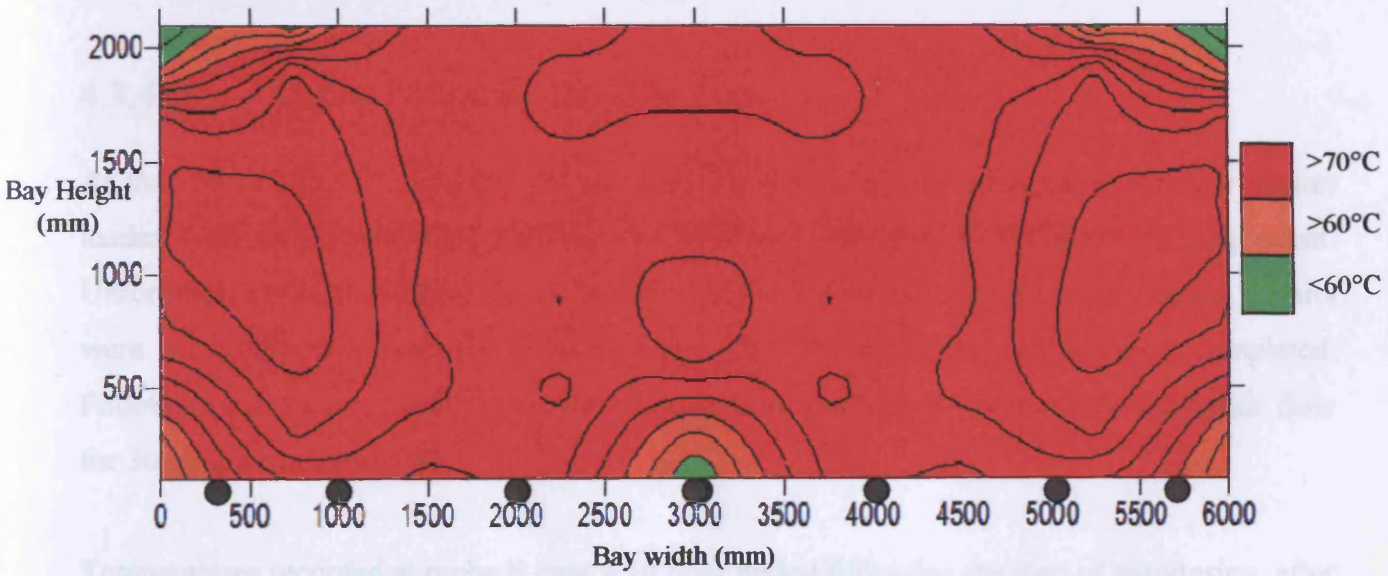

Figure 4.19. Temperature profile in the bay after the aeration system has been turned of following 4 positive aeration events, contour lines are at 5°C. ● = Aeration pipe location.

A power failure occurred after the fan was switched off resulting in the temperatures not being monitored for the first 20.5 hours. The temperatures were then only recorded from 20.5 to 42 hours after the fan was switched off, as there was a further power loss. The temperatures recorded at probe E, located in the centre of the bay, for this period are generally rising from 21 to 33 hours, as shown in Figure 4.20. E01 is located 100mm up from the bay base, and in this position there is an increase of 10°C, from 55°C to 65°C. At location E12, which was located 2200mm from the bay base, temperature increased for the first 6 hours of the period and then reduced over the remainder of the period by approximately 10°C.

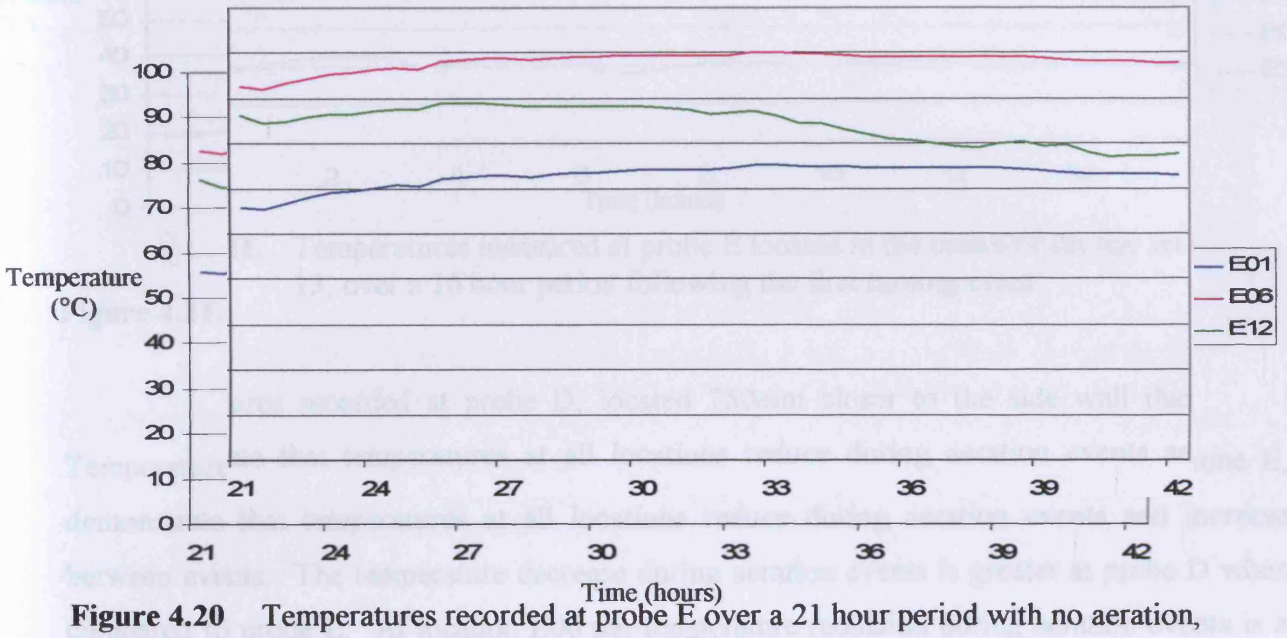

Figure 4.20 Temperatures recorded at probe E over a 21 hour period with no aeration, starting 5 days after the bay was filled.

4.3.4.2 Period Following the First Turn

At the end of the 11th day after the bay was initially filled, it was emptied with the bucket loader with the intention of refilling the following morning to imitate a turning event. Unfortunately whilst refilling the bay on day 12 the loader experienced a breakdown, repairs were not undertaken until the following day (day 13) when the refilling was completed. Following the turning event the aeration system was configured to produce negative air flow for 30 minutes in every 180.

Temperatures recorded at probe E over a 16 hour period following the start of monitoring, after the turning event, indicate that during the aeration events temperature increases by approximately 10°C to 15°C at location E01, as shown in Figure 4.21. During the 150 minute period between aeration events the temperature at this location reduces slightly less than the

increase, resulting in an overall increase in temperature from 60°C at the start of the period, to 75°C at the end of the period. The other monitored locations on probe E demonstrate the opposite trend with temperature reducing during aeration events and increasing between aeration events.

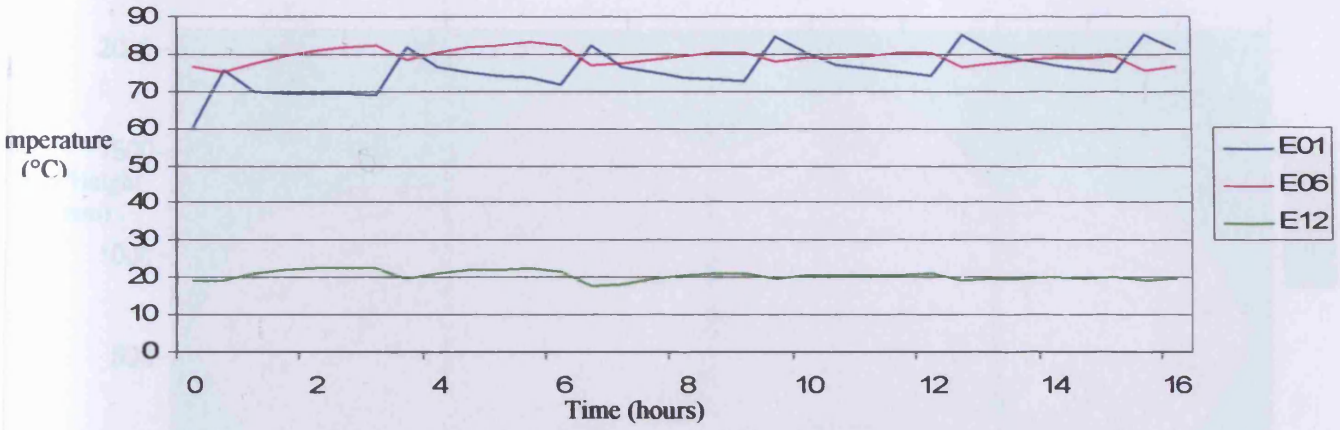

Figure 4.21. Temperatures measured at probe E located in the centre of the bay on day 13, over a 16 hour period following the first turning event. .

Temperatures recorded at probe D, located 750mm closer to the side wall than probe E, demonstrate that temperatures at all locations reduce during aeration events and increase between events. The temperature decrease during aeration events is greater at probe D when compared to probe E. At location E06 the temperature reduction during aeration events is a maximum of 5°C at hour 6, whilst the temperature reduction at D06 is 12°C at the same aeration event, as shown in Figure 4.22. Probe E is located directly above an aeration pipe whilst probe D is located 250mm from an aeration pipe.

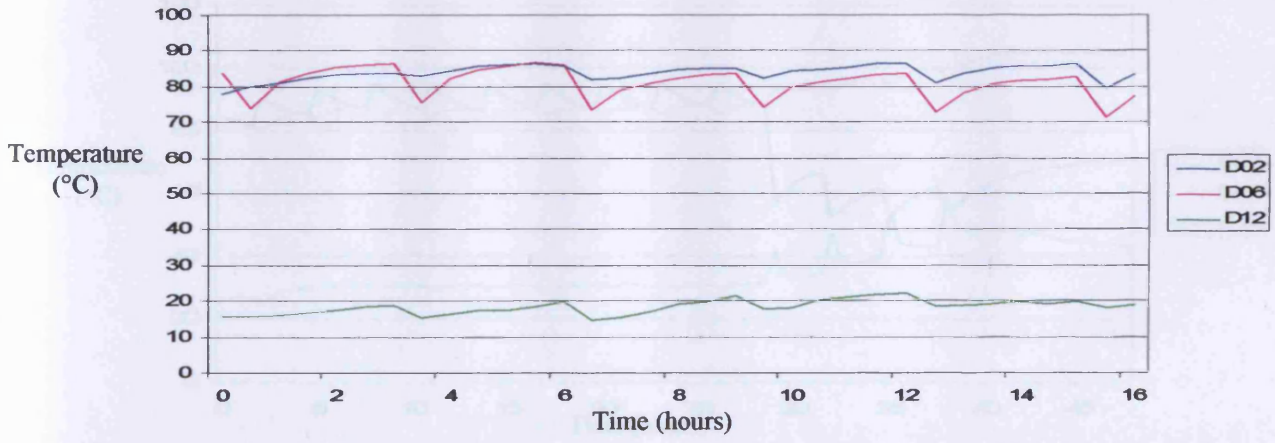

Figure 4.22. Temperatures measured at probe D located 750mm from the centre of the bay on day 13, over a 16 hour period following a turning event. Aeration was negative for 30 minutes in every 180 minutes

A temperature profile was constructed from the data recorded at the start of the period demonstrated in Figure 4.22. This temperature profile was used to calculate the proportion of the compost matrix in the monitored area that was greater than 60°C and 70°C, which was 53 to 62% and 32 to 46% respectively, and is shown in Figure 4.23.

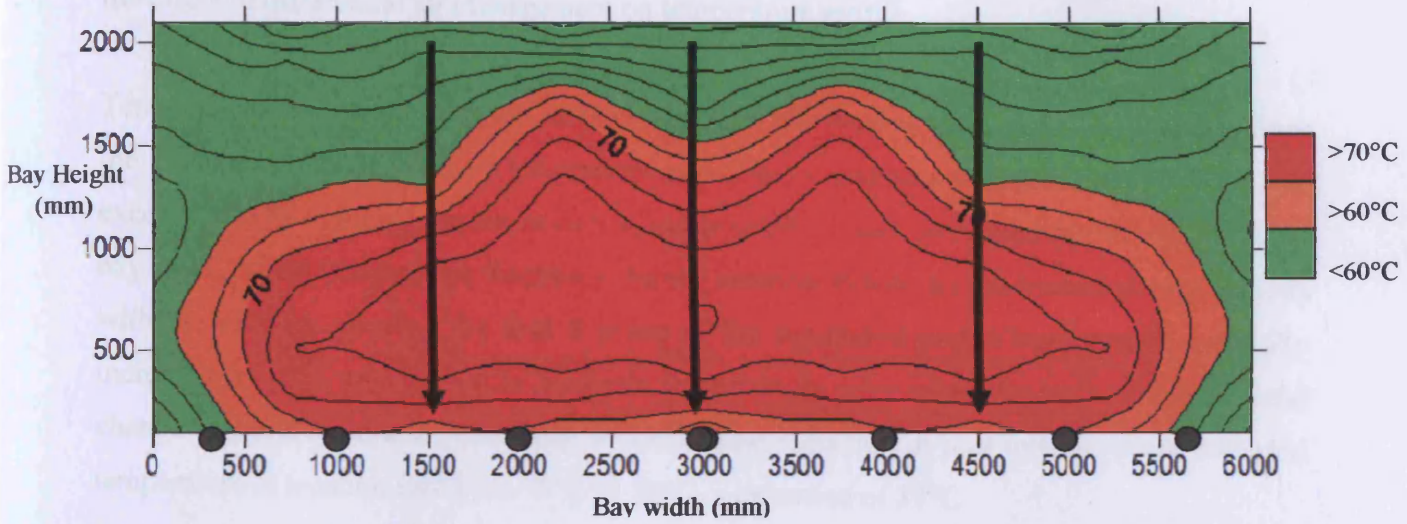

Figure 4.23 Temperature profile in the aerated bay, constructed from data recorded at the start of temperature monitoring on day 13. Aeration was negative and operating for 30 minutes in every 180, arrows indicate gas flow direction. ● = Aeration pipe location.

On day 18 the aeration system was changed to positive for 4 aeration events and then switched off, with the aim of distributing heat from the lower areas of the bay to promote an even temperature profile prior to a turning event. These events are demonstrated by changes in temperatures recorded at probe E over a period of 47 hours, starting on day 17, as shown in Figure 4.24.

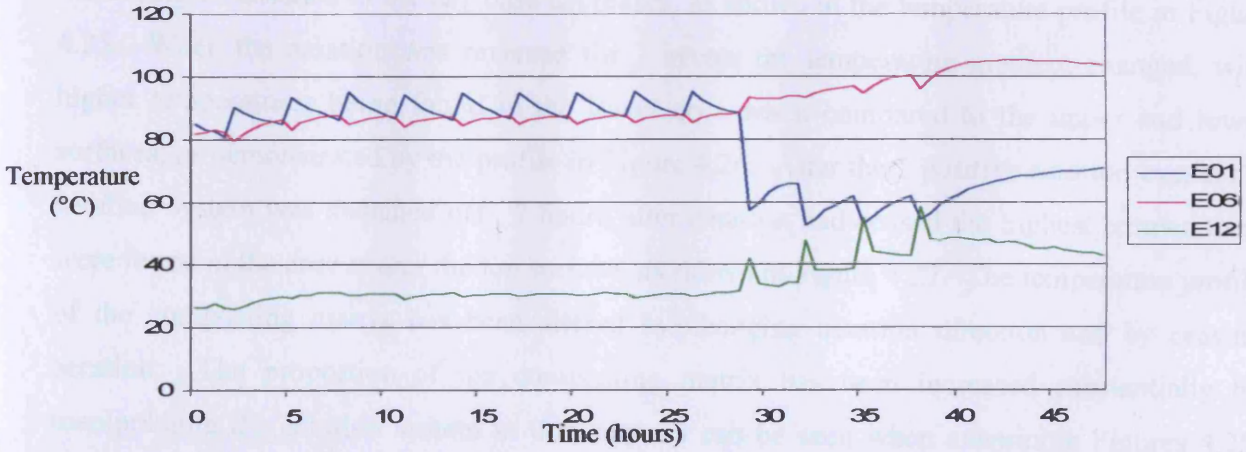

Figure 4.24 Temperatures recorded at probe E, located in the centre of the bay, over a 47 hour period starting on day 17. Aeration prior to hour 29 was negative for 30 minutes in 180, from hour 29 to hour 38 it was positive for the same duration and frequency, after hour 38 the aeration system was not operating.

Due to movement of the instrument box at hour 29 the temperature recording error increased from a maximum of +6°C to an unknown error which could be as high as +20°C. The reasons for this are described in Section 4.3.3. This unknown error occurred until the bay was turned on day 27 when the instrument box was moved back to its original position. During this period the absolute temperatures should be disregarded but the change in temperature is accurate as is the effect of differential air management on temperature profile.

Temperatures recorded during the negative aeration phase generally decrease as distance from the bay base increases, as does temperature reduction in response to aeration events. The one exception to this general pattern occurs at location E01, which is located 100mm up from the bay base, where temperature increases during aeration events and decreases during periods without aeration. During the first 8 hours of the monitored period temperatures generally increased by 5°C, and from 8 to 28 hours temperatures were relatively static. Following the change to positive aeration there was an immediate reduction in post aeration event recorded temperature at location E01 from 95°C to 58°C, a reduction of 37°C.

There is a change in vertical temperature distribution during this positive aeration phase, from 28 to 38 hours, with locations less than 700mm from the bay base decreasing in temperature and those at, or above this point increasing. When the aeration system was switched off there was an increase in temperature at locations E01 to E10 whilst E11 and E12, which are located close to the compost matrix upper surface, show a reduction.

During the negative aeration phase there was a temperature gradient, with temperature increasing as distance to the bay base decreases, as shown in the temperature profile in Figure 4.25. When the aeration was reversed for 2 events the temperature gradient changed, with higher temperatures being found in the lower core when compared to the upper and lower surfaces, as demonstrated by the profile in Figure 4.26. After the 2 positive aeration events the aeration system was switched off. 7 hours after aeration had ceased the highest temperatures were found in the core nearer the top surface, as shown in Figure 4.27. The temperature profile of the composting matrix has been altered by changing aeration direction and by ceasing aeration. The proportion of the composting matrix has been increased substantially by manipulating the aeration system in this way, as can be seen when examining Figures 4.25, 4.26 and 4.27 in sequence.

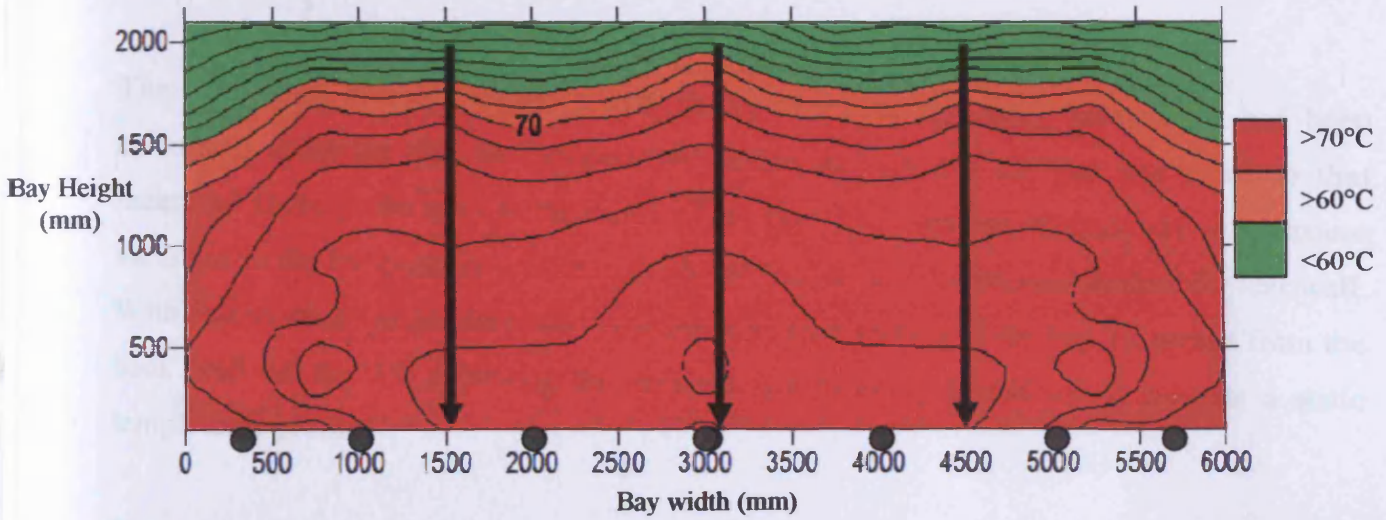

Figure 4.25. Temperature profile in the aerated bay following 5 days of negative aeration for 30 minutes in every 180. Arrows indicate gas flow direction. ● = Aeration pipe location.

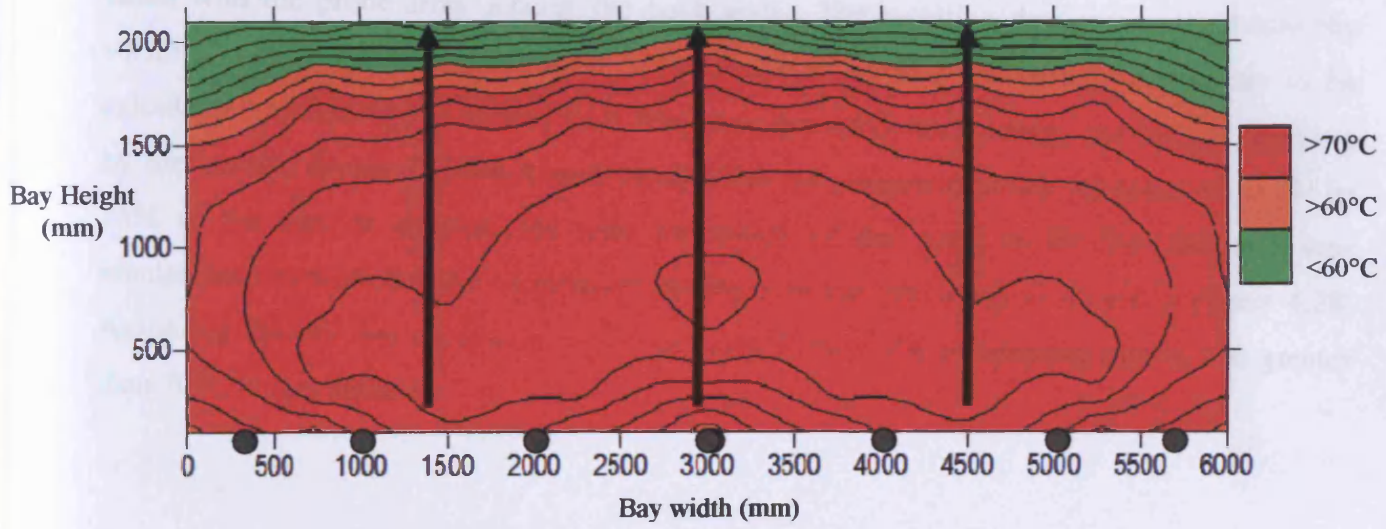

Figure 4.26. Temperature profile in the aerated bay after 1 positive aeration event of 30 minutes, following 5 days of negative aeration for 30 minutes in every 180. Arrows indicate gas flow direction. ● = Aeration pipe location.

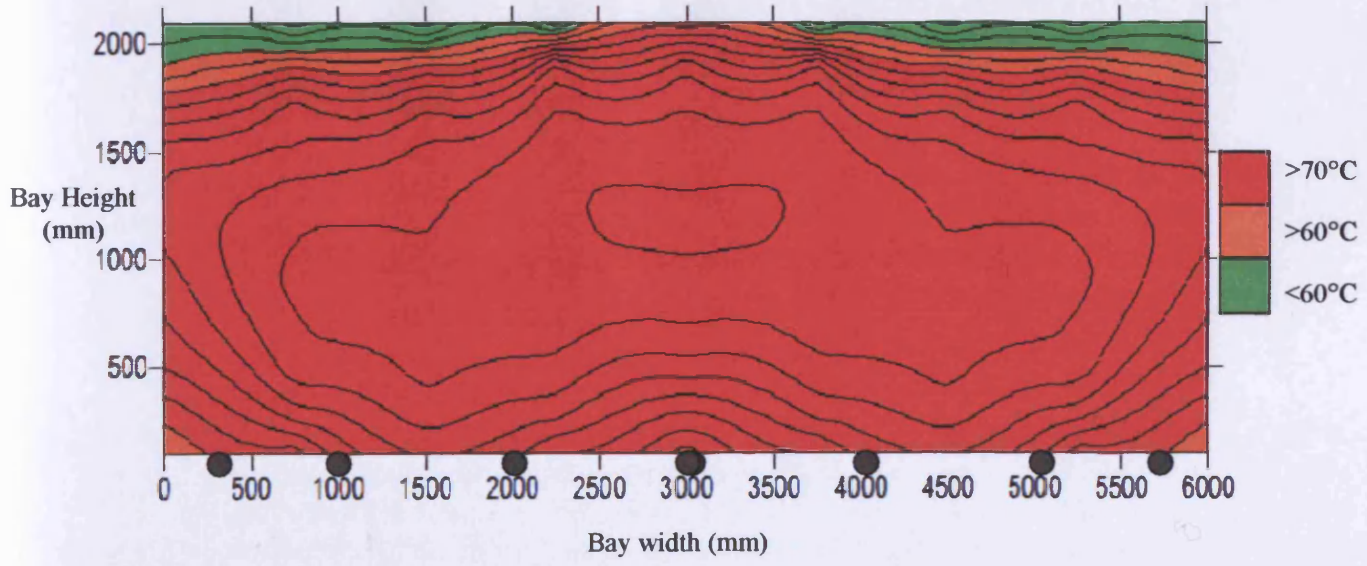

Figure 4.27. Temperature profile in the aerated bay after 7 hours with no aeration, on day 18. ● = Aeration pipe location.

The proportion of the compost matrix in the bay over the target temperature had been calculated assuming that the temperature profile through out the bay was equal to that measured at the probe array in the centre of the bay. This method does not take into account variation in the temperature profile through out the bay and differences against the rear wall. With this in mind temperature was recorded in a cross section of the bay 2.8 meters from the back wall on day 19, following the aeration system being turned off to promote a static temperature profile.

The probe array was then moved 700mm towards the back wall of the bay, and temperatures were recorded again. This was repeated 4 times at hourly intervals, with the final reading taken with the probe array against the back wall. The resulting data was entered into the surform software in horizontal slices. The software allowed the volume in the bay to be calculated by totalling the area of each slice over the target temperature, and then multiplying by the vertical distance between each slice. This data represented the temperature profile in 25% of the bay, to estimate the total proportion of the waste in the bay this data was manipulated to represent the temperature profile over the whole bay as shown in Figure 4.28. Assuming the bay was enclosed on all four sides, 81% of the composting matrix was greater than 70°C in this instance.

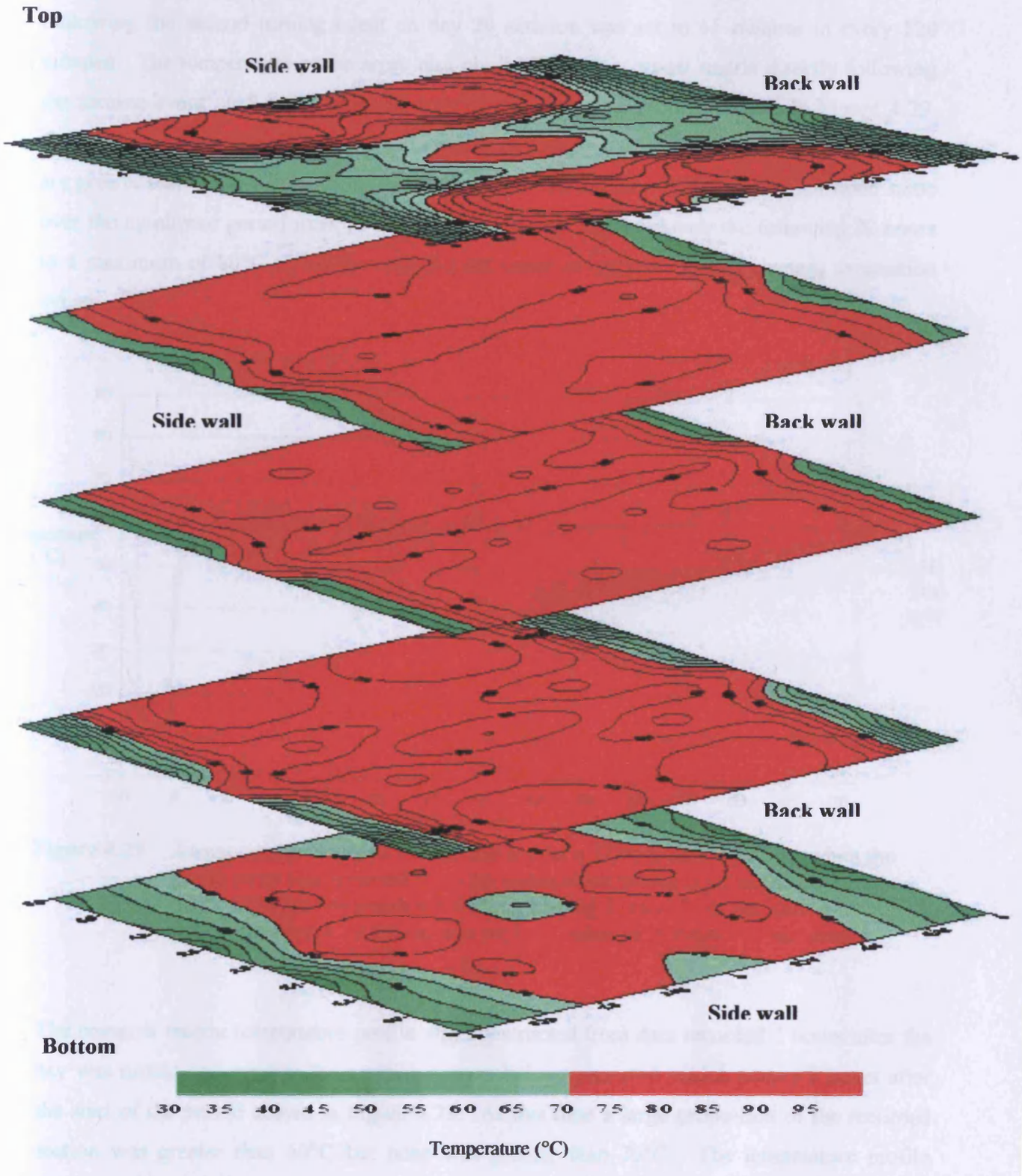

Figure 4.28. Temperature profile on day 18 represented in horizontal cross sections, 81% of the monitored compost matrix is greater than 70°C. Temperatures were recorded in one quarter of the bay, from the centre to the side wall and at five equal distanced sections up to the rear wall. The whole profile assumes all 4 quarters are the same as the measured section.

4.3.4.3 Period Following the Second Turn

Following the second turning event on day 20 aeration was set to 15 minutes in every 120 minutes. The temperature probe array was placed into the compost matrix directly following the turning event, at 5 hours after the start of the 72 hour period, as shown in Figure 4.29. Temperature at locations E01 to E06, lower half of the compost matrix in the centre of the bay, are greater than 60°C within 15 hours of the start of the period. Temperatures remained static over the monitored period from 15 to 50 hours and then increased over the following 22 hours to a maximum of 80°C. This increase did not occur in response to any changes to aeration events.

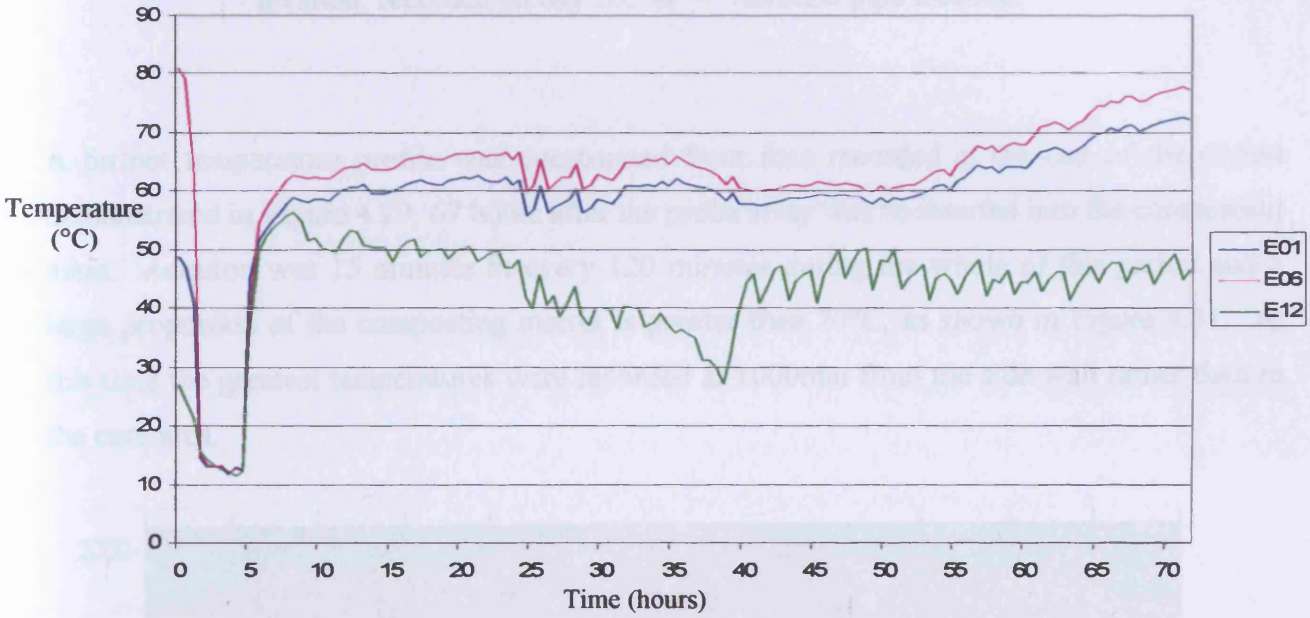

Figure 4.29 Temperatures recorded from probe E over a 72 hour period starting when the probe array was removed from the composting matrix prior to turning and the probe array was re-inserted following turning 5 hours from the start of the monitored period. Aeration was set to 15 minutes in every 120 minutes.

The compost matrix temperature profile was constructed from data recorded 3 hours after the bay was turned and prior to the aeration system being connected, which occurs 8 hours after the start of the period shown in Figure 4.29. At this time a large proportion of the recorded section was greater than 60°C but none was greater than 70°C. The temperature profile demonstrates that the periphery was the coolest area and that there was a small area in the centre of the bay that was less than 60°C, as shown in Figure 4.30.

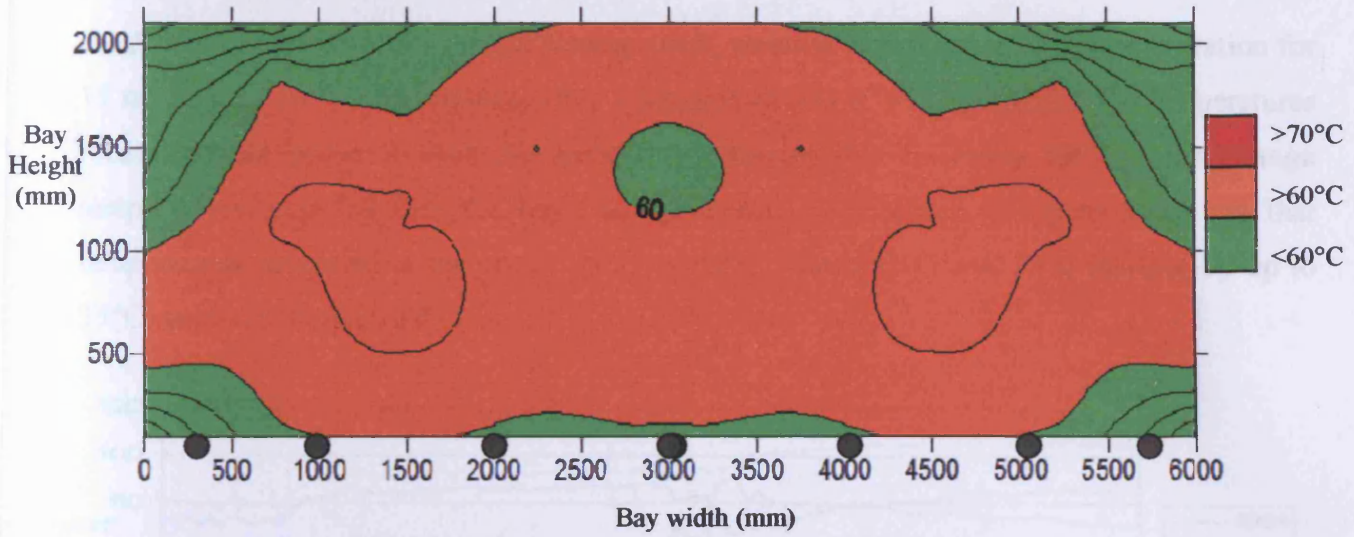

Figure 4.30. Temperature profile in the aerated bay 3 hours after a turning event, with no aeration, recorded on day 20. ● = Aeration pipe location.

A further temperature profile was constructed from data recorded at the end of the period demonstrated in Figure 4.29, 67 hours after the probe array was re-inserted into the composting mass. Aeration was 15 minutes in every 120 minutes during the whole of this period and a large proportion of the composting matrix is greater than 70°C, as shown in Figure 4.31. At this time the greatest temperatures were recorded at 1000mm from the side wall rather than in the core area.

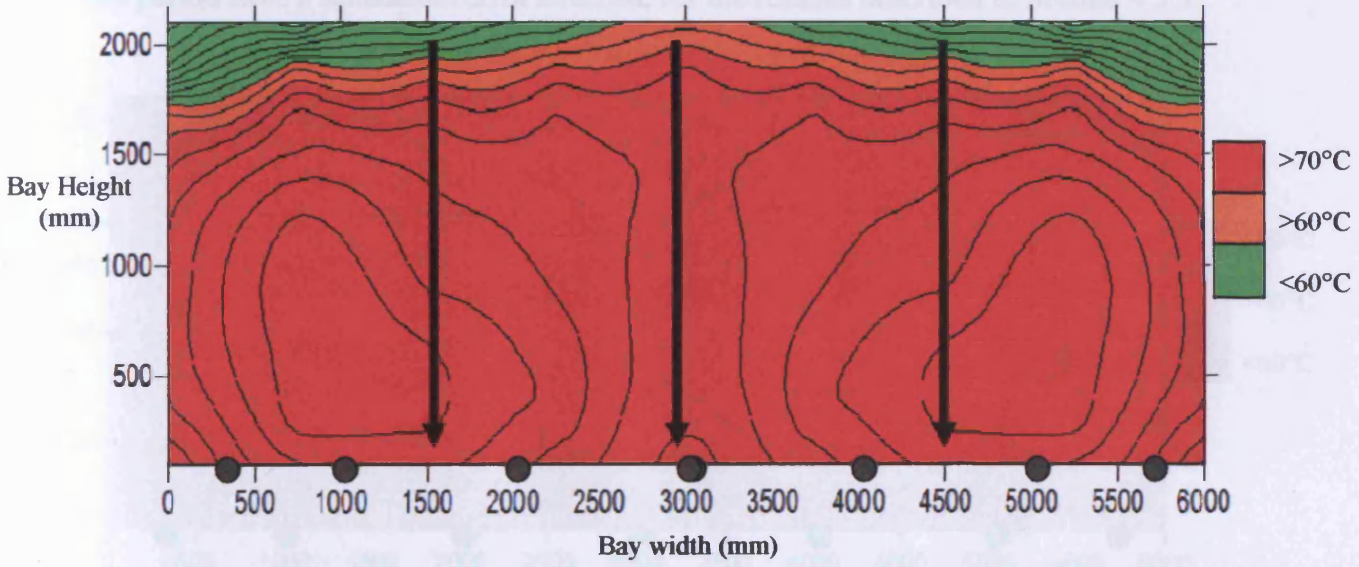

Figure 4.31 Temperature profile in the aerated bay 67 hours after the temperature probe array was re-inserted following a turning event on day 20, aeration was negative and set on 15 minutes in every 120 minutes. Arrows indicate gas flow direction.● = Aeration pipe location.

On day 26, 6 days after the second turning event, aeration was changed to positive aeration for 15 minutes in every 120 minutes, after 3 aeration events it was switched off. Temperatures recorded from probe E over this period demonstrate that following the aeration change temperatures recorded near the bay base (E01 and E02) reduce by up to 20°C and that temperatures measured at the top of the composting matrix (E11 and E12) increase by up to 35°C, as shown in Figure 4.32.

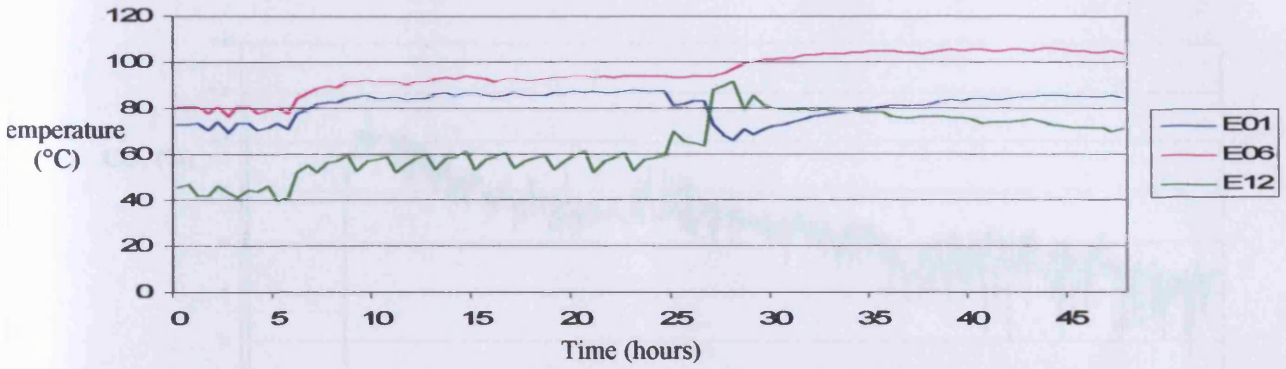

Figure 4.32 Temperatures recorded from probe E over a 48 hour period starting on day 25. Aeration was changed from negative at 15 minutes in every 120 minutes to positive for the same period and frequency on hour 25, and was then turned off at hour 28.

A temperature profile was constructed from data recorded at hour 45 when temperatures were a maximum prior to the third turning event. During this period there was no aeration and the greatest temperatures are found in the upper part of the core. The absolute temperatures during this period have a substantial error attached, for the reasons described in Section 4.3.3.

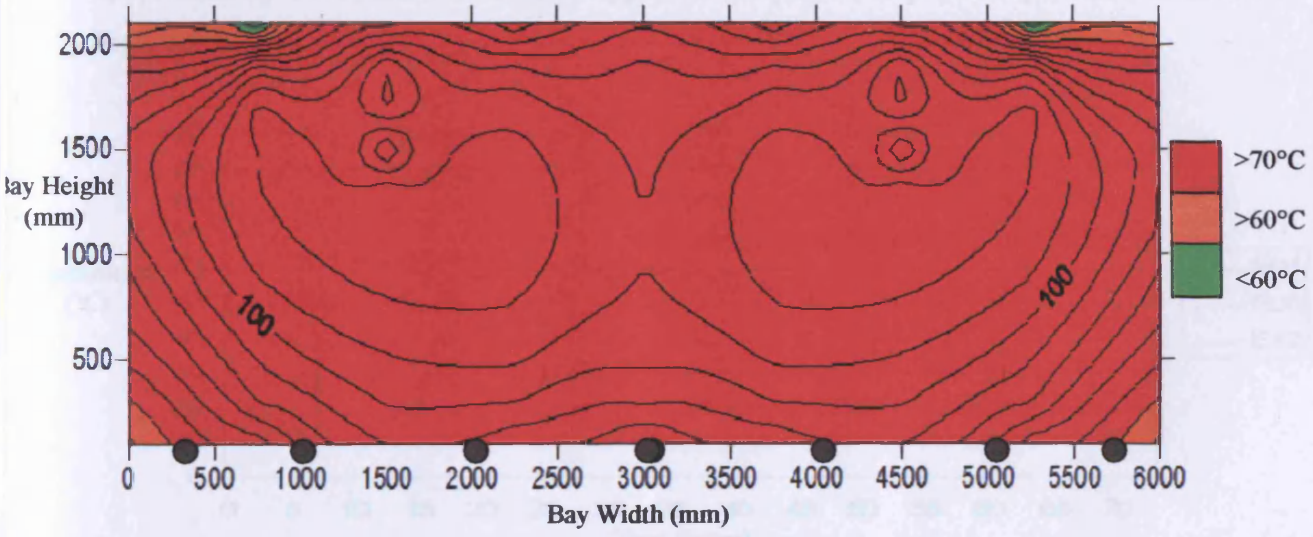

Figure 4.33 Temperature profile in the aerated bay following 17 hours without aeration, recorded on day 27. ● = Aeration pipe location.

4.3.4.4 Period Following the Third Turn

The third turn occurred on day 27 and there was no forced aeration during the 66 hour period after recommencement of sampling. CO_2 concentration measured 300mm out from the centre of the bay sidewall at 1000mm down from the compost matrix surface, reduced from 10% at 7 hours after the start of the sampled period to approximately 4% at the end of the period, as seen in Figure 4.34.

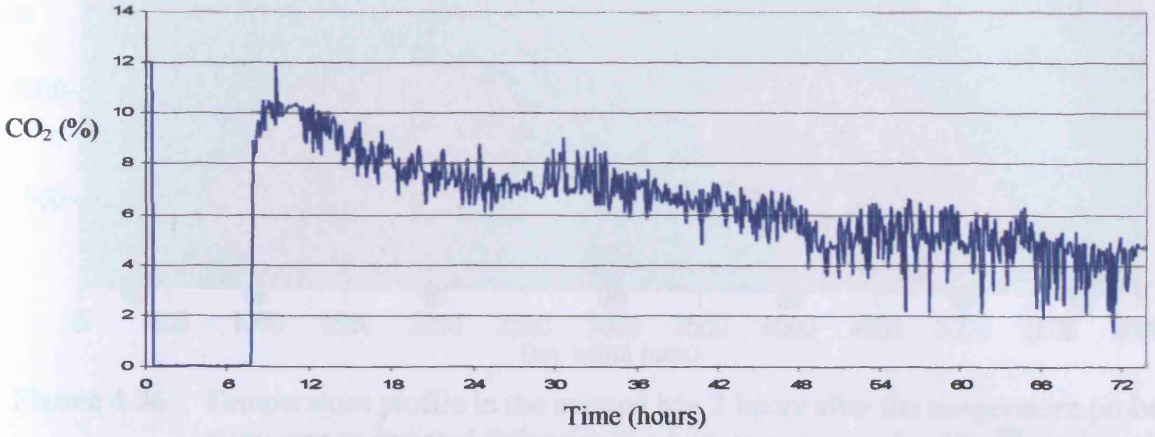

Figure 4.34. CO_2 concentration sampled 300mm from the centre of the bay wall, 1000mm vertically down in the compost matrix, against time. The bay was emptied and refilled to imitate a turning event and sampling re-started on hour 7.

During this period temperature was generally increasing at all points on probe E, as was the temperature gradient. The vertical temperature gradient following the turning event was approximately 10°C, and increased to approximatelly 30°C at peak temperature, as shown in Figure 4.35.

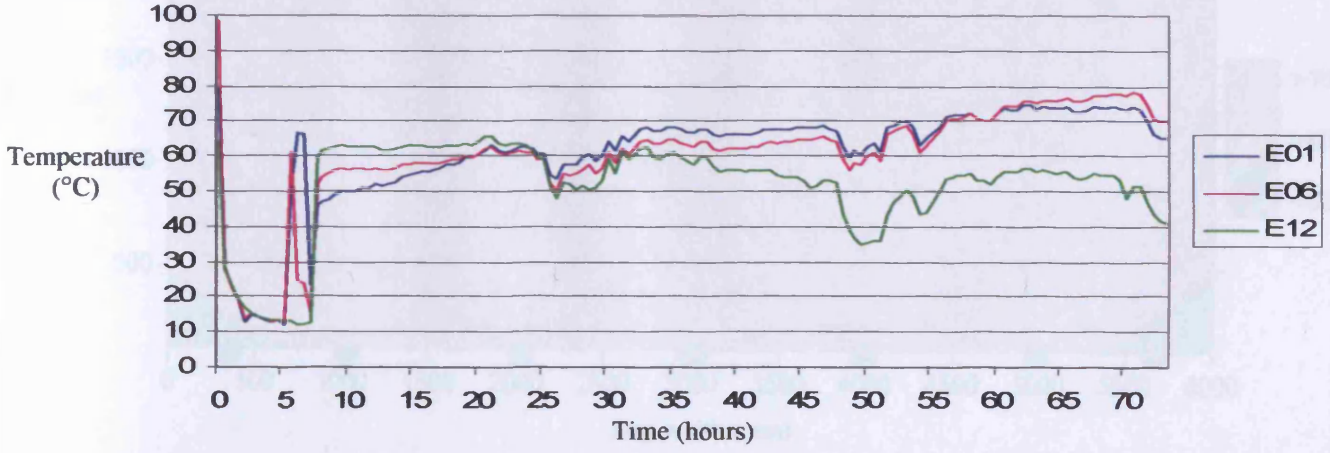

Figure 4.35 Temperatures recorded from probe E over a 72 hour period starting on day 27.

A temperature profile was constructed for the compost matrix in the bay from data recorded 8 hours after the start of the 72 hour period shown in Figure 4.35. At this time 3% to 27% of the composting matrix was >60°C and none of the compost matrix had reached 70°C, as shown in Figure 4.36.

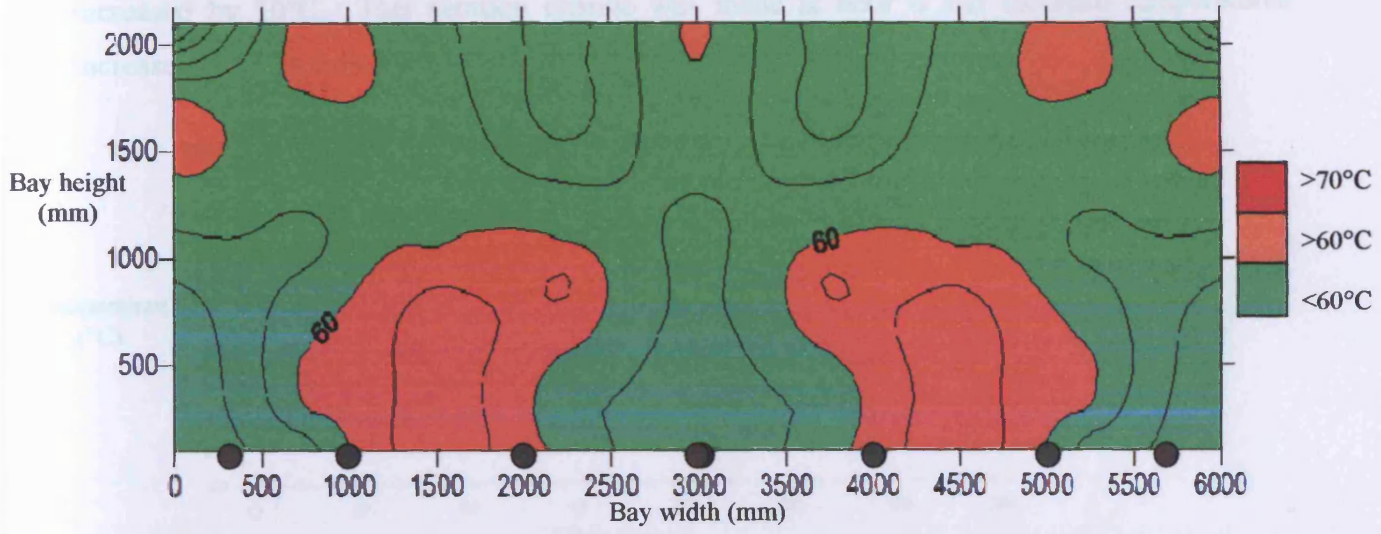

Figure 4.36 Temperature profile in the aerated bay 2 hours after the temperature probe array was re-inserted following the turning event on day 27. ● = Aeration pipe location.

A further temperature profile was constructed for the compost matrix in the bay from data recorded 70 hours after the start of the 72 hour period shown in Figure 4.35. There had been no aeration since the turning event 64 hours earlier and at this time 85% to 94% of the composting matrix was >60°C and 62% to 77.6% was >70°C, as shown in Figure 4.37.

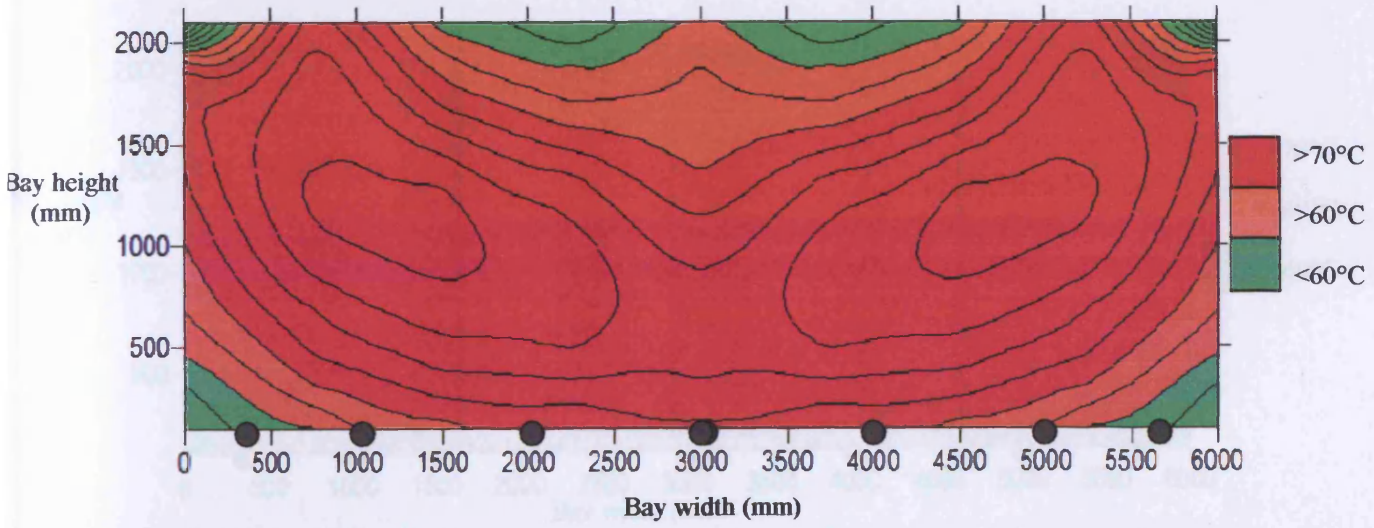

Figure 4.37 Temperature profile in the aerated bay 64 hours after the temperature probe array was re-inserted following the 3rd turning event on day 27. ● = Aeration pipe location.

On day 30, aeration was turned on and set to negative for 15 minutes in 120 minutes. CO_2 concentration in the composting matrix remained below the minimum target of 4% for the following 24 hours. In response aeration was reduced to negative for 15 minutes in every 180 minutes on day 31. Following this change, temperatures measured at E01 to E06 generally increased by 10°C. This aeration change was made at hour 6 and recorded temperatures increased over the following 6 hours, as shown in Figure 4.38.

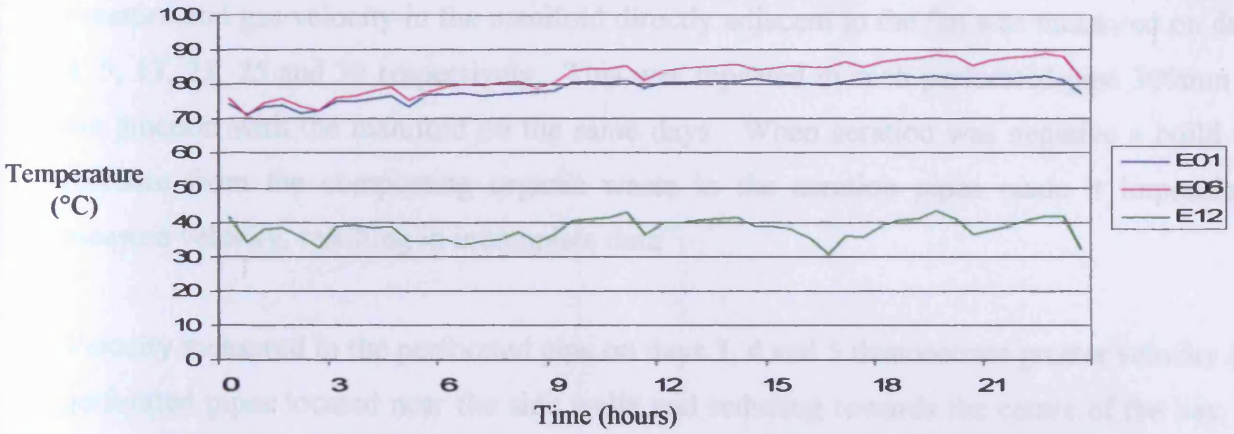

Figure 4.38 Temperatures recorded from probe E over a 24 hour period starting on day 31. Aeration was changed from negative for 15 minutes in every 120 minutes to 15 minutes in every 180 minutes at hour 6.

Aeration was changed from negative for 15 minutes in every 180 minutes to positive for the same period and frequency on day 33. Following 3 positive aeration operations at this frequency a temperature profile was constructed, as shown in Figure 4.39. At this time 91% to 96% of the composting matrix was greater than 60°C and 75% to 85% was greater than 70°C.

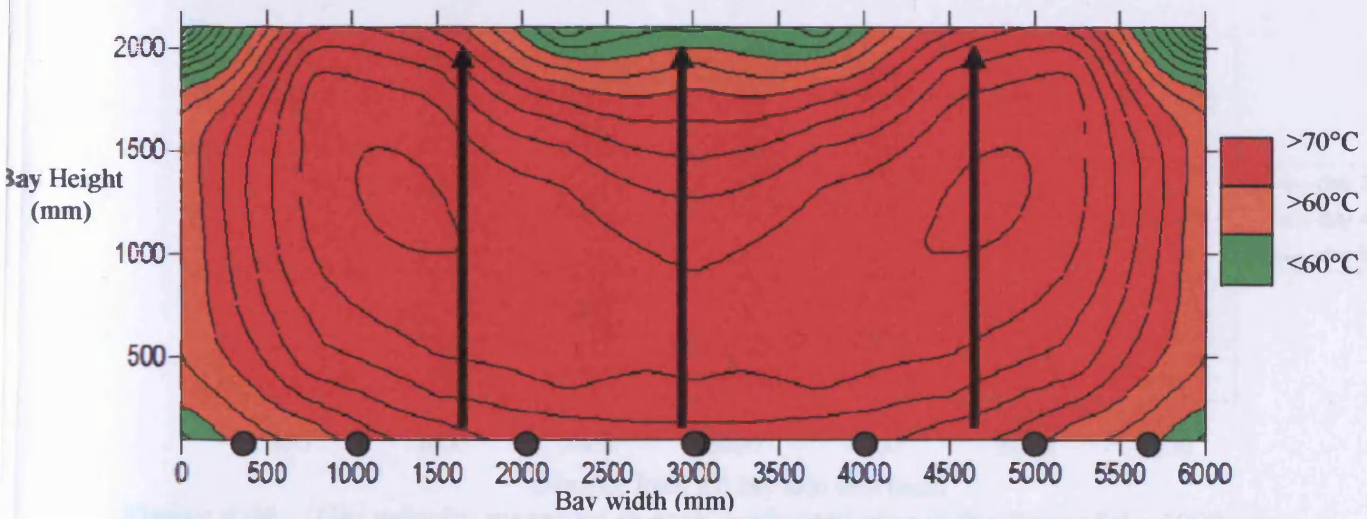

Figure 4.39 Temperature profile in the aerated bay on day 33, aeration positive for 15 minutes in every 180 minutes, for the following 9 hours. Arrows indicate gas flow direction. ● = Aeration pipe location.

4.3.4.5 Forced Air Distribution

The forced aeration system comprised of a fan connected to one end of a 110mm diameter distribution manifold. Connected to the manifold were seven 60mm diameter perforated pipes, placed in the temporary floor at 300mm, 1000mm, 2000mm and 3000mm from each side wall, as shown in Figure 4.3.

Pressure and gas velocity in the manifold directly adjacent to the fan was measured on days 3, 4, 5, 13, 23, 25 and 32 respectively. This was repeated in each perforated pipe 300mm from the junction with the manifold on the same days. When aeration was negative a build up of leachate from the composting organic waste in the aeration pipes made it impossible to measure velocity, resulting in incomplete data.

Velocity measured in the perforated pipe on days 3, 4 and 5 demonstrate greater velocity in the perforated pipes located near the side walls and reducing towards the centre of the bay. The fan was connected to the left hand end of the manifold, and velocity was greater in the perforated pipes connected to this end of the manifold (300mm and 1000mm) than those located in the same place in relation to the side wall on the end of the manifold furthest from the fan (5000mm and 5700mm), as shown in Figure 4.40. Velocity measured in the perforated pipe in the centre (3000mm) of the bay was consistent on all three days at between 3.2 and 3.4 ms^{-1}. The largest variation was measured in the perforated pipe located 300mm from the side wall nearest to the fan end of the manifold, at between 18.5 and 25.7 ms^{-1}.

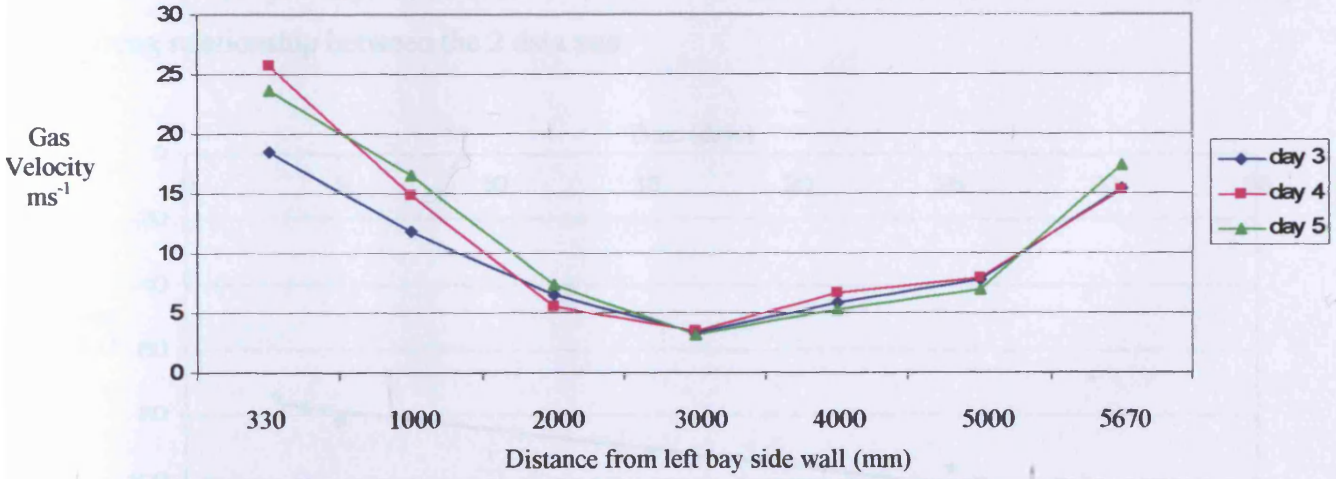

Figure 4.40 Gas velocity measured in each perforated pipe in the floor of the 6000mm wide aerated bay on days 3, 4 and 5.

Pressure measured in the perforated pipes on days 3, 4, 5, 13, 23, 25 and 32 demonstrate a general decrease in negative pressure as distance from the fan end of the manifold increases, apart from the pipe located 300mm from the right hand side wall. Pressure generally increases at each location over time, though pressures measured at 300mm and 1000mm vary more than those at the other location, as shown in Figure 4.41.

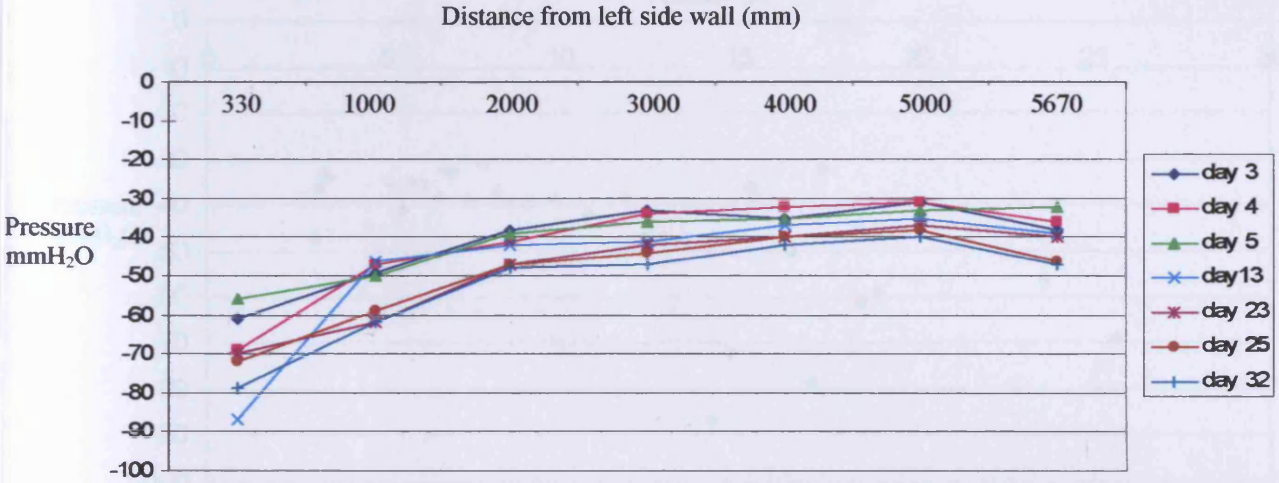

Figure 4.41 Pressure measured in each perforated pipe in the floor of the 6000mm wide aerated bay on days 3, 4, 5, 13, 23, 25 and 32.

Pressure measured in the manifold directly adjacent to the fan indicates an increase in negative pressure over the period from approximately 80 mmH_2O on days 3-5, to 95 mmH_2O on day 25 and 113 mmH_2O on day 32, as shown in Figure 4.42. A linear trend line was fitted to this data and described the relationship between pressure and time as an increase in negative pressure of 1.13 mmH_2O per day. The linear trend line had an R^2 value of 0.94 demonstrating a very strong relationship between the 2 data sets.

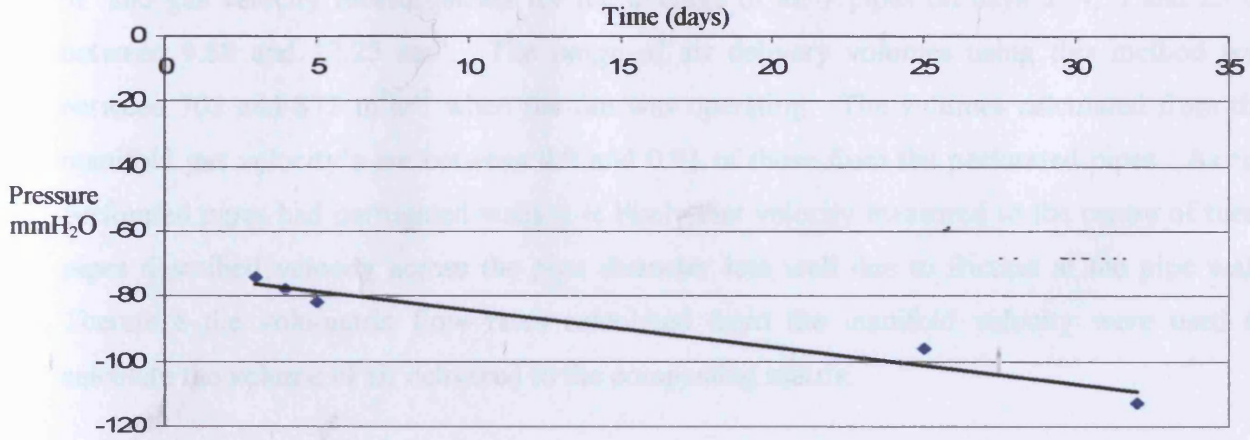

Figure 4.42 Pressure measured in the bay aeration manifold over time. (The equation of the linear trend line is P = -1.1336td – 72.956 with an R^2 value of 0.9417.)

Gas velocity measured in the perforated pipes was then plotted against pressure, as shown in Figure 4.43, and in general velocity increased with pressure. A number of trend lines were fitted to the data, and a linear trend line passing through the x and y axis at 0 was the best fit, but with an R^2 value of -0.56 it showed only a moderate inverse relationship. The trend line suggested an increase of $1ms^{-1}$ in velocity for every $3.5mmH_2O$ increase in negative pressure.

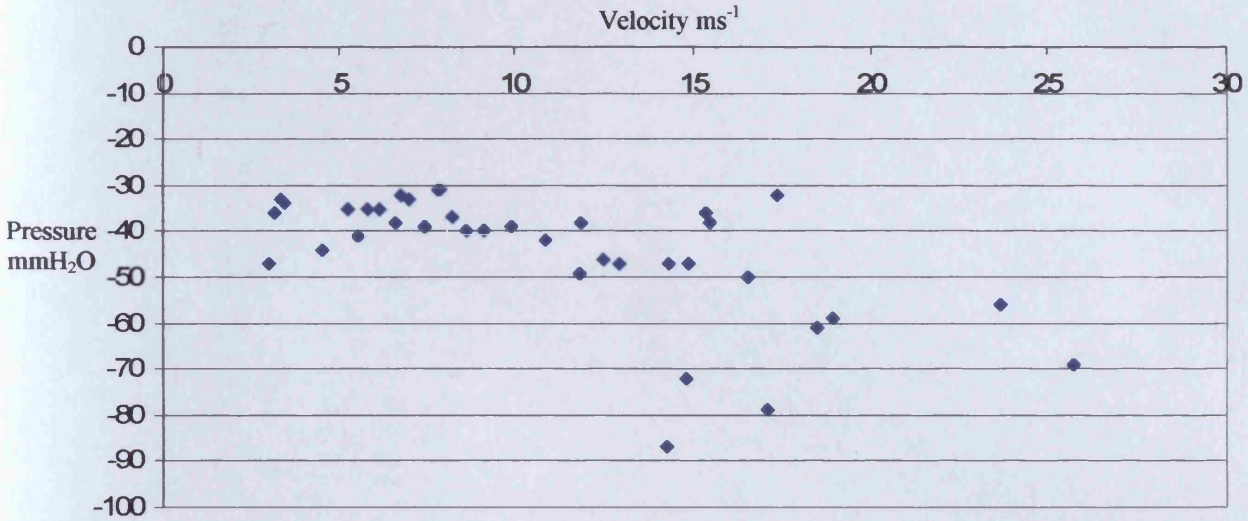

Figure 4.43 Pressure (mmH_2O) measured in the bay aeration perforated pipes, plotted against gas velocity (ms^{-1}).

The volume of air supplied to the composting matrix was calculated from gas velocity in the manifold and the frequency and duration of fan operation through out the period. The internal diameter of the manifold was 110mm with a cross section area of 9.5×10^{-3} m^2, and gas velocity ranged between 18.4 and $23.23ms^{-1}$. The volume of air delivered, when the fan was operating, was between 630 and $794m^3hr^{-1}$. To verify these calculations the same study was carried out for the 60mm internal diameter pipes, which had a cross sectional area of 2.8×10^{-3} m^2 and gas velocity measurements for the average of all 7 pipes on days 3, 4, 5 and 25 of between 9.88 and 12.25 ms^{-1}. The range of air delivery volumes using this method was between 703 and 872 m^3hr^{-1} when the fan was operating. The volumes calculated from the manifold gas velocity's are between 0.9 and 0.91 of those from the perforated pipes. As the perforated pipes had corrugated walls it is likely that velocity measured in the centre of these pipes described velocity across the pipe diameter less well due to friction at the pipe wall. Therefore the volumetric flow rates calculated from the manifold velocity were used to calculate the volume of air delivered to the composting matrix.

The volume of air delivered to the compost was calculated from gas velocity in the manifold measured at different points during the period, as well as fan frequency and duration. The volume of air delivered to the composting matrix to manage CO_2 concentration in the composting matrix reduced from between 4000 and 4500m^3day^{-1} at the beginning of the period, to 1500 m^3day^{-1} at the end of the period, as shown in Figure 4.44. A linear trend line was fitted to the data, demonstrating that there is a decrease in the volume of air supplied to the composting matrix of nearly 74m^3 day^{-1}, and with an R^2 value of 0.6617 there is a moderate relationship between the 2 data sets.

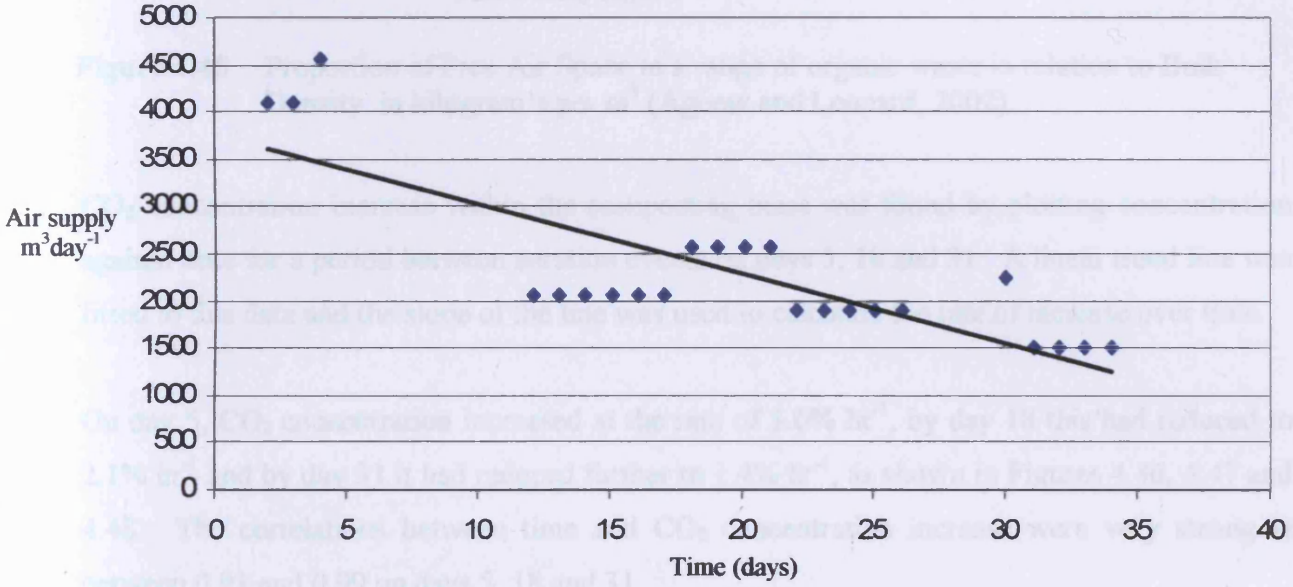

Figure 4.44 Air supplied to the composting matrix in m^3day^{-1} over the period of the trial.

4.3.4.6 Estimated Respiration Rate

The respiration rate of the composting matrix was estimated at three points during the trial. The estimate was calculated from the rate of CO_2 concentration increase in the pore spaces within the composting matrix.

The 90m^3 bay was filled with 46.2 tonnes of processed vegetable waste and shredded green waste, giving a bulk density of 0.513kgm^{-3}. Moisture content was estimated to be 70% of total mass, giving a remaining dry matter mass of 15,900kg of which volatile solid content was estimated to be 60%. The pore space or free air space within the composting matrix was estimated at 50%, from data published by Agnew and Leonard (2003) as shown in Figure 4.45.

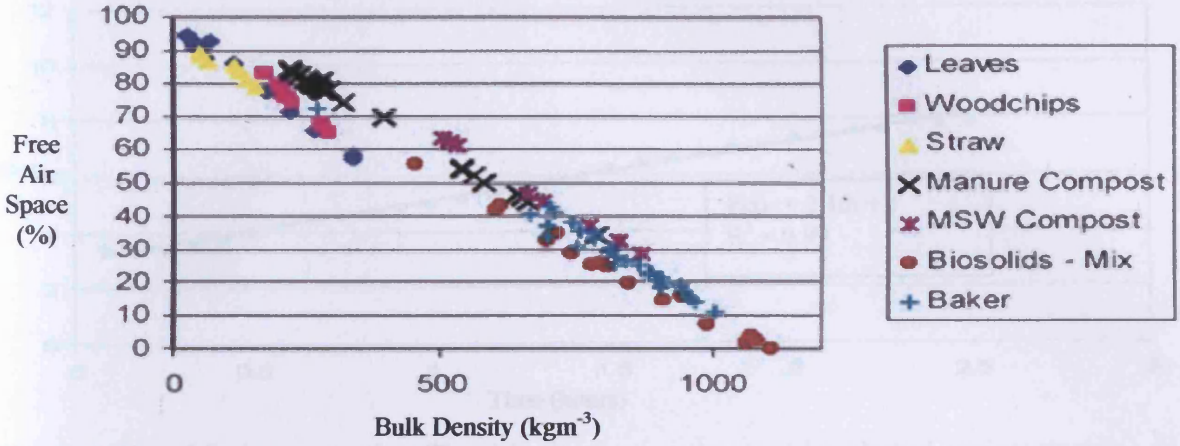

Figure 4.45 Proportion of Free Air Space in a range of organic waste in relation to Bulk Density in kilogram's per m^3 (Agnew and Leonard, 2002).

CO_2 concentration increase within the composting mass was found by plotting concentration against time for a period between aeration events on days 5, 18 and 31. A linear trend line was fitted to this data and the slope of the line was used to calculate the rate of increase over time.

On day 5, CO_2 concentration increased at the rate of 3.6% hr^{-1}, by day 18 this had reduced to 2.1% hr^{-1} and by day 31 it had reduced further to 1.4% hr^{-1}, as shown in Figures 4.46, 4.47 and 4.48. The correlations between time and CO_2 concentration increase were very strong at between 0.91 and 0.99 on days 5, 18 and 31.

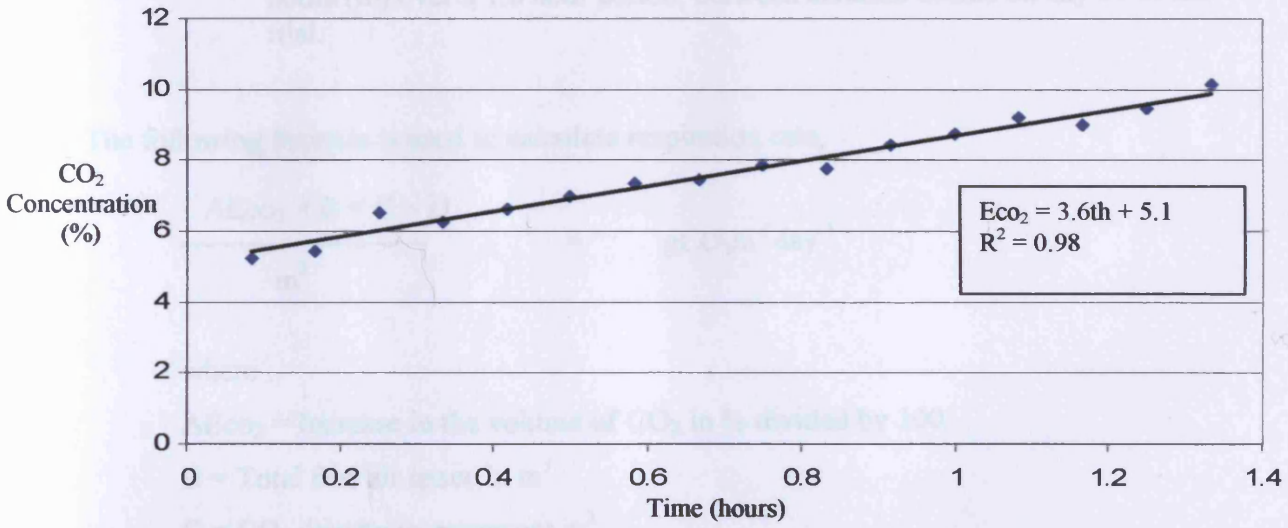

Figure 4.46 CO_2 concentration (Eco_2) in the composting matrix, plotted against time in hours (th) over a 1.4 hour period, when no aeration was occuring.

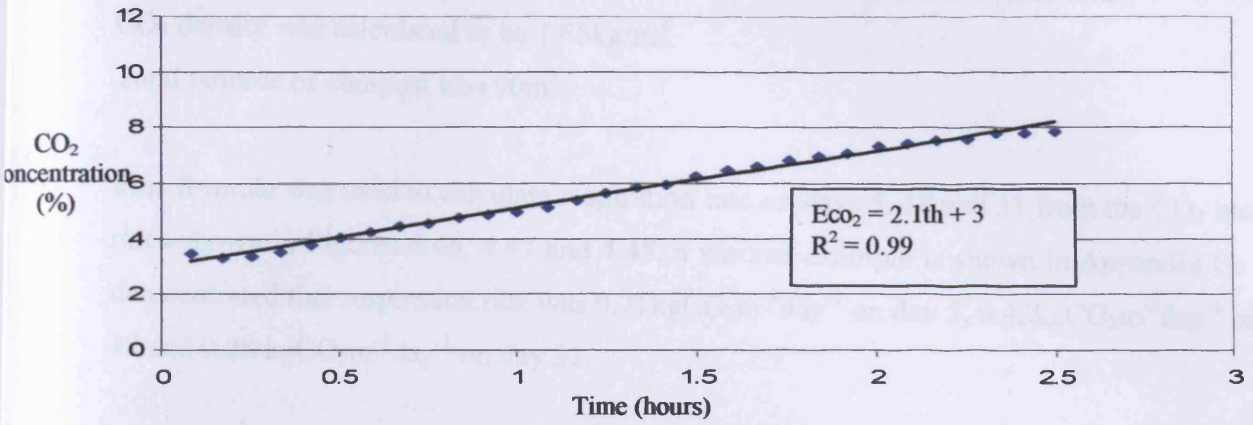

Figure 4.47 CO_2 concentration (Eco_2) in the composting matrix, plotted against time in hours (th) over a 3 hour period, between aeration events on day 18 of the trial.

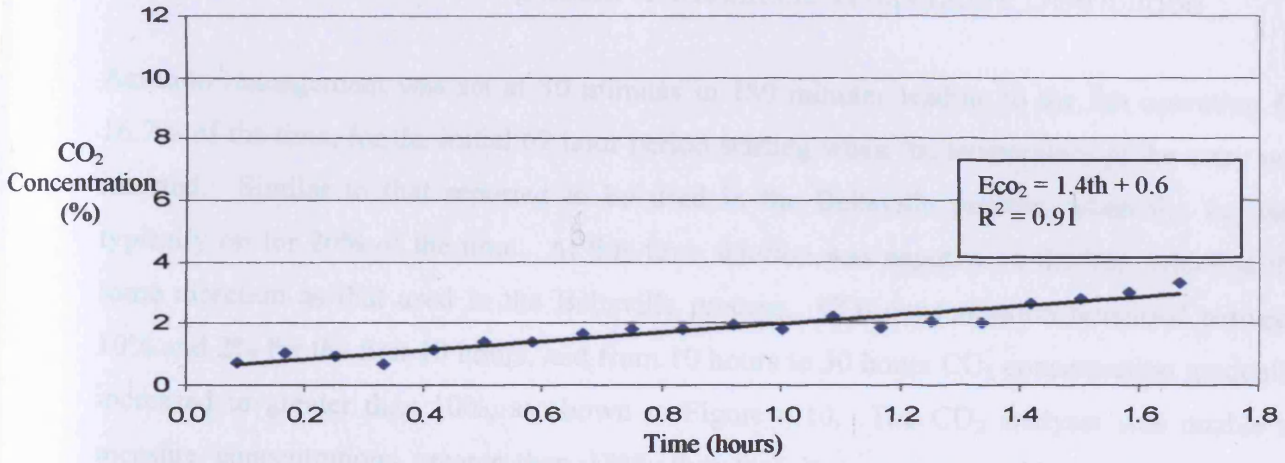

Figure 4.48 CO_2 concentration (Eco_2) in the composting matrix, plotted against time in hours (th) over a 1.8 hour period, between aeration events on day 31 of the trial.

The following formula is used to calculate respiration rate,

$$\frac{AEco_2 \times B \times C \times D}{m^3} = gCO_2m^{-3}day^{-1}$$

where

$AEco_2$ = Increase in the volume of CO_2 in % divided by 100

B = Total free air space in m^3

C = CO_2 density in grams per m^3

D = Convert hours to days

m^3 = Cubic meters of compost

Total free air space was estimated to be 50% of total volume which equals $45m^3$.
CO_2 density was calculated to be $1.65kg/m^3$.
Total volume of compost was $90m^3$.

This formula was used to calculate respiration rate on days 5, 18 and 31 from the CO_2 increase rates shown in Figures 4.46, 4.47 and 4.48, a worked example is shown in Appendix C. This demonstrated that respiration rate was $0.71kgCO_2m^{-3}day^{-1}$ on day 5, $0.42kgCO_2m^{-3}day^{-1}$ on day 18 and $0.28\ kgCO_2m^{-3}day^{-1}$ on day 31.

4.3.5 Discussion

4.3.5.1 Aeration Management to Maximise Temperature Distribution

Aeration management was set at 30 minutes in 180 minutes leading to the fan operating for 16.7% of the time, for the initial 62 hour period starting when the temperature probe array was inserted. Similar to that reported to be used in the Beltsville process, when the fan was typically on for 20% of the time. At this time aeration was negative in the bay, which is the same direction as that used in the Beltsville process. CO_2 concentration remained between 10% and 2% for the first 10 hours, and from 10 hours to 30 hours CO_2 concentration gradually increased to greater than 10%, as shown in Figure 4.10. The CO_2 analyser was unable to measure concentrations greater than 12%; therefore it was not possible to ascertain CO_2 concentrations greater than this limit.

In the first 10 hour period peak temperatures measured at location B01, increased from 50°C to above 60°C, and a peak temperature of 82°C was reached 50 hours from the start of monitoring. Temperatures at all locations were increasing from the start of the period up to hour 48, at which point temperatures generally remain static, as seen in Figure 4.11.

Fan operation frequency was modified from 30 minutes in 180 minutes to 30 minutes in 120 minutes in response to CO_2 concentration being greater than the target of 4 – 10% during the first 62 hour period. This increased the time the fan was operating, from 16.7% to 25% of the time, 5% greater than that advised for the Beltsville process. Following this change CO_2 concentration remained within the range of 5 – 10% from 8 hours to 24 hours in the 24 hour period following the initial 62 hour period, as shown in Figure 4.12. Following the aeration

change, temperature at B01 and B02 increased from 80°C to 90°C, as shown in Figure 4.13. Demonstrating that managing aeration to maintain CO_2 concentration in the target range of 4 – 10% has resulted in high peak temperatures.

Aeration was negative in the first 100 hour period and this is reflected in the highest temperatures being recorded in the lower area of the bay, as demonstrated by the bay temperature profiles shown in Figures 4.14 and 4.15. Aeration events have differential effects on temperature, dependant upon location. Temperature 100mm up from the bay base, where B01 was located, increased by up to 13°C during aeration events and then decreased by a similar amount between fan events. At locations towards the top of the compost matrix the opposite occurs, during aeration events temperature reduces by up to 10°C, as shown at location B11 in Figure 4.16.

The proportion of the compost matrix >60°C and >70°C reduced from between 89% to 95% and 35% to 65% respectively prior to aeration, to between 71% to 88% and 34% to 55% respectively following the aeration event, as shown in Figures 4.17 and 4.18. In an attempt to maximise the temperature profile of the bay, the aeration system was changed to provide positive pressure to the system for 30 minutes in every 120 minutes, after four fan operations it was then turned off. Changing the direction of aeration resulted in heat from the bottom area of the composting matrix being distributed to a larger proportion of the composting matrix. The aeration system was then turned off to ensure a top down temperature gradient did not occur in response to continued positive aeration, and to test if the temperature profile could be maintained without aeration. As meeting the ABPR treatment requirements for a turned system, required 80% of the composting matrix to be >60°C for at least 48 consecutive hours, there was some concern that aeration operation during that period may result in short time periods when the proportion of the composting matrix would fall below the required 80% and result in extended treatment time.

Directly after the 4 positive aeration events a temperature profile was constructed which demonstrated that between 97% and 99% of the monitored compost matrix was >60°C and between 92% and 95% was >70°C, as shown in Figure 4.19. Due to power losses the whole of the 48 hour period following inactivation of the aeration system was not recorded, but the temperature profile constructed from data recorded 42 hours later, indicate a very slight increase in the proportion of the composting matrix >60°C and 70°C.

Following the first turn event the aeration system was set to negative for 30 minutes in every 180 minutes and after 5 days 83% of the compost matrix was >60°C. At this point aeration was switched to positive for the same frequency and duration and then switched off after 4 positive aeration events, as shown in Figure 4.24. The proportion of the composting matrix >60°C increased following each aeration turning event. The hottest area moved upwards in response to positive aeration events. At the end of the negative aeration period it was located in a small area 300 – 500mm up from the bay base in the centre of the bay, as seen in Figure 4.25. Following the first positive aeration the hottest area remained in the centre of the bay but was located 600 – 900mm up from the bay base, as seen in Figure 4.26. 7 hours after aeration was turned off, the hottest area in the bay was located in the centre and 1000 – 1300mm from the bay base, shown in Figure 4.27.

Following the second turn aeration was 15 minutes in every 120 minutes and 67 hours after the turning event >80% of the composting matrix was >60°C, as shown in Figures 4.30 and 4.31. The proportion of the composting matrix >60°C had reduced following 5 days of negative aeration when the system was operating for 30 minutes in every 180 minutes. This difference is likely to be due to the fan operating for 12.5% of the time rather than 16.7%. This reduction in aeration operation allowed heat energy to migrate upwards in the extended periods between aeration events, resulting in a greater proportion of the composting matrix being >60°C. Therefore higher air delivery rates result in a vertical temperature gradient, top to bottom when aeration is positive and bottom to top when aeration is negative. When aeration was reduced in response to lower demand for CO_2 removal, negative aeration resulted in the required proportion of the composting matrix above the target temperature. This was due to passive heat distribution transferring heat upwards between aeration events.

8 hours after the third turning event, when there was no aeration, only between 3% and 27% of the composting matrix was >60°C, 56 hours later that had increased to between 85% and 94%, as shown in Figures 4.36 and 4.37. These temperature increases can only be due to the production of heat energy from microbial activity and as heat production is linked to oxygen uptake and CO_2 production, gas exchange must be occurring through the compost matrix. As CO_2 concentration decreased from 10% directly after turning to approximately 4%, 54 hours later as shown in Figure 4.34. Therefore gas exchange must have been occurring at a rate greater than the rate of CO_2 production from microbial activity. It is likely that this gas exchange was driven by passive airflow through the aeration system. Although the fan was not

operating the pipe work was not blocked in any way and hotter and therefore less dense gases exiting the top of the composting matrix are likely to have produced a bottom to top airflow. It is likely that microbial activity was greatly reduced by thermal inhibition, as demonstrated by respiration rate calculations which demonstrated that peak rate was only 20% of that measured in green waste windrows, as shown in Figures 3.7, 3.12 and in Section4.3.4.6.

4.3.5.2 Time Taken to Meet Treatment Requirements at each Phase

The data used to construct the 3 dimensional temperature profile represented in Figure 4.28, when 81% of the compost matrix in the bay was >70°C, was recorded directly after the data for the 2 dimensional temperature profile was recorded, shown in Figure 4.27. The 2 dimensional temperature profile was constructed from data recorded across the centre of the bay and 91% of the composting matrix in the monitored zone was >70°C. In this instance, assuming there was no change in temperature distribution during the intervening 5 hour period, the relationship between the proportion of the area >70°C in a vertical section across the centre of the bay and that for the calculation of the total volume >70°C is 0.89. Therefore multiplying the central cross section temperature profile by this factor will more accurately indicate the proportion of the composting matrix greater than the specified temperature. So the cross sectional temperature profile in the centre of the bay is required to be greater than 90% to ensure 80% of the whole composting matrix is greater than the specified temperature.

Within 100 hours of the start of the trial 80% to 95% of the composting matrix was greater than 60°C, shown in Figure 4.17. Following the next turn, aeration was not managed to maximise the proportion of the composting matrix above the target temperature until day 17, 6 days after the turning event. Aeration had been negative for the 6 day intervening period and 83% of the compost matrix was greater than 60°C, as shown in Figure 4.25. 67 hours after the second turn a temperature profile was constructed and demonstrated that 91.8% was greater than 60°C, as shown in Figure 4.31, and 64 hours after the third turn between 85% and 94% of the composting matrix was greater than 60°C, as shown in Figure 4.37.

Assuming that 80% of the composting matrix had exceeded 60°C following the first turn in a similar time as that achieved following the second and third turning of 64 and 67 hours, respectively. Then the time taken for the material to have met the treatment requirements of 60°C for 48 hours for 4 phases, with a turn between each phase would be 100 hours for the first

phase, assumed 67 hours for the second phase, 67 hours for the third phase and 64 hours for the fourth phase. As the composting matrix is required to be over this temperature for 48 hours at each phase, a total time of 21 days would be required to treat the waste. Though it would be technically challenging to provide a temperature monitoring system that demonstrates at least 80% of the composting matrix has exceeded 60°C for 48 hours between each turn.

4.3.5.3 Airflow

Gas flow was measured in each perforated distribution pipe on days 3, 4 and 5 and generally speaking velocity increased in relation to the distance from the pipe to the side wall. The fan was connected to one end of the manifold and velocity in the pipes 300mm and 1000mm from the bay wall on the side furthest from the fan was less than those located at the same distance from the wall nearest to the fan, shown in Figure 4.40. The increased flow at locations 5000mm and 5700mm when compared to the central location of 3000mm was not driven by greater negative pressure, as on day 5 the negative pressure was less at these locations than it was at the central location, as seen in Figures 4.40 and 4.41. Pressure was equal to or less than the central location at 5000mm on days 3, 4 and 5 but flow was greater. It was likely that this difference was due to the composting matrix being generally more porous at the bay side walls than it was in the centre. This was likely to be due to either increased compression in the bay centre or preferential flow along the bay side wall.

Differential gas flow rates are indicated by temperature changes recorded within the composting matrix by the probe array. Temperature reduces by between 3°C and 7°C at probe location E05 in response to the 6 aeration events over the 16 hour period demonstrated on day 13, as shown in Figure 4.21. Whilst temperature at location D05, located 750mm horizontally from E05, reduces between 10°C and 12°C in response to the same aeration events over the same period, as shown in Figure 4.22. Even though pressure was less at the aeration pipe located below probe E (3000mm) and the nearest to the probe D location (4000mm) during this period, as shown in Figure 4.41.

Higher gas flow rates at the bay side wall could effect the time taken to manage this area of the composting matrix above the target temperature. The side walls are areas where heat loss will be greater than the core area due to the insulative qualities of the compost, if airflow was greater in these areas then the rate of heat loss will be greater in the areas where heat retention is most important. A fully commercial system would not be able to insulate the side walls in

the same way that it has been undertaken in this trial and without insulated walls this effect may have a significant impact on the proportion of the bay meeting the target temperature. It would be possible to counteract this effect by modifying the aeration system to deliver more or less air to areas to equalise airflow.

Pressure was measured in the manifold on days 3, 4, 5, 25 and 32. The resulting data was plotted against time in days and a linear trend line was fitted to the resulting data. The trend line equation indicates that there was an increase in negative pressure of $1.13 mmH_2O day^{-1}$ and the R^2 value of 0.94 indicates a very strong correlation between the 2 data sets, as shown in Figure 4.42. Pressure was plotted against velocity in the perforated pipes and a linear trend line was fitted to the resulting data. The trend line equation indicated that negative pressure increased at the rate of 3.5 mmH_2O for every $1 ms^{-1}$ increase in velocity, though with an R^2 value of 0.56 there is only a moderate correlation. There was no indication that as pressure increased over time volumetric flow decreased. Though it is likely that the fan was operating at its performance limit and that as pressure increased delivery volume decreased.

The volume of air delivered to the compost matrix to maintain CO_2 in the range of 4% - 10% was calculated from the velocity in the manifold and the frequency and duration of fan operations through out the trial period and is presented in Figure 4.44. The equation of the linear trend line fitted to air supply versus time in days indicates that $73.7 m^3$ less air was delivered for every day that the trial was conducted. The R^2 value for this trend line was 0.66 which demonstrates a moderate relationship between the 2 data sets. Using a simple timer to manage the CO_2 concentration within the composting mass was not accurate due to changes over time only being adjusted to periodically. If CO_2 concentration in the matrix was to be managed accurately fan operation would need activation in response to concentration. The aim of managing aeration in response to CO_2 concentration is to ensure only sufficient air is added to ensure oxygen concentration does not limit microbial activity. Therefore heat energy removal from the system through aeration was minimised without having an adverse impact on microbial respiration rate and therefore heat production. This method has achieved high temperatures in a large proportion of the composting matrix.

There was a difference in the pressure required to provide the calculated superficial velocity in a bed of green waste using this aeration system, which was described in Section 4.2.1 as 10mm H_2O to provide a superficial velocity of $8.6 \times 10^{-4} ms^{-1}$. On days 3, 4 and 5 there was 80mm of

negative pressure in the aeration manifold and average velocity in the manifold produced a volumetric flow rate of $712m^3hr^{-1}$. This converts to a superficial velocity through the 2.2m deep compost matrix of 4.7×10^{-3} ms^{-1}. Using the same data as that used to calculate the pressure required to produce a superficial velocity of 8.6×10^{-4} ms^{-1}, indicates only a slight pressure increase to provide the measured superficial velocity. In this case the pressure required was 8 times greater than that suggested; the discrepancy is likely to be due to differences in the 2 systems. Firstly the aeration system was providing negative pressure in the aeration system and not positive pressure which was used to gain the data used for the initial estimates. Secondly the data used for the initial estimates measured pressure directly under the column of compost whilst this data was recorded adjacent to the fan at the end of the aeration system. Therefore the pressure required to drive air through the distribution system was not indicated in the base data.

The different flow rates and pressures measured in the 7 perforated distribution pipes, as shown in Figures 4.40 and 4.41 indicate that airflow through the compost matrix was differential and that distance from the distribution system to the side wall is an important variable. The reason for reduced air flow at the bay centre when compared to areas near the side walls cannot be determined from the recorded data, but compaction is likely to be greater in the bay centre. The smooth side walls may also be a route of less resistance for gases when compared to the compost matrix and result in greater airflow without increases in pressure.

The data used to estimate the volume of air delivered to the composting matrix assumed a respiration rate of 4.5 $kgCO_2m^{-3}day^{-1}$. The calculated respiration rate for the composting matrix in the bay was in the range of 0.28 to $0.71kgCO_2m^{-3}day^{-1}$, far less than expected. The same data indicates the volume of air required to supply oxygen at a respiration rate of $1.2kgCO_2m^{-3}day^{-1}$ was $1\times10^{-4}m^3s^{-1}$ for every m^3 of compost matrix in the bay. The rate of air supply assumes that all of the oxygen in the supplied air is used, in practice exhaust CO_2 ranged from 4% to 10%. Therefore the supply rate has to be increased by between 2 and 5 times the rate suggested by these calculations. This gives an estimated supply rate of between $2\times10^{-4}m^3s^{-1}$ and $5\times10^{-4}m^3s^{-1}$ for every m^3 of compost matrix. The actual volume of air delivered to the compost matrix, was $5.1\times10^{-4}m^3s^{-1}$ on day 5, $3.2\times10^{-4}m^3s^{-1}$ on day 18 and $1.9\times10^{-4}m^3s^{-1}$ on day 31, when respiration rates were $0.71kgCO_2m^{-3}day^{-1}$, $0.42kgCO_2m^{-3}day^{-1}$ and $0.28kgCO_2m^{-3}day^{-1}$ respectively. The actual volume of air supplied was within, or very close to, the expected range for the volume of composting matrix respiring at $1.2kgCO_2m^{-3}day^{-}$

[1], indicating that the calculated volume of air required to supply sufficient oxygen to the composting matrix using this data, was accurate.

4.3.5.4 Respiration Rate

Respiration rate decreased over the trial period, from 0.71kg$CO_2m^{-3}day^{-1}$ on day 5 to 0.28 kg$CO_2m^{-3}day^{-1}$ on day 31. This is very low when compared to green waste windrow composting where respiration rates are 5 times greater following turning events than the highest rate experienced in the vegetable and green waste bay, as highlighted in Chapter 3.

The low respiration rates are likely to be due to high temperatures in the composting matrix, average temperature in the bay was 84°C on day 5 and 87°C on day 18. In green waste windrow composting respiration rate reduced from 1.7kg$CO_2m^{-3}day^{-1}$ at 66°C to below 0.8 $CO_2m^{-3}day^{-1}$ at 70°C, as shown in Figure 3.17. These respiration rates are compared to core temperature which is the area of greatest temperature, therefore the average temperature will be less than this core temperature in windrows.

The aeration management method employed in this trial has successfully managed to create and maintain the required proportion (80%) of the composting matrix at the required temperature (60°C) to meet the ABPR treatment requirements. But the maintenance of high temperatures has impacted upon respiration rate in a negative way, resulting in respiration rates of approximately 20% of that measured in green waste windrow composting.

4.4 Summary

- Maintaining CO_2 concentration between 4% and 10% in the composting matrix resulted in high temperatures being achieved and maintained, in both trials. The error determined in the temperature monitoring system in the vegetable and green waste trial, introduces an element of doubt, though temperatures measured with a calibrated probe in the green waste trial indicate temperatures between 80°C and 90°C are maintainable.

- The target proportion of 80% of the composting matrix greater than the 60°C target temperature for 48 hours was exceeded for the required 4 phases, with a turn between each phase. This was achieved within 100 hours after initial filling and approximately 67 hours following turning events, it was also achieved without employing aeration. When the required proportion of the composting matrix had achieved the target temperature it was maintained and in some instances increased, with no aeration.

- An indicated minimum time of 21 days was required for the organic waste to meet the ABPR treatment requirements using the method demonstrated here. This demonstrates the extent of infrastructure required to treat a specified volume of organic waste.

- Single direction aeration will create and maintain a temperature gradient, resulting in a smaller proportion of the compost matrix exceeding the target temperature, when compared to a mixture of positive and negative aeration.

- If aeration is in the negative direction and infrequent the temperature gradient is reduced due to heat energy migrating upwards within the composting matrix. This does not occur when aeration is in the positive direction

- Gas flow within the composting matrix and the aeration distribution system is heterogeneous, with more flow occurring at the bay sides, when compared to the bay centre.

- The data used to calculate the volume of air required to supply sufficient oxygen to the composting matrix in relation to the respiration rate has proven to be accurate.

5 Compost Processing Test Rig

5.1 Introduction

During the forced aerated bay trials, the results of which are discussed in Chapter 4, it was noted that temperatures over a cross sectional area in the centre of the bay indicated that 99% of the composting matrix was greater than the required ABPR treatment temperature of 60°C. Being able to meet the treatment requirements of these regulations by maintaining 100% of the composting matrix above 60°C for 48 hours or above 70°C for 1 hour, depending on maximum particle size, would greatly reduce the processing time and therefore the infrastructure needed to treat a certain volume of organic waste, when compared to the turned bay system.

The turned bay aeration system utilised uni-directional airflow, and CO_2 concentration was managed within the composting matrix by altering aeration event timings in relation to measurements from the directly preceding time period. The high proportion of the composting matrix maintained above 60°C in the aerated bay trials suggested that improvements to aeration management and control could yield 100% of the matrix greater than 60°C.

To examine this premise a composting processing test rig was designed and built to manage the key parameters of temperature and CO_2 concentration. It was also designed to re-circulate gases at variable rates. Re-circulation of gases would allow heat energy to be retained within the composting matrix, and dependent upon this rate, deliver heat energy to the periphery at a rate greater than the rate of loss. This design and gas management method was likely to minimise the time taken for the composting matrix to reach the target temperature, and ensure that 100% of the matrix was greater than the target temperature. As unequal airflow was found in the aerated bay trials, 5 separate in-floor distribution plenums were incorporated into the test rig design as well as a method of measuring and altering the volume of air delivered to each of these plenums. The design of the test rig and the rational behind several key features are described in Section 5.2.

5.2 Design and Build

The basis of the design and the theory of operation of the test rig are described in Section 5.2.1, the physical design and layout are described in detail in Section 5.2.2 and the details of the monitoring and process control system are highlighted in Section 5.2.3.

5.2.1 Test Rig Description

The compost processing test rig system was designed to contain one cubic meter of organic waste in one side of a highly insulated vessel, with the gas re-circulation system in the other; a picture of the test rig is shown in Figure 5.1. It was also designed to automatically manage CO_2 concentration in the re-circulating gases between upper and lower limits, and to manage the temperature of these gases. Managing CO_2 concentration in the composting mass proved to be an effective method of ensuring temperatures greater than the ABPR minimum treatment requirements were achieved and maintained in a forced aerated bay composting system, as demonstrated in Chapter 4.

Figure 5.1 Highly insulated pilot scale in-vessel system.

The rig contained five separate aeration plenum zones in the floor; airflow into each plenum was measured with individual rotameters and controlled with a manual ball valve, thus allowing airflow to be managed separately in each zone, a diagram of the test rig is shown in Figure 5.2. A forced aeration system was installed to provide positive pressure to the plenum floor, and the head space above the composting matrix was connected by pipe work, via the cooling system to the inlet of the fan, allowing gases to recycle back through the plenum. To manage CO_2 concentration, inlet and exhaust pipes were connected to the recirculation system, via actuated valves. The inlet was located close to the suction side of the fan and the exhaust close to the pressure side of the fan. Both actuated valves were connected to the process control system which opened and closed both of these valves in response to the CO_2 concentration in the recycling gases. Ensuring that only a proportion of the recycling gases were exhausted should allow the input of ambient air at a rate that does not cool the recycling gases, and lead to excessive temperature reduction at the compost matrix periphery. If all of the re-circulating gases were exhausted to manage CO_2 concentration the resulting input of ambient air would reduce periphery temperature below the treatment minimum.

To ensure experimental rigour and reproducibility CO_2 concentration in the re-circulating gases were sampled continuously. This was done by connecting a sample pipe to the re-circulation system at the pressure side of the fan. The sample passed through a moisture trap into a CO_2 measuring device and then back into the head space above the compost matrix. Readings from the CO_2 measurement device were monitored by the process computer, and when the concentration reached a specified upper level, the inlet and exhaust valves were opened, and when concentration had reduced to a lower limit the valves shut.

The forced aeration system was designed to ensure that sufficient air could be supplied to the compost matrix within the vessel so that oxygen concentration did not limit microbial degradation. It was decided that the system should be designed to deliver air at a rate sufficient to supply oxygen to the composting matrix when respiring at $80gCO_2kgVS^{-1}day^{-1}$, more than twice the peak rate observed in windrow systems. Using calculations produced by Notton (2005) based on the stoichiometric requirement for oxygen based on the rate of CO_2 production of $1m^3$ of organic waste with a

moisture content of 50% and a volatile solids content of 60% of dry matter. The volume of air required to provide sufficient oxygen to that volume of organic waste with a density of 500kg m^{-3}, and a respiration rate of $80gCO_2kgVS^{-1}day^{-1}$, which was equivalent to $9kgCO_2m^{-3}day^{-1}$, was 4.5×10^{-4} m^3 of air, per second. This assumed that all of the oxygen in the input air was used; in practice air would be exhausted when the CO_2 concentration reached 10%. Therefore the maximum volume of air required to maintain that composting rate was 9×10^{-4} m^3s^{-1}, which equated to $3.24m^3hr^{-1}$.

To allow the effect of different recirculation rates to be ascertained a fan was specified with a maximum output of $2400m^3day^{-1}$ to allow recirculation rates of up to $100m^3hr^{-1}$. To ensure that the fan could deliver sufficient pressure to drive the required maximum volume of air through the compost matrix, published data addressing gas flow through compost matrix was consulted. The required volumetric flow rate of $100m^3hr^{-1}$ was converted into a superficial velocity within the test rig and was found to be $0.028ms^{-1}$. The physical properties and moisture content of the matrix through which the gas is being driven, has a large impact upon the pressure required to produce a superficial velocity (Giner and Denisienia, 1996, Dairo and Ajibola, 1994 and McGuckin, 1999). Mu and Leonard (1999) found fresh compost with a bulk density of $720kgm^{-3}$ required a static pressure of 1kPa to create a superficial velocity of $0.03ms^{-1}$ in a bed depth of 1 meter, which equates to approximately $100mmH_2O$. Whereas Notton (2005) using a similar method found that a static pressure of between 5 and $10mmH_2O$ was required to create a superficial velocity of $0.03ms^{-1}$ in a 1000mm deep bed of freshly shredded green waste with a bulk density of $349kgm^{-3}$. When 10mm screened mature compost with a bulk density of $893kgm^{-3}$ was used, the pressure required to produce a superficial velocity of $0.02ms^{-1}$ was approximately 20mm H_2O. A fan was specified that could supply a minimum airflow rate of $100m^3hr^{-1}$ at a static pressure of 20mm H_2O.

To monitor the respiration rate of the organic waste in the test rig, the total volume of gas leaving the system has to be known, as does the CO_2 concentration in that gas. To achieve this an M+W Instruments D-6200 mass-flow meter with a maximum capacity of 100 litres/minute that was capable of operating at 70°C with 100% humidity was installed in the gas exhaust pipe work. CO_2 concentration in the re-circulated gases was monitored adjacent to where the exhaust pipe work was connected. The CO_2 concentration in the exhaust gases would be equal to that in the re-circulating gases.

This would allow the mass of CO_2 lost from the system to be calculated and then related to the volume of the organic waste to produce a respiration rate.

To gain an insight into the effect of different recirculation rates upon temperature distribution within the organic waste, a matrix of thermocouples were mounted in the walls and embedded in the matrix. The thermocouple matrix may also demonstrate the effectiveness of aeration management recycling heat energy from the hotter core zone to the cooler periphery.

5.2.2 Layout

The test rig was manufactured from steel sheet forming a sandwich to which insulation was added and was designed to have 3 distinct sections, which were.

- One cubic metre of organic waste contained in one section, with a total of 21 thermocouples mounted in the wall and 3 probes designed to be inserted into the compost matrix with a total of 29 thermocouples.
- An air distribution system which contained a fan, 5 separate flow zones in the plenum floor (shown in Figure 5.5), each with rota-meters and manual flow control valves (shown in Figure 5.3). The aeration system also has inlet and outlet ports with actuated control valves to allow CO_2 concentration in the re-circulating gases to be controlled.
- A console was mounted on the side of the test rig that contained the monitoring and data logging equipment as well as a computer to control process management (shown in Figure 5.9).

Figure 5.2 shows the general layout of the aeration system within the insulated sections of the test rig. The red arrows show the direction of air flow when pressure is normally positive and the green arrows when pressure is normally negative. The locations of the thermocouples that were mounted on the wall in the organic waste compartment are shown as red dots, as are the other key elements which are described in the key. Each element is described more fully in the following paragraphs.

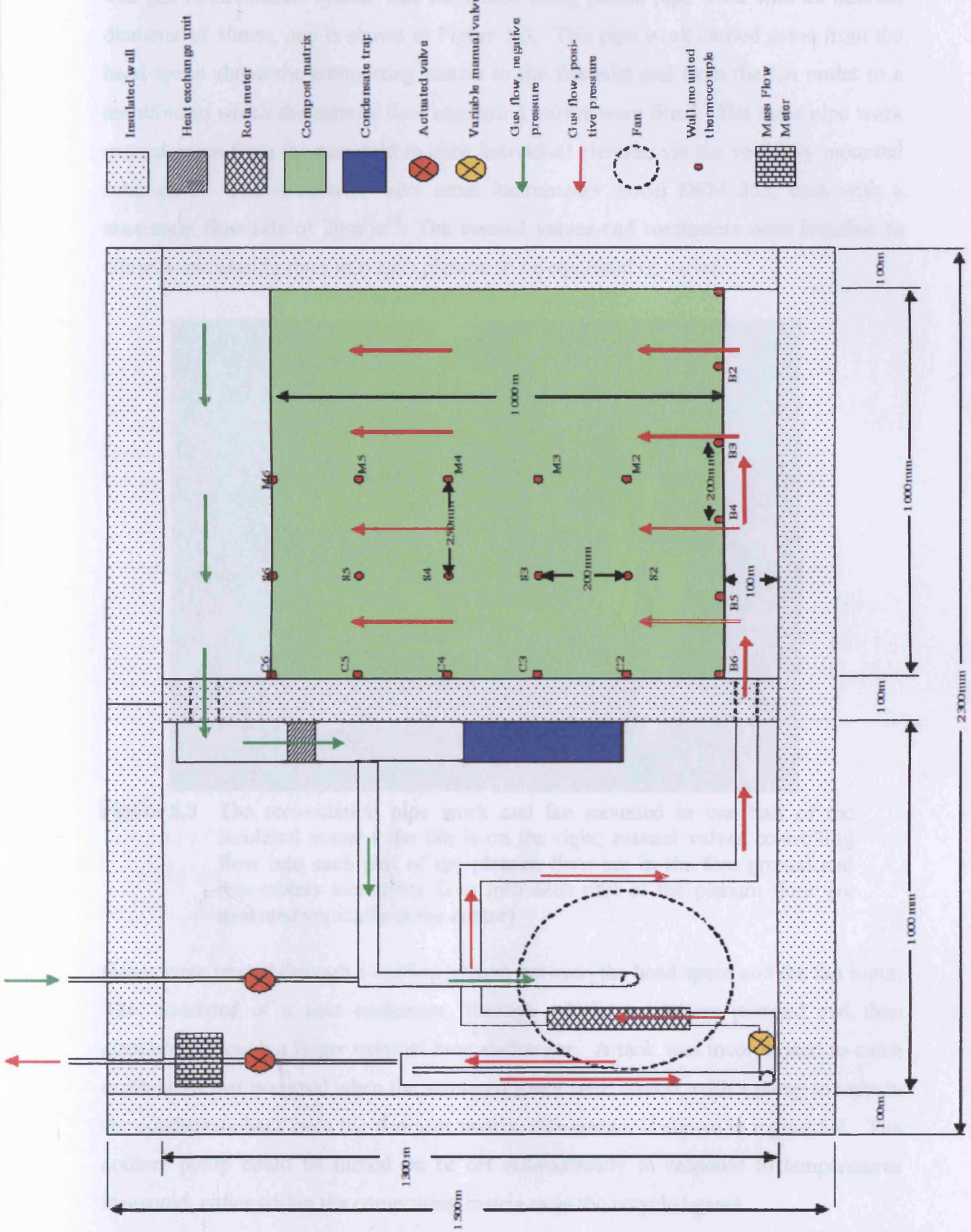

Figure 5.2 Diagram showing the general internal lay out of the test rig with key components and air flow direction indicated.

The gas re-circulation system was fabricated using plastic pipe work with an internal diameter of 50mm, and is shown in Figure 5.3. This pipe work carried gases from the head space above the composting matrix to the fan inlet and from the fan outlet to a manifold to which the manual flow regulating valves were fitted. The same pipe work carried gases from the manifold to each individual plenum, via the vertically mounted rotameters. The rotameters were omni instruments model DFM 355, each with a maximum flow rate of $20m^3hr^{-1}$. The manual valves and rotameters were installed to allow re-circulation rates into each plenum to be equalised or varied.

Figure 5.3 The recirculation pipe work and fan mounted in one half of the insulated vessel (the fan is on the right, manual valves controlling flow into each part of the plenum floor are in the fore ground and rota-meters measuring flow into each part of the plenum floor are mounted vertically in the centre).

Gases were passed through a cooling system between the head space and the fan input. This consisted of a heat exchanger, through which, water was pumped and then circulated through a larger external heat exchanger. A tank was incorporated to catch condensate that occurred when the saturated gases were cooled, with a pump to recycle the condensate back onto the compost matrix; this system is shown in Figure 5.4. The coolant pump could be turned on or off automatically in response to temperatures measured, either within the composting matrix or in the recycled gases.

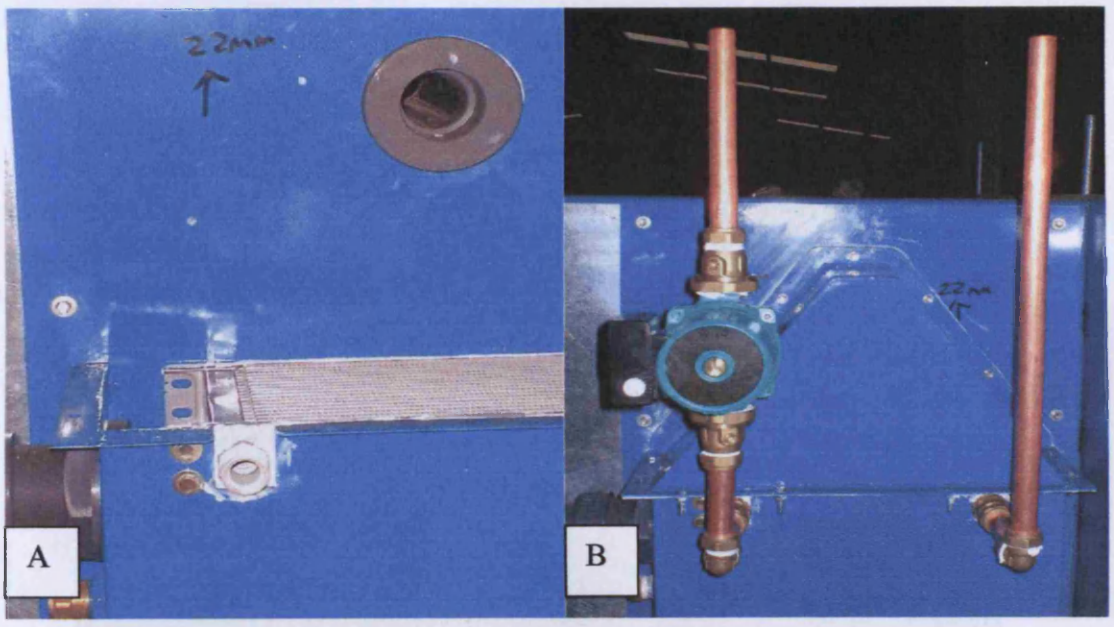

Figure 5.4 The gas cooling system. A: shows the pipe leading from the head space and the heat exchange unit in silver. B: shows the same location with the cover over the heat exchange unit and the pipes and pump connected to the heat exchange unit.

Thermocouples embedded in the probes and those in the wall of the vessel, are shown in Figure 5.5. Three probes were designed and constructed for insertion into the composting matrix, one was labelled BP and was designed to be located across the centre of the floor to measure temperature at the floor, and this was made up of a total of 9 thermocouples that were mounted at 100mm intervals along the length of the probe. Two further probes were labelled CP and MP; on which 10 thermocouples were mounted every 100mm along their lengths. Probe CP was designed to be inserted vertically in the centre of the composting matrix, but could be inserted anywhere within the composting matrix. Probe MP was designed to be inserted vertically mid way between probe CP in the centre of the composting matrix and the side wall on which the thermocouples were mounted. Thermocouples mounted in the vessel wall were labelled B 1-6 (every 200mm along the bottom corner where the plenum floor meets the vessel side wall), C 2-5 (every 200mm in the vertical corner of the vessel, starting 200mm up from the plenum floor), S 2-5 (every 200mm vertically, 250mm from the middle of the side wall, starting 200mm from the plenum floor) and M 2-5 (every 200mm vertically in the middle of the side wall, starting 200mm up from the plenum floor). The side wall mounted thermocouples are visible in the side wall as white protrusions in Figure 5.4 and their exact location is demonstrated in Figure 5.2.

Figure 5.5 Compost side of test rig showing the 5 separate plenums and thermocouples mounted in the walls and probes.

To measure CO_2 concentration in the re-circulating gases a 6mm plastic pipe was inserted into the gas re-circulation system on the pressure side of the fan. It was placed in this location as the highest pressure was experienced at this point and this would ensure flow from this point to where the sample gases were exhausted. The pipe was connected to the CO_2 sample head and then exhausted into the headspace above the compost matrix; the sample pipe connection to the re-circulation pipe system is highlighted in Figure 5.6A. The CO_2 sample head is within the black field sample head, also highlighted, which directs the gas flow over the measuring head, and the orange lead carries the output to the transmission unit. The CO_2 sample head was a Vaisala GMP220, which is based on non dispersive infrared single-beam dual-wavelength principle, with a range of 0 – 20%. The probe was calibrated prior to purchase and the reading was 0.007% CO_2 at 0% and 19.917% CO_2 at 20%. The probe was connected to a Vaisala GMT221, which converted the measurements into a 0-20mA signal, with 0mA being 0% CO_2 and a linear increase to 20mA which was

equivalent to 20% CO_2. This is shown in Figure 5.6B and is located in the process control and data logger console, where temperatures are within the technology specification. This is because the test rig recycling system was placed in an insulated compartment which due to the temperature of the re-circulating gases may reach as high as 70°C.

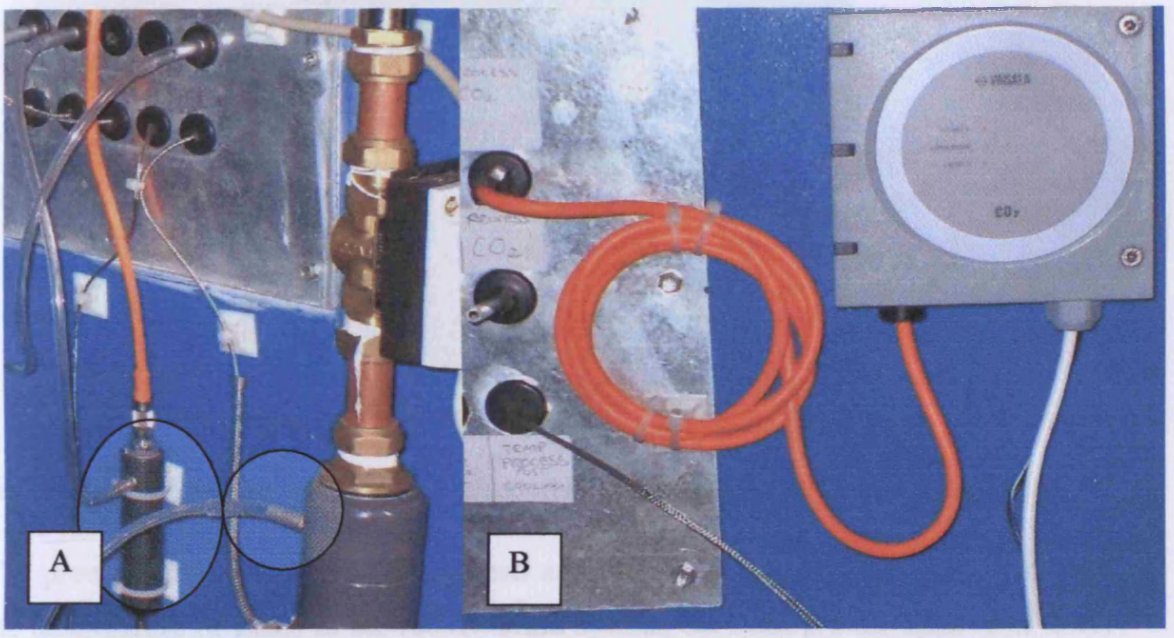

Figure 5.6 CO_2 monitoring system in the test rig. A: shows the measurement head and the sample pipe connection to the re-circulation system. B: shows the transmission unit located in the instrument console.

5.2.3 Data Recording and Process Control System

The data recording and process control system was located in a console on the side of the vessel. 49 of the 50 K – Type thermocouples that were located on the internal wall of the test rig and in the 3 probes inserted into the compost matrix were connected to a Delta-T Devices Ltd DL2e Data Logger, as shown in Figure 5.7. The data logger was set to record these temperatures every 10 minutes, though it was possible to record temperatures at different frequencies. Data from the logger was periodically down loaded onto the computer that was used to process control. The remaining thermocouple was located on the probe identified as CP at 500mm from the inserted end of the probe. As probe CP was inserted into the centre of the 1000mm deep compost matrix, this remaining thermocouple was located at the point within the compost matrix that was the greatest distance from the vessel periphery. This thermocouple was connected to the process control system.

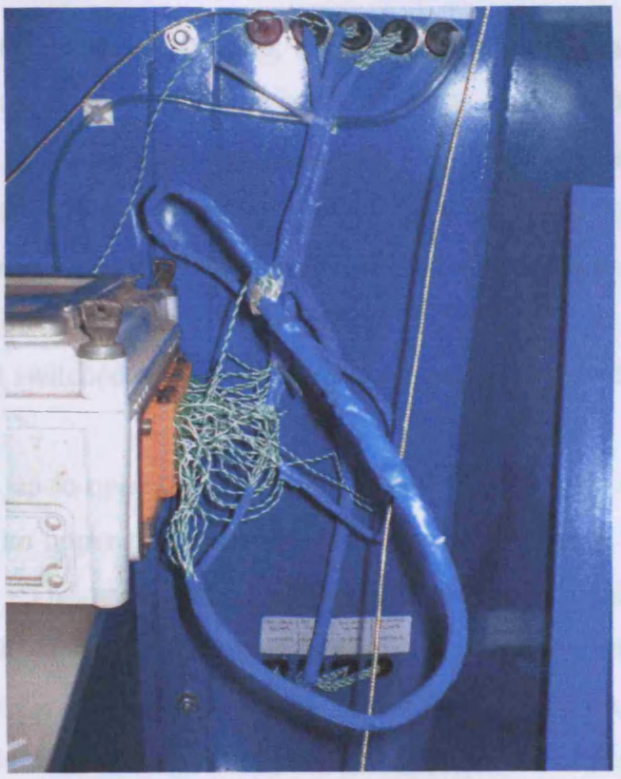

Figure 5.7 Data logger with 49 thermocouples connected via screw terminals.

The process control system was designed and built to manage CO_2 concentration and the temperature of gases in the recirculation system, between pre set upper and lower limits, the layout of which is shown in Figure 5.8. The thermocouple at location CP5 and the CO_2 monitoring device measuring concentration in the re- circulation system were connected to a microlink 593 thermocouple connection unit, which had integrated cold junction compensation. The microlink 593 unit was connected to a microlink 751 unit, which was connected to the process control computer via a USB cable for 2 way data transmission.

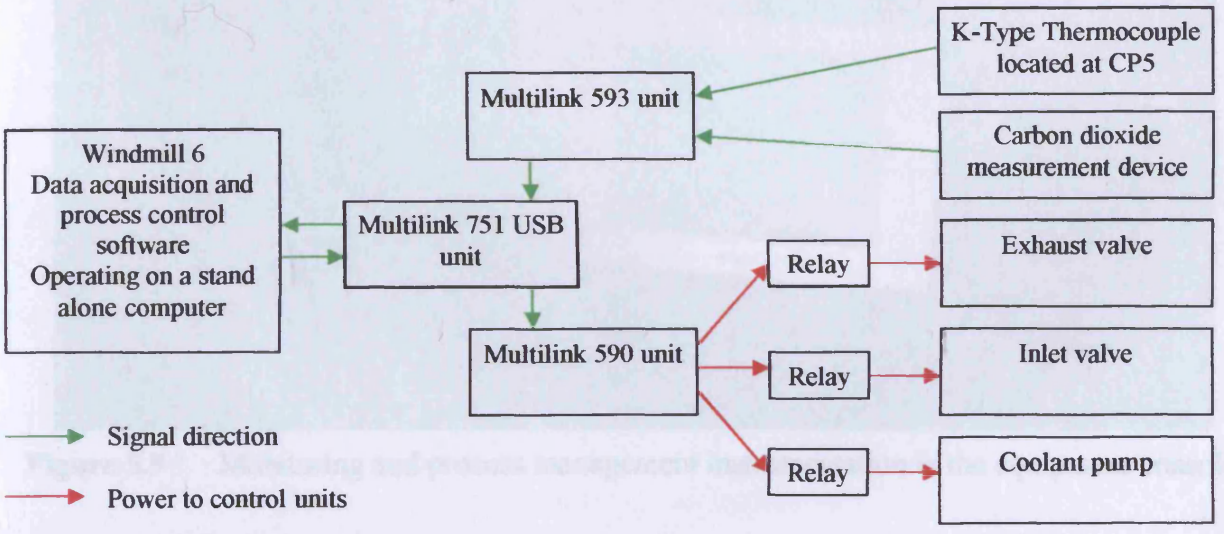

Figure 5.8 Layout of process control system.

The software used to control processing, analysed incoming signals continuously and then recorded the data at preset frequencies. A facility on the software allowed upper and lower limits to be set for each input channel. Continuous readings were compared to these limits and if the measured parameter increased above, or reduced below the set limits an output channel could be triggered. The software sent a signal to a specified channel in the multilink 590 unit via the Multilink 751 USB unit, which sent a 5 volt signal to a relay that switched on, or off the relevant process control unit.

The system was set up to open the inlet and exhaust valves in the recirculation system when CO_2 reached an upper concentration, and then shut when a lower concentration had been reached. The same feedback mechanism was available to cool the re-circulating gases. When the core temperature increased above a set limit, measured by the thermocouple at CP5, the coolant pump would be switched on, and when the core temperature had reduced below a set level the pump would be turned off. The layout of the hardware for the monitoring and process control system in the equipment console is shown in Figure 5.9.

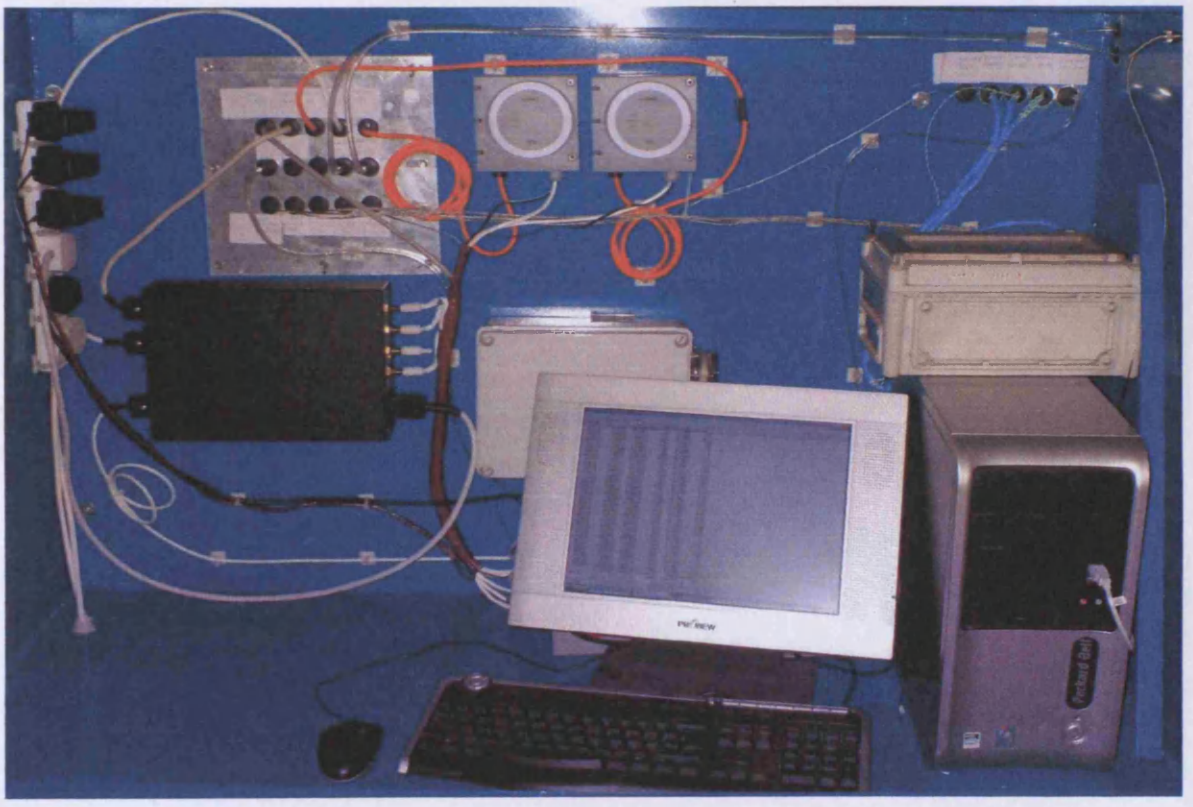

Figure 5.9 Monitoring and process management instrumentation in the equipment console.

5.3 Commissioning Test 1

5.3.1 Introduction

The test rig was filled with freshly shredded green waste and the inlet and exhaust actuated valves were set to open when CO_2 concentration in the re-circulation system increased to 10%, and to shut when CO_2 concentration reduced to 4%. The fan and process control system was turned on 2.5 hours after the rig was filled and core temperature and CO_2 concentration had started recording. The re-circulation rate was set to maximum of $100m^3hr^{-1}$. 24 hours after the rig was filled the exhaust actuated valve was found to be not shutting or opening fully. The valve was opened manually and from that point forward stopped functioning and remained in the open position.

5.3.2 Process Control

CO_2 concentration during the 70 hour period starting when the rig was filled, fluctuated mainly between 4 and 10% in the first 10 hours, and then remained between 6 and 7.5%, as shown in Figure 5.10. When the exhaust actuated valve stuck fully open after intervention at 24 hours, CO_2 concentration reduced to approximately 1% three hours later, and then reduced further to ambient levels for the remainder of the period.

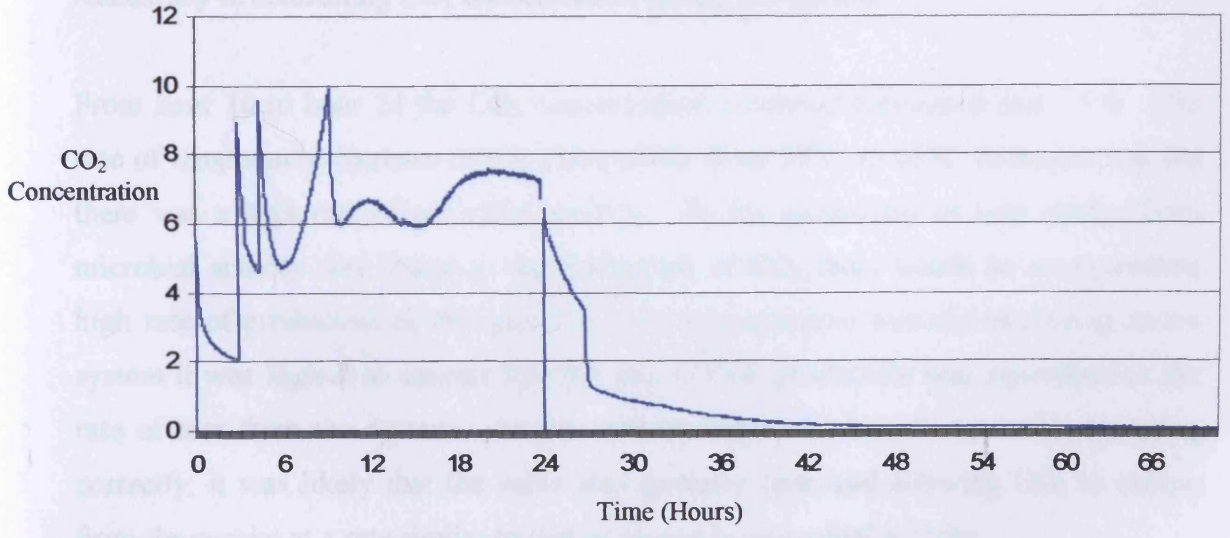

Figure 5.10 CO_2 concentration in the re-circulating gases over a 70 hour period in the first test run of the compost processing test rig.

The temperature 500mm up from the plenum floor in the centre of the compost matrix increased from 15°C when the rig was filled to a maximum of 63°C 24 hours later. Following the exhaust actuated valve sticking fully open core temperature reduced to 35°C over the following 24 hours, and reduced further to 30°C by the end of the monitored period, as shown in Figure 5.11.

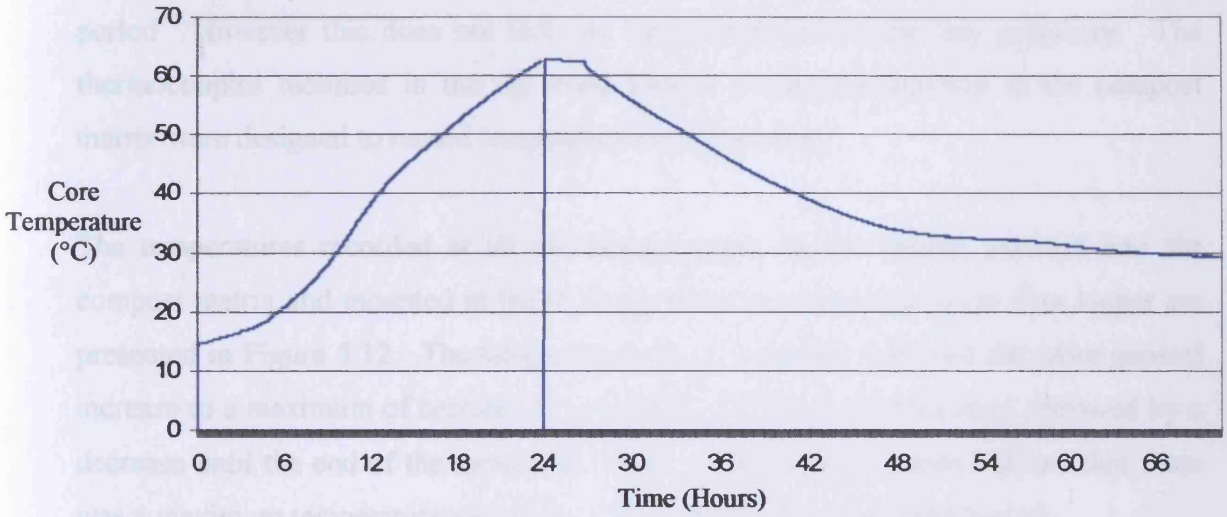

Figure 5.11 Core temperatures in the test rig over a 70 hour period.

The peaks and troughs in CO_2 concentration during the first 10 hours of operation demonstrate that control levels set were not being accurately maintained, as shown in Figure 5.10. The actuated valve on the exhaust system was found to be not opening or shutting fully 24 hours after the start. This was likely to be the reason for the inaccuracy in controlling CO_2 concentration during this period.

From hour 10 to hour 24 the CO_2 concentration remained between 6 and 7.5%. The rate of temperature increase during this period, from 30°C to 63°C, indicates that the there was a high rate of microbial activity. As the production of heat energy from microbial activity was linked to the production of CO_2 there would be an equivalent high rate of production of this gas. As CO_2 concentration was not increasing in the system it was logical to assume that the rate of CO_2 production was equivalent to the rate of loss from the system. As the exhaust valve was known not to be operating correctly, it was likely that the valve was partially open and allowing CO_2 to escape from the system at a rate similar to that produced by microbial activity.

5.3.3 Temperature Distribution

Even though the process management system did not accurately maintain CO_2 concentration in the re-circulation system due to the exhaust valve not operating correctly, the CO_2 concentration remained between the set levels during the first 24 hour period, and core temperature increased to above 60°C over the first 24 hour period. However this does not indicate the temperature at the bay periphery. The thermocouples mounted in the rig walls and in the probes inserted in the compost matrix were designed to record temperatures in these areas.

The temperatures recorded at all 49 thermocouples in the probes inserted into the compost matrix and mounted in the test rig walls and connected to the data logger are presented in Figure 5.12. The temperatures at all locations followed the same general increase to a maximum of between 57 and 65°C, 27 hours after the start, followed by a decrease until the end of the monitored period. These temperatures indicate that there was a maximum temperature variation of 10°C during the monitored period.

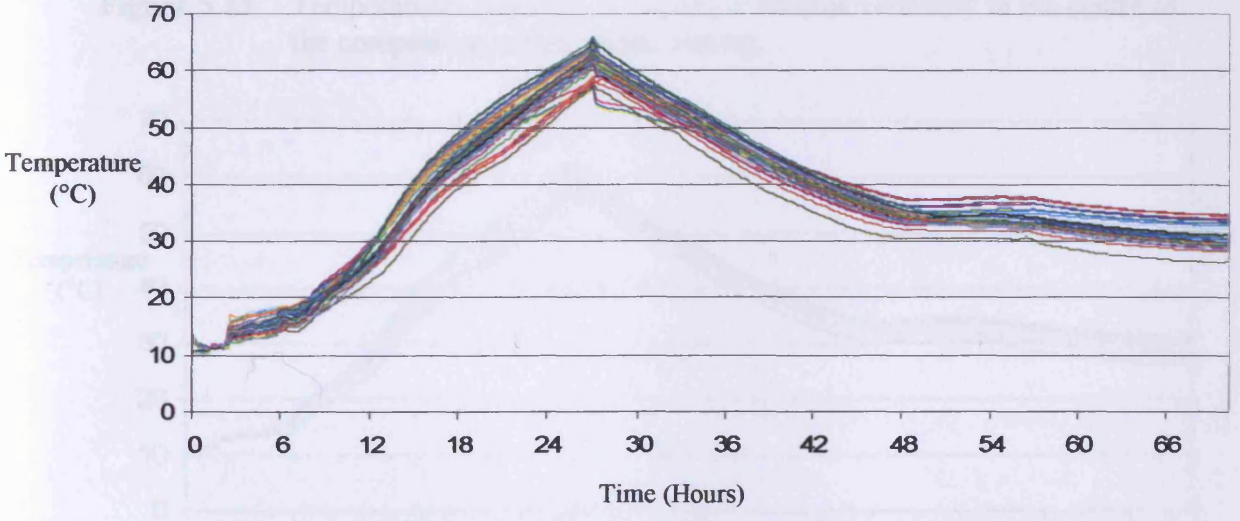

Figure 5.12 Temperatures recorded from a total of 49 thermocouples inserted in the compost matrix and mounted on the internal walls of the test rig over a 70 hour period.

The temperatures recorded at probe CP, which was inserted vertically in the centre of the composting matrix indicate that there was a total temperature variation from top to bottom of the test rig of only 3.5°C, as shown in Figure 5.13. The total temperature variation between locations B1 to B6, which were located every 200mm along the

bottom of the sidewall where it meets the top of the plenum floor, were slightly greater at a maximum of 6°C, as shown in Figure 5.14. Figure 5.15 demonstrates the temperature profile of a vertical section through the centre of the compost matrix in the test rig, and was constructed from data recorded at the time when temperature was at its greatest, 27 hours after the start. At this time there is a maximum temperature variation of 9°C throughout the composting matrix.

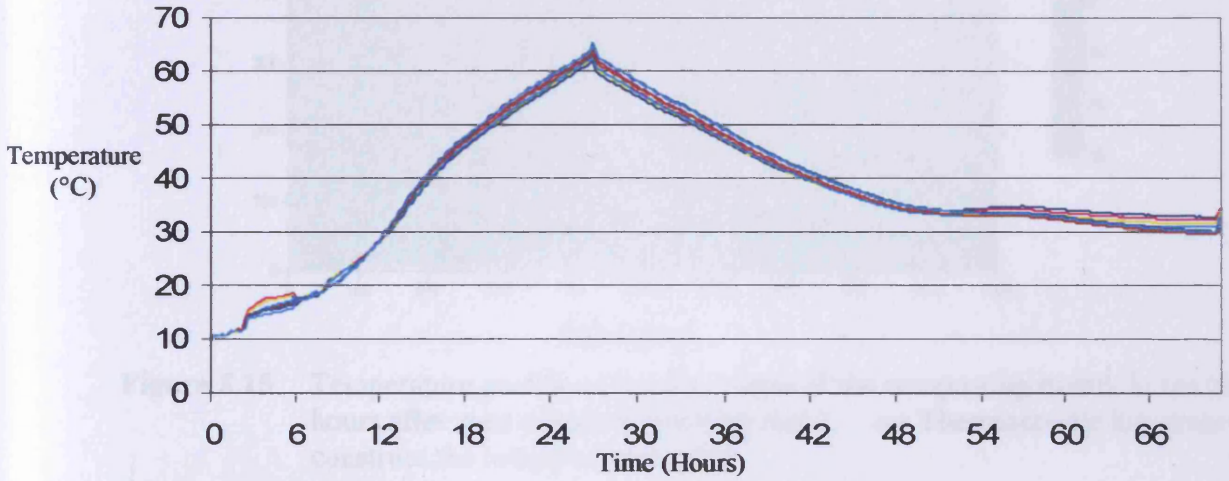

Figure 5.13 Temperatures recorded at probe CP located vertically in the centre of the composting matrix in the test rig.

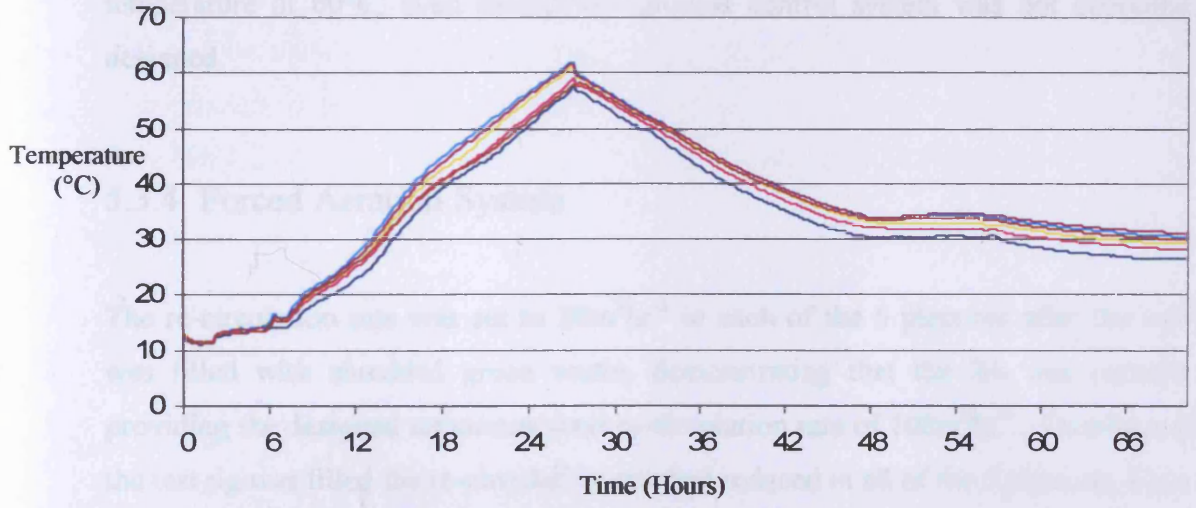

Figure 5.14 Temperatures recorded at locations B1 – B6 located every 200mm along the bottom of the side wall at the top of the plenum floor in the test rig. (probe location shown in Figure 5.2)

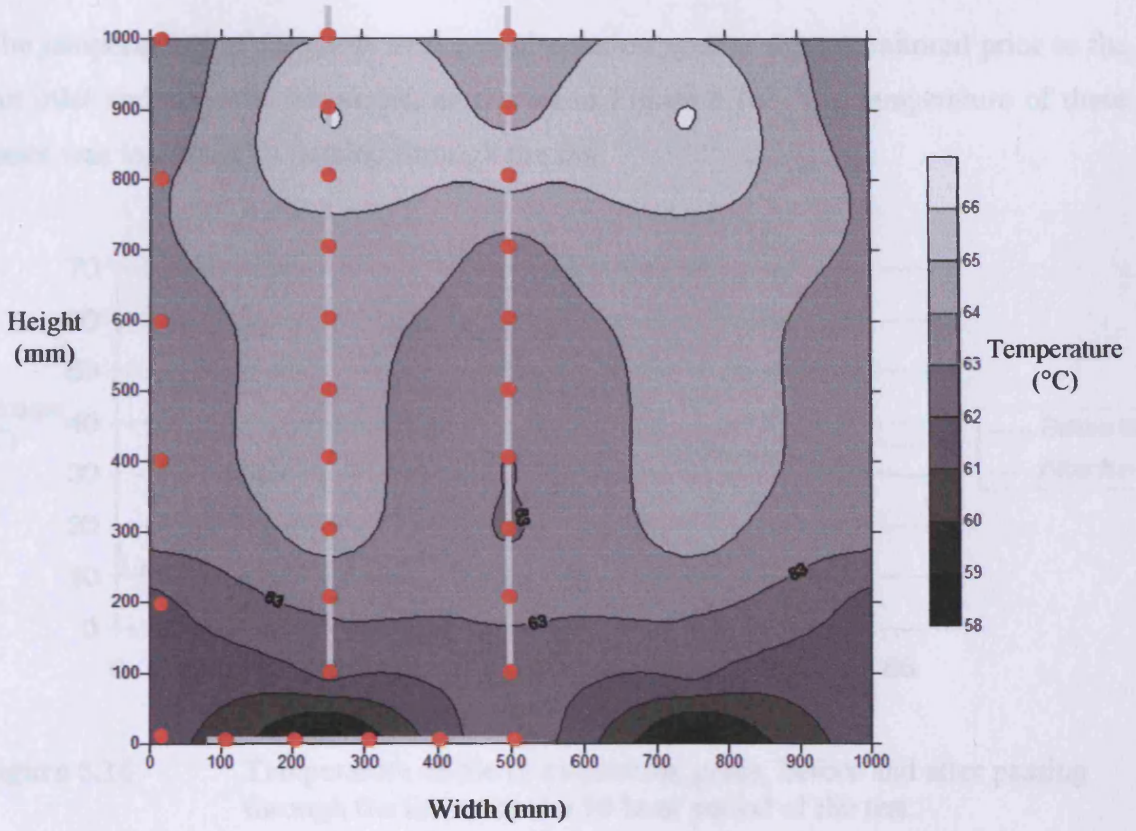

Figure 5.15 Temperature profile across the centre of the composting matrix in the test rig 27 hours after start of commissioning test 1. ● = Thermocouple locations used to construct the temperature profile.

Virtually the entire composting matrix had reached the ABPR minimum treatment temperature of 60°C, even though the process control system was not operating as designed.

5.3.4 Forced Aeration System

The re-circulation rate was set to $20m^3hr^{-1}$ in each of the 5 plenums after the test rig was filled with shredded green waste, demonstrating that the fan was capable of providing the designed maximum total re-circulation rate of $100m^3hr^{-1}$. Five days after the test rig was filled the re-circulation rate had reduced in all of the 5 plenums, from 20 m^3hr^{-1} to 14, 15, 18, 17.5 and 14.5 m^3hr^{-1}, measured from left to right from the perspective shown in Figure 5.3. As the manual valves had not been altered since setting the original re-circulation rate, the reduction in gas flow rates was likely to be due to the compost matrix compacting over time and reducing porosity. The flow rate reduction experienced in the central plenum is less than that measured in outer plenums.

The temperatures of the gases in the re-circulation system were monitored prior to the fan inlet and after the fan outlet, as shown in Figure 5.16. The temperature of these gases was increased by passing through the fan.

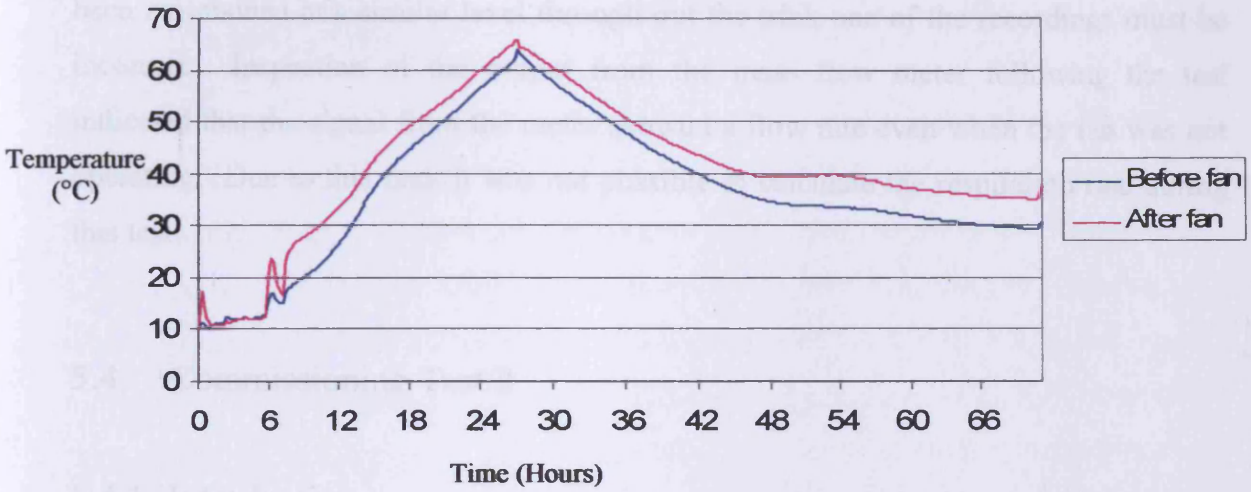

Figure 5.16 Temperature of the re-circulating gases, before and after passing through the fan, over the 70 hour period of the test.

5.3.5 Respiration Rate Analysis

The test rig was designed to measure the volume of gas exhausted from the system using a mass flow meter and this combined with measurement of CO_2 concentration in the re-circulation system allows the total mass of CO_2 produced to be calculated. Examination of the flow rate recorded by the mass flow meter indicated that flow had been between 110 and 100 litres per minute (lm^{-1}), as shown in Figure 5.17.

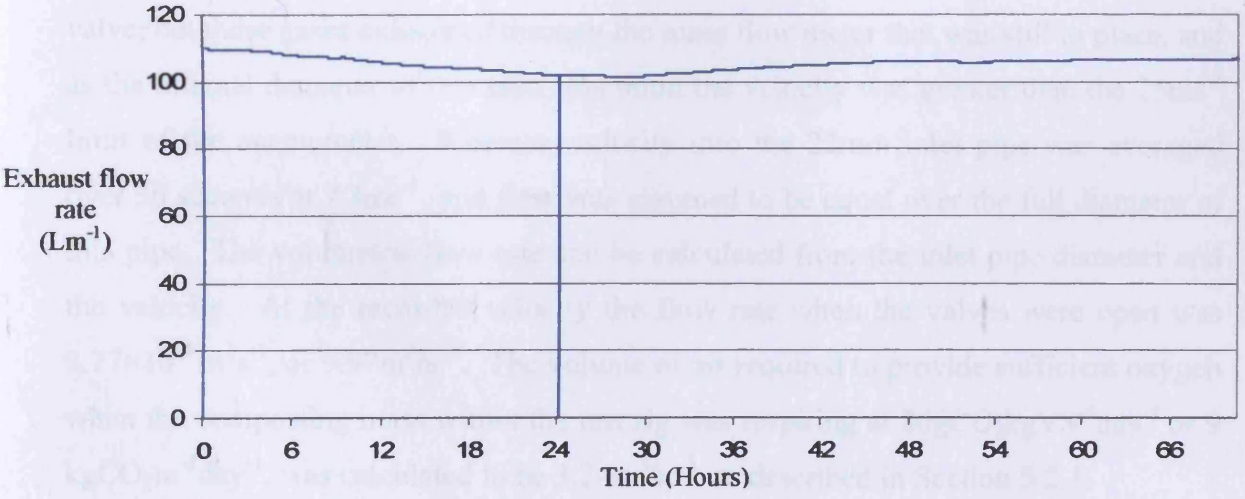

Figure 5.17 Recorded exhaust flow rate from the test rig over the 70 hour test period.

The three peaks and troughs in CO_2 concentration, apparent in the first 10 hours of the test period, suggest that the actuated exhaust and inlet valves were operating during this period, as shown in Figure 5.10. If the valves were operating then the flow rate at the exhaust would have been zero when the valves were shut, as the recorded flow rate had been maintained at a similar level through out the trial, one of the recordings must be incorrect. Inspection of the output from the mass flow meter following the test indicated that the signal from the meter showed a flow rate even when the fan was not operating. Due to this fault it was not possible to calculate the respiration rate during this test.

5.4 Commissioning Test 2

5.4.1 Introduction

Following the first test the faulty exhaust valve was replaced and the faulty flow meter was disconnected but left in place. The test rig was then refilled with freshly shredded green waste. The re-circulation rate was set to $10m^3hr^{-1}$ in each plenum, giving a total re-circulation rate of $50m^3hr^{-1}$. The process control system was set to open the inlet and exhaust valve when CO_2 concentration reached 8% in the re-circulating gases and to shut when concentration had reduced to 4%.

As the flow meter was not operating, a hot wire anemometer was used to measure the velocity of gas entering the 22mm inlet pipe when the valves were open. It would have been preferable to measure the velocity of gases exiting the system through the exhaust valve, but these gases exhausted through the mass flow meter that was still in place, and as the internal diameter of this pipe was 6mm the velocity was greater than the $25ms^{-1}$ limit of the anemometer. Whereas, velocity into the 22mm inlet pipe was averaged over 30 seconds at $7.3ms^{-1}$, and flow was assumed to be equal over the full diameter of this pipe. The volumetric flow rate can be calculated from the inlet pipe diameter and the velocity. At the recorded velocity the flow rate when the valves were open was $2.77\times10^{-3}\ m^3s^{-1}$, or $9.97m^3hr^{-1}$. The volume of air required to provide sufficient oxygen when the composting mass within the test rig was respiring at $80gCO_2kgVS^{-1}day^{-1}$ or 9 $kgCO_2m^{-3}day^{-1}$, was calculated to be $3.24m^3hr^{-1}$, as described in Section 5.2.1.

The recorded velocity of air entering the re-circulating gases allowed for approximately 3 times as much air being delivered, than was required to supply oxygen at the specified respiration rate.

5.4.2 Process Control

CO_2 concentration in the first 3 hour period was managed between 4 and 8% as designed, the exhaust valve had opened and shut 3 times in response to CO_2 concentration. From 3 to 23 hours the concentration remained between 4 and 8% but did not show the peaks and troughs associated with the valves opening and shutting that were apparent in the first 3 hour period. Examination of the test rig during this period indicated that the process control was operating correctly, but even with the exhaust and inlet valves being fully open, not enough CO_2 was removed from the re-circulating gases to reduce the concentration down to the valve shutting limit of 4%. Therefore the maximum velocity of gases through the small exhaust pipe size of 6mm was not sufficient to reduce CO_2 concentration. As the velocity, and therefore the volume of gases exiting the system was at a maximum, the CO_2 concentration trigger limit was increased at 23 hours to open at 10% and shut when concentration had reduced to 8%. Although the volume of gases exiting the rig was at a maximum, by increasing the concentration of CO_2 in the exhaust gases, a greater mass of CO_2 was removed even though the total volume of gases leaving the system had not increased. CO_2 concentration was then managed accurately between the set limits of 8 to 10%, and again when the limits were changed to 6 to 10% at hour 46, as shown in Figures 5.18.

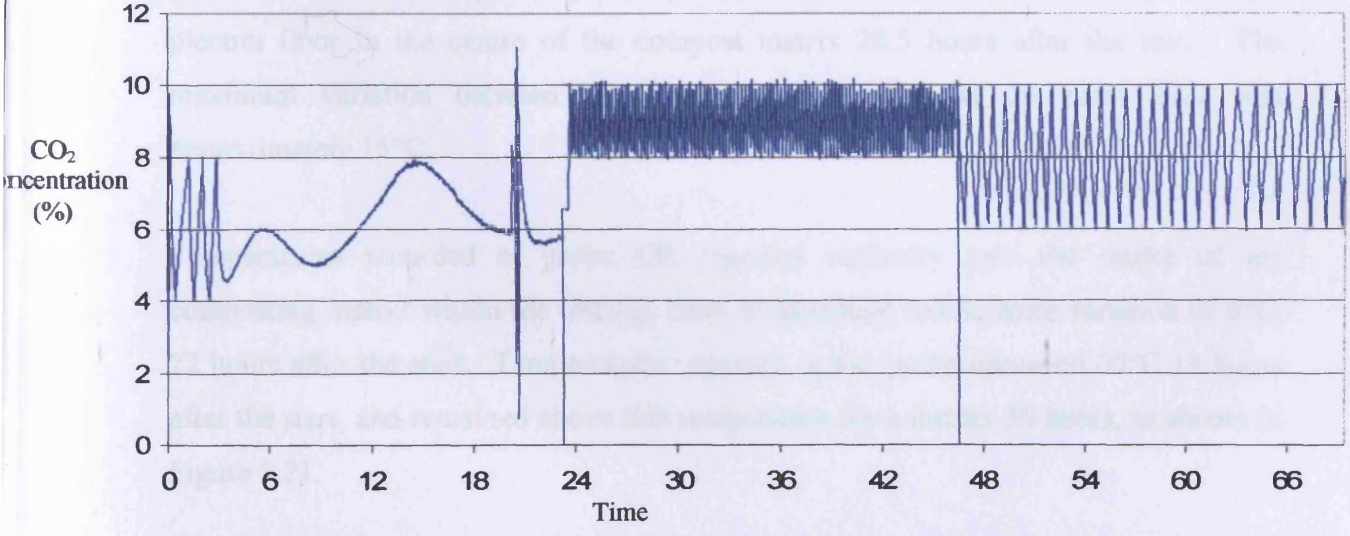

Figure 5.18 CO_2 concentration measured in the re-circulation system of the test rig over a 69 hour period, from the start of the second

Temperature in the core of the composting matrix was again recorded on the process control system. Core temperature increased from 22°C at the start, to 60°C 14 hours later, and remained above 60°C until hour 60. A peak temperature of 72.6°C was reached at hour 29, as shown in Figure 5.19. The 2 vertical lines in Figure 5.19 occur when the process control system was turned off to allow the data logger to be down loaded.

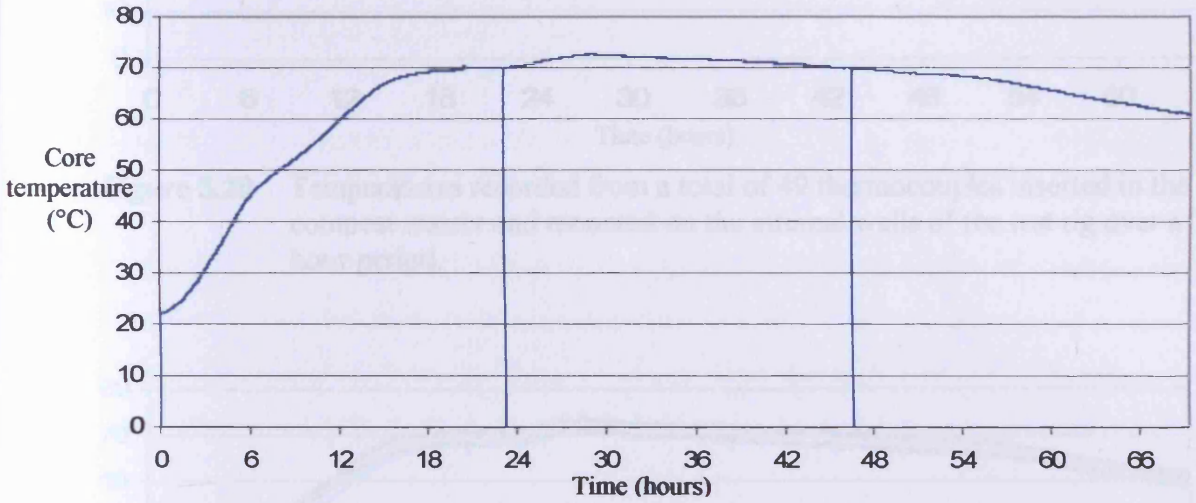

Figure 5.19 Core temperature measured in the centre of the composting matrix in the test rig over a 69 hour period.

5.4.3 Temperature Distribution

Temperatures recorded at all 49 thermocouples located on the probes inserted into the composting matrix and those mounted in the side wall are shown in Figure 5.20. The maximum recorded temperature was 74.5°C, which was recorded 200mm up from the plenum floor in the centre of the compost matrix 28.5 hours after the start. The maximum variation between all temperatures recorded at the same time was approximately 15°C.

Temperatures recorded at probe CP, inserted vertically into the centre of the composting matrix within the test rig, show a maximum temperature variation of 6°C, 22 hours after the start. Temperatures recorded at this probe exceeded 60°C 13 hours after the start, and remained above this temperature for a further 50 hours, as shown in Figure 5.21.

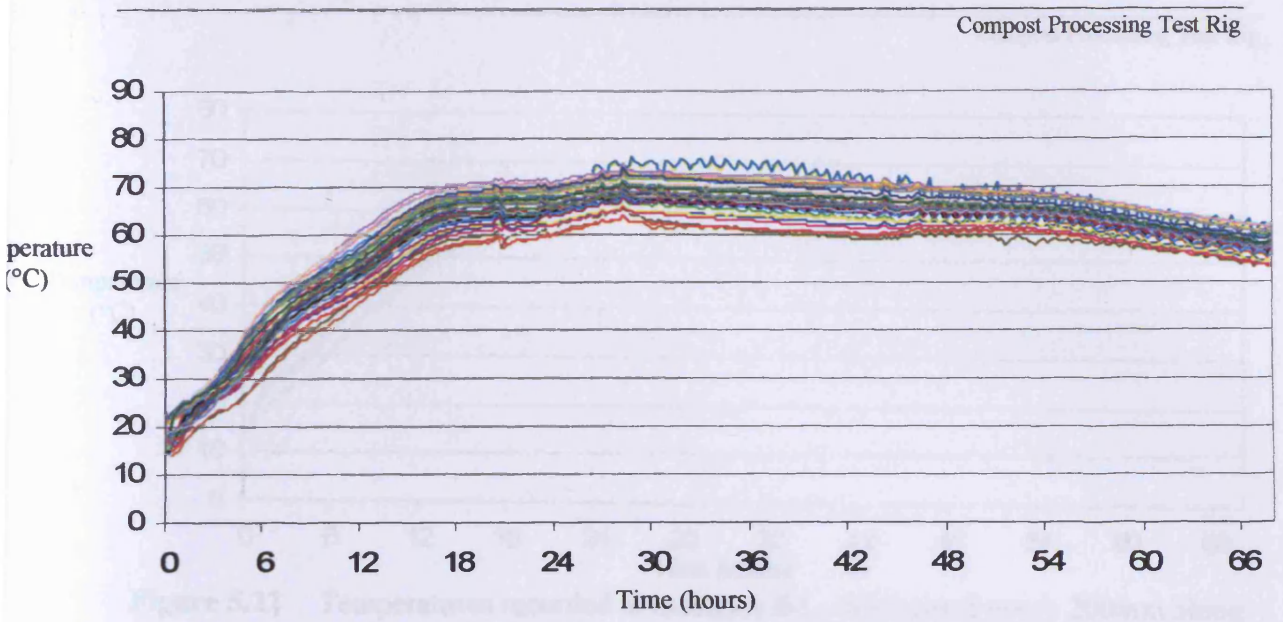

Figure 5.20 Temperatures recorded from a total of 49 thermocouples inserted in the compost matrix and mounted on the internal walls of the test rig over a 70 hour period.

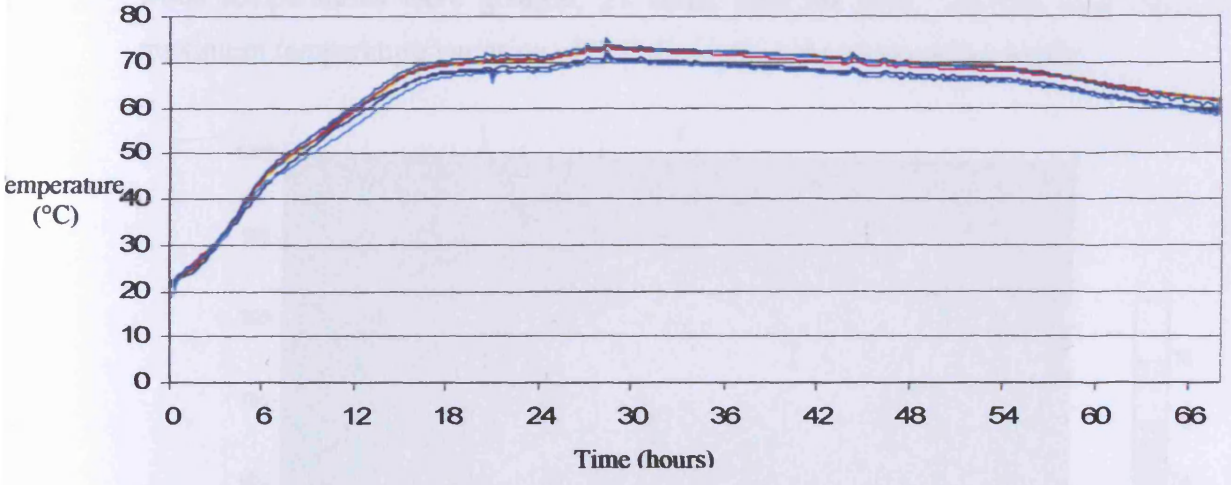

Figure 5.21 Temperatures recorded at probe CP, inserted vertically in the centre of the compost matrix over a 68 hour period.

Temperatures recorded at locations B1 – 6, located every 200mm along the bottom of the side wall at the junction with the plenum floor, did not exceed 60°C until 24 hours after the start and only remained above this temperature for approximately 18 hours, shown in Figure 5.22. The maximum variation in temperature at any one time between these locations was 7°C, slightly more than that found at probe CP.

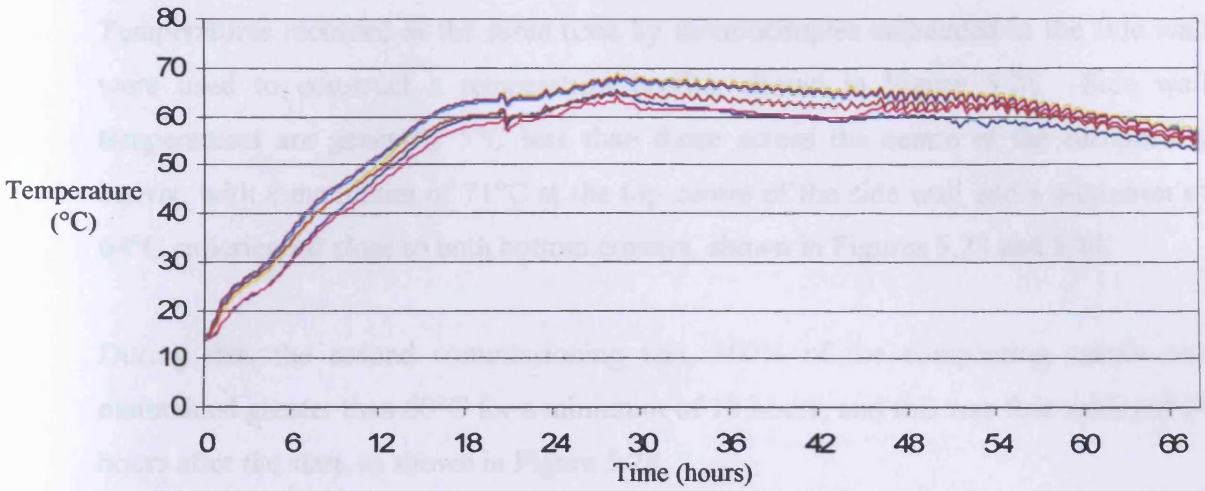

Figure 5.22 Temperatures recorded at locations B1 – B6 located every 200mm along the bottom of the side wall at the top of the plenum floor in the test rig.

Figure 5.23 demonstrates the temperature profile of a vertical section through the centre of the compost matrix in the test rig, and was constructed from data recorded at the time when temperatures were greatest, 27 hours after the start. At this time there is a maximum temperature variation of 9°C throughout the composting matrix.

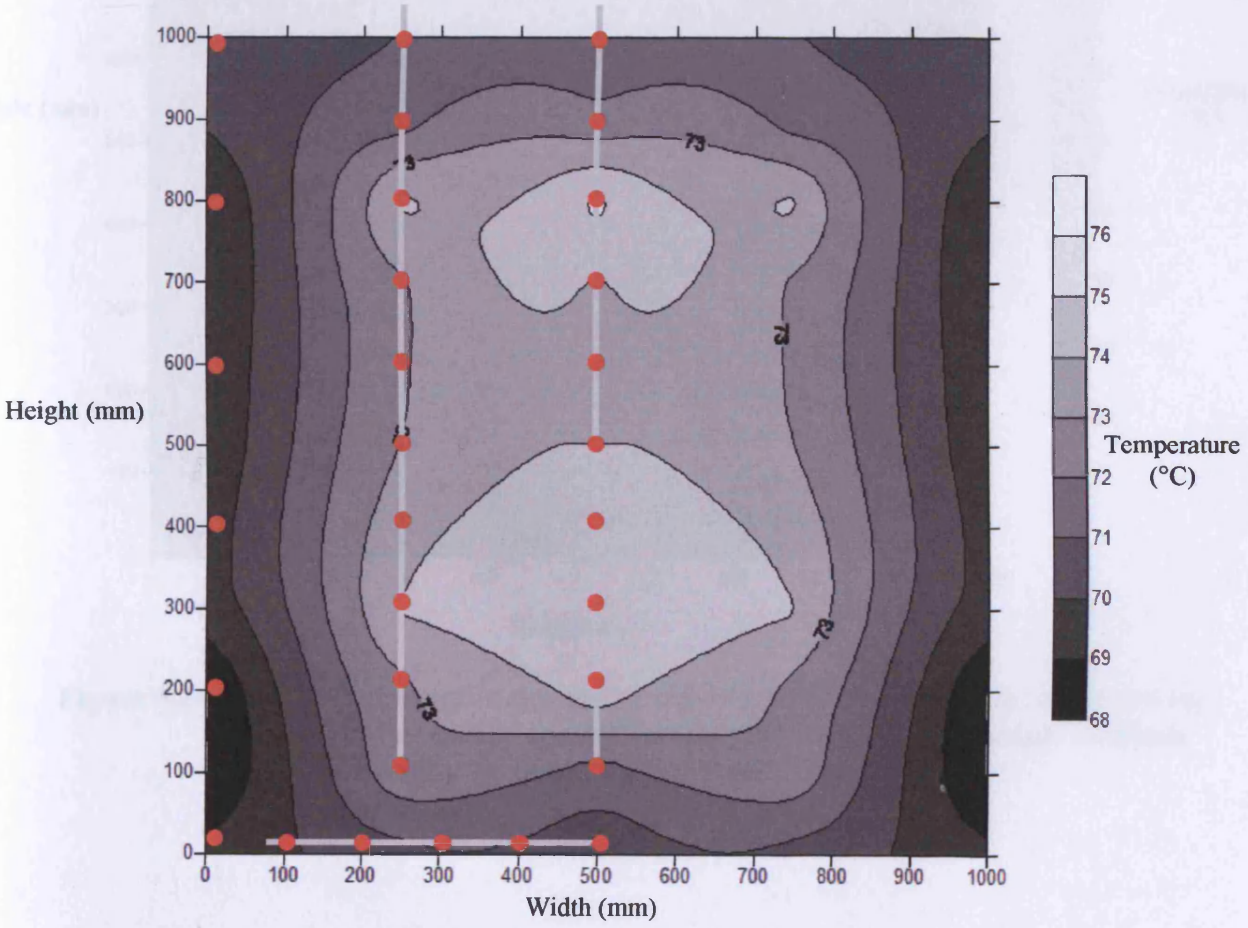

Figure 5.23 Temperature profile across the centre of the composting matrix in the test rig 27 hours after start of commissioning test 2. ● = Thermocouple location used to construct the temperature profile.

Temperatures recorded at the same time by thermocouples embedded in the side wall were used to construct a temperature profile, shown in Figure 5.24. Side wall temperatures are generally 5°C less than those across the centre of the composting matrix, with a maximum of 71°C at the top centre of the side wall and a minimum of 64°C experienced close to both bottom corners, shown in Figures 5.23 and 5.24.

During this, the second commissioning test, 100% of the composting matrix was maintained greater than 60°C for a minimum of 18 hours, and this was first achieved 24 hours after the start, as shown in Figure 5.24.

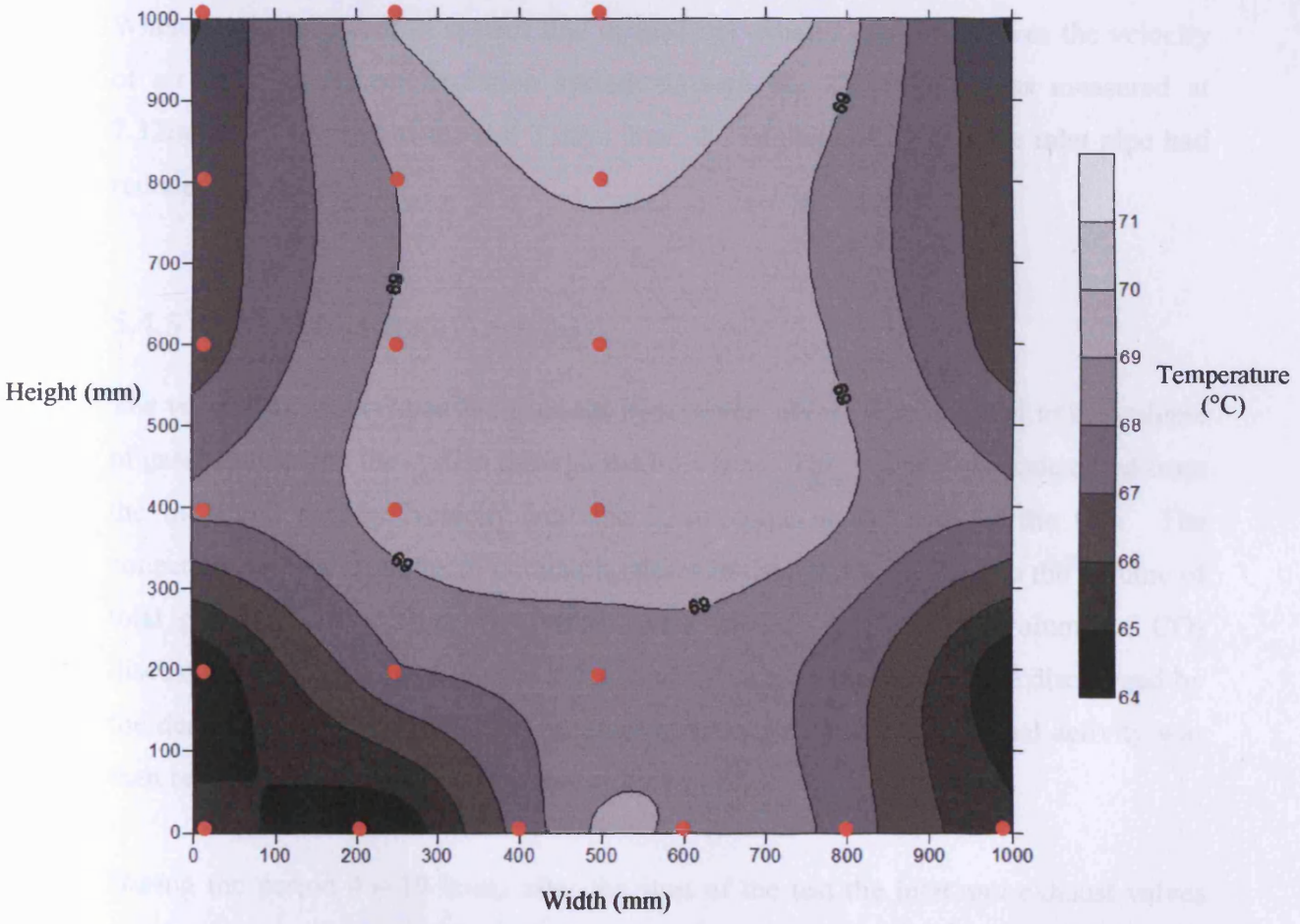

Figure 5.24 Temperature profile against the side of the composting matrix in the test rig 27 hours after start of commissioning test 2. ● = Thermocouple locations used to construct the temperature profile.

5.4.4 Forced Aeration System

After the test rig was filled with shredded green waste the re-circulation rate was set to a total of $50m^3hr^{-1}$, 50% of that for the first test. The re-circulation rate into each plenum had been set to $10m^3hr^{-1}$ at the start of the test, at the end of the test the airflow rate was recorded from the rotameter attached to each plenum. Three days after the test rig was filled the re-circulation rate had reduced in all of the 5 plenums, from 10 m^3hr^{-1} per plenum, to 6.5, 7, 9.5, 8.5 and 9.5 m^3hr^{-1}, measured from left to right from the perspective shown in Figure 5.3. It was noted that there was a certain amount of liquid in the rotameter feeding into the 2 plenums to the left of the central plenum.

When the process control system first opened the exhaust and inlet valves the velocity of air entering the re-circulation system through the 22mm inlet was measured at $7.32ms^{-1}$. At the end of the test 3 days later, the velocity of air into the inlet pipe had reduced to $5.62ms^{-1}$.

5.4.5 Respiration Rate Analysis

The volume of gases exhausted from the system was assumed to be equal to the volume of gases drawn into the system through the inlet pipe. This volume was calculated from the measured average velocity into the 22mm pipe at the start of the test. The concentration of CO_2 in the re-circulating gases in the system, along with the volume of total gases exhausted from the system, were used to calculate the volume of CO_2 discharged. The mass of CO_2 was calculated by multiplying the volume discharged by the density $1.65kg/m^3$ at 60°C. The mass of CO_2 produced by microbial activity was then related to the volume of compost in the test rig.

During the period 4 – 19 hours after the start of the test the inlet and exhaust valves were open permanently and using an estimated exhaust flow rate of $9.57m^3hr^{-1}$. This was estimated as an average gas flow rate at the exhaust during this period, as the exhaust gas flow rate reduced from 10 m^3hr^{-1} at the start of the test, to 7.7 m^3hr^{-1} at the end of the test 3 days later. This flow rate combined with the proportion of CO_2 in the exhaust gases and the volume of compost in the test rig ($1m^3$) allowed the respiration rate for this period to be determined in kilogram's of carbon dioxide per cubic meter of

compost per day ($kgCO_2m^{-3}day^{-1}$). As flow was constant during this period it allowed the respiration rate to be demonstrated on a continuous basis. When inlet and exhaust valves opened and closed in response to CO_2 concentration in the re-circulation system, a series of peaks and troughs occur in the concentration recordings, as seen in Figure 5.18. This non-continuous data makes it more problematical to produce constant respiration rate data.

The calculated dynamic respiration rate was 18 $kgCO_2m^{-3}day^{-1}$ 4 hours after the start of the test, when core temperature was 33°C. This increased to 23$kgCO_2m^{-3}day^{-1}$, 2 hours later when core temperature had increased to 43°C. The respiration rate then reduced back to 18$kgCO_2m^{-3}day^{-1}$ when core temperature was 50°C, 9.5 hours after the start. It then increased to a peak of 30$kgCO_2m^{-3}day^{-1}$ at hour 15, when core temperature was 65°C. From hour 15 to the end of the monitored period respiration rate reduced back to 18$kgCO_2m^{-3}day^{-1}$, whilst core temperature increased to 69.4°C. This sequence of events is shown in Figure 5.25.

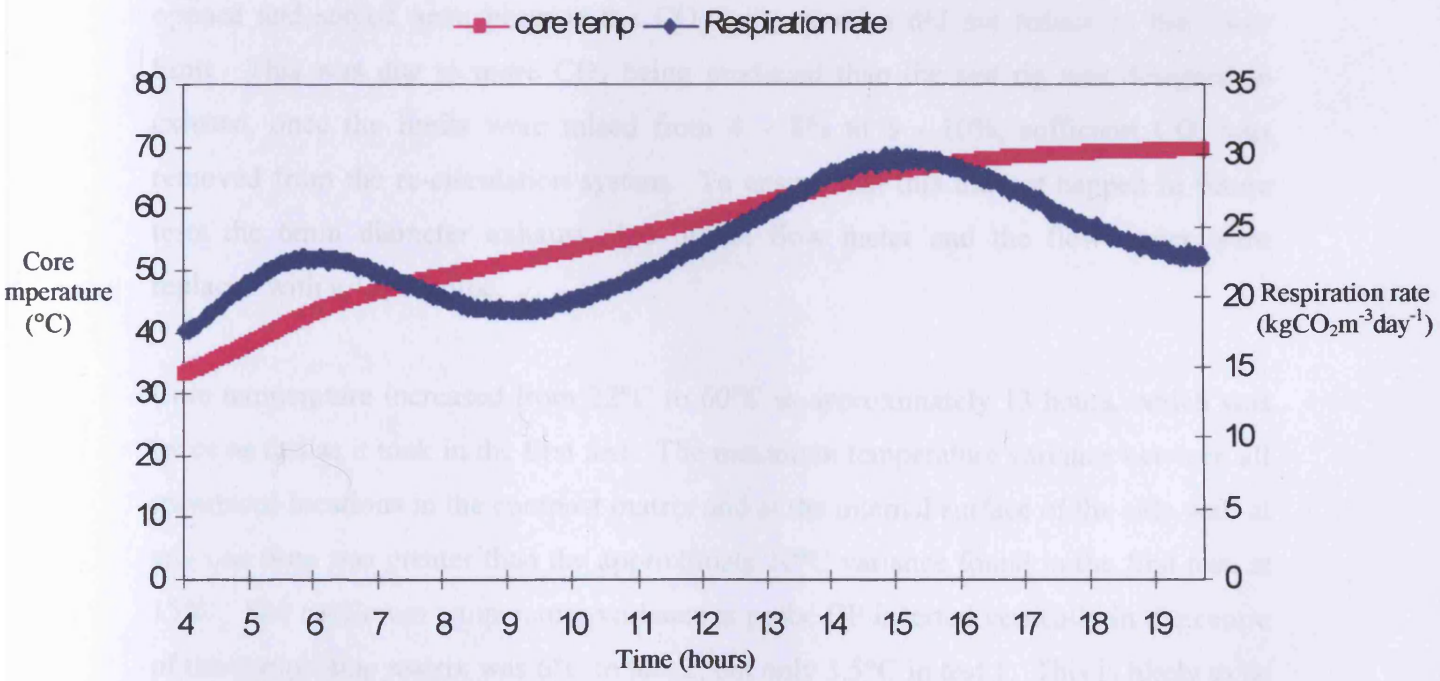

Figure 5.25 Respiration rate and core temperature over a 15.5 hour period, starting 4 hours after the start of the test.

5.5 Discussion

During the first commissioning test the failure of the exhaust valve ensured that the process control system was unable to manage CO_2 concentration in the re-circulation system in the designed manner. Though the process control system did not operate to design, the composting matrix core temperature increased from 15°C to 63°C in 24 hours, as shown in Figure 5.11. The maximum temperature variance between all monitored locations in the compost matrix and at the internal surface of the side wall at any one time was less than 10°C, as shown in Figure 5.15. The temperature variation measured by probe CP inserted vertically in the centre of the composting matrix was only 3.5°C, and across the junction between the internal side wall and the top of the plenum floor the temperature variation was 6°C, as shown in Figures 5.13 and 5.14. The maximum temperature in the composting matrix was 66°C and this occurred close to the upper surface in the centre.

During the second test the process control system successfully managed CO_2 between set limits, though during the 18 hour period from 3 – 21 hours the control valves opened and stayed open because the CO_2 concentration did not reduce to the lower limit. This was due to more CO_2 being produced than the test rig was designed to exhaust, once the limits were raised from 4 – 8% to 8 - 10%, sufficient CO_2 was removed from the re-circulation system. To ensure that this did not happen in future tests the 6mm diameter exhaust pipe of the flow meter and the flow meter were replaced with a 15mm pipe.

Core temperature increased from 22°C to 60°C in approximately 13 hours, which was twice as fast as it took in the first test. The maximum temperature variance between all monitored locations in the compost matrix and at the internal surface of the side wall at any one time was greater than the approximate 10°C variance found in the first test, at 15°C. The maximum temperature variance at probe CP inserted vertically in the centre of the composting matrix was 6°C in test 2, but only 3.5°C in test 1. This is likely to be due to the first test having an initial re-circulation rate of $100m^3hr^{-1}$, which was double that for the second test.

The maximum temperature recorded during test 1 was 66°C but during the second test the maximum recorded temperature was 74.5°C. During the second test the coolest location in the composting matrix was B1, which was located at the corner of 2 side walls and the top of the plenum floor as shown in Figure 5.2. This location was >60°C for a period of 18 hours in the second test, but never reached this temperature during the first test. This indicates that managing the process by maintaining CO_2 concentration between set limits promotes heat retention, and is an effective method of ensuring high temperatures are attained within the composting matrix.

It was not possible to measure the respiration rate during the first test, due to the exhaust mass flow meter not being capable of operating in the conditions experienced at this point. But it is likely that the respiration rate experienced during the period that temperature was increasing was less than that experienced in the second test. This is because the rate of CO_2 production is linked to the rate of heat production (Notton 2005). As the rate of temperature increase in the first test was approximately 50% of that occurring in the second test, it was likely that the rate of heat production and therefore the CO_2 production rate was approximately 50% of that experienced in the second test. Although the constant exhaust of an unknown volume of gases through the faulty exhaust valve may have resulted in a greater rate of heat loss leading to the reduced rate of temperature increase, rather than a reduced heat production rate.

Respiration rate during the second test was calculated from the volume of gas exiting the system along with the concentration of CO_2 in that gas. This volume of gas was calculated from the velocity of gas exiting the system. The velocity was measured at the start of the test when it was $7.32ms^{-1}$ and at the end of the test 3 days later it has reduced to $5.62ms^{-1}$. The period for which the respiration rate was calculated was early in the three day test, from 4 to 20 hours and the flow rate was estimated to be $7ms^{-1}$. During this period the exhaust and inlet valves were open continuously due to insufficient CO_2 being removed from the system at the maximum flow rate through the 6mm exhaust pipe, when the CO_2 limits were set to 4-10%.

The dynamic respiration rate calculated from continuous recordings of CO_2 concentration and volume of gas exhausted from the system over the period from 4 to 20 hours coincides with the period when temperatures were increasing. There are 2

peaks in respiration rate demonstrated by the data during this period, the first occurs when core temperature was 42°C at 23kg$CO_2m^{-3}day^{-1}$, and the second was when core temperature was 65°C at 30kg$CO_2m^{-3}day^{-1}$, highlighted in Figure 5.25.

The highest respiration rates of 30kg$CO_2m^{-3}day^{-1}$ was more than 3 times greater than the rate used to design the test rig aeration system, of 9 kg$CO_2m^{-3}day^{-1}$. This is the reason for the exhaust and inlet valves staying open continuously for this period, as the volume of air required to be exhausted from the system was above the designed maximum. Average respiration rate for the monitored period in test 2, was 23.6 kg$CO_2m^{-3}day^{-1}$. This is more than 13 times greater than the average respiration found in a green waste windrow, of 1.75kg$CO_2m^{-3}day^{-1}$, demonstrated in Chapter 3.

The two peaks in respiration rate during the heat up period, when core temperatures were 42 and 65°C are outside the optimum temperature range of 55 - 60°C indicated by the literature review in Chapter 2. MacGregor et al (1981) were of the opinion that the rate of degradation was linked to moisture loss and that maximum moisture loss had occurred in a static aerated pile managed at 45°C, when compared to those managed at 55 and 65°C. This is at odds with results of this test which indicate a greater respiration rate at 65°C when compared to 45°C. Finstein et al (1983) indicate an optimum temperature of 60°C and Suler and Finstein (1977) found an optimum of 56°C, with only a slight reduction in respiration rate at 60°C. Jeris and Regan (1973) found an optimum of 40 - 50°C for municipal waste with a high paper content and an optimum of 60°C for mixed refuse. Cathcart et al (1986) found a different optimum temperature for crab scrap that had been shredded (56°C), and that which had not been shredded (63°C).

Research undertaken by Waksman et al (1939) suggests that the optimum temperature changes as the composting process progresses. This is likely to be due to different microbial populations being better adapted to degrading different chemical compounds in the organic waste, and that each successive population has different environmental optimums. Therefore the optimum temperature is highly dependent on the physical and chemical properties of the waste and to the extent that decomposition has already occurred.

5.6 Summary

- Following replacement of the actuated exhaust valve after test 1, the CO_2 concentration was accurately managed between the set limits in test 2, but the system was unable to exhaust sufficient gases during the period between 3 and 23 hours after the start of the test. This was due to the peak respiration rate being 3 times more than the test rig was deigned to supply air for.

- When the CO_2 concentration limits were increased from 4 – 8% to 8 – 10% after 23 hours, core temperature increased from 70°C to 73°C, as shown in Figure 5.19. Demonstrating that, partially replacing re-circulating gases intermittently, increases maximum temperature at all locations, when compared to the constant partial replacement that had occurred from hour 3 to 23, as shown in Figure 5.20.

- The design and management of the test rig produced an average respiration rate 13 times greater than the average found in a green waste windrow. If this could be maintained it would result in a similar level of stabilisation in 7 days as that which would require 13 weeks in a windrow.

- Air flow into the individual plenums had reduced by a maximum of 30% in test 1 and by a maximum of 35% in test 2, and the reduction was greater in the plenums near the side walls compared to the central plenum.

- The reducing frequency of actuated valve operation demonstrated from 48 hours to the end of the second test period would suggest that respiration rate is starting to reduce at this point, as shown in Figure 5.18.

- The higher re-circulation rate in test 1 of $100m^3hr^{-1}$ when compared to the rate in the second test of $50m^3hr^{-1}$ has resulted in a lower temperature variation at all monitored locations in the test rig.

- The test rig when operating to design has demonstrated that it is possible to manage 100% of the compost matrix up to the ABPR minimum treatment temperature in 24 hours, though this was only maintained for an 18 hour period in the test rig.

- The volume of air required to provide sufficient oxygen to the composting matrix at a respiration rate of $9kgCO_2m^{-3}day^{-1}$ was calculated to be $3.24m^3hr^{-1}$. During the second test the calculated air supplied was $9.57m^3hr^{-1}$, when the respiration rate was $30kgCO_2m^{-3}day^{-1}$. This respiration rate was approximately 3 times the calculated rate as was the volume of air required to supply sufficient oxygen. This demonstrated the accuracy of the original calculations in estimating the volume of air required to supply sufficient oxygen in relation to the respiration rate.

6 Analysis of Test Rig Process Management

6.1 Introduction

The tests undertaken during the commissioning of the compost processing test rig, described in Chapter 5, demonstrated that the initial supposition of managing CO_2 concentration in the re-circulating gases would lead to rapid temperature gain was accurate. A further set of tests were undertaken to gain further understanding of the effect of process management and operational management options on several key parameters.

The test rig was primarily designed and built to examine if 100% of the composting matrix could be maintained above the minimum treatment temperatures of 60°C for 48 hours or 70°C for 1 hour. The first commissioning test was undertaken with a re-circulation rate of $100m^3hr^{-1}$ and the second with a re-circulation rate of $50m^3hr^{-1}$. The higher re-circulation rate produced a smaller temperature variation throughout the composting matrix. The peak temperature recorded in the test with the higher re-circulation rate was more than 8°C lower than the recorded peak in the test with the lower flow rate. In the first test some areas of the composting matrix did not reach the minimum target temperature of 60°C, but this may have been due to the rig not operating correctly. In the second test when the rig operated in the designed manner, 60°C was exceeded in 100% of the composting matrix for 18 hours.

To further examine the effect of re-circulation rates on temperature distribution within the composting matrix, three green waste composting tests were undertaken using different re-circulation rates. The methods used and the results gained from these tests are described and compared to each other and to those found in the second commissioning test when the re-circulation rate was $50m^3hr^{-1}$, in Section 6.2.

The treatment requirements of the ABPR stipulate that if meat has not been excluded from the catering waste, then it will require a second phase of treatment. The second phase of treatment is the same as the first but the waste must be mixed between the phases. To examine if the required minimum temperatures were attained after a turning

event, two green waste tests were managed to meet the first phase of treatment. The waste was then unloaded from the test rig and immediately reloaded back into the test rig to imitate a turning event. The methods used and results from these tests are described in Section 6.3.

The test rig was designed to manage organic waste composting at a maximum rate of $80gCO_2kgVS^{-1}day^{-1}$ or $9kgCO_2m^{-3}day^{-1}$ assuming the green waste has a moisture content of 60% and volatile solids are 60% of dry matter. This rate was more than twice as high as the greatest rate found in green waste windrows. During commissioning test 2 respiration rates of up to $30kgCO_2m^{-3}day^{-1}$ were found, more than three times greater than the design limit. The very high respiration rates recorded have a significant impact upon the rate of heat production and therefore the time taken for the composting matrix to attain the minimum target temperature. The maintenance of high respiration rates may be required to maintain these temperatures in the test rig.

Respiration rate was measured during the tests to determine the effect of re-circulation rate on temperature distribution and to measure the effects of a turning event. The methods and results from these measurements are demonstrated in Section 6.4, and summarised in Section 6.5.

6.2 Effect of Re-circulation Rate on Temperature Distribution

6.2.1 Introduction

The rate that gases are re-circulated through the composting matrix will affect temperature distribution, as heat energy is distributed by these gases. Therefore the higher the re-circulation rate the less variation there is in temperature through out the matrix. Results from the commissioning tests suggest that higher recirculation rates may also lead to reduced maximum temperatures, which may result in the target temperatures not being achieved in all areas of the matrix. The energy costs of producing re-circulation rates greater than that required to meet the regulations would be substantial in a commercial scale system.

Three separate tests using green waste were undertaken. The first used a re-circulation rate of $10m^3hr^{-1}$, the second a re-circulation rate of $30m^3hr^{-1}$ and the third a re-circulation rate of 40 m^3hr^{-1}. These along with an earlier test using a re-circulation rate of $50m^3hr^{-1}$, are analysed to determine the effect of changing re-circulation rate on temperature distribution.

6.2.2 Methodology

For each test the rig was filled with $1m^3$ of freshly shredded green waste and re-circulation was continuous. The process management system settings for each test are listed in Table 6.1.

Table 6.1 Rate of continuous re-circulation and CO_2 lower and upper limit set points during each of the three tests.

	Test 3	**Test 4**	**Test 5**
Re-circulation Rate	$10m^3hr^{-1}$	$30m^3hr^{-1}$	$40m^3hr^{-1}$
CO_2 limit settings	0-8 hours no control 8-23 hours 8-10% 23-25 hours 6-10% 25-97 hours 4-6%	0-21 hours 6-8% 21-96 hours 8-10% 96-158 hours 4-6%	0-27 hours 8-10% 27-167 hours 6-8%

Core temperature was measured at CP5 which was located in the centre of the composting matrix and was recorded on the process control computer, as was the CO_2 concentration of the re-circulating gases. Probe CP was located vertically in the centre of the composting matrix, MP was located vertically in the composting matrix 250mm from the centre of the side wall and BP was located across the surface of the plenum floor. The remaining thermocouples were mounted in the side wall as described in Figure 5.2. The temperatures recorded by the probe and wall mounted thermocouples were recorded on the data logger and periodically down loaded onto the process control computer.

6.2.3 Results

6.2.3.1 Green Waste Composting in the Test Rig with a Re-circulation rate of $10m^3hr^{-1}$

Due to an error, the process control system was not set until 8 hours after commencement of the test, during this period CO_2 concentration increased to a maximum of 18%, as shown in Figure 6.1. When the process control system was initiated the CO_2 concentration in the re-circulating gases was managed mainly between the set limits of 8 – 10%.

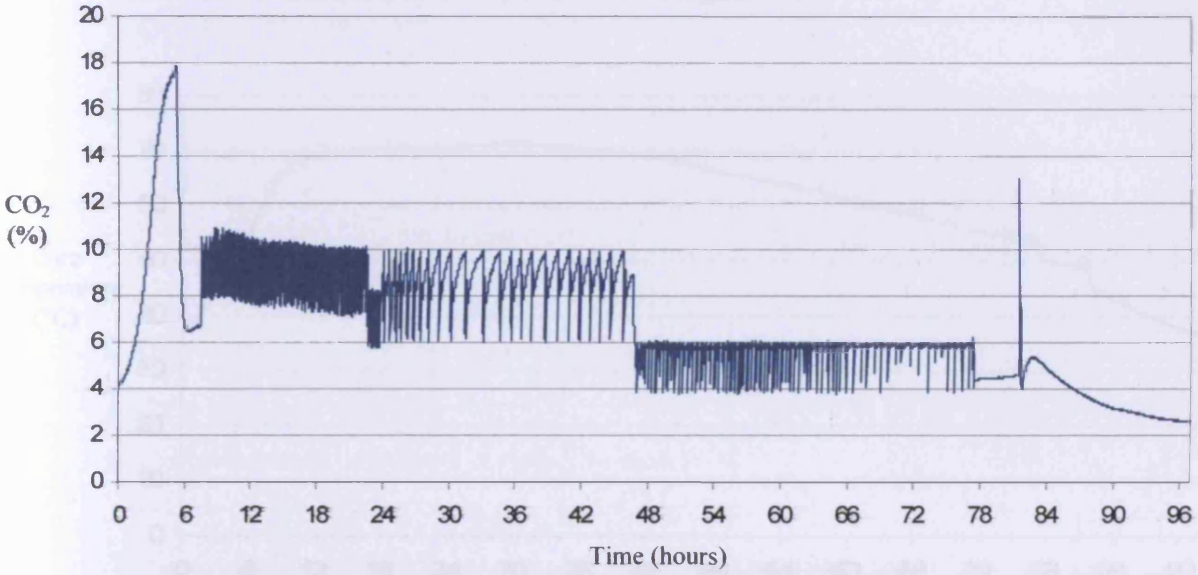

Figure 6.1 CO_2 concentrations in the re-circulating gases over the 97 hour period of test 3 when the re-circulation rate was $10m^3hr^{-1}$.

Between hours 23 to 25 the CO_2 set limits were changed to 6 – 8%, from 8 – 10%. At hour 25 the limits were changed again to open the inlet and exhaust valves when CO_2 concentration reached 10% and to shut when it had reduced to 6%. The CO_2 set limits were changed again at hour 46 to open when concentration had increased to 6% and to shut when it had reduced to 4%. These limits remained in place to the end of the test at 97 hours. At hour 77 the fan was turned off to reduce heat loss as the door into the side of the rig containing the aeration distribution system had to be removed for repair. When the door was repaired the fan was switched on at hour 82. Following this the peak and trough pattern of CO_2 concentration that is caused by the opening and closing

of the exhaust and inlet valves, stopped. This indicated that CO_2 concentration was not reaching the upper set limit that results in the valves opening, and CO_2 concentration reduced from 5% at hour 83 to below 3% at the end of the test.

Core temperature increased from 38°C at the start of the test to 70°C approximately 12 hours later and the peak temperature of 71.5°C was reached 30 hours after the start. Core temperature reduced to 70°C by hour 41 and continued to reduce over the remaining period of the test to 34°C at the end. When the fan was turned off at hour 77 there was a 5°C reduction in core temperature, and over the 5 hour period that the fan was off, core temperature remained at 50°C. Once the fan was restarted there was a further 5°C reduction to 45°C, as shown in Figure 6.2.

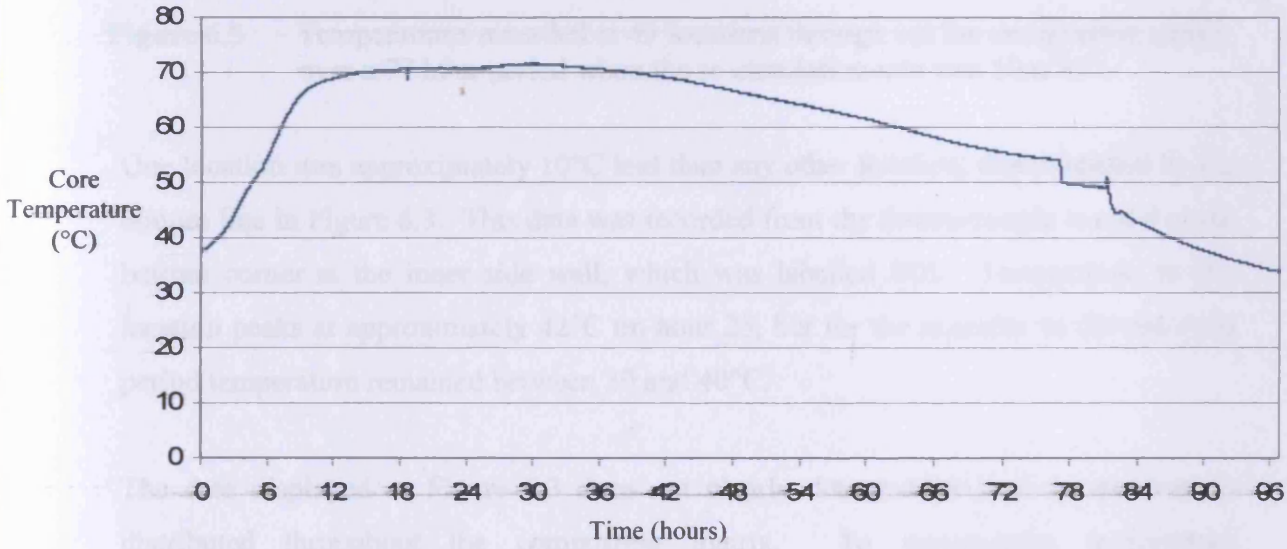

Figure 6.2 Core temperatures in the test rig over a 97 hour period when the re-circulation rate was $10m^3hr^{-1}$.

Although core temperature peaked at more than 70°C there was a large variation in temperature through out the composting matrix. The 49 temperatures recorded on the data logger, every 10 minutes over the first 77 hours of the test are located through out the compost matrix and in one of the rig side walls. Temperatures recorded at these locations demonstrate a temperature variation of over 30°C for the majority of the test, as shown in Figure 6.3. Unfortunately the data logger stopped recording at hour 77 when the power was switched off to undertake repairs to the door due to the back up batteries being flat.

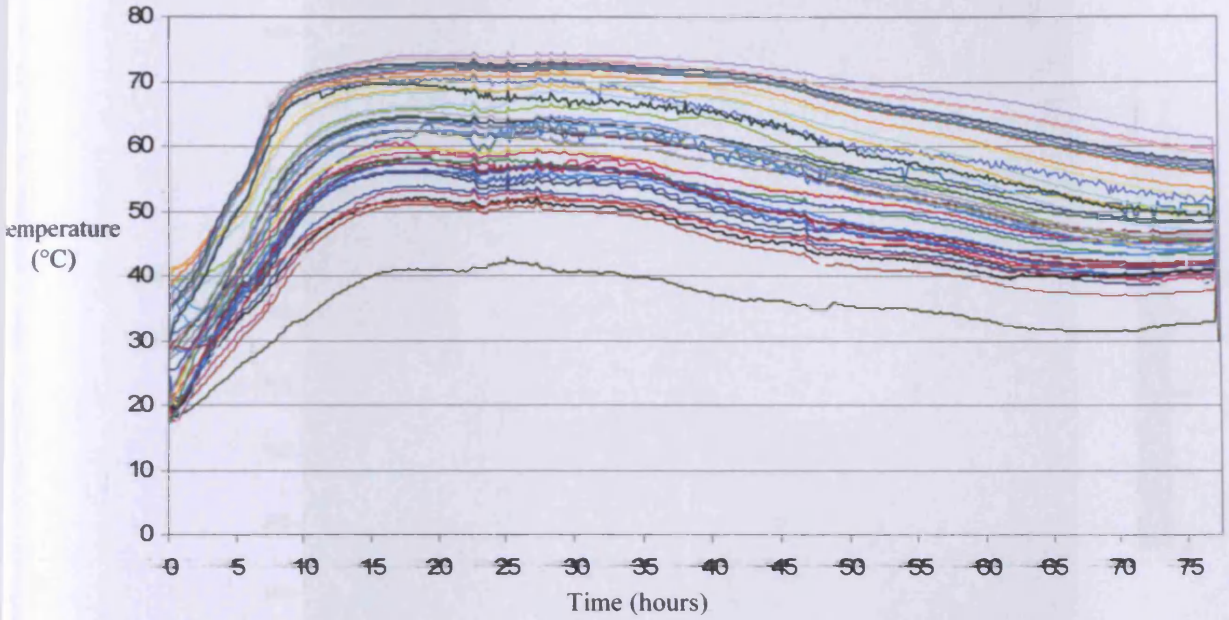

Figure 6.3 Temperatures recorded at 49 locations through out the composting matrix over a 77 hour period when the re-circulation rate was $10m^3hr^{-1}$.

One location was approximately 10°C less than any other location, demonstrated by the bottom line in Figure 6.3. This data was recorded from the thermocouple located in the bottom corner at the inner side wall, which was labelled B01. Temperature at this location peaks at approximately 42°C on hour 25, but for the majority of the recorded period temperature remained between 30 and 40°C.

The data displayed in Figure 6.3 does not clearly demonstrate how temperature is distributed throughout the composting matrix. To demonstrate temperature distribution, data from all relevant locations were used to construct a temperature profile through the centre of the composting matrix, as shown in Figure 6.4. Data recorded from the thermocouples embedded in the rig side wall at the same point in time were used to construct a temperature profile against the side wall, as shown in Figure 6.5.

These profiles demonstrate that despite a large proportion of the core being greater than 70°C the bottom corners are below 55°C, and at the side wall the bottom corner is less than 45°C. Therefore, at no time has all of the composting matrix achieved the minimum treatment temperature of 60°C and the maximum temperature achieved at the coolest location was approximately 18°C less than the target temperature.

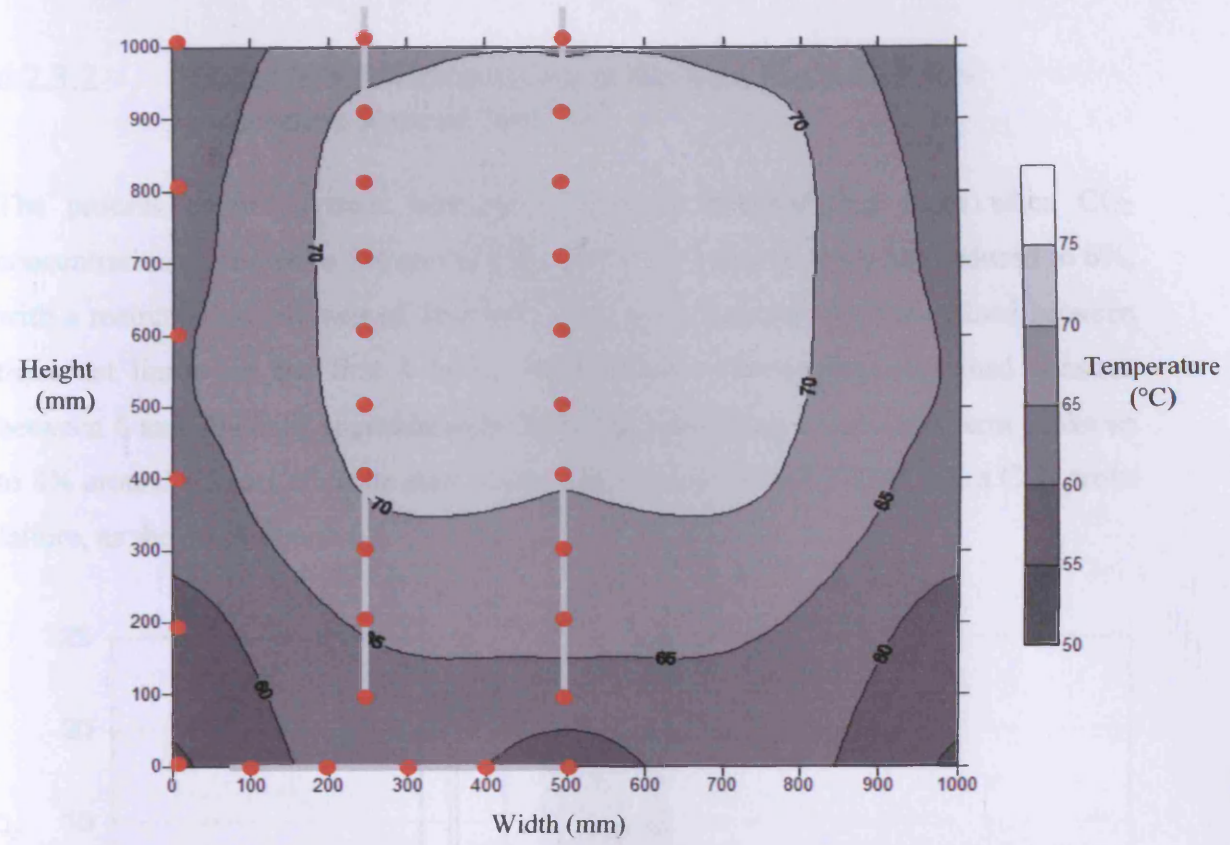

Figure 6.4 Temperature profile across a vertical section through the centre of the compost matrix in the test rig, 26 hours after the start. ● = Thermocouple locations used to construct the temperature profile.

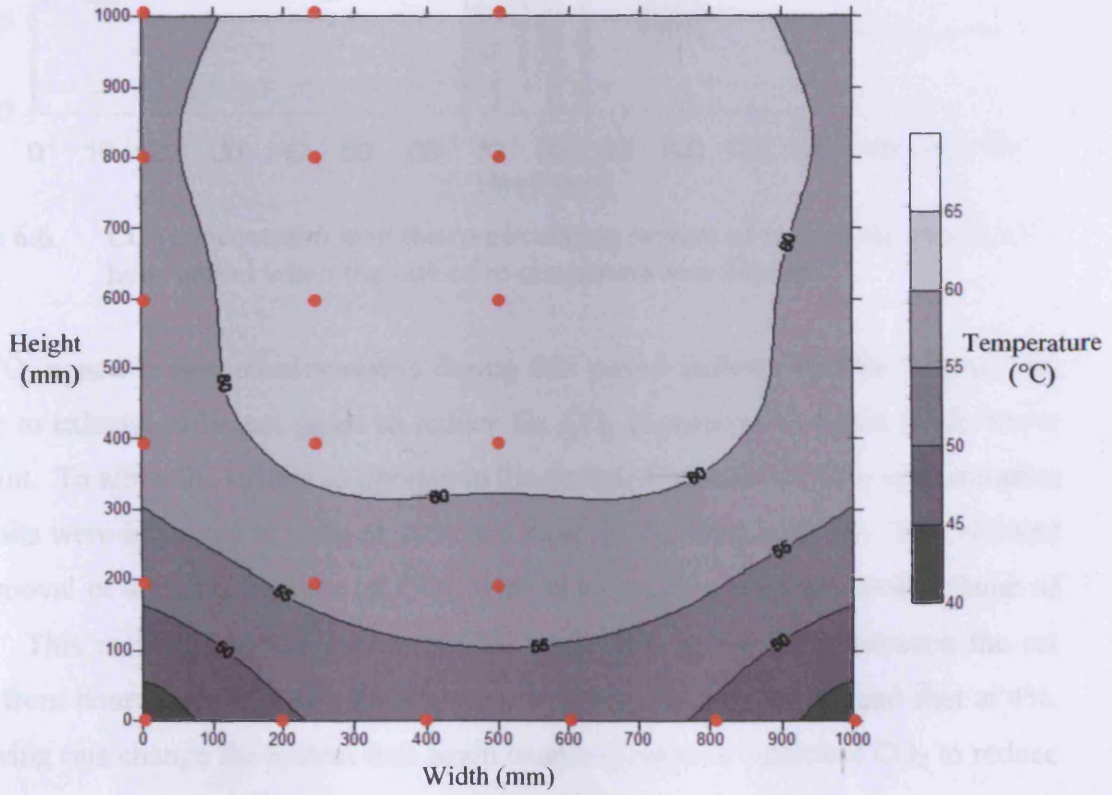

Figure 6.5 Temperature profile at test rig side wall, 26 hours after the start. ● = Thermocouple locations used to construct the temperature profile.

6.2.3.2 Green Waste Composting in the Test Rig with a Re-circulation Rate of $30m^3hr^{-1}$

The process control system was set to exhaust re-circulating gases when CO_2 concentration increased to 8% and to close when the concentration had reduced to 6%, with a recirculation rate was of $30m^3hr^{-1}$. CO_2 concentration was maintained between these set limits for the first 4 hours, after which concentration remained constant between 6 and 7% until approximately 20 hours, apart from some short term peaks up to 8% around 9 hours after the start, from hour 49 until hour 86 there was a CO_2 probe failure, as shown in Figure 6.6.

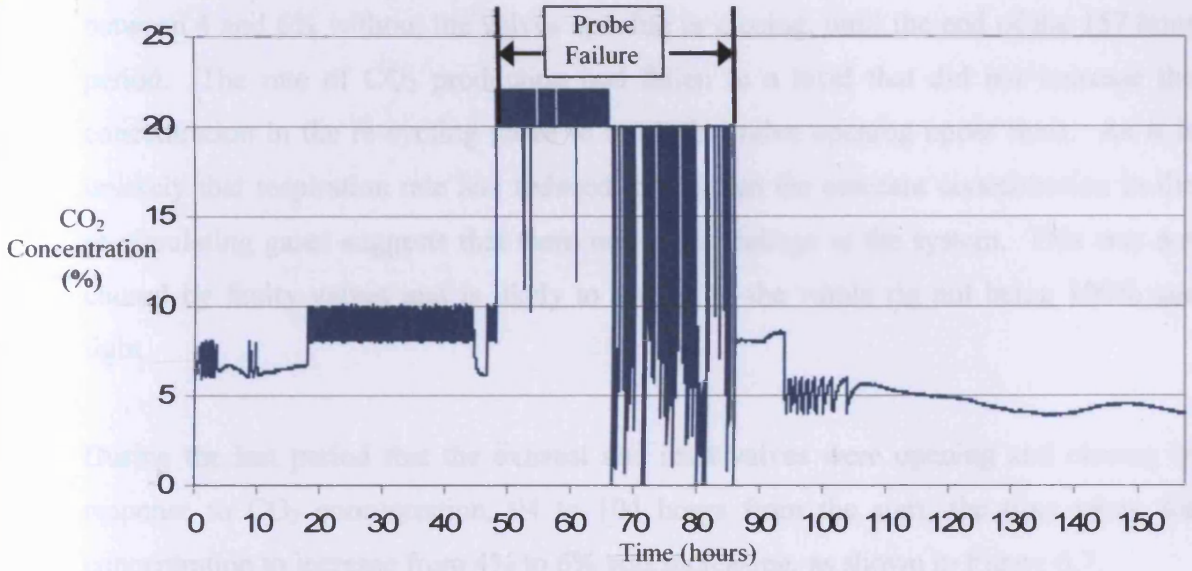

Figure 6.6 CO_2 concentrations in the re-circulating system of the test rig over a 157 hour period when the rate of re-circulation was $30m^3hr^{-1}$.

The CO_2 concentration measurements during this period indicate that the system was unable to exhaust sufficient gases to reduce the CO_2 concentration down to the lower set point. To allow the system to operate in the designed manner the CO_2 concentration set limits were increased to open at 10% and close at 8% from hour 20. This allowed the removal of a greater volume of CO_2, without exhausting a greater total volume of gases. This method was successful as CO_2 concentration remained between the set limits from hour 20 to 44, when the limits were changed to open at 8% and shut at 4%. Following this change the system was again unable to remove sufficient CO_2 to reduce the concentration to the lower set limit of 4%, so the control limits were increased back to 8 – 10% two hours later. From hour 49 to hour 86 the measured CO_2 concentrations

were very erratic. At hour 86 the reason for the erratic measurements was investigated. Initial observation of the probe head suggested the build up of condensate had immersed the sample portion of the probe in liquid and caused an error. The sample head was removed and dried but was still not operating correctly, at this point a spare probe was fitted. The inoperable probe was sent to the manufacturer, who reported that the condensate build up had caused failure due to corrosion.

At hour 94 the system was switched back on, the CO_2 concentration limits were set to open the valves at 6% and shut them at 4% and the CO_2 concentration was managed between these limits for 10 hours. Following this period CO_2 concentration remained between 4 and 6% without the valves opening or closing, until the end of the 157 hour period. The rate of CO_2 production had fallen to a level that did not increase the concentration in the re-cycling gases to reach the valve opening upper limit. As it is unlikely that respiration rate had reduced to nil, then the constant concentration in the re-circulating gases suggests that there was a gas leakage in the system. This was not caused by faulty valves and is likely to be due to the whole rig not being 100% gas tight.

During the last period that the exhaust and inlet valves were opening and closing in response to CO_2 concentration, 94 to 104 hours from the start, the time taken for concentration to increase from 4% to 6% was increasing, as shown in Figure 6.7.

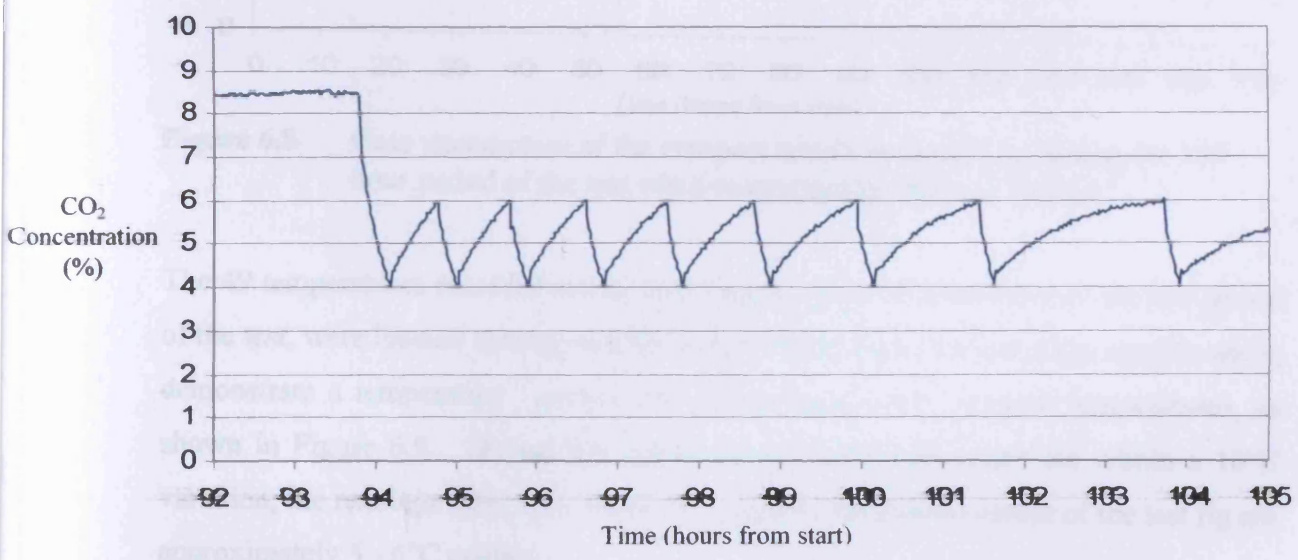

Figure 6.7 CO_2 concentrations in the re-circulating gases from 92 to 105 hours from the start.

Between hours 94 and 95 the time between the exhaust and inlet valves shutting at the lower limit, and opening at the upper limit was 0.58 hours. Just 5 hours later, between 98.9 and 100 hours, the time period between these events was nearly double at 1.1 hours. This had nearly doubled again, to 2.1 hours in the final event, between 101 and 103 hours. Therefore the time taken for the CO_2 concentration in the re-circulating gases to increase from 4 to 6% has multiplied by more than 3.5 times in a 10 hour period.

Core temperature increased from approximately 32°C at the start of the 157 hour monitored period, to 60°C 13 hours later and to a maximum of 70°C at 30 hours from the start, as shown in Figure 6.8. Core temperature remained at 70°C until hour 55 and then reduced to 62°C by hour 69, it then remained between 62 and 61°C for a further 15 hours. From hour 84 to 140 hours the core temperature reduced further, down to 45°C, from then to the end of the monitored period it remained between 45 and 47°C.

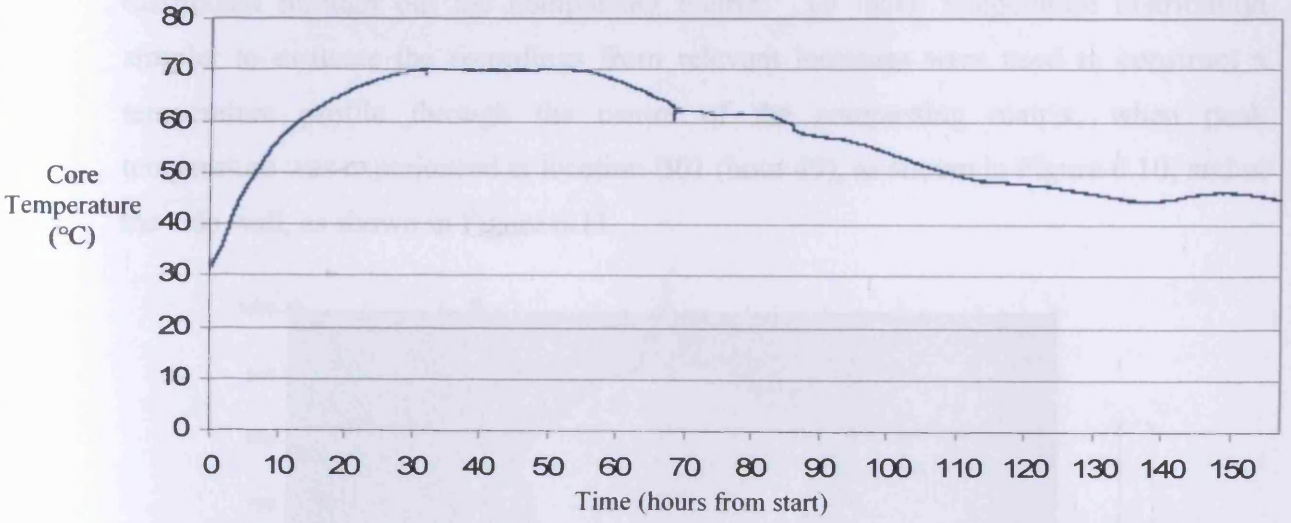

Figure 6.8 Core temperature of the compost matrix in the test rig during the 157 hour period of the test when re-circulation rate was $30m^3hr^{-1}$

The 49 temperatures recorded on the data logger, every 10 minutes over the full period of the test, were located through out the compost matrix and in one of the rig side walls, demonstrate a temperature variation of approximately 16°C at peak temperatures, as shown in Figure 6.9. Though the great majority of the locations are within a 10°C variation, the readings from B01 which is located in the bottom corner of the test rig are approximately 5 - 6°C cooler.

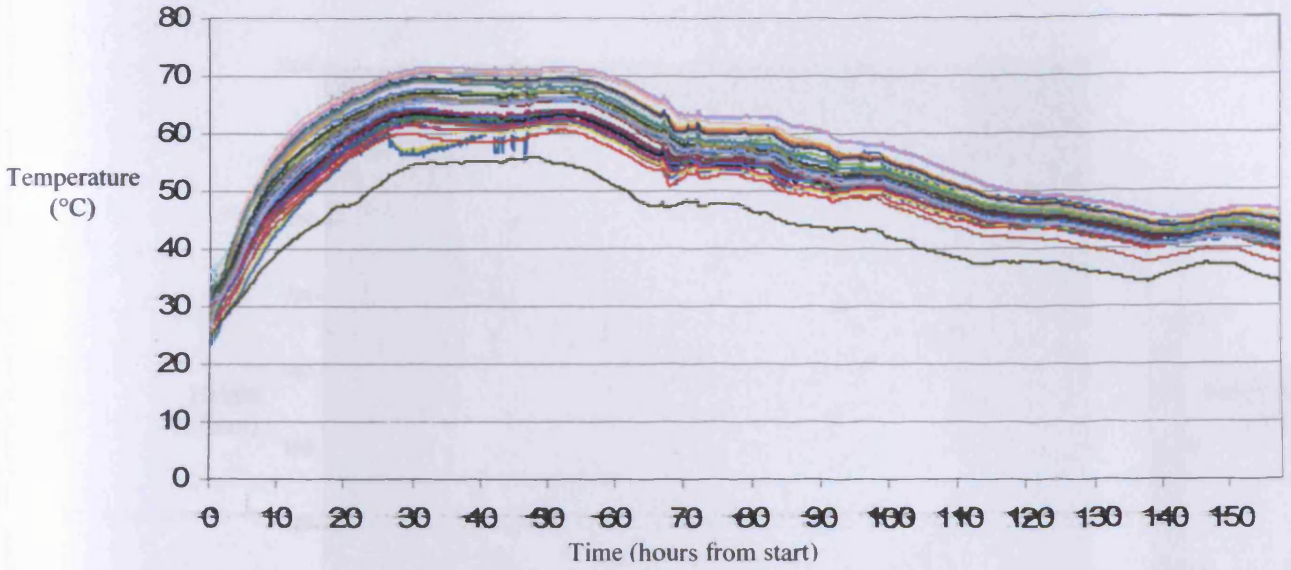

Figure 6.9 Temperatures recorded at 49 locations through out the composting matrix over a 157 hour period when the re-circulation rate was $30m^3hr^{-1}$.

The data displayed in Figure 6.9 does not clearly demonstrate how temperature is distributed through out the composting matrix. To make temperature distribution simpler to evaluate the recordings from relevant locations were used to construct a temperature profile through the centre of the composting matrix, when peak temperature was experienced at location B01 (hour 49), as shown in Figure 6.10, and at the side wall, as shown in Figure 6.11.

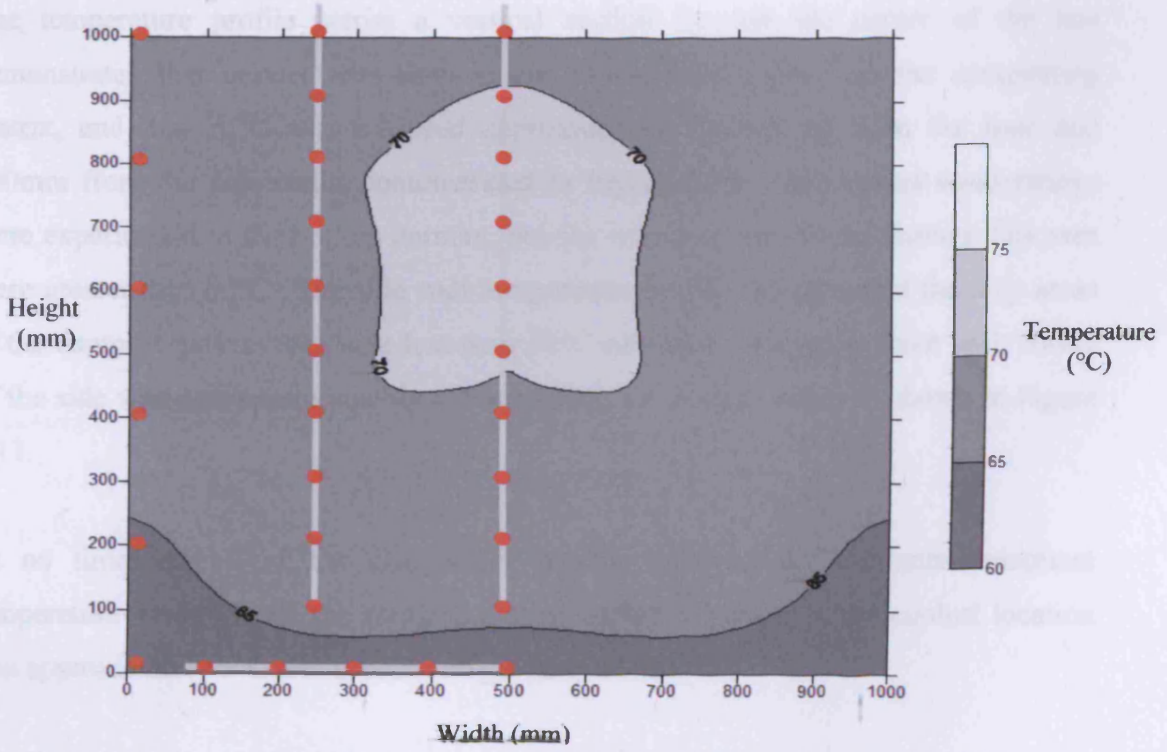

Figure 6.10 Temperature profile across a vertical section through the centre of the compost matrix in the test rig, 49 hours after the start, when the re-circulation rate was $30m^3hr^{-1}$. ● = Thermocouple locations used to construct the temperature profile.

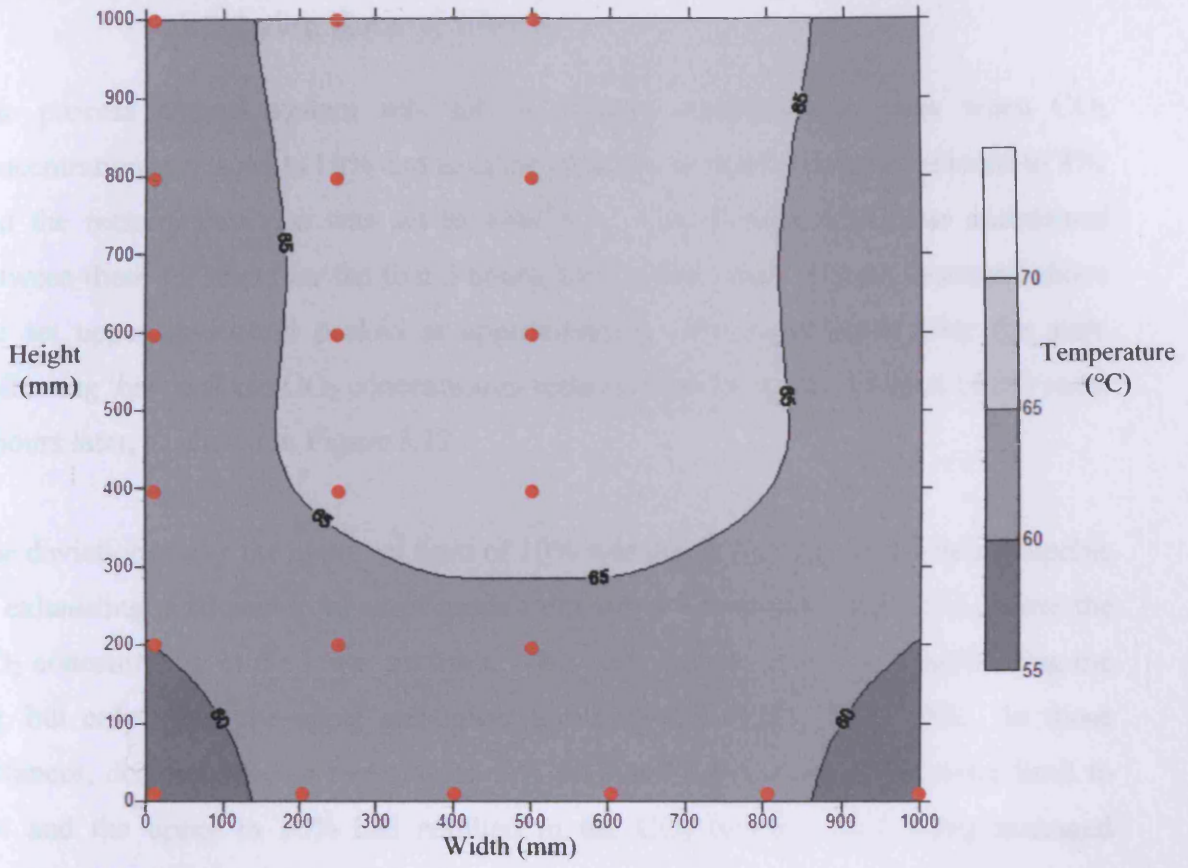

Figure 6.11 Temperature profile at test rig side wall, 49 hours after the start, when the re-circulation rate was $30m^3hr^{-1}$. ● = Thermocouple locations used to construct the temperature profile.

The temperature profile across a vertical section through the centre of the bay demonstrates that greater temperatures are experienced higher up the composting matrix, and that 70°C was achieved approximately 450mm up from the base and 300mm from the side walls, demonstrated in Figure 6.10. The lowest temperatures were experienced in the bottom corners, but the whole of the matrix through this area were greater than 60°C. The side wall temperature profile indicates that the only areas of the compost matrix that were less than 60°C extended 200mm up from each corner of the side wall and approximately 150mm along the bottom edge, as shown in Figure 6.11.

At no time has all of the composting matrix achieved the minimum treatment temperature of 60°C and the maximum temperature achieved at the coolest location was approximately 5°C less than the target temperature.

6.2.3.3 Green Waste Composting in the Test Rig with a Re-circulation Rate of $40m^3hr^{-1}$

The process control system was set to exhaust re-circulating gases when CO_2 concentration increased to 10% and to close when the concentration had reduced to 8%, and the recirculation rate was set to $40m^3hr^{-1}$. CO_2 concentration was maintained between these set limits for the first 5 hours, after which concentration increased above the set upper limit, and peaked at approximately 12% eight hours after the start. Following this peak the CO_2 concentration reduced back to the lower limit of 8% some 4 hours later, as shown in Figure 6.12.

The deviation above the upper set limit of 10% was due to the system not being capable of exhausting sufficient volume of gases from the re-circulation system to reduce the CO_2 concentration to the lower set limit. This had occurred in previous tests using the rig, but only when the upper and lower limits were less than 8 to 10%. In those instances, demonstrated in Figures and 5.9, 5.17 and 6.6, changing the lower limit to 8% and the upper to 10% had resulted in the CO_2 concentration being managed between the set limits.

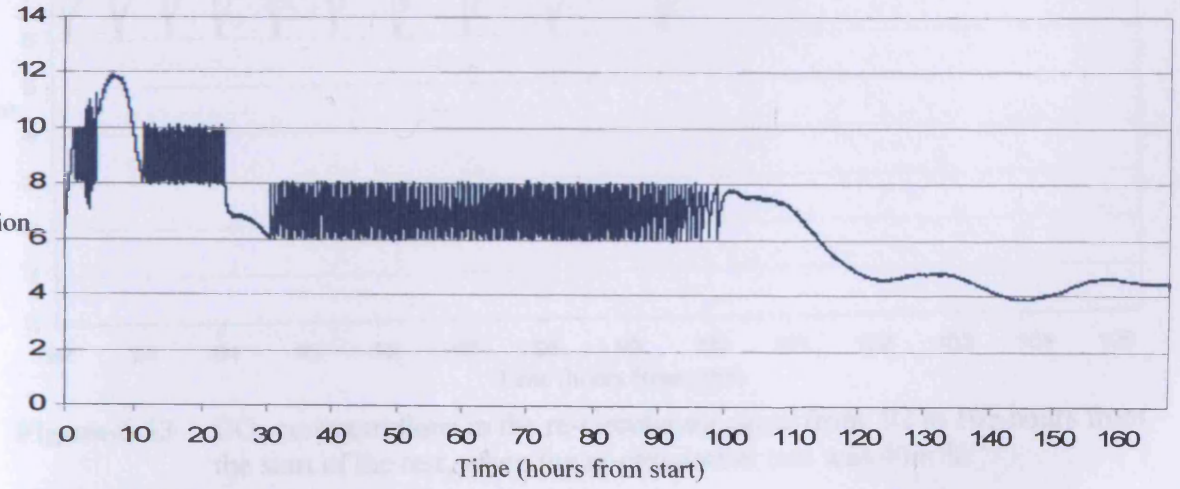

Figure 6.12 CO_2 concentrations in the re-circulating gases over a 167 hour period from the start to the end of the test conducted with a re-circulation rate of $40m^3hr^{-1}$.

Following hour 12 the CO_2 concentration was again managed between the set limits of 8 to 10% until hour 23 when the set limits were changed to open the exhaust and inlet valves when CO_2 concentration reached 8% and to close when it reduced to 6%. Following this change the valves were open continuously until hour 30 as CO_2

concentration did not reduce to the new lower set limit of 6% until that point. From hour 30 until hour 100, CO_2 concentration remained between these set limits. 100 hours from the start of the test the CO_2 concentration failed to reach the valve opening level of 8% and declined to approximately 4.5% by hour 120. From hour 120 to the end of the test at 167 hours from the start the CO_2 concentration remained between 4 and 4.5%.

The time taken for CO_2 concentration in the re-circulating gases to rise from 6% to 8%, between valves shutting and opening, was increasing during the period 92 to 100 hours from the start, as shown in Figure 6.13. The time taken for CO_2 concentration to increase from 6 to 8%, following the valves shutting at hour 94 was 36 minutes. Approximately 2 hours later (hour 96) this period had increased to 46 minutes and at hour 98 the time taken for the same increase had extended to 76 minutes. Therefore the time taken for the CO_2 concentration in the re-circulating gases to increase from 6 to 8% has more than doubled in a 5 hour period.

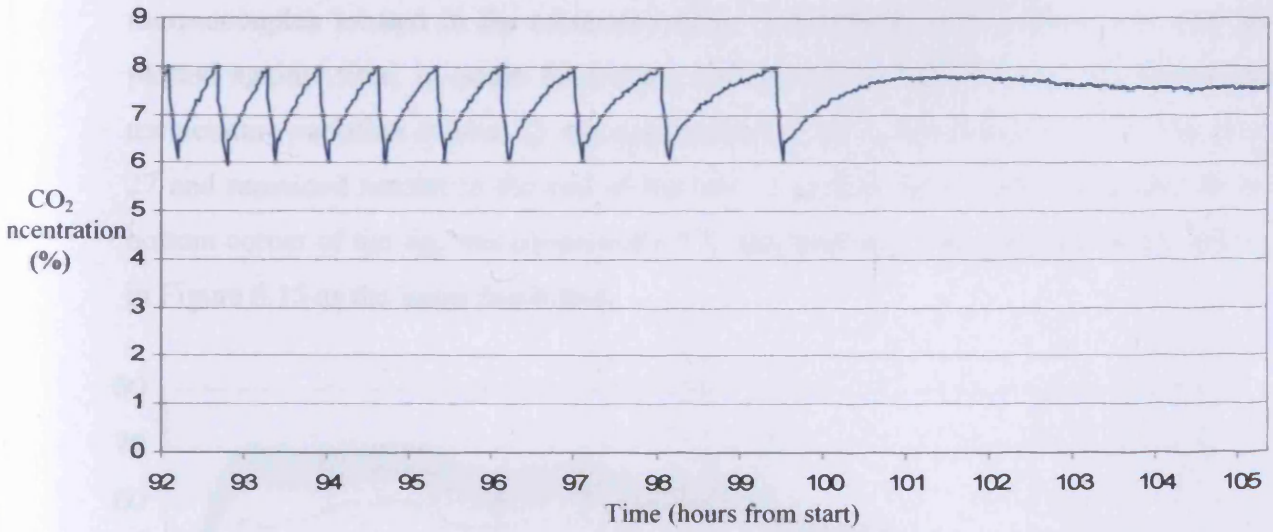

Figure 6.13 CO_2 concentrations in the re-circulating gases from, 92 to 105 hours from the start of the test, when the re-circulation rate was $40m^3hr^{-1}$.

Core temperature increased from 40°C at the start to 68.5°C thirteen hours later and remained at that level for 3 hours, as shown in Figure 6.14. From hour 16 to hour 24 core temperature fluctuated between 45°C and 68°C and then became less variable until hour 33 when temperature peaked at 70°C and remained there for approximately 5 hours. From this point onwards core temperatures became far less erratic but continued to decrease until the end of the test at 167 hours from the start, when the core

temperature was 43°C. The temperature reduction was generally linear but followed the pattern of a decrease, then a period of stability followed by a further decline.

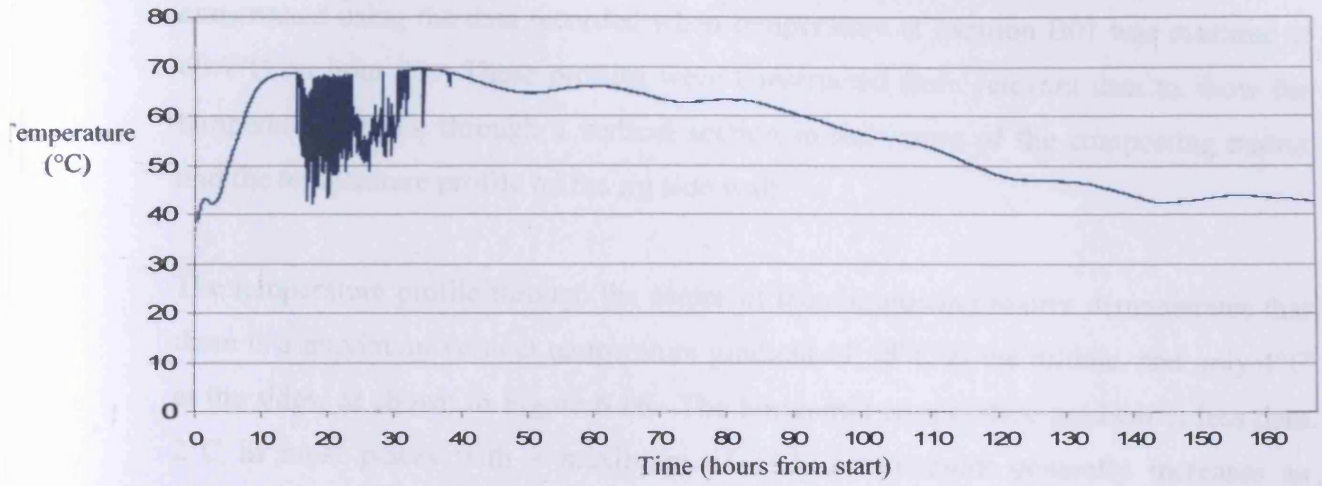

Figure 6.14 Core temperatures during the 167 hour test period when the re-circulation rate was $40m^3hr^{-1}$.

To demonstrate temperature variation through out the composting matrix all 49 thermocouples located in the compost matrix and embedded in the rig side wall are plotted against time, in hours from start, and shown in Figure 6.15. The maximum temperature variation at hour 15 was approximately 15°C, this reduced to 10°C by hour 27 and remained similar to the end of the test. Location B01, which is located in the bottom corner of the rig, was consistently 5°C less than any other location and is shown in Figure 6.15 as the lower black line.

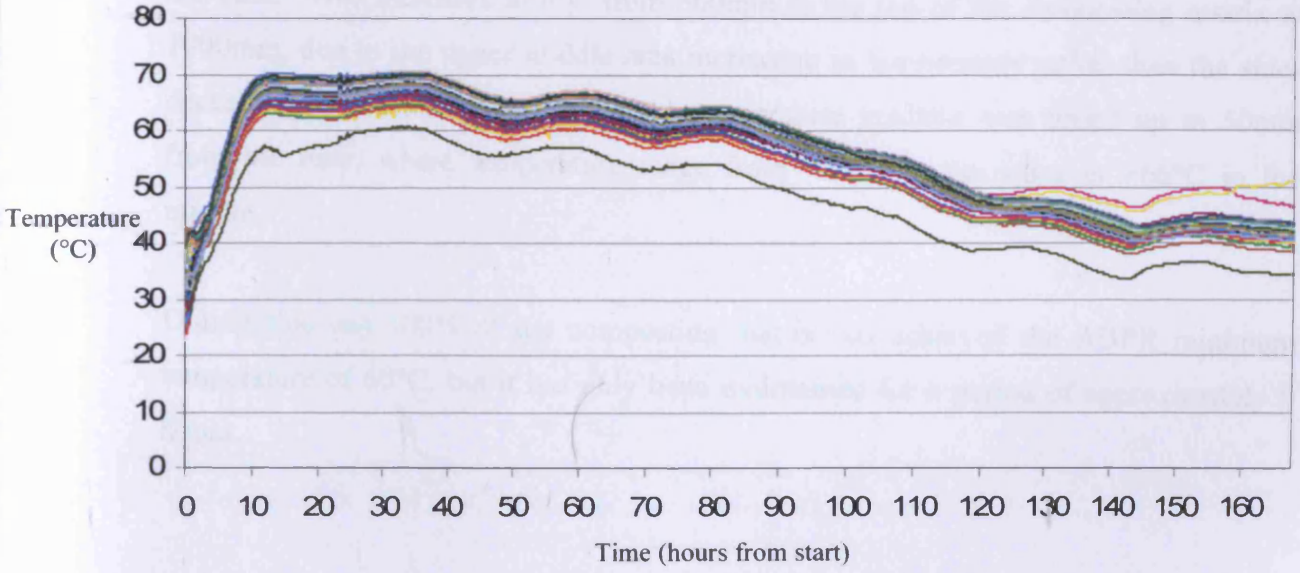

Figure 6.15 Temperature measured at 49 locations through out the composting matrix and the side wall over the 167 hour period of the test when the re-circulation rate was $40m^3hr^{-1}$.

The temperature data shown in Figure 6.15 does not clearly demonstrate how temperature is distributed through out the composting matrix. To demonstrate a snapshot of the temperature distribution, 2 dimmensional temperature profiles were constructed using the data recorded when temperature at location B01 was maximal at 60.7°C on hour 33. These profiles were constructed from relevant data to show the temperature profile through a vertical section in the centre of the composting matrix and the temperature profile on the rig side wall.

The temperature profile through the centre of the composting matrix demonstrates that there is a maximum vertical temperature gradient of <8°C in the middle, and only 4°C at the sides, as shown in Figure 6.16. The horizontal temperature gradient is less than 2°C in most places with a maximum of 4°C. Temperature generally increases as distance from the base increases in both the centre and the side wall profiles, though the actual temperatures recorded at the side wall are less than those found in the centre. Temperature varies between 64 and 72°C in the centre and between 60 and 68°C at the side wall, both demonstrating a temperature variation of 8°C, as shown in Figures 6.16 and 6.17.

The side wall temperature profile indicates that at 250mm horizontally from the sides there is a vertical temperature gradient of less than 2°C, whilst there is a 6°C variation at the sides. The minimum horizontal temperature gradient at the side wall was 4°C which occurs from less than 200mm up from the base to approximately 500mm up from the base. This increases to 6°C from 500mm to the top of the composting matrix at 1000mm, due to the upper middle area increasing in temperature rather than the sides decreasing. The maximum horizontal temperature gradient was found up to 50mm from the base, where temperature range from <62°C at the sides to >66°C in the middle.

During this test 100% of the composting matrix has achieved the ABPR minimum temperature of 60°C, but it has only been maintained for a period of approximately 6 hours.

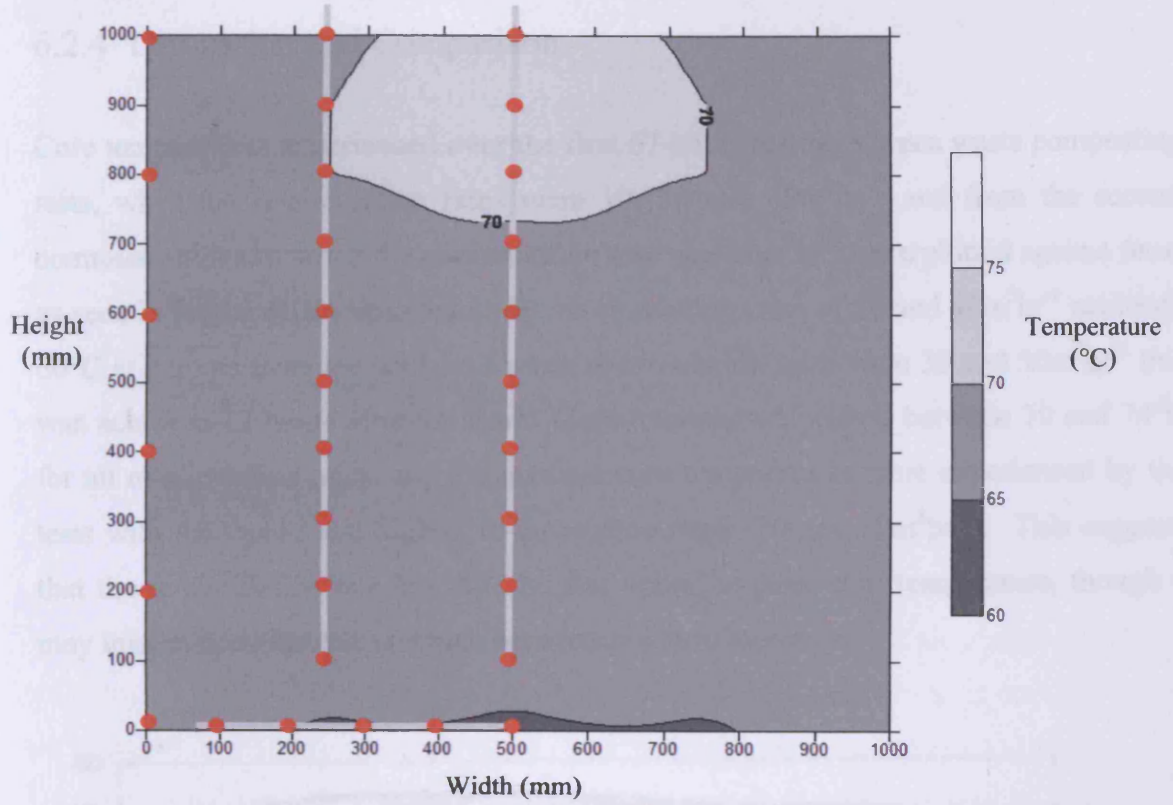

Figure 6.16 Temperature profile through centre of the composting matrix 33 hours after the start of the test when re-circulation rate was $40m^3hr^{-1}$. ● = Thermocouple locations used to construct the temperature profile.

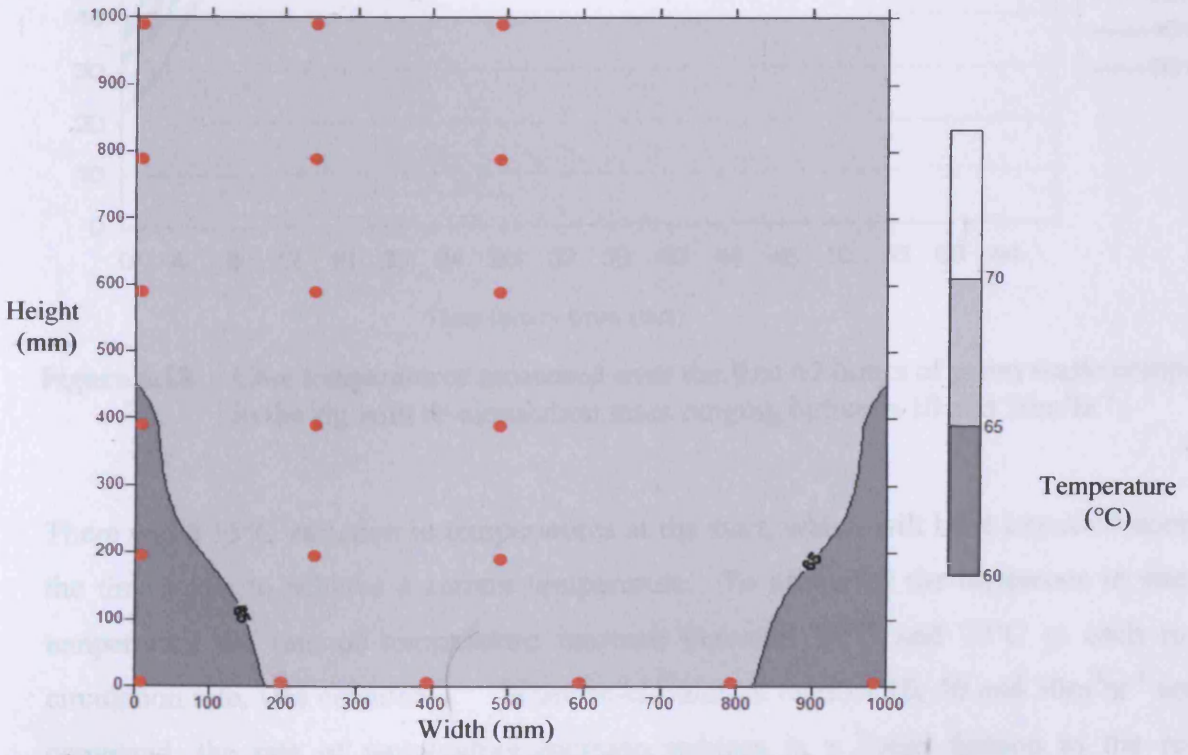

Figure 6.17 Temperature profile at the side wall of the rig, 33 hours after the start of the test when re-circulation rate was $40m^3hr^{-1}$. ● = Thermocouple locations used to construct the temperature profile.

6.2.4 Discussion and Comparison

Core temperatures experienced over the first 67 hours for the 3 green waste composting tests, when the re-circulation rates were 10, 30 and 40m^3hr^{-1}, and from the second commissioning test when the re-circulation rate was 50m^3hr^{-1} were plotted against time, as seen in Figure 6.18. Both tests with re-circulation rates of 10 and 40m^3hr^{-1} achieved 60°C at 7 hours from the start, and when re-circulation rates were 30 and 50m^3hr^{-1} this was achieved 12 hours after the start. Core temperature peaked between 70 and 74°C for all re-circulation rates, and the greatest core temperatures were experienced by the tests with the lowest and highest re-circulation rates (10 and 50m^3hr^{-1}). This suggests that the re-circulation rate has little impact upon the peak core temperature, though it may impact upon the rate at which core temperature increases.

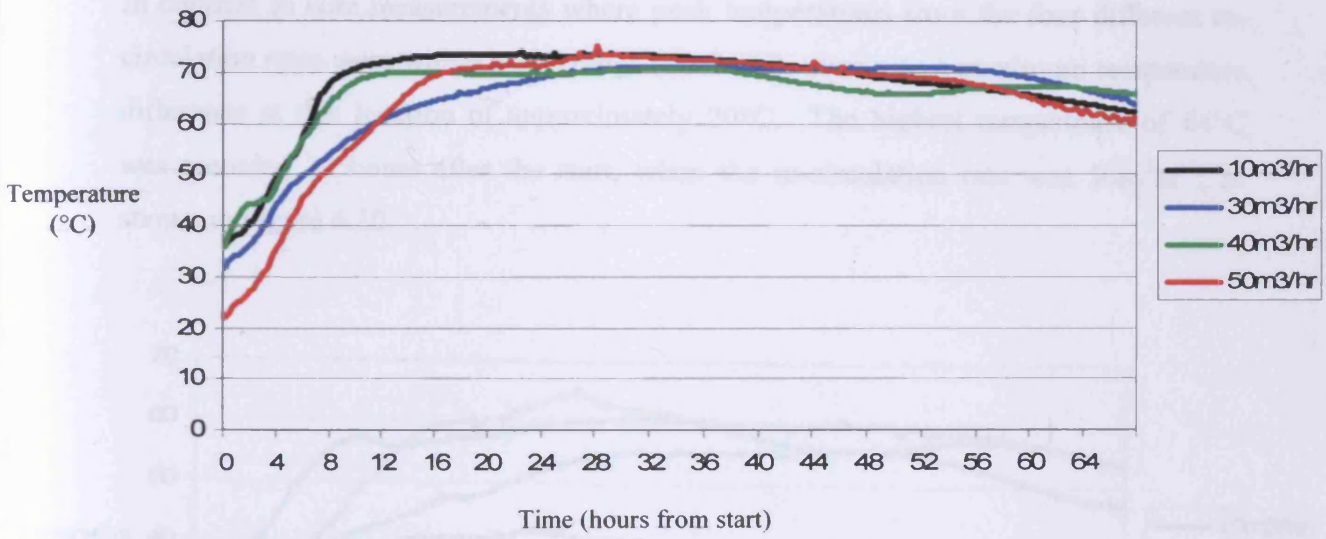

Figure 6.18 Core temperatures measured over the first 67 hours of green waste composting in the rig with re-circulation rates ranging between 10 and 50m^3hr^{-1}.

There was a 15°C variation in temperatures at the start, which will have impacted upon the time taken to achieve a certain temperature. To allow for the difference in start temperature the rate of temperature increase between 36°C and 70°C at each re-circulation rate, was calculated. When re-circulation rates of 10, 40 and 50m^3hr^{-1} are compared, the rate of temperature increase reduces in a linear fashion as the re-circulation rate increases. This is not true when the re-circulation rate of 30m^3hr^{-1} is taken into account, as shown in Figure 6.19.

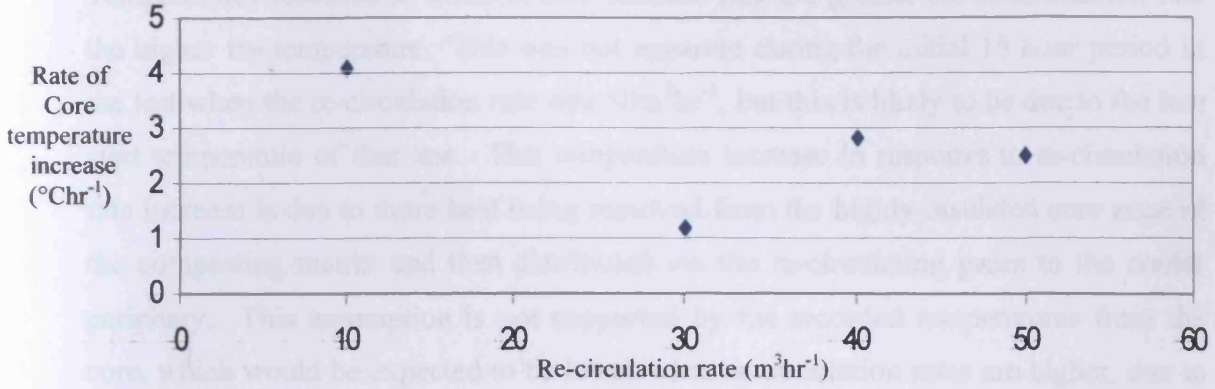

Figure 6.19 Rate of core temperature increase in °C per hour at different re-circulation rates.

Temperatures recorded at location B01, which was the location of the lowest recorded temperatures in each test, were plotted against time for the first 67 hours of each test. In contrast to core measurements where peak temperatures from the four different re-circulation rates were within a 4°C range (70-74°C), there was a maximum temperature difference at this location of approximately 20°C. The highest temperature of 64°C was recorded 30 hours after the start, when the re-circulation rate was $50m^3hr^{-1}$, as shown in Figure 6.20.

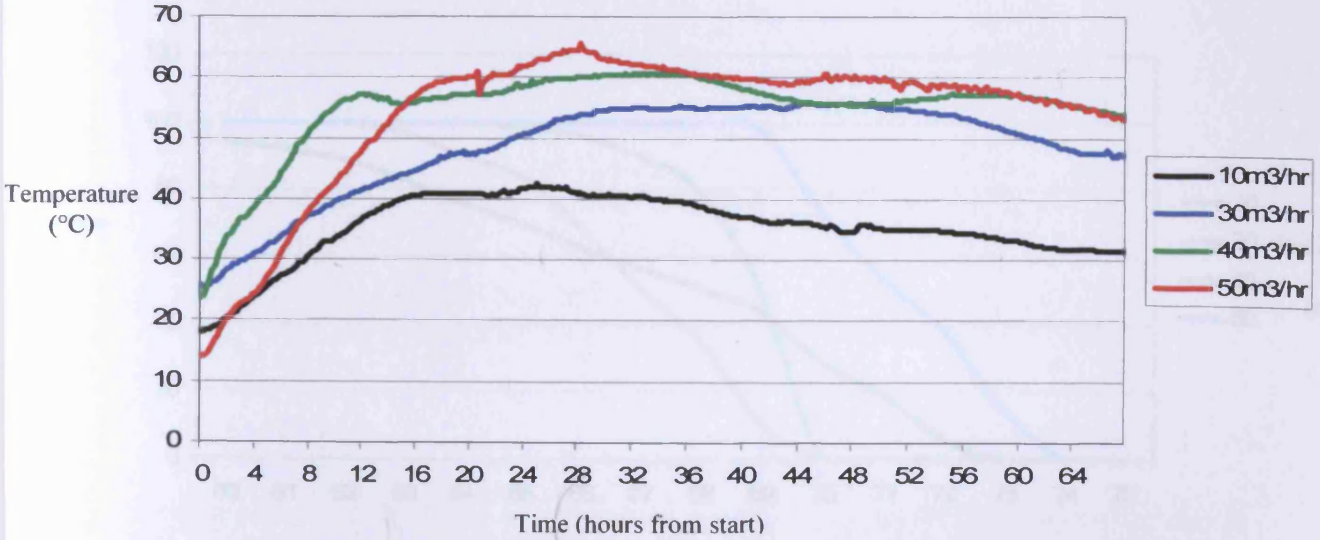

Figure 6.20 Temperatures recorded at location B01(bottom corner) over a 67 hour period from four different tests with re-circulation rates of between 10 and 50 m^3hr^{-1}.

Temperatures recorded at location B01 indicate that the greater the re-circulation rate the higher the temperature. This was not apparent during the initial 15 hour period in the test when the re-circulation rate was $50m^3hr^{-1}$, but this is likely to be due to the low start temperature of that test. This temperature increase in response to re-circulation rate increase is due to more heat being removed from the highly insulated core zone of the composting matrix and then distributed via the re-circulating gases to the cooler periphery. This assumption is not supported by the recorded temperatures from the core, which would be expected to be lower when re-circulation rates are higher, due to higher heat removal rates from this area.

The core temperatures demonstrated in Figure 6.18 only show the temperature at one point within the centre of the composting matrix. To gain further understanding of the effect of re-circulation rate on temperature distribution within the composting matrix, a series of temperature profiles, similar to those shown in Figures 6.4, 6.10 and 6.16 were constructed covering a vertical section across the centre of the matrix. The Surfer software package used to construct these profiles allowed the proportion of the profile greater than a certain temperature to be calculated. These calculations were made for each re-circulation rate, at 1°C intervals, from 60 to 75°C, and the results are show in Figure 6.21.

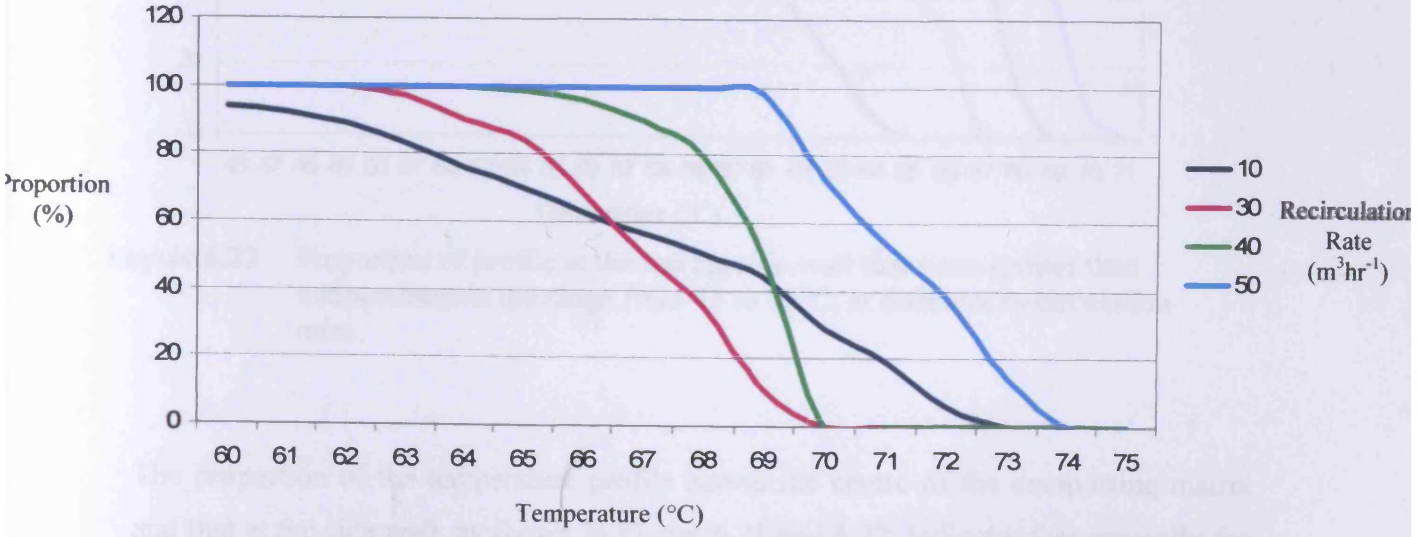

Figure 6.21 Proportion of profile through the centre of the test rig greater than temperatures in the range from 60 to 75°C, at different re-circulation rates.

When re-circulation rates were 30, 40 and 50m^3hr^{-1}, the greater the re-circulation rate the greater the proportion of the composting matrix is above the temperatures through out the range. This is also true when the re-circulation rate was 10m^3hr^{-1} from 60 to 66°C, but above this temperature the relationship changed. All of this section of the composting matrix was greater than 69°C with a recirculation rate of 50m^3hr^{-1}, 64°C at 40m^3hr^{-1}, 62°C at 30m^3hr^{-1} and when the re-circulation rate was 10m^3hr^{-1} 60°C was not achieved at any point.

This process was repeated using data recorded at the test rig side wall, and demonstrates the proportion of the compost matrix at the side wall that is above temperatures in the range from 45 to 75°C, as shown in Figure 6.22. At the side wall it is generally true that the higher the re-circulation rate the greater the proportion of the profile is above the measured temperatures, across the range.

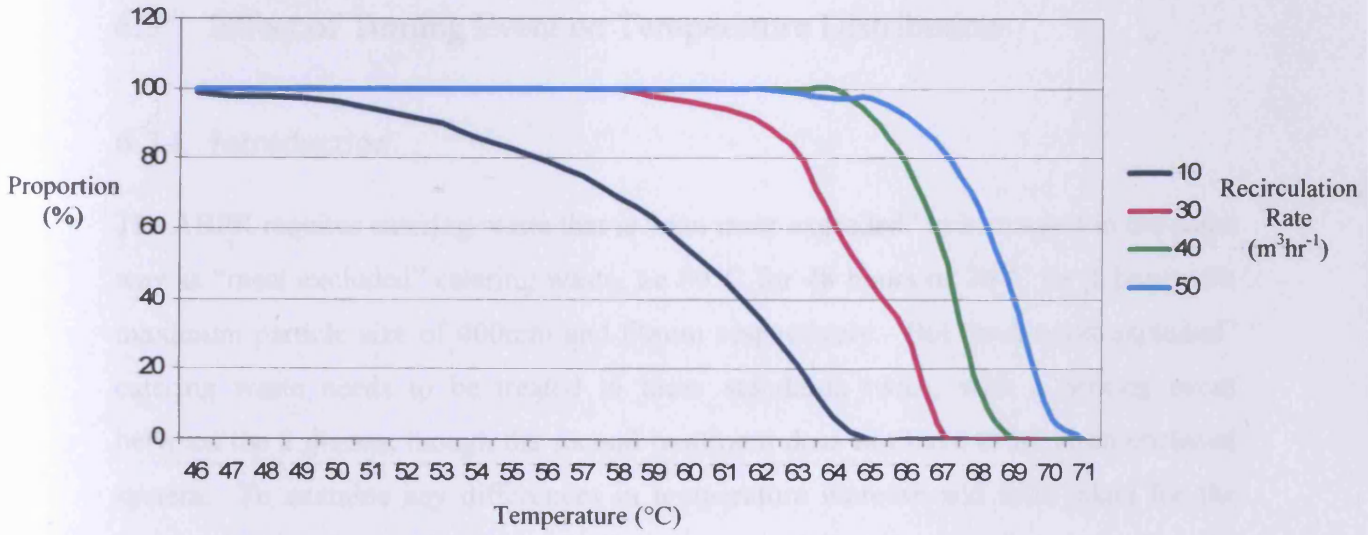

Figure 6.22 Proportion of profile at the test rig side wall that were greater than temperatures in the range from 45 to 75°C, at different re-circulation rates.

The proportion of the temperature profile across the centre of the composting matrix and that at the side wall, as shown in Figure 6.21 and 6.22, indicates that generally the greater the re-circulation rate the greater the temperature. This is true within the composting matrix and at the matrix periphery.

It was demonstrated in Chapter 3 that respiration reduces at the rate of 0.28 to 0.29kg$CO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, in the range of 66°C to 70°C, in a green waste windrow. As the core temperature in all of the re-circulation rate tests was greater than 66°C, then increasing the re-circulation rate would reduce the core temperature and in doing so increase the respiration rate and therefore the total heat energy produced. Therefore, transferring heat energy from the core to the periphery, increased respiration rate by increasing temperature at the periphery and decreasing temperature in the core. Although total heat loss will have increased by transferring heat from the highly insulated core to the periphery where heat is lost at a greater rate, the respiration rate increase has the knock on effect of producing more heat. It is logical to assume that as the tests with higher re-circulation rates had similar core temperatures but greater periphery temperatures, the increase in heat production is greater than the increase in heat loss.

6.3 Effect of Turning Event on Temperature Distribution

6.3.1 Introduction

The ABPR requires catering waste that is "non meat excluded" to be treated in the same way as "meat excluded" catering waste, i.e 60°C for 48 hours or 70°C for 1 hour with maximum particle size of 400mm and 60mm respectively. But "non meat excluded" catering waste needs to be treated to these standards twice, with a mixing event between the 2 phases, though the second treatment does not have to be in an enclosed system. To examine any differences in temperature increase and time taken for the composting matrix to gain the required temperature following a turning event, 2 green waste tests were run in the rig.

The process management system was the same for both tests and following 100% of the compost matrix reaching the target temperature in the first phase the rig was emptied and re-filled with the same waste. This was done to imitate a turning event, and the waste was then managed in the same way for the second phase to allow the second phase of treatment to be compared to the first phase.

6.3.2 Method

Following the test described in Section 6.2 when the re-circulation rate was $40m^3hr^{-1}$, the compost matrix was removed from the rig and then re-loaded. Following this turning event the process control system was set to manage CO_2 concentration between 8 and 10% with a re-circulation rate of $40m^3hr^{-1}$.

A further test was undertaken using $1m^3$ of freshly shredded green waste, which was loaded into the rig and the process control system was set to manage CO_2 concentration between 8 and 10% with a re-circulation rate of $40m^3hr^{-1}$. After the temperature had reached 60°C at location B01, which constantly recorded the lowest temperature, the matrix was emptied and re-loaded. The process control system was left unchanged during the second phase of treatment.

6.3.3 Results

Following the first phase of treatment when the maximum core temperature was 70°C and the temperature at location B01 reached 60°C, which occurred between hours 30 and 40 in both cases, as shown in Figures 6.14 and 6.15. The matrix was emptied and re-loaded into the rig.

The CO_2 concentration in the re-circulation system took 12 hours to increase from less than 2% at the start to the upper trigger level of 10%. It was then managed between the set limits of 8 and 10% until hour 21 when the set limits were changed to between 4 and 8%. Following this change CO_2 concentration reduced to 5% and increased slowly over a 3 hour period at the end of which the limits were changed to between 6 and 8%. CO_2 concentration remained between these set limits for a further 20 hours at which point the limits were changed to between 4 and 10%. From hour 70 to the end of the test at hour 110 during the second phase of treatment the rate of CO_2 production was less than the leakage rate from the vessel as concentration declined even though the control valves were shut, as shown in Figure 6.23. Core temperature during the same period increased from 27°C at the start to a peak of 59°C on hour 40, and then declined to approximately 45°C at the end of the test, as shown in Figure 6.24.

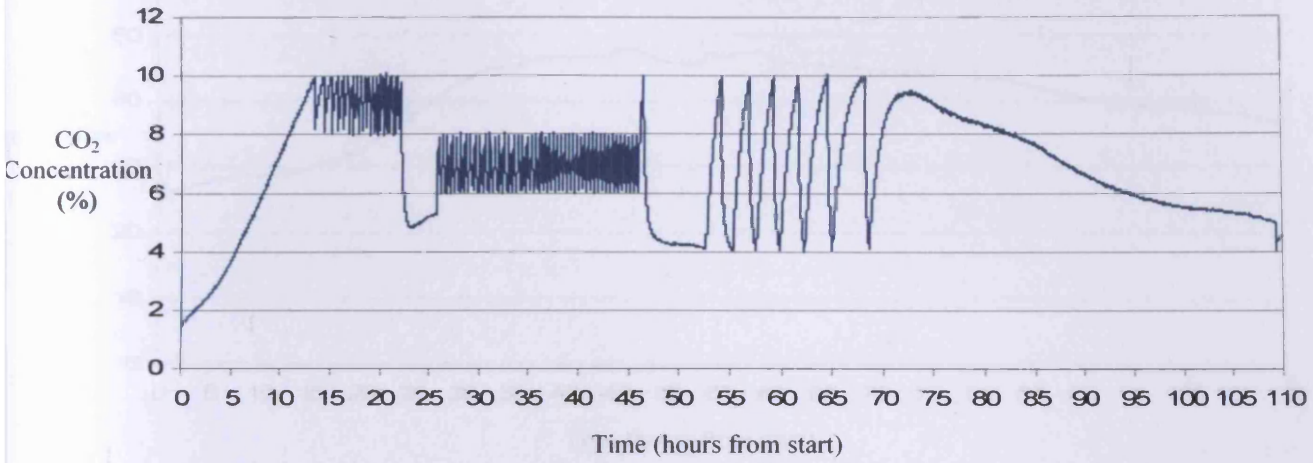

Figure 6.23 CO_2 concentrations in the re-circulating gases in the test rig, over the 110 hour period of the second phase of treatment.

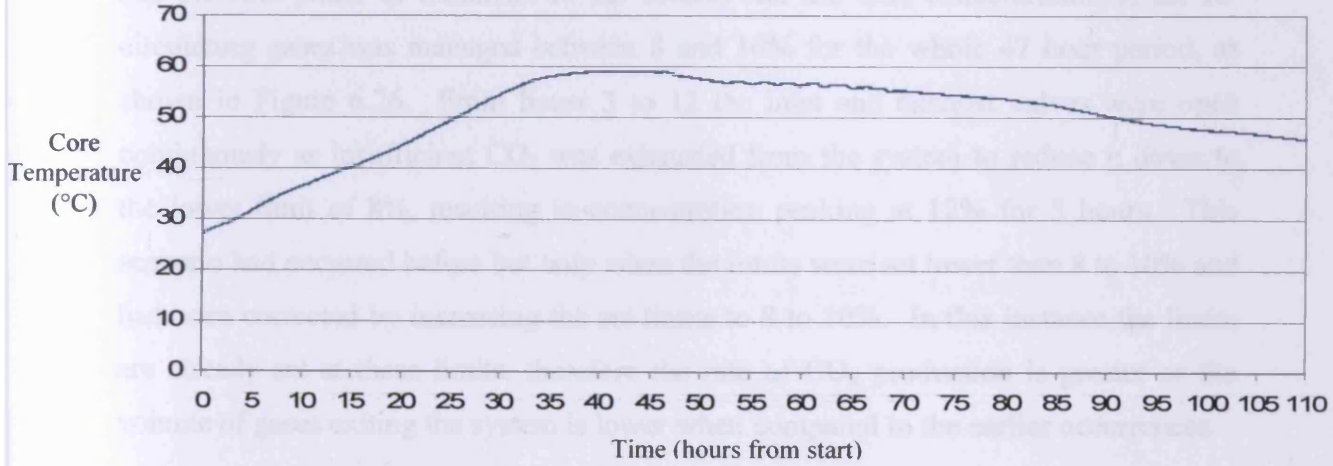

Figure 6.24 Core temperatures during the 110 hour period of the second phase of treatment.

The temperatures recorded at location B01 (bottom corner) indicate that the maximum temperature achieved during the second phase of treatment was 48°C. This was achieved 45 hours after the start, and after this time, temperature at this location declined to a low of 37°C at the end of the 110 hour period, as shown in Figure 6.25.

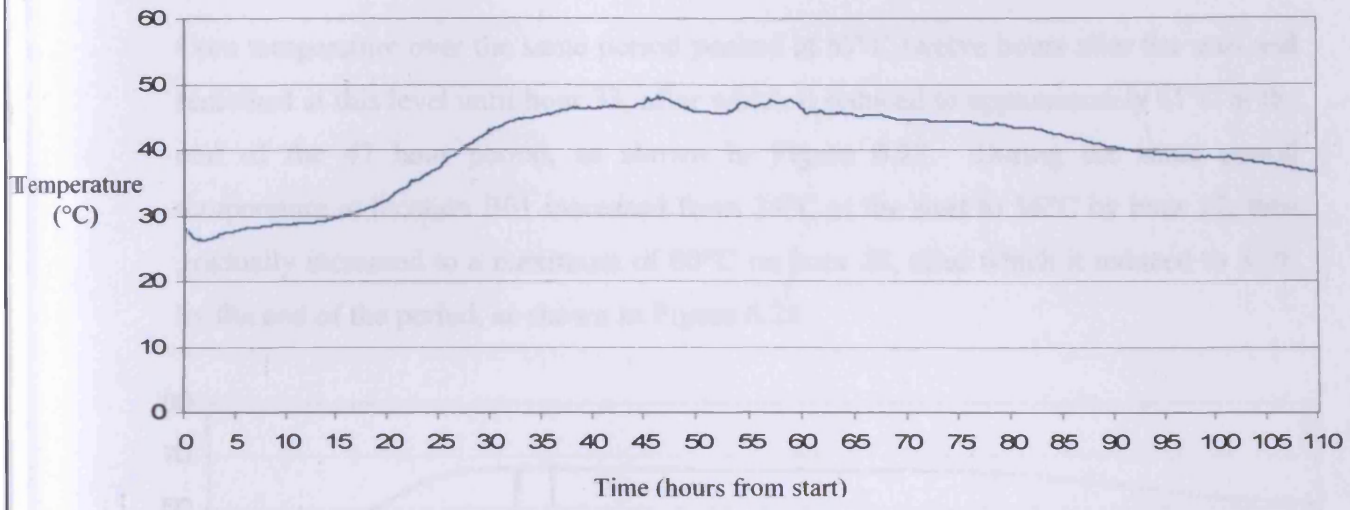

Figure 6.25 Temperature recorded at location B01 during the 110 hour period of the second phase of treatment.

For the first phase of treatment in the second test the CO_2 concentration in the re-circulating gases was managed between 8 and 10% for the whole 47 hour period, as shown in Figure 6.26. From hours 3 to 12 the inlet and exhaust valves were open continuously as insufficient CO_2 was exhausted from the system to reduce it down to the lower limit of 8%, resulting in concentration peaking at 12% for 5 hours. This scenario had occurred before but only when the limits were set lower than 8 to 10% and had been corrected by increasing the set limits to 8 to 10%. In this instance the limits are already set at these limits, therefore the rate of CO_2 production is greater or the volume of gases exiting the system is lower when compared to the earlier occurrences.

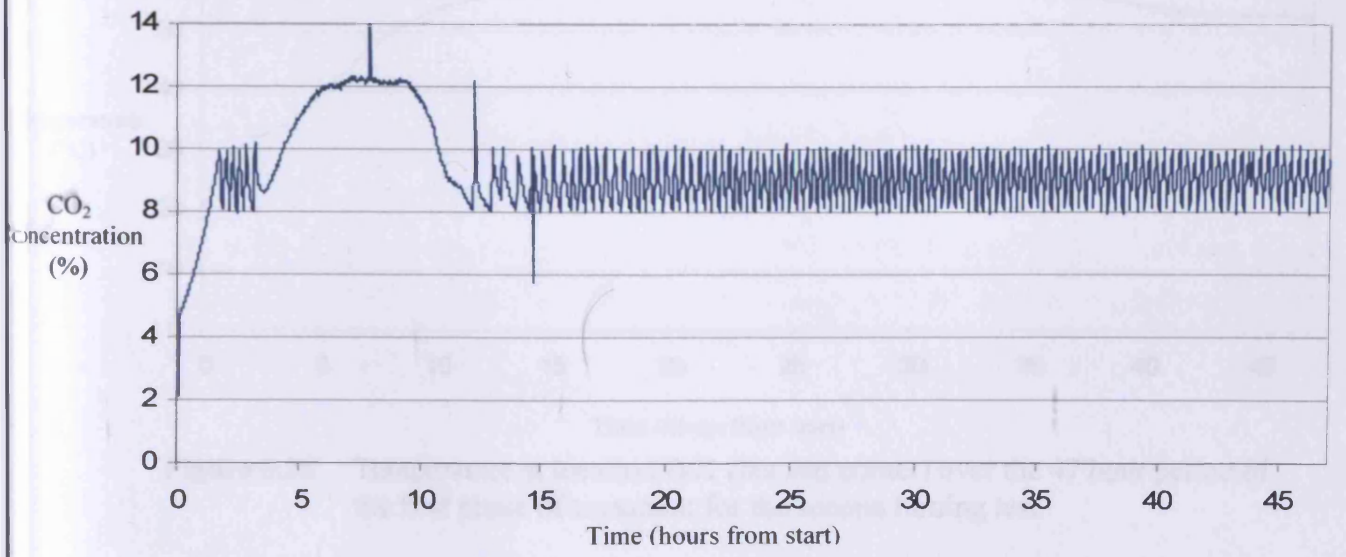

Figure 6.26 CO_2 concentrations in the re-circulating gases of the test rig, over the 47 hour period of the first phase of treatment in the second test.

Core temperature over the same period peaked at 67°C twelve hours after the start and remained at this level until hour 33, after which it reduced to approximately 61°C at the end of the 47 hour period, as shown in Figure 6.27. During the same period temperature at location B01 increased from 24°C at the start to 56°C by hour 12, then gradually increased to a maximum of 60°C on hour 28, after which it reduced to 53°C by the end of the period, as shown in Figure 6.28.

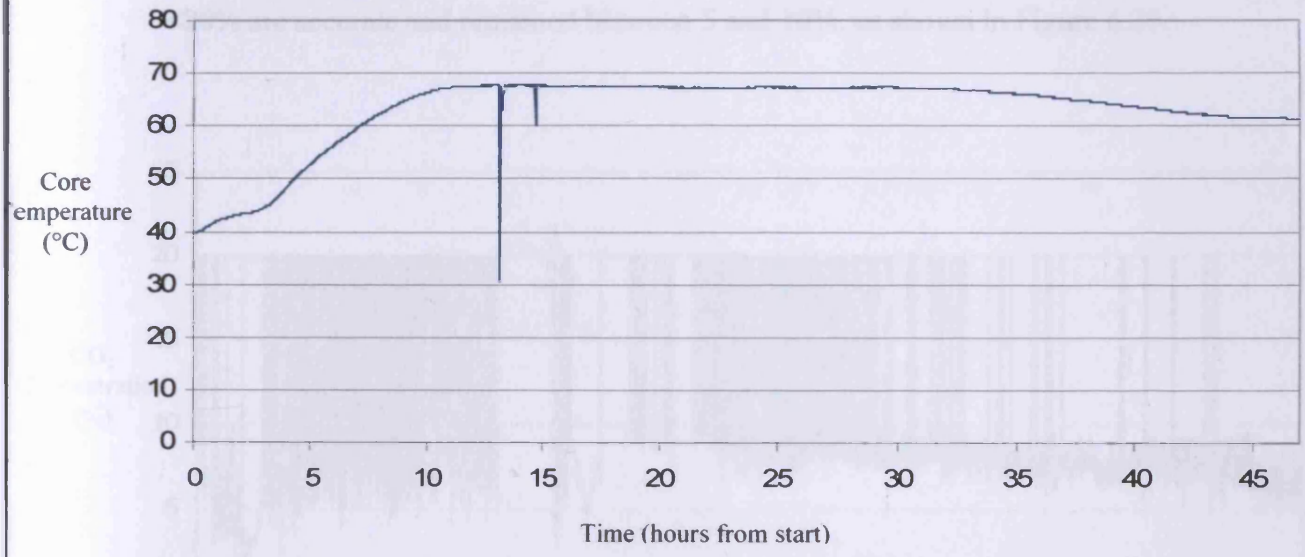

Figure 6.27 Core temperatures over the 47 hour period of the first phase of treatment for the second turning test.

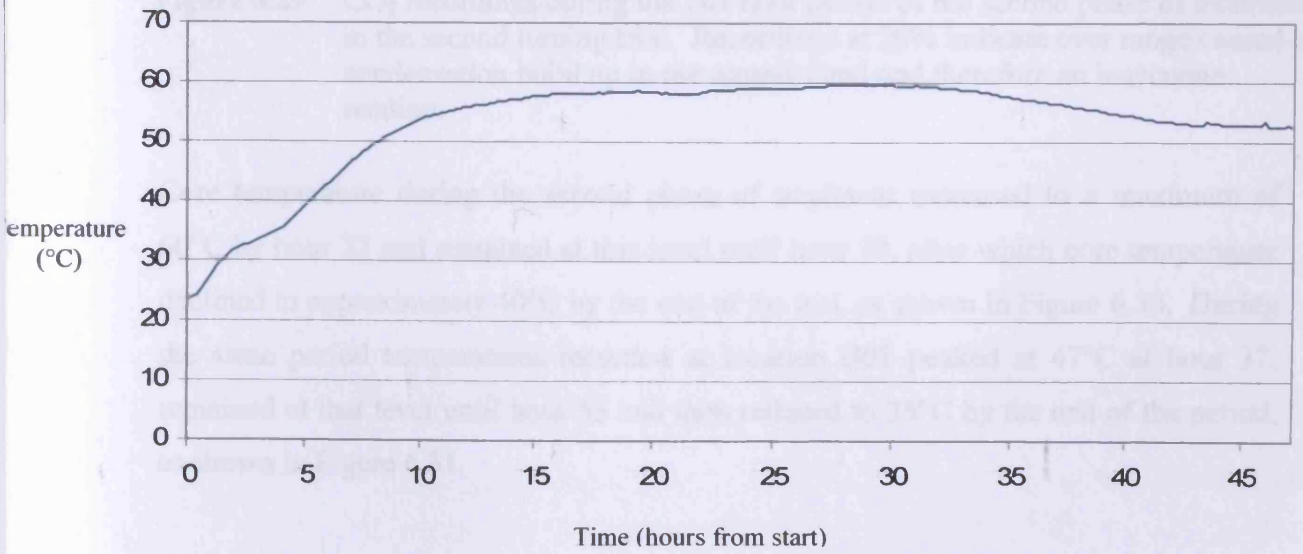

Figure 6.28 Temperature at location B01 (bottom corner) over the 47 hour period of the first phase of treatment for the second turning test.

The test rig was switched off for 24 hours, directly before the end of this period, and the compost matrix in the rig was removed and then reloaded. After reloading the re-circulation rate was re-set to $40m^3hr^{-1}$ and the CO_2 set limits remained between 8 and 10%. Unfortunately condensate periodically built up in the sample head, and when this occurred the system recorded readings of over range, which are recorded at 20%. Therefore readings of 20% were not a measure of actual gas concentration, but an indication that the probe was not operating correctly. Recorded CO_2 concentrations of <20% are accurate and remained between 5 and 10%, as shown in Figure 6.29.

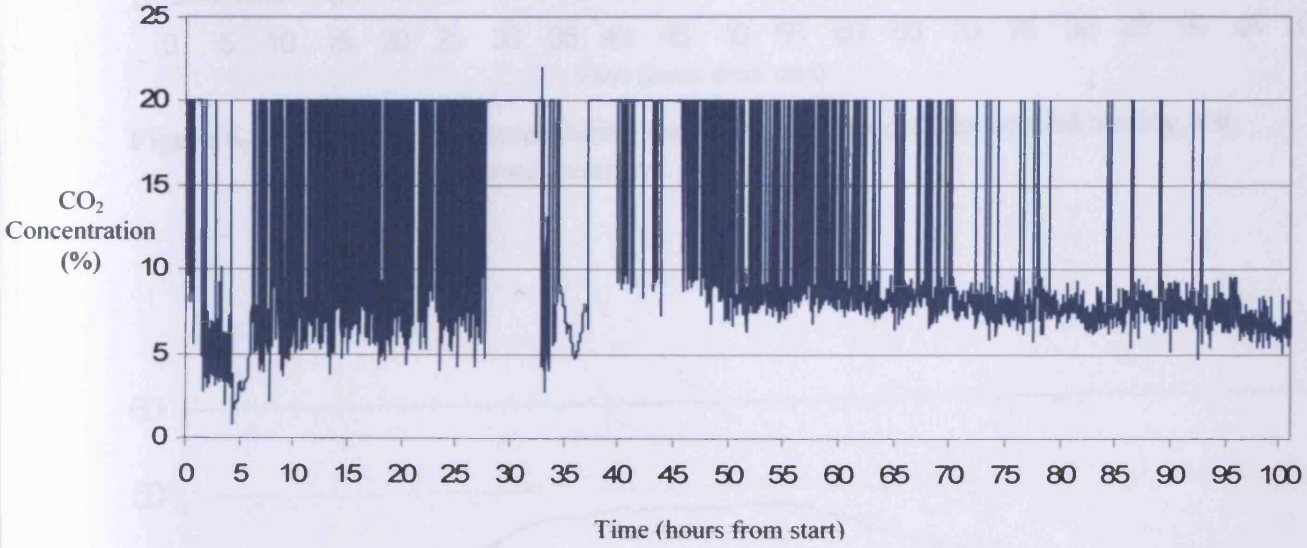

Figure 6.29 CO_2 recordings during the 101 hour period of the second phase of treatment in the second turning trial. Recordings at 20% indicate over range caused by condensation build up in the sample head and therefore an inaccurate reading.

Core temperature during the second phase of treatment increased to a maximum of 60°C by hour 32 and remained at this level until hour 57, after which core temperature declined to approximately 40°C by the end of the test, as shown in Figure 6.30. During the same period temperatures recorded at location B01 peaked at 47°C at hour 37, remained at that level until hour 55 and then reduced to 35°C by the end of the period, as shown in Figure 6.31.

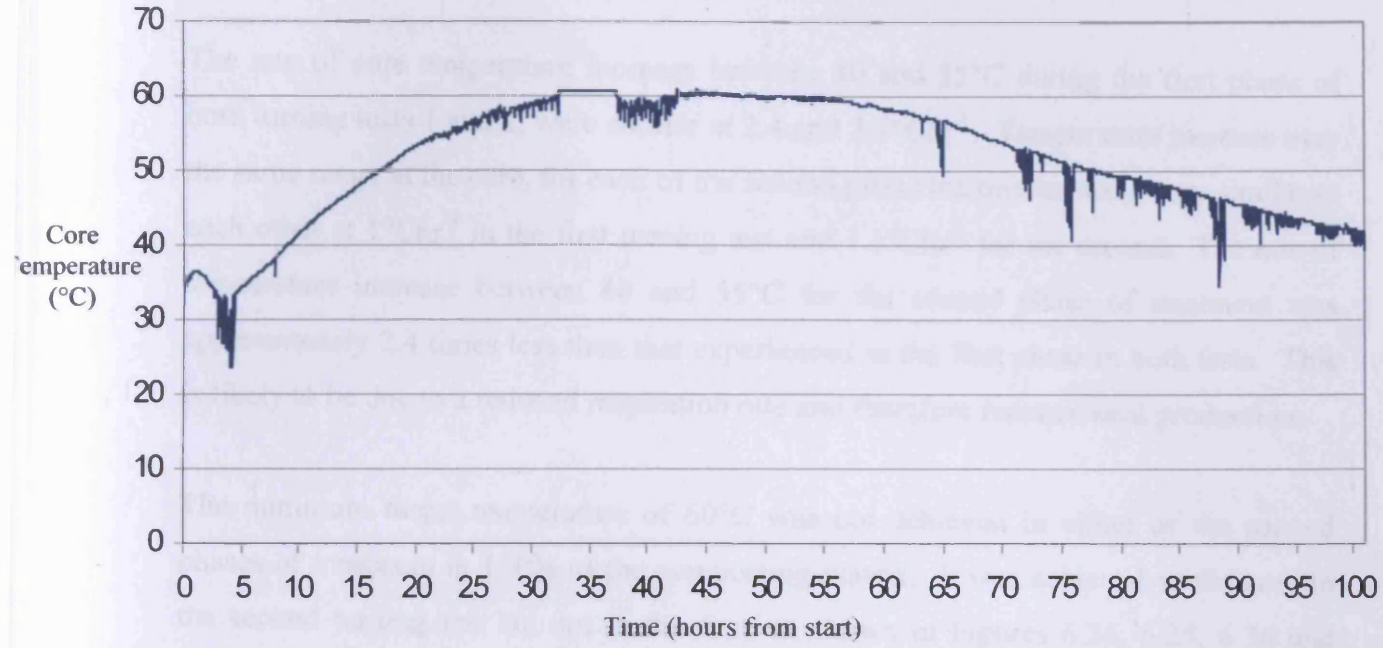

Figure 6.30 Core temperatures during the 101 hour period of the second turning test, during the second treatment phase.

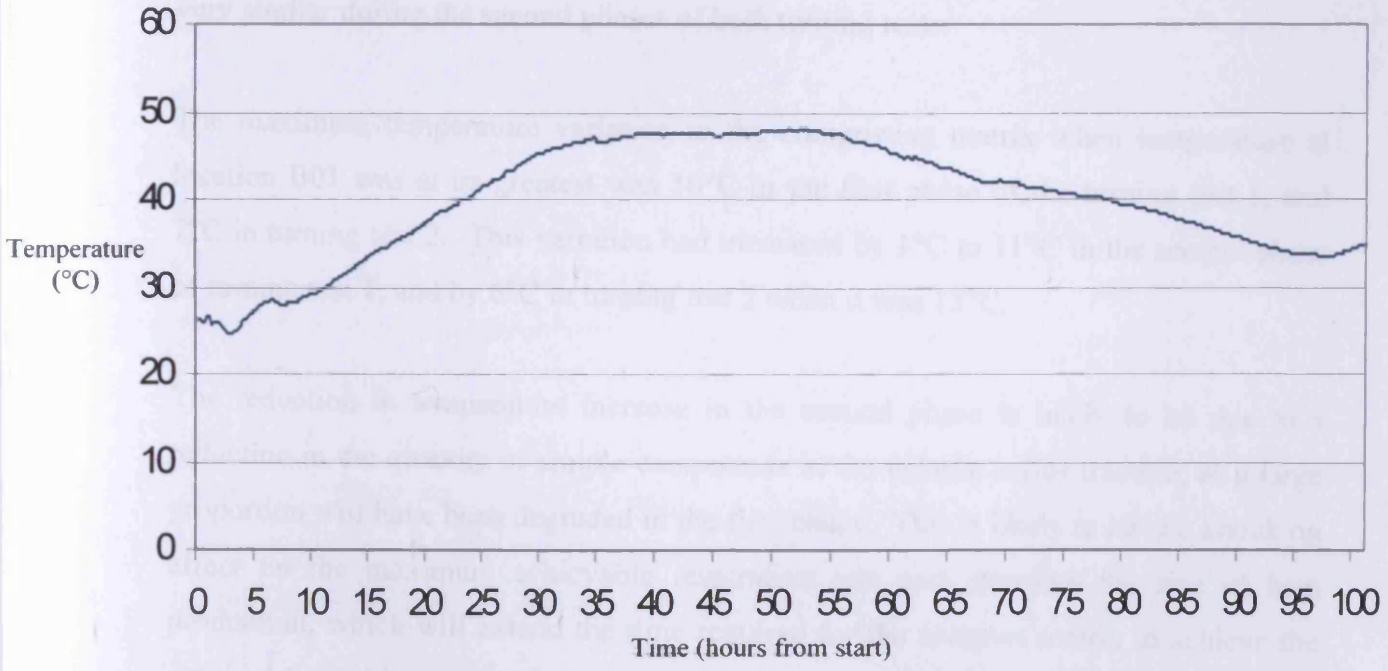

Figure 6.31 Temperatures recorded at location B01 during the second treatment phase of the second turning test, over the 101 hour test period.

6.3.4 Discussion and Comparison

The rate of core temperature increase between 40 and 55°C during the first phase of both turning tests 1 and 2, were similar at 2.4 and 2.7°Chr^{-1}. Temperature increase over the same range at the core, for each of the second phase treatments, were very similar to each other at 1°Chr^{-1} in the first turning test and 1.1°Chr^{-1} for the second. The rate of temperature increase between 40 and 55°C for the second phase of treatment was approximately 2.4 times less than that experienced in the first phase in both tests. This is likely to be due to a reduced respiration rate and therefore reduced heat production.

The minimum target temperature of 60°C was not achieved in either of the second phases of treatment in 100% of the composting matrix. It was achieved in the core in the second turning test but not in the first, as shown in Figures 6.24, 6.25, 6.30 and 6.31. Although the CO_2 concentration in the re-circulating gases was not controlled between the set limits during phase 2 of the second test. When the system was operating correctly the CO_2 concentration was between 5 and 10% which is within the overall limits (4 to 10%) which had been shown to promote high temperatures whilst reducing heat loss. The temperature increase and peak temperatures achieved were very similar during the second phases of both turning tests.

The maximum temperature variation in the composting matrix when temperature at location B01 was at its greatest was 10°C in the first phase of the turning test 1, and 7°C in turning test 2. This variation had increased by 1°C to 11°C in the second phase of turning test 1, and by 6°C in turning test 2 when it was 13°C.

The reduction in temperature increase in the second phase is likely to be due to a reduction in the quantity of simple compounds in the volatile solids fraction, as a large proportion will have been degraded in the first phase. This is likely to have a knock on effect on the maximum achievable respiration rate and therefore the rate of heat production, which will extend the time required for the compost matrix to achieve the required temperatures in the second phase. The respiration rate during these second phases is analysed in the following section, which may indicate the reason for the differences.

6.4 Respiration Rate Analysis of Green Waste Trials in the Test Rig

6.4.1 Introduction

As previously stated in Chapter 3 there is at present no widely used method to measure the rate of decomposition in commercial composting systems. It has been demonstrated that the most accurate methods of determining the rate of decomposition in small scale laboratory based trials is to measure the rate of activity of the microbial population (Cathcart et al, 1986, Cronje et al, 2004, Suler and Finstein, 1977, MacGregor et al 1981, Mari et al, 2003). Micro-organisms like humans consume oxygen and evolve carbon dioxide and produce heat energy when undertaking activity. Measuring any of these three parameters will indicate the rate of decomposition.

The respiration rate of green waste composting in the test rig was calculated from the total mass of CO_2 exhausted from the system per day, and this mass was related to the volume of compost in m^3. To measure the effect of time, temperature and turning events on microbial activity, the respiration rate from a number of the green waste tests in the rig are described.

6.4.2 Methodology

The rate of CO_2 production in the composting matrix was calculated in 2 ways. The first method could only be employed when the inlet and exhaust valves were open continously. This occurred when CO_2 production was greater than could be exhausted from the re-circulating gases, leading to the concentration not reducing to the lower set limit at which the valves were shut, resulting in a constant volume of gases being exhausted. The volume of CO_2 produced was calculated from its concentration in the re-circulation system and the total volume of gases exhausted from the system. The volume of gases exhausted from the system was assumed to be equal to the volume of air entering the system through the inlet pipe which was measured manually periodically though out each test.

The other method was to measure the total volume of gases exhausted over the period between the inlet and exhaust valves opening and shutting, this period is demonstrated between lines B and C in Figure 6.32. This along with the average CO_2 concentration in the exhaust gases, again calculated by assuming the manual recordings of air entering the inlet pipe were the same as that exiting the system, whilst the valves were open, allowed the total volume of CO_2 exhausted to be calculated. The volume of CO_2 exhausted was determined to be equal to the total produced since the valves were last open, which is the period between lines A and C in Figure 6.32.

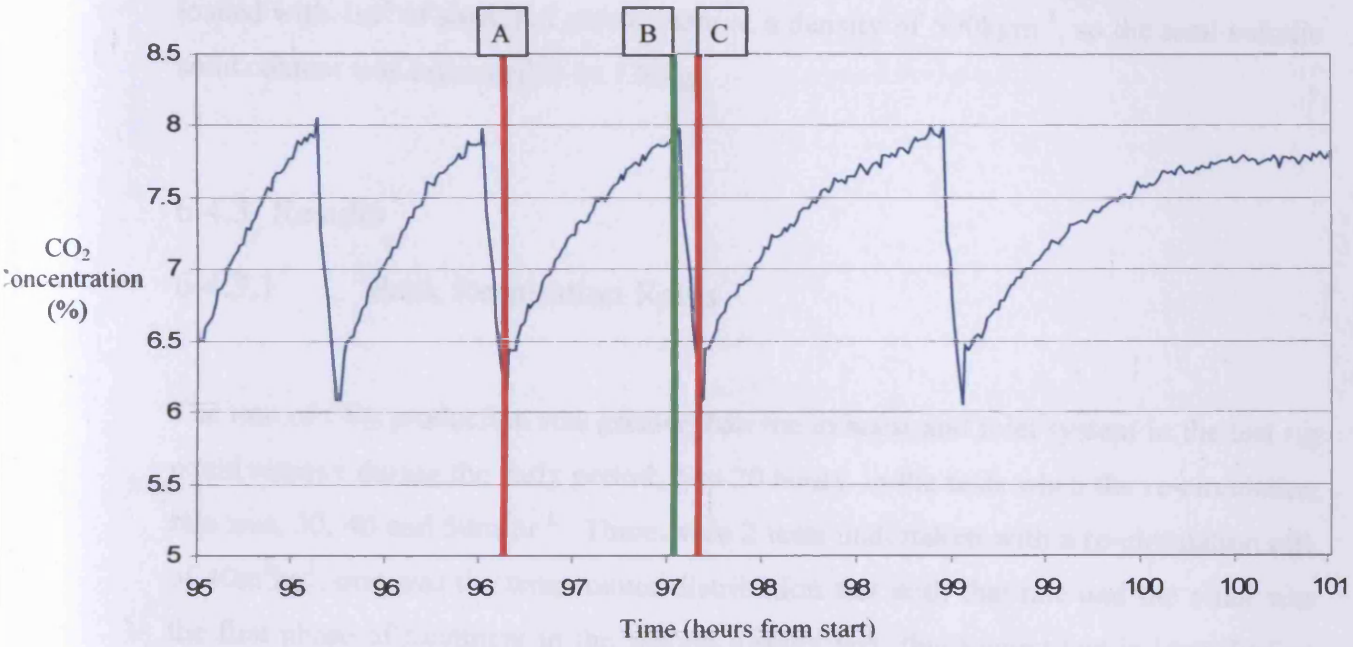

Figure 6.32 CO_2 concentrations in the re-circulation system of the test rig. Line A marks the start of a period, line B indicates the inlet and exhaust valves opening and line C indicates the valves shutting and the end of a period.

This was repeated for three consecutive peaks and troughs for each calculation of respiration rate using this method. Except when the frequency of peaks and troughs were reducing rapidly, as demonstrated in Figures 6.7 and 6.13. In these circumstances each peak and trough was calculated separately so that the rate of change could be demonstrated.

The volume of CO_2 produced in m^3 was converted to a mass in kilograms by multiplying by 1.65, which is the density of CO_2 at 60°C. The mass of CO_2 produced during the period was divided by the length of the period in minutes and then multiplied by the number of minutes in a day (1440) to give a mass of CO_2 produced per day. This mass was then divided by the volume of initial compost in the test rig ($1m^3$) to give a CO_2 production rate in relation to the volume of compost, and was expressed as $kgCO_2m^{-3}day^{-1}$. The green waste used for the tests was estimated to have the following characteristics based on previous measures. Moisture content was estimated to be 60% and volatile solids content was estimated to be 60% of dry matter. The test rig was loaded with $1m^3$ of shredded green waste at a density of $500kgm^{-3}$, so the total volatile solid content was estimated to be 120kg.

6.4.3 Results

6.4.3.1 Peak Respiration Rates

The rate of CO_2 production was greater than the exhaust and inlet system in the test rig could remove during the early period, 3 to 20 hours, in the tests when the re-circulation rate was, 30, 40 and $50m^3hr^{-1}$. There were 2 tests undertaken with a re-circulation rate of $40m^3hr^{-1}$, one was the temperature distribution test with that rate and the other was the first phase of treatment in the second turning test, this second test is identified as 40(2). The respiration rate during these periods was the maximum for each test, and the period varies for each re-circulation rate.

The test with a re-circulation rate of $30m^3hr^{-1}$ showed a maximum respiration rate of $18kgCO_2m^{-3}day^{-1}$ at 6 and 16 hours after the start. The period of continuous exhaust was from approximately 4 to 17 hours, with a period between 8 and 10 hours when CO_2 concentration became non-continuous due to the valves opening and closing. When the re-circulation rate was $40m^3hr^{-1}$(40) the peak respiration rate was nearly double at $34.89kgCO_2m^{-3}day^{-1}$, and it remained close to this rate from 6 to 10 hours. The measured period for this test was between 4 and 12 hours, and respiration rate was approximately $24kgCO_2m^{-3}day^{-1}$ at the beginning and end of this period. The second test with a re-circulation rate of $40m^3hr^{-1}$ (40(2)) was recorded from 5 to 11 hours and

shows a peak rate of 30kgCO_2m^{-3}day^{-1} from 6 to 9 hours, reducing to 18kgCO_2m^{-3}day^{-1} by the end of the period. The test with a re-circulation rate of 50m^{3}hr^{-1} had 2 distinct peaks, one at approximately hour 5 of 22.8kgCO_2m^{-3}day^{-1} and a further one at hour 15 of 30kgCO_2m^{-3}day^{-1}, as shown in Figure 6.33.

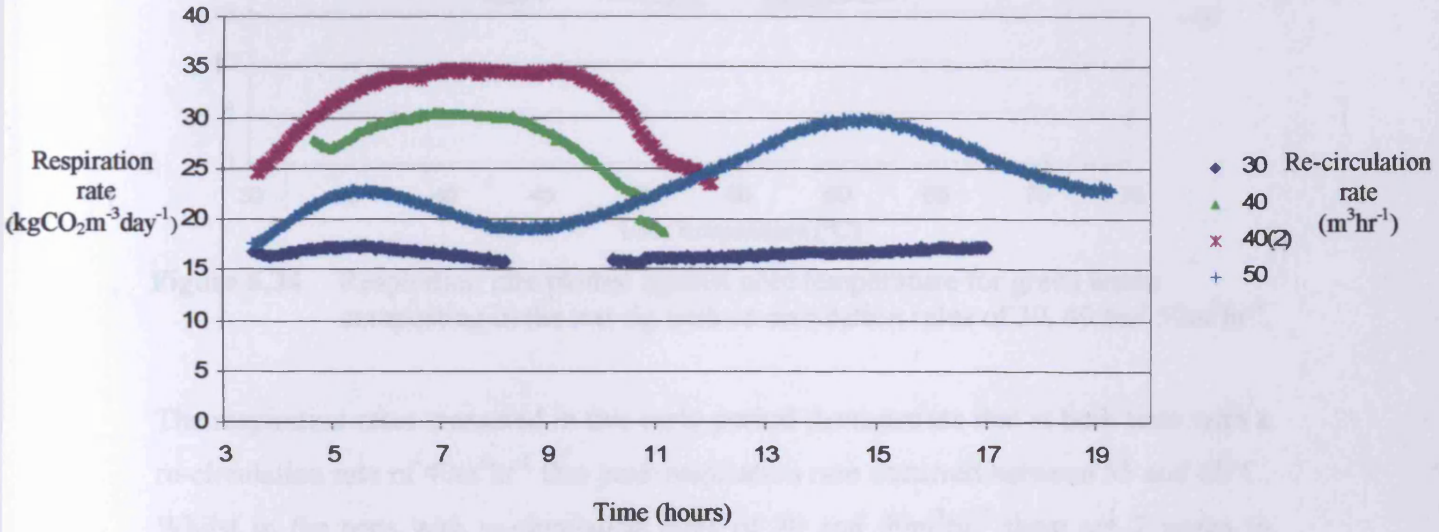

Figure 6.33 Respiration rate plotted against time for green waste composting in the test rig with re-circulation rates of 30, 40 and 50m^{3}hr^{-1}.

The respiration rates were then plotted against the temperature of the compost matrix core for each test, as shown in Figure 6.34. This demonstrated that the peaks in respiration rate when the re-circulation rate was 30m^{3}hr^{-1} occurred at approximately 47 and 64°C, and that over the temperature range, between 42 and 64°C respiration rate remained between 15.7 and 18kgCO_2m^{-3}day^{-1}. In the first test with a re-circulation rate of 40m^{3}hr^{-1} respiration rate peaked at approximately 30kgCO_2m^{-3}day^{-1} between 55 and 66°C, and reduced rapidly to less than 20kgCO_2m^{-3}day^{-1} from 66 to 68°C. During the second test when the re-circulation rate was 40m^{3}hr^{-1} respiration rate peaked at 34.5kgCO_2m^{-3}day^{-1} when core temperature was between 55 and 64°C, and reduced rapidly to 23kgCO_2m^{-3}day^{-1} when core temperature increased to 68°C. During the test when the re-circulation rate was 50m^{3}hr^{-1} there were 2 distinct peaks, the first of 22.8kgCO_2m^{-3}day^{-1} occurring at a core temperature of 44°C and the other, of 30kgCO_2m^{-3}day^{-1} at 65 to 66°C, and from 66 to 69°C respiration rate reduced rapidly to 23kgCO_2m^{-3}day^{-1}.

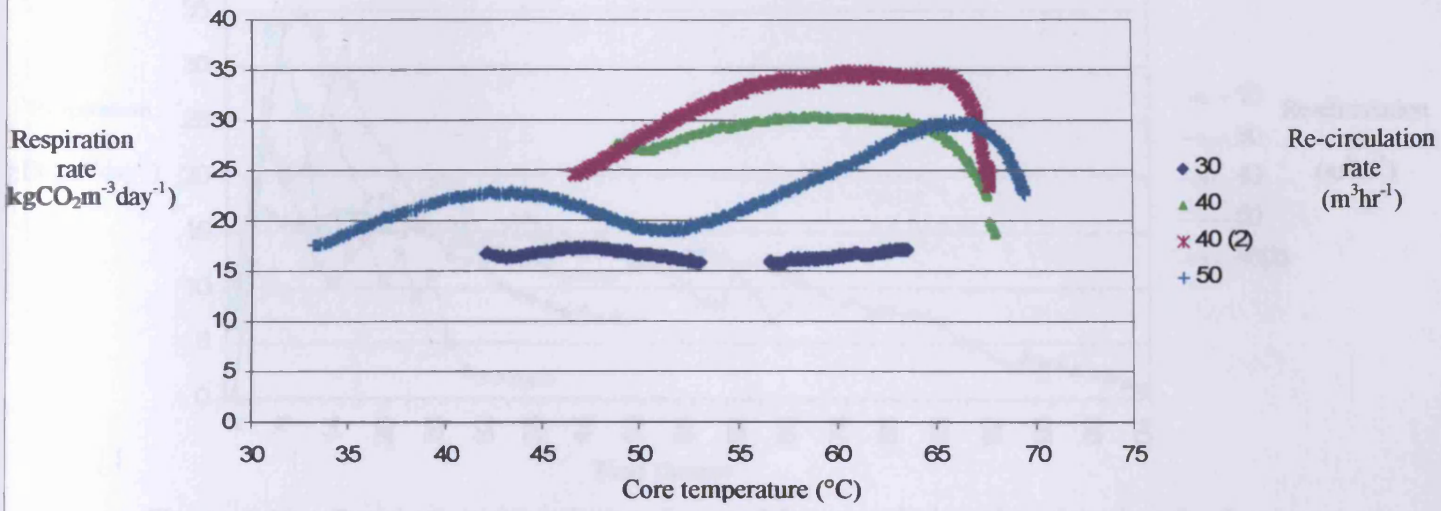

Figure 6.34 Respiration rate plotted against core temperature for green waste composting in the test rig with re-circulation rates of 30, 40 and 50m^3hr^{-1}.

The respiration rates measured in this early period demonstrate that at both tests with a re-circulation rate of 40m^3hr^{-1} that peak respiration rate occurred between 55 and 65°C. Whilst in the tests with re-circulation rates of 30 and 50m^3hr^{-1} there are 2 peaks in respiration rate, at 43 to 47°C and at 63 to 67°C. Respiration rates are only recorded for the tests with re-circulation rates of 40m^3hr^{-1} at core temperature above 46°C, so it is possible that a peak at the lower temperature range occurred but was not recorded. This assumption is supported by the data from the first test when the re-circulation rate was 40m^3hr^{-1} (40) as the respiration rate is decreasing between 48 and 50°C before it starts to increase after 50°C.

6.4.3.2 Long Term Respiration Rate Analysis

The respiration rate was calculated from the peaks and troughs that occur in CO_2 concentration due to the control valves opening and shutting, every 2 hours during each test. There are some periods in which there were failures in process control or recording equipment, in these instances no respiration rate could be calculated. The data from these calculations were plotted against time and are shown in Figure 6.35.

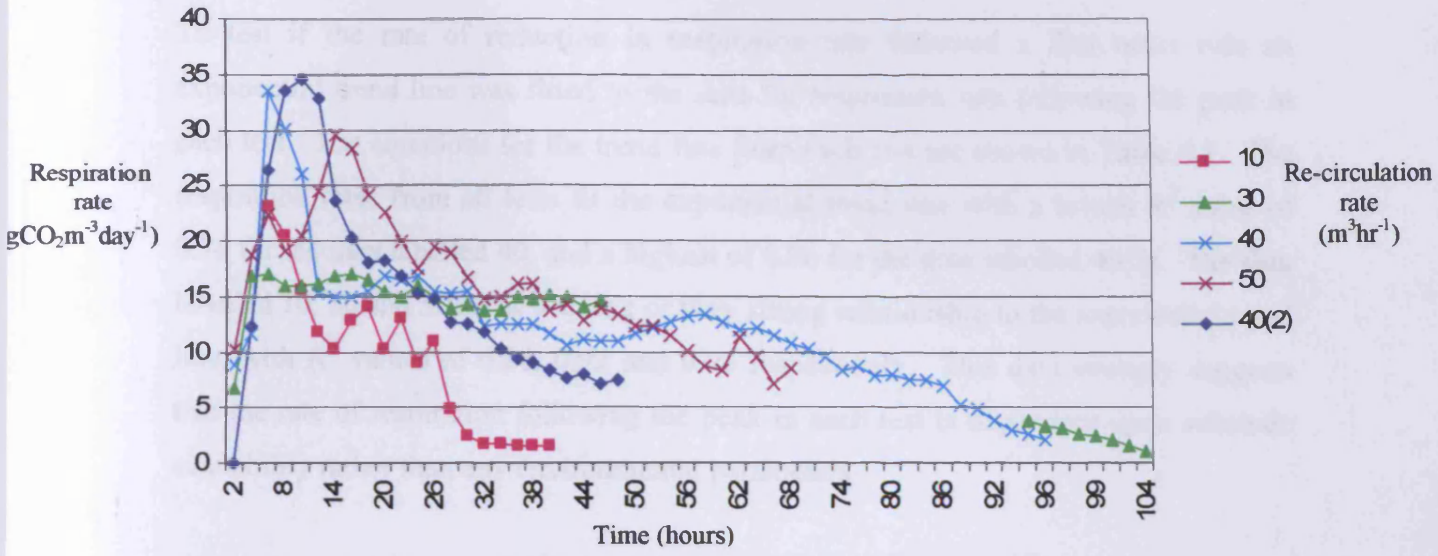

Figure 6.35 Respiration rate calculated every 2 hours and plotted against time for 5 different green waste trials with re-circulation rates from 10 to 50m^3hr^{-1}.

Both tests when the re-circulation rate was 40m^3hr^{-1}, 40 and 40(2), demonstrate the greatest peaks in respiration rate at 34.5$kgCO_2m^{-3}day^{-1}$ 6 hours from the start and 33.5$kgCO_2m^{-3}day^{-1}$ 10 hours after the start, respectively. When the re-circulation rate was 50m^3hr^{-1} the peak in respiration rate was less, at 29$kgCO_2m^{-3}day^{-1}$ and did not occur until 14 hours after the start. The peak was smaller again in the test with a re-circulation rate of 10m^3hr^{-1}, at 23$kgCO_2m^{-3}day^{-1}$ 6 hour from the start. During the test with a re-circulation rate of 30m^3hr^{-1} there was no obvious peak in respiration rate, but it did increase at a similar rate to the other tests but reached a maximum of only 17$kgCO_2m^{-3}day^{-1}$ at hour 4. It then remained between 14 and 17$kgCO_2m^{-3}day^{-1}$ for the following 40 hours.

All re-circulation rates peaked within the first 14 hours and then reduced. The rate of reduction was reducing over time suggesting a first order rate of reduction. The 10m^3hr^{-1} test reduced to a low of 2$kgCO_2m^{-3}day^{-1}$ 32 hours after the start of the test, and the tests at 40m^3hr^{-1} and 30m^3hr^{-1} reduce to a similar level at between 96 and 98 hours. Test 40(2) and 50 were not recorded after hours 50 and 70 respectively, but they both follow a similar reduction curve prior to this, suggesting that the respiration rate in these 2 tests would also reduce to similar levels in the same time period. The reasons for the test with a re-circulation rate of 10m^3hr^{-1} reducing to 2$kgCO_2m^{-3}day^{-1}$ after 32 hours, a third of the time for tests 30 and 40m^3hr^{-1} after the start of the test are not clear but it is unlikely to be stabilised in such a short period.

To test if the rate of reduction in respiration rate followed a first order rule an exponential trend line was fitted to the data for respiration rate following the peak in each test. The equations for the trend line from each test are shown in Table 6.2. The respiration rates from all tests fit the exponential trend line with a lowest R^2 value of 0.76 for the data labelled 40, and a highest of 0.96 for the data labelled 40(2). The data labelled 10, 30 and 50 show a strong or very strong relationship to the exponential trend line, with R^2 values of 0.86, 0.92 and 0.93 respectively. This data strongly suggests that the rate of respiration following the peak in each test is dependent upon substrate availability rather than any environmental parameters.

Table 6.2 The exponential trend line equation and R^2 value when the respiration rate (K) was reducing, against time in hours (th), for each green waste composting test.

Test (m^3hr^{-1})	Trend line equation	R^2 value
10	$K = 46.94e^{-0.087th}$	0.86
30	$K = 33.06e^{-0.026th}$	0.92
40	$K = 26.74e^{-0.018th}$	0.76
40(2)	$K = 38.93e^{-0.04th}$	0.96
50	$K = 34.37e^{-0.021th}$	0.93

The core temperatures for each test were plotted against time and are presented in Figure 6.34. The rate of temperature increase in the first 14 hour period was very similar in tests labelled 10, 40 and 40(2), and the data labelled 50 had a similar rate but started from a lower temperature, but the data labelled 30 had a noticeably reduced rate from 50 to 70°C. The data labelled 40 shows a lower and more variable core temperature than the other tests from 14 to 34 hours and the data from 40(2) started reducing at a greater rate than the others from hour 34. Peak temperatures in all are between 68 and 72°C and occur in all tests between 14 and 34 hours, and in all tests the core temperature was reducing within 40 hours of the start. Although no single test has complete data, the general rate of reduction from 40 hours to the end of the period approximately 60 hours later, is likely to follow the pattern demonstrated in Figure 6.36.

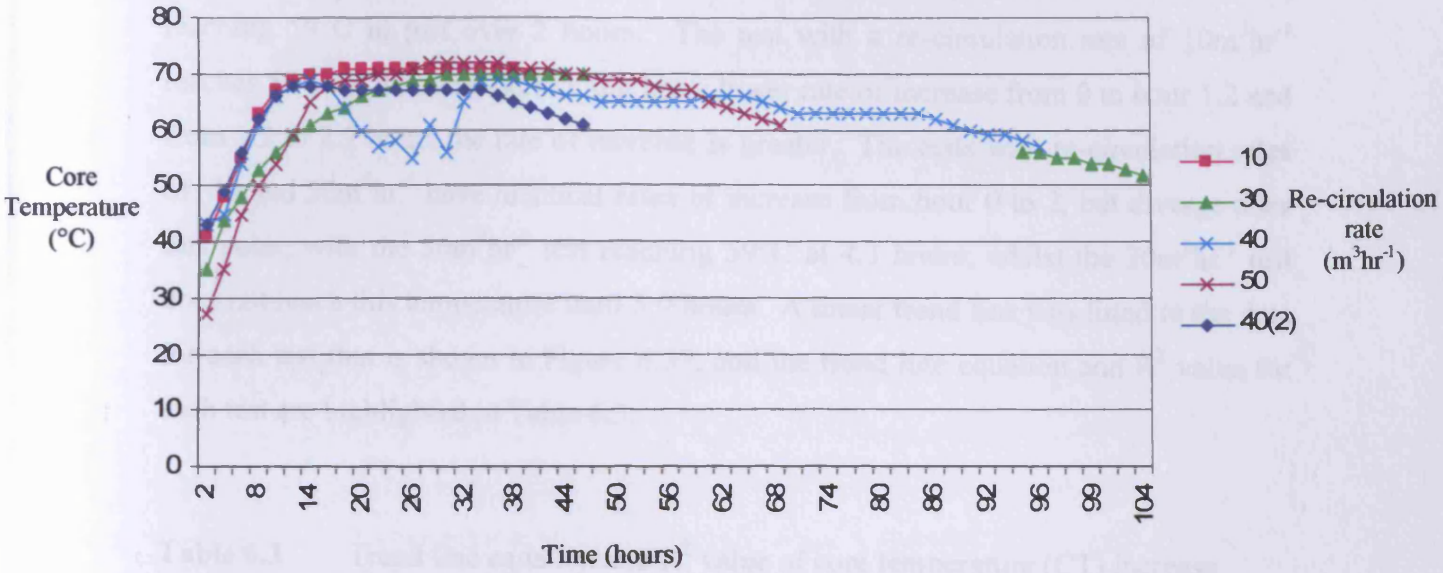

Figure 6.36 Core temperatures plotted against time for green waste composting in the test rig at re-circulation rates between 10 and 50m^3hr^{-1}.

To examine the rate of increase during each test the data was normalised by examining the rate of core temperature increase between 49 and 59°C for each test. Core temperature data for the test with a re-circulation rate of 30m^3hr^{-1} was only available for between 0 and 2 hours and from 4 to 6 hours, and the rate during the first 2 hours was virtually identical to that found in the test with a re-circulation rate of 50m^3hr^{-1}, making the data plotted on the graph shown in Figure 6.37 hard to distinguish.

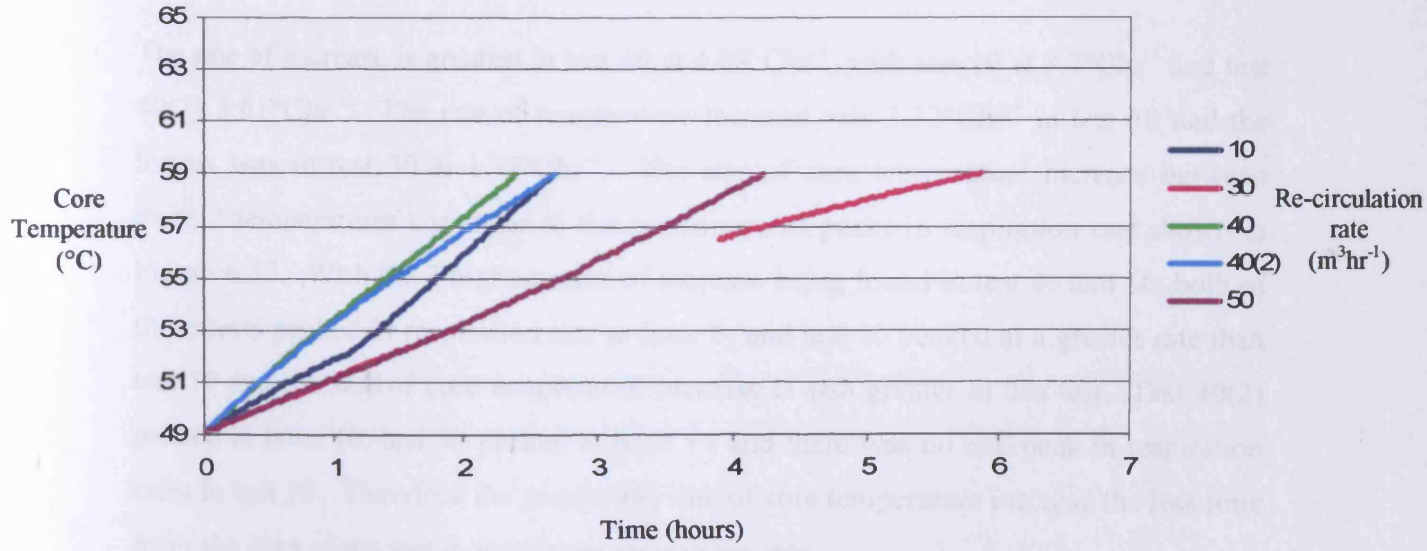

Figure 6.37 Core temperature increase from 49 to 59°C for green waste composting in the test rigs at re-circulation rates between 10 and 50m^3hr^{-1}.

The tests with a re-circulation rate of $40m^3hr^{-1}$ have a very similar rate of increase, reaching 59°C in just over 2 hours. The test with a re-circulation rate of $10m^3hr^{-1}$ reaches 59°C in the same period, but has a lower rate of increase from 0 to hour 1.2 and from 1.2 to 2.2 hours the rate of increase is greater. The tests with re-circulation rates of 30 and $50m^3hr^{-1}$ have identical rates of increase from hour 0 to 2, but diverge after this point, with the $50m^3hr^{-1}$ test reaching 59°C at 4.3 hours, whilst the $30m^3hr^{-1}$ test does not reach this temperature until 5.9 hours. A linear trend line was fitted to the data for each test that is shown in Figure 6.37, and the trend line equation and R^2 value for each test are highlighted in Table 6.3.

Table 6.3 Trend line equation and R^2 value of core temperature (CT) increase against time in hours (th) between 49 and 59°C in green waste composting in the test rig with re-circulation rates between 10 and $50m^3hr^{-1}$.

Test	Trend line equation	R^2 value
10	CT = 3.7th	0.99
30	CT = 1.72th	1
40	CT = 4.08th	1
40(2)	CT = 3.61th	1
50	CT = 2.32th	1

The rate of increase is greatest in test 40 at $4.08°Chr^{-1}$, with test 10 at $3.7°Chr^{-1}$ and test 40(2) $3.61°Chr^{-1}$. The rate of temperature increase was $2.32°Chr^{-1}$ in test 50 and the lowest was in test 30 at $1.72°Chr^{-1}$. The rate of core temperature increase between these 2 temperatures correlates to the occurrence of peaks in respiration rate shown in Figure 6.35. With the 2 highest rates of increase being found in test 40 and 10, both of these tests peaked in respiration rate at hour 6, and test 40 peaked at a greater rate than test 10 and the rate of core temperature increase is also greater in this test. Test 40(2) peaked at hour 10, test 50 peaked at hour 14 and there was no real peak in respiration rates in test 30. Therefore the greater the rate of core temperature increase the less time from the start of the test to maximum respiration rate .

During the temperature distribution tests it was noted that the frequency of the peaks and troughs in CO_2 concentration associated with the inlet and exhaust valves opening and shutting to maintain the concentration between the set limits reduced rapidly and then stopped at approximately 100 hours from the start. This occurred in the tests when the re-circulation rate was $30m^3hr^{-1}$, as shown in Figure 6.7, and when it was $40m^3hr^{-1}$, as shown in Figure 6.13.

The respiration rate for the final 8 peaks in CO_2 concentration when the re-circulation rate was $30m^3hr^{-1}$, between 94 and 104 hours from the start, were calculated. These respiration rates were then plotted against time, and a linear trend line was fitted to the resulting data, as shown in Figure 6.38. The trend line equation demonstrates that over the duration of the period the respiration rate reduced at the rate of $0.32kgCO_2m^{-3}day^{-1}$ per hour. With the respiration rate at the end of the period being 27% of that experienced at the start of the period.

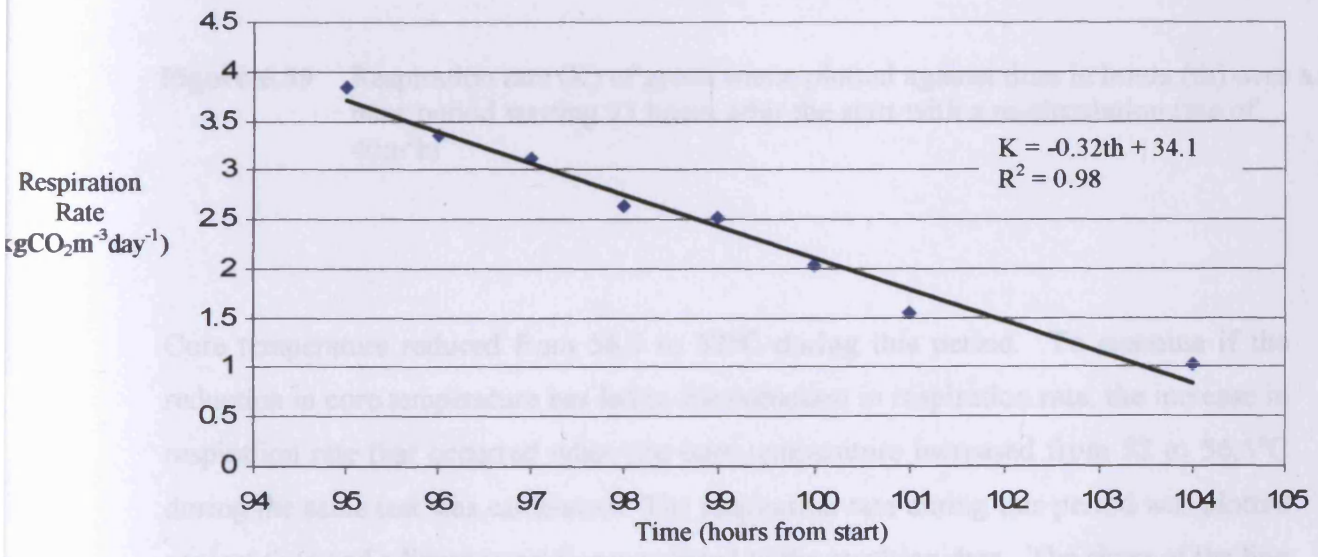

Figure 6.38 Respiration rate (K) of green waste plotted against time in hours (th) over a 10 hour period starting 94 hours after the start with a re-circulation rate of $30m^3hr^{-1}$.

The respiration rate was then calculated for the final 7 peaks in CO_2 concentration in the test with a re-circulation rate of $40m^3hr^{-1}$, which occurred between 93 and 99 hours from the start. These respiration rates were then plotted against time and a linear trend line was also fitted to the resulting data, as shown in Figure 6.39. Respiration rate is reducing at slightly lower rate of $0.3kgCO_2m^{-3}day^{-1}$ per hour.

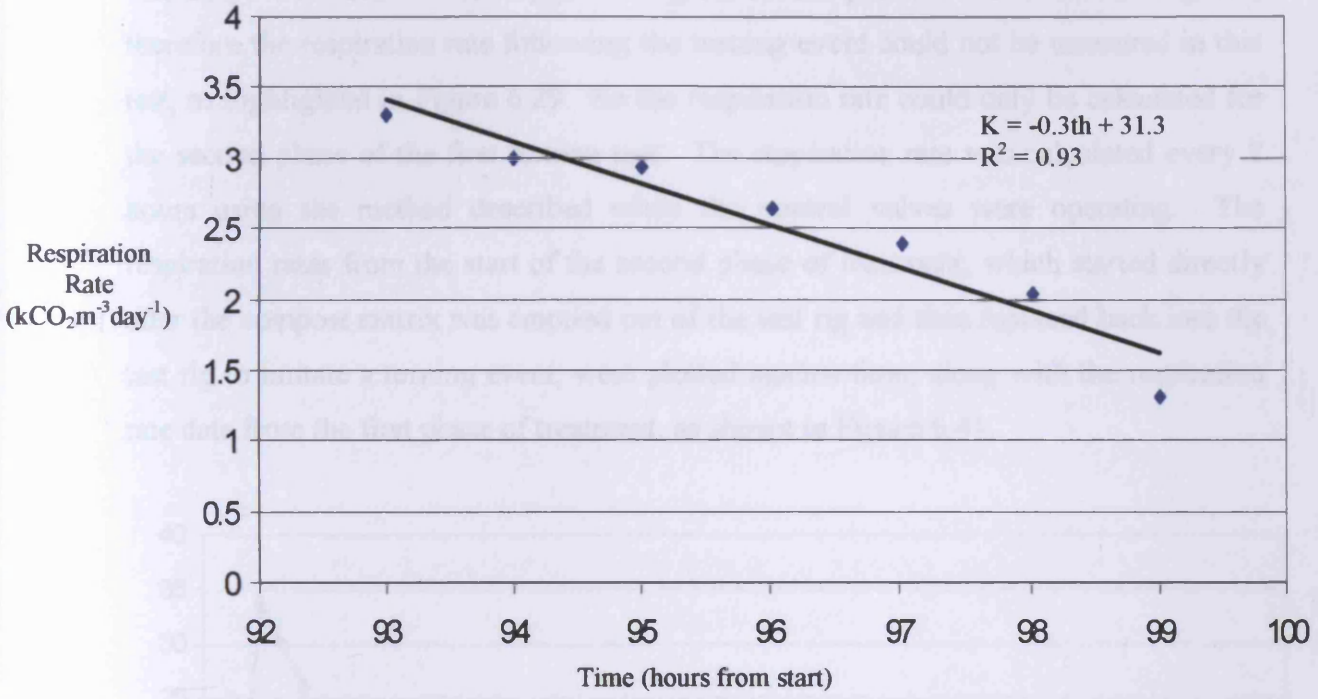

Figure 6.39 Respiration rate (K) of green waste plotted against time in hours (th) over a 6 hour period starting 93 hours after the start with a re-circulation rate of $40m^3hr^{-1}$.

Core temperature reduced from 56.5 to 52°C during this period. To examine if the reduction in core temperature has led to the reduction in respiration rate, the increase in respiration rate that occurred when the core temperature increased from 52 to 56.5°C during the same test was calculated. The respiration rate during this period was plotted against time and a linear trend line was fitted to the resulting data. The slope of the line was K = 2.8th, indicating that the respiration rate had increased by $2.8kgCO_2m^{-3}day^{-1}$. The reduction in respiration rate when the core temperature reduced from 56.5 to 52°C was approximately 10 times less than the rate of increase that occurred when core temperature increased by the same range earlier in the test. This suggests that the respiration rate reduction that occurred during this period was not primarily caused by the reduction in core temperature.

6.4.3.3 Analysis of Turning Event on Respiration Rate

The CO_2 probe became waterlogged during the second phase of the second turning test; therefore the respiration rate following the turning event could not be measured in this test, as highlighted in Figure 6.29. So the respiration rate could only be calculated for the second phase of the first turning test. The respiration rate was calculated every 2 hours using the method described when the control valves were operating. The respiration rates from the start of the second phase of treatment, which started directly after the compost matrix was emptied out of the test rig and then replaced back into the test rig to imitate a turning event, were plotted against time, along with the respiration rate data from the first phase of treatment, as shown in Figure 6.41.

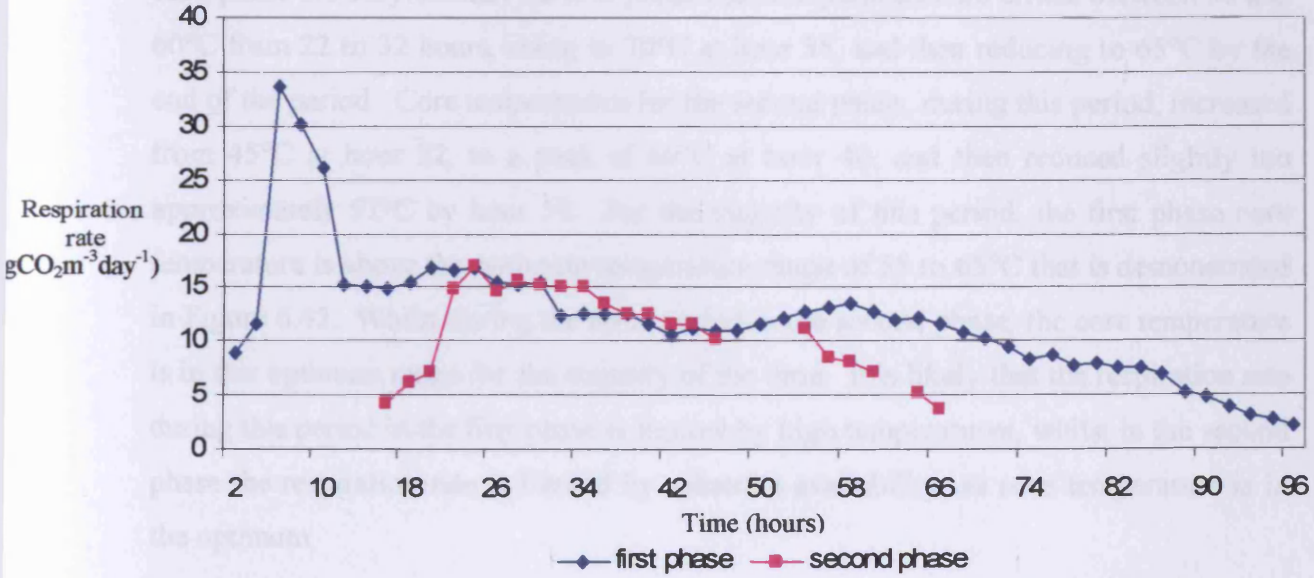

Figure 6.41 Respiration rate from the first phase of treatment and the second phase following a turning event, of green waste composting in the test rig.

The first phase of treatment occurred in the heat distribution test with a re-circulation rate of $40m^3hr^{-1}$, and the second phase of treatment used the same re-circulation rate. The first phase had a peak in respiration rate of $33.5kgCO_2m^{-3}day^{-1}$ 6 hours after the start, whilst there was no obvious peak in respiration rate in the second phase, though the maximum respiration rate of $17kgCO_2m^{-3}day^{-1}$ occurred 22 hours after the start. The peak in respiration rate in the second phase at 22 hours was identical to the rate occurring in the first phase at the same period from the start. Respiration rates from both tests then remained virtually identical from hour 22 to hour 54, at which point the rate in the second phase started to reduce at a greater rate than that from the first test.

The rate of respiration rate (K) reduction plotted against time (th) from the first phase was best described with an exponential trend line with the equation $K = 26.74e^{-0.018th}$ but with an R^2 value of 0.76, as shown in Table 6.2. An exponential trend line was fitted to the data from the second phase this had an equation of $K = 36.5e^{-0.028th}$ and had a R^2 value of 0.85. Though, when a linear trend line was fitted to the data the relationship was stronger with an R^2 value of 0.94 and an equation of $K = -0.27th + 23.3$. A linear trend line fitted to the respiration rate data from the first phase had a R^2 value of only 0.72, with an equation of $K = -0.19^{th} + 22$.

The core temperatures from both phases were plotted against time and are presented in Figure 6.43. During the period from 22 to 54 hours when the respiration rates from each phase are very similar, the first phase core temperatures are erratic between 50 and 60°C from 22 to 32 hours, rising to 70°C at hour 35, and then reducing to 65°C by the end of the period. Core temperatures for the second phase, during this period, increased from 45°C at hour 22, to a peak of 60°C at hour 40, and then reduced slightly too approximately 57°C by hour 54. For the majority of this period, the first phase core temperature is above the optimum temperature range of 55 to 65°C that is demonstrated in Figure 6.42. Whilst during the same period in the second phase, the core temperature is in this optimum range for the majority of the time. It is likely that the respiration rate during this period in the first phase is limited by high temperatures, whilst in the second phase the respiration rate is limited by substrate availability, as core temperature is in the optimum.

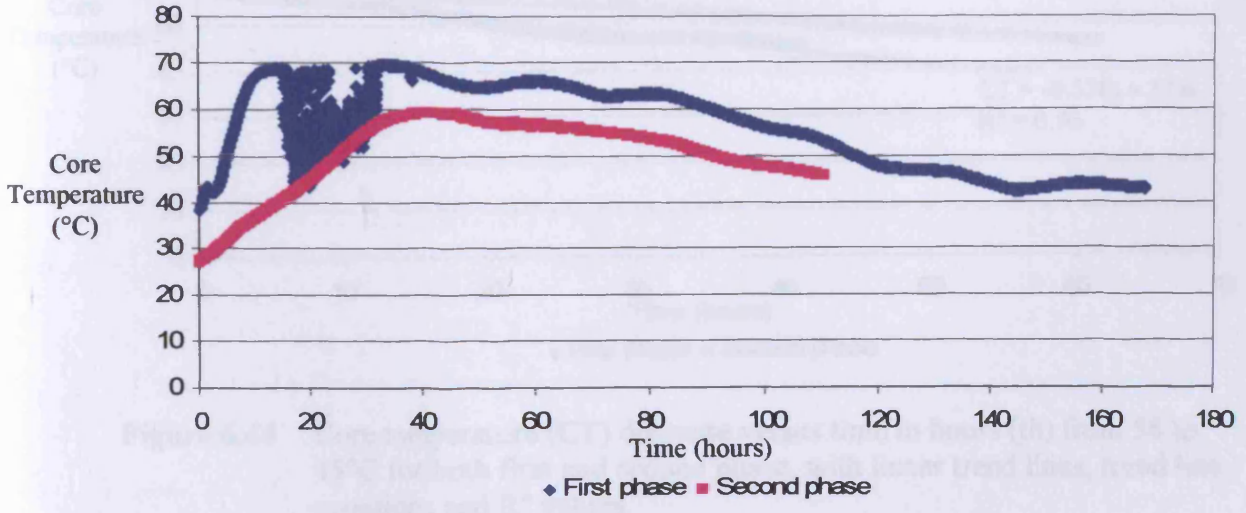

Figure 6.42 Core temperatures from the first and second phase of green waste composting in the test rig with a re-circulation rate of $40m^3hr^{-1}$.

The rate of core temperature increase from 45 to 58°C during the first phase of treatment was 4.5 times greater than that in the second phase, at 4.3°Chr^{-1} and 0.95°Chr^{-1} respectively, as shown in Figure 6.43. The rate of core temperature reduction between the same temperatures demonstrated the opposite. Core temperature from the first phase of treatment reduced at the rate of -0.33°Chr^{-1}, but the rate was less in the second phase at -0.21°Chr^{-1}, as shown in Figure 6.44.

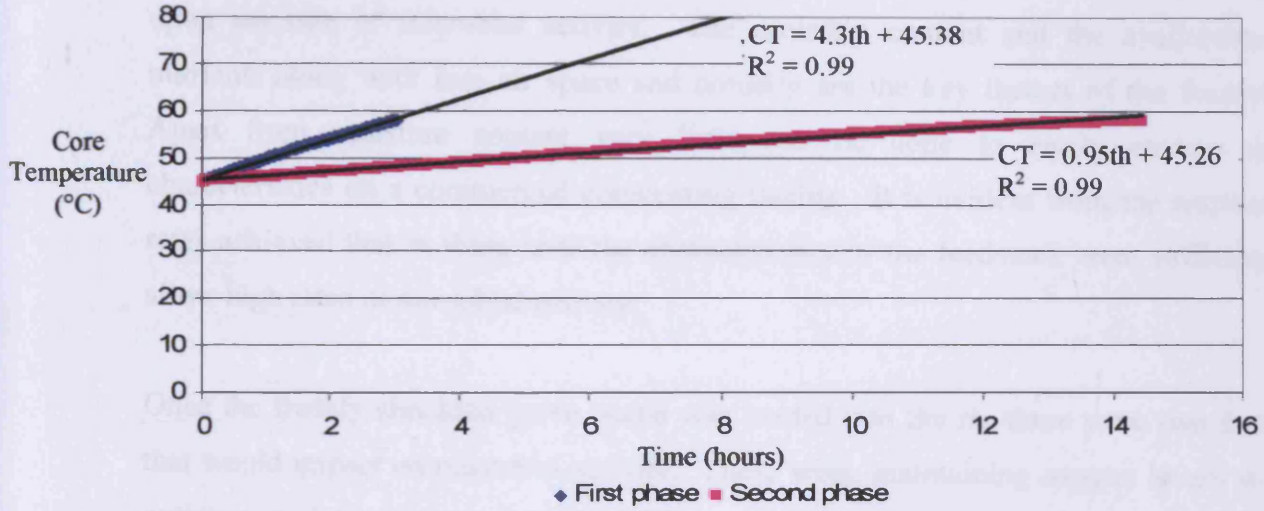

Figure 6.43 Core temperature (CT) increase versus time in hours (th) from 45 to 58°C for both first and second phase, with linear trend lines, trend line equations and R^2 values.

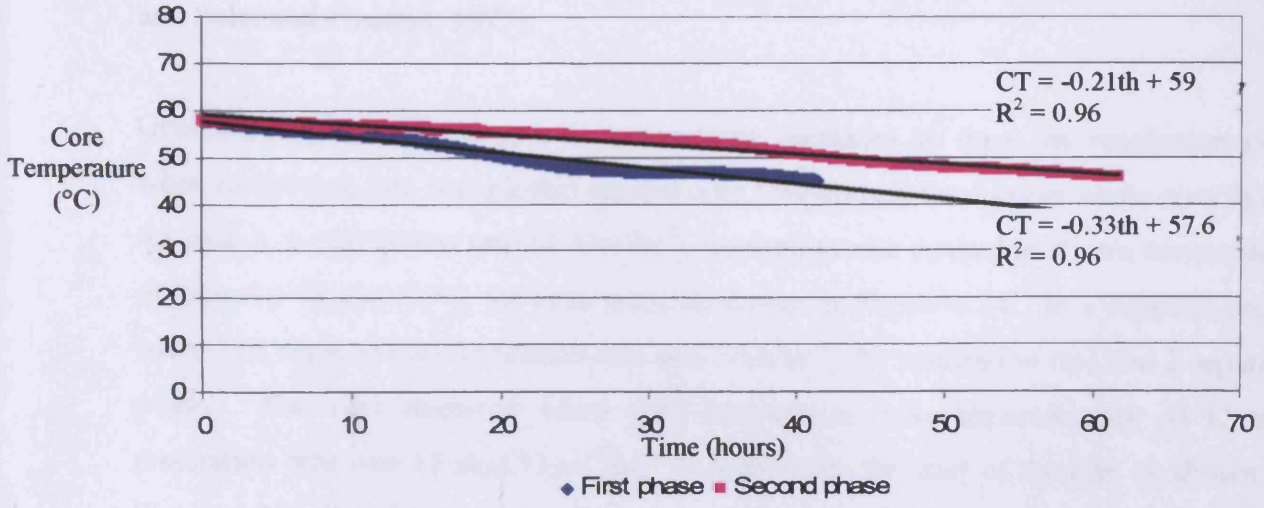

Figure 6.44 Core temperature (CT) decrease versus time in hours (th) from 58 to 45°C for both first and second phase, with linear trend lines, trend line equations and R^2 values.

6.4.4 Discussion

Respiration rate is a measure of the metabolic activity of the micro-organisms degrading the organic waste. Therefore the higher the respiration rate the greater the rate of degradation. The method used here demonstrates the total output of CO_2 produced by the microbes that are active within the system.

There are a number of physical, chemical and environmental factors that will impact upon the rate of microbial activity. The moisture content and the availability of nutrients along with free air space and porosity are the key factors of the feedstock. Apart from moisture content very little can be done to easily change these characteristics on a commercial composting facility. It is evident from the respiration rates achieved that in these tests the characteristics of the feedstock were sufficient to allow high rates of microbial activity.

Once the freshly shredded green waste was loaded into the rig there were two factors that would impact on microbial activity. These were, maintaining oxygen levels at the optimum and temperature which in this case was not managed. The process control system managed CO_2 concentration in the re-circulating gases at below 10% when it was operating correctly, as managing CO_2 below 10% results in oxygen concentration greater than 11%, then oxygen was not limiting activity at any time (MacGregor, 1981 and Suler and Finstein, 1977).

Generally in the early stages, as temperature increases so does the respiration rate, when respiration rate was plotted against core temperature for 2 green waste tests in the rig with a re-circulation rate of $40m^3hr^{-1}$, respiration rate peaked at a core temperature of between 58 and 61°C for both tests, as shown in Figure 6.34. In a separate green waste test when the re-circulation rate was $30m^3hr^{-1}$, the respiration rate had 2 separate peaks. The first occurred when core temperature was approximately 48°C and respiration rate was $17.3kgCO_2m^{-3}day^{-1}$ 6 hours after the start of the test, as shown in Figure 6.33. Respiration rate reduced to $15.8kgCO_2m^{-3}day^{-1}$ approximately 2.5 hours later, whilst core temperature increased to approximately 54°C. Ten hours after the start of the same test, respiration rate was $15.7kgCO_2m^{-3}day^{-1}$ and increased to $17.2kgCO_2m^{-3}day^{-1}$ 7.5 hours later, at which point it was starting to level off, as shown

in Figure 6.33. During the same period core temperature increased from approximately 56 to 64°C and both core temperature and respiration rate were increasing at the same rate over this 7.5 hour period.

Two peaks in respiration rate were also evident in the second commissioning test, which employed a re-circulation rate of $50m^3hr^{-1}$ and is shown in Figures 6.33 and 6.34. Respiration rate peaked at approximately $24kgCO_2m^{-3}day^{-1}$, 6 hours after the start when core temperature was 40°C. The respiration rate had reduced to approximately $18.2kgCO_2m^{-3}day^{-1}$ three hours later, when core temperature had increased to 52°C. Six hours later the respiration rate had increased to $30kgCO_2m^{-3}day^{-1}$, and the core temperature had increased to between 61 and 62°C.

The peak in respiration rate found in the test with a re-circulation rate of $30m^3hr^{-1}$when core temperature was 40°C was slightly greater than the rate when core temperature was between 60 and 64°C. This is at odds to the majority of research and the data presented here, that suggests the optimum temperature for composting is between 55 and 60°C as stated in Section 2.2.3. Though MacGregor et al (1981) found that in three static aerated pile composting trials, which were managed at 45, 55 and 65°C, the greatest moisture loss, occurred in the trial managed at 45°C. They then equated the loss of moisture to heat energy removal and concluded that as the greatest moisture loss was found at 45°C; therefore the greatest heat production from microbial activity had occurred at this temperature. Jeris and Regan (1973) found the optimum temperature for composting paper waste was between 40 and 50°C, though the rate was one tenth of that found when composting mixed refuse at 60°C.

In both tests when the re-circulation rate was $40m^3hr^{-1}$ the respiration rate peaked at between 58 and 61°C but there was only a small variation in respiration rate in the core temperature range between 55 and 65°C, as shown in Figure 6.34. The core temperature increase has had a positive effect on respiration rate up to the peak at between 58 and 61°C, a slight negative impact when it increased to 65°C. When temperature increased above this, core temperature had a greater negative impact on respiration rate causing a rapid reduction, again shown in Figure 6.34. Finstein et al (1983) concludes that the impact of temperature on respiration rate changes from positive to negative at 60°C, which is supported by the data presented here.

It is evident from the respiration rates plotted against core temperatures in Figure 6.34 that a simple relationship between respiration rate and core temperature does not exist. Apart from test 40(2), the respiration rate is decreasing as temperature increases from 45 to 50°C. Respiration rates generally increase from 50 to 60°C, but whilst tests 40 and 40(2) show a relatively stable respiration rate from 55 to 65°C, test 50 has the greatest rate of increase in this temperature range. At temperatures >65°C all 3 tests show a decrease in the respiration rate, indicating that microbial temperature optimums have been exceeded. The rate of chemical reactions increases with temperature and the Arrhenius equation was developed to show the mathematical relationship. This equation is designed to compare the relationship between 2 parameters, but the rate of microbial activity in a composting matrix is also impacted upon by other parameters.

A more simplistic method of expressing the effect of temperature on the reaction rate is to determine the reaction rate at a temperature (k_2) and divide it by the rate at the temperature 10°C lower (k_1). This ratio is termed the temperature coefficient Q_{10}. Generally, chemical reactions in a closed system double for each 10°C increase in temperature i.e. $Q_{10} = 2$. Biologically mediated reactions also exhibit a similar relationship over a limited temperature range. A reaction that is dependant upon physical processes like diffusion or conductivity will have a Q_{10} value less than 1.5 as diffusion coefficients vary less with temperature (Haug, 1980).

The respiration rates for trials when the recirculation rate was 40, 40(2) and 50m^3hr^{-1} were plotted against temperature in Figure 6.34. The temperature coefficient between 50 and 60°C for these trials were calculated, and are shown in Table 6.4.

Table 6.4 Temperature coefficient (Q_{10}) for trials 40, 40(2) and 50 m^3hr^{-1}.

Trial	k_1 (Respiration rate at 50°C in $kgCO_2m^{-3}day^{-1}$)	k_2 (Respiration rate at 60°C in $kgCO_2m^{-3}day^{-1}$)	Q_{10} (Temperature coefficient)
40	27	30.3	1.12
40 (2)	28.4	34.9	1.23
50	19.2	25.2	1.3

The temperature coefficient (Q_{10}) for the 3 trials shown in Table 6.4, are between 1.12 and 1.3. As temperature dependant chemical reactions are expected to have a Q_{10} of 2 and physical processes, such as diffusion and conductivity dependant chemical reactions are expected to have a Q_{10} of less than 1.5. Then the temperature coefficients of between 1.12 and 1.3 demonstrated in this temperature range suggest that the rate of CO_2 production is impacted upon by a physical process, such as diffusion rather as well as temperature.

Measuring the respiration rate when the core temperature had started to reduce indicates that temperature is no longer the major controlling factor in respiration rate. During the temperature distribution test when the re-circulation rate was $10m^3hr^{-1}$ and core temperature was 70°C, 14 hours after the start of the test, the respiration rate was $10.8kgCO_2m^{-3}day^{-1}$. Twenty six hours later the core temperature was still 70°C but the respiration rate had reduced to $1.32kgCO_2m^{-3}day^{-1}$. Sixteen hours after the start of the first phase of the second turning test when re-circulation rate was $40m^3hr^{-1}$ the core temperature was 67°C and the respiration rate was $17.6kgCO_2m^{-3}day^{-1}$, and fourteen hours later the core temperature was 67°C and the respiration rate had reduced to $11.2kgCO_2m^{-3}day^{-1}$.

A greater reduction was found in the temperature distribution test with a re-circulation rate of $40m^3hr^{-1}$. Core temperature was 60°C and the respiration rate was $30kgCO_2m^{-3}day^{-1}$, 7.4 hours after the start of the test. The core temperature was again at 60°C, 90 hours after the start of the test, but at this time the respiration rate had reduced to $4.5kgCO_2m^{-3}day^{-1}$. The respiration rate for this test was also calculated every 2 hours over a 34 hour period, starting 65 hours after the start. The core temperature during this period was between 60 and 65°C, which were in the optimum range demonstrated in Figure 6.34. But respiration rate reduced from 12 to $4.8kgCO_2m^{-3}day^{-1}$ during this period.

Analysing the time of the different respiration rates when the core temperature was the same, allows the time at which the major controlling factor on respiration rate changes from temperature to another parameter, to be estimated at between 16 and 30 hours from the start. The other parameter is likely to be substrate availability, as the rate of

respiration rate decay has a strong relationship to an exponential trend line, as shown in Table 6.2.

This strong relationship suggests a first order reaction in relation to substrate availability; the respiration rate will reduce in line with substrate availability. But the respiration rate from the temperature distribution test when the re-circulation rate was $30m^3hr^{-1}$ does not fit that estimate. During that test the respiration rate was calculated when the core temperature was 70°C, 33 hours after the start, when it was $13.5kgCO_2m^{-3}day^{-1}$. Thirteen hours later the core temperature was 70°C and the respiration rate was similar at $14.2kgCO_2m^{-3}day^{-1}$, demonstrating that the respiration rate was virtually identical at the same core temperature. This indicates that temperature was still the major controlling factor of respiration rate 40 hours after the start of this test.

The temperature distribution test with a re-circulation rate of $30m^3hr^{-1}$ did not fit the trend for higher re-circulation rates to induce lower rates of core temperature increase that is demonstrated in Figure 6.19. The same test did not fit the general trend of the lower the re-circulation rate the less time was taken for the core to reach 70°C, as shown in Figure 6.18. Both of these occurrences where this test did not fit in with general trend in relation to re-circulation rate and temperature increase can be explained by the low respiration rate experienced in the first 3 to 17 hours when compared to the tests with different re-circulation rates, as shown in Figure 6.33. During this period the respiration rate for the $30m^3hr^{-1}$ test was approximately $17kgCO_2m^{-3}day^{-1}$, whilst the three other tests, that had re-circulation rates of 40 and $50m^3hr^{-1}$ peaked at between 30 and $34.5kgCO_2m^{-3}day^{-1}$. As heat production is related to respiration rate the test with a re-circulation rate of $30m^3hr^{-1}$ will have been producing 0.52 to 0.6 the heat energy produced by the other tests. This difference explains why this test did not fit the trends for core temperature increase rates.

Waksman et al (1939), concludes that in the initial stages organisms that are more able to utilise the more readily degradable compounds like carbohydrates, lipids and proteins, are present. Once these simpler compounds have been degraded, organisms that have the capacity to degrade more complex organic compounds like lingo-cellulose and chitin become more prevalent. Therefore the comparatively low respiration rates found in the test with a re-circulation rate of $30m^3hr^{-1}$ was likely to be due to reduced

content of these easily degradable compounds. The long term respiration rates from the 5 tests in Figure 6.35 back up this assumption, as respiration rates for tests 40, 40(2) and 50 have very similar respiration rates as those from test 30 from hours 20 to 50. Therefore it is likely that the very high respiration rates measured during the early stages, 0 - 24 hours, of green waste composting in the test rig, which are 8 to 10 times greater than the peaks seen in the windrow composting of green waste, are reliant on the microbial community utilising the more easily degradable compounds. Once these easily degradable compounds have been depleted the rate of activity is limited to the rate at which the remaining compounds can be degraded. If the content of these easily degradable substrates is low, as suggested in test 30, these substrates will be degraded quickly and therefore cannot produce and maintain the short term peaks seen in tests 10, 40, 40(2) and 50. Once these simpler compounds have been depleted there is likely to be a change in the microbial community as the organisms that are best adapted to degrade the simpler compounds will be out competed by organisms that are better adapted to degrading the more complex compounds. Peters et al (2000) found that actinomycetes diversity increased during compost maturation, and that this was due to their ability to degrade complex organic compounds like lignin, chitin and proteins that other organisms have not been able to decompose earlier in the composting process. And the complex lignin's found in wood are predominantly degraded by enzymes excreted by fungal hyphae.

The reduced respiration rate during the second phase of treatment when compared to the first phase in the turning test can also be explained in these terms, as shown in Figure 6.41. The easily degradable substrate has been depleted during the first 14 hours at the start of the first phase; therefore the rate of core temperature increase in the second phase is 4.5 times less than that in the first phase, as shown in Figure 6.43. Once core temperature has reached optimum levels the respiration rate experienced in the second phase is equal to the rate experienced during the same period of the first phase, as demonstrated in Figure 6.41.

The respiration rate reduction noted at around 100 hours in the temperature distribution tests when re-circulation rates were 30 and $40m^3hr^{-1}$ were calculated and presented in Figure 6.38 and 6.39. There was an apparent rapid decrease at this point as there was a visible change in the frequency between peaks in CO_2 concentration. The actual rate of

respiration rate decrease was between 0.3 and 0.32kg$CO_2m^{-3}day^{-1}$ hour for both tests. To determine if the core temperature reduction during this period, from 56.5 to 52°C would explain the respiration rate decrease it was compared to an earlier period (hour 5 to 6) when core temperature increased between these temperatures. During this period respiration rate was increasing at the rate of 2.8kg$CO_2m^{-3}day^{-1}$hour, between 8.5 and 9 times greater than when the core temperature was decreasing within the same range.

If the reduction in core temperature was the sole reason for the reduction in respiration rate, the rate of reduction would have been similar to the rate of increase within the same core temperature range. The respiration rate was then calculated every 2 hours over a 34 hour period from 64 to 98 hours, for the same test in which the rate of reduction was 0.3kg$CO_2m^{-3}day^{-1}$ per hour, between hours 93 and 99. The rate of respiration rate reduction was slightly less during this period, at 0.285kg$CO_2m^{-3}day^{-1}$ per hour, as shown in Figure 6.40. This similarity suggests that there had been no sudden change in respiration rate at approximately 100 hours in both tests. So the apparently rapid decrease in CO_2 concentration peak frequency demonstrated in Figures 6.7 and 6.13 indicate that the rate of CO_2 production is approaching the lower limit that the test rig can control due to leakage, rather than a sudden decrease in respiration rate.

The turning event has had a positive impact upon respiration rate, as the rate during the majority of the second phase is greater than it was during the last thirty hour period of the first phase. This increase is likely to have been caused by either the physical action of the turning event making more substrate available or by a microbial population adaptation to the changing nature of available substrate. The second of which is likely to have occurred without the turning event.

The composting matrix achieved 100% greater than 60°C in all tests when the re-circulation rate was $40m^3hr^{-1}$ or greater, though it was not maintained above this temperature for a minimum of 48 hours. If the waste being composted is "non meat excluded" then these treatment requirements have to be met twice with a turn between each phase, and 60°C was not achieved in 100% of the composting matrix in either of the tests in which a second phases of treatment was imitated.

It is likely that the small scale of the test rig had a large impact upon the heat loss characteristics. The test rig had a total external surface of $16m^2$ with only $1m^3$ of compost matrix. The aeration system at Bryn Compost Limited's 20,000 tonnes per annum ABPR compliant in-vessel composting system was designed to provide the re-circulation rates that were derived from the test rig, shown in Figure 6.45. This in-vessel system was opened in September 2006 and the aeration system has proven to be a robust method of meeting the time/temperature requirements. The tunnels at this facility have a surface area of $541m^2$ and the shredded waste is filled to a depth of 3 meters, and when full has $396m^3$ of waste. This gives a surface to compost volume ratio of less than $1.4m^2/m^3$. This commercial system has a surface area to compost volume ratio less than one tenth of that of the test rig, and therefore the heat energy required to maintain a certain temperature is greatly reduced.

Figure 6.45 Bryn Compost's facility and the tunnel vessels at this site.

A new 14,000 tonnes per annum in-vessel system is being constructed at the CERT composting facility. This system was designed to produce the re-circulation rates that were demonstrated to ensure 100% of the compost within the test rig. It was also designed to use an identical aeration management to that installed in the test rig, by managing gas concentrations in the re-circulation system to within set limits. It is envisaged that implementing these control strategies will minimise the time required to meet the treatment requirements of the ABPR.

6.5 Summary

- Peak respiration rates were experienced with a core temperature between 58 and 61°C, though there was little variation between 55 and 65°C. Core temperatures greater than 65°C had a large negative impact on respiration rate.

- A peak in respiration rate was found between 40 and 50°C in two tests, and in one case respiration rate was greater in this range than it was when core temperature was 60°C.

- Peak respiration rates of between 30 and 35kg$CO_2m^{-3}day^{-1}$ were experienced in the test rig, approximately 10 times greater than the peaks seen in windrow composting, but these rates were short lived and only occurred in the first 24 hours.

- The temperature coefficient (Q_{10}) of less than 1.5 suggests that the rate limiting factor when all other parameters are in the optimum maybe a physical parameter, like gas diffusion through microbial membranes.

- The minimum re-circulation rate that achieved a minimum temperature of 60°C in 100% of the compost matrix within the rig was $40m^3hr^{-1}$, but at this re-circulation rate the maximum temperature achieved at the coldest location (B01) was less than 1°C above 60°C. Whilst the maximum temperature achieved at this location when the re-circulation rate was $50m^3hr^{-1}$ was 64°C, giving a larger safety margin.

- Respiration rate increased following a turning event, from <2.4kg$CO_2m^{-3}day^{-1}$ to 17kg$CO_2m^{-3}day^{-1}$, under the same management regime.

- The respiration rates measured after five days retention in the test rig were similar to the peaks experienced in windrow composting, at less than 4kg$CO_2m^{-3}day^{-1}$.

- Higher re-circulation rates in the test rig resulted in a greater proportion of the compost matrix and the compost periphery being greater than a specific temperature.

- The minimum ABPR treatment requirement of 60°C for 48 hours was not achieved in any of the tests. This is likely, at least in part, to be due to the test rig having a surface area to compost volume ratio 10 times greater than would be experienced in a commercial system, and therefore have a greater rate of heat loss. This was confirmed by the performance of Bryn compost Ltd's in-vessel system.

- The data provided by the trials in the test rig regarding aeration, re-circulation and potential respiration rates are valuable additions to the understanding and management of in-vessel composting systems. This is demonstrated by their application in commercial systems.

7 Conclusions, Recommendations and Future Work

7.1 Conclusions

It has been demonstrated that there are a number of parameters impacting upon the rate of microbial activity occurring within a composting matrix. The key ones are nutrient availability, temperature, moisture and O_2 availability, and any of these can be impacted on by each other and the physical status (bulk density, porosity and particle size) of the compost matrix. Measuring just one of these parameters cannot indicate the rate of activity that is occurring within that matrix, but measuring the dynamic respiration rate demonstrates the sum effect of environmental, physical and chemical parameters on the rate of microbial activity.

The dynamic respiration rate monitoring methodologies presented have proven to be a reliable and robust method of determining the rate of microbial activity occurring within the composting matrix of turned windrows, an aerated bay and in a processing test rig. Respiration rates measured ranged from a low of 0.36 $kgCO_2m^{-3}day^{-1}$ in the aerated bay to a high of 34.5$kgCO_2m^{-3}day^{-1}$ in the processing test rig. Respiration rates found in the turned windrow system had a smaller range of between 0.48 and 4.2$kgCO_2m^{-3}day^{-1}$, but remained between 1.2 and 2.4 $kgCO_2m^{-3}day^{-1}$ for the majority of the monitored periods.

Peak respiration rates in windrows were associated with the period directly after a turning event, and are primarily due to heat loss during this event, resulting in lower core temperatures. Respiration rate in green waste windrows reduced at the rate of between 0.068 and 0.17$kgCO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature, in the temperature range of 55°C to 70°C. Whilst in the range of 66°C to 70°C the measured reduction increased to between 0.258 and 0.274$kgCO_2m^{-3}day^{-1}$ for every 1°C increase in core temperature.

Chicken litter was added to a green waste windrow to increase the nitrogen content, as it is determined to be a rate limiting factor in green waste composting. The respiration rate measured in this windrow was less than that found in the 2 green

waste only windrows. This difference was determined to be due to the smaller particle size of this amendment material reducing porosity, which led to reductions in passive airflow and therefore O_2 availability. Demonstrating that changing a single parameter in a complex system does not always bring about the expected response, and indicating one of the advantages of monitoring respiration rate.

The respiration rates measured with green waste in the processing test rig demonstrates the level of microbial activity that can be achieved when parameters are managed in their optimum reported ranges. These peaks were between 18 and 34.5kg$CO_2m^{-3}day^{-1}$, and in each trial the peaks occurred within the first 18 hours. It can be concluded that these very high respiration rates can only be maintained when there is a sufficient quantity of easily degradable substrates available. This is supported by lower respiration rates measured later in each trial when the environmental conditions within the composting matrix are identical to those occurring when the peaks were found.

The respiration rate reduction over time of the green waste in the test rig suggest that approximately 100 hours after the start of each trial, the rate has reduced to that experienced in turned windrow composting, at approximately 1.8kg$CO_2m^{-3}day^{-1}$. It was demonstrated that the respiration rate was restored following a turning event, when it increased to a maximum of 17.4kg$CO_2m^{-3}day^{-1}$. Respiration rates from both the first and second phase were virtually identical from hour 22 to hour 54 of each phase, though the core temperature was some 10°C less during this period in the second phase. Demonstrating that, optimum temperature is partially dependant upon the extent of decomposition.

The data used to calculate the O_2 required by a composting matrix that was derived from the stoichiometry of the microbial mediated chemical reactions was shown to be accurate in the test rig. This demonstrates a sound methodology that can be used to calculate the volume of air required by a composting matrix to supply sufficient O_2 once the maximum expected respiration rate is known.

Managing the forced aerated system in the aerated bay has demonstrated that maintaining the CO_2 concentration in the composting matrix at between 4 and 10%

will promote maximum temperatures. The same methodology was used in the test rig, but being computer controlled allowed the system to be more reactive, which allowed more accurate control from the start of each trial. In the test rig green waste trials the core temperature increased to 60°C within 12 hours, demonstrating that the same process management method reliably ensures rapid temperature increase.

The trials conducted in the forced aerated bay demonstrated that a non re-circulating aeration system could not ensure that 100% of the composting matrix could be managed to more than 60°C. It was determined that the mass of compost at the vessel periphery, especially in the bottom corners, could not produce heat at a rate greater than the rate of heat loss experienced in these zones. This situation was exacerbated by unequal air flow through out the composting mass, as the rate of airflow in the aeration pipes was greater, the closer they were to the side walls. This unequal flow resulted in a greater level of cooling in the side wall zones, where it was desired to increase temperatures, than in the core zone where high temperatures were maintained.

A series of trials using green waste subjected to different re-circulation rates demonstrated that a minimum re-circulation rate of $40m^3hr^{-1}$ was required to ensure 100% of the compost matrix in the test rig was greater than 60°C. The rate of re-circulation determines the rate that heat energy is distributed from the highly insulated core zone to the periphery. It was also demonstrated that generally, the higher the recirculation rate the greater the proportion of the compost matrix core was over a certain temperature, in the range of 60 - 74°C. The same was true at all re-circulation rates for the proportion of the periphery greater than a certain temperature, in the range 45 - 71°C. This result is counter intuitive as the greater the rate of re-circulation, the more heat energy is distributed to the less well insulated periphery, which would lead to an overall increase in heat loss. It is likely that transferring heat energy from the core to the periphery has increased respiration rate due to higher temperatures at the periphery and decreased temperatures in the core, therefore bringing both zones closer to the optimum. So the increase in heat production due to higher respiration rates is greater than the increased heat loss experienced at higher re-circulation rates. This assumption is not demonstrated in the respiration rate data when compared to re-circulation rate.

The research presented in this thesis demonstrates methodologies that can be used to determine the rate of microbial activity in any system. It also demonstrates that knowing the respiration rate of a composting matrix allows the demand for O_2 to be calculated, as well as the rate of heat production. Knowing the rate of heat production indicates the amount of heat energy that needs to be removed from a compost matrix, to maintain a target temperature. Process management options that promote the rapid development of high temperatures, and those that reduce temperature gradients through heat distribution in forced aerated systems are also described. This work will aid those who are designing in-vessel composting systems, and especially those designing systems to meet the ABPR treatment requirements.

The amount of biodegradable waste produced will increase inline with predicted economic and population growth on a world wide basis. The efficient processing of biodegradable wastes will reduce the global warming potential of these operations. Not only in the reduction of methane lost to the atmosphere from landfills, but also from more efficient operation of the compost process itself and that of the processing equipment, which at present predominantly derives its energy from fossil fuel sources.

7.2 Recommendations

The dynamic respiration rate measurement methodologies presented in this thesis are valuable tools in optimising commercial scale composting processes management. They are capable of demonstrating the rate of microbial activity, but cannot determine the underlying parameters that are impacting upon the rate of microbial activity. The application of these methods in future research or commercial environments would be enhanced through the measurement of the key processing parameters of temperature, O_2, moisture and nutrient content. This would allow the impact of these parameters on the rate of microbial activity to be more fully described.

It is recommended that managing the CO_2 content in the re-circulating gases of forced aerated in-vessel systems between 4 and 10% should be implemented in these types of systems as it will ensure rapid temperature increase and maximum temperature gain. Managing CO_2 between these limits ensures that there is sufficient O_2 available to

ensure microbial activity is not limited. As CO_2 has been used, in this instance, to infer O_2 concentrations it would be logical to measure O_2 concentration if probes were available that were capable of operating reliably and accurately to the required specification. This aeration management technique minimises the time taken to reach the ABPR treatment minimum temperatures, by maximising the respiration rate and therefore heat production, as well as minimising heat loss. The very high respiration rates that have been demonstrated in the first 8 to 72 hours of composting, when using this method, will require an aeration system that has sufficient capacity to meet the O_2 demand, which can be calculated.

Temperature management is a key process parameter in composting, although the optimum range has been well described, it is regularly not managed effectively at commercial composting facilities. The research presented in this thesis reinforces the reported optimum temperature range as well as demonstrating management techniques and associated impacts. The optimum core temperature to promote microbial activity has been demonstrated to be approximately 55°C in green waste windrows, but in the early stages in the test rig there was little variation in microbial activity between 55 and 65°C, with large reductions over 65°C. In passively aerated composting systems like windrows and most vertical plug flow systems there is very little opportunity to manage temperature, which are typically well above 70°C. High rates of microbial activity can only occur when temperature is managed within the optimum, which will inevitably lead to rapid moisture loss, and reduced moisture content will have a negative impact on microbial activity. It has been demonstrated that managing temperature with forced aeration will ensure there is sufficient O_2 available. Therefore it is recommended that managing temperature and moisture in the optimum range will ensure the greatest level of microbial activity that can be supported by a composting matrix is achieved.

7.3 Future Work

The calculations for heat removal have not been analysed here, but having demonstrated the accuracy of the O_2 requirement calculations, it is likely that those suggested for heat removal are accurate. It would be valuable to determine the

accuracy of the calculations for heat removal and to determine the moisture loss that would result from cooling a composting matrix using forced aeration.

The suggestion that different compounds in the composting matrix are decomposed more efficiently by different microbial communities infers that optimum conditions will change over time. Applying dynamic respiration rate measurement at the commercial scale may indicate process management methods that will increase the efficiency of the composting process.

Mechanical and biological treatment of municipal solid waste is a further technique that is being used in an attempt to reduce the amount of biodegradable waste going to landfill. These types of systems are required to demonstrate the mass of biodegradable waste that has been removed from the waste undergoing biological treatment. The dynamic respiration rate measurement methods demonstrated here can be used to help optimise these types of systems. As the mass of CO_2 gas exhausted from these systems is the major route for carbon loss, then measuring the respiration rate on a dynamic basis will allow the mass of carbon that has been diverted from landfill to be calculated.

Measuring the dynamic respiration rate constantly would allow the mass of CO_2 that has been lost from the system to be calculated. If the carbon loss by this route was compared to standardised stability tests undertaken at different times during treatment. Then a level of stability could be indicated by the total loss of carbon from the system, depending on feedstock variation. This would allow facilities to identify when a compost matrix had met a desired level of decomposition, which would aid process efficiency and lead to less variation in product.

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Appendix A

Conversion of Reported Respiration Rates

To convert $mgCO_2g$total solids$^{-1}day^{-1}$ to $gCO_2kgVS^{-1}day^{-1}$

$mgCO_2g$ total solids$^{-1}day^{-1}$ divided by the proportion of volatile solids in total solids, equals $mgCO_2g$ volatile solids$^{-1}day^{-1}$. Multiply the result by 1000 to express the result in $gCO_2kgVS^{-1}day^{-1}$.

Therefore $36mgCO_2g$ total solids$^{-1}day^{-1}$ when 86.8% of total solids were volatile solids =

$36 \div 0.868 = 41.47mgCO_2g$ volatile solids$^{-1}day^{-1}$

$\times 1000 = 41.47gCO_2kg$ volatile solids$^{-1}day^{-1}$

To convert $mmolesCO_2gVS^{-1}day^{-1}$ to $gCO_2kgVS^{-1}day^{-1}$.

To convert mmoles of CO_2 into moles of CO_2 divide by 1000.
To convert moles of CO_2 into a mass in grammes multiply by the mass of a mole of CO_2 in grammes, 44.
To convert gVS^{-1} to $kgVS^{-1}$ multiply by 1000.

Therefore $4.3mmolesCO_2gVS^{-1}day^{-1}$ =

$4.3 \div 1000 = 4.3\times10^{-3}molesCO_2gVS^{-1}day^{-1}$

$4.3\times10^{-3} \times 44 = 0.189gCO_2gVS^{-1}day^{-1}$

$0.189 \times 1000 = 189gCO_2kgVS^{-1}day^{-1}$

To convert $gCO_2/100gdrymatter^{-1}96hrs^{-1}$ to $gCO_2kgVS^{-1}day^{-1}$ when volatile solid content is 92% of dry matter.

To convert drymatter to volatile solids content divide by 0.92.
To convert volatile solids content to kg multiply by 10.
To convert to days divide by 4 (96hrs = 4 days).

Therefore $26gCO_2/100gdrymatter^{-1}96hrs^{-1}$

$26 \div 0.92 = 28.26gCO_2/100gvolatile\ solids^{-1}96hrs^{-1}$

$28.26 \times 10 = 282.6gCO_2/kgvolatile\ solids^{-1}96hrs^{-1}$

$282.6 \div 4 = 70.65gCO_2/kgVS^{-1}day^{-1}$

Appendix B

Calculating Windrow Respiration Rate

The mass of CO_2 evolved in a windrow is calculated using equation B1.

$$M_{CO2} = \frac{P \times \overline{U} \times A \times \Delta E_{CO2}}{R_{CO2} \times T_g \times 100}$$

Where

M_{CO2} is the mass of CO_2 evolved in kilograms,

P is the atmospheric pressure 101325 Pa,

$\overline{U}$ is the mean velocity of gas through the chimney in m/s,

A is the cross sectional area of the chimney $8.22\times10^{-3}m^2$,

ΔE_{CO2} is the change in concentration of carbon dioxide in %v/v (between inlet and outlet),

R_{CO2} is the characteristic gas constant for carbon dioxide 188.96 J/kg K,

T_g is the temperature of the gas being released in Kelvin,

100 converts the % CO_2 into a proportion of the gases.

Assuming that the CO_2 concentration increase above ambient is 1% v/v, and the velocity of gases in the chimney are 1 meter per second with a temperature of 20°C.

Then $\overline{U} = 1$, $\Delta E_{CO2} = 1$ and $T_g = 293$.

Therefore =

$$\frac{101325 \times 1 \times 8.22\times10^{-3} \times 1}{188.96 \times 293 \times 100} = \frac{832.8}{5536528} = 1.5\times10^{-4}\ kgCO_2s^{-1}$$

Multiplying the mass of CO_2 evolved per second by 86400, the number of seconds per day, gives the mass of CO_2 evolved in a day.

$1.5\times10^{-4}\ kgCO_2s^{-1} \times 86400 = 12.96kgCO_2day^{-1}$

Dividing the mass of CO_2 evolved per day by the number of m^3 of compost below the canopy gives the rate of CO_2 production in kg for every m^3 of compost per day.

Windrow volume was $4.2m^3$ per linear, and the canopy covered 2.4 meters of the windrow, then the volume of compost under the canopy was 10.08 m^3.

$12.96kgCO_2day^{-1} \div 10.08m^3 = 1.286kgCO_2\ m^3\ day^{-1}$

Appendix C

Calculating Bay Respiration Rate

The mass of CO_2 evolved in bay was calculated and related to compost volume using the following equation.

$$K = \frac{AEco_2 \times B \times C \times D}{V}$$

Where

K = Composting rate in $gCO_2m^{-3}day^{-1}$

$AEco_2$ = Increase in the volume of CO_2 in % divided by 100

B = Total free air space in m^3

C = CO_2 density in grams per m^3

D = Convert hours to days

V= Total volume of compost in m^3

For example, on day 5 the CO_2 concentration in the free air space (FAS) of the composting matrix was increasing at the rate of 3.6% per hour, as shown in Figure 4.46. The bulk density of the composting matrix was $500kg/m^3$ and at this density the FAS within the composting mass was estimated to be 50% from the data presented in Figure 4.45, and the total volume of compost was estimated to be $90m^3$.

When	$AEco_2$ =	0.036	(CO_2 increase in % divided by 100)
	B =	45	(total compost volume multiplied by FAS)
	C =	1.65	(CO_2 density in kg per m^3)
	D =	24	(converts hours to days)
	V =	90	(total volume of compost matrix in m^3)

Therefore =

$$\frac{0.036 \times 45 \times 1.65 \times 24}{90} = \frac{64.15}{90} = 0.71 kgCO_2m^{-3}day^{-1}$$