Airflow Characteristics of a Horizontal Airflow Biofilter

By

Edward Michael Garlinski

A Thesis Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the
Degree of

MASTER OF SCIENCE

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba, Canada

August 2004

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
*****
COPYRIGHT PERMISSION

Airflow Characteristics of a Horizontal Airflow Biofilter

BY

Edward Michael Garlinski

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

ABSTRACT

The technology of biofiltration is consistently finding new applications, but an obstacle for more applications has been the ability to make a small footprint low-pressure biofilter. This thesis looked at the design of a horizontal airflow biofilter, which offers the ability to build a low pressure, small footprint biofilter.

A full-scale prototype horizontal airflow biofilter was built at the University of Manitoba's research farm located at Glenlea. The biofilter was an $80{:}20_{(wb)}$ woodchip: compost biofilter with a volume of 17 m^3, a design pressure requirement of 136 Pa, an assumed airflow of 1.89 m^3/s, and the contaminated air being supplied from a stage two fan of a four stage ventilation system of a weanling room. Two booster fans were installed inline to be supply the airflow at the required pressure to move the air through the biofilter media. Testing of this design involved the monitoring of airflow, pressure drop, settling of biofilter media, and hydrogen sulphide removal. From the data collected over the summer of 2003, the second summer of operation, it can be determined that this design works.

The data for pressure and airflow suggested the assumed airflow at the time of designing the biofilter was high and a better estimate would have been 1.16 m^3/s or lower. However, comparing the airflow vs. pressure drop for the biofilter, the data collected does match the theoretical pressure drop through the biofilter, based on the limited

information available for predicting pressure drop through biofilter media. The average pressure drop through the biofilter media during the summer of 2003 was 135 Pa.

When designing this biofilter, the largest concern was stratification and its effects on airflow and pressure drop. After this research, stratification of airflow that occurred within the biofilter media was identified as being caused by the design of the biofilter, not a result of aging (settling) or compaction of the media.

Settling appeared uniform except with respect to the different fill methods used. With the design of this biofilter, the amount of media settling caused problems. The problems encountered could have been foreseen, the pressurized headspace failed, if the amount of settling was accurately predicted. From the data collected, this biofilter settled uniformly by approximately 10% over the first 12 months of use.

When the biofilter was operating properly, 80% or more of the inlet concentrations of hydrogen sulphide was removed. Improvements could be achieved with a better designed watering system, as specific locations within the biofilter were being insufficiently watered; thus the poor removal rates of hydrogen sulphide at these locations.

ACKNOWLEDGEMENTS

I would like to thank Dr. D.D. Mann, my thesis advisor for offering me the chance to work on such an interesting project and test many new ideas related to biofiltration. I would also like to thank my committee members Dr. N. Cicek, Dr. D. McCartney, and Dr. Q. Zhang.

My thanks to Manitoba Hydro in cooperation with Chemawawin Cree Nation and Manitoba Livestock Manure Management Initiative for funding this project.

I express a large amount of thanks to the numerous students that have been part of this project: James Allen, Nathan Dueck, Curtis Garlinski, and Rexson Tse.

I would like to thank Doug Pauls of Highplain Farms for allowing us to test the full-scale biofilter on his commercial swine unit.

Thanks to the Jack Brogan of the University of Manitoba Glenlea Station Research for the patience and Jody Philippe from the swine unit, location of the prototype biofilter.

I would like to thank all my friends that did not leave me during the summer because I smelled a little bit "fresh" from working on the biofilter.

I would like to thank Marie Bowers, Van Doan, and Carl Pronyk for being willing to proofread this thesis.

I would like to thank my parents for their encouragement during this project.

Moreover, I could not to forget the technicians that provide much of the practical knowledge that was required to do this project Dale Bourns, Aime Chaput, Matt McDonald, and Gerry Woods.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND TERMS

H – Height (m) - This the measurement of biofilter media in term of height above ground level

t - Thickness (m) – This is the measurement of the biofilter media parallel to the airflow

W – Width (m) – This is the small measurement of biofilter media's footprint

L – Length (m) – This is the larger measurement of the biofilter media's footprint

EBCT – Empty Bed Contact Time (s)

EBRT – Empty Bed Residence Time (s)

V – Volume (m^3)

Q – Air flow rate (m^3/s)

τ - True Residence Time (s)

f – Porosity (%)

ϵ – Removal Efficiency (%)

C_{Gi} – Inlet Concentration (ppmv, g/m^3)

C_{Go} – Outlet Concentration (ppmv, g/m^3)

S_L – Surface Loading or Face Velocity ((m^3 m^{-2}) s^{-1} or m/s)

A – Area (m^2)

1. INTRODUCTION

Swine units have always produced odours, but with the introduction of industrial agricultural techniques, these odours have become a nuisance to the people living near these factory farms. Presently there are a number of technologies available for removing these odours, but many of these technologies, in terms of capital and operating costs, are currently too expensive for the profitable operation of a swine unit. One technology that has been suggested as a possible solution is biofiltration.

Biofiltration is a recent technology when compared to other technologies for odour removal, with research for agricultural application only starting in the 1970s. Biofilters, the physical part of the technology of biofiltration, has contaminated air drawn through the media contained within the biofilter, where micro-organisms living on the media use a number of biological processes to break down the odorous compounds, thus removing the odours and volatile organic compounds (VOCs). This thesis will investigate the design of a horizontal airflow woodchip:compost biofilter; treating exhaust air from a research swine unit at the University of Manitoba.

1.1 Background

Research begun in the 1970s has been attempting to design an agricultural biofilter for the removal of odours from a number of agricultural sources. The combination of two of the many properties of the biofilter has limited the success of the technology, which is pressure drop and footprint size. An agricultural biofilter needs to operate at low pressure to reduce the operating costs, but this typically results in a biofilter with a large footprint. Most farm sites are not limited with space as a whole but, with the size of the newer swine units, space near the swine unit is sometimes limited. This results in a biofilter with a smaller footprint, driving up the pressure requirements of the fans for moving the air through the biofilter and increasing operating costs. Research conducted at the University of Manitoba has shown that horizontal airflow through biological material such as biofilter media requires less pressure than moving the same air vertically through the same thickness of material. This is the idea behind a horizontal airflow biofilter that can offer a low-pressure small footprint biofilter.

2. LITERATURE REVIEW

2.1 Swine Unit Air Quality

Normal air, which most people define as clean air, consists of many components, but is mainly limited to nitrogen, oxygen, argon, carbon dioxide, a number of trace gases, water vapour, and small quantities of microscopic and sub microscopic solid matter (ASHRAE 1999). If the quantities of microscopic and sub microscopic material increase or other materials are present, the air quality is lowered as the air is considered contaminated. To maintain air quality within a swine unit during hot weather, the ventilation system is designed and built to meet the requirement of temperature control with a high flow rate, approximately 56.6 L/s of air per pig. During the winter, the flow rates are reduced to approximately 5 L/s per pig to control air contaminant levels within the swine unit, while still maintaining acceptable temperatures and minimizing the cost of heating (Midwest Plan Service 633 1983). An ideal ventilation system for a finishing barn would attempt to control the temperature and within the range of 15 to 22 C year round with the exact temperature being dependant on the age of the housed pigs. Temperatures outside this small range affect pig growth resulting in more time required for the pigs to reach their desired weight, therefore increasing costs. Reducing ventilation airflows and/or adding heaters can increase temperatures that are below this ideal range; increasing the ventilation airflow rates is a common solution to control temperatures above this range. However, the technique of increasing flow rates can only cool the swine unit to approximately 3 to 5 C higher than the ambient temperature outside the swine unit.

The large amounts of air that are moved through the swine unit contain low levels of contaminants with a majority of the released contaminants being harmless but extremely odorous at these levels (Albright 1990; Bensafi et al. 2003; Bensafi et al. 2002; CHEMINFO 2003; Lim et al. 2001; Schiffman et al. 2001; and Zhou 2001). The contaminants in the swine unit air are generally a result of anaerobic microbial decomposition. They include a mixture of gases, vapours, dust, and other particles (Hammond et al. 1979; Hobbs et al. 1999a; Hobbs et al. 1999b; O'Neill and Phillips 1992; Wood et al. 2001; and Zhu et al. 1999). The major gas compounds in the swine unit air are: carbon dioxide, hydrogen sulphide, methane, ammonia, nitrous oxide, acetone, and a number of trace gases which consist of four major types; fatty acids, phenols, indoles, and methylamines (Hobbs et al. 1999a; Hobbs et al. 1999b; Lim et al. 2001; Ni et al. 2002; O'Neill and Phillips 1992; Schmidt et al. 2002; Wood et al. 2001; and Zhu et al. 1999,). There are a number of odour management practices available for the control of odours, but the majority of these controls still leave the odorous compounds at noticeable levels (Bottcher et al. 2001; CHEMINFO 2003; Goodrich and Mold 1999; Jacobson et al. 1999; Lemay 1999; Schiffman et al. 2001; Sheridan et al. 2003; Tyndall and Colletti 2000; Wilhelm and McKinney 1999; William 1984; Zhu et al. 2000; and Zhu and Schmidt 1999).

An acceptable past practice for dealing with contaminated air was to increase the amount of dispersion with a clean air stream. One of the methods of increasing dispersion is to build large stacks that move the contaminated air higher into the atmosphere where better dispersion can occur (De Nevers 1995). An idea similar to this has been studied as a solution to the odour problems surrounding swine units, but under certain weather conditions, the odours still do not disperse enough (Guo et al. 2001; and Jacobson et al. 2001).

As the air quality of the swine unit is important, current barn designs and the conditions placed on the design because of Manitoba's climate requires a variable flow rate air handling system. The design needs to be able to maintain large airflows in the summer to control temperature. In the winter, the swine units require low ventilation rates with supplemental heating to control contaminants. With this range of flow rates, the ventilation systems of most swine units are usually divided into four or five stages. The first stage is the minimum airflow required to ensure proper air quality in the swine units during the coldest temperatures. The final stage is when all the fans are operating to cool the swine unit in the summer. The rest of the stages are controlled by monitoring the swine unit's internal temperature. These key internal temperatures for activating and deactivating the fans are commonly referred to as set points. There are a number of different methods for determining these set points.

Empirical equations have been developed to predict the levels of contaminants inside swine units so that proper ventilation systems can be designed. From this research, the concentrations of contaminants inside the swine unit is dependent on a number of environmental conditions such as time of year, barn design, and current ventilation rates (Harting and Phillips 1994; Hobbs et al. 1999a; Hobbs et al. 1999b; Jacobson et al. 2001; O'Neill and Phillips 1992; Ritter 1989; Wilhelm and McKinney 1999; Zhou and Zhang

2003; Zhu and Jacobson 1999; and Zhu et al. 1999). Including some of these environmental conditions, a ventilation system design similar to the one shown in Fig. 1 will be created. In this chart, the production level of carbon dioxide and relative humidity is also included (Albright 1990; Campbell et al. 2003; and Manitoba Pork 2003).

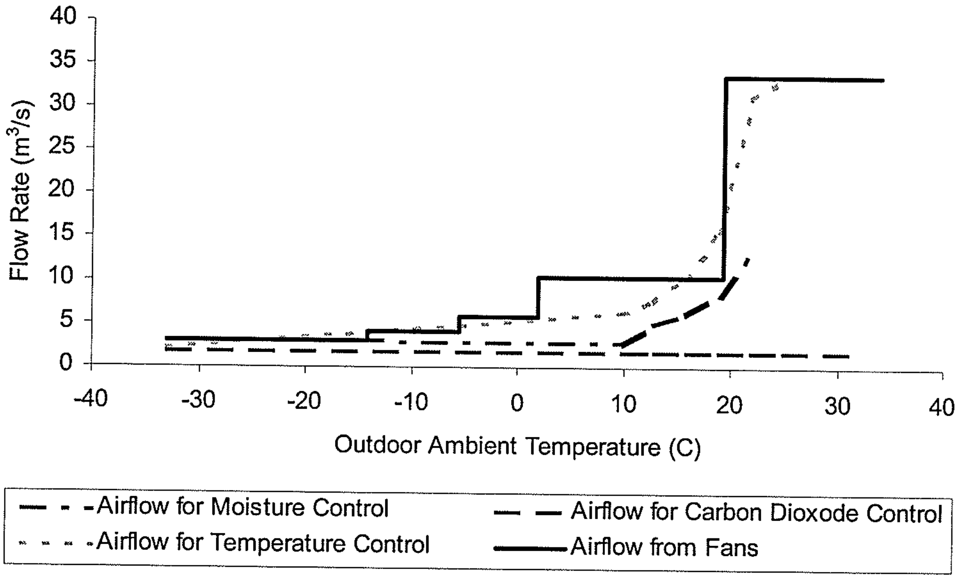


Figure 1 Ventilation Flow rate vs. Outside Temperature within a modern commercial swine unit. This design is for an 800 – 80 kg pig swine unit in Brandon, Manitoba, using standard construction materials for swine units in Manitoba.

2.2 Biofiltration

The application of biofiltration for the treatment of odours and VOCs is a recent technology with the first patents being awarded in the 1950s (Devinny et al. 1999). There are numerous other technologies available for removing odours and VOCs, such as incineration, membranes, and adsorption. Costs and removal efficiency are usually the deciding factor for the selection of the technology used (Devinny et al. 1999).

Biofiltration has been suggested as an ideal method for the removal of odours and VOCs from sources with the combination of low concentrations of contaminants and high flow rates (Devinny et al. 1999). In addition, the waste or end products of biofiltration rarely require further treatment for safe disposal. Table 1 illustrates the advantages and disadvantages of several of these technologies available for treatment of odours and VOCs.

In biofiltration, micro-organisms living on the surface of the biofilter media, often referred as to the biofilm, survive by consuming the chemical compounds that are the contaminants as a source of food with water, carbon dioxide, biomass, heat, and various salts being produced from this biological process (Devinny et al. 1999).

The process is expressed graphically in Fig. 2. A majority of the compounds that are easily treated through biofiltration are water soluble, thus these contaminants are easily absorbed into the biofilm, as it is made up largely of water. After the contaminants have been absorbed into the water around the biofilm, the biological community will break down the compounds into water, carbon dioxide, and biomass or other chemical compounds. These other chemical compounds will be broken down further through the same process by other members of the biological community within the biofilm (Devinny et al. 1999).

Table 1 Comparison of odour and VOC treatment technologies

Control Technology	Advantage	Disadvantage
Biofiltration	Low operating and capital costs Effective removal of compounds Low pressure drop No further waste streams produced	Large footprint requirement Medium deterioration will occur Less suitable for high concentrations Moisture and pH difficult to control Particulate matter may clog
Biotrickling filters	Medium operating and capital costs Effective removal of compounds Treats acid-producing contaminants Low pressure drop	Clogging of biomass More complex to construct and operate Further waste streams produced
Carbon adsorption	Short retention time / small unit Effective removal of compounds Suitable for low / moderate loads Consistent, reliable operation	High operating costs Moderate operating costs Carbon life reduced by moist gases Creates secondary waste streams
Incineration	System is simple Effective removal of compounds Suitable for very high loads Performance is uniform and reliable Small area required	High operating and capital costs High flow / load concentrations not cost effective Creates a secondary waste stream Scrutinized by public
Wet scrubbing	Low capital costs Effective removal of odours No medium disposal required Can operate with a moist gas stream Can handle high flow rates Ability to handle variable loads	High operating costs Need for complex chemical feed systems Does not remove all VOCs Water softening often required Nozzle maintenance often required

(Devinny et al. 1999)

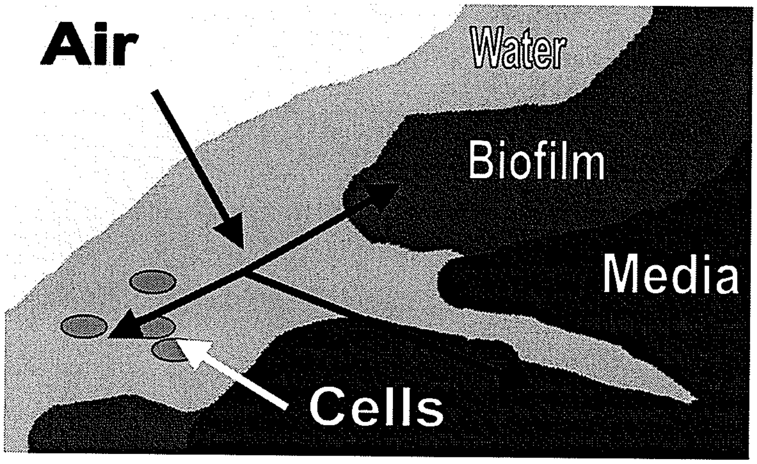


Figure 2 Adsorption process in a biofilter. Contaminate are dissolved into the water from the air which is then uptake by cells, and adsorbed by the biofilm and organic matter in the media

(Devinny et al. 1999)

As mentioned earlier, the products produced by biofiltration are water, heat, various salts, gases, and biomass. Biofilters can fail in a number of ways. Many of the causes are the result of insufficient removal of certain by-products from the process of biofiltration, however most of these by-products are easily removed with the existing air, which consists of waste gases, water and some of the heat.

The by-products that cause problems in the biofilter are biomass and salts. The various salts produced by the biofiltration process accumulate within the biofilter, which affects the pH of the media and in turn harms the biological community and results in reduced removal rates. This problem can be controlled by the addition of various chemical compounds to the biofilter media to attempt to control changes in the media's pH (Devinny et al. 1999; and Smet et al. 1996). Biomass accumulates on the surface of the biofilter media, reducing the void space and eventually stopping airflow through the pore spaces resulting in increases in pressure drop through the biofilter media.

With the biofiltration process, there are a number of variables that can affect the performance of the biofilter. Important parameters of the biofilter are residence time and volume of airflow being treated, which determine the volume of the biofilter (Devinny et al. 1999). These properties are predetermined, thus the availability to change these values is limited. The footprint of the biofilter, surface loading, and pressure drop through the biofilter media are optimized in terms of capital and operating costs (Marek et al. 1999; and Philips et al. 1995).

After these biofilter parameters have been determined, other biofilter properties can be addressed, which include the selection of the biofilter media and the operation of the biofilter (Aizpuru et al. 2003; and Devinny et al. 1999). The most important of these properties is the biofilter media, home to the biological community. Large amounts of research have been conducted in determining the optimum bacteria and biofilter media combination for the treatment of specific VOC (Devinny et al. 1999; VDI 1991). With selection of the biofilter media, cost, lifespan of the media, porosity, and pressure drop through the media are optimized for the lowest capital and operating costs with respect to removal efficiency of the biofilter (DeBruyn 2000; Gerrard 1997; Li et al. 1996; Nicolai 2002; Noren 1985; Philips et al. 1995; and Sweeten et al. 1991). Included in the selection of biofilter media are the requirements of the micro-organisms for the adequate removal of contaminants. These requirements include various nutrients, water, and other necessities required for the survival of the micro-organisms (Devinny et al. 1999).

After the selection of the proper biofilter media, certain management procedures can be addressed for effective biofilter operation. Biofilter media water content is probably the most important property after the selection of the biofilter media and micro-organisms because water is required by the micro-organisms for optimal performance (Hartung et al. 2001; Krailas et al. 2000; Satida et al. 2000; Sun et al. 1999; van Lith et al. 1997; and VDI 1991).

2.3 Biofilters Use on Swine Units

A majority of the odorous chemicals produced at a swine unit are effectively eliminated with the technology of biofiltration (Devinny et al. 1999; and VDI 1991).

One of the main reasons for limited use of any type of odour control technology for the treatment of exhaust air from a swine unit has been the installation cost, and more importantly, the operating costs of these technologies (Nicolai 2002; O'Neill and Phillips 1992; and Yang and Allen 1994). Biofiltration has been shown to be cost-effective when compared to other technologies for treatment of odours when high flow rates are present. Biofilter installation costs are similar to other odour control technologies, but a properly designed biofilter will have lower operating costs and the benefit of not having to treat secondary by-products (van Lith et al. 1997). Most other technologies that remove the chemical compounds that cause the odour usually transform the target pollutant into an easier form or chemical compound to deal with, requiring more processing to make the new compounds safe for disposal (Devinny et al. 1999).

Investment costs of a commercial biofilter can be as low as $1 000 (US) / floor space for one finishing pig ($5 (US) / m^3h^{-1} of air treated) (Boyette 1998; and Devinny et al. 1999). Biofilter designs that have been investigated by researchers for agricultural applications have been built for approximately $18 / floor space for one finishing pig ($0.09 (US) / m^3h^{-1} of air treated) (Nicolai and Janni 1998; and Noren 1985). People within the agricultural industry suggest an installed cost in the range of $0.69 to $1.69 per m^3h^{-1} of treated air and a removal efficiency of 70% as adequate (Cochrane 2003).

Published research on biofilters used to treat agricultural odours produced by swine has been conducted in the mid-70s in Europe (Zeisig 1977). Since this initial research, research conducted at the University of Minnesota by K. Janni and R. Nicolai have offered a more cost-effective biofilter design for the treatment of odours from agricultural sources (Nicolai 2002). The results of this research and others have suggested that agricultural biofilters need to be extremely low pressure and large footprint biofilters (DeBruyn 2000; Gerrard 1997; Hobbs et al. 1999b; Li et al. 1996; Nicolai 2002; Noren 1985; Philips et al. 1995; and Sweeten et al. 1991). A number of patents have been granted for the application of treating odours from agricultural sources with a biofilter, using a number of different biofilter designs (Bruns and Zimmer 1998; Firth 1998; Hartmann 2002; and Tumchenok 2001).

As most biofilters are used in warmer climates for the treating of odours from composting and waste treatment facilities, a concern with agricultural biofilters in Northern climates is the ability of the biofilter to be able operate effectively in the extremely cold temperatures experienced in winter. Research shows minor reductions in the performance of the biofilter operating in these extreme temperatures (Clark et al. 2004; Krishnayya et al. 1999; Mann et al. 2002; and Ross et al. 2002).

2.4 Biofilter Parameters

In order to properly construct a biofilter, certain design constraints such as air source, location, and media choices available need to be addressed. Other design constraints are thickness of biofilter media, footprint of biofilter, airflow, surface loading, porosity, residence time, pressure drop, temperature, water content, pH and removal efficiency with limited ability to modify a number of these constraints. Table 2 lists the typical values for most of these biofilter parameters with continuing research improving the understanding of the roles of various parameters in the performance of a biofilter.

2.4.1 Airflow through a biofilter

The airflow being treated by a biofilter is usually predetermined with the biofilter being sized to meet the requirements of the airflow. Nevertheless, with many applications, the maximum airflow and the average airflow rates are not the same with many biofilters being designed for the maximum airflow. Systems that use biofiltration for the treatment of odours or other contaminants usually are supplied by a number of fans, with some or a majority of these fans being non-operational for long periods. With ventilation systems determining the operation of the fans, these periods of reduced airflow may result in the starvation of the biofilter's micro-organisms when fans are offline.

Table 2 Biofilter Parameters

Parameter	Typical Value
Biofilter Thickness (t)	1 – 1.5 m
Biofilter Area (A)	1 – 3 000 m^2
Waste Air Flow (Q)	0.01 – 83.3 m^3/s
Surface Loading (S_L)	0.001 – 0.14 $(m^3m^{-2})s^{-1}$
Bed Void Volume (Porosity f)	50 %
Gas Residence Time	15 – 60 s
Pressure Drop / Meter of Biofilter Thickness	20 – 100 Pa / m (Max 1 000 Pa / m)
Operating Temperature	15 – 30 C
Water Content of Biofilter Media	60 % by mass
pH of Biofilter Media	PH 6-8
Typical Removal Efficiencies	60 – 100 %

(Devinny et al. 1999)

Research into the starvation of the micro-organisms within the biofilter has shown that the length of time that the biofilter is starved will predict the amount of time before the biofilter will be able to return to previous contaminant removal levels again. Studies by Wani et al. (1998) on the biofilter's ability to treat airflow after these periods of low or no airflow suggests that the diverse biological community within the biofilter is able to handle these changes. The research determined that for up to seven days without airflow, a biofilter is able to achieve previous removal rates within 30 hours of coming back on line. With most fan staging on swine units, limited reduction of removal efficiency should be expected because of the fans not operating continuously.

Another problem that might occur is sudden spikes in the contaminant concentration levels. This is likely to occur in the spring and the fall when the outdoor temperature is near one of the set points in the ventilation system resulting in one of the fan stages having non-continuous operation. During the rest of the year, most of the fans will either be operating continuously (summer) or taken off line (winter). The periods of higher concentration will likely occur right after a fan stage is activated. Research into this problem has shown that, depending on the size of the spike, most biofilter systems are able to handle spikes in contaminant levels (Wani et al. 1998).

2.4.2 Gas Residence Time

The residence time is a standardized method to describing the volume of a biofilter in terms of an unit airflow. Residence time can be expressed in various forms, such as empty bed residence time (EBRT), empty bed contact time (EBCT), and many other variations on these names (Devinny et al. 1999). Equation 1 (Devinny et al. 1999) shows the formula:

$$EBCT = \frac{V}{Q} \tag{1}$$

Where:
EBCT = Empty Bed Contact time (s)
V = volume of biofilter (m^3)
Q = airflow from fans (m^3/s)

The second form of expressing the biofilter size for an unit airflow is true residence time (τ), which is shown by Eq. 2 (Devinny et al. 1999). This form incorporates the porosity of the biofilter media in determining the time the air spends in the biofilter media. This form provides a truer measure of the actual time the air spends in the biofilter as the media does reduce space available for the air within the biofilter.

$$\tau = \frac{V_p \times f}{Q} \tag{2}$$

Where:
τ = true residence time (s)
V = volume of biofilter (m^3)
f = porosity (%)

True residence time will always be smaller than the EBCT because of the addition of porosity in determining the time the air spends in the biofilter. True residence time is a better description than empty bed contact time when two different biofilters are being compared with different media, as large differences in porosity can be present affecting the performance of two biofilters of equal volume. One of these two formulas will be used to determine the volume of the biofilter as the other variables are defined already.

In determining the appropriate residence time, the level of odour reduction needs to be determined with the understanding that reductions in residence time result in lower removal efficiencies for the biofilter. Equation 3 (Devinny et al. 1999) is one of the many formulas available for determining the removal rate of the biofilter. With the use of a biofilter on a swine unit, the aim would first be the removal of all the combined concentrations of odorous compounds to below their detection level at some given distance from the source as a goal of 100% removal does not offer enough benefits for the additional costs. In addition, the biofilter itself does produce an odour, but it is often described as a woody smell, which can be considered pleasant. From the literature, a biofilter is expected to produce approximately 20 – 100 OU/m^3 of exiting air (DeBruyn et al. 2001; and Devinny et al. 1999).

$$\varepsilon = \left(\frac{C_{Gi} - C_{Go}}{C_{Gi}} \right) \times 100\% \qquad (3)$$

Where:

ε = removal efficiency (%)
C_{Gi} = inlet concentration (ppmv or g m^{-3})
C_{Go} = outlet concentration (ppmv or g m^{-3})

In published research for the treatment of odours from swine units, an EBCT of 6 s has been suggested as an acceptable length of time (Nicolai 2002). Figure 3 helps explain the reasoning for this design graphically. After air has been contained for a certain length of time in the biofilter, increases in the time spent in the biofilter provide little improvement in removal efficiency while greatly increasing the costs of the biofilter (Yang and Allen 1994).

2.4.3 Surface Loading and Pressure Drop through Biofilter Media

Surface loading, often referred to as face velocity, is the speed at which air leaves the biofilter. In terms of designing a biofilter, the pressure drop through the biofilter media is the pressure required for the air to travel through the biofilter media without reducing the flow rate. Surface loading and pressure drop through the biofilter media are inter-related as can be seen by the Eq. 4 (Sadaka et al. 2002). With Eq. 5 (Devinny et al. 1999) and 6, the thickness of the biofilter media bed can be determined. From the literature and a basic understanding of fluid mechanics, surface loading has been limited to a maximum of about 0.2 $m^3s^{-1}m^{-2}$ as the fan requirements for higher pressure drop through the media for higher surface loading make the design impractical (Mann and Garlinski 2002; Hartung et al. 2001).

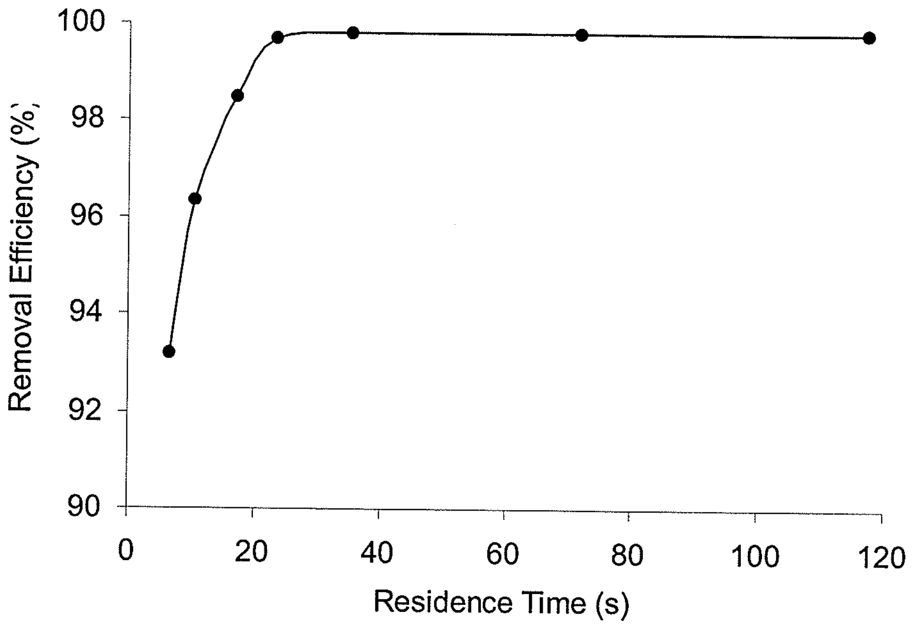


Figure 3 Hydrogen Sulphide removal efficiency as a function of residence time (Yang and Allen 1994)

$$\frac{P}{t} = \frac{a \times S_L^{\ 2}}{\ln(1 + b \times S_L)} \tag{4}$$

Where:
P = total pressure drop experienced by media (Pa)
S_L = surface loading of biofilter ($m^3s^{-1}m^{-2}$)
a and b = constants for specific biofilter media (unit less)
(Sadaka et al. 2002)

$$S_L = \frac{Q}{A_s} \tag{5}$$

Where: A_s = surface area perpendicular to airflow (m^2)

$$t = \frac{V}{A_s} \tag{6}$$

Where : t = total thickness of biofilter perpendicular to airflow (m)

In practice, the combinations of these three equations are used to physically design the dimensions of the biofilter. When using these equations, certain variables should be known, such as airflow, space available, and maximum pressure drop through biofilter media allowed. The pressure requirements are probably the most important constraint as the fans or booster fans that supply the air at a given pressure are usually determined because of capital or operating costs. Previous knowledge of the biofilter media, from either published data or previous experience, is required to use Eq. 4. However, slight changes in the properties of the biofilter media might have large effects on the pressure drop through the biofilter media as other factors such as direction of airflow can affect the pressure drop. The variables that affect pressure drop will be discussed in a later section (Sec. 2.6) as most of this knowledge comes from airflow research through biological material like grain and oil seeds. As surface loading can be determined from the information already described, the surface area and thickness of biofilter media are determined relatively easily from the volume of the biofilter.

2.4.4 Control of Moisture Content of the Biofilter Media

Moisture content is one of the few properties of biofilter media that can be easily controlled and that affects the performance of the biofilter. Low moisture levels within the biofilter are one of the most common reasons for the poor biofilter performance, but too much water in the biofilter will also reduce the performance of the biofilter (Neal and Loehr 2000; Sun et al. 2000; and van Lith et al. 1997).

To determine the best method of controlling moisture content in a biofilter, the media's ability to store water and easily release water when needed needs to be addressed with an ideal media being hydrophilic. Extra attention is needed in the selection of biofilter media to ensure the media is not hydrophobic as large problems can occur when the biofilter media needs to be rewetted (Devinny et al. 1999).

A biofilter should consistently have a moisture content in the range of 40 to 80 $\%_{wb}$ with a porosity between 40 to 80 % (Devinny et al. 1999). The upper limit for the moisture content is the field capacity of the biofilter media, which is usually 80%. The lower limit usually is the point at which noticeable changes in performance of the biofilter occur because of water stress to the micro-organisms.

There are two basic methods for controlling the moisture content of the biofilter media. One method is direct irrigation using "soaker hoses" installed into the bed or on the bed and the other is indirect watering with the use of a humidification chamber upstream of the biofilter. A humidification chamber attempts to make all incoming air entering the biofilter have a relative humidity (RH) of 100% (Devinny et al. 1999). It is common practice to use a combination of both systems, but a biofilter can be built using one of the two systems discussed (Devinny et al. 1999). The selection of either or both moisture control systems is usually a result of investigating the different benefits and faults of each of the systems.

One of the problems with only using soaker hoses is that the water will strip the upper levels of the biofilter of nutrients as it moves down through the media. In addition, this same process moves the biomass and various salts down through the biofilter, clogging and or creating areas of high acidity which causes problems with the micro-organisms abilities to properly treat the contaminants at the lower levels of the biofilter (Devinny et al. 1999).

Alternately, the use of humidification chambers directly upstream of the biofilter has problems, as the chamber attempts to raise the RH of the air to the 95 to 100 % range. As it is impossible to always have the air at 100% RH, small amounts of water are removed from the biofilter media until an equilibrium is achieved between the air and the biofilter media, thus the biofilter slowly dries out unless water is added from a different source such as soaker hoses (Devinny et al. 1999).

2.5 Biofilter Media Properties

When designing a biofilter, there are a number of different concerns with the biofilter media's properties. These properties include porosity, bacterial and organic content, and pressure drop (Devinny et al. 1999; and VDI 1991).

2.5.1 Porosity of the Biofilter Media

The porosity of the biofilter media is one of the most important properties as it greatly affects the pressure drop requirements of the fans moving air through the biofilter media (Sadaka et al. 2002). With respect to water content, the porosity will help provide uniform moisture content throughout the biofilter media and help with the movement of water within the biofilter media. Porosity also greatly influences the locations where the bacteria in the biofilter can and will live as the micro-organisms require certain sized void spaces (Devinny et al. 1999). According to the literature, a porosity of 50 % or higher is desirable. Published porosities of some woodchip:compost mixture are around 55 % with Fig. 4 showing the porosities of various woodchip:compost mixtures from the research conducted by Sadaka et al. (2002).

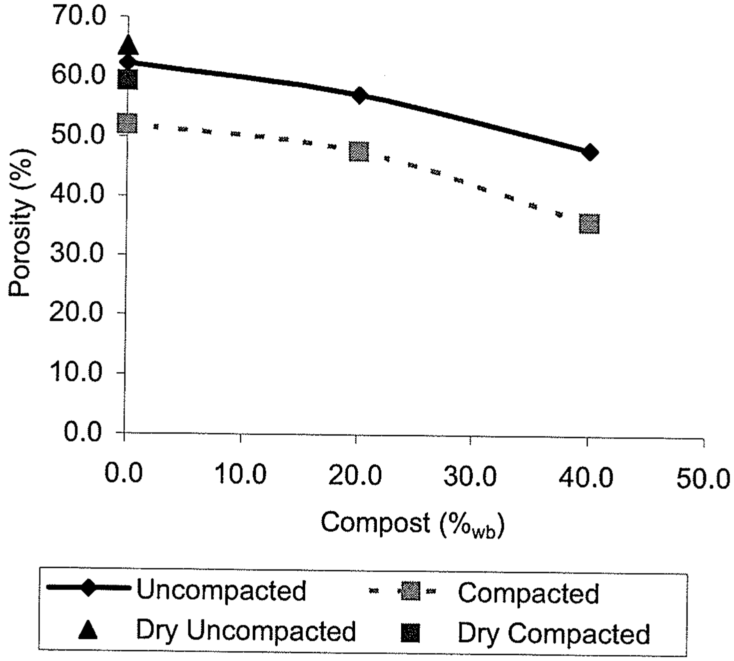


Figure 4 Change in porosity with respect to compost content in a woodchip mixture. (Moisture content of material is approximately 52% $_{wb}$ unless stated otherwise) (Sadaka et al. 2002)

2.5.2 Micro-organisms and the Nutrient Source

The micro-organisms present in a biofilter media tend to be a diverse mixture of bacteria and fungi that reduce the odorous compounds to simple non-odorous compounds (Devinny et al. 1999; and VDI 1991). For agricultural applications, nitrifiers and sulfate reducing bacteria tend to be the best given the chemical compounds present in the odorous exhaust air from a swine unit (Li et al. 1996; and Williams and Miller 1992a).

Research has been conducted into seeding specific lines of micro-organisms into a biofilter for the treatment of specific compounds. However, outside the lab, some research conducted in Europe has shown that during the operation of a specifically seeded biofilter, other bacteria spores have entered the biofilter which were better suited to the target chemicals and thus dominated the original micro-organisms (Damborsky et al. 1999).

In addition, within the biofilter media, there are a number of different ecological niches to be occupied by bacteria for the proper removal of the contaminant compounds (Devinny et al. 1999). These different niches are a result of the non-uniformity of the biofilter media and the biological processes that are required to reduce the contaminants. For the biofilter to properly treat all contaminants in the airflow, different bacteria are required to operate in these different conditions and treat different contaminants. The use of well-aged compost with its very diverse biological community works well as a source of bacteria (Devinny et al. 1999; Janni et al. 1998; and Smet et al. 2000).

During the biofilter's operation, the different micro-organisms within the biofilter have a variety of demands for different nutrients. Some of these nutrients are supplied through the contaminants in the air, but usually the contaminated airflow is missing some key nutrients. From the literature, a C:N:P mixture that resembles 200:10:1 is considered a good mixture (VDI 1991). The contaminated airflows tends to supply the carbon source, with the operator of the biofilter adding the nitrogen and phosphorous as required.

2.5.3 Biofilter Media Material (Synthetic / Organic)

There are two basic types of biofilter media; organic or synthetic. Organic biofilter media are usually a mixture of varying ratios of compost and wood chips, peanut shells, or other "hard" organic materials that provide a stable long-term structure available for the micro-organisms to live on. Inorganic material such as gravel is also included in this type of biofilter media. The compost or sewage sludge supplies the nutrients and micro-organisms for the biofiltration process (Devinny et al. 1999; and VDI 1991). The selection of a good medium will greatly increase the porosity of the media resulting in decreasing the pressure drop through the media. A negative aspect of organic type medias is the tendency to for the media to decrease in porosity and increase in pressure drop with the passing of time as the media is compacted (Devinny et al. 1999). The benefit of these types of media is that they are usually locally available and thus cost effective, making them inexpensive source for biofilter media, which can be replaced when the biofilter starts to fail (Devinny et al. 1999; and van Lith et al. 1997).

Synthetic biofilter media tends to be used in industrial applications as the synthetic media offers benefits over the organic compounds. Materials that are considered synthetics are biofilter medium that are made from plastics or porcelain. A synthetic biofilter media is more uniform than an organic media, which reduces the likelihood of channelling of the air (Devinny et al. 1999; Luttighuis 1998). In addition, the pressure drop through a synthetic media tends to be lower than the organic biofilter media partly due to the uniformity and the ability to design the shape of the synthetic media (Devinny et al. 1999). Two of the major problems with synthetic media are the cost of the media, as the media tends to not be locally available with limited suppliers (Devinny et al. 1999), and the need to monitor and feed nutrients to the biofilter to maintain the health of the micro-organisms. As most synthetic media mixtures do not have a compost or sludge component to supply micro-organisms and nutrients and has a limited water holding capacity, a more and closer monitoring is required than an organic media biofilter.

2.6 Airflow Resistance through Organic Material

When air travels through a material such as wood chips, some pressure loss is expected, as pressure is the potential energy available in the system that allows the air to travel through the media. There is a small amount of published research available related to the pressure loss through woodchips, but a larger amount has been conducted in grain research. This section will look at pressure drop through grain, with some of the explanation being able to be carried over to biofilter media.

The pressure change occurring as the air travels through grain or woodchips is because of energy lost due to friction and turbulence of the air moving through these materials (Alagusundaram and Jayas 1990). There are numerous variables that affect this resistance, including air velocity, viscosity, moisture content of biological material, shape and size of material, surface characteristics, and airflow direction. As mentioned earlier, an inorganic media could be designed to minimize the effects of many of these variables, thus reducing pressure drop through the biofilter media.

The ASAE Standard D272.3 discusses resistance to airflow for a variety of agricultural products. This Standard is based on loose filled material in a bin; in terms of a biofilter media, this would represent a fresh or non-compacted media. Information contained within this Standard states that packing of the material might increase the pressure drop through the media by as much as 50%. In addition, this Standard shows that horizontal airflow may represent only 60 to 70% of pressure drop for the same airflow and thickness as vertical airflow, a reduction in pressure requirements of between 30 to 40%.

Sokhansanj et al. (1990) looked at the changes in pressure drop that occurred with differences in moisture content, fill method, varietal difference, airflow direction, and fines concentrations for lentils. From these experiments, increases in moisture content reduced the pressure drop, which was already known as research conducted by Shedd (1953) saw decreases in pressure drop with increases in moisture content. However, as related to biofilter media, the moisture content for their material, lentils, was below 30%, while almost all biofilter media have a much higher moisture content.

With varietal difference, lentils showed increases in pressure drop with the reduction in seed size. Seed size differences can have a large effect on the porosity and bulk density of the samples. In other research by Jayas et al. (1987b), it was determined that the method used to fill the bin had a greater effect on the pressure drop than the size and moisture content of the seed being tested. From this research, it was shown that different filling methods could greatly increase the bulk density, which in turn lowers the porosity of the grain and increases the pressure drop through the grain.

Kumar and Muir (1986) noted that the pressure drop was less when the air traveled through the grain in the horizontal direction than if the air travelled through in the vertical direction. This difference in pressure drop represented about 50 to 80 % of the pressure drop of air travelling through in the vertical direction for wheat. Kumar and Muir felt that kernel orientation had an effect on the pressure drop difference that was observed in their research. The research found that the grain is usually oriented with the major axis of the kernel in the horizontal axis. Similar research by Calderwood (1973) showed that for the same rice variety, the length of the grain affects the pressure drop experienced. Rice with a longer major axis offered reduced airflow resistance with respect to vertical airflow than rice with a shorter major axis in the vertical direction.

If kernel orientation is responsible for these difference in pressure drop, a more symmetric seed like canola (rapeseed), a sphere, should have minor differences in pressure drop between the vertical and horizontal airflow. Research by Jayas et al. (1987a) on pressure drop through canola still experienced the differences in pressure drop, similar to wheat and barley, when comparing horizontal and vertical airflow. Based on these results, it can be concluded that the shape of the grain is not the only property of the kernels that affects the pressure drop.

From the information that is available, it appears that the moisture content, porosity, shape of the grain, and the airflow direction have a substantial effect on the pressure drop experienced. Shape of the grain and fill method have an effect on the porosity, which in turn affects the pressure drop experienced by the material. As demonstrated in this research, the direction of airflow has the largest effect on the pressure drop and the researcher suggests that this is a result of the orientation of the material.

2.7 Airflow Resistance through the Biofilter Media

From the available information, it is demonstrated that horizontal airflow results in a lower pressure requirement than vertical airflow for the same thickness of biofilter media (Sadaka et al. 2002). Figure 5 shows pressure drop versus airflow for two mixtures of biofilter media, which indicates that direction of airflow has a considerable effect on pressure drop.

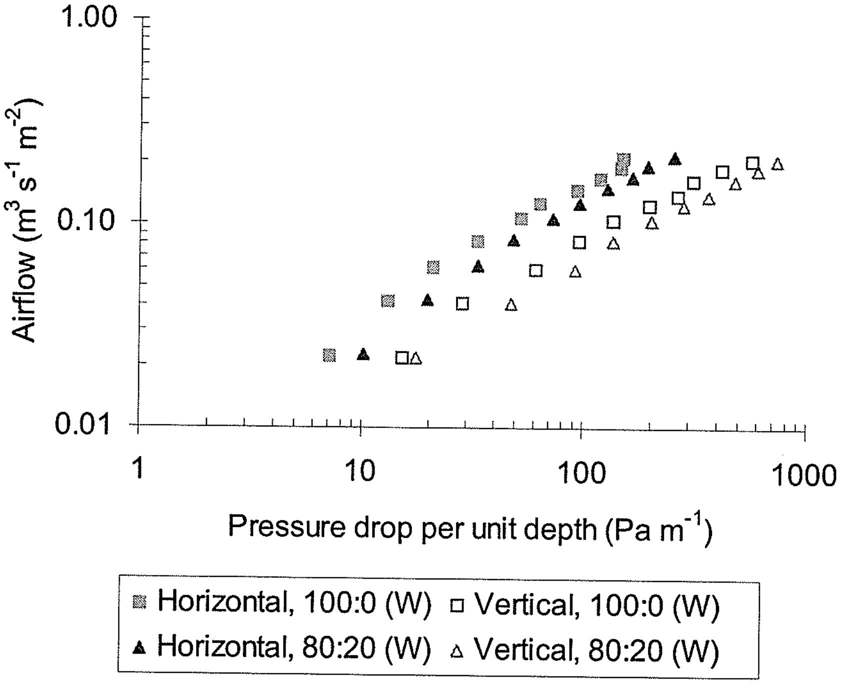


Figure 5 Airflow vs. Pressure Drop

W= 55% water content
Ratio is woodchips : compost $_{(wb)}$ (Sadaka et al. 2002)

2.7.1 Vertical Airflow

Presently, almost all commercial biofilters are vertical airflow biofilters divided into two configurations, up flow or down flow. Both of these designs operate with either positive pressure where air is forced through the biofilter media, or negative pressure where air is sucked through the biofilter media (Devinny et al. 1999). The simplest design is the up flow system. This design consists of a simple pressurized air plenum system buried under the biofilter media with the air travelling up through the media. The one major problem with this design is that watering usually occurs from the top, but the bottom of the biofilter is where water is needed as the media dries out first at the bottom and while the top is over-watered. This causes nutrients from the top layer of the media, as well as various acids or salts that might harm the micro-organisms, to move down to in the lower areas of the biofilter (Devinny et al. 1999).

The other design is a down flow system, which requires the biofilter media to be enclosed and the space above the media to be pressurized forcing the air down through the media. A benefit of this system is that the water is usually applied to the top, which is also the first to dry out. The problem with this design is the increased cost because of having to enclose the biofilter as compared to the up flow biofilter.

2.7.2 Horizontal Airflow

Currently, little information is available about the performance of any full-scale horizontal airflow biofilters in the literature other than the material published as part of this project (Garlinski and Mann 2003; and Mann and Garlinski 2002). Some research has been conducted with lab scale horizontal airflow biofilters (Lee 1999). The research looked at different woodchip:compost mixtures as well as results from vertical and horizontal airflow biofilters. With the design of the lab scale biofilters, it was determined that the horizontal airflow biofilter performed better than the vertical airflow biofilter. From their research, the better results from the horizontal airflow biofilter were because of better mixing and thus more uniform airflow through the biofilter media. The horizontal airflow had a higher pressure requirement of the two biofilter designs, but this is due to a different layout of the biofilter than the vertical airflow as the horizontal airflow biofilter was considerably thicker in terms of direction of airflow. (Choi et al. 2003; and Lee et al. 2001).

Research published by Sadaka et al. (2002) provides data about the pressure drop through biofilter media in vertical and horizontal airflow directions. From this research, it was shown that if all factors were equal, horizontal airflow would have a lower pressure drop through biofilter media than vertical airflow for the same thickness of biofilter media.

A concern with any horizontal airflow biofilter is the ability to ensure that no channelling occurs across the top of the biofilter media. In the lab scale design, baffles were installed into a packed biofilter media to reduce the channelling (Choi et al. 2003), but possible settling of the biofilter media could result in failure of this baffle design.

3. RESEARCH OBJECTIVES

Biofiltration has been shown to be able to remove a majority of the contaminants produced by a swine unit, but pressure requirements, i.e. associated costs, have limited the popularity of using biofiltration as a technology for odour removal. Research into pressure drop through biological material has shown a lower pressure requirement for moving air horizontally rather than vertically through the same thickness of biological material. Combining these two ideas, a design for a horizontal airflow biofilter was created with this thesis determining if this idea is practical.

With this knowledge, the purpose of this thesis is to design an operational full-scale horizontal airflow biofilter for the removal of contaminants from a swine unit. Although the idea of a horizontal airflow biofilter is not a new idea, only small amounts of literature could be located that discuss the performance of such a design over any length of time, including the few lab scale experiments conducted. Thus, the objectives of this thesis are the following:

A. Pressure Drop Through Biofilter Media

In order to build a biofilter, the ability to accurately predict the pressure drop through the biofilter media is important. In addition, what effect does length of time operating the biofilter have on the pressure drop through the biofilter media? This will be done by:

- Comparing measured pressure drop against theoretical pressure drop at specific distances from the internal plenum.

- Plotting measured airflow against pressure drop per unit depth and comparing to theoretical values.

B. Airflow Through the Biofilter

A biofilter is designed to handle a specific flow rate. The ventilation system of a swine unit requires specific flow rates and if the ventilation system does not meet these requirements, negative results occur. Thus, research has shown that with a vertical airflow biofilter, flow rates through the biofilter decrease with age. With horizontal airflow, are the reductions of airflow similar? Also, as no information was found discussing the variability of the airflow of a biofilter face, determining the variability and monitoring it for changes is important, i.e. stratification of the biofilter in terms of airflow. Answering these questions will be done by the following:

- Monitoring airflow over the majority of the biofilter face.
- Determining any problem areas by investigating measured airflow as Z values.
- Determining if stratification is occurring by using Z values and comparing them over time.

C. Settling of Biofilter Media

From literature, settling of the biofilter media does occur with negative results usually with a vertical airflow biofilter, but with a horizontal airflow biofilter because of headspace design, too much settling will result in the failure of the biofilter. The ability to predict the overall settling is important. With this, determining if layers within the biofilter media settle at different rates is just as important as this might affect airflow or pressure drop through the biofilter media. In this thesis, this analysis will be done by:

- Monitoring overall settling of the biofilter media.
- Determining if settling is linear throughout biofilter media volume.

D. Hydrogen Sulphide Removal

As the biofilter purpose is the removal of contaminants from a swine unit's exhaust air, with this thesis only looking at hydrogen sulphide, does the biofilter remove these contaminants? As with the airflow data, is the contaminant removal uniform over the biofilter face and what are the effects of time on this removal rate? The processes for this are similar to airflow, as the following will be done:

- Monitoring hydrogen sulphide readings over the majority of the biofilter face.
- Determining problem areas by investigating measured hydrogen sulphide readings as Z values.
- Determining if stratification is occurring by using Z values and comparing them over time.

This experiment started in the fall of 2001, with the full-scale prototype biofilter being constructed in the summer of 2002. Modifications to this design occurred in the spring of 2003 as design flaws became apparent. Most of the data for this thesis was collected after these modifications.

4. MATERIAL

4.1 Location of the Biofilter

The prototype biofilter was located at the southwest corner of the research swine unit at the University of Manitoba Glenlea Research Station. Figure 6 shows the location in relation to the barn as well as other fans on the west side of the west wing of the swine unit.

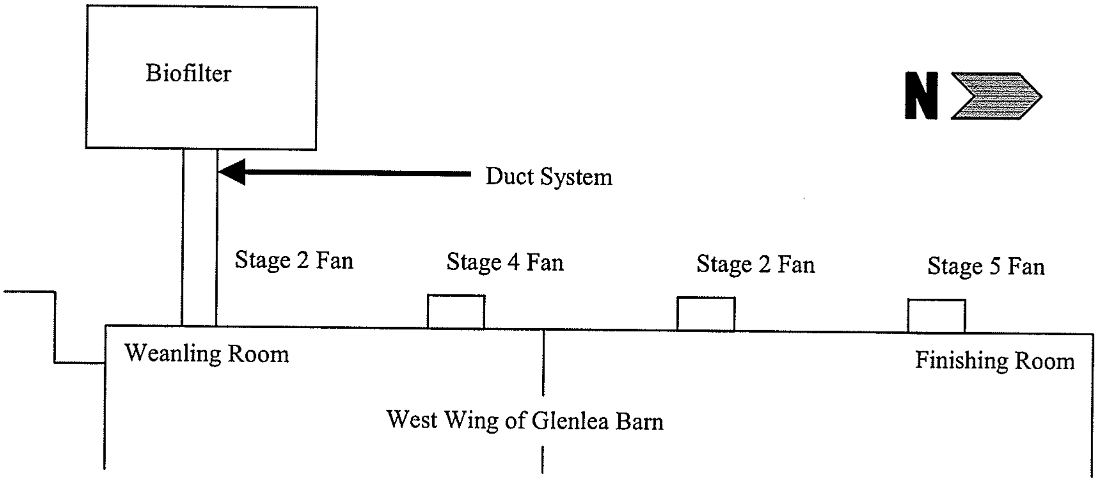


Figure 6 Location of Biofilter at Glenlea

4.2 Ventilation Systems of Swine Units

The exhaust fan supplying the contaminated air to the prototype biofilter was a 0.48 m diameter – 124 W, (19"-1/6 hp) axial fan with an assumed flow rate of 1.89 m^3/s (4 000 cfm). (Note: factory specifications for the fan are not available.) This flow rate was based on an assumption that a similar size and style fan, 0.51 m diameter – 370 W (20"-½ hp) fan operating at a static pressure of 37 Pa (0.15" of water) (BETTER AIR 2002). This fan is a stage two fan in a four-stage system ventilating a weanling room. The fan is expected to operate a majority of the summer months, mid-May to early September as explained in literature on swine unit air quality.

The assumed airflow was determined to be high, when originally designing the biofilter, but this value will be used throughout the thesis. After collecting data and analysing the results, a better assumption for airflow would have been 1.26 m^3/s (2 680 cfm). The information comes from MidWest Service (1983) for a fan that is 0.45 m diameter – 186 W (18" – ¼ hp) at 25 Pa (1/8") backpressure. Research by Lim et al. (2003) has shown that factory specifications for fans tend to over estimate when compared to the actual performance of the installed fan, therefore, even this new flow rate should have been verified. Ideally, a device that would measure airflow accurately, such as Fan Assessment Numeration System (FANS) (Gates et al. 2002), should have been used.

4.3 Design of a Horizontal Airflow Biofilter

As previously mentioned, designing a biofilter with horizontal airflow requires the prevention of channelling across the top of the biofilter media (Choi et al. 2003). A novel design of biofilter was created for this project. Until just recently, little was available on designing a biofilter of this type. Looking at the design of the test biofilter used by Sadaka et al. (2002) and the apparatuses used to test pressure drop for grain, a biofilter was designed that used a pressurized headspace to attempt to limit channelling across the top of the biofilter medium (Kay et al. 1989; and Kumar and Muir 1986). To help reduce construction costs, the idea of supplying air from an internal plenum was included (Mann and Garlinski 2002). The internal plenum allows for "two" biofilters to be supplied from either side of the plenum, only half as much plenum is required with this design. Near the end of the project, a patent was issued for a very similar biofilter design, but little is available about construction and performance of the biofilter described in the patent (Yoran et al. 2003). Schematics of the "Glenlea" biofilter can be found in Appendix A. Figure 7 shows a top view of this biofilter design with the arrows representing the direction of airflow. In this design, the air enters the biofilter unit from a duct at one end of the plenum of the biofilter and once in the internal plenum, the air will exit by traveling out through the biofilter media on either side of this internal plenum.

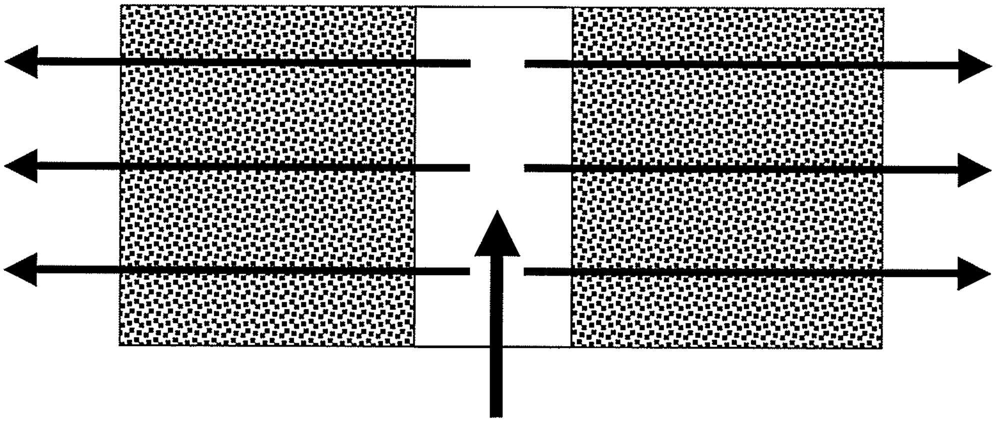
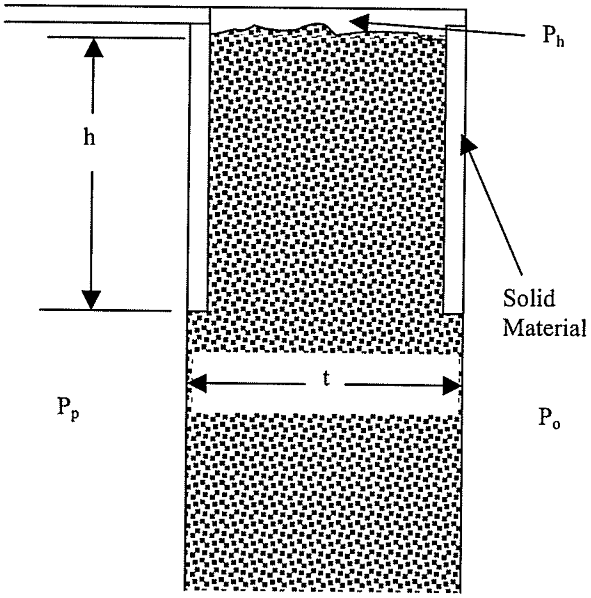


Figure 7 Overhead view of a biofilter showing airflow through the biofilter media

The method originally used by the researchers to study horizontal airflow through grain was to use a wooden box constructed with the two opposing walls of expanded metal, which represent the inlet and outlet for the airflow. Polyethylene was placed on the top of the grain with rubber foam being placed above the plastic to form a tight seal between the grain and the polyethylene after the lid was placed on the box. The foam was compressed to eliminate air from escaping from the top of the grain sample (Kay et al. 1989; and Kumar and Muir 1986). As a small-scale unit was used in their research for a short period, any settling occurring will not have influenced the results. With a full-scale biofilter, a similar design would work, but the idea is not practical. For the foam design to work, large amounts of foam would need to be added during construction or dismantling the biofilter to add more foam after the media settles would have to be done, neither idea is practical for a biofilter sized to treat the odours from an entire swine unit.

An ideal method of sealing the top of the biofilter would be one that applies just enough pressure on the biofilter media to form the seal to stop untreated air from escaping through the top of the biofilter. In the research conducted by Sadaka et al. (2002), the use of a pressurized headspace was used. A pressurized bladder was installed in place of the rubber foam and polyethylene. The bladder was pressurized from a line coming in from the plenum feeding the biofilter.

Results of their research showed that the pressure drop through a unit thickness of material in the horizontal direction (ΔP_h (Pa/m)) is lower than the pressure drop per unit thickness in the vertical direction (ΔP_v (Pa/m)) (Sadaka et al. 2002). This knowledge offers the possibility of another biofilter design that does not require a pressurized headspace. The explanation of these two designs of biofilter will be shown with the use of Fig. 8. The two designs of biofilters offered are a "thick," sealed pressurized headspace biofilter, and a "thin," non-pressurized headspace, biofilter. The terms thick and thin are used to describe the ratio of thickness (t) to height of solid material (h) sealing the top of the biofilter. With both designs, the height of h must be minimized, as by the manner in which these biofilters are explained, the biofilter media located behind this solid material will not treat any contaminated airflow.



Where the variables are the following:

P_h is headspace pressure (Pa)
P_o is ambient pressure (Pa)
P_p is plenum pressure (Pa)
t is thickness of biofilter media (m)
h is height of biofilter media above biofilter wall without direct access to pressurized plenum (m)

Figure 8 Headspace design when pressurizing a horizontal airflow biofilter

4.3.1 Sealed Pressurized Headspace Horizontal Biofilter Design

A thick biofilter would be one where the following conditions exists:

- $P_p < \Delta P_v \bullet h + P_h$
- $\Delta P_h \bullet t < \Delta P_v \bullet h + P_h$
- $P_h > P_o$

With this design, the headspace is sealed and can be pressurized directly from the plenum or from another pressure source. The pressurized bladder should be free to move down within the space above the biofilter media to accommodate the settling media. If the bladder is not able to make contact with the entire top surface of the biofilter media, channelling is possible. Depending on which of these conditions fail, the biofilter will allow the contaminated air to leave the biofilter vertically into the headspace or the air will channel across the top of the biofilter media, depending on the final dimensions of the biofilter.

This design works because the contaminated air will attempt to move as much air as possible with as little pressure loss as possible. Without the pressurized headspace, the path of least resistance would be to exit through the top or channel across the top if not open to the atmosphere. With the design of the sealed pressurized headspace, it required less pressure for the air to move horizontally through the biofilter media than to move vertically through the biofilter media and attempt to exit through the top or channel across the top.

When designing this type of biofilter, the height of the solid material (h) needs to still exist in some form after the biofilter media has settled over time. When selecting the design of the biofilter, this design would be better suited when the costs of the biofilter media is greater than the costs of fans (in terms of pressure), as only a minimal amount of biofilter media is not used to treat contaminants.

4.3.2 Non-Pressurized Headspace Horizontal Biofilter Design

A thin walled biofilter would be one where the following conditions exists:

- $\Delta P_h \bullet t < P_p << \Delta P_v \bullet h$
- $P_h = P_o$

When these two conditions are true, the air will travel through the biofilter media horizontally. This design works similar to the pressurized headspace design with the exception that the biofilter material itself stops the contaminated air from travelling vertically through the biofilter media and leaving. This design will fail when the pressure requirements for the air to travel vertically through the biofilter media (h) is less than the pressure requirements for the air to travel horizontally through the biofilter media (t). If the air were to follow this path, the biofilter would not necessarily fail, as the contaminated air still travels through some biofilter media and is treated nonetheless. This is not recommended, as this path would offer less in terms of residence time as compared to the horizontal path through the media.

To limit the amount of unused biofilter media, this design works best when the horizontal path is relatively small, thus low pressure, as higher pressures or longer horizontal paths will require more media on top not being used to treat contaminants, just stopping the air from travelling vertically through the biofilter media.

4.4 Media Selection of the Biofilter

The media for the biofilter is a woodchip:compost mixture, which is a common material for agricultural biofilters. This is a good biofilter media selection as the compost provides the biological community as well as the nutrient source, and the woodchips provide a good structure for the media to slow compaction, as well as increase the porosity of the mixture thus reducing the pressure drop through the biofilter media. The woodchips that were used in this prototype biofilter experiment are ¼" woodchip (woodchips are ¼" (6 mm) thick, 1" (25 mm) wide and of various lengths) created from driftwood at Cedar Lake, Manitoba. The compost for this biofilter was purchased from Rockwood Ag Inc. in Stonewall, Manitoba.

From the literature for agricultural biofilters, an EBCT of six s with a 70:30 woodchip: compost mixture is recommended as a minimum (Nicolai 2002). In order to decrease the pressure drop through the biofilter media, a thinner mixture, 80:20 was used, but in hopes of maintaining good removal efficiencies, a longer EBCT of 9 s was used. From research by Nicolai (2002), this mixture should work, but a media mixture with a larger compost content would likely result in a higher contaminant removal rate.

As this biofilter media mixture is similar to the mixtures described in the literature (Sadaka et al. 2002), it was assumed that the properties of the biofilter would be similar to those presented in Table 3. Figure 9 shows the particle distribution in terms of length of the woodchips as a percentage of mass of sieved media.

Table 3 Actual design parameter and media characteristics of prototype biofilter

Parameter	Biofilter Design
Waste Air Flow (Q)	1.89 m^3/s
Bed Void Volume (Porosity *f*)	57 %
EBCT	9 s
Pressure Drop / Meter of Biofilter Thickness	40 Pa/m
Maximum Water Content of Biofilter Media	54 $\%_{wb}$
Bulk Density	387 kg/m^3

(Sadaka et al. 2002)

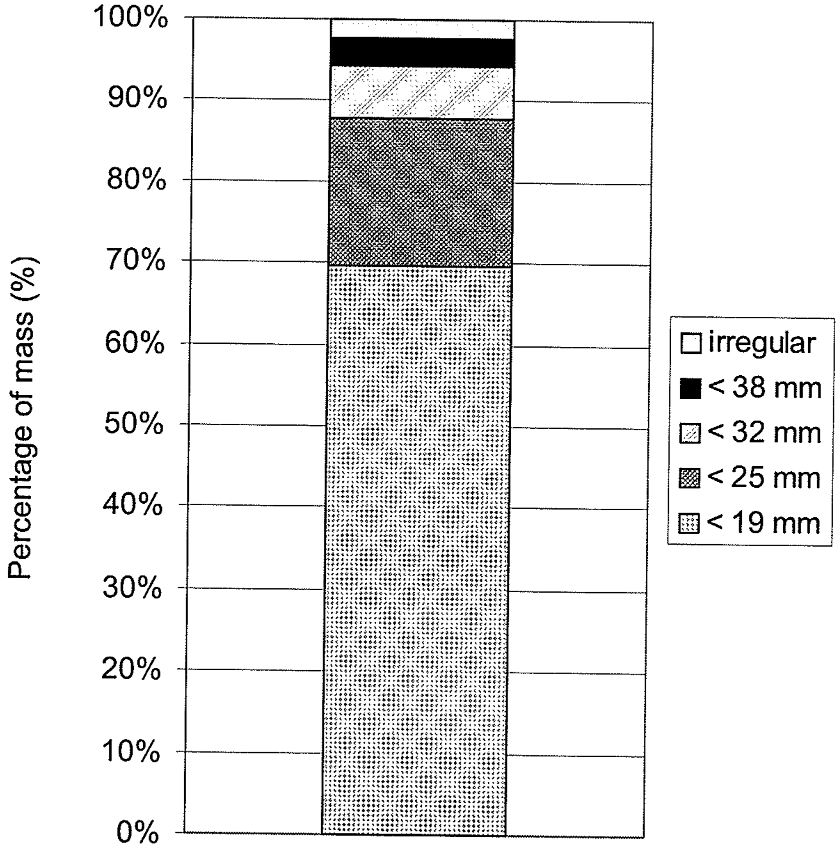


Figure 9 Particle distribution of woodchips in terms of length
(Sadaka et al. 2002)

4.5 Sizing the Prototype Biofilter

The prototype biofilter at Glenlea was designed to handle an airflow of 1.89 m^3/s with an EBCT of 9 s, which would results in a true residence time of 5.4 s assuming the porosity of the media is 60%. From the calculations in this section, it was determined that the biofilter dimensions would be 1.83 m long, 3.05 m high and 4.27 m thick of which 3.05 m is biofilter media, with 1.52 m of on either side of the plenum, with a design static pressure drop of 136 Pa.

Assuming the following:

$Q = 1.89\ m^3/s$
$EBCT = 9\ s$
$a = 5396.6$
$b = 61.37$
$h = 3.05\ m$

The values for a and b were selected from the 60:40 mixture data (Sadaka et al. 2002). The information for the 60:40 was used as it was felt that the aging media would result in media more similar to a 60:40 mixture than an 80:20 mixture. Therefore using Eq. 1:

$$\begin{aligned} V &= EBCT \times Q \\ &= 9\ s \times 1.89\ m^3/s \\ &= 17\ m^3 \end{aligned}$$

With the design of the biofilter, it was predetermined that the thickness of the biofilter media had to be at least 1.52 m (5 ft). The intention is to use a skid-steer loader to remove the woodchips, which is approximately 1.35 m wide. With Eq. 6, the biofilter's surface area can be determined.

$$\begin{aligned} A &= V/t \\ &= 17\ m^3/1.5\ m \\ &= 11.3\ m^2 \end{aligned}$$

From the design of the biofilter's internal plenum, only 80% of the surface area is available in the plenum for air to travel through to reach the biofilter media, thus the actual area is $A_a = 9.0\ m^2$. This is because the construction of the headspace requires the top fifth of the internal plenum to be constructed of solid material to achieve a pressurized headspace. This will result in a shorter residence time as the entire volume of biofilter is not available to treat the contaminants, but none of the literature into biofilters has ever discussed this issue and it will be assumed the media is inactive. Surfacing loading is determined using Eq. 5.

$$S_L = Q/A_a$$
$$= 1.89\ m^3/s\ /\ 9.0\ m^2$$
$$= 0.21\ m^3/s/m^2$$

The length of the biofilter was divided in two as the plenum supplies contaminated air to both sides of the plenum. Finally, the pressure required to move the air through the biofilter media is determined using Eq. 4 and the final dimension of the biofilter can be calculated.

$$P = t \times [(a \times S_L^2)/(\ln(1+b \times S_L)]$$
$$= 1.5\ m \times (5396.6 \times (0.21\ m^3/s/m^2)^2)/(\ln(1+61.37 \times 0.21\ m^3/s/m^2)$$
$$= 135.7\ Pa$$

$$L = (A/h)/2$$
$$= (11.3\ m^2\ /\ 3.05\ m)/2$$
$$= 1.85\ m$$

To supply the desired airflow of 1.89 m^3/s at a pressure of 136 Pa, two 0.51 m – 370 W (20"-½ hp) fans (Better Air) where installed in series. It was expected that the barn fan would supply about 30 Pa of pressure, and the two booster fans, although not an ideal match with the current barn fan, are expected to supply approximately 50 Pa of pressure while maintaining an airflow of 1.89 m^3/s. Figure 10 shows a fan curve of a single booster fan, with the straight lines on the graph showing approximately, where the fan is expected to operate. The fan curve was extrapolated assuming a standard fan curve. The area of concern for most fans is for a certain range of static pressures; large decreases in airflow result with only slight increases in static pressure. With the barn and booster fans, it is strongly desirable not to operate in this range as maintaining a specific airflow is required from the fans in the swine unit. From Fig. 10, looking at the design airflow of

1.89 m^3/s, it can be seen that the booster fans will match the requirements relatively well, but looking at the actual airflow of 1.16 m^3/s, the booster fans have excess capacity to meet the pressure requirements of the biofilter. Appendix C contains calculations of the pressure requirements with new EBCT for the better estimate of airflow of 1.16 m/s.

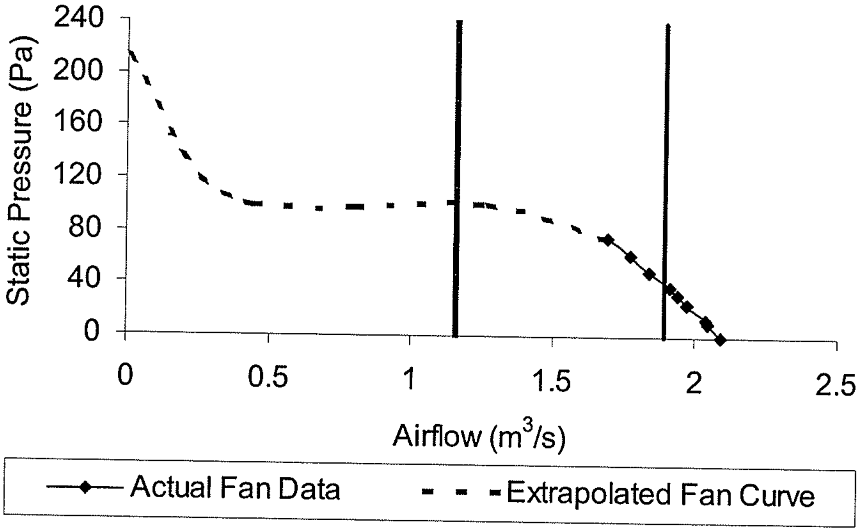


Figure 10 Fan curve for a 0.51 m (20") Better Air fan (Model 2000)
Solid line is design requirement of 1.89 m^3/s. Shaded line is actual airflow of 1.16 m^3/s

4.6 Construction of the biofilter

4.6.1 Headspace Design

As discussed earlier in this thesis (Sec 4.3), two methods are available for the design of the biofilter. With the prototype biofilter, the sealed headspace method was selected as the conditions for the thick biofilter design were met with the layout of the biofilter. The headspace contained a custom built plastic bladder. In this set-up, the supply of pressurized air entered the headspace through a circular 152 mm (6") flexible aluminium duct with the source of the pressurized air being the inlet duct system as seen in Fig. 11. With this design, the pressure in the headspace should be equal or close to the pressure in the internal plenum.

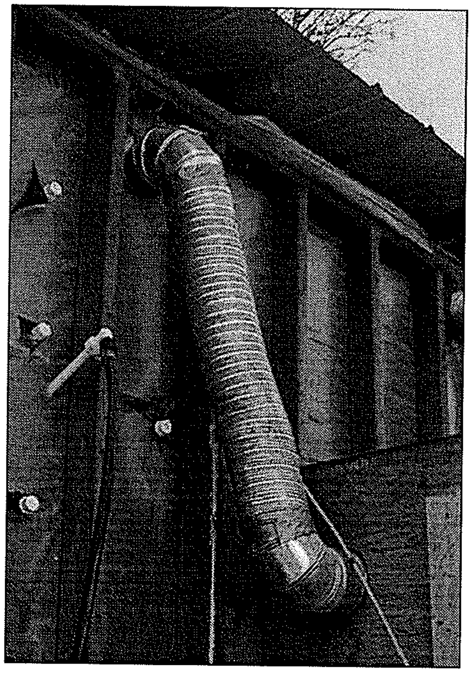


Figure 11 Duct system to pressurize the headspace of the biofilter.

4.6.2 Duct System and Internal Plenum

This prototype biofilter design uses an internal plenum, which allows air to exit through both sides of the biofilter structure. With this design, for a given thickness of biofilter media, the length of the biofilter can be halved, as the internal plenum is able to supply contaminated air to twice as much biofilter media for a given length of plenum.

The duct system is important to the biofilter as it can cost as much as the biofilter if not designed correctly (Boyette 1998). To reduce the cost of the duct system on this biofilter, a 0.36 m^2 (555 in^2) square plywood duct was built. This duct was constructed out of dimensional lumber and 13 mm (½") plywood with a 39 x 89 mm (2x4) dimensional lumber inside the duct to provide the structural support. The final design was a straight duct from the exhaust fan to the biofilter as it was felt that the two 90 degree bends to lower the ducting to the level of the floor were reducing airflow to the biofilter from higher than calculated pressure losses through the duct (Fig. 12). In Appendix C, the calculations are contained for both designs.

4.6.3 Biofilter Structure

The biofilter was constructed of pressure treated lumber as this type of material can be modified easily without special tools and moderate construction skills. The biofilter was constructed with a 39 x 140 mm (2x6) joist floor, 406 mm (16") on centre covered with heavy polyethylene and 13 mm (½") plywood. The walls were standard 39 x 89 mm (2x4) stud wall, 300 mm (12") on centre covered with heavy polyethylene and 13 mm (½") plywood on the media side (inside of the biofilter). Figure 13, shows the biofilter in the middle of construction. The inlet and outlet walls were sheets of ½-16F expanded metal on the media side of the stud wall with the top 600 mm (2 ft) of the walling being 13 mm (½") plywood to help pressurize the headspace. The roof was 39 x 140 mm (2x6) notched to produce a four-degree slope, which was covered with corrugated steel. The internal plenum was sealed on the top by 13 mm (½") plywood. Schematics for the final design of the Glenlea biofilter are in Appendix A.

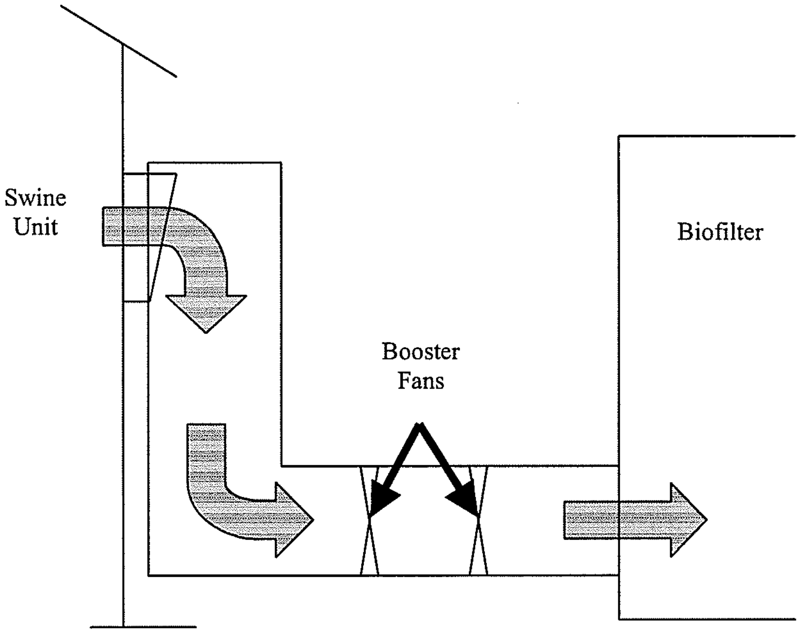


Figure 12 Original duct design for the biofilter
Current duct design is duct goes straight from swine unit to biofilter

4.6.4 Filling of Biofilter

As this biofilter design was untested, filling of the biofilter was done in stages to monitor the performance of the biofilter. Two different methods of filling were used. The woodchips were not sieved, thus the media is not uniform. The compost and woodchips were not thoroughly mixed, which is known to help increase the possibility of channelling. In the filling process, both sides of the biofilter were filled manually to the height of 1.5 m (5 ft). At this height, a 0.2 m (8") layer of compost was then added to the south side of the biofilter where a moisture sensor was buried in the layer of compost. The south side was then filled to the height of 1.8 m (7 ft) manually. The remainder of both sides of the biofilter were filled with a grain auger to a height of 3 m (10 ft).

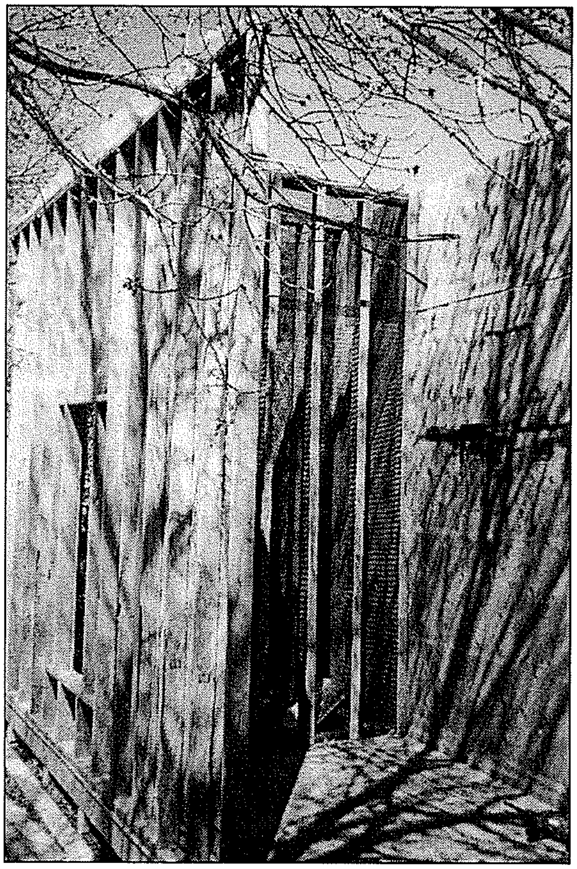


Figure 13 Showing partial structure of prototype biofilter before end wall is installed and filled with biofilter media.

4.7 Irrigation System

4.7.1 Watering System

With the prototype biofilter, two different watering systems were used. The final design was three 13 mm (1/2") diameter flexible plastic hose water lines with 1.5 mm (1/16") holes drilled at a spacing of 0.5 m (20") for the length of the hose spaced approximately 0.35 m (14") apart buried approximately 150 mm (6") below the top layer of the biofilter media. Fig. 14 shows the locations of the watering lines in the final and initial designs.

The water was controlled independently for each side of the plenum by a single timed solenoid (Melnor, Model 3015 Electronic Aqua Timer). The final water cycle was 120 s, every 12 h per side with a water flow rate of 5 L/min, which resulted in 0.04 m^3 of water per day.

In the original design, the expected water demand for the biofilter was determined from the water used by the biofilter constructed by DeBruyn in 1999-2000. A water demand of 3×10^{-3} m^3/day/m^3 of biofilter media was used in this research (DeBruyn 2000). Thus, for the prototype biofilter, a water demand of 0.05 m^3/day was expected.

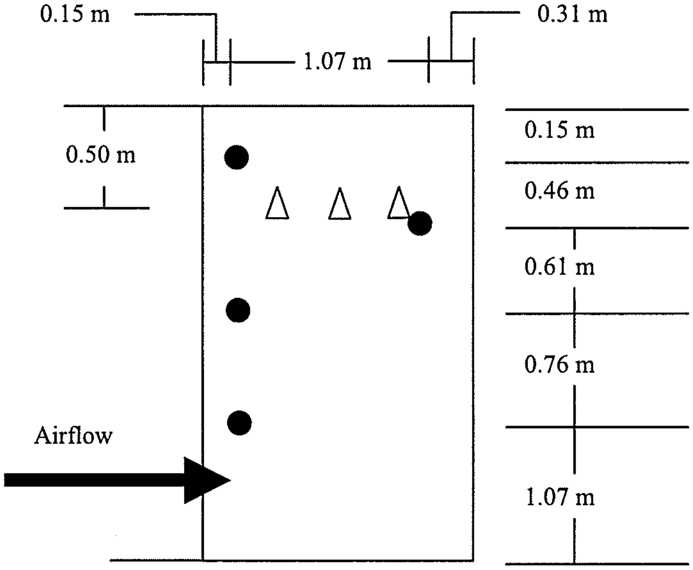


Figure 14 Location of water hoses on north side of prototype biofilter
(triangles represent the final locations (2003) of the plastic watering lines
circles represent the original locations (2002) of the copper waterlines)

The original design (2002) was four copper lines constructed similarly to the flexible plastic lines in the current watering system, but located at different locations as seen by the circles in Fig. 14. In this design, all eight lines were controlled by one solenoid activated by a moisture sensor located in the south side of the biofilter. In the 2002 design, the lines were placed in locations to address possible concerns over a drying front that was expected to move through the biofilter media. As well, the length of time for water to travel through the media was unknown and addressing concerns of nutrients transporting were involved in the placing of the watering lines. Insufficient water pressure caused by the use of a single solenoid in combination with splitting of this line into eight, resulted in insufficient water pressure to be supplied to all the lines at once, i.e. non-uniform watering of the media.

4.7.2 Moisture Monitoring

As the original watering system required monitoring of the moisture content, a single Aquaflex sensor was buried approximately 1.5 m (5 ft) above the floor of the biofilter media with a layer of compost approximately 200 mm (8") thick. The Aquaflex sensor was attached to a Taurus KS102 data acquisition unit, which controlled the solenoid in the original watering system (2002). The signal from the sensor was converted to a water content (%) using the formula supplied in the User's Manual for a Sand/Silt soil.

The moisture sensor was placed in the layer of compost as recommended by the manufacturer. The layer of compost was required for the sensor to determine the moisture content of the material surrounding it, as the biofilter media's particles were too large for the sensor to work properly. The recorded moisture content was not the true moisture content as the moisture sensor was not in contact with the woodchip:compost mixture. An attempt to calibrate the sensor to determine the true moisture content of the biofilter media resulted in discovering a shortcoming in the method of installation of the moisture sensor. The layer of compost was wrapped in a weed barrier to limit the transportation of the compost as water moved down through the biofilter media. This weed barrier also limited the amounts of water that was able to flow through the compost. The water flowed around the compost layer and moisture sensor unless it was allowed to pool above the layer and slowly flow through the weed barrier.

The Aquaflex sensor is a time domain transmission (TDT) sensor. This technology is based on the idea of a pulse being sent down the sensor and the time is measured for this pulse to travel the known distance. The moisture content of the material surrounding the sensor will affect the time required to travel this known distance. This can be used to determine the moisture content of the material by the difference in time required to travel this distance (Streatashead 2002). A problem with this type of technology for monitoring moisture content is that the biofilter media cannot be measured directly because a large percentage of the sensor needs to be in contact with the material. The biofilter media is too large for proper contact with the sensor. During the second year (2003) of operation, issues between the thermocouples and the data acquisition resulted in small amounts of poor data being collected.

The set points for controlling the watering system in 2002 were determined manually by first bringing the moisture content of the biofilter media to field capacity. That was reached when water was seen leaving the bottom of the biofilter. This reading was then recorded and became the upper limit for moisture content of the media. The biofilter was then allowed to operate for approximately 8 h, as it is common practice to water a biofilter two to three times a day, and the moisture content was recorded again. This lower limit was the moisture content point at which the watering would start. The sensor was never calibrated, as the method of installation of the sensor within the biofilter was flawed.

4.8 Operation of the Biofilter

Being this was a prototype biofilter, design improvements occurred during the operation of the biofilter. The biofilter's operation was divided into three basic operation styles. The data from the original design with the ducting that contained two 90-degree elbows was collected from June 26, 2002 to mid-Oct 2002 and is referred to in this thesis as 2002 biofilter data or summer 2002. In the spring of 2003, a headspace failure was discovered as well as a malfunctioning booster fan. Data collected from May 2003 to July 8, 2003 is referred to as spring 2003 biofilter data, which is the data when the biofilter had problems. All data collected after July 8, 2003 until the fall of 2003 is referred to as summer 2003 data, when the biofilter operated as designed.

4.9 Cost of Biofilter

As this is a research project, the cost of building this biofilter is important, as an agricultural biofilter needs to be cost effective. The following table lists the costs of various components of the biofilter. It is not recommended to follow this design for the treatment of odours from a swine unit. This design performed excellent as a research biofilter, but there are many improvements available to improve performance and reduce costs.

Table 4 Cost of Final Prototype Biofilter Design

Product	Unit Cost	Number of Units	Cost
Water lines	\$0.70 / m	7.3 m	\$5.11
Solenoids	\$30 / unit	2	\$60.00
Booster Fans [B]		2	\$957.60
Woodchips [A]	\$7.65 / m^3	17.03 m^3	\$130. 20
Compost [C]	\$15.70 / m^3	0.67 m^3	\$10.52
Ducting	\$ 34.19 / m	4 m	\$136.75
Roofing 3x8	\$ 45 / sheet	5	\$225.00
2x4	\$ 4.95 / 8 ft	12	\$ 59.40
	\$ 5.15 / 10 ft	64	\$ 329.60
	\$ 8.24 / 16 ft	4	\$ 32.96
2x6	\$ 6.57 / 8 ft	20	\$ 131.40
	\$ 13.23 / 16	6	\$ 79.38
5/8" Plywood	\$ 31.77 / sheet	18	\$ 571.86
Expanded Metal 4x8[D]	\$ 65.03 /sheet	8	\$ 520.24
10 – 3 ½" Screws	\$ 58.28 / 500	3	\$ 174.84
4x4 Posts	\$ 8.27 / 8 ft	6	\$ 49.62
Subtotal			\$ 3 474.48
Shipping	10 % of total		\$347.45
Misc.	10 % of total		\$347.45
Labour	30 % of total		\$1 042.34
Total			\$ 5 211.72 + tax

All wood products are pressure treated for extended life
All material was purchased from Home Depot unless noted.
A = Anseeuw Bros. Ltd. B = Better Air
C = Rockwood Ag Business D = Brunswick Steel

As the booster fans used in this project were available as they were purchased for a previous project, they were used even though they were not properly sized for this biofilter. In the cost analysis, the filling of the biofilter was not listed as this was done manually and with equipment that was available on the farm site. A concern with having to obtain equipment to fill the biofilter is the wall height of 3 m, which might require specialized equipment to reach this height, which should be reflected in the cost of filling the biofilter.

5. METHODOLOGY

5.1 Settling of Biofilter Media

Settling is one of the main reasons for replacing the biofilter media. Two methods were used to monitor the amount of settling that occurred within the prototype biofilter. The computer software that was used to analyze the data was Microsoft Excel 2000 (Microsoft, Seattle, WA) and SAS V 8.2 (SAS Institute, Cary, NC)

5.1.1 Overall settling of Biofilter Media

The first method used to monitor the settling of the biofilter media is a periodic method, as it can only be performed when the biofilter is dismantled. This method measures the change in height of the biofilter media on a 300 mm grid over the top surface of the media. In order to use this method, the headspace of the biofilter needs to be accessible, which is why this method can only be done periodically. The purpose of this method is that it can determine if the settling of the media is uniform over the entire surface of the biofilter media or if certain areas are prone to different rates of settling. However, this method cannot determine if layers within the biofilter media are settling at different rates.

As these samples are referenced to a specific location, a contour map can be created of the amounts of settling. In addition to calculating the average and standard deviation of settling, z values can be calculated to determine the probability of the amount of settling that occurred. To do this, it will be assumed that the data represents a normal distribution, therefore, calculating Z values using the mean and standard deviation of each side, specific locations can be identified as extreme values ($1.96 < Z < -1.96$) and should be investigated later.

5.1.2 Layered Settling of Biofilter Media

As the other method of monitoring biofilter settling is restricted in the ability to do repeated sampling, this method allows for continuous sampling without disrupting the operation of the biofilter. In addition, this method can be used to determine if specific zones or layers within the biofilter are settling at different rates than others. This method consisted of applying paint to the biofilter media and the expanded metal being used to contain the media. The expanded metal provides the reference point for the corresponding painted biofilter media that has moved down. To determine the amount of settling, the distance between the painted metal and the corresponding media is measured.

With this data, the amount the media settles at a specific level can be plotted against the physical height of this level (location of painted metal). If the data produces a straight line, the settling of the media is linear, and therefore uniform and if a curve is produced, the amount of settling then can be assumed a function of depth.

5.2 Face Velocity Sampling

5.2.1 Method of Sampling Face Velocity

Airflow sampling was conducted with a custom built cardboard amplifying cone. Figure 15 shows the dimensions of the amplifying cone. Two different anemometers were used to monitor velocity of the air exiting the centre of the amplifying cone, a vane anemometer (Turbo Meter, Davis Instruments) and later a hotwire anemometer (FlowRite, 800) when it was determined that the velocities of the air exiting from the cone might require more precise readings. The location of the sample was the centre of the cone with respect to the biofilter face and it was assumed that the anemometer reading was for that point only. This means that if channelling were occurring anywhere within the area the amplifying cone was sampling, the channelling would be recorded as being the centre of the amplifying cone. The actual airspeeds were back calculated using the dimensions of the amplifying cone, but with the assumption of no pressure loss from the cone. For most of the experiment, only half the biofilter face was sampled and at near the end of the experiment, almost the entire biofilter face was sampled.

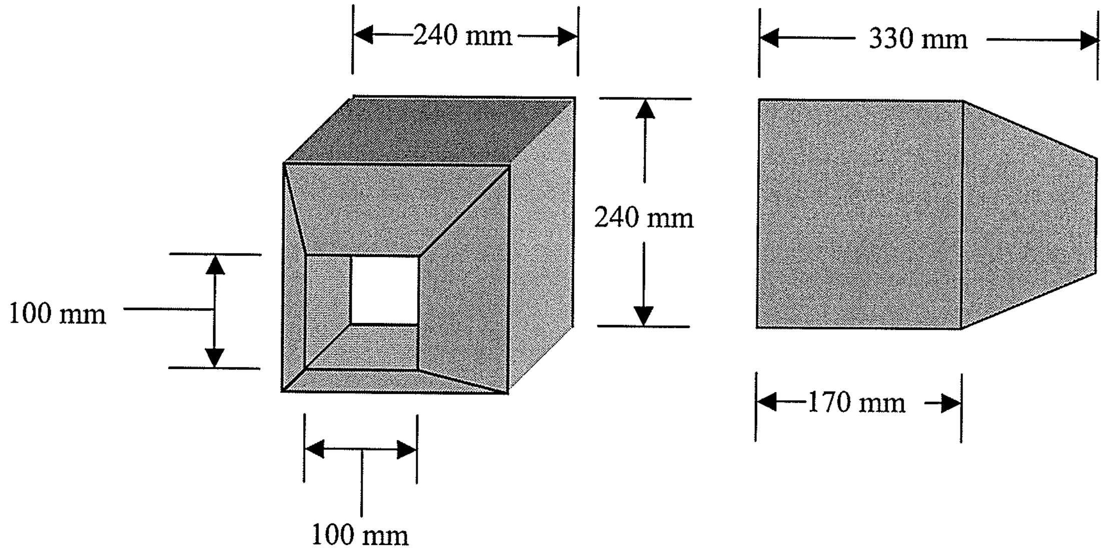


Figure 15 Amplifying Cone

5.2.2 Basic Statistical Analysis of Airflow Data

In biofilter research, certain information is provided when discussing the performance of a biofilter, which is average, standard deviation, maximum and minimum measured airflows. With this design of biofilter, the internal plenum is supplying air to “two” biofilters, the south and north side. A t-test was conducted to determine whether the two different sides of the biofilter were statistically different for each sampling date.

5.2.3 Identifying Biofilter Failures

With biofilters, usually a smoke test is conducted to determine if the biofilter is failing. However, this test will only illustrate the failure after it has occurred and does not provide any scale of the failure. As the airflow was measured from a majority of the biofilter face, Z-values can be calculated using the average and standard mean of that biofilter face for that sampling date. It is assumed that a properly operating biofilter would have face velocities that resemble a normal distribution. Thus, locations where the face velocity is above or below certain values could be considered extreme ($-1.96 > Z > 1.96$) and should be monitored or investigated further. A large negative or positive Z value would represent either a dead spot or channelling respectively. However, with the data, it is possible that a measured airflow of 0.0 m/s does not have a $Z < -1.96$. With an operating biofilter, 0.0 m/s is a dead spot by definition and thus a failure within the biofilter. These locations, airflow 0.0 m/s, will be noted even if the Z value does not identify it as an extreme value.

5.2.4 Airflow Stratification within Biofilter Media

The information provided from the measured face velocities can only provide information about the performance of the biofilter for a specific sampling date. A concern with this biofilter design is "will stratification occur within the biofilter?" It is thought that with the weight of the media, the material closer to the bottom of the biofilter volume would become more compact and therefore restrict airflow more than the top. As the biofilter underwent a number of modifications during the course of the experiment, to determine if airflow stratification has occurred a method needs to be developed, as looking at the data for the last sample date will not show stratification. Trends need to be identified. As Z values have been calculated, this has resulted in standardizing all the data points, which allows the data collected to be compared without concern because of differences in magnitudes between data collected on different sampling dates.

To reiterate, all data locations had a Z-value calculated using the mean and standard deviation for that biofilter face for that sampling date. To ensure dead spots are highlighted, locations with a measured airflow of 0.0 m/s will be given an exaggerated Z value of –3.50.

The technique suggested for determining if stratification is occurring, the average Z-value and the standard deviation of the Z values over time need to be calculated for that specific location. Specific combinations of average and standard deviations will locate areas of concern. To explain what the different combinations of averages and standard deviation represent, see the table below.

Table 5 Explanation of Determining Stratification Technique

Average Z Value	Standard Deviation of Z values	Explanation of Results
Z > 0.96	Any Value	In order to have an average Z value > 0.96, the location on average must be operating in the top 1/6 of the airflows. This would suggest channelling is occurring or the location is close to being considered channelling
-0.96 < Z < 0.96	> X	X represents the standard deviation of a point that moves from the top quarter (75 percentile) to the bottom quarter (25 percentile). This represents a change of 50%. Therefore, there is a problem with this area and needs to be investigated, i.e. unstable.
-0.96 < Z < 0.96	< X	Data collected from this location is remaining within desired airflows for a majority of the time, i.e. stable.
Z < -0.96	Any Value	In order to have an average Z value < -0.96, the location on average must be operating in the bottom 1/6 of the airflows. This would indicate low airflow or a dead spot; either would show that the area is suffering from insufficient airflow.

X = Standard Deviation of data set of n/2 0.676 and n/2 –0.676, if n is odd, than n/2+0.5 0.676 and n/2-0.5 –0.676 with n = number of sampling trials

5.3 Pressure Drop through Biofilter Media

5.3.1 Method of Sampling of Pressure Drop through Biofilter Media

The pressure drop through the biofilter media was measured using a pressure transducer (Omega, PX 143 {0-6.9 kPa}). Two different sampling schemes were conducted, one on each side of the biofilter with all sampling ports being located on the east side of the biofilter. The south side of the biofilter had two columns (495 and 571 mm from the internal plenum) of ten sampling ports each (20 sampling ports), spaced 304 mm apart in the vertical direction. The purpose of this layout of sampling ports is to determine if pressure drop through the biofilter media is a function of depth within the biofilter media. The north side of the biofilter had two rows (933 and 1872 mm above the floor of the biofilter) of four sampling ports (eight sampling ports), spaced 300 mm apart in the horizontal direction. The sampling design was used to monitor the pressure drop through the biofilter media with respect to distance from the internal plenum. Three pressure-sampling ports were also located along the duct, on either side of the booster fans and the internal plenum. Figure 16 shows the locations of the sampling ports on the biofilter.

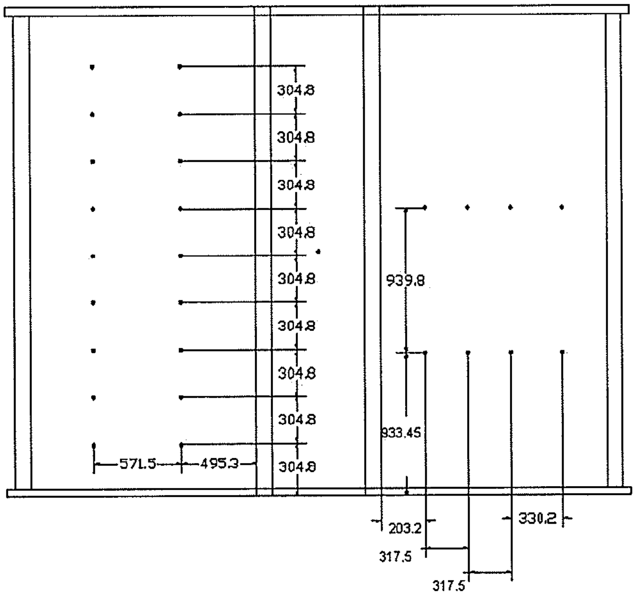


Figure 16 Pressure Sampling Ports on East side of biofilter

Left side is south / Right is north

5.3.2 Comparing Actual Pressure Data to Theoretical

In order to design a biofilter, the ability to be able to accurately predict the pressure drop through the biofilter media is important. Two different methods were used to compare the pressure data with theoretical values. The first method is to calculate the pressure drop at a specific distance from the internal plenum and compare it to the data collected at this distance. The second method is to plot the measured pressure drop per unit depth verses surface loading. These data points then can be compared against the theoretical values or ranges as calculated with the information provided in Sadaka et al. (2002). Both of these methods are beneficial as they both allow the comparison between the actual and theoretical pressure drop through the media and will help future designs.

5.4. Monitoring of Hydrogen Sulphide

As the biofilter purpose is to remove odours from the swine unit, a method needs to determine if the biofilter is removing the odours and how effectively. One method available for evaluating the biofilter's performance is a Jermone meter (Jermone 631-X Hydrogen Sulphide Analyzer, Arizona Instrument Corporation). This hand held machine measures levels of hydrogen sulphide, which can be used as an indicator of the odour from a swine unit (Zhou and Zhang 2003).

5.4.1 Hydrogen Sulphide Sampling

Hydrogen sulphide concentrations were sampled with a Jermone meter. The sampling port of the Jermone meter, placed approximately 30 mm into the centre of the outlet of the amplifying cone, was used for measuring face velocity. The sampling grid was spaced similar to the settling grid (samples were collected overtop of paint locations used in settling grid). The samples representing the contaminated airflow are the two pressure sampling ports after each booster fan. Ambient samples were collected at the same three locations, which were south and southwest of the biofilter. All samples collected are single samples with the exception of the contaminated air samples, which had one sample collected at the start of sampling and a second sample collected at the end of the sampling.

5.4.2 Statistical Analysis of Hydrogen Sulphide Data

As with the other measures of biofilter performance, the mean and standard deviation concentrations will be provided. As well, the removal rate for each sampling date will be included. As with the face velocity, Z values will be calculated for all sample locations with the biofilter's mean and standard deviation for that face and sampling date. As with face velocity, a t-test (independent means) will be conducted to determine if both sides of the biofilter can represent one biofilter.

5.4.3 Stratification of Removal of Hydrogen Sulphide

As with face velocity, determining if stratification is occurring in the biofilter media is important. The same procedure is used as with face velocity by calculating an average Z value and standard deviation for each location with respect to time.

6. RESULTS AND DISCUSSION

6.1 Settling of Biofilter Media

Figure 17 shows the overall settling of the biofilter media. See Appendix D for raw data. This provides important information when designing a biofilter. With the design of the headspace, ideal uniform settling of the biofilter media would allow one to minimize the amount of biofilter media that is used at the top of the biofilter with either design, pressurized or non-pressurized. The average settling for this biofilter was 0.30 m with a standard deviation of 0.04 m on the south side and 0.25 m with a standard deviation of 0.03 m on the north side. These differences in the amount of settling could be a result of the variety of methods used to fill the biofilter, but it is more likely that the layer of compost containing the moisture sensor on the south side is the cause for the difference between the two sides. Woodchips are added to the biofilter media to reduce the amount of compaction that occurs. This settling results in a range of 5 to 12% of the total height of the biofilter media with an overall average for settling of 9.5%.

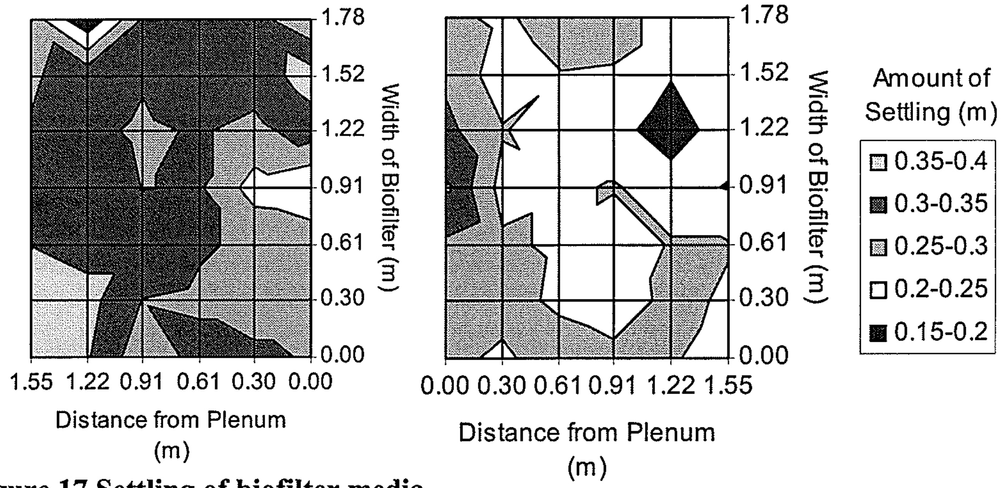


Figure 17 Settling of biofilter media

Left is South biofilter / Right is North Biofilter

Investigating the Z values, there are a few locations within the biofilter that settled considerably more than others (Fig. 18). No explanation is presently available for this; however, these locations should be noted and investigated in the future.

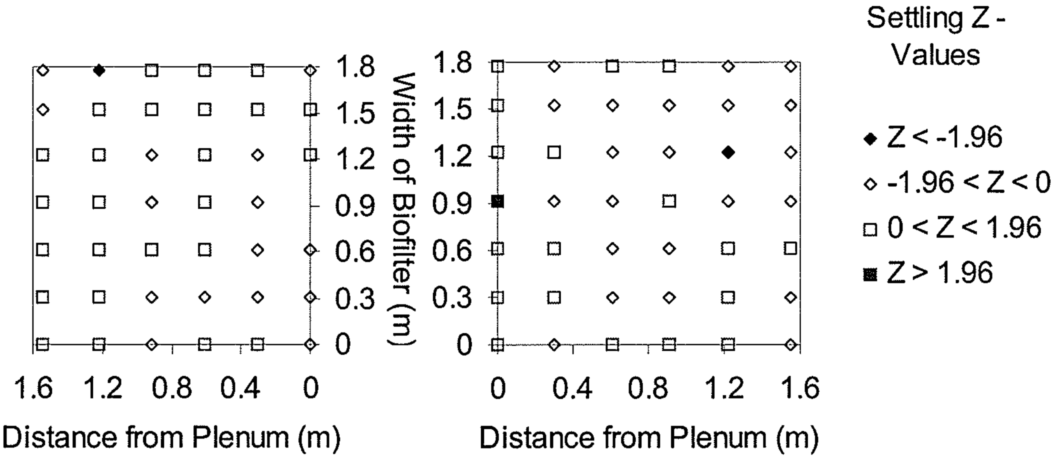


Figure 18 Z – Values for settling of biofilter media
Left is South biofilter / Right is North Biofilter

The other data collected for monitoring settling was the settling data with respect to depth. Figure 19 shows the results of two different sampling dates. The settling is the amount of settling that had occurred at a specific height with respect to the original location.

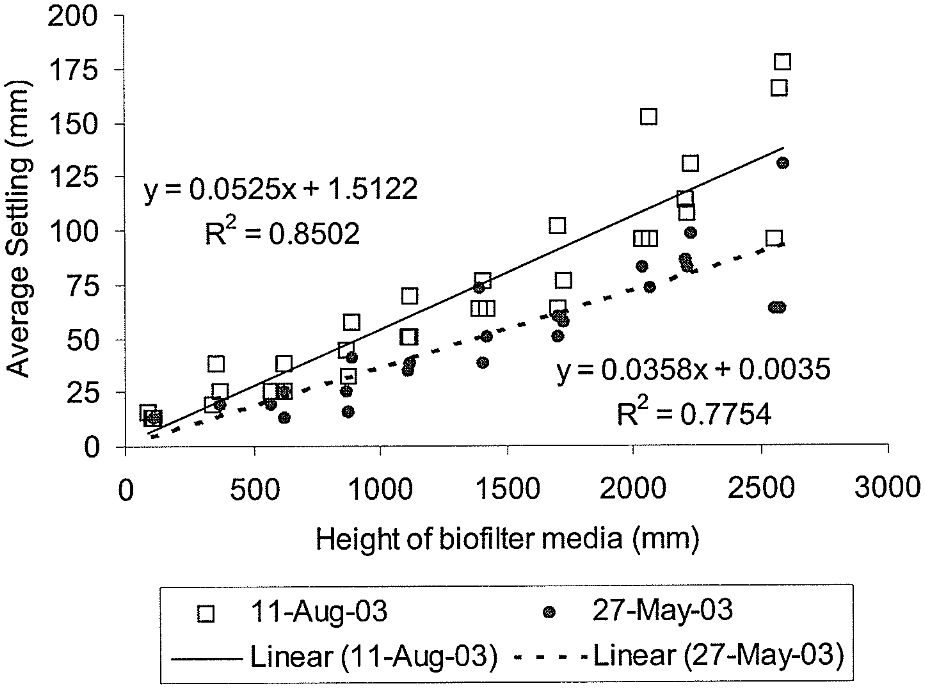


Figure 19 Plotting of settling data from north side of biofilter with respect to depth.

In this figure, it is shown that the settling of the biofilter media was uniform with respect to depth as can be seen by the fit of a linear line calculated from the data points. If the depth had affected the settling, a curved line would have better represented the data. With examination of the grouping of the data points, it appears that the settling is not uniform across a layer. By looking at the raw data, it appears that the media placed in the biofilter by manual labour is relatively uniform. The media that was placed in the biofilter with the grain auger had less settling where the auger dropped the material than where the media was placed with a shovel (Fig. 20). The west side of the north biofilter settled less than the east side. Sampling on a more intensive grid and more biofilters might result in determining if this is the case.

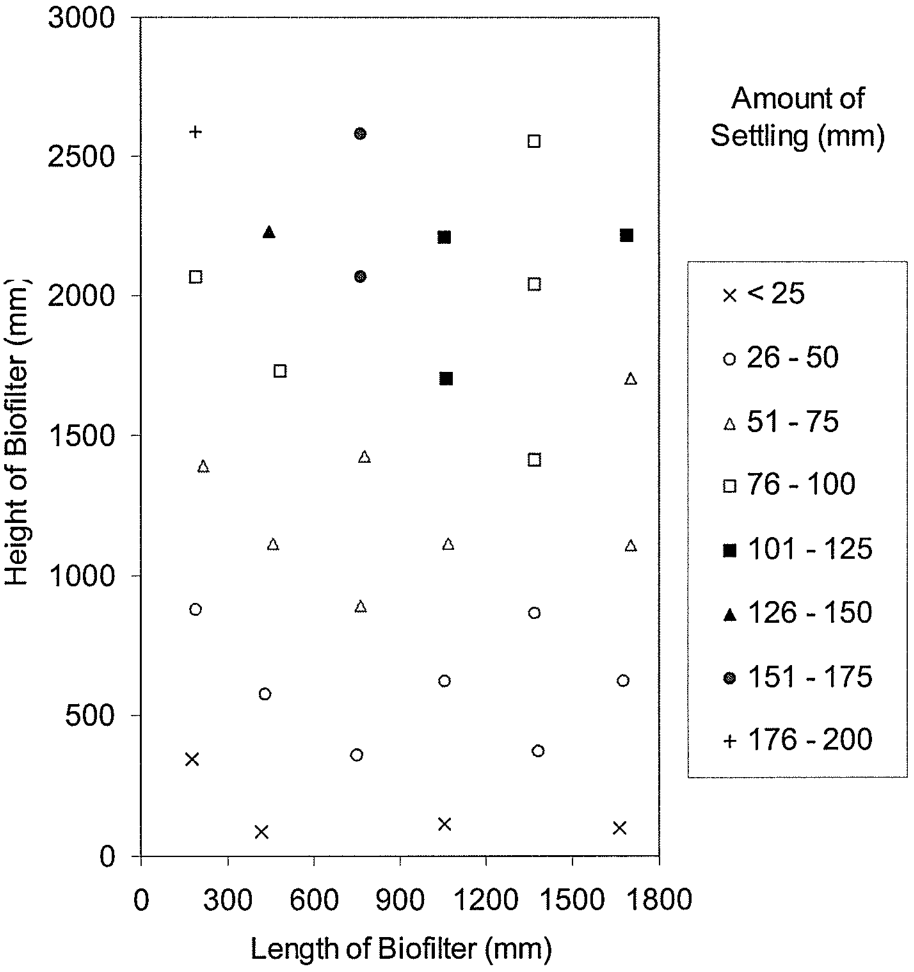


Figure 20 Settling of biofilter media with respect to location for data collect on Aug 12, 2003.

From the literature available on biofilters, settling results in changes to the porosity and bulk density. Using the assumed values of 57 % for porosity and 387 kg/m^3 for bulk density, with the average amount of settling and everything else remaining the same, the new porosity would be 52.5 % and the bulk density would be 427 kg/m^3.

6.2 Face Velocity of Biofilter

6.2.1 Statistical Analysis of Face Velocity Data

The following table (Table 6) shows the basic statistical data for the biofilter. This table also includes the t test results, which show that there is no significant difference between the two biofilter sides for each sampling date, even when the biofilter is channelling ($\alpha=0.05$). All airflow data is located in Appendix D. From the information that is provided in this form, it is relatively hard to determine if there are problems with the biofilter. An example is the data from May 27, 2003. The mean and standard deviation do not indicate that there are any problems with the biofilter. Even looking at the maximum and minimum values, it can be seen that there might be a problem with the biofilter as the maximum value is extremely large and the minimum values is zero m/s airflow. Unfortunately, with this information, the location or the scale of the problem cannot be determined. In order to identify problems with the biofilter, another method is required with Z values of the data collected at the different locations on the biofilter face.

These data can be used to help provide a solution to some of the issues of the biofilter. The assumed airflow from the biofilter was 1.89 m/s^3 (4 000 cfm). Using the highest average airflow for the biofilter (July 9, 2003), and the cross sectional area of the biofilter of 4.7 m^2, the resulting airflow would be 1.16 m/s^3 (2 450 cfm), which is considerably smaller than the assumed value. However, the pressure data collected from the duct suggests that this new flow rate is higher than the actual flow rate of the barn fan and will be explained in Sec 6.3).

Table 6 Air velocities observed from the exit faces of the north and south halves of the biofilter.

Sampling Date	Side	Air velocity (m/s)				Probability > t (%)
		Mean	Standard Deviation	Minimum	Maximum	
2002 06 26	South	$0.06^{n=28}$	0.04	0.00	0.14	79.78
	North	$0.07^{n=27}$	0.04	0.02	0.15	
2003 05 27	South	$0.04^{n=28}$	0.06	0.00	0.25	34.34
	North	$0.07^{n=28}$	0.11	0.00	0.60	
2003 06 10	South	$0.04^{n=34}$	0.06	0.00	0.28	6.12
	North	$0.06^{n=31}$	0.08	0.00	0.42	
2003 06 23	South	$0.00^{n=28}$	0.01	0.00	0.06	
	North	$0.01^{n=28}$	0.02	0.00	0.08	
2003 06 27*	South	$0.06^{n=25}$	0.02	0.03	0.11	34.98
	North	$0.07^{n=25}$	0.02	0.01	0.12	
2003 07 9*	South	$0.12^{n=25}$	0.03	0.08	0.17	44.72
	North	$0.13^{n=25}$	0.04	0.07	0.22	
2003 07 22*	South	$0.11^{n=25}$	0.03	0.06	0.16	81.23
	North	$0.12^{n=25}$	0.05	0.04	0.22	
2003 07 28*	South	$0.09^{n=50}$	0.03	0.05	0.14	13.20
	North	$0.11^{n=50}$	0.03	0.05	0.18	
2003 08 11*	South	$0.09^{n=50}$	0.03	0.04	0.16	49.57
	North	$0.10^{n=50}$	0.03	0.04	0.21	

* Hotwire anemometer used to measure airflow

^{n} is the number of data points used to calculate the mean and standard deviation

The following group of graphs are a result of looking at the Z values of the face velocities of the biofilter face. The graphs for May 27, 2003 show that channelling can clearly be seen in the top west corners on both faces. A safe assumption is that the same is occurring in the east corner, but these locations were not sampled. The other sampling date is August 11, 2003, which represents the biofilter operating at nearly the designed parameters.

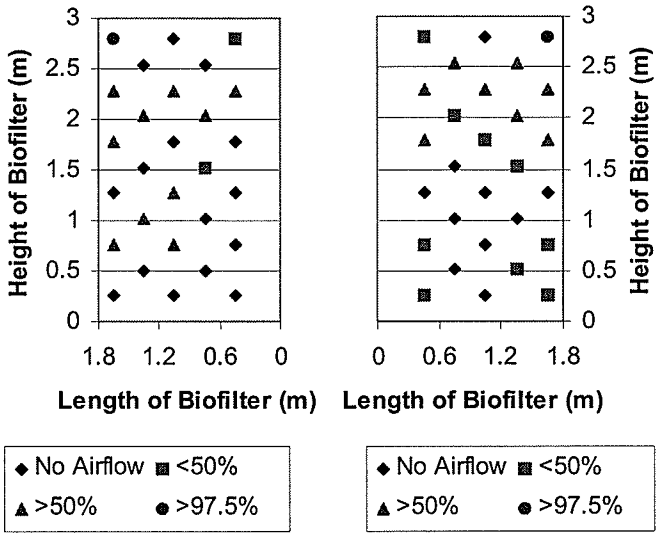


Figure 21 Z values for May 23, 2003 representing channelling data set

Left is South Biofilter / Right is North Biofilter

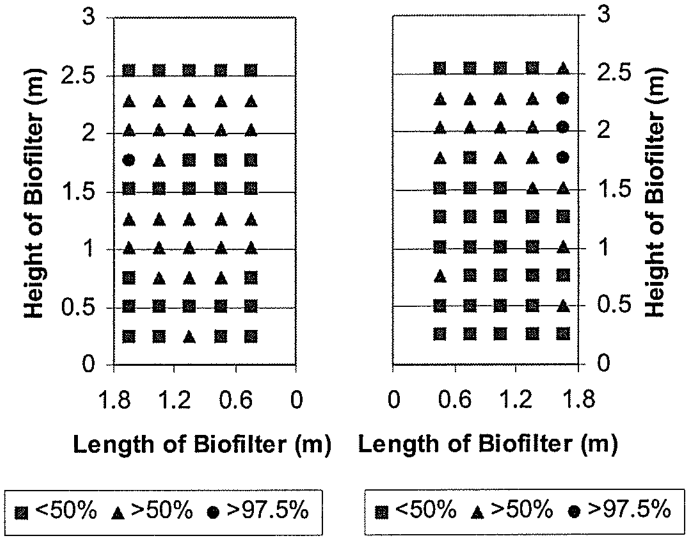


Figure 22 Z values for August 11, 2003 representing a good data set

Left is South Biofilter / Right is North Biofilter

From the data collected on May 23, 2003, it can be seen that there are locations that are channelling and this was a result of the failure of the headspace, which was fixed. The surprising observation from the biofilter at this time is that air was still moving through other areas of the biofilter. It was thought that areas channelling would represent the majority or the entire airflow with very little moving through the rest of the biofilter. This does bring up an issue with random sampling of the biofilter to determine if it is operating properly. There are a number of locations on either side of the biofilter. If these locations were the only locations collected from, the average measured airflow would have suggested that the biofilter was operating properly.

By looking at the statistical data collected from Aug 11, 2003, it appears that the biofilter is operating properly. Even the maximum and minimum values collected from either face suggest a biofilter that is working properly. Conversely, a few locations have airflow that suggests channelling due to extreme Z values. Using this method to locate these areas is beneficial as problem areas could be identified before the biofilter fails, i.e. channelling like shown in the May 23, 2003 data. With these few locations, random sampling would not likely have located the problem or the extent of the problem. With the modification to the ducting of the biofilter, the location that is channelling is the same height as the new ducting and the wall opposite the new location of ducting. It is believed that this is air leaving the ducting, moving across the internal plenum and then hitting the opposite wall. At this point, the air is being forced to the sides through the biofilter media. Baffles were installed in an attempt to address this problem, stopping air from being forced through the media at this location, but no data has been collected since their installation.

6.2.2 Stratification of Biofilter Media

From the previous section, the method used can detect channelling for a given sampling date. With investigating a new design when one of the expected problems in the design is stratification, a method needs to be used to determine if stratification of the biofilter is occurring. The method suggested in the methodology section of this thesis is to look at the mean and standard deviation of the airflow for a specific location of the biofilter over time. With this method, every time a major modification occurs to the biofilter, this should end the investigating of stratification as this modification might greatly affect the airflow patterns within the biofilter. The figures below show the results of this for the data collected when the biofilter was operating properly during the summer of 2003. The first set of graphs shows the average Z value and the second set is the standard deviation of the Z values over time.

From the average Z values, certain areas of the biofilter are identified as problem areas. The height of the fan is one of the areas. On both sides of the biofilter, at the height of the fan, the average Z values are consistently high as compared to the rest of the biofilter, with the edge that is opposite the fan being an area that shows extremely high average Z value. Looking back to the data for a single date and the average Z values, the area opposite the ducting appears to suffer from channelling. It is seen that this problem worsens with the passage of time. This method has identified the area before any large problems occurred with the biofilter.

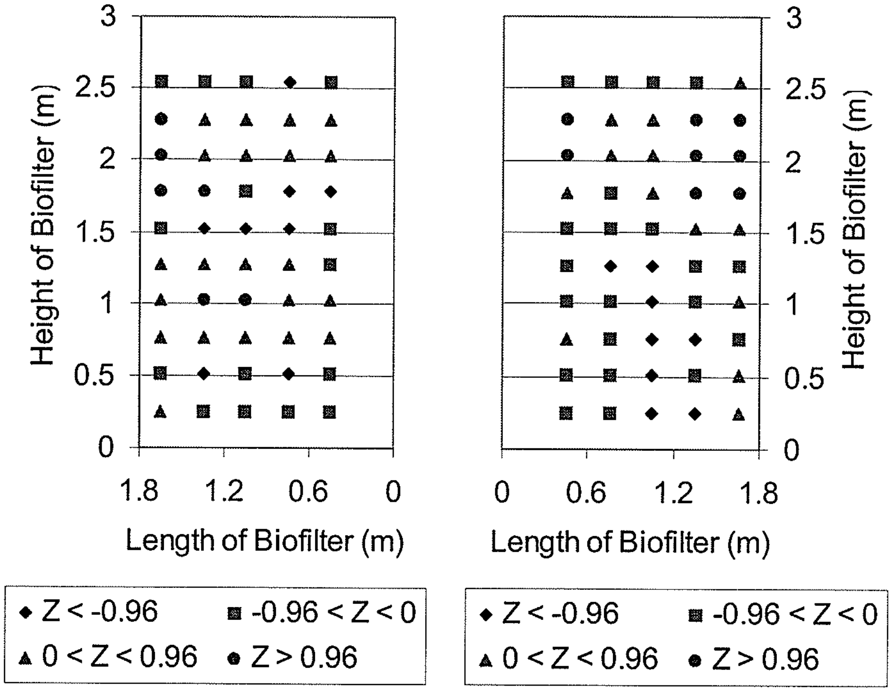


Figure 23 Average Z values for Summer 2003 investigating Stratification
Data is a combination of 2 and 4 sample points per location; Left is South Biofilter / Right is North Biofilter

Looking at sample sets for a single date, the area on the south side at the height of the layer of compost containing the moisture sensor is not identified as being outside any desired airflows, but looking at the average Z value, this area appears to be suffering constantly from low airflow. Another area that appeared with this method but not with a sample set for a single day is the area below the layer of compost. With the single sample sets this area did not appear as a problem, however, with this method it can be seen that this area is having high airflow on a consistent basis. An area that needs to be investigated is the centre column on the north side. With this technique, it has been identified as an area of low airflow but no explanation is available to the cause.

The standard deviation data provide an indication to the stability of the Z value. A low standard deviation would indicate that the average Z value is consistent, whereas a large Z value would indicate an area that moves around a lot in terms of airflow through it. It would be expected with an older biofilter that the airflows would become stable, as nothing is happening physically to the media. From the graphs (Fig. 24), the standard deviation of the Z values seems to be stable with the exception of a few areas on the south biofilter. Currently there is no explanation to the cause, but from the mean and standard deviation, these three locations should be monitored closely to see what occurs in the future. With this method, a larger data set might have provided a better view of the stability of these locations.

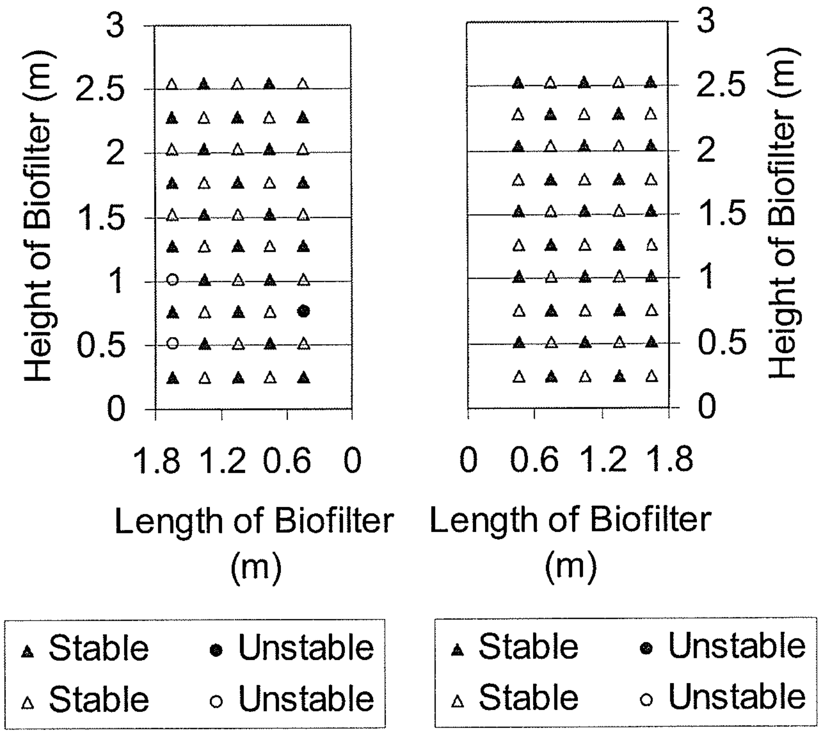


Figure 24 Standard Deviation of Z values for summer 2003 investigating Stratification

Left is south biofilter / Right is North Biofilter
(Hollow data points represent four samples and solid points represent two samples)

6.3 Pressure Drop Through Biofilter Media

Figure 25 shows the average pressure drop at specific distance from the plenum during the different layouts of the biofilter. All raw data for pressure is located in Appendix D. From this figure, it can be said that the final set up resulted in a biofilter that operated closely to the designed biofilter with respect to pressure. Looking at the data for spring 2003 (channelling / fan failure), the large deviation from the design and previous years results would suggest that there is a major problem with the biofilter. One of the problems was identified as channelling.

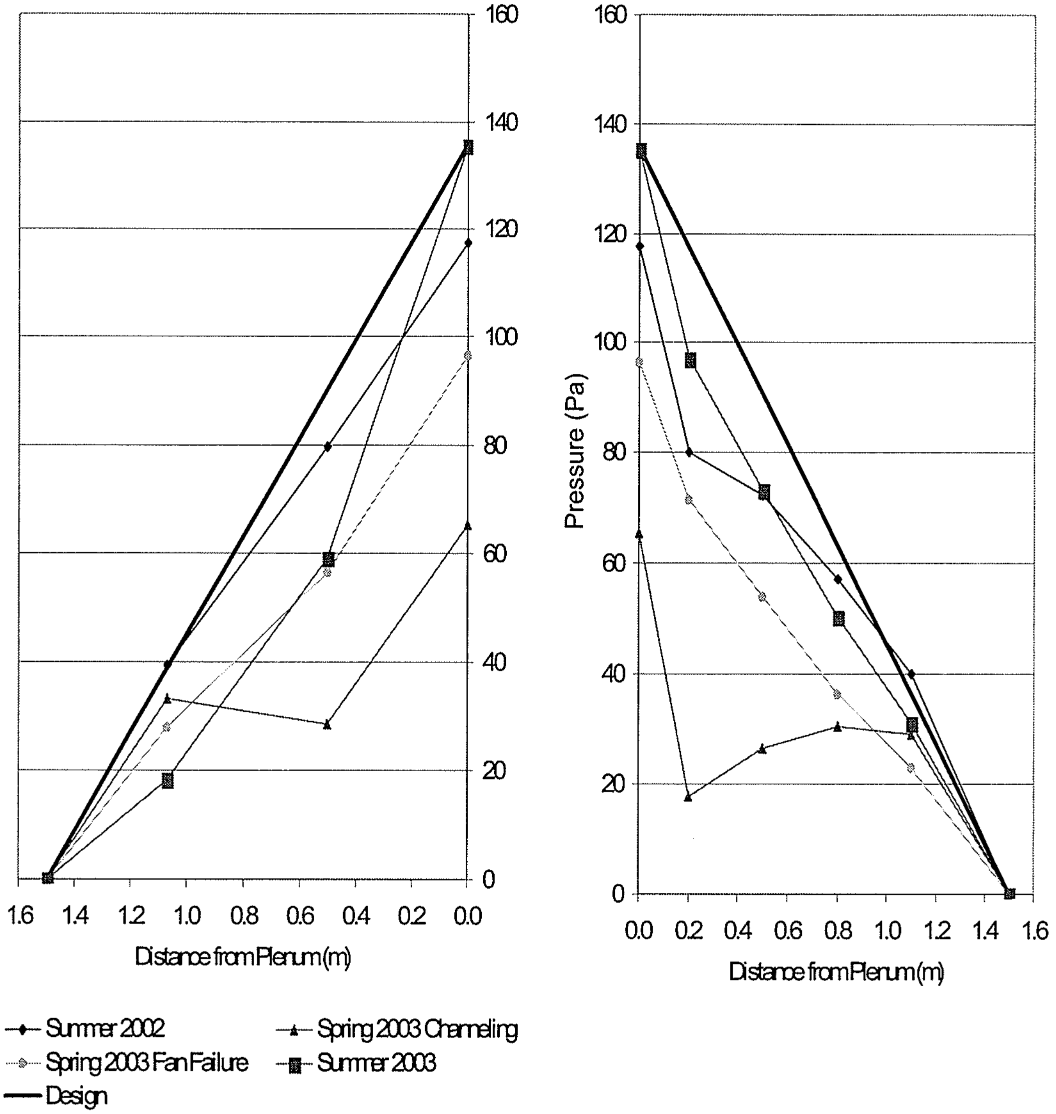


Figure 25 Pressure drop on north and south side of plenum
Left is South Biofilter / Right is North Biofilter

The fan failure was determined by the looking at the data collected from the incoming duct (Fig. 26). In this graph, the data located at 0 m from the biofilter is the pressure of the internal plenum. From the graph, is can be seen that no increase in pressure was occurring after passing through the first booster fan. Another problem with the original design was the design of the entrance into the biofilter's internal plenum, which was causing unnecessary pressure losses from the drop in pressure occurring after the second booster fan. This problem was addressed at the same time as the two 90 degree elbows were removed from the ducting in the early summer of 2003. As mentioned in the airflow section, the assumed airflow was overestimated; the data collected at 1.4 m from the biofilter is showing reasoning for this. If the booster fans were properly sized and the biofilter was exhausting the proper volume of air, the pressure reading at this location should be slightly positive (about 5 - 10 Pa). With the design of a barn ventilation system, the ventilation fans are supposed to cause a slight negative pressure inside the swine unit, which helps draw fresh air into the swine unit. This results in a corresponding positive pressure on the exhaust side of the fan. The large negative pressures seen on the exhaust side of the barn fan would indicate that the booster fans are demanding more air than the barn fan is supplying, i.e. the booster fans are oversized.

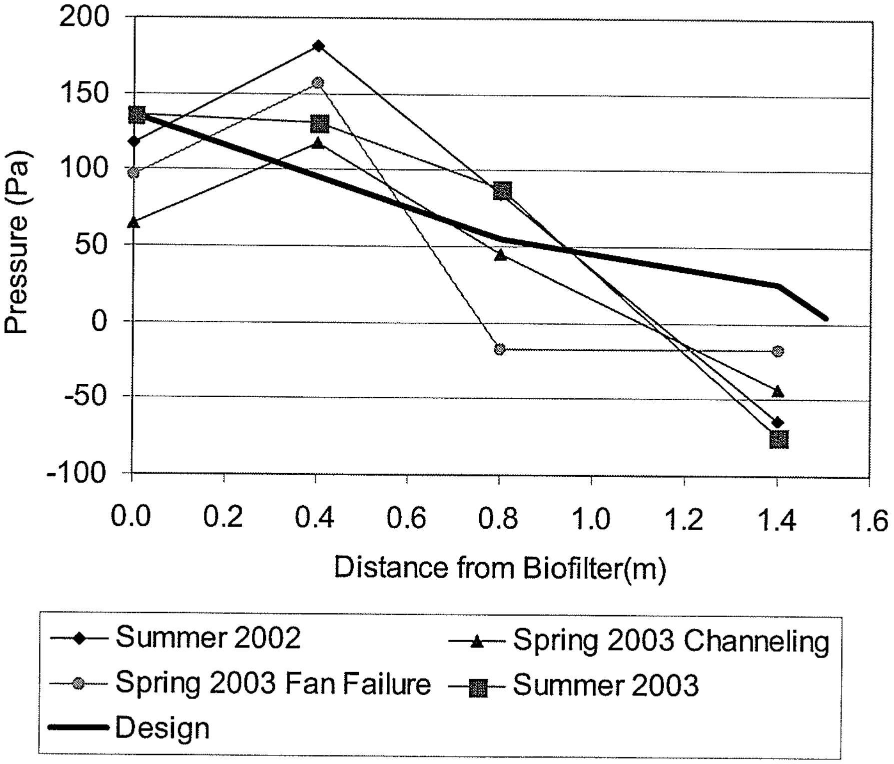


Figure 26 Pressure increases in the Duct

When designing the biofilter, the pressure drop through the media is determined with an empirical formula. When designing this biofilter, the pressure drop through the biofilter media was calculated using values that should have resulted in a larger theoretical pressure drops than actual. Figure 27 compares the actual pressure drop per unit depth against the measured airflow of the biofilter. From this graph, it can be seen that the actual data does match the theoretical values reasonably well. The periods during the experiment when problems such as channelling occurred, the results from the biofilter are outside the expected range of values. The expected range of values is the space between the two lines on the chart representing the two different biofilter media mixtures. More research into pressure drop and airflow would result in a larger data set allowing for better predictions as it was expected that the actual pressure drop through biofilter media would have followed the line representing the 80:20 mixture of woodchips and compost.

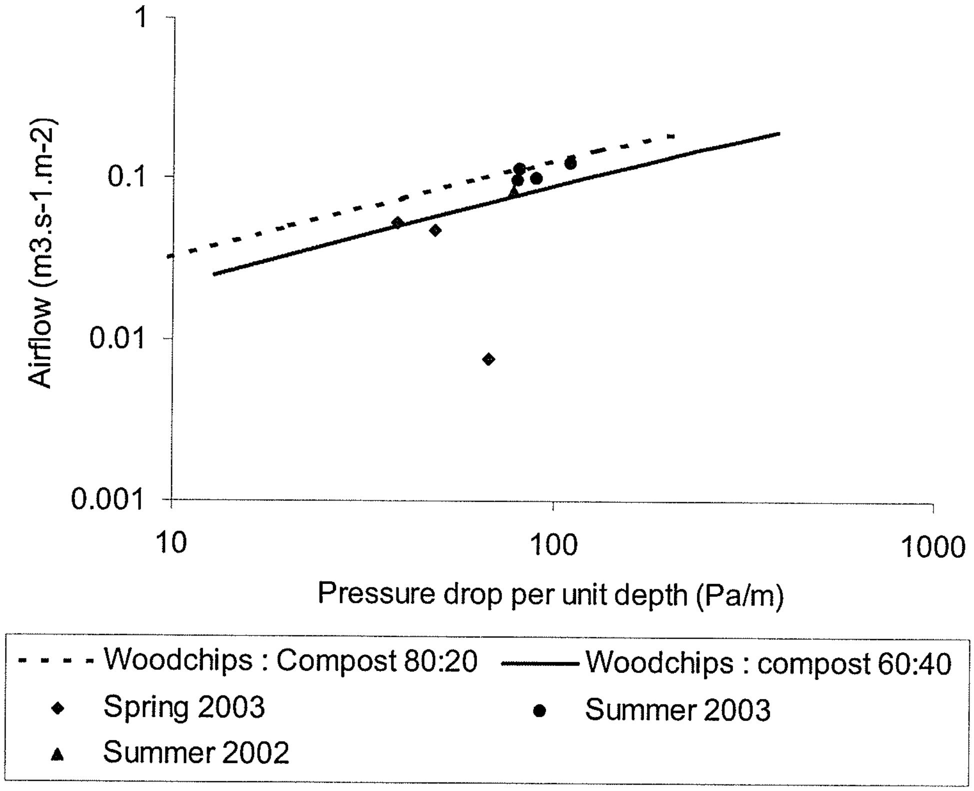


Figure 27 Actual pressure drop compared against theoretical

6.4 Hydrogen Sulphide

6.4.1 Statistical Analysis of Hydrogen Sulphide Data

Hydrogen sulphide is being used as a marker for the concentrations of odours in air from a swine unit in this thesis. The removal rates of hydrogen sulphide are important as this indicates the performance of the biofilter. The following table contains the average concentrations of hydrogen sulphide being exhausted from both the barn and the biofilter, and the ambient levels of hydrogen sulphide at this farm site. All the raw data is available in Appendix D.

Table 7 Concentrations of hydrogen sulphide (ppb)

Date	Inlet Mean (S.D.)	North Face Mean (S.D.)	South Face Mean (S.D.)	Ambient Mean (S.D.)
2002 08 27	1 207 (61)$^{n=4}$	76 (124)$^{n=21}$	158 (229)$^{n=21}$	54 (21)$^{n=3}$
2002 09 13^{A}	505 (52)$^{n=4}$	156 (200)$^{n=27}$	148 (190)$^{n=30}$	7 (2)$^{n=3}$
2003 05 26	1 075 (272)$^{n=4}$	194 (240)$^{n=30}$	260 (238)$^{n=30}$	5 (1)$^{n=3}$
2003 06 23	67 (20)$^{n=4}$	34 (33)$^{n=30}$	57 (29)$^{n=30}$	12 (3)$^{n=3}$
2003 07 09a	208 (34)$^{n=4}$	31 (57)$^{n=30}$	37 (55)$^{n=30}$	34 (13)$^{n=3}$
2003 07 09b	203 (93)$^{n=4}$	28 (70)$^{n=30}$	34 (66)$^{n=30}$	25 (6)$^{n=3}$
2003 07 28	213 (29)$^{n=4}$	32 (54)$^{n=30}$	32 (67)$^{n=30}$	13 (4)$^{n=3}$
2003 08 11	445 (35)$^{n=4}$		61 (140)$^{n=30}$	15 (6)$^{n=3}$
2003 08 12	390 (120)$^{n=4}$	38 (72)$^{n=30}$	43 (85)$^{n=30}$	23 (7)$^{n=3}$

^{n} = Number of Samples
^{A} = Samples collected 24 h after 10 d shut down

From this information, it would appear that the biofilter is operating well, as the hydrogen sulphide levels leaving the biofilter are almost equal to the ambient levels of the farm. Calculating the removal rates can provide a better explanation of the performance of the biofilter. Table 8 shows the removal efficiencies during the operation of the biofilter and the t-test data comparing the south and north sides of the biofilter to each other. From the t-test data, the removal rates for either side of the biofilter was not significantly different (α=0.05), except during the period when channelling was a problem.

From the hydrogen sulphide data, it appears that the biofilter is able to remove about 80+% of the hydrogen sulphide from the air entering the biofilter. The biofilter is probably removing more hydrogen sulphide because a majority of the biofilter face has measured hydrogen sulphide level at or below ambient levels. If the ambient levels of hydrogen sulphide were lower, the readings from the exhaust of the biofilter might be correspondingly lower. Due to a design problem of locating soaker hoses, as discussed later in the thesis, the top layer of the biofilter not treating hydrogen sulphide properly because of lack of water. If this problem were corrected, the biofilter's average concentrations of hydrogen sulphide exiting the biofilter would be reduced. At these removal efficiencies and research by Sheridan et al. (2003) modelling odour levels around farm sites, this biofilter design would remove sufficient amounts of contaminants to prove beneficial. The advantage of this design is this biofilter requires less space than a vertical airflow biofilter and demands the same or less in terms of fan requirements, reducing operating costs.

Table 8 T-test and Removal Efficiency Data for Hydrogen Sulphide Data

Date	Probability > t	Removal Efficiency (%)	
		South	North
2002 08 27	16.0	93.7	86.9
2002 09 13^A	87.8	69.2	70.7
2003 05 26	28.9	82.0	75.8
2003 06 23	0.4	50.0	15.0
2003 07 09a	67.9	85.1	82.3
2003 07 09b	73.0	86.4	83.4
2003 07 28	96.0	85.2	84.8
2003 08 11			86.2
2003 08 12	80.9	90.2	89.0

^{A} = Samples collected 24 h after 10 d shut down

The data that has been presented has shown that the biofilter is removing hydrogen sulphide from the exhaust air of the barn, but like airflow, problems in the biofilter are location specific and, depending on the sample location, problems might not be detected.

As was done with airflow, Z values were calculated for all sampling locations with the mean and standard deviation of that biofilter face for that sampling date. Figure 28 shows the results for Aug 13, 2003.

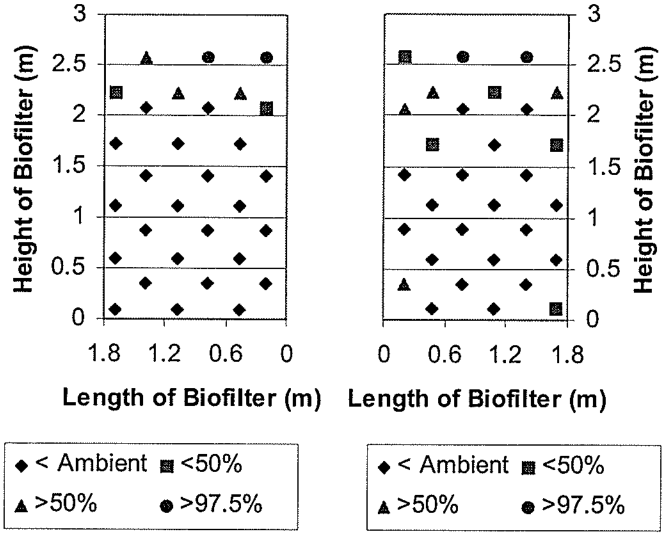


Figure 28 Z Values for Hydrogen Sulphide Data for August 13, 2003

Left is South Biofilter / Right is North Biofilter

From these graphs, it can be seen that a majority of the biofilter face is performing as desired by reducing hydrogen sulphide to ambient levels. However, there is a layer at the top of the biofilter that is not treating the hydrogen sulphide, but this is the same layer that is not receiving water as the water lines are buried approximately 150 mm below the top of the biofilter media.

6.4.2 Stratification of Hydrogen Sulphide Data

From the data, it can be seen that the biofilter is removing hydrogen sulphide, but as with airflow, stratification of the biofilter does not show itself with the methods of displaying data. The same method of determining stratification of airflow will be used with hydrogen sulphide.

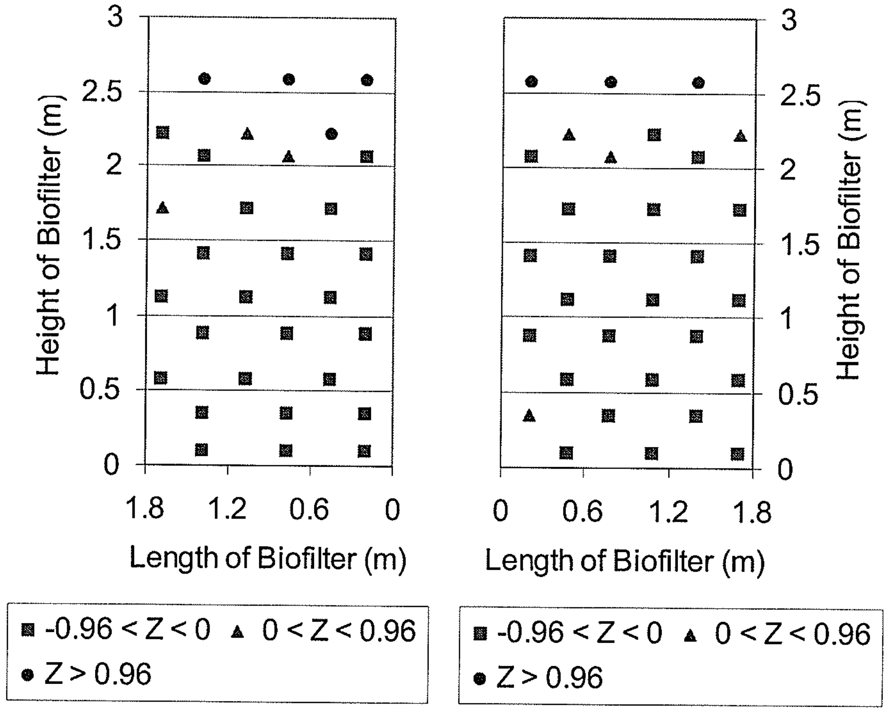


Figure 29 Average Z values for determining stratification for hydrogen sulphide reduction for Summer 2003

Left is South Biofilter / Right is North Biofilter

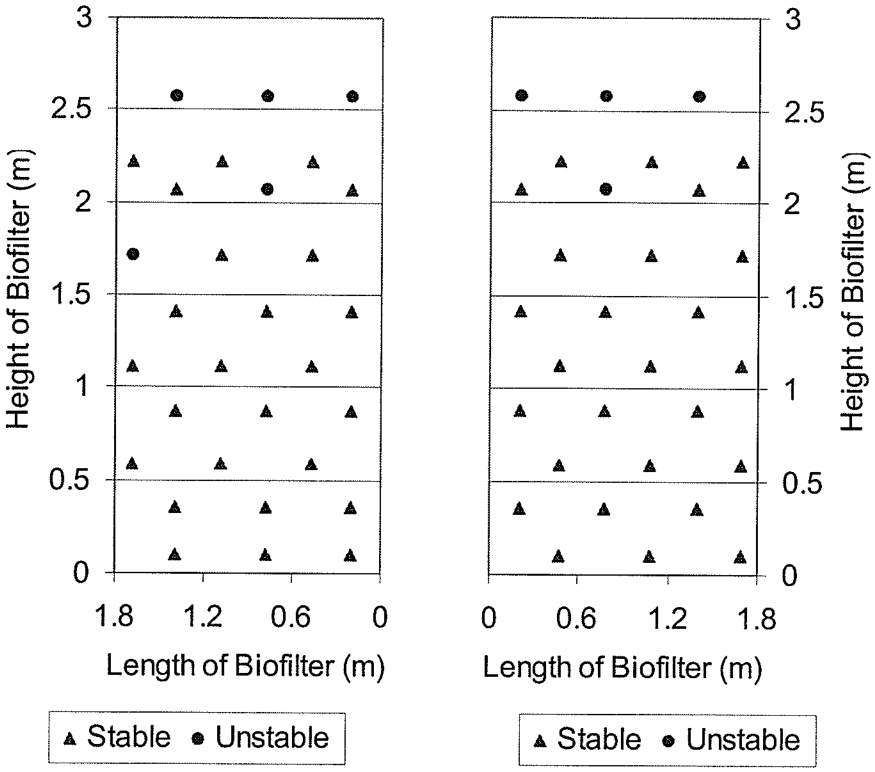


Figure 30 Standard Deviation of Z values for Hydrogen Sulphide investigating stratification for Summer 2003 data

Left is South Biofilter / Right is North Biofilter

From the combination of these two sets of graphs, it is shown that a majority of the biofilter face is removing most of the hydrogen sulphide and, unlike airflow, low numbers are ideal with this data. The areas of concern are the top layer, but these areas of poor removal are results of insufficient water as numerous articles available discussing the importance of moisture within a biofilter explains. As well, a few locations on the biofilter face near the top are of concern. These areas do correspond with some of the areas of higher airflow, thus these areas should be monitored and investigated if this trend continues.

7. FUTURE CONSIDERATIONS

One of the major areas of future research should be investigation of the effects of aging on biofilter media as this will help with the designing of biofilters. A second area of research should be the investigation of water content issues with the biofilter media, as water related problems are major causes of biofilter failures. Another area of research that should be continued is the removal efficiency of the biofilter as related to design properties such as surface loading, EBCT, and biofilter media. Lastly, with the construction of this biofilter, certain designs were used with some positive and some negative results, thus some of the construction issues should be documented, as better solutions might be available.

Aging of the biofilter media.

- The actual physical change in the biofilter media should be investigated in terms of partial size, porosity, and change in volume as well as the causes of the settling. The settling of the biofilter media can have a large effect on the airflow through the biofilter media. With designing the horizontal biofilter, it is possible that the biofilter media will settle in a manner that will result in a failure of the headspace seal, causing channelling or short-circuiting of air across the top of the biofilter. Research similar to the research conducted in the area of airflow through grain would help with designing future biofilters.
- Pressure drop through the biofilter media should be investigated. As with a vertical airflow biofilter, the aging of biofilter media will result in increased pressure drop through the biofilter media. The replacement of the biofilter media

usually occurs because the pressure drop through the media has increased past a predetermined limit, which results in insufficient airflow through the biofilter. With an horizontal airflow biofilter, as a lower pressure drop is required for the air to travel through the same thickness of media, understanding the causes of the pressure drop might result in longer life biofilter media that would reduce the costs of biofiltration.

Water movement through the biofilter media.

- In the design used, the final design of adding water to the biofilter media was from the top only. This probably resulted in "streams of water" forming that went down through the biofilter media which provided for poor control in terms of water content within the media (Fig. 31, the dark area is wet biofilter media with the lighter coloured media being dry). These "streams of water" also would make for good methods of transporting nutrients down through the media, slowly starving the top of the biofilter. As well, these streams would be moving salts and biomass, slowly poisoning the bottom of the biofilter. This will likely result in the replacement of biofilter media sooner than designed, raising the costs of the biofilter.

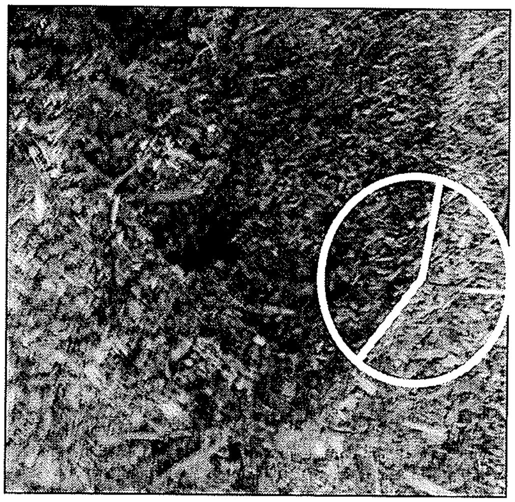


Figure 31 Watering from a point source of water providing non-uniform moisture content

- As with grain research, water movement in terms of the drying front through the biofilter media needs to be addressed. From grain research, it is known that if air is below the relative humidity of 100%, a drying front will be formed. Alternately, in grain research, the goal is the drying of the material, but with biofilter media, the goal is maintaining the present moisture content. With the application in biofiltration, ignoring this fact might result in insufficient watering on the dry side of the drying front while over watering on the other side with neither side of the drying front being able to operate at optimum levels due to water issues.

Improve predictions of design constraints

- The continuation of the research into determining optimum design constraints should be done, as the perfect biofilter has not yet been designed. This would include determining optimum combinations of surface loading, pressure, media, and EBCT. With a vertical biofilter, the three largest concerns have been the EBCT, pressure drop and footprint of the biofilter. The EBCT has been used to determine the volume of the biofilter, while pressure and area of the biofilter are optimized with a larger concern over lowering pressure drop through the biofilter than decreasing the footprint of the biofilter. The research that is being suggested is finding what effect does surface loading have on the removal efficiency of the biofilter. If everything is equal, does a thick or thin biofilter media perform better?

Future design considerations

As saw with the scaling up of the project, the failure of this design was related to the manifold design. A horizontal biofilter does offer the possibility of a low-pressure biofilter. However, it requires more pressure for the air to move through the manifold than the biofilter media.

- With this design, the optimization of the manifold design by any technique available would have benefited the overall project. Within this manifold, there are many places within the system where improvements could be included.
- With the scaling up of the biofilter, the media was switched to a wood mulch mixture instead of the woodchip mixture used in the prototype. As the wood mulch resulted in a larger pressure drop per unit thickness of biofilter media, research should be conducted into using large particles in the biofilter. As with grain research, large particles would result in a lower pressure drop through the biofilter media. In addition, large particles would reduce the energy requirements

used to produce the woodchips or wood mulch, as large particles are cheaper and easier to make than small particles.

- If this biofilter were to be rebuilt, the use of a thin biofilter would be selected, as the headspace does not need to be pressurized. A problem with the headspace being pressurized from the source air is that condensation can occur in the sealed headspace resulting in the water in the headspace forming into ice in the winter. (Fig. 32) An alternative to this design would be a negative pressure design were a single layer of plastic or rubber would self seal against the media. In addition, the reduction of corrosive material traveling through the fan housing would result in a long life for the fan.

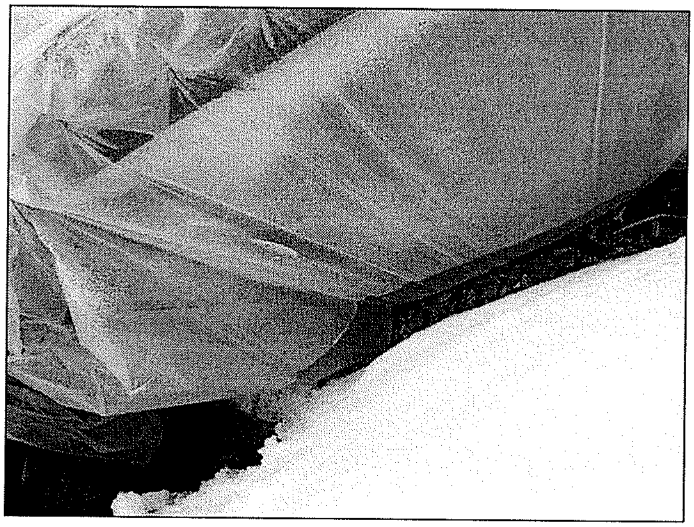


Figure 32 Water in the headspace of the biofilter during the winter

- With the design of this biofilter, the physical structure in all likelihood was over built, as there is no literature available on the forces produced by the biofilter media on the walls of the structure. With this design, the walls are strong enough to handle grain. With the modifications that were done to this biofilter, it can be seen that the angle of repose of biofilter media was larger than grain. This would change some of the assumptions of what forces are being applied to the wall of the biofilter. From Fig. 33 it can be seen that the lower part of the wall is creeping outward. It is felt that the high moisture in the biofilter causes part of this; the forces of the media are causing the wood to warp in this manner.

- The last area of research should be determining the maximum physical height of the biofilter media. With the research that was conducted by Sadaka et al. (2002), the depth of the media in the horizontal airflow biofilter was 1 m. This resulted in the construction and testing of a prototype biofilter to determine what the affects of building a biofilter with media that is 3 m deep. In industrial applications, the height of the media might be required to be higher than 3 m, but no information is available on the effects of having biofilter this high.

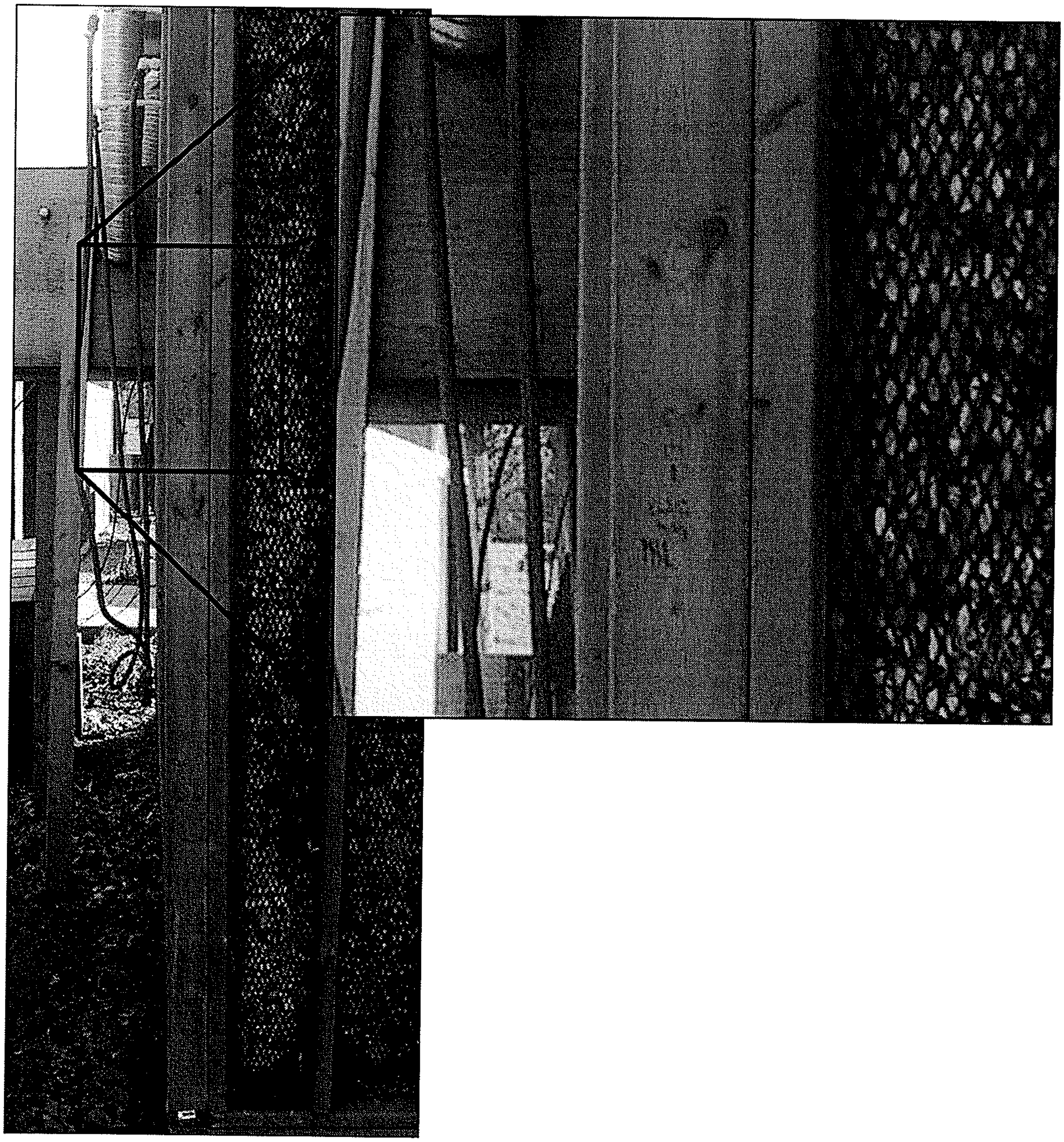


Figure 33 Biofilter wall creeping outwards

8. CONCLUSION

With the data collected from this full-scale prototype biofilter, it can be determined that horizontal airflow biofiltration is a technology that can offer a low-pressure biofilter and a small footprint, but some refining of the design is required. This prototype was able to use a majority of the biofilter's volume to adequately treat the odours from the swine unit. Most of the parts of the biofilter that did not operate properly can be explained with results from research conducted by others. More research should be conducted to gain a better understanding of the causes of some of these flaws. Additionally, more research is needed to be able to model the aging of the media in terms of pressure drop, settling, and airflow, so that the design of the biofilter can be optimized.

For the objectives of this research, these are the results:

1. Pressure Drop

The end data shows that the information available for designing the biofilter was accurate enough to build a biofilter that operated, but the information needs a larger database to improve the predictions and to see if other properties of the media influence the predicted values. With the full scale prototype, the pressure data collected shows that the pressure drop is slightly higher than predicted, (Fig. 27), but since aging of the media was expected to increase pressure requirements, this will only result in reducing the lifespan of the biofilter before replacing the media. Physical height of the biofilter does not appear to effect pressure drop in any manner as the biofilter was constructed to the height of three m with data originally collected from a one m high biofilter.

2. Airflow

From the data collected, the biofilter has worked better than expected. The idea of the internal plenum worked, as t-tests showed the two sides of the plenum, in statistical terms, could be considered one biofilter. Stratification was the largest concern due to the aging of the biofilter media. Originally, it was expected that compaction of the lower half of the biofilter would greatly reduce airflow through this part of the biofilter. Upon analyzing the data collected for airflow, the biofilter worked ideally except for problems with manifold design and installation of monitoring sensors within the biofilter. A manifold for future biofilters needs to uniformly allow air into the internal plenum, but not forming the stream created with the design of the manifold in this project. The other major cause of abnormal data was because of a moisture sensor in the biofilter. A timed watering system that will occasionally bring the media to field capacity would work, without disturbing the uniformity of airflow through the biofilter.

3. Settling

Settling of the biofilter media has caused the most concerns, which was not a major concern at the start of the project. Little is available for information about settling of the biofilter media besides references to compaction of the media. With the design of a horizontal airflow biofilter, slowing or being able to accurately predict settling is important. A failure to do this will result in the failing of the headspace designs, thus causing channelling and biofilter failure. From the data that was collected during this research, overall settling of the biofilter media appears to be uniform. As the data set used to investigate layered settling within the biofilter is small, it can only be suggested that fill method does influence settling. It appears that different fill methods, over time, will settle at different rates. This might only be a concern if more than one fill method was used to fill the biofilter as with this prototype. If one fill method is used, it should be expected that the media would settle linearly and uniformly. More research is required to investigate this issue.

4. Hydrogen Sulphide Removal

As with the airflow data, the hydrogen sulphide removal data showed good results. A design flaw was the main cause of insufficient hydrogen sulphide removal -- dry biofilter media. The data has showed that stratification of hydrogen sulphide removal is not present. With the media selection and residence time, being able to consistently remove 80%+ hydrogen sulphide when the biofilter is operating properly is adequate. A richer media mixture in terms of compost and lower EBCT would be recommended.

This design has shown that horizontal airflow biofilters can be constructed to function properly. This design worked well as a research biofilter. A design for a commercial version of a horizontal airflow biofilter can be constructed by optimizing the design through a number of modifications. The most important aspect to watch when optimizing the biofilter design is the design of the manifold. A poor manifold design will defeat the biofilter's ability to offer a low-pressure biofilter with a small footprint.

References

Aizpuru, A., N. Khammar, L. Malhautier, and J.L. Fanlo. 2003. Biofiltration for the treatment of complex mixtures of VOC influence of the packing material. Acta Biotechnologica. 23:211-226.

Alagusundaram, K., and D.S. Jayas. 1990. Airflow resistance of grains and oilseeds. Postharvest News and Information. 1(4):279-283.

Albright, L.D.. 1990. Environment control for animals and plants. St. Joseph, MI:ASAE.

ASAE Standard ASAE D272.3 MAR96. 1999. Resistance to airflow of grains, seeds, other agricultural products, and perforated metal sheets. St. Joseph, MI:ASAE.

ASHRAE. 1999. AHRAE Handbook CD.

Bensafi, M., C. Rouby, V. Farget, B. Bertrand, M. Vigouroux, and A. Holley. 2003. Perceptual, affective, and cognitive judgements of odors: Pleasantness and handedness effects. Brain and Cognition. 51:270-275.

Bensafi, M., C. Rouby, V. Farget, M. Vigouroux, and A. Holley. 2002. Asymmetry of pleasant vs. unpleasant odor processing during affective judgment in humans. Neuroscience Letters. 328:309-313.

Bottcher, R.W., R.D. Munilla, K.M. Keener, and R.S. Gates. 2001. Dispersion of livestock building ventilation using windbreaks and ducts. ASAE Paper No. 014071. St. Joseph, MI:ASAE.

Boyette, R.A.. 1998. Getting down to (biofilter) basics. BioCycle. 39(5):58-62.

Bruns, B., and F. Zimmer. 1998. Bio-filter with a housing in the form of a rectangular d. Deutschland Patent 19726635

Calderwood, D.L.. 1973. Resistance to airflow of rough, brown and milled rice. Trans. ASAE (Am. Soc. Agric. Eng.). 16(3):525-527.

Campbell, A.J., T.A. Van Lunen, J.A. MacLeod, D. Hurnik, and G. Linkletter. 2003. Design and performance of a swine finishing barn for production and manure research. Canadian Biosystems Engineering. 45:5.1-5.6.

CHEMINFO. 2003. WEBSITE. http://ccinfoweb.ccohs.ca/cheminfo/search.html. Accessed March 17, 2003

Choi, J.K., Y.H. Kim, D.J. Joo, S.J.Choi, T.W. Ha, D.H. Lee, I.H. Park, and Y.S. Jeong. 2003. Removal of ammonia by biofilters: A study with flow-modified system and kinetics. Journal of the Air and Waste Management Association. 53:92–101.

Clark, O.G., I. Edeogu, J. Feddes, R.N. Coleman, and A. Abolghasemi. 2004. Effects of operating temperature and supplemental nutrients in a pilot-scale agricultural biofilter. Canadian Biosystems Engineering. 46:6.7-6.16.

Cochrane, B.. 2003. Biofilters prove effective in swine barn odor control. Farmscape (Episode 1300; July 16, 2003)

Damborsky, J., M. Damborska, and V. Pistek. 1999. Sporulation as an effective strategy for the survival of bacteria in a biofilter with discontinuous operation. Biotechnology Letters. 21:835–838.

De Nevers, N.. 1995. Air pollution control engineering. New York, NY: McGraw-Hill, Inc.

DeBruyn, J.C., D.D. Mann, and Q. Zhang. 2001. Comparison of the odor levels of biofiltered air and ambient farmyard air. Canadian Biosystems Engineering. 43(6):7-11.

DeBruyn, J.C.. 2000. Biofiltration for odour control from swine housing in Manitoba. Unpublished M.Sc. Thesis. University of Manitoba, Winnipeg, MB.

Devinny, J.S., M.A. Deshusses, and T.S. Webster. 1999. Biofiltration for air pollution control. New York: Lewis Publishers

Firth, J.A.. 1998. Apparatus for biological control of noxious gas from swine waste. United States Patent Number 5738713.

Garlinski, E.M., and D.D. Mann. 2003. Design and evaluation of a horizontal airflow biofilter on a swine facility. ASAE Paper No. 034051. St. Joseph, MI:ASAE.

Gates, R.S., J.D. Simmons, K.D. Casey, T.J. Greis, H. Xin, E.F. Wheeler, C.L. King and J.R. Barnett. 2002. Fan Assessment Numeration System (FANS) design and calibration specifications. ASAE Paper No. 024124. St. Joseph, MI:ASAE.

Gerrard, A.M.. 1997. Economic design of biofilter systems. Journal of Chemical Technology and Biotechnology. 68:377-380.

Goodrich, P.R. and D.E. Mold. 1999. Evaluation of odor control technologies for curtain-sided swine barns. ASAE Paper No. 994153. St. Joseph, MI:ASAE.

Guo, H., L.D. Jacobson, D.R. Schmidt, and K.A. Janni. 2001. Simulation of odor dispersions as impacted by weather conditions. In Proceedings of the 6th International

Symposium, R.R. Stowell, R. Buekdin, and R.W. Bottcher, eds. ASAE Publication 701P0201, St. Joseph, MI. P687-695.

Hammond, E.G., C. Fedler, and G. Junk. 1979. Identification of dust-borne odors in swine confinement facilities. Trans. ASAE (Am. Soc. Agric. Eng.). 22:1186-1192.

Harting, J., and V.R. Phillips. 1994. Control of gaseous emissions from livestock buildings and manure stores. Journal of Agricultural Engineering Research. 57(3):173-189.

Hartmann A.. 2002. Biofilter for purifying waste air. European Patent 1238697 / Deutschland Patent 10110519.

Hartung, E., T. Jungbluth, and W. Buescher. 2001. Reduction of ammonia and odor emissions from piggery with biofilters. Trans. ASAE (Am. Soc. Agric. Eng.). 44(1):113-118

Hayward, R.. 2002. Study of airflow resistance characteristics of an 80:20 straw / compost media. Unpublished B.Sc. Thesis. University of Manitoba, Winnipeg, MB.

Hobbs, P.J., R. Johnson, and D. Chadwick. 1999a. A novel technique to determine organic processes in pig wastes. Journal of the Science of Food and Agriculture. 79:199-205.

Hobbs, P.J., T.H. Misselbrook, and T.R. Cumby. 1999b. Production and emissions of odors and gases. Journal of Agricultural Engineering Research. 72(3):291-298.

Jacobson, L.D., D. Paszek, R. Nicloai, D.R. Schmidt, B. Hetcher, and J. Zhu. 1999. Odor and gas emissions from animal manure storage units and buildings. ASAE Paper No. 994004. St. Joseph, MI:ASAE.

Jacobson, L.D., H. Guo, D.R. Schmidt, and R.E. Nicolai. 2001. Influence of weather conditions on field evaluation of odor dispersions from animal production sites. In Proceedings of the 6th International Symposium, R.R. Stowell, R. Buekdin, and R.W. Bottcher, eds. ASAE Publication 701P0201, St. Joseph, MI. P679-636.

Janni, K.A., W.J. Maier, T.H. Kuehn, B.B. Bridges, D. Vesley, and M.A. Nellis. 1998. Evaluation of biofiltration of air, an innovative air pollution control technology.

Jayas, D.S., S. Sokhansanj, E.B. Moysey, and E.M. Barber. 1987a. The effect of airflow direction on the resistance of Canola (Rapeseed) to airflow. Canadian Agricultural Engineering. 29:189-192.

Jayas, D.S., S. Sokhansanj, E.B. Moysey, and E.M. Barber. 1987b. Airflow resistance of Canola (Rapeseed). Trans. ASAE (Am. Soc. Agric. Eng.). 30(5):1484-1488.

Kay, R.L., C.J. Bern, and C.R. Hurburgh Jr. 1989. Horizontal and vertical airflow resistance of shelled corn at various bulk densities. Trans. ASAE (Am. Soc. Agric. Eng.). 32(2):733-736.

Krailas, S., Q.T. Pham, R. Amal, J.K. Jiang, and M. Heitz. 2000. Effect of inlet mass loading, water and total bacteria count on methanol elimination using upward flow and downward flow biofilters. Journal of Chemical Technology and Biotechnology. 75:299-305.

Krishnayya, A.V., J.G. Agar, T.T. Wong, B. Nevokshonoff, and R. Warren. 1999. Temperature effects on biofiltration of off-gases. Assessment and Remediation of Contaminated Sites in Arctic and Cold Climates, Edmonton, p. 186-195.

Kumar, A., amd W.E. Muir. 1986. Airflow resistance of Wheat and Barley affected by airflow direction, filling method, and dockage. Trans. ASAE (Am. Soc. Agric. Eng.). 29(5):1423-1426.

Lee, D.H., A.K. Lau, and K.L. Pinder. 2001. Development and performance of an alternative biofilter system. Journal of the Air and Waste Management Association. 51:78-85.

Lee, D.H.. 1999. Development of an alternative biofilter system for odor treatment. Unpublished PhD University of British Columbia, Victoria, BC.

Lemay, S.P.. 1999. Barn management and control of odours. Advances in Pork Production. 10:81-91.

Li., X.W., S.J. Hoff, D.S. Bundy, J. Harmon, H. Xin, and J. Zhu. 1996. Biofilter- a malodor control technology for livestock industry. J. Environ. Sci. Health, Pt. A: Environ. Sci. Eng. Toxic Hazard. Subst. Control. 31(9):2275-2285.

Lim, T.T., A.J. Heber, J.Q. Ni, A.L. Sutton, and D.T. Kelly. 2001. Characteristics and emission rates of odor from commercial swine nurseries. Trans. ASAE (Am. Soc. Agric. Eng.). 44(5):1275-1282.

Luttighuis, H.H.O. 1998. Improvement of biofilter – technology by a new type of packing material. In *proc for the Air and Waste Management Association's 91st Annual Meeeting and Exhibition.* Paper No. 98-WAA.01P. Air and Waste Management Association, Pittsburgh, PA.

Manitoba Pork. 2003. How pigs are raised. http://www.manitobapork.com/pdf/pigsraised.pdf. Accessed March 17, 2003

Mann, D.D., and E.M. Garlinski. 2002. Design of a horizontal airflow biofilter. CSAE/SCGR Paper No. 02-611. Mansonville, QC:CSAE.

Mann, D.D., J.C. DeBruyn, and Q. Zhang. 2002. Design and evaluation of an open biofilter for treatment of odour from swine barns during sub-zero ambient temperatures. Canadian Biosystems Engineering. 44(6):21-26.

Marek, J., J. Paca, B. Koutsky, and A.M. Gerrard. 1999. Determination of local elimination capacities and moisture contents in different biofilters treating toluene and xylene. Biodegradation. 10:307-313.

Midwest Plan Service. 1983. Midwest Plan Service - structural and environment handbook 11ed. Ames, Iowa : Iowa Sate University

Neal, A.B. and R. C. Loehr. 2000. Use of biofilters and suspended-growth reactors to treat VOCs. Waste Management. 20:59-68.

Nicolai, R.E., and K.A. Janni. 1998b. Comparison of biofilter residence time. ASAE Paper No. 984053. St. Joseph, MI:ASAE.

Nicolai, R.E.. 2002. Biofiltration of livestock facility exhaust air. Unpublished PhD Thesis. University of Minnesota, St.Paul, MN.

Noren, O.. 1985. Design and use of biofilters for livestock buildings. Odour Prevetion and Control of Organic Sludge and Livestock Farming eds. V.C. Nielsen, J.H. Voorburg, and P. L'Hermite. 234-237.

O'Neill, D.H., and V.R. Phillips. 1992. A Review of the control of odour nuisance from livestock buildings: Part 3, Properties of the odorous substance which have been identified in livestock wastes or in the air around them. Journal of Agricultural Engineering Research. 53:23-50.

Philips, V.R., I.M. Scotford, R.P. White, and R.L. Hartshorn. 1995. Minimum-cost biofilters for reducing odours and other aerial emissions from livestock buildings: Part 1, Basic airflow aspects. Journal of Agricultural Engineering Research. 62:203-214.

Ritter, W.F.. 1989. Odour control of livestock wastes: State of the art in North America. Journal of Agricultural Engineering Research. 42:51-62.

Ross, M., A.F. Smith, D.Shurb, and H. Sorensen. 2002. Glen Cairn trunk sewer pilot biofilter. Water Environment Association of Ontario 31st Annual Technical Symposium April 21-23, 2002 Hamilton, Ontario.

Sadaka, S., C. Magura, and D.D. Mann. 2002. Vertical and horizontal airflow characteristics of wood/compost mixtures. Applied Engineering in Agriculture. 18(6):735–741.

Satida, K., Q.T. Pham, R. Amal, J.K. Jiang, and M. Heitz. 2000. Effect of inlet mass loading, water and total bacteria count on methanol elimination using upward flow and downward flow biofilters. Journal of Chemical Technology and Biotechnology. 75:299-305.

Schiffman, S.S., J.A. Bennett, and J.H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology. 108:213-240.

Schmidt, D.R., L.D. Jacobson, and K.A. Janni. 2002. Continuous monitoring of ammonia, hydrogen sulfide and dust emissions from swine, dairy and poultry barns. ASAE Paper No. 024060. St. Joseph, MI:ASAE.

Shedd, C.K.. 1953. Resistance of grains and seeds to air flow. Agricultural Engineering. 12(5):145-148.

Sheridan, B.A., E.T. Hayes, T.P. Curran and V.A. Dodd. 2003. A dispersion modelling approach to determining the odour impact of intensive pig production units in Ireland. Bioresource Technology. 91:145-152.

Smet, E., H. Van Langenhove, and W. Verstraete. 1996. Long-term stability of a biofilter treating dimethyl sulphide. Applied Microbiology and Biotechnology . 46:191-196.

Smet. E., H. Van Langenhove, and K. Maes. 2000. Abatment of high concentrated ammonia loaded waste gases in compost biofilters. Water, Air, and Soil Pollution. 119:177-190.

Sokhansanj, S., A.A. Falacinski, F.W. Sosulski, D.S. Jayas, and J. Tang. 1990. Resistance of bulk lentils to airflow. Trans. ASAE (Am. Soc. Agric. Eng.). 33(4):1281-1285.

Sun, Y., C.J. Clanton, and K.A. Janni. 1999. Nitrogen and sulfur balances in biofilters affected by media content and gas retention time. ASAE Paper No. 994131. St. Joseph, MI:ASAE.

Sun, Y., C.J. Clanton, K.A. Janni, and G.L. Malzer. 2000. Sulfur and nitrogen balances in biofilters for odorous gas emission control. Trans. ASAE (Am. Soc. Agric. Eng.). 43(6):1861-1875.

Sweeten, J.M., R.E. Childers, J.S. Cochran, and R. Bowler. 1991. Odor control from poultry manure composting plant using a soil filter. Applied Engineering in Agriculture. 7(4):439-449.

Tumchenok V.I.E.. 2001. Biofilter for agricultural and industrial complex. Russian Patent 2170761.

Tyndall, J. and J. Colletti. 2000. Air quality and shelterbelts: Odor mitigation and livestock production a literature review. Lincoln, Nebraska, Project Number: 4124-4521-48-3209, The United States Department of Agriculture, National Agroforestry Center Sponsored Research Project Final Report.

van Lith, C., G. Leson, and R. Michelsen. 1997. Evaluating design options for biofilters. Journal of the Air and Waste Management Association. 47(1):37-48.

Verin Deutscher Ingenieure. 1991. Biological waste gas / waste air purification biofilter. VDI 3477. Verein Deutscher Ingeniere, Duesseldorf, Nordrhein-Westfalen, Germany.

Wani, A.H., R.M.R. Branion, and A.K. Lau. 1998. Effects of periods of starvation and fluctuating hydrogen sulfide concentration on biofilter dynamics and performance Journal of Hazardous Materials. 60:287–303.

Wilhelm, L.R., and D. McKinney. 1999. Environmental measurements in production swine facilities. ASAE Paper No. 993195. St. Joseph, MI:ASAE.

William, A.G.. 1984. Indicators of piggery slurry odour offensiveness. Agricultural Wastes. 10:15-36.

Williams, T.O., and F.C. Miller. 1992. Odor control using biofilters. BioCycle. 33(10):72-76.

Wood, S.L., K.A. Janni, C.J. Clanton, D.R. Schmidt, L.D. Jacobson, and S. Weisberg. 2001. Odor and air emissions from animal production systems. ASAE Paper No. 014043. St. Joseph, MI:ASAE.

Yang, Y. and E.R. Allen. 1994. Biofiltration control of hydrogen sulfide 1. Design and operational parameters. Journal of the Air and Waste Management Association. 44:863-868.

Yoran, A, E. Sandbank, and S. Kimchie. 2003. A method and apparatus for improving the quality of indoor air. World Intellectual Property Organization 03/059037 A2.

Zeisig, H.D., J. Kreitmeier, and J. Franzspeck. 1977. Untersuchungen uber Erdfilter sur Verringerung der Geruchsbelastigung aua Tier-haltungen. Schriftenreihe der Landtechnik, Weihenstephan, Freising-Weihenstephan.

Zhou, X. 2001. Odour emissions from swine operations in Manitoba. Unpublished M.Sc. Thesis. University of Manitoba, Winnipeg, MB.

Zhou, X. and Q. Zhang. 2003. Measurements of odour and hydrogen sulfide emissions from swine barns. Canadian Biosystems Engineering. 45:6.13-6.18.

Zhu, J. and L.D. Jacobson. 1999. Major odorous compounds in swine manure. Journal of Environmental Quality. 28:737-744.

Zhu, J., and D.L. Schmidt. 1999. Daylong monitoring of odor and gas emissions from animal facilities. ASAE Paper No. 994146. St. Joseph, MI:ASAE.

Zhu, J., G.L. Riskowski, and M. Torremorell. 1999. Volatile fatty acids as odor inductors in swine manure - A critical review. Trans. ASAE (Am. Soc. Agric. Eng.). 42(1):175-182

Zhu., J., L. Jacobson, D. Schmidt, and R. Nicolai. 2000. Daily variations in odor and gas emissions from animal facilities. Applied Engineering in Agriculture. 16(2):153-158.

APPENDIX A : CALCULATIONS AND DRAWINGS FOR GLENLEA BIOFILTER

Known

	Units	Variable	
2450	cfm		Airflow
1.16	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
80	%		Percentage of airduct open
8.82	s	r	True residence time
2		y	Layers
3.05	m	h	height of biofilter

Assume

3.05	m	t	Total thickness of biofilter media

Determine

V=(r*Q)/f

17.00	m^3	V	Volume of biofilter media

EBCT = Q/V

14.70	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)

1.8	m	L	Length

A=V/t

5.57	m^2	A	Surface Area of Biofilter

Actual area due to design of biofilter (80% of A)

4.46	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.259	m^3/s/m^2	SL	Surface Loading

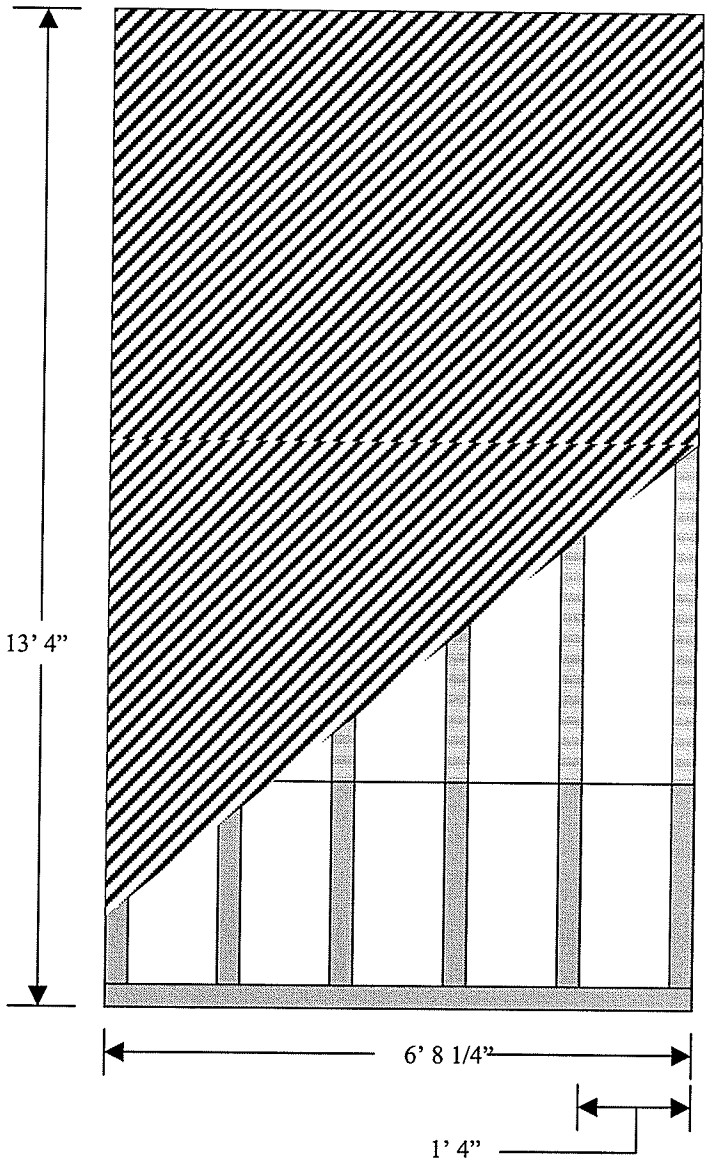
P=t/y*((a*SL^2)/ln(1+b*SL))

196	Pa	P	Pressure required for air to travel through media

Floor of Glenlea Biofilter

Top View

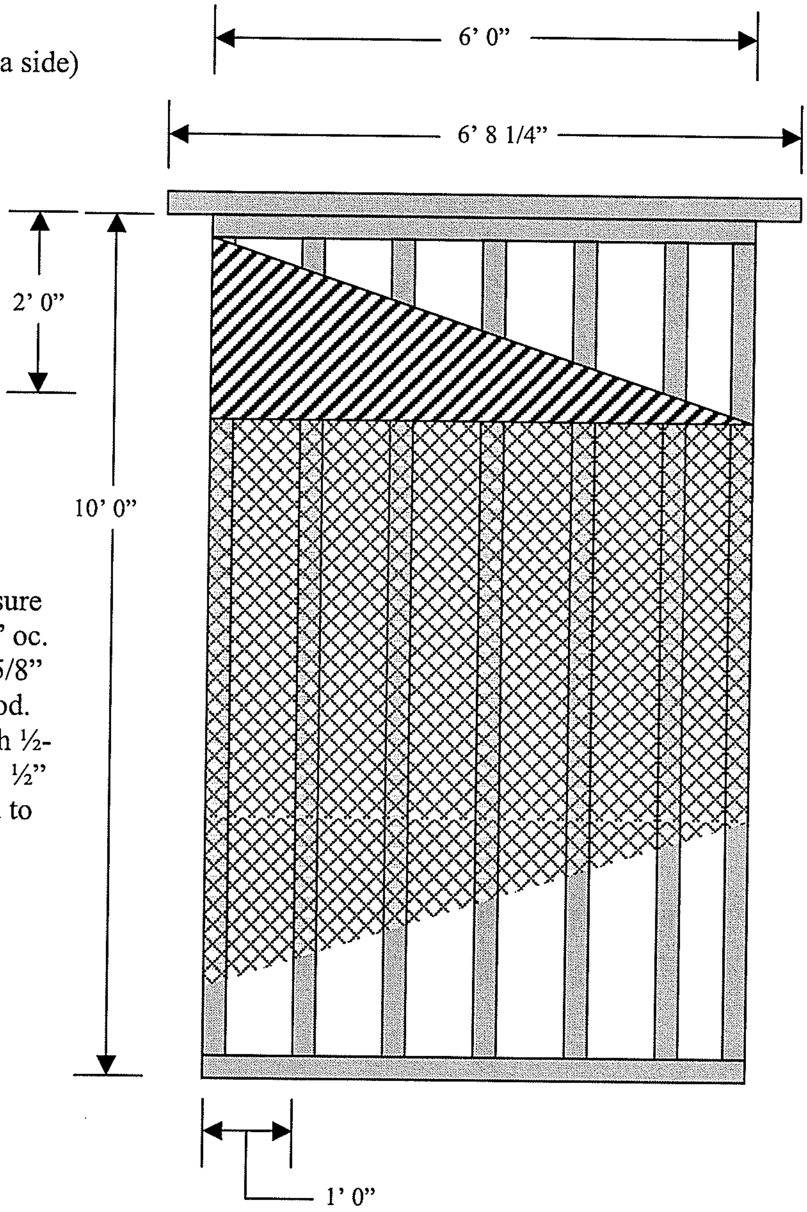
Constructed from pressure treated 2x6, spaced 16" on centre (oc). Covered with heavy poly and than covered with 5/8" pressure treated plywood. 3 ½" Deck screws were used to attached pieces to each other.



End Wall of Glenlea Biofilter

(4 required)

Plan View (from media side)

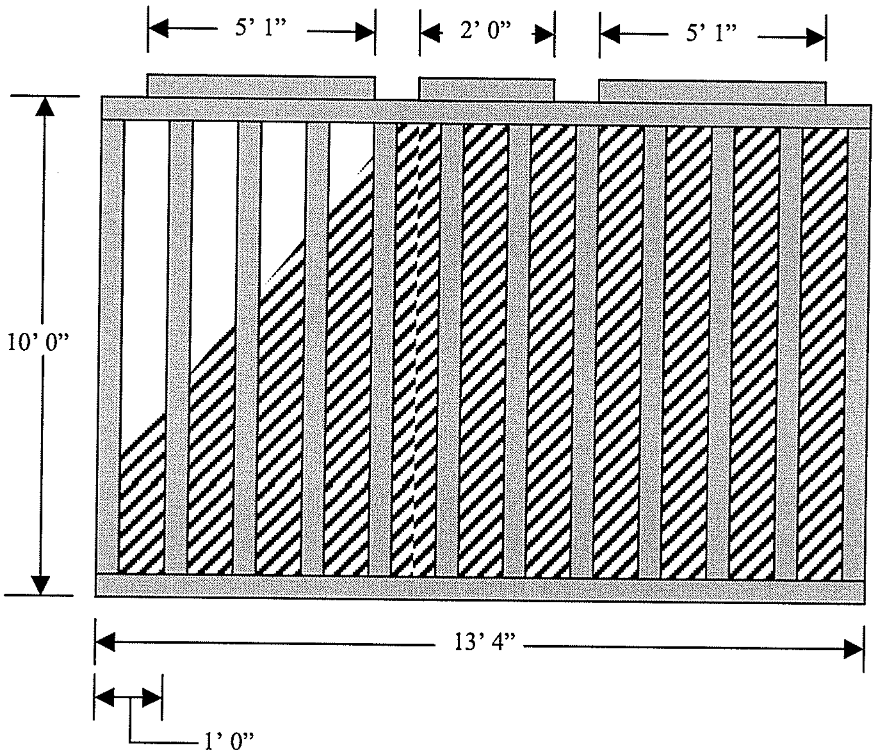


Constructed from pressure treated 2x4, spaced 12" oc. Top 2 ft covered with 5/8" pressure treated plywood. Lower 8 ft covered with ½-16F expanded metal. 3 ½" Deck screws were used to attached pieces to each other.

Side Wall of Glenlea Biofilter

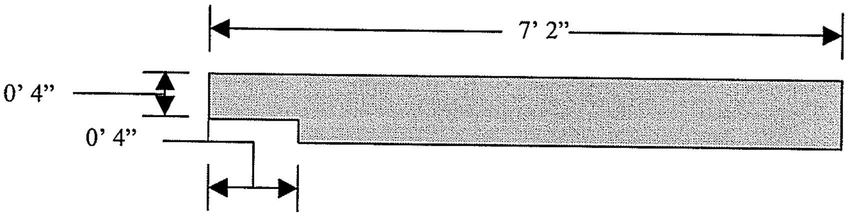
(2 required)

Plan View (from outside)



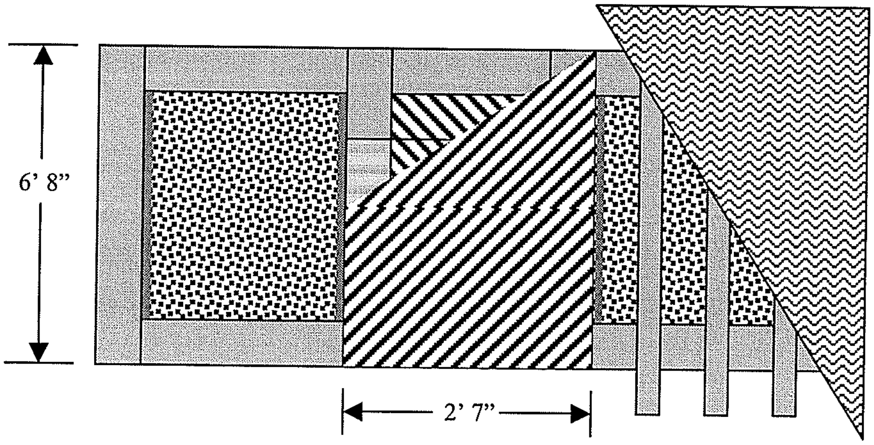
Constructed from pressure treated 2x4, spaced 12" oc. Side facing biofilter media is covered with heavy poly and than 5/8" pressure treated plywood. 3 ½" Deck screws were used to attached pieces to each other. One wall needs to have inlet installed into it. Other wall had door installed to allow for entrance into internal plenum.

Top View of Glenlea Biofilter



Simple Rafter (8 required)

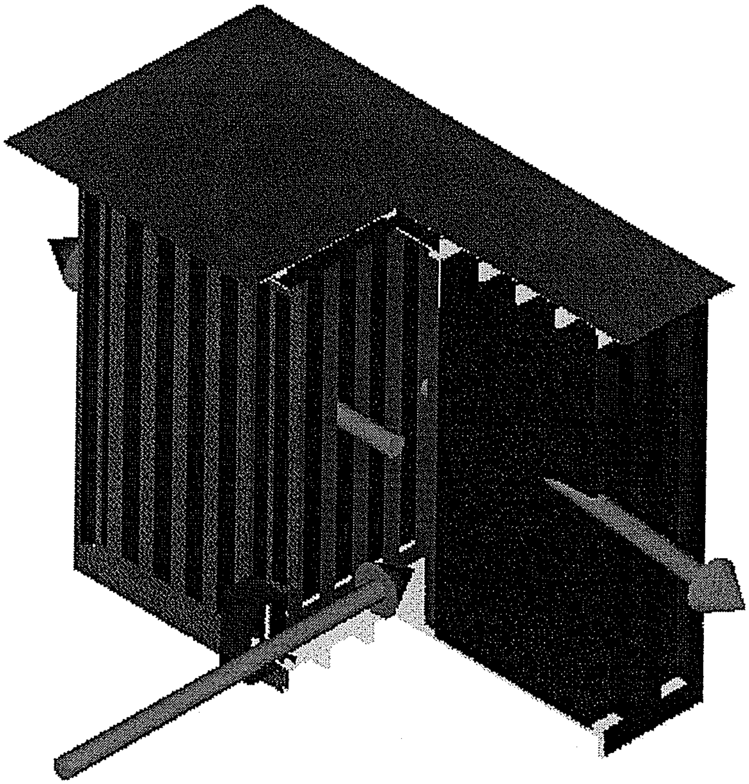
Made from 2 x 6 pressure treated lumber. Attempt to space every 24" oc. Notch is low end of roof. Toenail into place with 3 ½" deck screws



Dimension given are for cover to seal internal plenum from top. Internal plenum is covered with heavy poly and than 5/8" pressure treated plywood. 3 ½" Deck screws were used to attached pieces to each other. Rafters are attempted to be evenly spaced over top of biofilter structure. Rafters are covered with metal roof.

Glenlea Biofilter

Arrows represent airflow through the biofilter.



APPENDIX B – WATERING DATA

B.1 Raw Watering Data

As discussed in the literature review, water content of the biofilter is an important concern with a properly operating biofilter. The design of the watering system was discussed in the materials section, but not discussed after that point. Data was collected from 2002 and with the redesigning of the watering system, used to determine a watering schedule for 2003. In 2002, the sensor controlled the solenoid that determined when to water the biofilter. See Section 4.7 and sub-sections for explanation of the watering system. Figures B1 and B2 are samples of data collect from the summer of 2002. As discussed in the literature review, moisture content of the biofilter media can greatly affect the performance of the biofilter and knowledge of the watering of this biofilter is important when discussing the results of other data collected.

As the method used to determine the set points of the biofilter for watering were only rough estimates with an uncalibrated sensor, the data collected during the summer of 2002 shows that it still worked. In fig. B1, a pattern can be seen that shows the biofilter being watered (the high point), then approximately 10 h later the moisture content of the biofilter media has decreased enough for the sensor/solenoid set-up to initiate watering again (the low point). This can be better seen in fig. B2, over the course of two days. As the data collected showed a periodic water schedule, when the watering system was rebuilt in 2003, a timed solenoid was used.

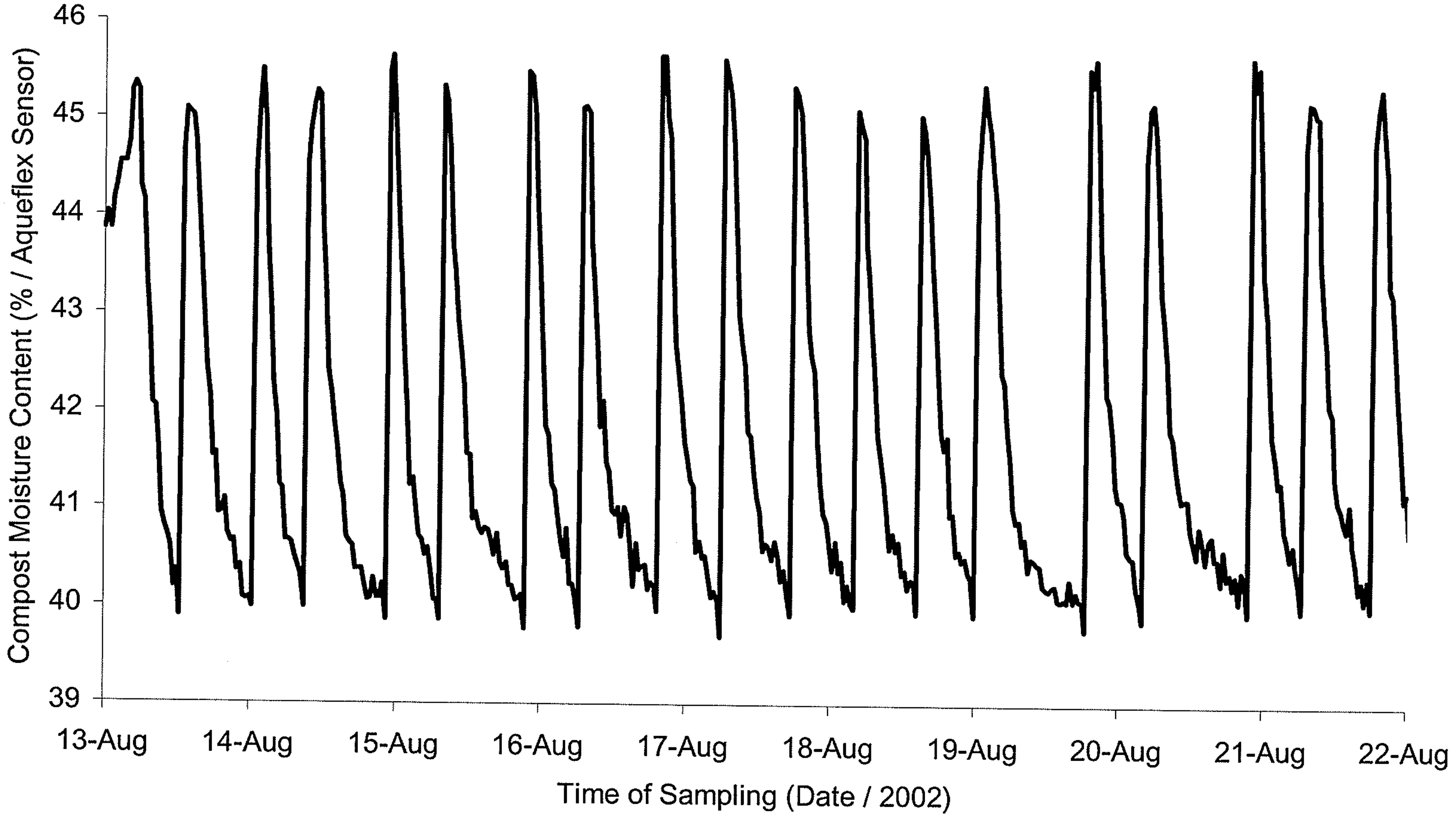


Figure B1 **Watering cycle for 216 hrs collect by uncalibrated Aquaflex sensor from Aug. 2002**

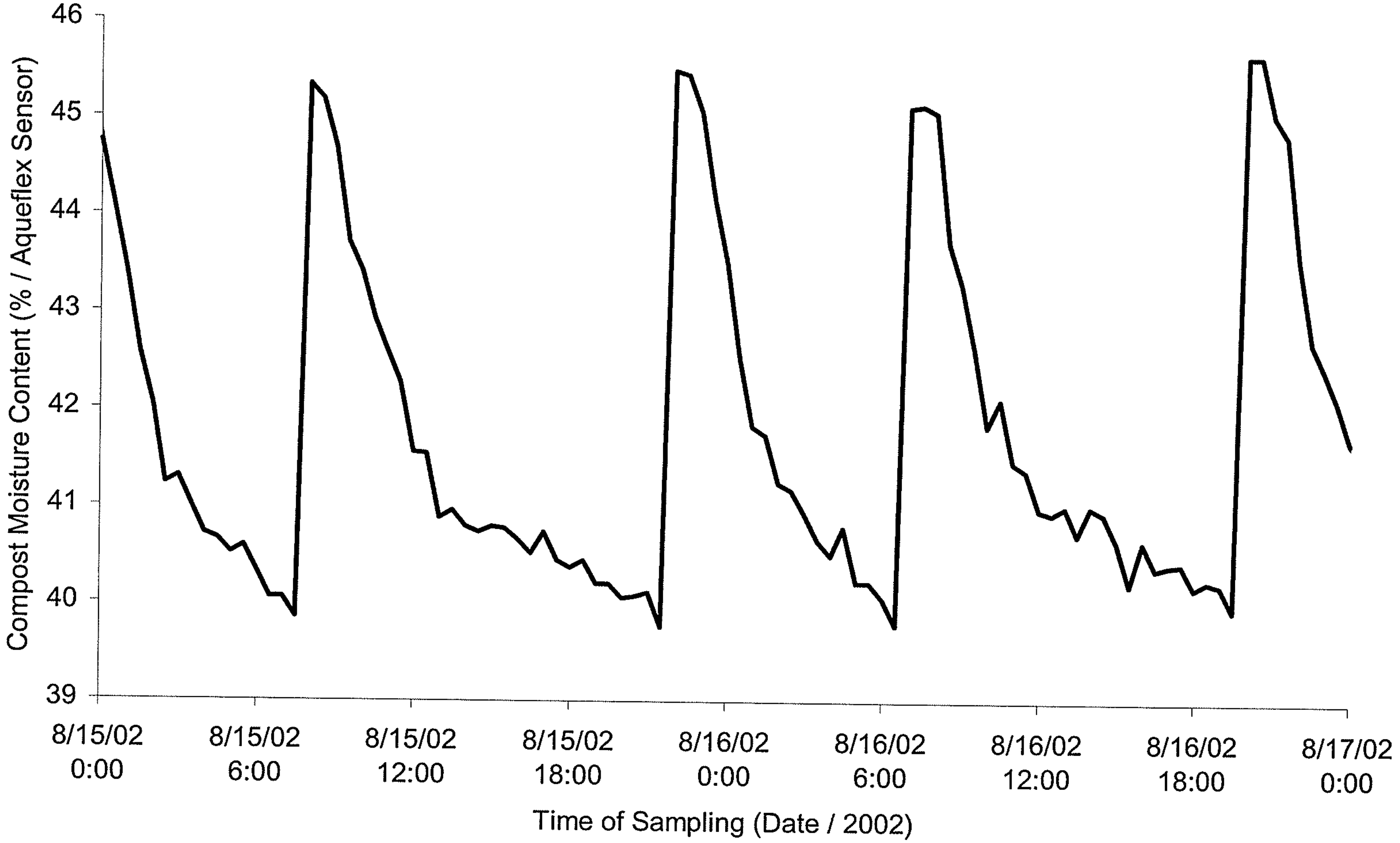


Figure B2 Watering cycle for 48 hrs with uncalibrated Aqueflex Sensor during Aug. 2002

B.2 Watering Effects on other Data Collected

B.2.1 Face Velocity

With the design of the watering system, a sensor was buried in a layer of compost, surrounded with weed barrier. Looking the data collected for airflow, a possible explanation is offered and supported for the above average airflows that appeared on the south side of the biofilter below the sensor.

Looking at the literature available discussing pressure drop and airflows through grain, it has been determined that increasing and decreasing in moisture content of grain will affect the pressure drop through the grain. As the fans used for this experiment supplied air for the both sides of the biofilter, difference in moisture content within the biofilter media should appear as differences in airflow.

Ideally, the internal plenum should have one pressure through the entire plenum. If this is the case, if certain areas of the biofilter required more pressure to move air through a given area of the biofilter in order to meet some target of a given airflow, the design of the biofilter will not increase the pressure to the area. With the design of the biofilter, the airflow only goes as high as possible for the given pressure available within the biofilter. Thus, other areas that require less pressure to move air through a given area of the biofilter will have higher airflows with the overall biofilter having a specific pressure available from the fans and an average airflow through the biofilter media. With this explanation, the pressure drop through the biofilter media in terms of physical height, at specific distances from the internal plenum, should by equal. However, as distance from the internal plenum increase and assuming a non-uniformly mixed biofilter media, difference could be expected. Another possible source of having non-uniform pressures within the biofilter at a given distance from the plenum is a flaw of the design, as was seen in the spring of 2003. At this time, the assumption of uniform pressure available within the plenum was disproved, and this was shown with the different pressures that were measure within the biofilter media.

Now returning the area of the biofilter below the sensor, when attempts to calibrate the moisture sensor where conducted, with the sensor being installed in bed of biofilter media. It became apparent that the water was not moving through the weed barrier and the compost, it was flowing around the sensor, thus the moisture content of the compost around the sensor never changed or changed only slightly after large amounts of water had been added to the media bed. As the set-up of the sensor was slightly different than the one actual designed and installed in the prototype biofilter, a possible explanation will be describe as to what was occurring. With the set-up of the prototype biofilter, it was only possible for small amounts of water to flow around the sensor unlike in the calibration experiment. It is assumed that the water instead would have pooled above the sensor, as it was laid out in the shape of a donut and slowly flow through the sensor layer. It is known that some water had went through the sensor layer as this area still removed pollutants from the air, unlike the top of the biofilter that is known to have received no water and thus was unable to remove pollutants. Thus, with the media above being possibly wetter than the rest of the biofilter media, the low flow rates through this area are probably a result of the excessive amounts of water. While, the area below the sensor had above average flow rates, this was possibly a result of only receiving just enough water to remove pollutants and as this area would require less pressure than other areas for the air to flow through, the higher flow rates occurred.

B.2.2 Hydrogen Sulphide

As briefly mentioned in the section discussing airflow, areas of the prototype biofilter had received insufficient amounts of water. The area that was most obvious was the top 150 mm (≈6"). The watering lines were installed below this volume of biofilter media, thus it was not possible for this area to receive any water. From the literature on biofilters, only supports the conclusion that this part of the biofilter was not able to treat pollutants because of a lack of water.

Looking at data collected in 2002, (Fig. B3), and knowing that problems where present with the watering system after the fact, the biofilter shows signs of insufficient watering. In the spring of 2003, when correcting problems in the biofilter's headspace, a problem with the watering system became visible. The water pressure was unable to supply water to all the water lines at the same time over their entire length of the soaker hoses. Water was not reaching the far ends of the water lines that were highest above the ground. The top of the side opposite the source of the water (west side) was receiving insufficient amounts of water. Using different methods of interpolating the data to provide an estimate for the amounts of hydrogen sulphide leaving the biofilter face, it can be seen that the west side of the biofilter is not performing as well as the east side. It is believed that the poorer performance is a result of insufficient water. As samples of the media were not collected from the biofilter at the time of the hydrogen sulphide sampling and when it was determined that there were problems with the watering system which was promptly redesigned, it was to late to determine the cause of the poorer hydrogen sulphide removal on the west side of the biofilter. Nevertheless, the fact that the problem did not reappear in the data collect from 2003, it is probably a safe assumption the poor removal of hydrogen sulphide on the west side was a result of insufficient watering.

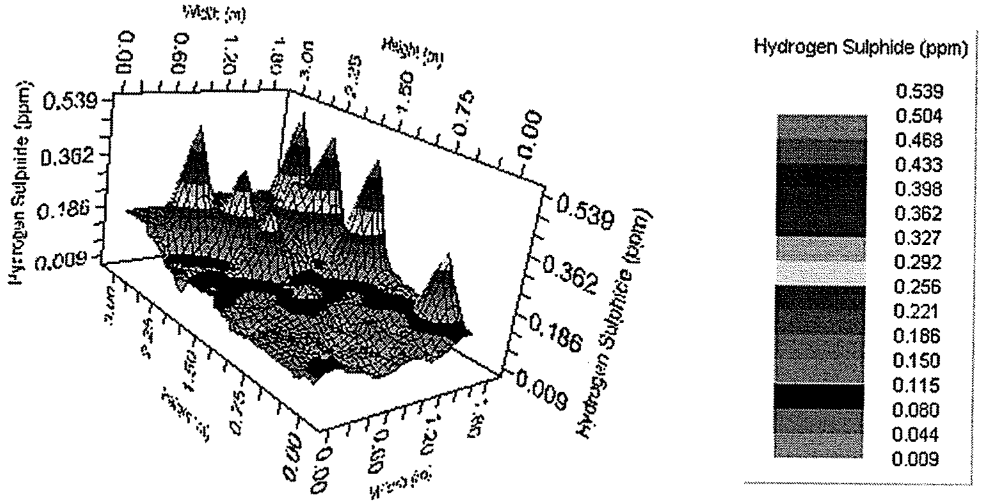
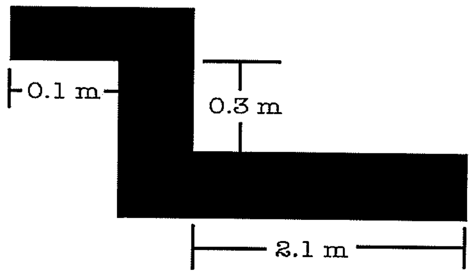


Figure B3 Hydrogen Sulphide removal on North face from Sept. 11, 2002.
Width is measure from east to west (larger value, further from barn)

APPENDIX C – DUCT DESIGN FOR GLENLEA BIOFILTER

Original Duct Design



Known

L =	2.5 m	length
Q =	1.89 m^3/s	Flow rate
A =	0.371 m^2	Cross-sectional Area (24"x24")
p =	2.44 m	perimeter

Assume

t =	300 k	Temerpature
E =	1 mm	Absolute roughness (Albright 1990; Table 12-1)
q =	1.1774 kg/m^3	density of air
u =	1.98E-05 kg/m-s	

Deq = 4(A)/p (Square Duct)
Deq = 0.608197 m hydraulic diameter

E/D = 0.001644 relative roughness

v = Q/A
v = 5.09434 m/s velocity

Re = qvD/u
Re = 1.84E+05

f = 0.02 Friction Factor from Moody Diagram

Pressure loss due to friction

P=f(L/D)(qv^2/2)
P = 1.256018 Pa

Dynamic Pressure losses

Re = 66.3Dv
Re = 205.4213
C =Kre*C' Table 3-6 Appendix 12-1 Albright 1990
H/W = 1 at 90
C' = 1.2

Kre = 1 Note 5 Appendix 12-1 Albright 1990
C = 1.2

P =C(qv^2/2)
P = 18.33374 Pa per 90 bend

Total pressure loss through ducting is 37.9 Pa

With this planned design, some assumptions were incorrect. They include the length of the ducting, the roughness factor of the duct wall, and the setup of the fans within the duct.

Current Duct Design

Known

L = 3.6 m length Straight ducting from barn to biofilter
Q = 1.89 m^3/s Flow rate
A = 0.371 m^2 Cross-sectional Area (24"x24")
p = 2.44 m perimeter

Assume

t = 300 k Temerpature
E = 3 mm Absolute roughness (Albright 1990; Table 12-1)
q = 1.1774 kg/m^3 density of air
u = 1.98E-05 kg/m-s

Deq = 4(A)/p (Square Duct)
Deq = 0.608197 m hydraulic diameter

E/D = 0.004933 relative roughness

v = Q/A
v = 5.09434 m/s velocity

Re = qvD/u
Re = 1.84E+05

f = 0.026 Friction Factor from Moody Diagram

P=f(L/D)(qv^2/2)
P = 2.351265 Pa

Total pressure loss is 2.4 Pa

APPENDIX D – GLENLEA DATA

Pressure Drop through Biofilter Media
Average Pressures in Pa

	South Distance from Plenum (m)			North Distance from Plenum (m)			
Date	1.0668	0.4953	Plenum	0.2032	0.5207	0.8382	1.1176
27-May-02 (2-5)	49.4	128.8		166.5	118.7	82.7	54.8
5-Jun-02 (1-5)	80.4	164.9					
5-Jun-02 (1-7)	52.5	131.8					
7-Jun-02 (1-10)	38.4	119.4					
26-Jun-02	28.5	70.6		81.4	64	45.1	28.4
11-Sep-02	49.9	88.5	117.5	78.3	80.5	68.9	51.5
27-May-03	45.1	14.5	58	-14.5	14.5	29	36.3
10-Jun-03	21.6	42.6	72.5	50	38.4	31.9	21.8
14-Jun-03	32.6	58.4	91.4	70.4	57.3	36.3	23.9
23-Jun-03	23.6	54.4	101.5	72.5	50.8	36.3	21.8
8-Jul-03	18	64.2	165.4	101.5	74.7	47.9	25.4
22-Jul-03	10.7	54.6	121.9	86.3	58.8	39.9	17.4
28-Jul-03	32.6	70.7	134.2	111.7	91.4	66.7	50
11-Aug-03	11.6	46.8	120.4	87.8	68.2	46.4	31.2

All other data is for a biofilter filled to 3 m (10 ft) on both side of the plenum

Pressure difference in incoming duct to biofilter
Average Pressures in Pa

		Duct Distance from Biofilter (m)		
Date	Plenum	1.3462	0.8382	0.4064
27-May-02 (2-5)		-13.3	158	271
5-Jun-02 (1-5)		20.6	199	306.4
5-Jun-02 (1-7)		-18.9	120.4	264
7-Jun-02 (1-10)		-21.8	145.1	264
26-Jun-02		-64.8	81.4	178.6
11-Sep-02	117.5	-63.1	88.5	184.2
27-May-03	58	-58	116.1	101.5
10-Jun-03	72.5	-29	-26.1	134.9
14-Jun-03	91.4	-20.3	-20.3	153.8
23-Jun-03	101.5	-14.5	-14.5	159.6
8-Jul-03	165.4	-23.2	111.7	143.6
22-Jul-03	121.9	-103	88.5	130.6
28-Jul-03	134.2	-66	87.8	132.7
11-Aug-03	120.4	-103	66.7	117.5

All other data is for a biofilter filled to 3 m (10 ft) on both side of the plenum

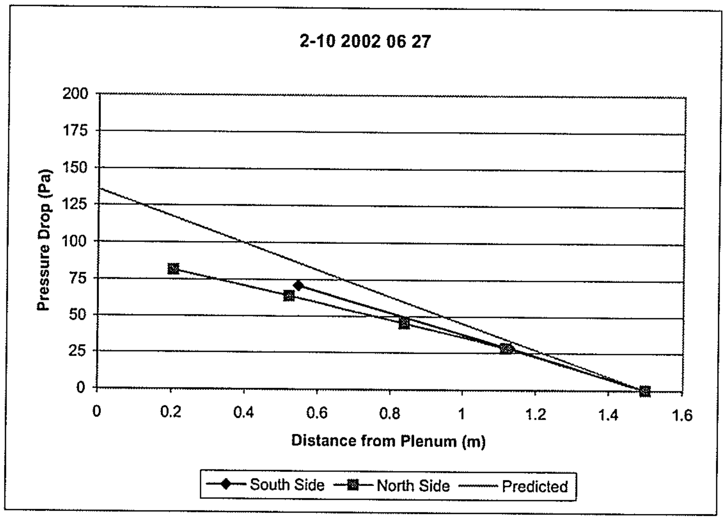
Date 26-Jun-02 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	34.96	75.58
2.46	37.86	66.87
2.16	33.51	71.23
1.85	27.71	74.13
1.55	23.36	72.68
1.24	20.45	66.87
0.94	24.81	71.23
0.64	26.26	72.68
0.33	27.71	63.97
Average	28.51	70.58
ST Dev	5.76	3.85

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30		68.33	49.47	32.06
2.24	81.38	59.62	40.76	24.81
Average	81.38	63.97	45.11	28.43
St Dev		6.15	6.15	5.13

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-64.84	81.38	178.57

Plenum	



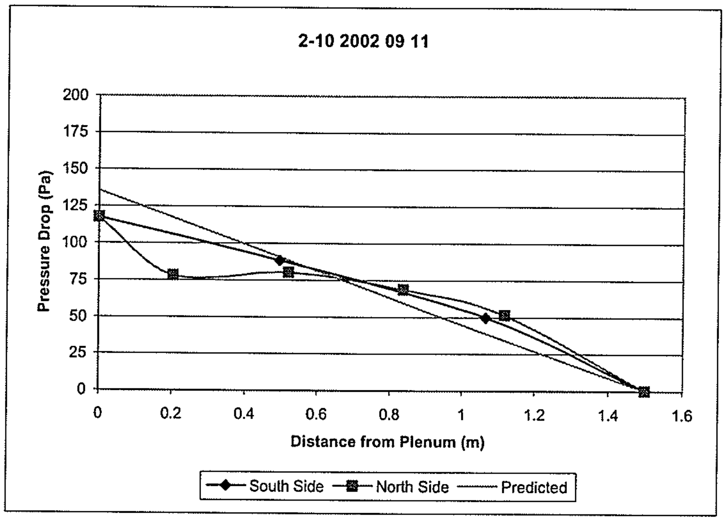
Date 11-Sep-02 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	36.99	103.00
2.46	52.22	91.39
2.16	52.22	81.24
1.85	52.22	88.49
1.55	52.22	88.49
1.24	50.77	82.69
0.94	49.32	84.14
0.64	50.77	87.04
0.33	52.22	89.94
Average	49.89	88.49
ST Dev	4.94	6.41

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30		82.69	72.53	50.77
2.24	78.33	78.33	65.28	52.22
Average	78.33	80.51	68.91	51.50
St Dev		3.08	5.13	1.03

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-63.10	88.49	184.23

Plenum	117.50



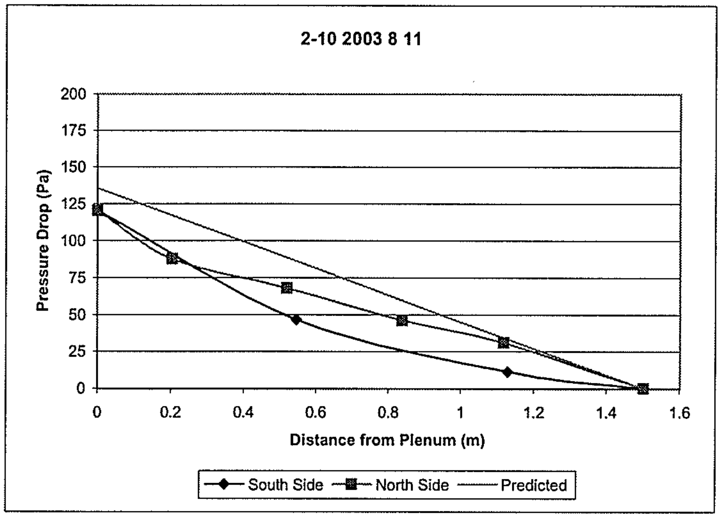
Date 11-Aug-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	60.93	58.03
2.46	-8.70	33.36
2.16	5.80	31.91
1.85	13.06	46.42
1.55	17.41	55.12
1.24	13.06	49.32
0.94	14.51	44.97
0.64	15.96	56.57
0.33	21.76	56.57
Average	11.61	46.78
ST Dev	9.37	9.80

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	87.04	72.53	50.77	34.82
2.24	88.49	63.83	42.07	27.56
Average	87.76	68.18	46.42	31.19
St Dev	1.03	6.15	6.15	5.13

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-103.00	66.73	117.50

Plenum 120.4031



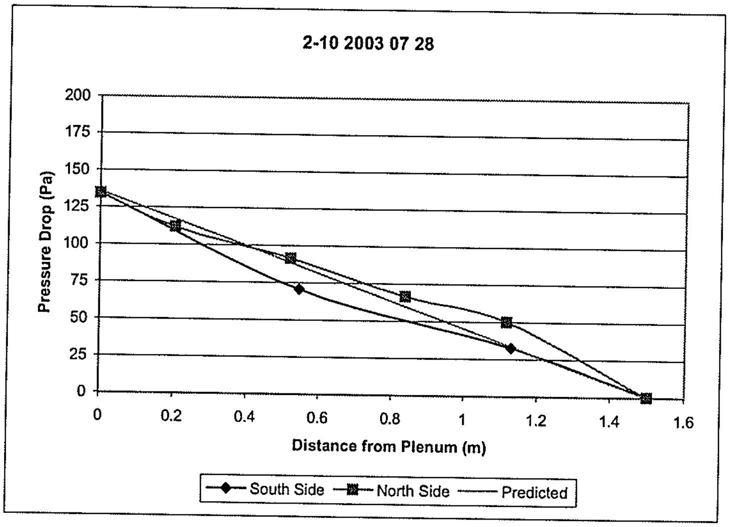
Date 28-Jul-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	84.86	89.21
2.46	19.58	52.95
2.16	31.19	63.10
1.85	36.99	77.61
1.55	38.44	81.96
1.24	36.99	76.16
0.94	34.09	66.00
0.64	32.64	71.81
0.33	31.19	76.16
Average	32.64	70.72
ST Dev	5.96	9.49

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	118.23	103.72	74.71	54.40
2.24	105.17	79.06	58.75	45.70
Average	111.70	91.39	66.73	50.05
St Dev	9.23	17.44	11.28	6.15

	(m) from to	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-66.00	87.76	132.73

Plenum	134.18



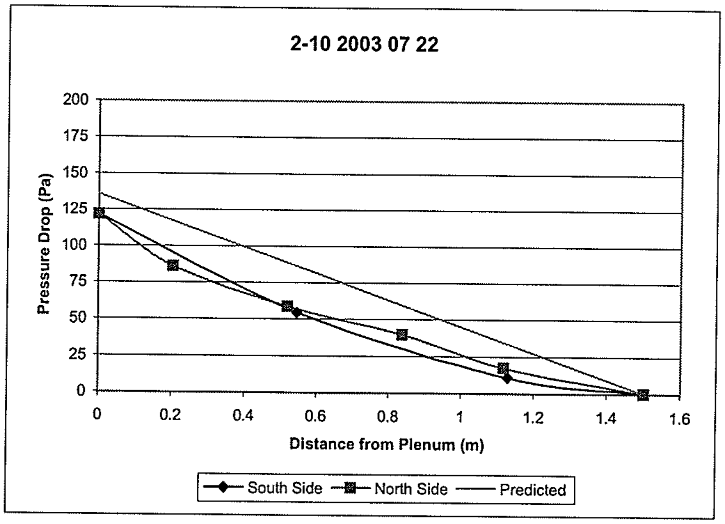
Date 22-Jul-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	59.48	66.73
2.46	10.15	39.17
2.16	7.25	46.42
1.85	11.61	62.38
1.55	18.86	59.48
1.24	8.70	50.77
0.94	11.61	53.67
0.64	8.70	63.83
0.33	8.70	60.93
Average	10.70	54.58
ST Dev	3.63	8.70

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	92.84	66.73	42.07	18.86
2.24	79.79	50.77	37.72	15.96
Average	86.31	58.75	39.89	17.41
St Dev	9.23	11.28	3.08	2.05

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-103.00	88.49	130.56

Plenum 121.85



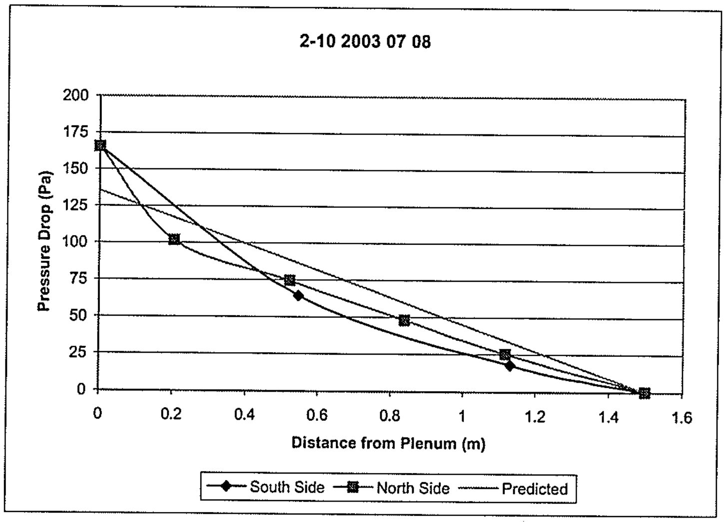
Date 08-Jul-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	107.35	100.09
2.46	13.06	53.67
2.16	26.11	56.57
1.85	20.31	65.28
1.55	14.51	71.08
1.24	14.51	63.83
0.94	17.41	59.48
0.64	20.31	69.63
0.33	17.41	73.98
Average	17.95	64.19
ST Dev	4.24	7.22

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	105.90	85.59	53.67	27.56
2.24	97.19	63.83	42.07	23.21
Average	101.54	74.71	47.87	25.39
St Dev	6.15	15.39	8.21	3.08

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-23.21	111.70	143.61

Plenum	165.37



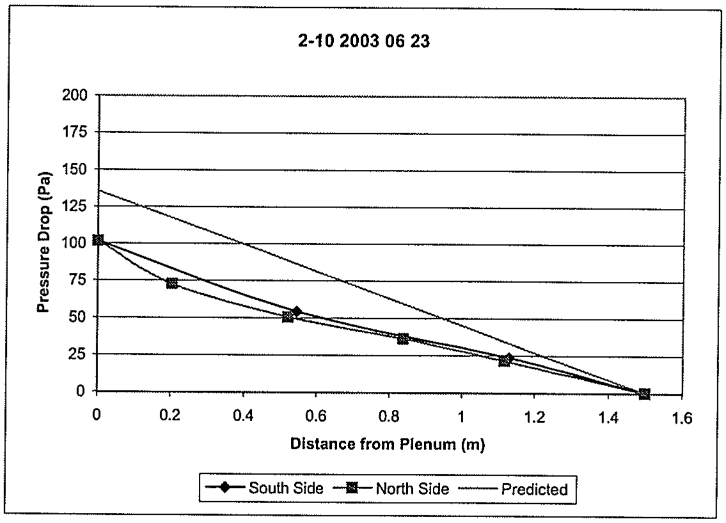
Date 23-Jun-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	130.56	116.05
2.46	14.51	43.52
2.16	14.51	43.52
1.85	29.01	58.03
1.55	29.01	58.03
1.24	29.01	58.03
0.94	29.01	58.03
0.64	29.01	58.03
0.33	14.51	58.03
Average	23.57	54.40
ST Dev	7.51	6.72

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	72.53	58.03	43.52	29.01
2.24	72.53	43.52	29.01	14.51
Average	72.53	50.77	36.27	21.76
St Dev	0.00	10.26	10.26	10.26

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-14.51	-14.51	159.57

Plenum 101.54



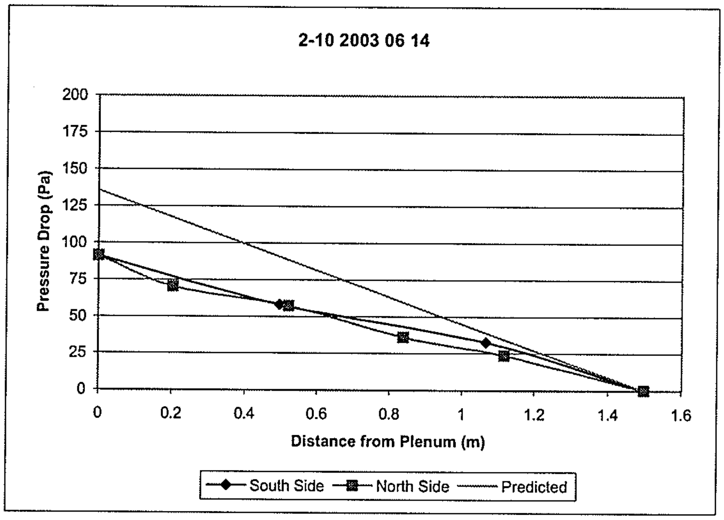
Date 14-Jun-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	113.15	110.25
2.46	29.01	60.93
2.16	34.82	58.03
1.85	33.36	62.38
1.55	33.36	58.03
1.24	31.91	59.48
0.94	31.91	52.22
0.64	31.91	58.03
0.33	34.82	58.03
Average	32.64	58.39
ST Dev	1.90	2.98

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30	69.63	58.03	37.72	26.11
2.24	71.08	56.57	34.82	21.76
Average	70.36	57.30	36.27	23.94
St Dev	1.03	1.03	2.05	3.08

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-20.31	-20.31	153.77

Plenum	91.39



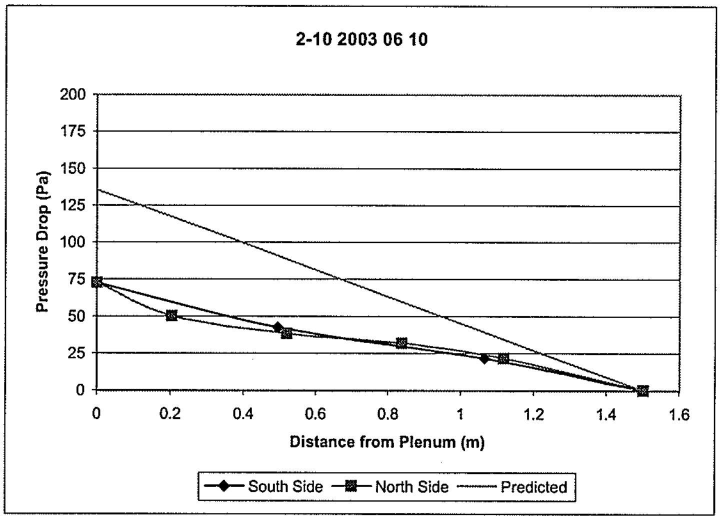
Date 10-Jun-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m)	
	1.13	0.55
2.77	5.80	82.69
2.46	7.25	63.83
2.16	36.27	53.67
1.85	24.66	44.97
1.55	23.21	29.01
1.24	14.51	43.52
0.94	24.66	39.17
0.64	13.06	37.72
0.33	29.01	29.01
Average	21.58	42.61
ST Dev	9.42	11.86

Depth from top (m)	Distance from plenum (m)			
	0.20	0.52	0.84	1.12
1.30	49.32	44.97	34.82	21.76
2.24	50.77	31.91	29.01	21.76
Average	50.05	38.44	31.91	21.76
St Dev	1.03	9.23	4.10	0.00

	(m) from top	Distance from biofilter (m)		
		1.35	0.84	0.41
Duct	0.15	-29.01	-26.11	134.91

Plenum	72.53



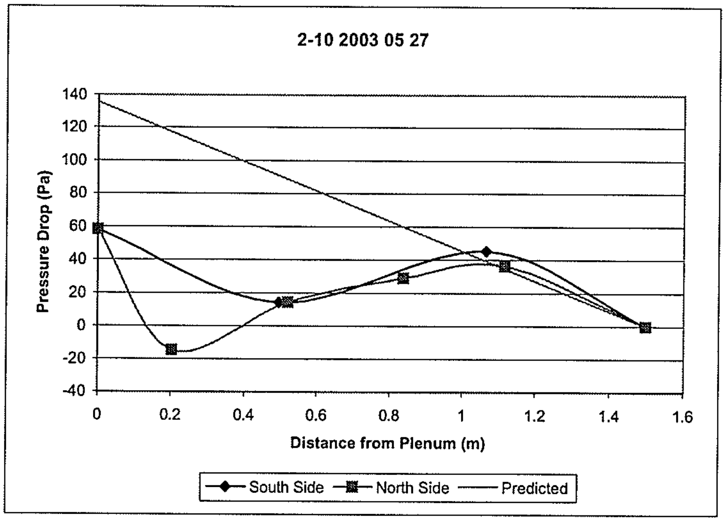
Date 27-May-03 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77	58.03	-14.51
2.46	43.52	0.00
2.16	29.01	14.51
1.85	43.52	29.01
1.55	72.53	29.01
1.24	43.52	14.51
0.94	43.52	29.01
0.64	43.52	14.51
0.33	29.01	14.51
Average	45.13	14.51
ST Dev	13.46	14.51

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30		14.51	29.01	29.01
2.24	-14.51	14.51	29.01	43.52
Average	-14.51	14.51	29.01	36.27
St Dev		0.00	0.00	10.26

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-58.03	116.05	101.54

Plenum 58.03



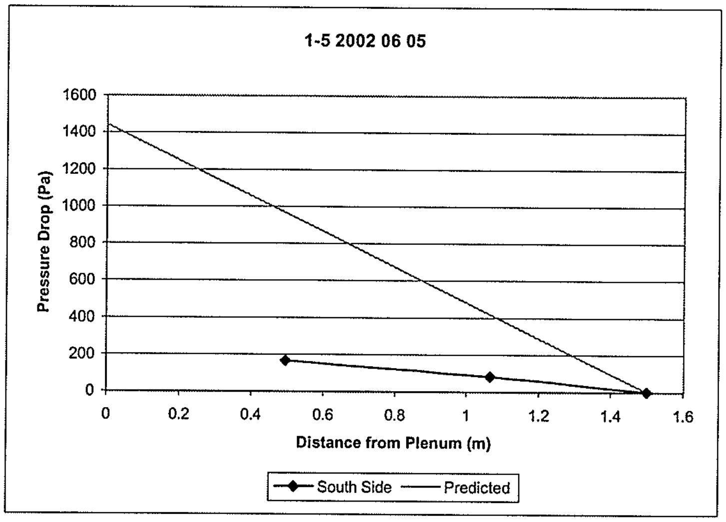
Date 05-Jun-02 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77		
2.46		
2.16		
1.85		
1.55		
1.24	85.88	151.16
0.94	82.98	165.66
0.64	78.62	171.47
0.33	74.27	171.47
Average	80.44	164.94
ST Dev	5.08	9.59

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30				
2.24				
Average				
St Dev				

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	20.60	199.03	306.38

Plenum



Date 05-Jun-02 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77		
2.46		
2.16		
1.85	60.93	132.01
1.55	58.03	129.11
1.24	53.67	133.46
0.94	49.32	133.46
0.64	46.42	132.01
0.33	46.42	130.56
Average	52.46	131.77
ST Dev	6.11	1.70

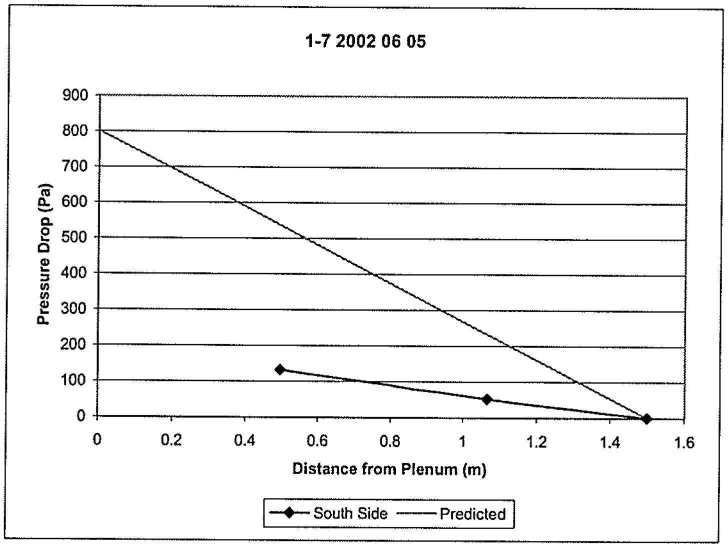
Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30				
2.24				

Average

St Dev

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-18.86	120.40	264.02

Plenum	



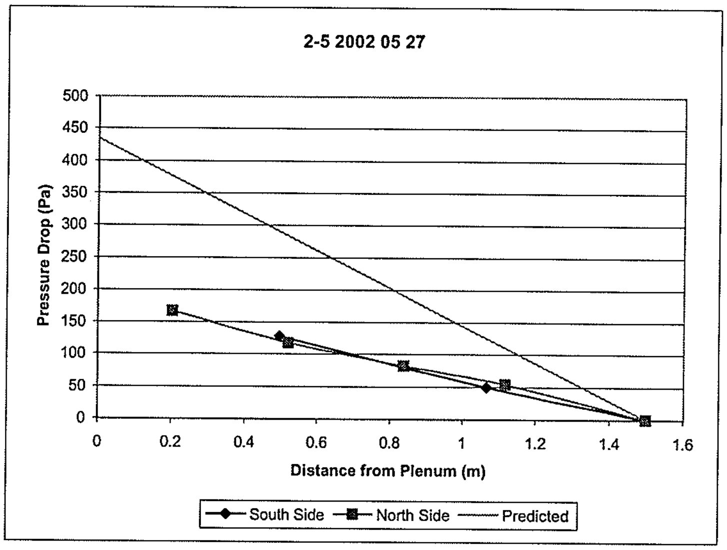
Date 27-May-02 Pressures in Pa

Depth from bottom (m)	Distance from plenum (m) 1.13	0.55
2.77		
2.46		
2.16		
1.85		
1.55		
1.24	62.09	130.27
0.94	49.03	128.82
0.64	43.23	128.82
0.33	43.23	127.37
Average	49.39	128.82
ST Dev	8.89	1.18

Depth from top (m)	Distance from plenum (m) 0.20	0.52	0.84	1.12
1.30				
2.24	166.53	118.66	82.69	54.83
Average				
St Dev				

	(m) from top	Distance from biofilter (m) 1.35	0.84	0.41
Duct	0.15	-13.35	157.97	270.98

Plenum	



Date 07-Jun-02 Pressures in Pa

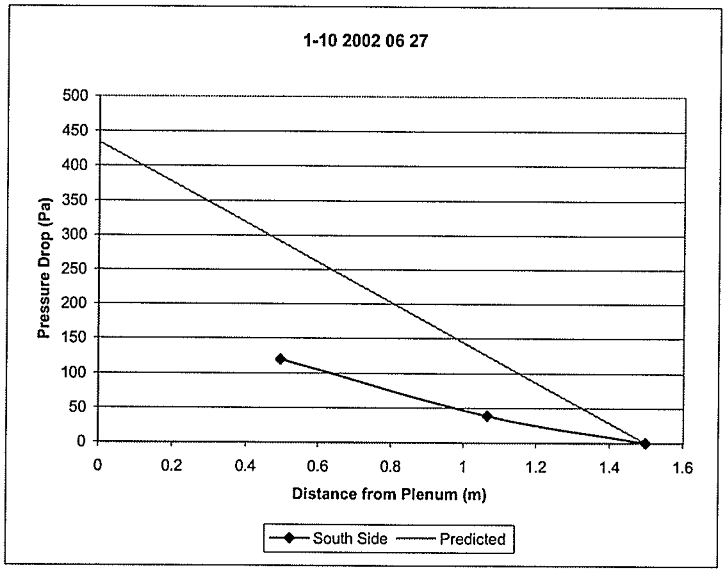
Depth from bottom (m)	Distance from plenum (m)	
	1.13	0.55
2.77	40.62	134.91
2.46	40.62	114.60
2.16	37.72	113.15
1.85	37.72	123.30
1.55	36.27	113.15
1.24	39.17	118.95
0.94	36.27	116.05
0.64	37.72	120.40
0.33	39.17	120.40
Average	38.36	119.44
ST Dev	1.64	6.80

Depth from top (m)	Distance from plenum (m)			
	0.20	0.52	0.84	1.12
1.30				
2.24				

Average
St Dev

		Distance from biofilter (m)		
	(m) from top	1.35	0.84	0.41
Duct	0.15	-21.76	145.06	264.02

Plenum	



All airflow are in the units of m/s

South all points

Date	27-May-02	05-Jun-02	05-Jun-02	07-Jun-02	26-Jun-02	11-Sep-02	27-May-03
Mean	0.17	0.16	0.14	0.15	0.06	0.08	0.04
St Dev	0.05	0.03	0.04	0.05	0.04	0.04	0.06
Skewness	1.27	0.29	-0.72	0.07	0.14	0.30	1.74
Kurtosis	1.73	0.02	1.46	1.03	-0.81	-0.86	3.34
Max	0.28	0.21	0.21	0.26	0.14	0.15	0.25
Min	0.12	0.11	0.04	0.03	0.00	0.01	0.00

North all points

Date	27-May-02 1-5	1-7	1-10	26-Jun-02 Windy	27-May-03
Mean	0.14			0.07	0.07
St Dev	0.03			0.04	0.11
Skewness	0.02			0.79	3.92
Kurtosis	-0.76			-0.88	18.04
Max	0.20			0.15	0.60
Min	0.09			0.02	0.00

South all points

Date	10-Jun-03	23-Jun-03	27-Jun-03	9-Jul-03	22-Jul-03	28-Jul-03	11-Aug-03
Mean	0.04	0.00	0.06	0.12	0.11	0.09	0.09
St Dev	0.06	0.01	0.02	0.03	0.03	0.03	0.03
Skewness	2.73	3.63	0.02	-0.05	-0.27	-0.19	0.09
Kurtosis	10.09	14.46	-1.09	-1.08	-1.22	-0.77	-0.79
Max	0.28	0.06	0.11	0.17	0.16	0.14	0.16
Min	0.00	0.00	0.03	0.08	0.06	0.05	0.04

North all points

Date	10-Jun-03	23-Jun-03	27-Jun-03	09-Jul-03	22-Jul-03	28-Jul-03	11-Aug-03
Mean	0.06	0.01	0.07	0.13	0.12	0.11	0.10
St Dev	0.08	0.02	0.02	0.04	0.05	0.03	0.03
Skewness	3.34	2.23	0.25	0.73	0.21	0.48	0.90
Kurtosis	14.55	4.19	-0.29	-0.03	-0.40	-0.41	1.04
Max	0.42	0.08	0.12	0.22	0.22	0.18	0.21
Min	0.00	0.00	0.01	0.07	0.04	0.05	0.04

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		5/27/02	6/5/02	6/5/02	6/7/02	6/26/02	9/11/02	5/27/03
1.65	2.79				0.19	0.10		0.25
1.65	2.54						0.15	
1.65	2.29				0.22	0.10		0.12
1.65	2.03						0.14	
1.65	1.78			0.19	0.17	0.04		0.13
1.65	1.52						0.06	
1.65	1.27	0.24	0.21	0.15	0.17	0.14		0.00
1.65	1.02						0.12	
1.65	0.76	0.17	0.18	0.17	0.16	0.09		0.04
1.65	0.51						0.03	
1.65	0.25	0.17	0.16	0.15	0.16	0.10		0.00
1.35	2.79							
1.35	2.54				0.23	0.06		0.00
1.35	2.29						0.15	
1.35	2.03			0.04	0.16	0.09		0.11
1.35	1.78						0.05	
1.35	1.52	0.28	0.16	0.21	0.16	0.02		0.00
1.35	1.27						0.07	
1.35	1.02	0.18	0.16	0.15	0.11	0.13		0.07
1.35	0.76						0.10	
1.35	0.51	0.13	0.15	0.12	0.12	0.04		0.00
1.35	0.25						0.07	
1.05	2.79				0.11	0.02		0.00
1.05	2.54						0.12	
1.05	2.29				0.26	0.05		0.11
1.05	2.03						0.10	
1.05	1.78			0.16	0.16	0.00		0.00
1.05	1.52						0.06	
1.05	1.27	0.19	0.18	0.15	0.13	0.12		0.05
1.05	1.02						0.10	
1.05	0.76	0.17	0.17	0.16	0.13	0.10		0.04
1.05	0.51						0.04	
1.05	0.25	0.12	0.13	0.11	0.03	0.04		0.00
0.75	2.79							
0.75	2.54				0.16	0.04		0.00
0.75	2.29						0.15	
0.75	2.03			0.13	0.15	0.05		0.10
0.75	1.78						0.04	
0.75	1.52	0.12	0.15	0.17	0.15	0.01		0.03
0.75	1.27						0.06	
0.75	1.02	0.14	0.13	0.12	0.09	0.07		0.00
0.75	0.76						0.07	
0.75	0.51	0.14	0.15	0.13	0.10	0.03		0.00
0.75	0.25							
0.45	2.79				0.15	0.00		0.01
0.45	2.54						0.08	

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		5/27/02	6/5/02	6/5/02	6/7/02	6/26/02	9/11/02	5/27/03
0.45	2.29				0.19	0.09		0.08
0.45	2.03						0.07	
0.45	1.78			0.19	0.18	0.00		0.00
0.45	1.52						0.01	
0.45	1.27	0.12	0.11	0.10	0.10	0.07		0.00
0.45	1.02						0.11	
0.45	0.76	0.19	0.21	0.17	0.13	0.09		0.00
0.45	0.51						0.04	
0.45	0.25	0.15	0.16	0.12	0.09	0.05		0.00

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		6/10/03	6/23/03	6/27/03	7/9/03	7/22/03	7/28/03	8/11/03
1.65	2.79	0.28	0.00					
1.65	2.54	0.00					0.09	0.08
1.65	2.29	0.06	0.00	0.08	0.12	0.14	0.12	0.15
1.65	2.03	0.10					0.14	0.13
1.65	1.78	0.08	0.00	0.09	0.16	0.16	0.14	0.16
1.65	1.52						0.07	0.07
1.65	1.27	0.04	0.00	0.08	0.13	0.12	0.10	0.11
1.65	1.02						0.09	0.14
1.65	0.76	0.02	0.00	0.04	0.14	0.13	0.12	0.08
1.65	0.51						0.09	0.06
1.65	0.25	0.00	0.00	0.06	0.12	0.12	0.10	0.09
1.35	2.79	0.00						
1.35	2.54	0.00	0.00	0.07	0.10	0.11	0.08	0.05
1.35	2.29	0.09					0.12	0.11
1.35	2.03	0.09	0.00	0.08	0.15	0.14	0.12	0.12
1.35	1.78						0.12	0.12
1.35	1.52	0.00	0.00	0.04	0.09	0.09	0.08	0.05
1.35	1.27						0.11	0.11
1.35	1.02	0.05	0.06	0.11	0.16	0.15	0.13	0.15
1.35	0.76						0.11	0.11
1.35	0.51	0.00	0.00	0.05	0.08	0.07	0.05	0.09
1.35	0.25						0.09	0.08
1.05	2.79		0.00					
1.05	2.54						0.08	0.05
1.05	2.29		0.02	0.09	0.14	0.13	0.12	0.12
1.05	2.03						0.12	0.12
1.05	1.78	0.01	0.00	0.03	0.11	0.10	0.08	0.08
1.05	1.52						0.06	0.06
1.05	1.27	0.03	0.00	0.08	0.14	0.12	0.10	0.10
1.05	1.02						0.13	0.15

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		6/10/03	6/23/03	6/27/03	7/9/03	7/22/03	7/28/03	8/11/03
1.05	0.76	0.00	0.00	0.08	0.13	0.13	0.13	0.10
1.05	0.51						0.08	0.07
1.05	0.25	0.00	0.00	0.04	0.11	0.09	0.07	0.10
0.75	2.79	0.00						
0.75	2.54	0.00	0.00	0.03	0.08	0.08	0.05	0.04
0.75	2.29	0.10					0.11	0.11
0.75	2.03	0.02	0.00	0.07	0.12	0.13	0.10	0.11
0.75	1.78						0.07	0.04
0.75	1.52	0.00	0.00	0.05	0.08	0.07	0.05	0.06
0.75	1.27						0.09	0.11
0.75	1.02	0.00	0.00	0.09	0.14	0.13	0.11	0.12
0.75	0.76						0.11	0.12
0.75	0.51	0.00	0.00	0.05	0.09	0.08	0.07	0.04
0.75	0.25						0.08	0.07
0.45	2.79	0.04	0.00					
0.45	2.54	0.00					0.08	0.08
0.45	2.29	0.10	0.01	0.09	0.17	0.14	0.10	0.12
0.45	2.03	0.04					0.11	0.10
0.45	1.78	0.00	0.00	0.03	0.08	0.07	0.05	0.04
0.45	1.52						0.06	0.08
0.45	1.27	0.03	0.00	0.06	0.10	0.11	0.10	0.10
0.45	1.02						0.11	0.11
0.45	0.76	0.04	0.02	0.08	0.15	0.15	0.14	0.07
0.45	0.51						0.08	0.07
0.45	0.25	0.00	0.00	0.04	0.12	0.06	0.08	0.08

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		5/27/02	6/26/02	5/27/03	6/10/03	6/23/03	6/27/03	7/9/03
1.65	2.79		0.15	0.60	0.42	0.00		
1.65	2.54				0.15			
1.65	2.29		0.13	0.15	0.11	0.04	0.11	0.22
1.65	2.03				0.11			
1.65	1.78		0.05	0.13	0.10	0.08	0.10	0.20
1.65	1.52							
1.65	1.27	0.17	0.09	0.00	0.04	0.00	0.06	0.09
1.65	1.02							
1.65	0.76	0.16	0.05	0.05	0.03	0.00	0.06	0.13
1.65	0.51							
1.65	0.25	0.20	0.04	0.03	0.03	0.00	0.08	0.15
1.35	2.79				0.00			
1.35	2.54		0.10	0.10	0.04	0.00	0.06	0.13

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Airflow (m/s)						
		5/27/02	6/26/02	5/27/03	6/10/03	6/23/03	6/27/03	7/9/03
1.35	2.29				0.10			
1.35	2.03		0.14	0.11	0.06	0.07	0.12	0.19
1.35	1.78							
1.35	1.52	0.09	0.04	0.03	0.06	0.00	0.06	0.12
1.35	1.27							
1.35	1.02	0.09	0.03	0.00	0.01	0.00	0.06	0.10
1.35	0.76							
1.35	0.51	0.13	0.07	0.01	0.00	0.00	0.05	0.10
1.35	0.25							
1.05	2.79			0.00		0.00		
1.05	2.54							
1.05	2.29		0.13	0.11		0.00	0.10	0.18
1.05	2.03							
1.05	1.78		0.02	0.06	0.02	0.02	0.09	0.14
1.05	1.52							
1.05	1.27	0.10	0.04	0.00	0.00	0.00	0.05	0.10
1.05	1.02							
1.05	0.76	0.13	0.04	0.00	0.00	0.00	0.01	0.07
1.05	0.51							
1.05	0.25	0.14	0.03	0.00	0.00	0.00	0.04	0.08
0.75	2.79							
0.75	2.54		0.02	0.07		0.00	0.04	0.10
0.75	2.29							
0.75	2.03		0.07	0.05	0.06	0.05	0.08	0.15
0.75	1.78							
0.75	1.52	0.09	0.03	0.00	0.03	0.00	0.06	0.11
0.75	1.27							
0.75	1.02	0.13	0.03	0.00	0.02	0.00	0.06	0.11
0.75	0.76							
0.75	0.51	0.16	0.04	0.00	0.00	0.00	0.05	0.12
0.75	0.25							
0.45	2.79		0.02	0.06	0.07	0.00		
0.45	2.54				0.07			
0.45	2.29		0.13	0.11	0.11	0.01	0.09	0.17
0.45	2.03				0.09			
0.45	1.78		0.13	0.10	0.07	0.02	0.06	0.15
0.45	1.52							
0.45	1.27	0.13	0.02	0.00	0.03	0.00	0.09	0.11
0.45	1.02							
0.45	0.76	0.17	0.07	0.03	0.00	0.00	0.05	0.12
0.45	0.51							
0.45	0.25	0.16	0.04	0.02	0.00	0.00	0.06	0.11

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)		Airflow (m/s)	
		7/22/03	7/28/03	8/11/03
1.65	2.79			
1.65	2.54		0.13	0.13
1.65	2.29	0.18	0.17	0.18
1.65	2.03		0.18	0.17
1.65	1.78	0.22	0.18	0.21
1.65	1.52		0.14	0.10
1.65	1.27	0.14	0.12	0.10
1.65	1.02		0.13	0.11
1.65	0.76	0.11	0.11	0.10
1.65	0.51		0.12	0.11
1.65	0.25	0.13	0.12	0.10
1.35	2.79			
1.35	2.54	0.12	0.08	0.09
1.35	2.29		0.14	0.15
1.35	2.03	0.18	0.14	0.14
1.35	1.78		0.16	0.16
1.35	1.52	0.13	0.11	0.10
1.35	1.27		0.09	0.09
1.35	1.02	0.08	0.07	0.07
1.35	0.76		0.08	0.06
1.35	0.51	0.07	0.08	0.06
1.35	0.25		0.07	0.05
1.05	2.79			
1.05	2.54		0.09	0.09
1.05	2.29	0.15	0.12	0.14
1.05	2.03		0.14	0.11
1.05	1.78	0.15	0.12	0.10
1.05	1.52		0.10	0.10
1.05	1.27	0.09	0.07	0.06
1.05	1.02		0.06	0.06
1.05	0.76	0.04	0.05	0.04
1.05	0.51		0.07	0.06
1.05	0.25	0.08	0.08	0.06
0.75	2.79			
0.75	2.54	0.09	0.08	0.08
0.75	2.29		0.13	0.13
0.75	2.03	0.17	0.12	0.12
0.75	1.78		0.11	0.09
0.75	1.52	0.09	0.10	0.10
0.75	1.27		0.07	0.08
0.75	1.02	0.04	0.09	0.08
0.75	0.76		0.08	0.08
0.75	0.51	0.09	0.10	0.09
0.75	0.25		0.08	0.09
0.45	2.79			
0.45	2.54		0.09	0.10

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)		Airflow (m/s)	
		7/22/03	7/28/03	8/11/03
0.45	2.29	0.175	0.15833333	0.14833333
0.45	2.03		0.155	0.125
0.45	1.78	0.13833333	0.13166667	0.12
0.45	1.52		0.09833333	0.08666667
0.45	1.27	0.105	0.08	0.09666667
0.45	1.02		0.09333333	0.1
0.45	0.76	0.12166667	0.11	0.11666667
0.45	0.51		0.115	0.08833333
0.45	0.25	0.08	0.08833333	0.07

All Hydrogen Sulphide readings in ppm

South all points

Date	S082702	S091302	S052603	S062303	S1070903	S2070903	S072803
Mean	0.076	0.156	0.194	0.034	0.031	0.028	0.032
St Dev	0.124	0.200	0.240	0.033	0.057	0.070	0.054
Skewness	2.663	0.806	1.481	0.515	2.126	4.156	2.207
Kurtosis	6.882	-1.065	1.275	-1.255	3.255	19.080	3.965
Max	0.490	0.570	0.840	0.100	0.190	0.360	0.210
Min	0.007	0.000	0.000	0.001	0.001	0.000	0.002

North all points

Date	N082702	N091302	N052603	N062303	N1070903	N2070903	N072803	N081103
Mean	0.158	0.148	0.260	0.057	0.037	0.034	0.032	0.061
St Dev	0.229	0.190	0.238	0.029	0.055	0.066	0.067	0.140
Skewness	2.077	1.213	1.712	-0.766	2.448	2.489	2.576	2.597
Kurtosis	3.272	-0.081	1.608	-0.340	7.102	5.156	5.392	5.541
Max	0.780	0.560	0.880	0.112	0.250	0.250	0.240	0.490
Min	0.024	0.000	0.065	0.005	0.003	0.000	0.003	0.001

Data from Aug. 12, 2003

	South	North	Inlet	Ambient
Date	S081203	N081203		
Mean	0.038	0.043	0.390	0.023
St Dev	0.072	0.085	0.120	0.007
Skewness	2.257	2.951	-0.370	1.415
Kurtosis	4.286	8.792	-3.901	
Max	0.280	0.370	0.490	0.031
Min	0.000	0.000	0.250	0.017

Inlet

Date	27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03	11-Aug-03
Mean	1.207	0.505	1.075	0.067	0.208	0.203	0.213	0.445
St Dev	0.061	0.052	0.272	0.020	0.034	0.093	0.029	0.035
Skewness	-1.757	-1.597	0.446	-0.017	0.628	0.339	0.517	
Kurtosis	3.120	2.340	-3.485	-5.878	-2.492	-3.974	1.649	
Max	1.250	0.540	1.400	0.085	0.250	0.310	0.250	0.470
Min	1.118	0.430	0.850	0.048	0.180	0.120	0.180	0.420

Ambient

Date	27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03	11-Aug-03
Mean	0.054	0.007	0.005	0.012	0.034	0.025	0.013	0.015
St Dev	0.021	0.002	0.001	0.003	0.013	0.006	0.004	0.006
Skewness	0.423	1.732	0.000	-0.586	0.872	1.293	0.722	0.935
Max	0.076	0.009	0.006	0.014	0.048	0.032	0.017	0.022
Min	0.034	0.006	0.004	0.009	0.022	0.020	0.009	0.010

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)						
		27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03
1.69	2.88							
1.69	2.58							
1.69	2.22		0.36	0.77	0.074	0.025	0.029	0.006
1.69	2.07							
1.69	1.71	0.047	0.014	0.49	0.058	0.001	0.002	0.11
1.69	1.41							
1.69	1.12	0.028	0	0.42	0.065	0.002	0	0.005
1.69	0.88							
1.69	0.58	0.019	0.001	0.017	0.002	0.004	0.001	0.003
1.69	0.36							
1.69	0.10			0.009	0.011	0.016	0.005	0.017
1.40	2.88							
1.40	2.58		0.57	0.84	0.086	0.08	0.113	0.134
1.40	2.22							
1.40	2.07	0.49	0.26	0.28	0.062	0.028	0.028	0.009
1.40	1.71							
1.40	1.41	0.011	0.015	0.083	0.029	0.001	0.001	0.002
1.40	1.12							
1.40	0.88	0.01	0.008	0.061	0.058	0.001	0.001	0.007
1.40	0.58							
1.40	0.36	0.081	0.004	0.002	0.002	0.005	0.001	0.008
1.40	0.10							
1.08	2.88							
1.08	2.58							
1.08	2.22		0.37	0.4	0.072	0.036	0.044	0.015
1.08	2.07							
1.08	1.71	0.021	0	0.13	0.054	0.005	0.005	0.006
1.08	1.41							
1.08	1.12	0.011	0.003	0.117	0.057	0.003	0.002	0.017
1.08	0.88							
1.08	0.58	0.015	0.001	0.002	0.001	0.004	0.002	0.007
1.08	0.36							
1.08	0.10			0	0.002	0.012	0.02	0.01
0.77	2.88							
0.77	2.58		0.45	0.66	0.09	0.17	0.03	0.16
0.77	2.22							
0.77	2.07	0.034	0.016	0.142	0.047	0.19	0.03	0.021
0.77	1.71							
0.77	1.41	0.008	0.005	0.143	0.01	0.002	0	0.002
0.77	1.12							
0.77	0.88	0.007	0.003	0.1	0.006	0.002	0	0.007
0.77	0.58							
0.77	0.36	0.043	0	0	0.001	0.006	0.001	0.008
0.77	0.10							
0.47	2.88							
0.47	2.58							

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)						
		27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03
0.47	2.22		0.43	0.25	0.062	0.118	0.12	0.11
0.47	2.07							
0.47	1.71	0.02	0	0.039	0.011	0.002	0.002	0.003
0.47	1.41							
0.47	1.12	0.019	0.026	0.052	0.002	0.001	0	0.006
0.47	0.88							
0.47	0.58	0.011	0	0.004	0.002	0.003	0.003	0.008
0.47	0.36							
0.47	0.10			0	0.004	0.009	0.006	0.008
0.20	2.88							
0.20	2.58		0.49	0.47	0.1	0.18	0.36	0.21
0.20	2.22							
0.20	2.07	0.107	0.14	0.079	0.018	0.01	0.018	0.03
0.20	1.71							
0.20	1.41	0.105	0.21	0.128	0.015	0.001	0	0.002
0.20	1.12							
0.20	0.88	0.141	0.44	0.099	0.003	0.002	0	0.002
0.20	0.58							
0.20	0.36	0.36	0.39	0.027	0.002	0.006	0.003	0.012
0.20	0.10							

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)
		12-Aug-03
1.69	2.88	
1.69	2.58	
1.69	2.22	0.035
1.69	2.07	
1.69	1.71	0.001
1.69	1.41	
1.69	1.12	0.004
1.69	0.88	
1.69	0.58	0.006
1.69	0.36	
1.69	0.10	0.014
1.40	2.88	
1.40	2.58	0.15
1.40	2.22	
1.40	2.07	0.013
1.40	1.71	
1.40	1.41	0
1.40	1.12	
1.40	0.88	0.004
1.40	0.58	

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)
		12-Aug-03
1.40	0.36	0.008
1.40	0.10	
1.08	2.88	
1.08	2.58	
1.08	2.22	0.13
1.08	2.07	
1.08	1.71	0.001
1.08	1.41	
1.08	1.12	0.003
1.08	0.88	
1.08	0.58	0.005
1.08	0.36	
1.08	0.10	0.012
0.77	2.88	
0.77	2.58	0.28
0.77	2.22	
0.77	2.07	0.019
0.77	1.71	
0.77	1.41	0.001
0.77	1.12	

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)
		12-Aug-03
0.77	0.88	0.003
0.77	0.58	
0.77	0.36	0.007
0.77	0.10	
0.47	2.88	
0.47	2.58	
0.47	2.22	0.17
0.47	2.07	
0.47	1.71	0.011
0.47	1.41	
0.47	1.12	0.002
0.47	0.88	
0.47	0.58	0.005

Raw data on South side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)
		12-Aug-03
0.47	0.36	
0.47	0.10	0.01
0.20	2.88	
0.20	2.58	0.21
0.20	2.22	
0.20	2.07	0.03
0.20	1.71	
0.20	1.41	0.002
0.20	1.12	
0.20	0.88	0.002
0.20	0.58	
0.20	0.36	0.006
0.20	0.10	

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)						
		27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03
1.69	2.88							
1.69	2.58		0.56					
1.69	2.22			0.59	0.068	0.1	0.112	0.077
1.69	2.07	0.46	0.52					
1.69	1.71			0.2	0.077	0.016	0.012	0.006
1.69	1.41	0.78	0.51					
1.69	1.12			0.145	0.059	0.009	0.002	0.006
1.69	0.88	0.087	0.12					
1.69	0.58			0.148	0.009	0.005	0.002	0.005
1.69	0.36	0.74	0.32					
1.69	0.10			0.22	0.056	0.015	0.016	0.011
1.40	2.88							
1.40	2.58			0.81	0.075	0.11	0.21	0.24
1.40	2.22		0.35					
1.40	2.07			0.16	0.071	0.041	0.002	0.006
1.40	1.71	0.061	0.035					
1.40	1.41			0.144	0.074	0.01	0.008	0.006
1.40	1.12	0.043	0.037					
1.40	0.88			0.146	0.009	0.004	0	0.004
1.40	0.58	0.031	0.012					
1.40	0.36			0.142	0.01	0.006	0.004	0.006
1.40	0.10		0.009					
1.08	2.88							
1.08	2.58		0.05					
1.08	2.22			0.22	0.068	0.037	0.028	0.011

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)						
		27-Aug-02	13-Sep-02	26-May-03	23-Jun-03	09-Jul-03	09-Jul-03	28-Jul-03
1.08	2.07	0.049	0.011					
1.08	1.71			0.143	0.073	0.008	0.007	0.004
1.08	1.41	0.025	0.011					
1.08	1.12			0.127	0.06	0.007	0.004	0.005
1.08	0.88	0.029	0.012					
1.08	0.58			0.148	0.005	0.004	0.003	0.003
1.08	0.36	0.024	0.006					
1.08	0.10			0.065	0.016	0.004	0.004	0.005
0.77	2.88							
0.77	2.58			0.8	0.08	0.12	0.25	0.22
0.77	2.22		0.4					
0.77	2.07			0.083	0.069	0.25	0.01	0.005
0.77	1.71	0.37	0.33					
0.77	1.41			0.106	0.059	0.009	0.008	0.006
0.77	1.12	0.111	0.16					
0.77	0.88			0.148	0.087	0.007	0.005	0.006
0.77	0.58	0.047	0.005					
0.77	0.36			0.4	0.065	0.011	0.007	0.009
0.77	0.10		0.01					
0.47	2.88							
0.47	2.58		0.53					
0.47	2.22			0.37	0.072	0.067	0.041	0.017
0.47	2.07	0.059	0.025					
0.47	1.71			0.12	0.074	0.009	0.009	0.006
0.47	1.41	0.075	0.052					
0.47	1.12			0.16	0.071	0.006	0.004	0.005
0.47	0.88	0.031	0.048					
0.47	0.58			0.13	0.01	0.005	0.002	0.005
0.47	0.36	0.032	0.024					
0.47	0.10			0.086	0.007	0.003	0.006	0.008
0.20	2.88							
0.20	2.58			0.88	0.112	0.11	0.19	0.21
0.20	2.22		0					
0.20	2.07			0.19	0.068	0.046	0.014	0.006
0.20	1.71	0.104	0.065					
0.20	1.41			0.117	0.084	0.008	0.006	0.006
0.20	1.12	0.035	0.024					
0.20	0.88			0.126	0.055	0.004	0.004	0.004
0.20	0.58	0.117	0.068					
0.20	0.36			0.67	0.066	0.073	0.039	0.061
0.20	0.10		0.13					

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)	
		11-Aug-03	12-Aug-03
1.69	2.88		
1.69	2.58		
1.69	2.22	0.14	0.099
1.69	2.07		
1.69	1.71	0.003	0.023
1.69	1.41		
1.69	1.12	0.001	0
1.69	0.88		
1.69	0.58	0.004	0.001
1.69	0.36		
1.69	0.10	0.017	0.027
1.40	2.88		
1.40	2.58	0.49	0.29
1.40	2.22		
1.40	2.07	0.004	0.011
1.40	1.71		
1.40	1.41	0.001	0.013
1.40	1.12		
1.40	0.88	0.001	0
1.40	0.58		
1.40	0.36	0.005	0.004
1.40	0.10		
1.08	2.88		
1.08	2.58		
1.08	2.22	0.019	0.042
1.08	2.07		
1.08	1.71	0.002	0.021
1.08	1.41		
1.08	1.12	0.002	0
1.08	0.88		
1.08	0.58	0.004	0.001
1.08	0.36		
1.08	0.10	0.003	0.004

Raw data on North side

Distance from East Side X (m)	Height from bottom Y (m)	Hydrogen Sulphide (ppm)	
		11-Aug-03	12-Aug-03
0.77	2.88		
0.77	2.58	0.48	0.37
0.77	2.22		
0.77	2.07	0.005	0.015
0.77	1.71		
0.77	1.41	0.002	0.001
0.77	1.12		
0.77	0.88	0.001	0.001
0.77	0.58		
0.77	0.36	0.007	0.009
0.77	0.10		
0.47	2.88		
0.47	2.58		
0.47	2.22	0.059	0.104
0.47	2.07		
0.47	1.71	0.002	0.024
0.47	1.41		
0.47	1.12	0.002	0
0.47	0.88		
0.47	0.58	0.005	0.003
0.47	0.36		
0.47	0.10	0.006	0.007
0.20	2.88		
0.20	2.58	0.42	0.038
0.20	2.22		
0.20	2.07	0.045	0.054
0.20	1.71		
0.20	1.41	0.002	0
0.20	1.12		
0.20	0.88	0.002	0.001
0.20	0.58		
0.20	0.36	0.108	0.13
0.20	0.10		

Settling of Biofilter media

Date 11-Aug-03

All Measurements are in inches and in the same direction as gravity

North face (Distance from west wall)

	7.5	18	30	41.5	54	66
113.5						
101.5	7		6 1/2		3 3/4	
87.5		5 1/8		4 1/2		4 1/4
81.5	3 3/4		6		3 3/4	
67.5		3		4		2 1/2
55.5	2 1/2		2 1/2		3	
44		2 3/4		2		2
34.5	1 1/4		2 1/4		1 3/4	
23		1		1 1/2		1
14	3/4		1 1/2		1	
4		5/8		1/2		1/2

Date 27-May-03

All Measurements are in inches and in the same direction as gravity

North face (Distance from west wall)

	7.5	18	30	41.5	54	66
113.5						
101.5	5 1/8		2 1/2		2 1/2	
87.5		3 7/8		3 3/8		3 1/4
81.5	2 7/8		2 7/8		3 1/4	
67.5		2 1/4		2 3/8		2
55.5	2 7/8		2		1 1/2	
44		1 1/2		1 1/2		1 3/8
34.5	5/8		1 5/8		1	
23		3/4		1		1/2
14					3/4	
4				1/2		

W

Date 26-Jun-02 S N

E

Height of Media (m)

Distance from Plenum (m) 1.55	1.22	0.91	0.61	0.30	0.00	Distance from East Wall (m)
2.95	2.95	2.95	2.93	2.88	2.82	1.78
2.96	2.92	2.90	2.87	2.85	2.89	1.52
2.97	2.90	2.86	2.84	2.80	2.88	1.22
2.98	2.91	2.86	2.84	2.79	2.82	0.91
3.00	2.90	2.88	2.84	2.83	2.86	0.61
2.98	2.92	2.89	2.84	2.81	2.83	0.30
2.98	2.95	2.91	2.91	2.87	2.86	0.00

South			
	Average	2.89	m
	St Dev	0.05	m

Distance from ice from Plenum (m)

East Wall (m)	0.00	0.30	0.61	0.91	1.22	1.55
1.78	2.85	2.84	2.90	2.93	2.88	2.94
1.52	2.86	2.80	2.83	2.83	2.87	2.91
1.22	2.85	2.81	2.81	2.81	2.82	2.94
0.91	2.88	2.79	2.82	2.84	2.88	2.91
0.61	2.84	2.81	2.82	2.84	2.90	2.95
0.30	2.84	2.82	2.83	2.84	2.91	2.95
0.00	2.88	2.85	2.91	2.92	2.97	2.91

North			
	Average	2.87	m
	St Dev	0.05	m

W

S N

E

Date 11-Jun-03

Height of Media (m)

Distance from Plenum (m)						
1.55	1.22	0.91	0.61	0.30	0.00	Distance from East Wall (m)
2.67	2.79	2.64	2.59	2.57	2.57	1.78
2.67	2.59	2.59	2.54	2.53	2.51	1.52
2.67	2.59	2.57	2.54	2.51	2.55	1.22
2.65	2.58	2.57	2.54	2.57	2.62	0.91
2.65	2.57	2.55	2.54	2.54	2.58	0.61
2.63	2.55	2.59	2.55	2.55	2.57	0.30
2.60	2.59	2.64	2.59	2.55	2.57	0.00

South	Average	2.59	m
	St Dev	0.05	m

Distance from East Wall (m)	Distance from Plenum (m)					
	0.00	0.30	0.61	0.91	1.22	1.55
1.78	2.59	2.60	2.63	2.64	2.68	2.71
1.52	2.57	2.58	2.58	2.59	2.67	2.71
1.22	2.54	2.55	2.59	2.59	2.64	2.72
0.91	2.53	2.57	2.58	2.59	2.65	2.72
0.61	2.55	2.55	2.58	2.62	2.64	2.69
0.30	2.55	2.54	2.59	2.63	2.64	2.71
0.00	2.60	2.62	2.62	2.65	2.71	2.71

North	Average	2.62	m
	St Dev	0.06	m

APPENDIX E – MANAGEMENT STRATEGIES

During the course of this experiment, the biofilter's operation and design was modified three times. A SNK comparison test was conducted to determine if all the data collected from the biofilter could be considered collected from one biofilter or a number of different biofilters. See Table E1 for the results.

Table E1 Statistical grouping of sampling dates

Date	Number of Samples	Mean	SNK Test Grouping	Actual Grouping of Operation Styles
2002 06 26	55	0.064	A	A
2003 05 27	54	0.040	B	B
2003 06 10	63	0.038	B	B
2003 06 23	53	0.004	C	C
2003 06 27^A	49	0.064	A	C
2003 07 09^A	49	0.123	D	D
2003 07 22^A	49	0.112	D	D
2003 07 28^A	96	0.101	E	D
2003 08 11^A	96	0.094	E	D

A – Hotwire Anemometer was used.

Looking at the results of the SNK comparison test, it appears that the assumption that each modification in the management of the biofilter would result in a "different" biofilter is correct. Within a management style of the biofilter, it appears with the SNK test, the data would suggest a different management style. However, the SNK was selected because it had been known to falsely detect significant differences, but this result is preferred as compared to not detecting significant differences. Thus showing a significant difference in the data collected after July 29, 2003, is not a problem.

One of the groupings that is of concern is the data grouped together from June 26, 2002 and June 27, 2003. Even though it is believed that these two dates should not be grouped, it is likely that they are grouped together because they have the same average airflow, and the data from 2003 has a large standard deviation.

A more interesting result would be to collect more data, such as from 2004 and 2005 and see if data collected from these time periods is grouped with the older data provided that no major changes occur in the operation of the biofilter during this time. From the literature, it is likely to expect that the airflow for the biofilter will decrease with time and thus, the data should not grouped together.

APPENDIX F – NIVERVILLE BIOFILTER

F.1 Scale Up of Horizontal Airflow

As the data of the prototype has shown positive results of the design, an attempt to construct a full scale horizontal airflow biofilter occurred in late 2002 with construct continuing through most of the summer of 2003. This appendix will discuss two designs of the biofilter built, the original design and the actual biofilter built.

F.2 Location of Biofilters at Swine Units

The full scale biofilter was construct outside a 650 all in, all out swine finishing unit location in the rural municipality of Taché (south east of Winnipeg, Manitoba). The original barn at the site was destroyed by fire in February 2002. The biofilter was originally planned be built at the same time as the barn with proper fans for the biofilter installed into the barn. Figure F1, shows the location of the full scale biofilter in relation to the swine unit with Fig. F3 and Fig. F5 showing the biofilter in detail. The swine unit became operational in September of 2002.

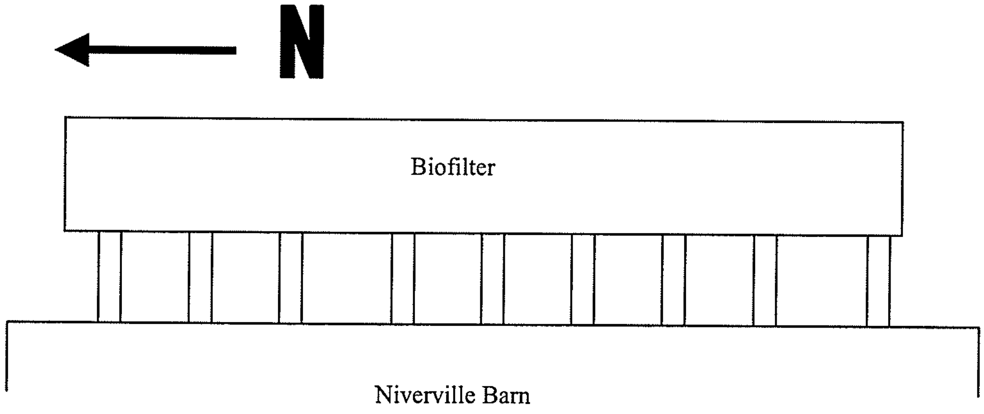


Figure F1 Location of Biofilter at Niverville

F.2.1 Ventilation Systems of Swine Units

The original ventilation system for the barn was to use the following fans in a four stage ventilation system as seen in Table F1. With this design, the biofilter was designed to treat an airflow of 39.0 m^3/s being supplied from nine fans ranging in size (diameters) from 0.45 to 0.91 m (18" to 36"). The original design volume of the biofilter was 340 m^3 (444 yd^3), thus the EBCT was expected to be 8.7 s.

Table F1 Original Fan Staging and Airflow for Niverville Barn

Stages	Fans & Airflow		Total Airflow	
	Size	Cfm	cfm	m^3/s
1	1 – 18" 1 – 24"	3 240 5 640	8 920	4.21
2	2 – 24"	11 280	20 200	9.53
3	2 – 36"	25 000	45 200	21.33
4	3 – 36"	37 500	82 700	39.03

Airflow is determined with a static pressure of 31 Pa (1/8" of water) (Prairie Pride)

During the construction of the biofilter, it was discovered that the fans being installed into the barn had changed in flow rates, numbers, and sizes (Table F2). In addition, the fans installed in the barn were standard ventilation fans and booster fans would be required.

Table F2 Actual Fan Staging and Airflow for Niverville Barn

Stages	Fans & Airflow		Total Airflow	
	Size	Cfm	cfm	m^3/s
1	1 – 24	5 564	5 564	2.63
2	2 – 25	12 100	17 664	8.34
3	1 – 25	6 050	23 714	11.19
4	2 – 36	21 996	45 710	21.57
5	1 – 48	17 200	62 910	29.69

Airflow is determined with a static pressure of 31.1 Pa (1/8" of water) (Better Air)

F.2.2 Duct System and Internal Plenum

As with the prototype biofilter, the idea of the centre plenum was used with the full scale design. The only major difference between these two designs was the ducting was to enter the internal plenum from the side (ducting would be perpendicular to the internal plenum). This design was attempting to take advantage of the scales of economy by building one large biofilter running parallel to the barn instead of a number of smaller biofilter perpendicular to the barn, as this would reduce the amount of building material required for the construction of the biofilter.

As was discovered with the plywood ducting constructed for the prototype biofilter, larger than expected pressure drops occurred through the plywood ducting, thus a plastic smooth walled duct was to be used instead which mated well with the axial fans in a circular housing that were purchased as booster fans. Figure F2, shows the ducting connecting the stage 1 fan to the biofilter. In this picture, the booster fans are located inside the ducting. The ducting to the biofilter is BOSS "O" (Armtec Ltd.) piping with the exception of the stage 5 fan, which was to investigate a cheaper alternative.

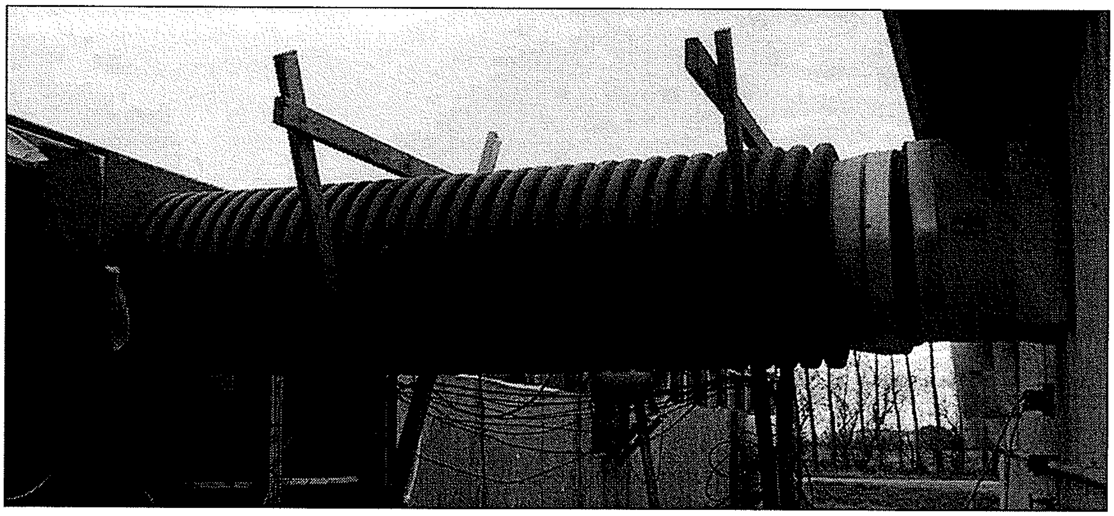


Figure F2 BOSS "O" ducting from swine unit to biofilter

F.2.3 Layout of the biofilter

Two different layouts of the full scale biofilter occurred because of the issues with the fans during the construction of the biofilter. The structure of the full-scale biofilter was outsourced to Building Alternatives Inc. The layout of the final design is not in the appendix, but the "thin" walled biofilter are a scaled down version of the "thick" walled biofilters. The blueprints of the biofilter are in located in Appendix G. This biofilter was constructed as a post frame structure with an earthen floor. Figure F3 shows the schematic of this original biofilter design. Figure F4 shows different aspects of this biofilter during construction.

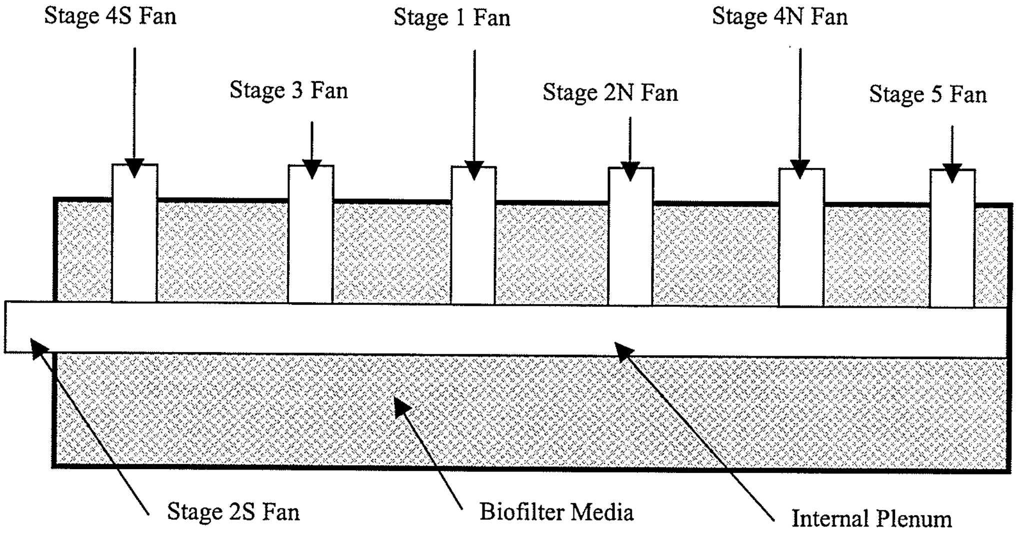
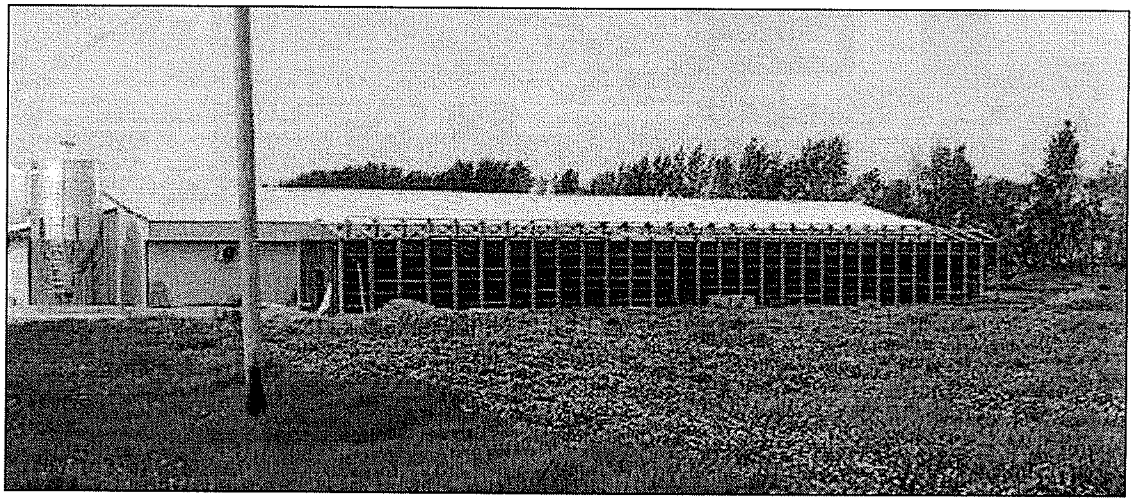
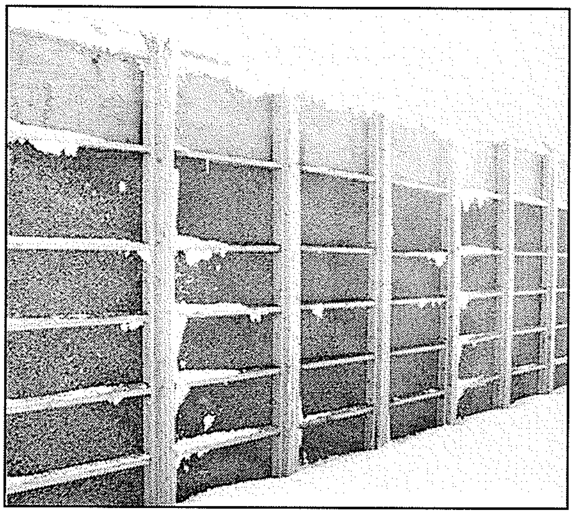


Figure F3 Original design of full scale biofilter

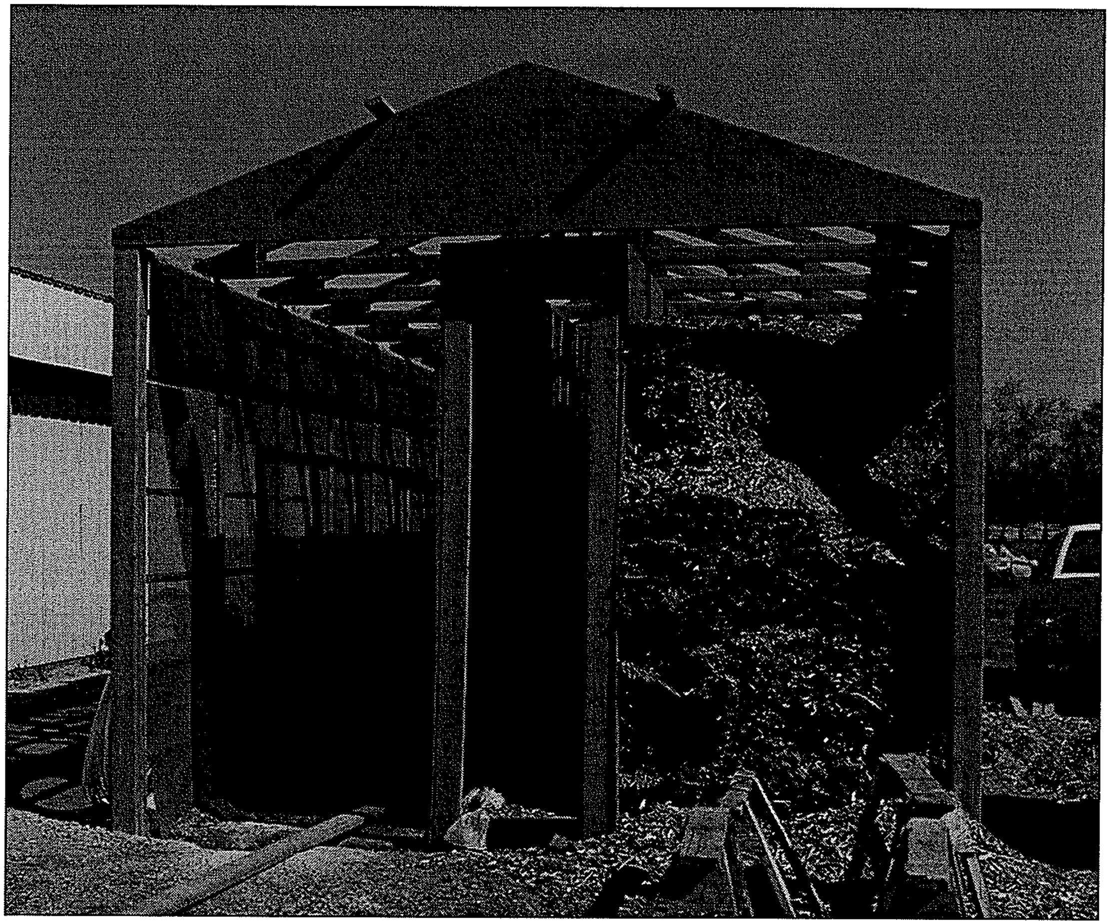


a) Entire Biofilter (Summer 2003)



b) Operating Biofilter (Feb. 2003)

c) Overhead view of west side of biofilter showing smaller west plenum and biofilter for Stage 2S and 3 fans and Stage 4S (Summer 2003)



d) Cross section of biofilter, viewed from south end of biofilter

Figure F4 Niverville Biofilter at varies stages of construction and operation.

As mentioned, the biofilter needed to be redesign mid-project, with Fig. F5 showing the schematic of the final design of the biofilter. The following lists the differences with each section of the biofilter with fans listed in order moving north along the barn.

- Stage 2S and Stage 3 – This biofilter was to investigate the combination of two fans from different stages supplying odorous air to a single sided thin walled biofilter with a small EBCT. The stage 2S fan was ducted parallel to the plenum and the Stage 3 was ducting into the biofilter perpendicular to the plenum.
- Stage 4S – This biofilter was investigating a single thin walled biofilter with a small EBCT. The fan was installed perpendicular to the biofilter's plenum.
- Stage 1 – This biofilter was based on the original design, a thick walled biofilter with the fan perpendicular to an internal plenum with the standard EBCT for the treatment of swine odours.
- Stage 2N – This biofilter was a thick single walled biofilter with a large EBCT as compared to standard agricultural biofilters with the fan installed perpendicular to the exterior plenum.
- Stage 4N – This biofilter is a copy of the original design, but with the use of thin walled biofilters with an internal plenum and an EBCT smaller than standard for agricultural applications. The fan was installed perpendicular to the plenum.
- Stage 5 – This biofilter was meant to be a straw:compost biofilter with the standard EBCT for agricultural applications. This biofilter was not suppose to require any booster fans.

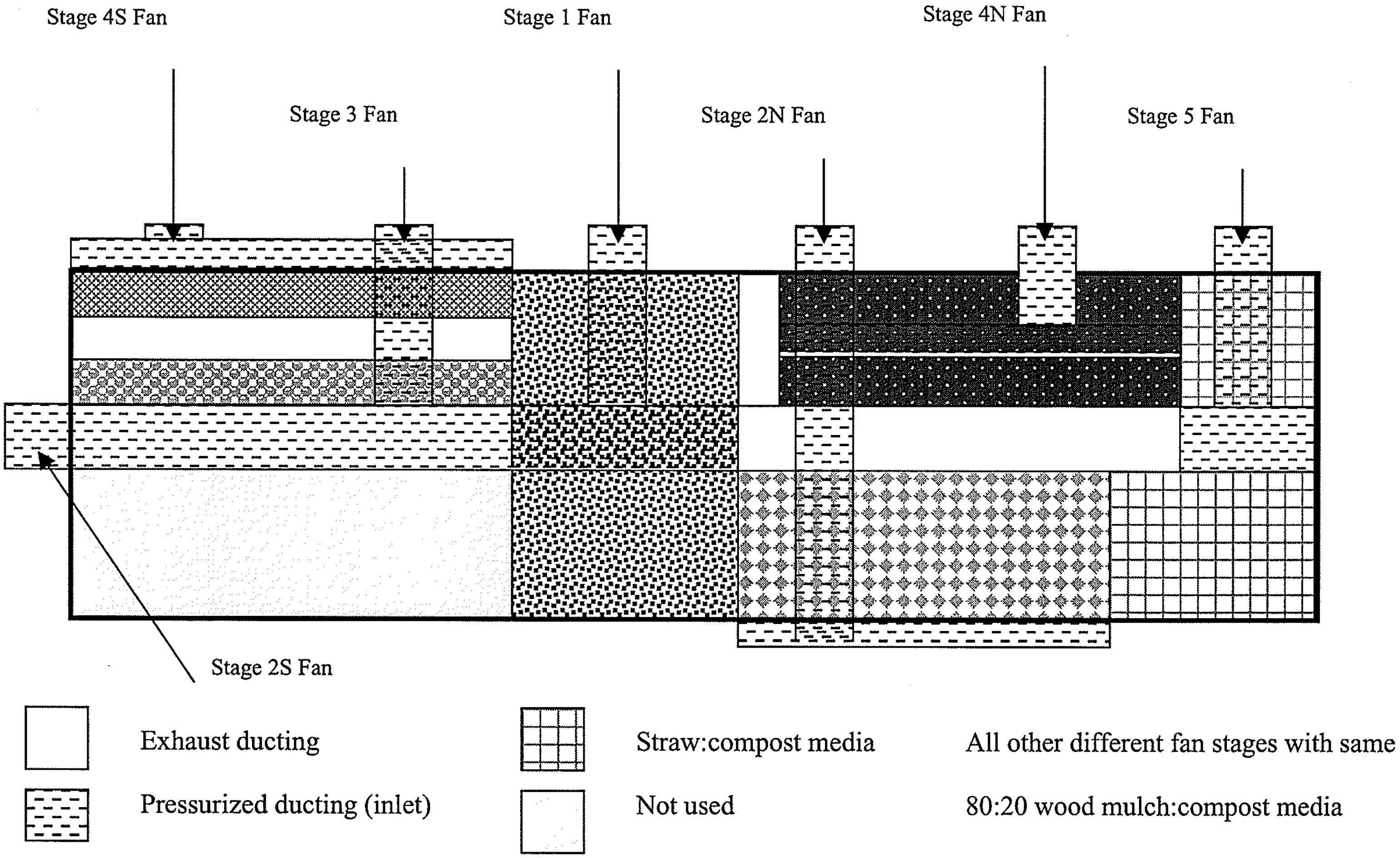


Figure F5 Actual design of full scale biofilter

F.2.4 Sizing the Full Scale Biofilter

The original full-scale biofilter was built to be a woodchip:compost (80:20) designed to handle a 39 m^3/s airflow with a true residence time of 5 s. The dimension were 3.05 m high, 4.27 m thick, of which 3.05 m is biofilter media, and 36.6 m long with a pressure drop of 102 Pa. Calculations for sizing the original and new design of the biofilter are located in Appendix G.

The final design of the biofilter resulted in six different wood mulch:compost (80:20) biofilters treating the total airflow of 30 m^3/s (63 500 cfm) with EBCT ranging from 3 to 17 s and designed pressure drops ranging from 25 to 100 Pa within the original footprint of biofilter (90 m^2) as the structure was partially built at the time of redesigning of the biofilter (Table F3).

Table F3 Biofilter parameters for different section of full scale biofilter

Fan	Flow Rate (m^3/s)	EBCT (sec)	Pressure Drop (Pa)	Surface Loading ($m^3s^{-1}m^{-2}$)
Stage 2S	2.86	3.6	27	0.16
Stage 4S	5.20	3.9	23	0.15
Stage 3	2.86	3.6	27	0.16
Stage 1	2.63	6.5	39	0.15
Stage 2N	2.86	17.9	46	0.11
Stage 4N	5.20	3.6	4	0.08
Stage 5	8.12	7.7	0	0.25

F.2.5 Booster Fan Requirements

As there is a variety of requirements for the full scale biofilter, Table F4 lists the different booster fan requirements for the biofilter with the design back pressure.

Table F4 Booster fan requirements for full scale Biofilter

Fan	Flow Rate (m^3/s)	Pressure Drop (Pa)	Booster Fan Selected
Stage 2S	2.86	27	3.07 m^3/s @ 25 Pa 24" 1 hp axial fan 0.61 m – 0.75 kW
Stage 4S	5.20	23	5.43 m^3/s @ 25 Pa 30" 1.5 hp axial fan 0.76 m – 1.11 kW
Stage 3	2.86	27	3.07 m^3/s @ 25 Pa 24" 1 hp axial fan 0.61 m – 0.75 kW
Stage 1	2.63	39	2.60 m^3/s @ 62 Pa 24" 3 hp axial fan 0.61 m – 2.2 kW
Stage 2N	2.86	46	3.07 m^3/s @ 124 Pa 24" 2 hp axial fan 0.61 m – 1.49 kW
Stage 4N	5.20	4	5.43 m^3/s @ 25 Pa 30" 1.5 hp axial fan 0.76 m – 1.11 kW
Stage 5	8.12	0	No Booster Fan

F.3 Data Collection at the Full Scale Biofilter

F.3.1 Airflow

The airflow data was collect with the same technique as used with the prototype biofilter. The same amplifying cone and hotwire anemometer (Flowrite, 800) were used as with the prototype biofilter. A coordinate system was employed on the biofilter, which was used to determine the locations of the measured airflow through out the biofilter face.

F.3.2 Pressure Drop

The pressure drop was measured after the booster fans installed with a pressure transducer (Omega model number PX 143 {0-6.9 kPa}). Sampling ports were installed after the booster fans and in the plenum for each of the biofilters. It was determined that from these sampling ports that the pressure requirements to move the air through the biofilter system could not be supplied with the set-up of the fans. It appears that the ducting system to get the air to the biofilter media was flawed and higher than designed pressure losses where occurring. As the barn cannot operate at lower airflows, as this might harm the animals. The experiment ended with further investigations of what was causing the higher than expected pressure losses in the ducting.

F.4 Results of Full Scale Biofilter

This section will look at the results of the different biofilter designs and the knowledge that was gained from their operation. All the data collected from the full-scale biofilter is in Appendix G. The stage 5 biofilter was not constructed as it was decided that major modification would be required to the structure of the biofilter with proposed construction planned for the summer of 2004.

F.4.1 Stage 3 and Stage 2S

The problem with this design of biofilter appears to be the stage 3 fan ducting into the plenum. In this ducting, the last 1.5 m (5 ft) of the ducting is plywood construct similar to the prototype's ducting. In addition, the odorous air is ducted perpendicular to the plenum. The problem with is design is the odorous air enters the plenum, but the design of the inlet with respect the plenum resembles a 90 degree bend. Firstly, the booster fan was not designed to handle this additional pressure drop and if it was, the higher pressure of the air entering the plenum would "blow" through the biofilter media near this location as only a small amount of pressure is required to move the air through the plenum. For the plenum to work correctly, the pressure within the biofilter's plenum needs to be almost uniform, higher pressure air results in higher airflows as was seen with the prototype biofilter at the high of the booster fan.

With the stage 2 fan, it appears that the problem is the fan is unable to maintain a uniform airflow at a desired pressure for the length of the plenum, opposite problem of the prototype biofilter with the airflow hitting the back wall and being forced out the sides of the biofilter (slight channelling). For a given design pressure (pressure require to move air through the biofilter media), the biofilter's length needs to be adjusted to optimize the fan, too short of a biofilter channelling, too long of a biofilter, insufficient pressure to move air through biofilter as distance from inlet increases.

The back pressure measured at the stage 3 fan is 73 Pa and the at the stage 2S fan is 29 Pa. From the airflows measured and represented in Fig. F6, it appears there is insufficient pressure in the plenum to maintain a uniform airflow over the face of the biofilter.

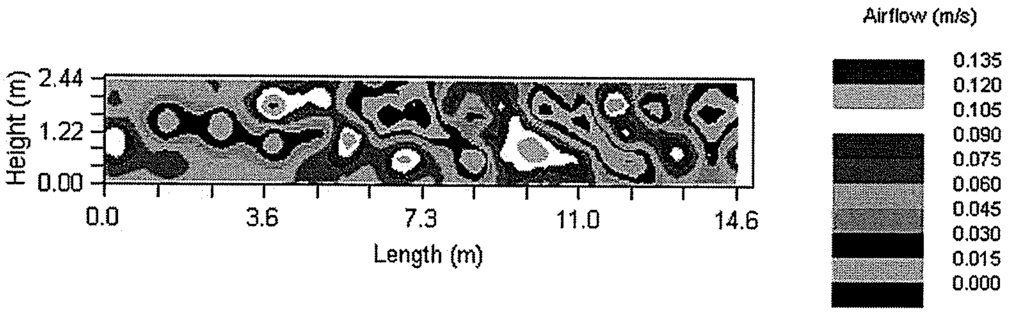
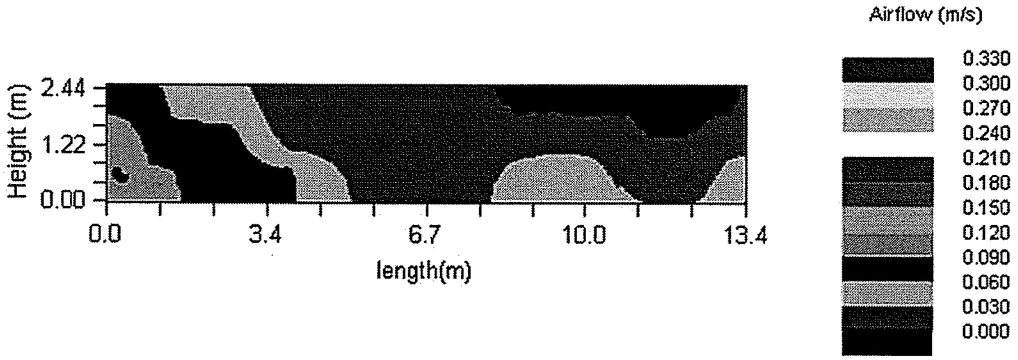


Figure F6 Airflow profile of Stage 3 and Stage 2S biofilter section

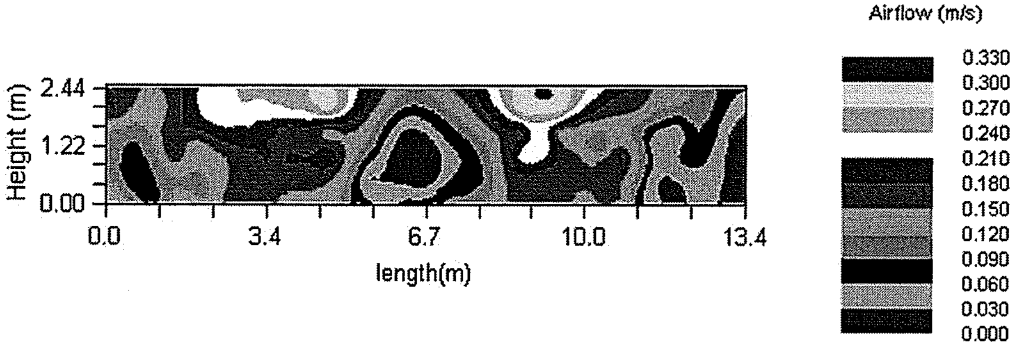
(Length 0 m is south end of biofilter. Black is 0 m/s airflow. Numbers represent the change between two colors.)

F.4.2 Stage 4N

From the data collected for this section, it appears that this biofilter failed because of the short ducting to the centre plenum and than the narrow plenum. As was the problem with the stage 3 fan, the air entering the biofilter, would be better represented in pressure calculations as a 90 degree bend. The backpressure at the stage 4N fan was 116 Pa. If this section was to be functional, the manifold design should be changed to reduce the affects of the ducting to internal plenum (perhaps two inlets at 45 degree angle entering the plenum). As well, at this low pressure, it is likely that the internal plenum is excessively long which reduces the amount of air that is able to travel the entire length of the internal plenum to take full advantage of the size of the biofilter.



a) East



b) West

Figure F7 Airflow profiles of both sections of Stage 4N
(Length 0 m is south end)

F.4.3 Stage 2N and Stage 4S

In these two sections, the manifold / plenum was located on the outside of the structure of the biofilter as a narrow plenum to be pressurized by a booster fan. This designed failed because of three things. One, the narrow manifold, in order to pressurized this entire volume with the current construction of the wall, the plenum was built too narrow for air to travel through properly. The second problem, is the fan is mounted perpendicular to this plenum, thus for air to travel into the plenum, the air needs to make this same 90 degree turn as with the other biofilter sections which would require a higher pressure airflow to manage this turn. The last problem would be amplified by increasing the pressure that would fix the other two problems. As only a pressure of 25 Pa is required for the air to travel through the media, a higher pressure airflow needed to fix the other flaws would result in the air from the booster fan being driven straight through the biofilter media, channelling. This short circuiting would be a result of the air taking the path of least resistance, which would be the biofilter media rather than through the manifold / plenum as designed. Figure F8 shows this problem, most of the biofilter has almost zero airflow, except for the location of the fan, which has an airflow, which is 50 to 100 times larger than the majority of the biofilter. As with the other sections of the biofilter, the manifold / plenum is probably too long for proper air distribution as explain in the section discussing the Stage2S and 3 biofilter section. With this design, the backpressure at the stage 4S fan is 319 Pa. Stage 2N was never completed as it was determine with Stage 4S, that the design would not work as this design of manifold, had more source of pressure loss than the Stage 4S design.

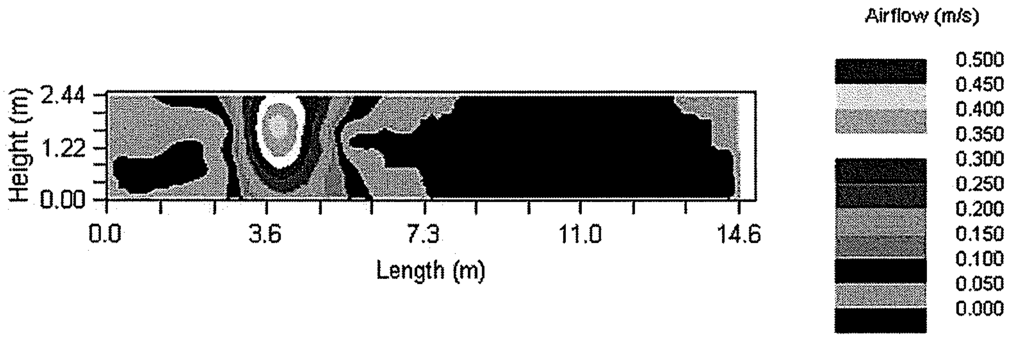


Figure F8 Airflow profile of Stage 4S section of the biofilter

F.4.4 Stage 1

As this biofilter was built similar to the prototype, it was expected that this section would perform as designed. The one flaw in this design that is common to the other sections of the biofilter is the ducting is perpendicular to the internal plenum, which resembles a 90 degree bend.

Another problem with this design of using one large centre plenum is the resulting large EBCT if none of the other fans are operating which occurs in the winter. This might result in the freezing of the biofilter media. This will only cause small problems as the this part of the biofilter was brought back online in February 2003 after being shut down for over a month. But if the biofilter is allowed to freeze, the micro-organisms will become inactive which introduces the idea of why use the biofilter if it is not working.

To attempt to address this problem, the active volume of the biofilter that was to be used was reduced with the use of walls in the internal plenum to seal off the large parts of the biofilter that were not required to be operational in the winter. These walls resulted in the airflow short circuiting around these walls as it was easier for the air to travel around the wall in the internal plenum than travel through the biofilter media. Two possible solutions to solve this were to build dividing walls in the biofilter media. However, this defeats the idea of the one large biofilter. This design however does not remove any of the volume of the biofilter media from treating odours when the other fans are activated and the rest of the internal plenum is used. The other solution is to seal the off the internal plenum from the media side of the wall as seen in Fig. F10. This idea works because it now makes it easier for the air to travel through the biofilter media than short circuit the wall blocking the internal plenum. A problem with this solution is it stops the air from short circuiting the wall in the plenum, but when the rest of the plenum / biofilter is being used, air is not able to travel through the biofilter media behind the wall, i.e. the biofilter is reduced in volume.

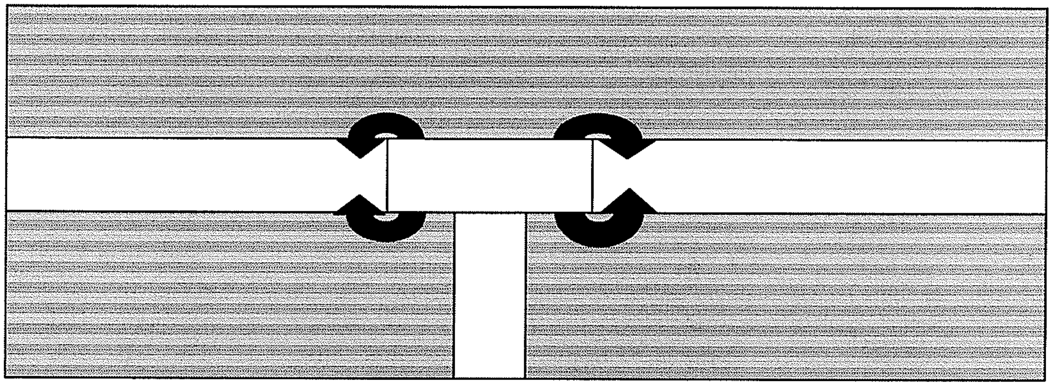


Figure F9 Airflow profiles of both Stage 1 sections of the biofilter

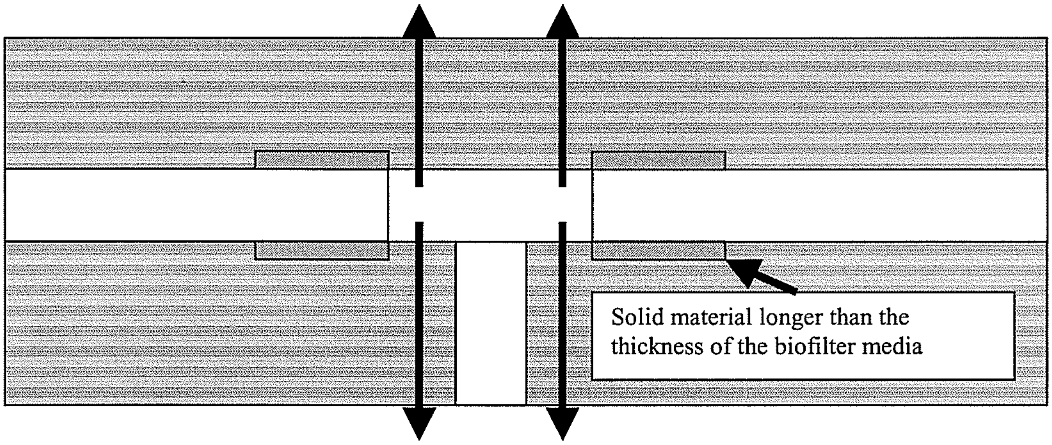


Figure F10 One solution to short circuiting at stage 1 fan of the biofilter

APPENDIX G – NIVERVILLE BIOFILTER AND DUCT DESIGN

Stage 2S Fan 1

Known

	Units	Variable	
6050	cfm		Airflow
2.86	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
2.14	s	r	True residence time
1		y	Layers
3.05	m	h	height of biofilter

Assume

0.46	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

10.18	m^3	V	Volume of biofilter media

EBCT = Q/V

3.57	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)/y

7.3	m	L	Length

A=V/t

22.14	m^2	A	Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

17.71	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.161	m^3/s/m^2	SL	Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

27	Pa	P	Pressure required for air to travel through media

Stage 4S Fan 2

Known

	Units	Variable	
10998	cfm		Airflow
5.19	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
2.36	s	r	True residence time
1		y	Layers
3.05	m	h	height of biofilter

Assume

0.46	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

20.42	m^3	V	Volume of biofilter media

EBCT = Q/V

3.93	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)/y

14.6	m	L	Length

A=V/t

44.38	m^2	A	Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

35.51	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.146	m^3/s/m^2	SL	Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

23	Pa	P	Pressure required for air to travel through media

Stage 3 Fan 3

Known

	Units	Variable	
6050	cfm		Airflow
2.86	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
2.14	s	r	True residence time
1		y	Layers
3.05	m	h	height of biofilter

Assume

0.46	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

10.18	m^3	V	Volume of biofilter media

EBCT = Q/V

3.57	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)/y

7.3	m	L	Length

A=V/t

22.14	m^2	A	Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

17.71	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.161	m^3/s/m^2	SL	Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

27	Pa	P	Pressure required for air to travel through media

Stage 1 Fan 4

Known

	Units	Variable	
5564	cfm		Airflow
2.63	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
7.76	s	r	True residence time
2		y	Layers
3.05	m	h	height of biofilter

Assume

1.53	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

33.96 m^3 V Volume of biofilter media

EBCT = Q/V

12.93 sec EBCT Empty Bed Contact Time

L=V/(t*h)/y

3.6 m L Length

A=V/t

22.20 m^2 A Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

17.76 m^2 Aa Surface Area of Biofilter

SL=Q/Aa

0.148 m^3/s/m^2 SL Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

78 Pa P Pressure required for air to travel through media

Stage 2N Fan 5

Known

	Units	Variable	
	Units	Variable	
6050	cfm		Airflow
2.86	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
10.71	s	r	True residence time
1		y	Layers
3.05	m	h	height of biofilter

Assume

1.53	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

50.97	m^3	V	Volume of biofilter media

EBCT = Q/V

17.85	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)/y

10.9	m	L	Length

A=V/t

33.31	m^2	A	Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

26.65	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.107	m^3/s/m^2	SL	Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

47	Pa	P	Pressure required for air to travel through media

Stage 4N Fan 6

Known

	Units	Variable	
10998	cfm		Airflow
5.19	m^3/s	Q	Airflow
60	%	f	Porosity
5396.6		a	ASAE pressure formula (60:40W) Sadaka et al. 2002
61.37		b	ASAE pressure formula (60:40W) Sadaka et al. 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
4.32	s	r	True residence time
2		y	Layers
3.05	m	h	height of biofilter

Assume

0.46	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

37.37 m^3 V Volume of biofilter media

EBCT = Q/V

7.20 sec EBCT Empty Bed Contact Time

L=V/(t*h)/y

13.3 m L Length

A=V/t

81.24 m^2 A Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

64.99 m^2 Aa Surface Area of Biofilter

SL=Q/Aa

0.080 m^3/s/m^2 SL Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

4 Pa P Pressure required for air to travel through media

Stage 5 Fan 7

Known

	Units	Variable	
17200	cfm		Airflow
8.12	m^3/s	Q	Airflow
60	%	f	Porosity
0.0289		a	ASAE pressure formula (80:20W) Hayward 2002
0.5339		b	ASAE pressure formula (80:20W) Hayward 2002
380	kg/m^3	d	Density of biofilter media
80	%		Percentage of airduct open
4.6	s	r	True residence time
1		y	Layers
3.05	m	h	height of biofilter

Assume

1.53	m	t	Thickness of biofilter media

Determine

V=(r*Q)/f

62.23	m^3	V	Volume of biofilter media

EBCT = Q/V

7.67	sec	EBCT	Empty Bed Contact Time

L=V/(t*h)/y

13.3	m	L	Length

A=V/t

40.68	m^2	A	Surface Area of Biofilter

Actual area due to desiegn of biofilter (80% of A)

32.54	m^2	Aa	Surface Area of Biofilter

SL=Q/Aa

0.249	m^3/s/m^2	SL	Surface Loading

P=t/y*((a*SL^2)/ln(1+b*SL))

0	Pa	P	Pressure required for air to travel through media

Orignal Duct Design

Known

L = 3.6 m length Straight ducting from barn to biofilter
Q = m^3/s Flow rate
A = m^2 Cross-sectional Area

Assume

t = 300 k Temerpature
E = 2 mm Absolute roughness (Albright 1990; Table 12-1)
q = 1.1774 kg/m^3 density of air
u = 1.98E-05 kg/m-s

D = m diameter

E/D = relative roughness

v = Q/A m/s velocity

Re = qvD/u

f = Friction Factor from Moody Diagram

P=f(L/D)(qv^2/2) Pa Pressure from friction (See Note 2)

		Duct Dimensions						
Fan Size	Q (m^3/s)	D (m)	A (m^2)	E/D	v (m/s)	Re	f	P (Pa)
24"	2.63	0.61	0.29	0.003279	8.985271	3.25E+05	0.018	5.0
25"	2.86	0.61	0.29	0.003279	9.770109	3.54E+05	0.019	6.3
36"	5.19	0.91	0.65	0.002198	7.980584	4.31E+05	0.016	2.4
48"	8.12	See Note 1						

Note 1: The planned design for the 48" fan was a custom made adapater to make two 0.91 m ducts going to the biofilter. Larger pressure drops would be expected with the adapter.

Note 2: The pressure loss through the ducting is only from the barn fan to the biofilter wall. In reality with the construction of this, adapters were made to get from the fan to the duct, two 20 degree bends were added to the ducting as the ducting could not enter the biofilter straight from the barn fans and ducting is required to get from the wall of the biofilter to the centre of the biofilter.

Pressure from Niverville Biofilter

	0 Pa	(Pa) Pressure
S4N	-308.8892	145.064
S2N	-294.3828	145.064
S4NP	-308.8892	29.0128
S1P	-308.8892	87.0384
S1	-308.8892	72.532
S4SP	-294.3828	0
S3	-308.8892	101.5448
S2S	-294.3828	58.0256
S4S	-323.3956	319.1408
S23P	-308.8892	29.0128

Design Pressure (Pa)		Actual Pressure (Pa)
25.4	Fan 2S	29.0128
25.4	Fan 4S	319.1408
25.4	Fan 3	72.532
154	Fan 1	-14.5064
154	Fan 2N	145.064
25.4	Fan 4 N	116.0512

Test Niverville

Time 7:48:00

Date 14-Aug-03

Niverville Airflow 1W

Mixture is 80:20 WC:C

converted to m/s and adjusted for funnel

Weather		
	clear	0
	warm	0
	windy	0

											Row Averages
M	0.020117					0.119211	0.096859		0.11176	S	0.086987
I				0.029803		0	0.044704		0.059605	O	0.033528
D		0			0			0		U	0
D	0		0	0		0	0		0.059605	T	0.009934
L		0			0			0		H	0
E	0		0	0		0	0		0		0
Column Averages	0.006706	0	0	0.009934	0	0.029803	0.035391	0	0.057743		

Niverville Airflow 1E

											Row Averages
S				0		0.059605	0.156464		0.156464	M	0.093133
O				0		0.029803	0		0.096859	I	0.031665
U		0.104309			0.044704			0.007451		D	0.026077
T				0		0.11176	0		0.11176	D	0.05588
H		0			0			0		L	0
				0		0.037253	0		0.059605	E	0.024215
Column Averages		0.052155		0	0.022352	0.059605	0.039116	0.003725	0.106172		

Test Niverville

Time 7:48:00

Date 14-Aug-03

Weather clear
warm
windy

Niverville Airflow 4N

Mixture is 80:20 WC:C

Flow Rates are in m/s

West

R Avg	0.2032	0.6096	1.016	1.4224	1.8288	2.2352	2.6416	3.048	3.4544	3.8608	4.2672	4.6736
0.182009	0.201168		0.096859	0.156464		0.245872				0.245872		0.327829
0.098987	0.10430933		0.134112	0.201168		0.201168				0.141563		0.067056
0.10017		0.081957			0.11176						0.163915	
0.133646	0.10430933		0.096859	0.193717		0.134112				0.201168		0.245872
0.083989		0.052155			0.104309			0.171365			0.156464	
0.114244	0.156464		0.059605	0.149013		0.11176	0.186267		0.163915	0.134112		0.141563
C Avg	0.14156267	0.067056	0.096859	0.175091	0.108035	0.173228	0.186267	0.171365	0.163915	0.180679	0.160189	0.19558

East

Distance (m)

R Avg	0.2032	0.6096	1.016	1.4224	1.8288	2.2352	2.6416	3.048	3.4544	3.8608	4.2672	4.6736
0.01397	0.07450667			0.052155			0.037253			0.014901		
0.019092	0.11921067			0.059605			0.081957			0		
0.017695	0.12666133			0.067056			0.067056			0		
0.039582	0.07450667			0.096859			0.074507			0.089408		
C Avg	0.09872133			0.068919			0.065193			0.026077		

South

Test Niverville

Time 7:48:00

Date 14-Aug-03

Weather clear
warm
windy

Niverville Airflow 4N

Mixture is 80:20 WC:C

Flow Rates are in m/s

West

5.08	5.4864	5.8928	6.2992	6.7056	7.112	7.5184	7.9248	8.3312	8.7376	9.144	9.5504	9.9568
			0.081957		0.119211				0.320379		0.320379	
			0.014901		0.081957				0.134112		0.089408	
	0.119210667			0			0.096859			0.275675		
			0		0.037253				0.260773		0.171365	0.171365
	0.014901333			0			0.081957			0.141563		
			0.067056		0.104309				0.178816		0.178816	0.134112
	0.067056		0.040979	0	0.085683		0.089408		0.22352	0.208619	0.189992	0.152739

east

5.08	5.4864	5.8928	6.2992	6.7056	7.112	7.5184	7.9248	8.3312	8.7376	9.144	9.5504	9.9568
0.014901	0	0	0	0	0.029803	0			0			0
0.044704	0	0	0	0	0	0			0			0
0	0	0.007451	0	0	0.014901	0			0			0
0.044704	0	0	0	0	0	0.014901			0.074507			0.081957
0.026077	0	0.001863	0	0	0.011176	0.003725			0.018627			0.020489

Test Niverville

Time 7:48:00

Date 14-Aug-03

Weather clear
warm
windy

Niverville Airflow 4N

Mixture is 80:20 WC:C

Flow Rates are in m/s

West

10.3632	10.7696	11.176	11.5824	11.9888	12.3952	12.8016	13.208	Height (m)
		0.156464		0.119211	0.119211		0.037253	2.032
		0.089408		0.014901	0.11176		0	1.524
0.037253			0.014901					1.27
	0.230970667	0.126661		0.081957	0.081957		0	1.016
0.156464			0.007451			0.037253		0.5334
	0.171365333	0.059605		0	0.059605		0	0.127
0.096859	0.201168	0.108035	0.011176	0.054017	0.093133	0.037253	0.009313	

East

10.3632	10.7696	11.176	11.5824	11.9888	12.3952	12.8016	13.208	Height (m)
		0			0		0	1.8288
		0			0		0	1.6256
		0			0		0	1.1938
		0			0		0.081957	0.7112
		0			0		0.020489	

North

Test Niverville

Niverville Airflow 4S

Time 0.325

Mixture is 80:20 WC:C

Flow Rates are in m/s

Date 37847

Weather clear
warm
windy

R Avg												
0.030867	0.01490133			0.037253			0.044704			0.439589		
0.021155	0.03725333			0.007451			0			0.417237		
0.022352	0			0			0.059605			0.387435		
0.020489	0			0			0.014901			0.290576		
C Avg	0.01303867			0.011176			0.029803			0.383709		
length (m)	0.2032	0.6096	1.016	1.4224	1.8288	2.2352	2.6416	3.048	3.4544	3.8608	4.2672	4.6736

South

Test Niverville

Niverville Airflow 4S

Time 0.325

Mixture is 80:20 WC:C

Flow Rates are in m/s

Date 37847

Weather clear
warm
windy

0.171365	0.074506667	0.052155	0	0.014901	0	0	0	0	0	0	0	0
0.11176	0.007450667	0	0	0	0	0	0	0	0	0	0	0
0.178816	0	0	0	0	0	0	0	0	0	0	0	0
0.134112	0.089408	0.044704	0	0	0	0	0	0	0	0	0	0
0.149013	0.042841333	0.024215	0	0.003725	0	0	0	0	0	0	0	0
5.08	5.4864	5.8928	6.2992	6.7056	7.112	7.5184	7.9248	8.3312	8.7376	9.144	9.5504	9.9568

Test Niverville

Niverville Airflow 4S

Time 0.325

Mixture is 80:20 WC:C

Flow Rates are in m/s

Date 37847

Weather clear
warm
windy

											Height (m)
0	0	0	0	0	0	0	0	0	0	0.014901	1.8288
0	0	0	0	0	0	0.003725	0	0	0	0.007451	1.6256
0	0	0	0	0	0	0	0	0	0	0	1.1938
0	0	0	0	0	0	0	0	0	0	0	0.7112
0	0	0	0	0	0	0.000931	0	0	0	0.005588	

10.3632	10.7696	11.176	11.5824	11.9888	12.3952	12.8016	13.208	13.6144	14.0208	14.4272

North

Test Niverville

Niverville Airflow 23S

Time 0.325

Mixture is 80:20 WC:C

Date 37847

Flow Rates are in m/s

Weather clear
warm
windy

R Avg												
0.041777	0.067056			0.029803			0.052155			0.126661		
0.028206	0.03725333			0			0			0.119211		
0.047631	0.11176			0.014901			0			0		
0.064661	0.10430933			0.074507			0.037253			0.014901		
Column Averages	0.08009467			0.029803			0.022352			0.065193		
length (m)	0.2032	0.6096	1.016	1.4224	1.8288	2.2352	2.6416	3.048	3.4544	3.8608	4.2672	4.6736

South

Test Niverville

Niverville Airflow 23S

Time 0.325

Mixture is 80:20 WC:C

Date 37847

Flow Rates are in m/s

Weather clear
warm
windy

0.119211	0.022352	0.022352	0	0	0	0	0.104309	0.044704	0.074507	0.096859	0.052155	0
0.052155	0.067056	0	0	0	0	0	0.074507	0.022352	0	0.081957	0.096859	0
0.022352	0.119210667	0.096859	0	0.022352	0.022352	0	0.007451	0.037253	0.096859	0.067056	0.096859	0.104309
0.081957	0.096858667	0.074507	0.074507	0.11176	0.11176	0.059605	0.052155	0	0	0.104309	0.104309	0.119211
0.068919	0.076369333	0.048429	0.018627	0.033528	0.033528	0.014901	0.059605	0.026077	0.042841	0.087545	0.087545	0.05588
5.08	5.4864	5.8928	6.2992	6.7056	7.112	7.5184	7.9248	8.3312	8.7376	9.144	9.5504	9.9568

Test Niverville

Niverville Airflow 23S

Time 0.325

Mixture is 80:20 WC:C

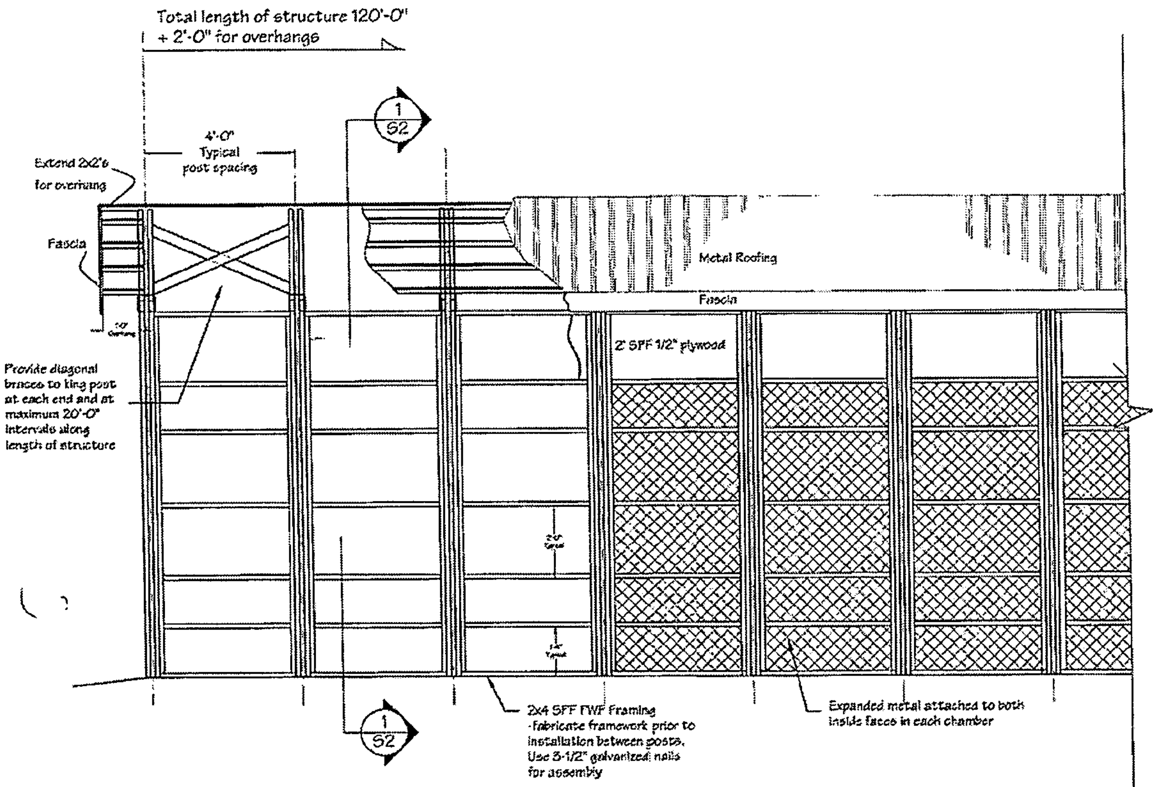
Date 37847

Flow Rates are in m/s

Weather clear
warm
windy

											Height (m)
0	0.044704	0	0.119211	0.119211	0.014901	0	0.059605	0	0	0	1.8288
0	0	0	0.089408	0.059605	0.059605	0	0.029803	0	0	0	1.6256
0.059605	0.022352	0	0	0.11176	0.074507	0.081957	0.067056	0.052155	0	0.044704	1.1938
0.104309	0.096858667	0.067056	0	0	0	0.059605	0.096859	0.081957	0	0.081957	0.7112
0.040979	0.040978667	0.016764	0.052155	0.072644	0.037253	0.035391	0.063331	0.033528	0	0.031665	
10.3632	10.7696	11.176	11.5824	11.9888	12.3952	12.8016	13.208	13.6144	14.0208	14.4272	

North



1 / S1 **Side Elevation**

-portions removed for clarity

Scale: 3/8"=1'-0"

PROVINCE OF MANITOBA
R. J.
DICK
02/06/26
REGISTERED PROFESSIONAL ENGINEER

ENGINEER SEAL

No.	Date	Description

Revisions

Building Alternatives Inc.

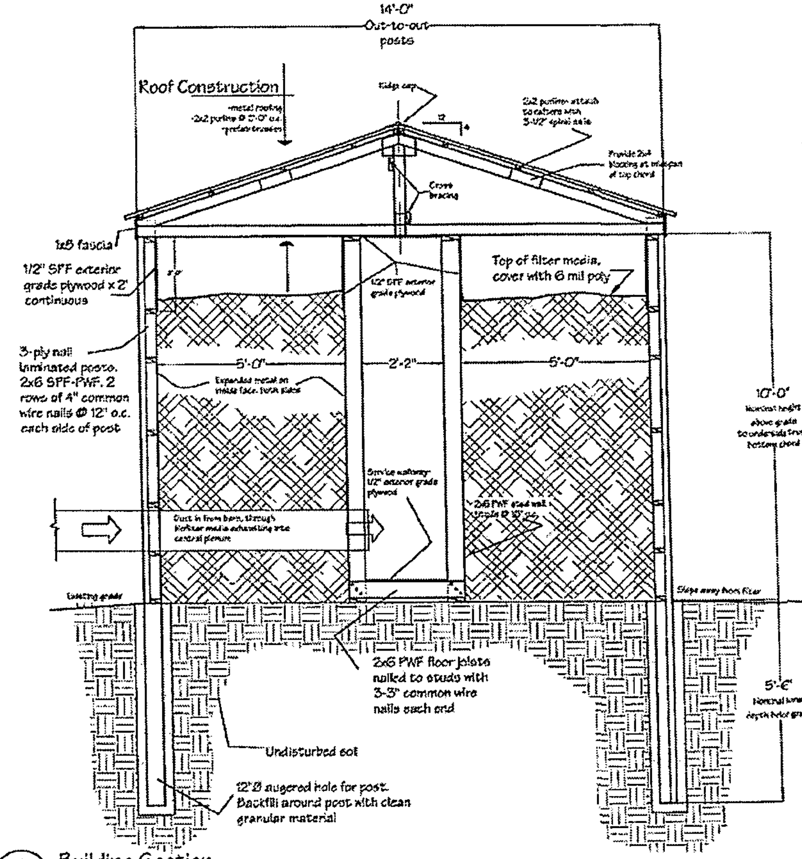
P.O. Box 22, ANOLA
Manitoba, Canada, R0E 0A0
Tel (204) 866-3521
Fax (204) 866-3287

Project
U of M Biosystems
Engineering
Department
- Biofilter Project

Sheet Title
Side Elevation

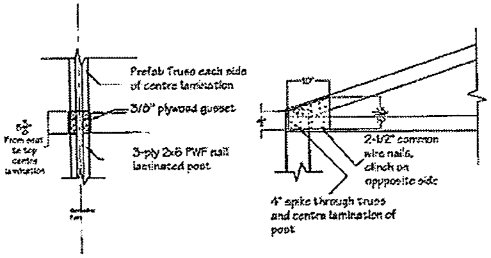
Dwg. No. 202118

DWG BY kjd		SHEET NO.
SCALE as shown		S1
DATE 02/06/27		



1 / S2 Building Section

Scale: 3/8"=1'-0"



2 / S2 Truss Heel and Connection to Post

Scale: 1/2"=1'-0"

1.0 Permanent Wood Foundations (PWF)

1.1 Design:

- The PWF is to be constructed in accordance with the Manitoba Building Code 1998 and the NBCC 95.
-Design and construction is in accordance with CSA 086.1-01 and CSA S406 "Construction of Preserved Wood Foundations" and also CWC Wood Text Series 3 "Permanent Wood Foundations"

1.2: Material Specifications:

1.2.1. Lumber and Plywood:

-All lumber and plywood used in PWF construction must be pressure treated with preservative in accordance with CAN/CSA-080.15 and bear the CSA PWF stamp.
- Field cut lumber members are to be treated with an "end-cut" preservative treatment
- PWF lumber is not to be cut longitudinally
-Design is based on lumber from Species Group 1 including Jack Pine, Lodgepole Pine, Ponderosa Pine, and Balsam Fir.
-Plywood is to be unsanded, exterior with a minimum 4 plies and conform to latest version of CAN/CSA-0121

1.2.2 Nails and Staples:

-Nails are to be stainless steel or hot-dipped galvanized and conform to CAN/CSA-B111.
-Staples must be stainless steel with a minimum diameter of 1.6mm with a 9.5mm crown conforming to AISI Type 304 or 316.
-Framing anchors and straps are to be a minimum 20 gauge and must be hot-dipped galvanized to ASTM A446.

K. J. DICK
02/06/28

ENGINEER SEAL

No.	Date	Description

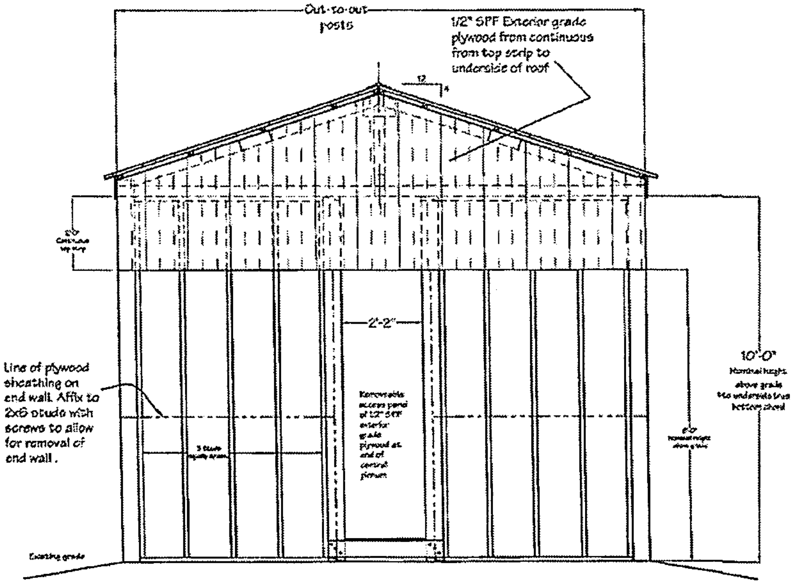
Revisions

Building Alternatives Inc.
P.O. Box 22, ANOLA
Manitoba, Canada, R0E 0A0
Tel (204) 866-3521
Fax (204) 866-3287

Project
U of M Biosystems Engineering Department - Biofilter Project

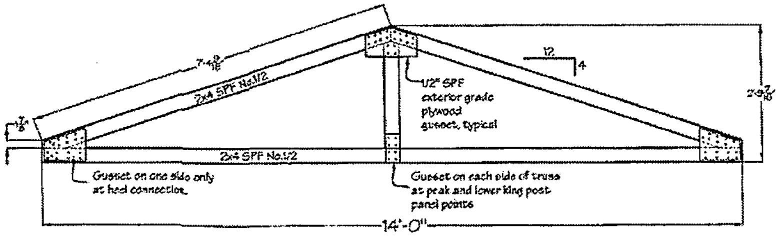
Sheet Title
Building Section

Dwg. No. 202118
DWN BY: kjd
SCALE as shown
DATE 02/06/27
SHEET NO. S2



1/S3 End Wall Framing

Scale: 3/8"=1'-0"



2/S3 Common Truss (One pair per post)

Scale: 1/2"=1'-0"

Wood Notes:
- Wood design in accordance with CAN-CSA 086.1-01 Engineering Design in Wood, Limit States Design.
- Framing lumber to be minimum SPF No. 1/2 as per NLGA.
- Trusses, LVL and any engineered wood product to be designed under the supervision of a registered professional engineer.

Structural Loads:
Unfactored Loads:
Ss= 1.9 kPa, Sr = 0.2 kPa, Roof dead load = 0.5kPa

K. J. DICK
02/06/28
ENGINEER SEAL

No.	Date	Description

Revisions

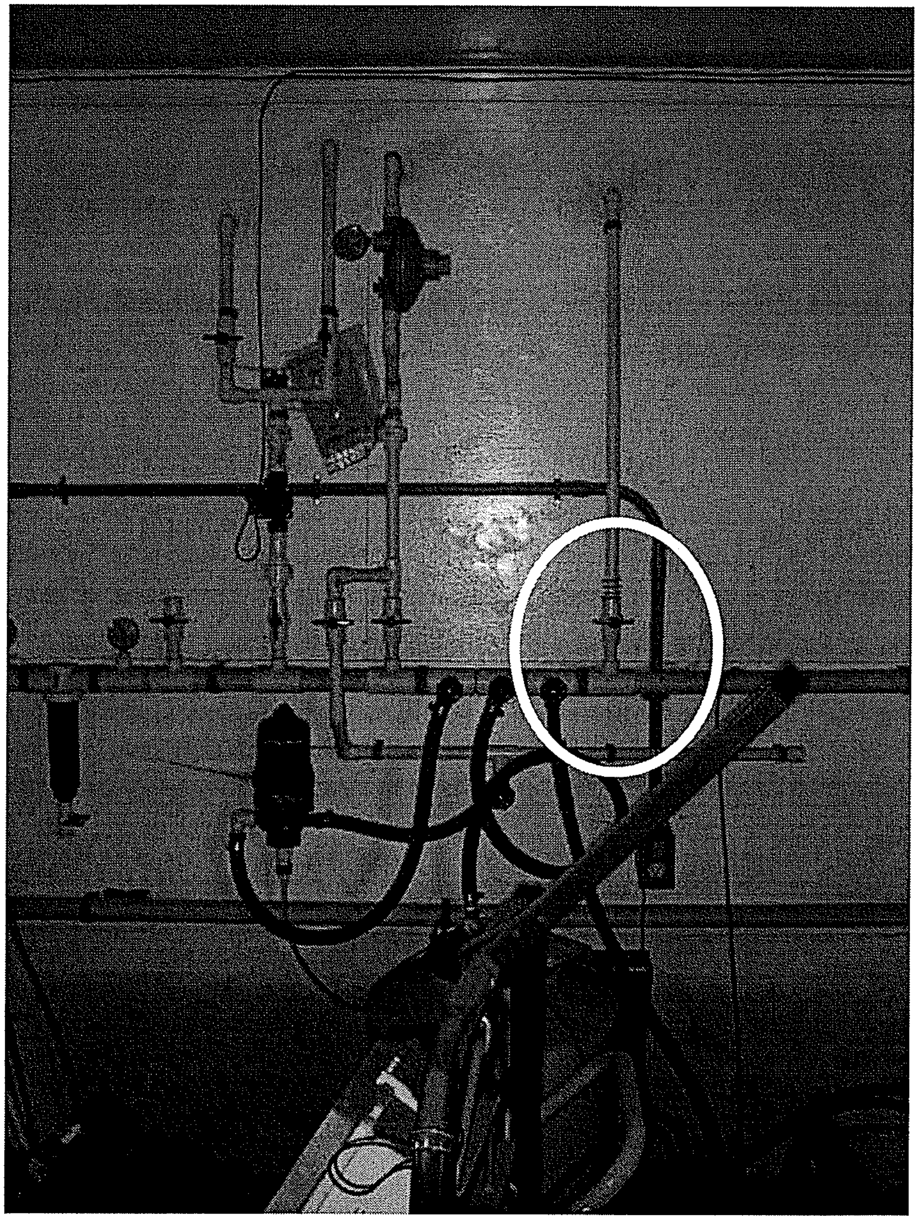
Building Alternatives inc.
P.O. Box 22, ANOLA
Manitoba, Canada, R0E 0A0
Tel (204) 866-3521
Fax (204) 866-3287

Project
U of M Biosystems Engineering Department - Biofilter Project

Sheet Title
Details

Dwg. No. 202118
CALC BY: kjd
SCALE as shown
DATE 02/06/27
SHEET NO. S3

Value that controls water outside the barn



White circle in picture is the value that controls the tap outside the barn that is the source of water for the biofilter.

Control of booster fan plugs outside barn.

Stage 1 booster fan plug is live all the time, not controlled by ventilation system.

Stage 3, 4, and 5 booster fan plugs are control by ventilation system, live only when barn fan is live.

Stage 2 booster fan plugs are controlled by switch next to fuse box, as seen in picture below. When switch is in the up position, Stage 2 booster fan plugs for live all the time, ventilation system does not control plugs. When the switch is in the down position, Stage 2 booster fan plugs become live when ventilation system activates Stage 3 fan in the barn.