2015

DEVELOPMENT OF A METHOD FOR IN-SITU TESTING OF OXYGEN CONCENTRATIONS IN COMPOST BEDDED PACK BARNS

John T. Evans IV
University of Kentucky, jtevans505@gmail.com

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

John T. Evans IV, Student

Dr. Michael Sama, Major Professor

Dr. Donald Colliver, Director of Graduate Studies

DEVELOPMENT OF A METHOD FOR IN-SITU TESTING OF OXYGEN CONCENTRATIONS IN COMPOST BEDDED PACK BARNS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biosystems and Agricultural Engineering in the College of Engineering at the University of Kentucky

By

John Thomas Evans IV

Lexington, Kentucky

Director: Dr. Michael Sama, Professor of Biosystems & Agricultural Engineering

Lexington, Kentucky

ABSTRACT OF THESIS

DEVELOPMENT OF A METHOD FOR IN-SITU TESTING OF OXYGEN CONCENTRATIONS IN COMPOST BEDDED PACK BARNS

Compost bedded pack barns are a relatively new type of dairy housing system that is being implemented in Kentucky. Extensive research has been done on the composting of animal manure, however, little has been done on composting animal manure in place. One of the most concerning challenges is aeration. Improper aeration can cause system failure. The ability to quickly and accurately measure the oxygen concentration would allow researchers the ability to determine which methods of tillage/aeration are most effective in compost bedded pack barns. The research in this thesis focused on the development of a method for simultaneously testing oxygen concentrations at different locations and depth in compost *in-situ*. A probe was developed that vertically aligned Apogee Instruments oxygen sensors (SO-120) in order to generate an oxygen profile of the compost. The probe was used to test the effect of different tillage/aeration strategies in a composted bedded pack barn. The results indicated the probe was effective at measuring the oxygen concentrations in active compost tested in laboratory conditions and it was determined that there was a significant difference in oxygen concentration with respect to depth. However, when applied in the compost bedded pack barn, large amounts of variation occurred randomly in the data, causing no difference to be detected as a result of varying tillage aeration treatments.

KEYWORDS: Compost, Aeration, Dairy, Housing, Oxygen, Pack

John T. Evans IV

March 24, 2015

DEVELOPMENT OF A METHOD FOR IN-SITU TESTING OF OXYGEN CONCENTRATIONS IN COMPOST BEDDED PACK BARNS

By

John Thomas Evans IV

Dr. Michael Sama

(Director of Thesis)

Dr. Donald Colliver

(Director of Graduate Studies)

March 24, 2015

(Date)

For my parents

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Michael Sama, for his support and advice, without which this project would have not been completed. I would like to thank my committee, Dr. Taraba, Dr. Day, and Dr. Bewley for their advice and thesis edits.

I would like to thank my good friend and officemate Aaron Turner for his help though out this project. I would like to thank Josh Jackson for his help with GIS and his volleyball organizational skills. I would also like to thank all the graduate students in the department who have made the last two year so enjoyable. To Nicole, for her love and support over the last two years.

I would like to thank the UK ¼ Scale Tractor Team and Tim Smith for the opportunity to gain real world experience, and for teaching me what it means to be an engineer.

Most importantly I would like to thank my family. To my mother, for her endless love and support. To my father, for his support and for instilling a love of farming and equipment that led me to pursue this degree. To my uncle, David, who knew what I should be doing before I did.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE OF EQUATIONS

CHAPTER 1:LITERATURE REVIEW

1.1 Introduction

The housing of dairy cattle for part of or all of the year is common among dairy producers in the United States. Housing provides the animals with protection from the weather, while allowing producers to have more animals in a smaller area. Housing dairy cows also allows for more producer-animal interaction that can lead to improved herd management. A survey conducted by the United States Department of Agriculture (USDA) showed that in 2006 over 90% of dairy operations in the United States housed the cattle, while under 10% kept the animals on pasture (USDA 2007).

1.2 Compost Bedded Pack Barns

Compost bedded pack (CBP) barns are a relatively new type of dairy housing system that is gaining popularity with producers. As of 2006, compost bedded pack barns comprised only 3.2% of all operations in the United States (USDA 2007). However, the number of CPB barns in Kentucky has risen three-fold from 30 in 2008 to 90 in 2014. CBP barns were developed by farmers in an effort to improve cow comfort, reduce lameness, and increase cow longevity. CPB barns are a variation on conventional pack barns that incorporate composting as a way to control moisture and improve cow cleanliness. CBP barns have the potential to be very cost effective when compared to free stall and tie stall barns, which account for 82% of the dairy housing currently in use. CBP barns require more space per cow than free stall or tie stall barns, approximately 7.5 to 9.3 m^2 (80 to 100 ft^2) per cow (Bewley et al. 2013), however, the initial investment is over 40% less than sand base free stall barns and mattress based free stall barns. Bedding material costs are higher in CBP barns than in free stall barns, but if properly managed the bedding cost can be offset by the increased milk production and reduced lameness observed in CPB barns (Black 2013).

1.2.1 Animal Health

Lameness is one of the costliest diseases affecting the dairy industry. Lameness can be caused by either hoof and leg injuries or bacterial infections (Clarkson et al. 1996). It

not only directly costs money to treat lame animals, but also causes reduced milk production in the affected animals. Green et al. (2002) and Warnick et al. (2001) conducted separate studies in which the loss of milk production per lame cow was found to be 1.2 kg/d and 2.6 kg/d, respectively. The economic impact per case of sole ulcer, digital dermatitis and foot rot were found to be $216.07, $132.96 and $120.70, respectively. These costs were calculated based on lost milk production, treatment cost, and reduced fertility (Cha et al. 2010). A similar study conducted by Liang (2013) found the total lameness cost to be $179.37 and $217.66 for primiparous and multiparous cow, respectively. These costs can accumulate quickly considering that, on average, producers reported 14% of cows in herds as lame (USDA 2007).

CBP barns have shown reduced incidences of lameness when compared to free stall barns. A study of six CBP barns in Minnesota found that, through four seasons, 9.1% of the cows were rated as lame (locomotion score ≥ 3), and 2.5% of cows were rated as severely lame (locomotion score ≥ 4)(Shane et al. 2010). A similar study conducted by Barberg et al. (2007) of 12 CBP barns found 7.8% of cows had lameness. In a comparison of cross ventilated free stall barns, naturally ventilated free stall barns, and tie stall barns in North Dakota (Lobeck et al. 2011) the lameness prevalence was found to be 13.1, 15.9, and 4.4%, respectively. Cook (2003) found the lameness prevalence in tie stall barns averaged 19.6% year-round.

Mastitis is another costly disease affecting dairy cows. Mastitis is an infection of the mammary gland, and results in expensive treatment and loss of milk production. A recent study by Liang (2013) calculated the cost per clinical mastitis case was $310 and $340 in primaparous and multiparous cows, respectively. In a study conducted by the USDA (2007), 94.9% of U.S. dairy herds reported at least one case of clinical mastitis. On average 16.5% of the cows in each herd were affected, resulting in heavy producer cost.

High mastitis occurrences are often associated with cow hygiene. Intuitively, producers think that cows in CBP barns would have lower hygiene scores (and thus higher mastitis occurrences) than cows housed in free stall or tie stall barns, where the manure is removed more frequently. However, a study of CBP barns in Minnesota found that producers actually reported fewer cases of clinical mastitis in herds after moving to CBP barns from other facilities (35.4% to 27.7%)(Barberg et al. 2007). A study by Eckelkamp

(2014) found no significant difference between the reported cases of clinical mastitis in Kentucky CBP barns and sand bedded free stall barns.

1.2.2 Barn Layout

CPB barns consist of a large open rest area that is filled to a depth of 30 to 45 cm with bedding material (usually sawdust) for the cows to lay on (Figure 1-1). There are no stalls in CBP barns allowing for more social interaction and exercise for the cattle. Social interaction and exercise have been proven to be beneficial to cow wellness (Popescu et al. 2013). The bottom of the pit is either compacted clay or concrete to prevent ground infiltration of any excess liquid. Walls, typically made of concrete, surrounding the pit are used to contain the compost as it increases in depth. The pit is usually separated from the feed ally by a retaining wall to prevent excess moisture build up in the pack. Openings in the wall allow cows access to the feeding alley between milkings. Many new barns are modified from other systems to mitigate initial cost. Proper ventilation in CBP barns is of great importance. Ventilation helps remove heat and moisture generated by the compost and by the cows. Without proper ventilation, high moisture can slow composting and require more costly bedding to maintain cow cleanliness (Janni et al. 2007). Barn design can facilitate increased natural ventilation and mechanical fans can be used to mix reduce stagnate areas and increase cow cooling (Bewley et al. 2010).

Figure 1-1: Compost bedded pack barn.

1.2.3 Waste Management

Waste in free stall and tie barns is removed from the barns daily and stored in expensive holding structures until it can be spread (Kleinman et al. 2003). In CBP barns up to 75% of the animal waste is incorporated into the bedding daily with the remaining manure scraped from feed alley, holding area, and parlor to storage. The composting process reduces the organic matter and moisture which can provide up to a 50% reduction in the volume of waste (Rynk 1992). The reduction of material volume allows producers between 6 months and a year before barn clean out is necessary. The plant nutrients, primarily N and P, in the manure are converted to more stable organic forms of biomass. In more stable forms, the nutrients are less likely to leach into the ground water or run off in to water sources when field spread on cropland. The reduced volume is easier to store until it can be field applied as compared to liquid manures (Kashmanian et al. 1996). The reduction of material in the solid state allows for more economical transportation of composted manure as compared to raw manure (Wiederholt et al. 2011). The composting process itself also provides many benefits in addition to improved waste management. Odors from the manure are reduced, and fly eggs cannot survive in the high temperatures (60 to 70° C) generated in the composting process.

1.2.4 Pack Management

Several studies have indicated the key to the successful operation of CBP barns is the CBP management (Janni et al. 2007, Bewley et al. 2013, Black 2013). The process of composting relies on thermophyllic microorganisms to break down organic matter. The microorganisms consume oxygen, nutrients in the manure, urine, and carbon in the bedding, and produce carbon dioxide, water, and heat. Maintaining proper composting, and taking advantage of the benefits associated with CBP barns, requires achieving proper carbon to nitrogen (C/N) ratios, moisture content, and aeration to facilitate composting. Mismanaged packs can lead to decreased composting rates and excessive material build-up. Even short term mismanagement of the pack can have negative impacts that are difficult to correct and negatively affect cow welfare and productivity.

1.2.4.1 Bedding Material

The type of bedding used in compost pack barns is an important consideration. The bedding is used, among other things, to maintain the C/N ratio. It is also used in conjunction with aeration techniques to manage the moisture in the compost. Upon startup, CBP barns contain a 30 to 45 cm depth of loose bedding. Fresh bedding is added as needed to control the moisture of the compost. Sawdust is the most commonly used bedding material in CBP barns (Shane et al. 2010). Kiln dried sawdust is recommended over green saw dust because of its higher water holding capacity. Green sawdust has also been linked to increased Klebsiella species bacteria counts (Bewley et al. 2013). Owing to its use in energy production (Baratieri et al. 2008), sawdust can be expensive to buy, and sometimes hard to find. Cheaper bedding materials such as straw have been used. Michel et al. (2004) conducted a study that compared the effect of manure amended with sawdust and straw. The results showed that manure amended with sawdust maintained higher composting temperatures than manure amended with straw. Minnesota dairy farmers have used a variety of bedding materials including: sawdust, wood chips, flax straw, wheat straw, strawdust, oat hulls, soybean straw, and soybean stubble. All of the bedding types were able to maintain composting temperatures, but most producers preferred to use sawdust, if available (Shane et al. 2010).

1.2.4.2 Temperature

Temperature is the most commonly used metric when judging compost performance because it is directly related to microbial activity. But moisture content between 40%-60% wb achieves the highest microbial rate under aerobic conditions (Haug 1995). Temperature is also quickly and economically measured by producers and researches alike. Temperatures between 40 and 50° C have been found to achieve the highest cellulose degradation (Kuter et al. 1985). This is important to producers because, as previously stated, the reduction of material extends the time between barn clean out and reduces hauling cost. Barberg et al. (2007) reported the average bed temperature, recorded in early summer, to be 42.5° C ± 7.6° C. In a separate study by Shane et al. (2010) the average temperature of six CBP barns was found to be between 31.8° C to 48.1° C in the summer and 13.8° C to 40.6° C in the winter. These studies indicated that a

large number of samples were not operating in the optimal range to see maximum cellulose degradation.

Composting also has the ability to kill harmful pathogens that may be in the pack. However, higher temperatures (55° C to 65° C) are more effective at pathogen destruction. Neither of the previously mentioned studies recorded temperatures in this range, indicating that producers may not be capitalizing on one of the biggest advantages that composting has to offer.

1.2.4.3 Moisture

Moisture is one of the biggest factors in CBP performance. Moisture is added to the bed though a combination of manure, urine, and microbial respiration (Janni et al. 2007). Too much moisture is undesirable because it affects cow cleanliness and creates an environment for pathogens to grow. Composting at higher temperatures increases moisture evaporation. Natural and forced ventilation in the barns also help promote evaporation as air moves over the bed surface. Forty to 65% moisture content is generally recommended for composting (Rynk 1992). However, in a study by Black et al. (2013) the optimal moisture range for CBP was suggested to be between 45 and 55%. The results were based on plotting temperature vs. moisture content from data collected at 47 CBP barns across Kentucky.

1.2.4.4 Stocking Density

The number of cows that a CBP can sustain is based on the amount of moisture that can be added and evaporated from the compost while maintaining the desired moisture content (Janni et al. 2007). Overstocking can lead to increased moisture content, requiring additional bedding to maintain balance. When the CBP barn was first developed in Virginia, 9.4 m^2 per cow was used (Wagner 2002). Janni et al. (2007) recommended 7.4 m^2 per cow weighing 540 kg and 6.0 m^2 per cow weighing 410 kg, based on manure and urine output. Black et al. (2013) found 9.4 m2/ Holstein cow (640 kg liveweight, producing 23 kg milk/day) was required to achieve a balance between water added and water evaporated during the KY summer climate. Larger cows and higher milk production required more area per cow to account for increased moisture production. . Janni et al.

(2007) recommended 7.4 m^2 per cow weighing 540 kg and 6.0 m^2 per cow weighing 410 kg, based on manure and urine output.

1.2.4.5 Aeration

Maintaining an oxygen level above 5% in the manure/bedding mixture is a key component to facilitating the desired microorganism activity. When the oxygen concentration drops below 5%, the microorganisms in the mixture begin to consume organic matter at a reduced rate. If the oxygen concentration in the pack reaches 0%, the system becomes completely anaerobic. Anaerobic composting utilizes different microorganisms, or microorganism that are facultative, that break down and metabolize organic matter more slowly than aerobic microorganisms. Slower material degradation leads to reduced time between barn clean outs. Anaerobic composting produces less heat, which is necessary to drive moisture from the compost. Increased pack moisture content requires more costly bedding to be added, reducing profit for the producers. Anaerobic composting also produces undesirable gases such as methane, ammonia, and hydrogen sulfide.

One of the biggest challenges with aeration in CBP barns is the compaction generated from cows walking and lying on the compost. Compaction limits free air space, reducing the amount of available oxygen (Das et al. 1997, El Kader et al. 2007). In an effort to reduce compaction and improve aeration, producers mix the pack 2-3 times daily (Barberg et al. 2007, Shane et al. 2010, Black 2013). The depth of mixing can also affect pack performance. Deeper mixing aerates more of the pack volume, leading to deeper active composting. Janni et al. (2007) recommended mixing to a depth of 25 to 30 cm. Bewley et al. (2013) recommended daily mixing to 30 cm deep with periodic mixing to 45 cm deep. However, a study by Barberg et al. (2007) found that producers were only aerating to a depth of 18 to 24 cm, and Black et al. (2013) found that producers on were only achieving a mean (n=42) mixing of 24 cm.

1.2.4.6 Hybrid Tillage Tool

Producers currently manage aeration though the use of soil tillage tools such as rototillers and cultivators. Rototillers are only able to aerate the pack to an average depth of 20 cm. However, they break the material into small particles, which creates more surface

area for the microbes to digest, and leaves a smooth, fluffy surface finish for the cows. Rototillers also do an excellent job of incorporating manure into the bed, which helps maintain cow cleanliness. Cultivators allow for deeper aeration, but do not incorporate manure or reduce particle size as well as rototillers. Cultivators also leave a rough, uneven surface, for the cows to lay on, particularly at high moisture contents (>60% wb). As previously discussed, producers were not able to aerate to the recommended depth using these tools. The ideal aeration tool would fully incorporate the manure, leave a smooth surface finish for the cows, and would completely aerate the bedded pack tillage layer.

A custom tillage tool was designed as part of a capstone senior design course at the University of Kentucky. The team of students (John Evans, Jeff Clark, and Stephanie Hunt) were tasked with designing a tool that would better meet the needs of the producers. The goal was to create an implement capable of aerating the bedded pack to a depth of ~45 cm, while still maintaining the material incorporation and surface finish. Aerating the bedded pack to a greater depth would increase the aerobic depth, thus providing more complete breakdown of the material and increased temperatures. Increasing the volume of the bed operating at higher temperatures (40 to 60° C) would allow the bed to function longer into the cold winter months.

The custom tool (Figure 1-2), combined two of the most common tillage methods: the rototiller and deep shank cultivators. The rototiller was chosen because of its ability to incorporate fresh waste with the compost, and the smooth, comfortable surface it provided for the cows. The deep shank tillage was chosen for its ability to aerate the compost to a greater depth than the rototiller alone. The tool attached to the three point hitch between the tractor and the rototiller. Hydraulic cylinders actuated a four point linkage that controlled the depth of the deep shanks in the compost. Owing to the relatively confined spaces in which the implement was required to operate, the size of the tractor towing the implement was restricted to 50 to 70 hp for the project. Three shanks were used in order to achieve as much deep aeration as possible while still adhering to the power restrictions.

Figure 1-2: Hybrid Tillage/Aeration Tool

The Custom Aeration Tillage tool was tested in a CBP at the Harvest Home Dairy in Crestwood, Oldham County, KY. While the tool met the goal of keeping the surface finish and power requirements, there was no way to measure the aeration effect. The producer reported higher bed temperatures after the tool was implemented, but because so many factors (moisture, ambient temperature, C/N ratio) are involved it could not be definitively stated that the aeration provided by the tool was the cause of the temperature rise.

1.3 Project Objectives

The objectives of the research are as follows:

1) Design an *in-situ* method for simultaneously testing oxygen concentrations at different locations and depth in compost.
2) Develop a mobile forced-air injection system using a previously designed hybrid tillage/aeration tool as the base platform.

3) Compare the oxygen concentrations before and after treatment using the custom hybrid tillage tool in rototiller, rototiller + deep shank, and rototiller + deep shank + forced aeration configurations.

1.4 Organization of Thesis

Chapter 1 gives background information about dairy housing systems and introduces the problem of aeration in CBP barns. Chapter 1 also outlines the specific objectives for this research. Chapters 2 through 5 discusses how each objective was achieved, the results that were found, and the conclusions that could be made. Chapter 6 reviews potential future work that would improve on the knowledge gained though this research. The appendix includes charts, tables, and programming code that were not included in the body of the text.

CHAPTER 2: OXYGEN SENSOR CALIBRATION

2.1 Introduction

The available oxygen in compost systems has a direct effect on the metabolic rate of the aerobic bacteria present. If the compost is not aerated then bacteria will consume the oxygen until the system becomes anaerobic. Anaerobic systems metabolize organic matter slower than aerobic systems and produce undesirable compounds such as methane, organic acids, and hydrogen sulfide (Rynk 1992). It is generally accepted that compost is "working well" when the system has the right combination of organic materials, moisture level, oxygen level, and is producing enough heat to support thermophilic microorganisms. Temperature has been the most common metric used in composting because it is recognized as a good indicator of how the system is working, although it is a trailing indicator affected by the moisture content. The main disadvantage of using temperature as a system indicator is that it is not an instantaneous measure of the state of the compost. It takes time for the microorganisms to generate heat once they have the proper mix of ingredients. Instantaneous feedback is desirable when developing methods for providing necessary levels of individual ingredients, such as oxygen.

The challenge with measuring oxygen in compost is that most sensors are developed for either ambient temperatures or extremely high temperatures environments, such as automotive exhaust systems. Composting can produce temperatures as low as ambient air and as high as 70°C. The goal of the experiment was to test a commercially available soil oxygen sensor and determine if and if it could be calibrated to accurately measure oxygen concentrations in compost.

2.2 Materials and Methods

An Apogee Instruments (Apogee Instruments, Inc., Logan, UT) Oxygen Sensor (SO-120) was chosen for the experiment because of its relative close operating range (-20 to 60°C) to that of compost. The sensor utilized a galvanic cell to measure the oxygen concentration as a voltage signal. The sensor output in ambient air conditions (20.95% O2) was approximately 50 mV, or 2.4 mV per 1% O2. The O2 sensor was also temperature dependent and came with an internal type K thermocouple. The thermocouple output was 0.798 mV at 20°C and linearly changed 0.397 mV per 10°C. A Measurement Computing

USB-2416 DAQ (Measurement Computing Corporation, Norton, MA) board was used to convert the voltages to digital signals that could be read by a computer. The signals were read into a program that was developed using Microsoft Visual Studio (Microsoft Visual Studio 2012, Microsoft Corporation, Redmond, WA). The program logged the raw voltage from two oxygen sensors, their reference temperatures, and the time the measurements were taken. The program also logged temperatures from additional thermocouples that were used in the experiment. Data was written to a comma-separated value (CSV) text file that could be directly opened in Microsoft Excel (Microsoft Excel, Microsoft Corporation, Redmond, WA) for analysis.

Initially the sensors were placed in an oven in order to control the temperature of the gas and the sensor body during calibration. Early experiments showed that the oven was unable to maintain a constant and repeatable temperature, so the sensors were moved to a Lauda (LAUDA-Brinkmann, LP., Delran, NJ) E300 water bath. Water baths are commonly used in experiments because of their ability to precisely and stably control temperature. The sensors were originally placed outside the bath with the air being pumped though a PVC manifold (Figure 2-1).

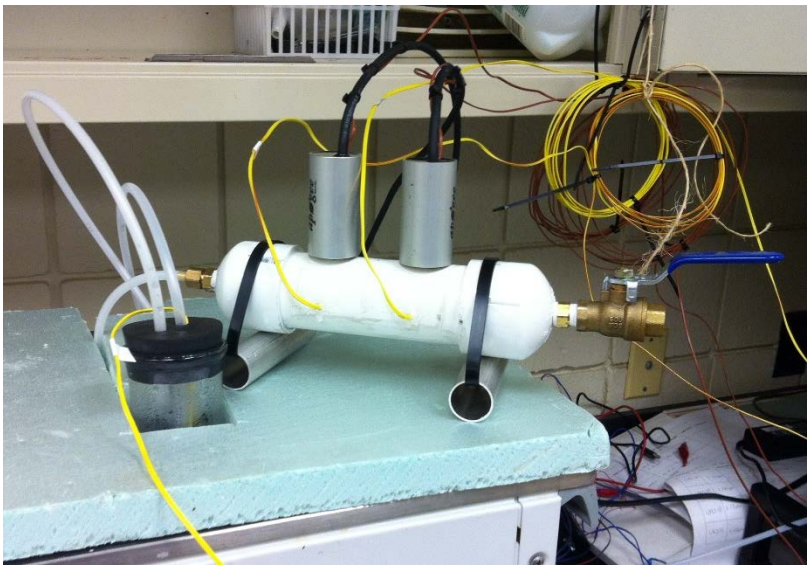

Figure 2-1: Original Water Bath Setup

The sensors came equipped with a 12V internal heater that was designed to prevent condensation, but at higher temperature gradients, condensation still formed on the interior of the Teflon membrane when the warm saturated air came in contact with the cooler

sensors. This caused the sensors to malfunction as exhibited by a loss of voltage signal, or an apparent 0% O2 measurement. The sensors could be repaired by placing them in an oven at 50°C until the condensation evaporated and the voltage output returned to normal. The final design (Figure 2-2) featured the sensors mounted in an aluminum manifold that sat partially submerged in the water to conduct water bath temperature to the O2 sensor. The sensors were covered in insulation during the test to prevent condensation, which kept them at the approximately at the temperature of the water and prevented condensation.

Figure 2-2: Calibration Setup

The water bath featured an RS-232 port, which allowed for the calibration process to be automated. Relay switches (Opto 22 ODC5, Opto 22, Temecula, CA) and solenoid operated valves (Burkert W26UT, Burkert Contromatic Corporation, Irvine, CA) were added to control the flow of calibration gases using the DAQ board's digital outputs. The program that was developed to log the data was modified to control the calibration process. The sensors were calibrated at five different oxygen concentrations, 0% O_2 (4% CO_2 balance nitrogen), 5, 10, 15, and 20% O_2 balance nitrogen, and six different temperatures (10, 20, 30, 40, 50, and 60°C). The program (Figure 2-3) featured two tabs, Main and Sampling Order. The Sampling Order tab (right) allowed the user to randomized the

sampling order. The Main tab (left) handled the connection to the water bath and the DAQ board.

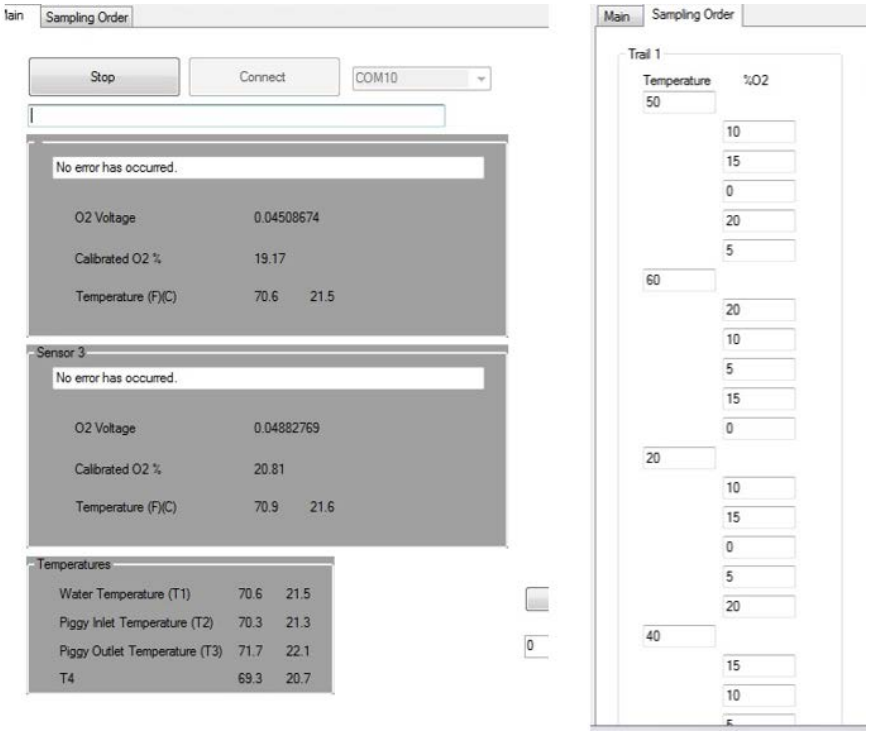

Figure 2-3: Calibration Program

The program also displayed the raw voltage, temperature, error messages (if necessary), and the calibrated %O2 (if a previous calibration had been completed) for each sensor. When the sampling order was set, and the on-screen start button was selected, the program set the water bath to the randomly selected temperature. One of the additional thermocouples monitored the temperature of the bath. When the actual temperature reached the set temperature, the program triggered the relay switch of the first calibration gas. The program simultaneously began logging the voltage output and temperature from the sensors. The program stored the collected data in individual CSV files. Each of the calibration gas cylinders had a Concoa (Concoa Corporation, Virginia Beach) pressure/flow regulator that was used to set the flow rate of the gas though the system to 2 liter/min, at the lowest pressure possible. A Dywer flow meter (Dwyer VFA-24, Dwyer Instruments, Inc., Michigan City, IN) was used to measure the flow and ensure the rate was the same for all the calibration gases. The flow was maintained during the process to create a small positive pressure that prevented any outside air from entering the manifold. All the

gases were at ambient air temperature (21°C) during testing. The air in compost was assumed to be saturated (Hogan et al. 1989) so the gas was saturated in a flask of water submerged in the water bath. The gas then flowed out of the flask and into a set of copper coils in the water bath. The gas reached the temperature of the bath in the coils and flowed into the manifold that contained the sensors. The manifold contained thermocouples at each end to insure the gas was at the proper temperature. The gas flow through the system was maintained until the sensor outputs were at equilibrium. The program then stopped the flow of gas using the relay switch and turned on the next calibration gas to be read. The program repeated this process until all five calibration gases were measured and then set the water bath temperature to the next desired value in the order specified in the Sampling Order tab and repeated the process until the all combinations of O_2 concentration and temperature were measured.

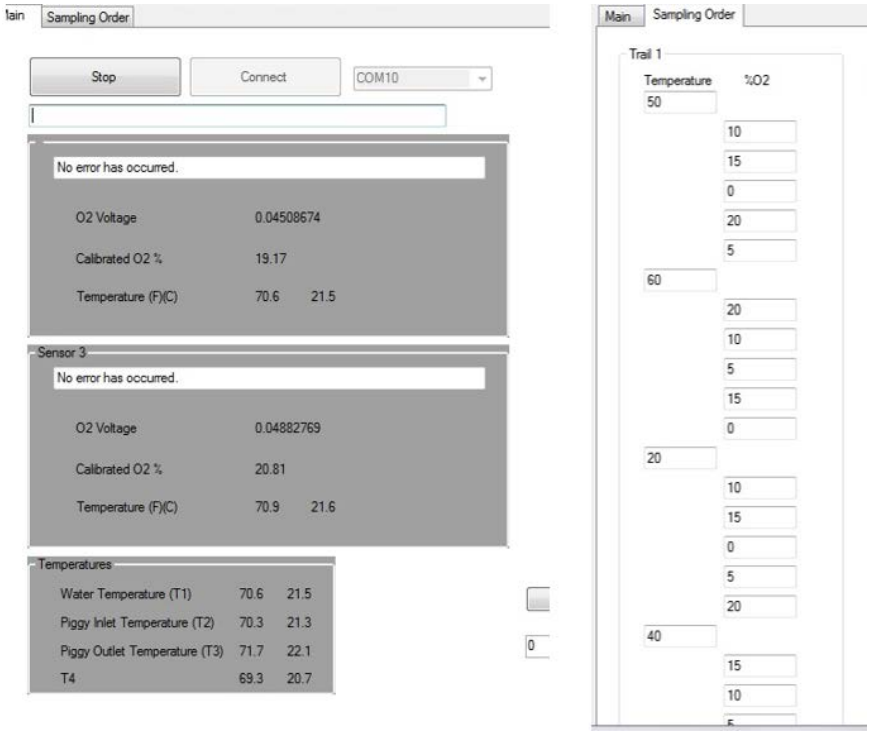

Figure 2-4: Calibration Program

Owing to the condensation problems that occurred during the development of the calibration process, there was concern that moisture would condense in the sensor at ambient temperature when placed into the warmer compost. Laboratory tests were

conducted to simulate field conditions that would most likely result in condensation forming in the sensors. Compost was placed in an oven at 70°C. A sensor that was 20°C was then inserted into the heated compost. This process was repeated three times and the sensor reading never indicated that there was internal condensation.

2.3 Results and Discussion

The calibration program was executed three times, recording a total of ninety response curves from each sensor. MATLAB (R2013a) code was written to determine the steady-state value of the sensors from each response curve and compile it in a single array for each sensor. With the data compiled, the "createfit" function in MATLAB was used to create the calibration equations which calculated oxygen percentage as a function of the output voltage and the temperature. First, second, and third order polynomial fits were created from each sensor and then applied to a second set of calibration data to validate the models. The root mean squared error (RMSE) was calculated for each order of each sensor. Table 2-1 shows that a third order polynomial equation produces the lowest RSME's for each sensor.

Table 2-1: RMSE Values (%O2)

Polynomial Order	Sensor	
	1	2
First	0.816	0.8825
Second	0.3771	0.4726
Third	0.2539	0.3878

However, one of the coefficients of the third order polynomial for the second sensor was not significant (confidence interval crossed zero), indicating that the second order (Equation 2-1) should be used.

$$\%O2(x,y) = p00 + p10*x + p01*y + p11*x*y + p02*y^2 \qquad \text{Equation 2-1}$$

Where:

x = Voltage output of sensor

y = Temperture output of sensor

p00, p10, p01, p11, and p02 = Calibration coefficients

The data in Figure 2-5 show that as the oxygen concentration and temperature of the measured gas increased the signal showed a non-linear response. This response highlights the importance of the temperature correction.

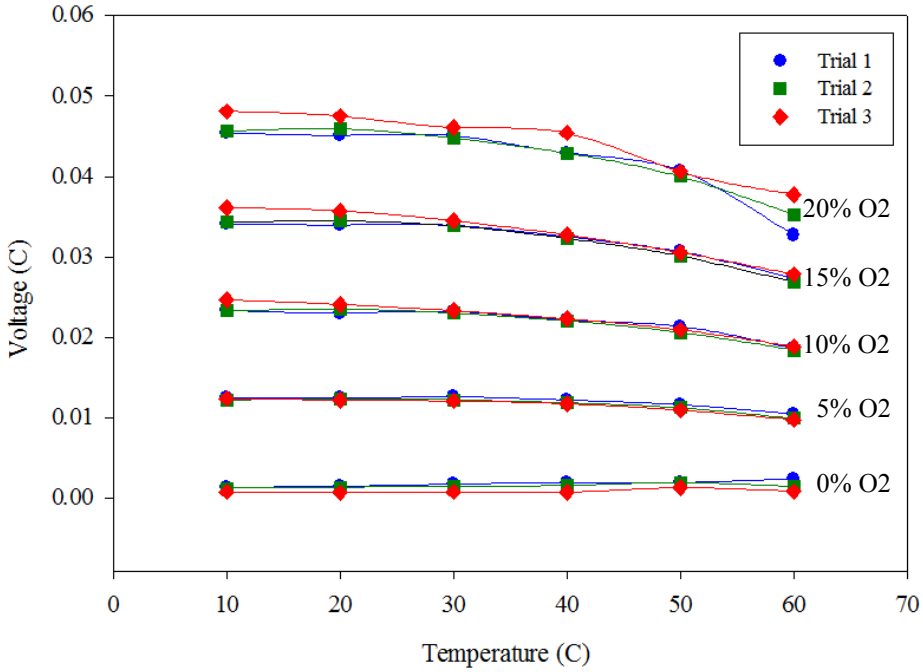

Figure 2-5: Sensor 1 Calibration Data

Using second order fit, 95% prediction intervals for the two sensors were calculated according to Equation 2-2. The prediction intervals were calculated to be ± 0.75% and 0.95% for sensor 1 and 2, respectively

$$95\%\ PI = \pm 2 * RMSE$$ Equation 2-2

2.4 Conclusions

A method for calibrating an oxygen sensor, that was both oxygen and temperature dependent, was developed. Multiple sensors were calibrated in the ranges that were expected in composting conditions (0 to 20% O2, 10 to 60°C). The calibration process took between 8 to 13 hours depending on the randomized order of the temperatures. 600 liters (120 liters per concentration) of calibration gas was used per trial. Three trials were used to create the calibration curve which meant that the total time to complete a calibration was about 32 hours using 1800 liters of calibration gas. The number of sensors that could be calibrated simultaneously was limited only by the size of the water bath and the number of ports on the DAQ board.

The number of points sampled and the repeatability of the sensors lead to small prediction intervals (± 0.75% O2) which meant that small differences in oxygen concentration levels could be detected in the field.

CHAPTER 3: OXYGEN PROBE DESIGN

3.1 Introduction

The Apogee Instruments oxygen sensors (SO-120) were determined to be suitable for use in composting conditions. However, testing the effect of aeration methods in compost required before and after *in-situ* measurement of the oxygen concentration at multiple depths. This required the design of a probe that could be inserted into the CBP and hold multiple sensors in a vertical array. The major design goals for the probe were:

1) Require little to no material extraction for placement.
2) Integrate multiple oxygen sensors in vertical alignment.
3) Be portable enough to measure at any location in the barn.

3.2 Methods

3.2.1 Probe Design

In order to get the probe inserted in the compost without removing material the outside diameter of the probe needed to be as small as possible. This meant that the sensors would need to be stacked directly on top of one another. The final design of the probe required a 5.1 cm outside diameter aluminum tube that held the sensors. The tube diameter was limited by the diameter of the oxygen sensors (3.1 cm) and the space required for the sensor wires to travel though the probe. The aluminum tube housed an internal ABS plastic structure fabricated on a three dimensional printer that secured the oxygen sensors in place (Figure 3-1). The sensors were threaded into diffusion heads, which interlocked together to form the inner structure. The length of the oxygen sensors required that the diffusion heads be spaced a minimum of 11 cm apart. The diffusion heads featured a permeable barrier that allowed gases to flow in but kept solid material from entering. The barrier was placed on opposite sides of the circular diffusion head with each covering 90 degrees of the surface. Each barrier was separated by 90 degrees of solid plastic. The outer aluminum probe body featured corresponding 90 degree slots that when aligned with a diffusion head, allowed gases to flow from the pack into the diffusion heads. When the slots and solid plastic were aligned no solid material, and very little gas, could enter the diffusion chamber.

This setup allowed the probe to be inserted into the pack without allowing material to clog the permeable barrier.

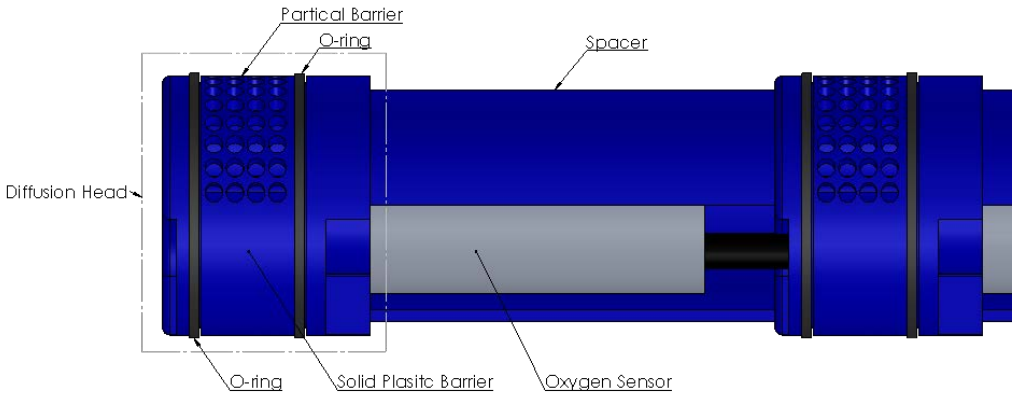

Figure 3-1. Inner Probe Structure

The probe also featured a 60 degree cone to aid in placement. Figure 3-2 shows how the probe would be inserted in the CBP. Once the probe was inserted, the inner structure was rotated 90 degrees clockwise to allow gasses to flow into the diffusion head. Each of the diffusion heads contained an O-ring gasket on the top and the bottom of the diffusion head that limited gasses from traveling vertically inside the probe body.

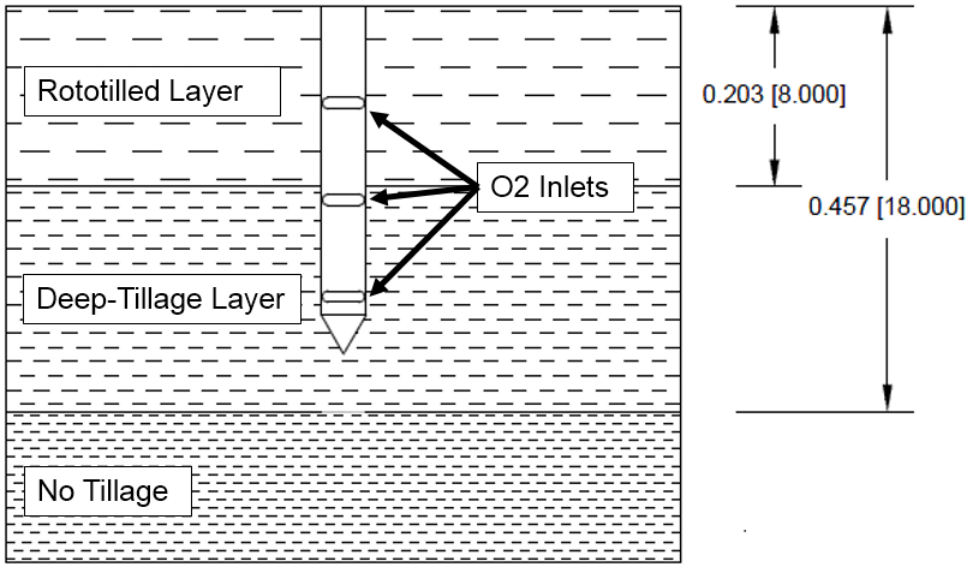

Figure 3-2. Probe in CBP

A sample probe containing four sensors at 11, 22, 33, and 44 cm deep was fabricated and taken to Harvest Home Dairy in Crestwood, KY to determine how it would

perform in field conditions. The goal of the field testing was to determine if there were any design problems that needed to be addressed before a comparison of tillage/aeration methods could be performed.

It was also of interest to know the time required to sample when using the diffusion chambers. The diffusion chambers were necessary in order to create discrete sampling areas. However, they introduced a small amount of ambient air into the compost when implemented. The time it took for the air in the chamber to counter-diffuse with the gases in the compost plus the sensor response time was the total time it took to take a reading. This time (sampling time) is important because the composting process consumes oxygen making it potentially difficult to distinguish between the system response and the actual oxygen consumption that is occurring.

The tests were conducted in mid-February after a deep freeze. Temperatures in the compost were at or below ambient air temperatures, indicating there was no active composting and thus there should have been no consumption of oxygen. This should have allowed for only the system response time to be present and measured.

It was immediately apparent that probe placement was an issue for the pre-tillage/-aeration reading. The probe was made as small as possible to fit the sensors, but was still 5.1 cm in diameter. The compost was extremely wet (~70%) and compacted during testing, making it impossible to insert the probe. After the tillage/aeration was conducted it was possible to insert the probe, but with difficulty, especially at deeper depths. Since taking pre-tillage/-aeration oxygen concentrations was necessary to determine differences in aeration methods, and the probe diameter was already as small as possible, it was therefore decided for future testing to excavate a hole prior to probe placement was necessary. Even though the pre-tillage/-aeration measurements could not be taken the post-tillage/-aeration measurements were taken to give an initial idea of the probe performance. The sensors without the diffusion heads showed a response time of approximately 7 minutes when calibrated in the laboratory. However, in a field test, the sampling times for 3 replications were between 40 minutes and 80 minutes. This was deemed undesirable for two reasons: long diffusion times would limit the number of samples that could be taken, and such high variability in sampling times would cause the confidence interval to be undesirably large when taking a single measurement.

Through examination of the sampling process, two possible causes of the variable and slow diffusion times were proposed. The first was the size for the holes in the diffusion heads. According to Fick's law of diffusion (Equation 3-1) the diffusion rate is proportional the surface area the gas is diffusing across.

$$J = -D\frac{\partial c}{\partial x} \qquad \text{Equation 3-1}$$

Where:

J = diffusion flux [(amount of substance) per unit area per unit time], $\frac{mol}{m^2 \cdot s}$

D = diffusion coefficient or diffusivity, $\frac{m^2}{s}$

c = concentration, $\frac{mol}{m^3}$

x = distance, m

Thus the smaller the area, the longer the diffusion takes to occur. The original diffusion head had a square orifice design with a total diffusion area of 2.7 cm^2. Two more diffusion heads where designed with increased areas. The areas for all three diffusion heads are shown in Table 3-1.

Table 3-1: Areas of diffusion heads

Design	Area (cm^2)
Original (Square)	2.71
Medium (Round)	5.07
Large (Round)	6.89

The large hole design shown on the far right of Figure 3-3 had the largest diffusion area. However, field tests revealed the holes allowed for compost material to pass partially or completely though the barrier. This caused plugging of holes, effectively reducing the surface area, and made removal of the probe difficult. The medium hole size design shown in the middle of Figure 3-3 had nearly twice the diffusion surface area of the original design and did not allow solid material to pass through. Therefore, the medium hole size design was chosen to be the best of the three designs.

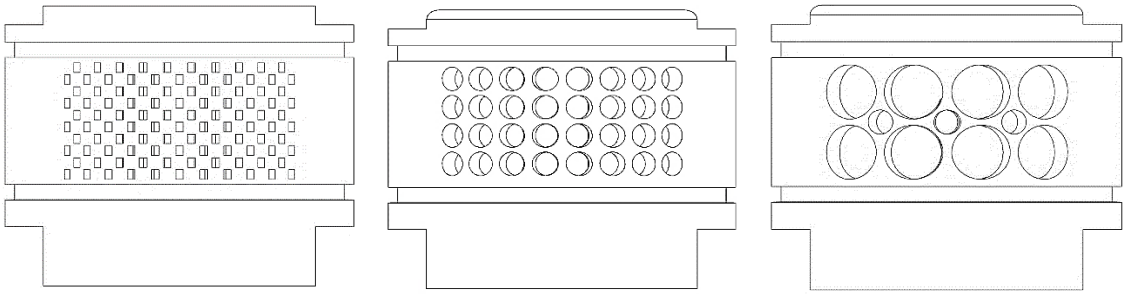

Figure 3-3: Small square, medium round, and combination large/ medium diffusion heads. (Left to right)

A second possible cause of the slow diffusion times was hypothesized to be excessively high moisture in the CBP. The CBP was noticeably wet on the day the initial tests were conducted. Liquid could be squeezed from the material which indicated the moisture was approximately 70% - an estimation based on observations made in the laboratory with compost of a known moisture content. As the moisture content of the compost increases, the gas-filled volume of the compost decreases (Oppenheimer et al. 1997). According to a paper by Van Ginkel et al. (2002) the oxygen diffusion coefficient is proportional to the gas-filled volume fraction raised to the power. This indicates a direct relationship between the moisture and diffusion time. The diffusion heads could be redesigned to facilitate quicker diffusion, however, no changes to the probe design would decrease the diffusion time if the moisture of the compost was the limiting factor.

3.2.2 Data Collection Development

The last goal of the probe design was to be able to take measurements at any location in the barn. However, the Measurement Computing DAQ USB-2416 that was used for the calibration data collection required a power source and was not suitable for use in a composting environment. This was not practical for field testing because access to power outlets was limited. The USB-2416 also did not have enough differential analog inputs to handle 9 sensors (18 required) or the ability to power the internal 12V heater. It was determined that a different solution was required to collect data in the field.

A custom instrumentation system was developed to amplify and sample the small voltage signals from the O_2 sensors and thermocouples and transmit that information

wirelessly to a PC. A simple amplifier and cold-junction compensation circuit was tested as part of the system development to ensure that temperature could be accurately determined (Figure 3-4). The circuit used a MAX6610 (Maxim Integrated Products Inc., San Jose, CA) temperature sensor, an INA333 (Texas Instruments Inc., Dallas, TX) instrumentation amplifier, and an OPA333 (Texas Instruments Inc, Dallas, TX) operational amplifier. The temperature sensor provided a reference measurement of the cold-junction temperature of the thermocouple. The instrumentation amplifier provided a differential gain of 243.9, which resulted in a relative output of 10 mV/°C for a type K thermocouple. The operation amplifier supplied a nominal 2.5 V reference to center the instrumentation amplifier output between the 0 to 5 V supply range. The positive end of the thermocouple was also connected to the 2.5 V reference voltage via a 10 kΩ pull-up resistor to keep the thermocouple inputs close to the center of the operating range.

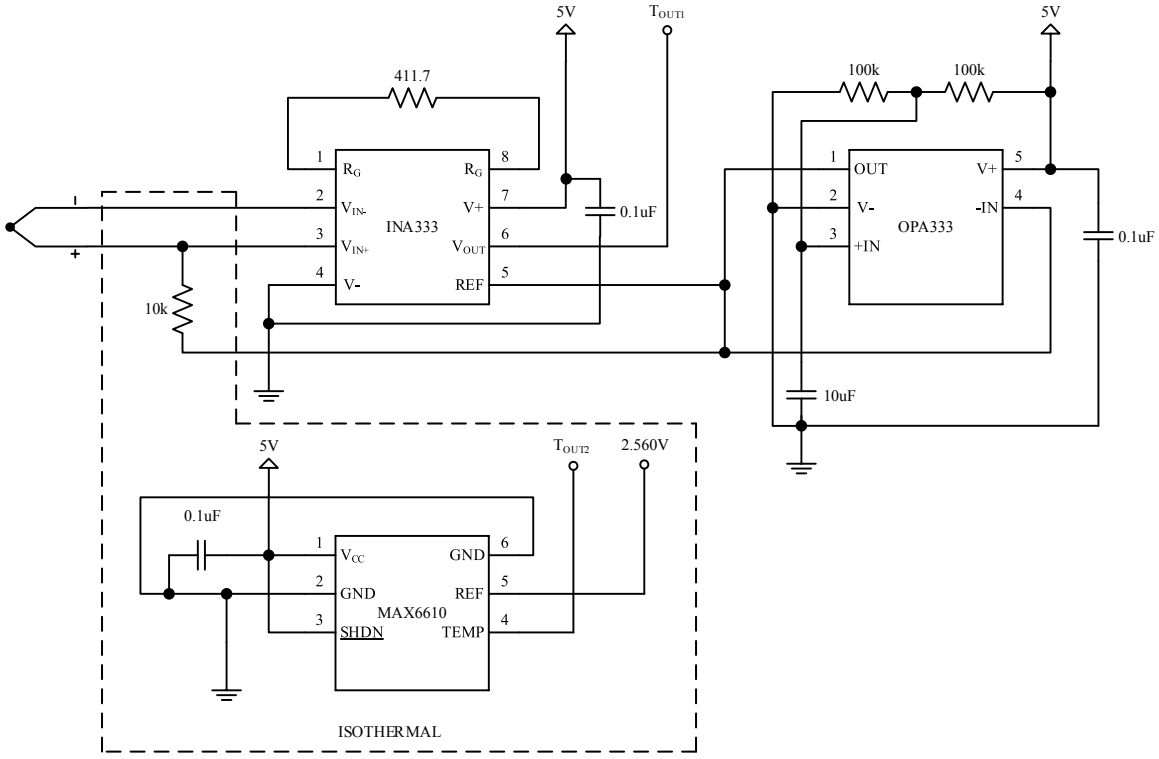

Figure 3-4: Thermocouple Amplifier and Cold-Junction Compensation Test Circuit

A printed circuit board (PCB) was designed using PCB Artist (v3.0, WestDev Ltd) (Figure 3-5) and assembled using a reflow soldering process for surface mount components

followed by hand soldering of through-hole components (Figure 3-6). The PCB included nine amplifier circuits, six configured with a gain of 243.9 for type K thermocouples and three with a gain of 40.22 for O_2 sensors. The operational amplifier that provided a 2.5 V offset was replaced with a linear voltage regulator. A dsPIC30F4013 digital signal processor (DSP) (Microchip) was used to sample the amplifier voltages. Voltages were packaged into a serial data string and converted to RS-232 using a Maxim MAX232 level-shifter. An additional RS-232 serial port and a controller area network (CAN) interface were included for future use. Wire-to-board terminals provided interfacing between external sensors, power supply and switches. A thermal barrier was included between the sensor input section of the PCB and the remaining components. Only small traces carrying power and signals were allowed to cross the barrier, which limited the thermal conductivity between the two sides. A ground plane construction on the top and bottom of the PCB was used to tie all components to ground. The ground planes also helped to ensure that all components on a particular plane were at a similar temperature – a crucial requirement for cold-junction compensation. Scale drawings of the individual PCB CAD layers can be found in Appendix G

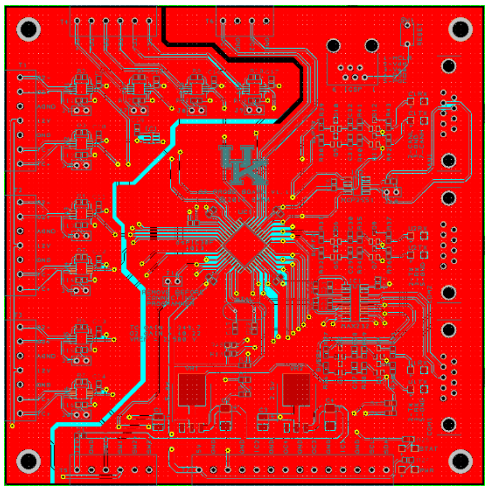

Figure 3-5: PCB CAD Drawing (Scale 1:2)

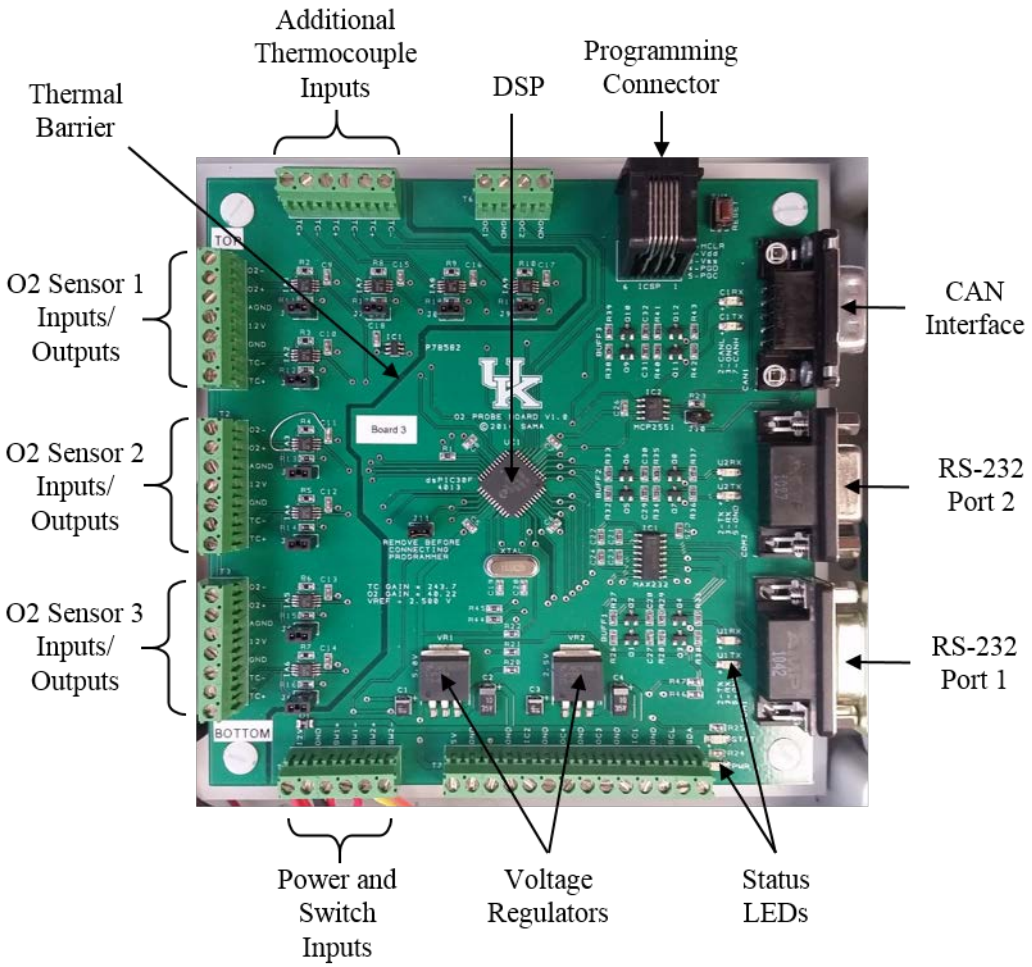

Figure 3-6: PCB Populated with Components

The PCB was enclosed in an IP-66 rated polystyrene electronics enclosure (Model TK PS 2518-6f-to, Altech Corp., Chūō, TR) with a clear polycarbonate lid (Figure 3-7). Eight AA-size batteries supplied a nominal 12 V to the PCB which was regulated to 5.0 V for the DSP and supporting components. A power switch was used to selectively connect the batteries to the PCB and a data logging switch was used to indicate whether or not data should be recorded by the PC. Cable glands provided access for probe wiring into the enclosure and were tightened to create a water resistant seal after a probe was connected.

A 2.4 GHz Zigbee radio with an RS-232 interface (Model XA-Z14-CS2PH-A, Digi International Inc., Minnetonka, MN) was mounted underneath the PCB and connected to an external antenna using RG-58 coaxial cable with reverse polarity SMA connectors. A

similar Zigbee radio with a universal serial bus (USB) interface was connected to a PC for data acquisition. The Zigbee radios from all three probes were configured to operate in a mesh network. The mesh network allowed data messages to hop from one node to the next in the event that one or more of the probes could not establish direct communication with the PC.

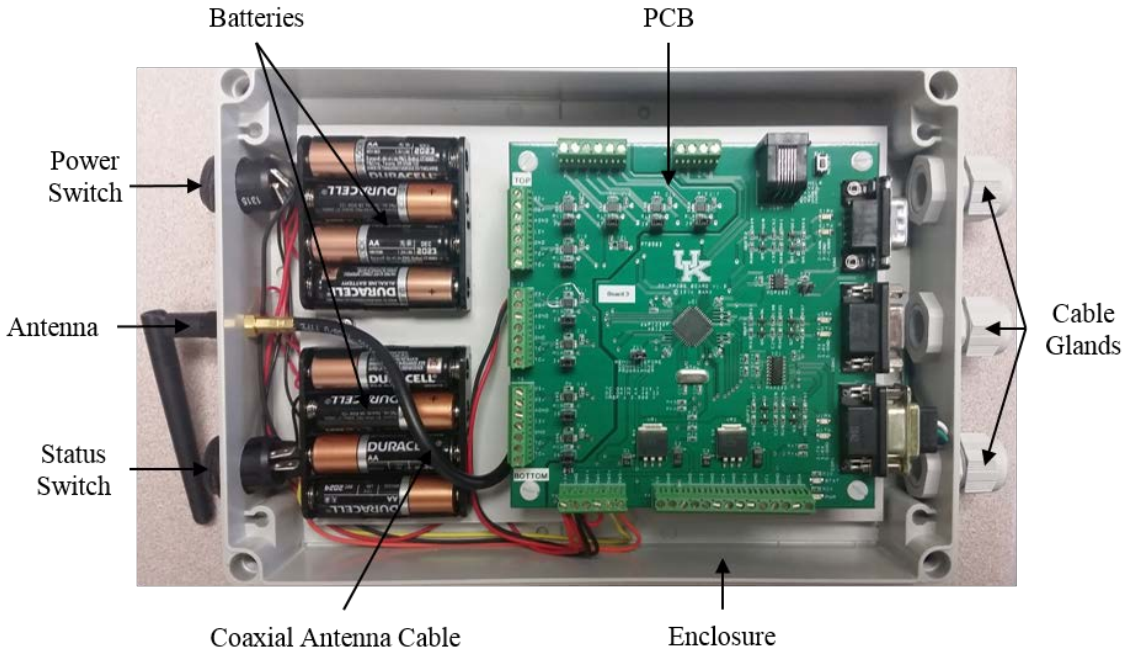

Figure 3-7: Electronics Enclosure (lid and radio not shown)

A C-language program was written for the DSP using the MPLAB IDE (v8.46, Microchip Technology Company, Chandler, AZ) and compiled using the C-30 compiler (v3.26, Microchip). The program configured an internal timer to sample the voltages associated with each O2 sensor along with the cold-junction temperature sensor, battery voltage, and 2.5 V reference signal at an 1 Hz interval. Each 12-bit analog-to-digital (A/D) measurement was oversampled 32 times and averaged before being assembled into a serial data string. The serial data string was comprised of a starting character, an identifier, data elements, a checksum, and terminating characters. Data elements were comma-delimited to facilitate processing and recording with a PC. A complete version of the program is included in Appendix G

The Zigbee radio receiver was used to transmit the serial string from the radios to the computer via USB port. A program (See Appendix G), written in Microsoft Visual Studio (2012), was used to log and display the data. The information included voltage from the oxygen sensors, voltage from the thermocouples, voltage from the cold junction, the battery voltage, and character to indicate if the logging button was pressed and an identifier for each data collection box. The program parsed the data from the string and used the following set of equations to calculate the corresponding values:

$$O2\ (V) = \ (\frac{D_{in} * 5}{4095} - 2.5)/40.22 \qquad \text{Equation 3-2}$$

$$CJ\ (C) = \left(\frac{D_{in} * 5}{4095}\right) * 100 - 75 \qquad \text{Equation 3-3}$$

$$TC\ (C) = \ \left(\frac{D_{in} * 5}{4095} - 2.5\right) * 100 + CJ \qquad \text{Equation 3-4}$$

$$B\ (V) = \ \left(\frac{D_{in}*5}{4095}\right)/0.099 + 0.291 \qquad \text{Equation 3-5}$$

Where:

D_{in} = Digital value

O2 = Voltage output from sensor

CJ = Cold junction temperature

TC = Thermocouple temperature

B = Battery Voltage

The program displayed the values in a Graphical User Interface (GUI) (Figure 3-8). The GUI also allowed for the user to specify the file name and location for the data to be saved. The files were created when the user clicked the "Enable Logging" button. However, logging was not started until the switch on the data collection box was pressed. When the logging started, a counter displayed the elapsed logging time on the screen for the user.

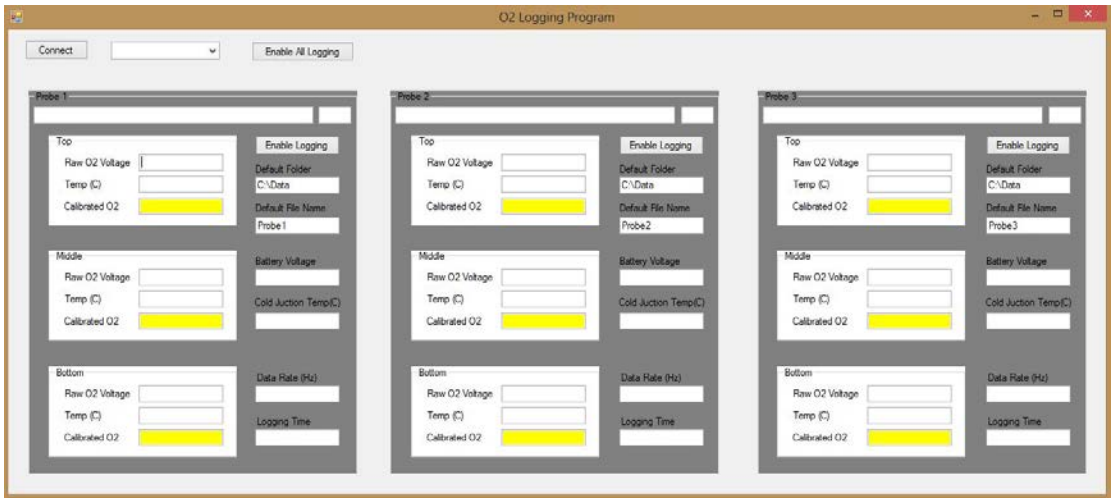

Figure 3-8: O2 Logging Program Graphical User Interface

3.3 Results and Discussion

3.3.1 Probe Design

Initial testing showed that a small amount of material removal was required for probe placement. Later testing found that a drill mounted auger could be used to create a pilot hole to aid in probe placement. Initial field testing also showed that diffusion times with the original probe design were undesirably long and variable. In an effort to decrease diffusion times the diffusion heads were redesigned to create a permeable barrier with the largest free space area possible without allowing material to enter the diffusion head. The redesign nearly doubled the open area of the permeable barrier from 2.7 cm^2 to 5.1 cm^2.

The final probe design can be seen in Figure 3-9. The design featured a 60 degree tip to aid in placement, the redesigned diffusion heads, and three Apogee oxygen sensors. Initial testing showed that there was almost no difference in the oxygen levels at 33 and 44 cm deep. That result, combined with the sensor cost ($256 per sensor), led to the decision to only use three sensors per probe as opposed to four. Less sensors per probe financially allowed for three probes to be manufactured and ability to take more replications.

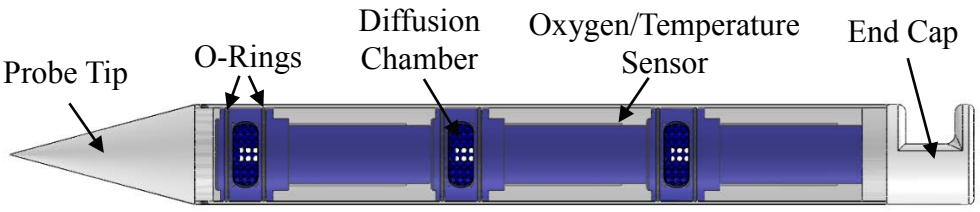

Figure 3-9: Final Probe Design

3.3.2 Data Collection Development

Two replications of the amplifier/cold-junction compensation circuit were assembled and tested with type K thermocouples. The warm-junctions of the thermocouples were placed in a temperature controlled water bath at values between 10 and 70°C in 5°C increments. Table 3-2 shows the averages of the amplifier output voltages, cold-junction temperature sensor voltages, and the compensated output voltages from 10 samples at each temperature setting. The maximum standard deviation in compensated output voltage for all temperatures was 0.43 mV. Therefore, standard deviation is not shown.

Table 3-2: Thermocouple Amplifier and Cold-Junction Compensation Test Circuit Results

Water Bath Temperature (°C)	Amplifier 1 (V)	Cold-Junction 1 (V)	Amplifier 2 (V)	Cold-Junction 2 (V)	Compensated Output 1 (V)	Compensated Output 2 (V)
10	0.821	1.03	0.820	1.02	0.204	0.195
15	0.762	1.01	0.761	1.00	0.248	0.241
20	0.744	1.05	0.740	1.04	0.306	0.298
25	0.665	1.01	0.664	1.00	0.345	0.339
30	0.616	1.01	0.613	1.00	0.398	0.391
35	0.563	1.01	0.560	1.00	0.444	0.438
40	0.514	1.01	0.511	1.00	0.495	0.488
45	0.461	1.00	0.459	1.00	0.543	0.538
50	0.413	1.01	0.411	1.00	0.594	0.588
55	0.367	1.01	0.364	1.00	0.645	0.641
60	0.318	1.02	0.314	1.01	0.698	0.693
65	0.262	1.01	0.260	1.00	0.746	0.742
70	0.213	1.01	0.209	1.00	0.796	0.791

The compensated output voltages were plotted as a function of the water bath temperature (Figure 3-10). A linear regression demonstrated that the relationship between the warm-junction temperature of the thermocouple and the compensated output voltage of the circuit was 10 mV/°C, as designed. The voltage offset varied slightly between each circuit, 102 mV at 0°C for circuit 1 versus 93 mV at 0°C for circuit 2, but this offset can be easily accounted for in the thermocouple calibration process. The R^2 value for both circuits was 1.000 which indicated that the output voltage from each circuit was linear with respect to temperature.

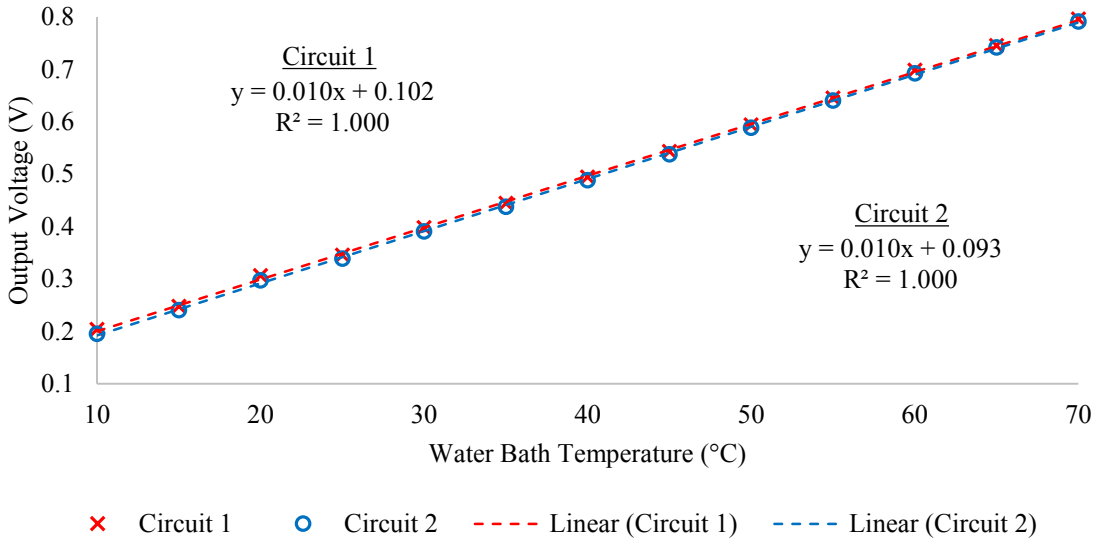

Figure 3-10: Circuit Output Voltage vs. Water Bath Temperature

3.4 Conclusions

A probe was designed to incorporate multiple Apogee oxygen sensors in a vertical alignment. It was determined that pilot holes were necessary to aid in probe placement. Initial field tests showed the sensors appeared to produce actual oxygen readings, i.e. the sensors placed deeper the compost reported less oxygen. However, the time it took to reach these readings was unacceptably long and variable. The diffusion heads were redesigned in an effort to decrease the sampling times, but it was determined that a controlled laboratory test was required to quantify the sampling times for different bed conditions.

Custom instrumentation electronics were designed using a PCB to interface multiple probes to a single PC using a Zigbee mesh network. The electronics amplified, sampled, and filtered sensor voltages and provided an output data rate of 1 Hz. The amplifier and

cold-junction compensation circuit used in the PCB was tested using a controlled water bath. The results showed that the circuit output could produce both an accurate and a precise measure of temperature.

CHAPTER 4: DIFFUSION TIME TEST

4.1 Introduction

A substantial challenge with measuring oxygen concentrations in compost was differentiating the sensor response from the natural consumption of oxygen in the compost. The diffusion heads required by the sensors in the probe made this differentiation even more difficult because of the added time required for the air in the diffusion head to come to equilibrium with the air in the compost. Initial testing (discussed in chapter 3) showed large amounts of variation in the diffusion times. The diffusion times changed depending on the moisture and compaction of the compost. The diffusion heads were redesigned with larger openings for the air to diffuse through in effort to decrease diffusion times. It was also hypothesized that pulling a vacuum on the diffusion heads, upon initial exposure to the compost, could decrease diffusion times.

The objective was to create a method for testing sampling issues that may have led to long diffusion times observed during the initial field testing of the oxygen probe.

4.2 Materials and Methods

Given the variability of the conditions found in the CBP, it was determined the tests should be conducted in the laboratory to control as many of these variables as possible. Testing in a laboratory environment offered the ability to control the moisture content of the compost, the oxygen concentration, and test a hypothesis that drawing a vacuum would decrease diffusion times.

4.2.1 Test Chamber

A test chamber (Figure 4-1) was designed that allowed for sampling times (diffusion time + sensor response time) to be measured in conditions that were similar to what was observed in the field. The test chamber consisted of a 30.5 cm (12”) section of 15.2 cm (6”) diameter PVC pipe that was used as the main chamber. One end of the chamber was sealed with standard PVC cap. The other end was sealed with a clean-out cap that featured a removable plug, which allowed for the loading and unloading of compost. A piece of the 5.1 cm aluminum tube used in the probe was glued in the center of the chamber, and featured the same diffusion slots as the probe. The slots were aligned in the center of the

chamber. A modified diffusion head (Figure 4-2) was fabricated that had an extended solid outer wall, and an orifice in the bottom of the diffusion head. The extended wall was aligned with the slots while the chamber was being filled with gas, sealing the chamber and allowing the diffusion head to remain at ambient oxygen levels. The orifice allowed for a vacuum to be drawn on the diffusion head using an external syringe.

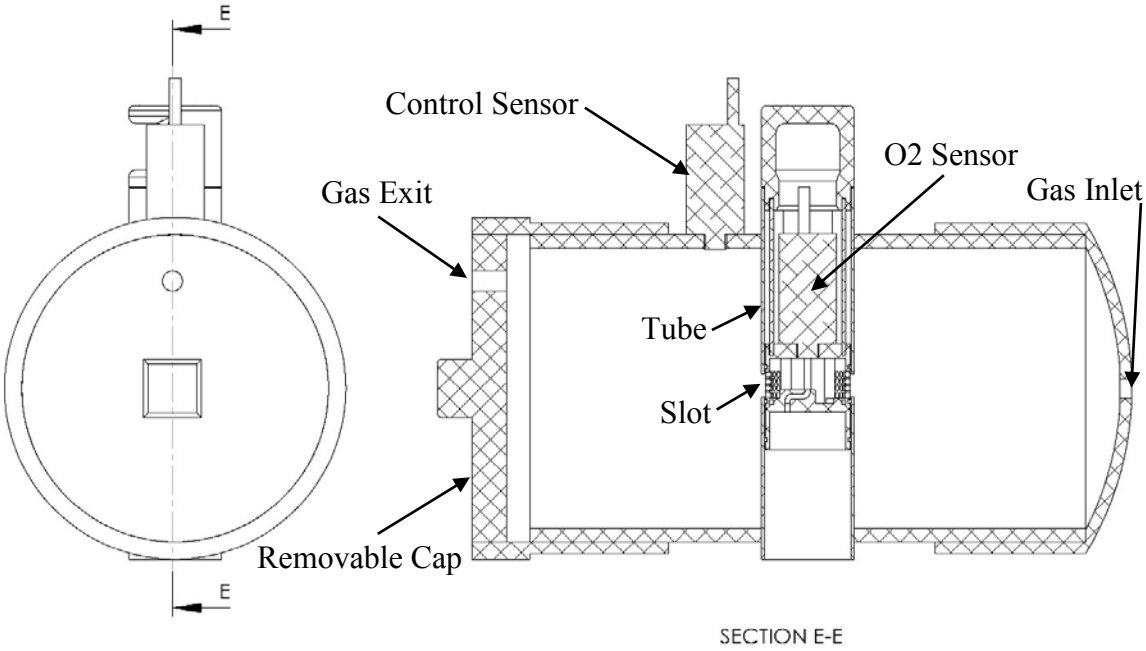

Figure 4-1. CAD Model of Testing Chamber

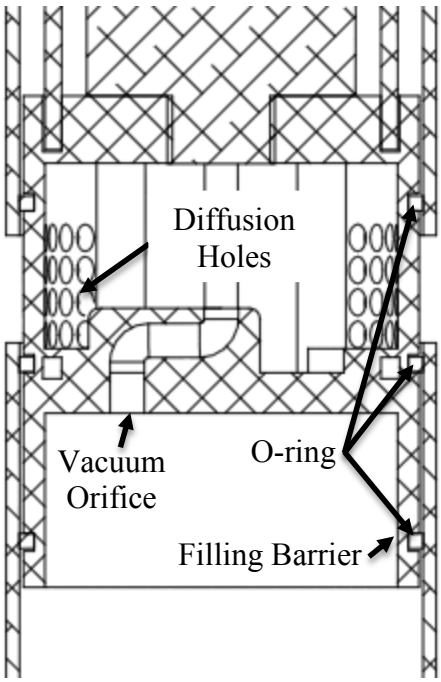

Figure 4-2: Modified Diffusion Head

4.2.2 Test Procedure

Compost was gathered from a local dairy and dried according to ASAE Standard 358.3 (ANSI/ASAE 2012). Three moisture contents (40, 55, and 70%) were prepared by dividing the compost into samples and adding water to achieve the desired moisture contents according to Equation 4-1.

$$MC = \frac{M_{wet} - M_{dry}}{M_{wet}} \, x \, 100 \qquad \text{Equation 4-1}$$

Where:

MC = Percent moisture content

M_{wet} = Mass of wet material

M_{dry} = Mass of dry material

The compost was placed in a refrigerator for 24 hours to allow compost to reabsorb the water. After the rewetted compost reached equilibrium, the prepared compost was placed in the chamber though the removable cap. The sampling times were tested at two levels of compaction in attempt to replicate CBP barn conditions before and after tillage. The after-

tillage condition was replicated by simply filling the chamber with loose compost. The before condition was replicated by packing the compost in the chamber by hand. Table 4-1 shows both the density and the bulk density for each of the configurations tested.

Table 4-1: Densities

Moisture	Compaction Level	Bulk Density (g/cm^3)	Density (g/cm^3)
40%	fluffy	0.240	0.400
	compact	0.356	0.593
55%	fluffy	0.224	0.498
	compact	0.339	0.754
70%	fluffy	0.195	0.650
	compact	0.369	1.231

The modified diffusion head was moved into place after the compost was loaded in the chamber. The filling barrier was aligned over the slot so that the gas filling the chamber were sealed from the ambient air in the diffusion head. A valve at the gas exit was left open while the calibration gas at 0% O_2 was pumped though the chamber until the control sensor readings were stable. In an ideal situation, the gas would have been pumped in until the control sensor read zero but, owing to error in the calibration, and a small variability in the sensor reading, a zero reading was not feasible. Once the control sensor readings were stable, the gas flow was stopped and the valve was closed, thus sealing the chamber. The reading sensor was then introduced into the chamber by pushing the diffusion head down until the diffusion holes aligned with the slot in the tube. The output from each sensor was recorded until the reading sensor was at steady-state. The time from introduction to the chamber to steady-state was recorded as the desired sampling time in the field. Three replications were completed for each combination of moisture content, compaction level, and vacuum application.

4.2.3 Data analysis

The data were logged using a Measurement Computing USB-2416 DAQ board, and saved into a CSV text file using a program written in Microsoft Visual Studio (Microsoft Visual Studio 2012, Microsoft Corporation, Redmond, WA). The statistical analysis was performed using the GLM procedure in the statistical software package SAS (SAS Institute

Inc., Cary, NC). The effect of moisture, compaction, and pulling a vacuum on the sampling times were tested for significance ($\alpha = 0.05$). The LSMEANS function of SAS was used to find the significance between individual levels of factors.

4.3 Results and Discussion

The results of the test (Table 4-2) show that there was a significant difference between the sampling times at 70% MC and 55%. There was also a significant difference between the 70% and 40%, but no difference between the sampling times at 55% and 40% MC.

Table 4-2: SAS Output

Comparisons significant at the 0.05 level are indicated by ***.				
moisture Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
70 - 40	1242.80	1062.43	1423.17	***
70 - 55	1271.71	1091.34	1452.08	***
40 - 70	-1242.80	-1423.17	-1062.43	***
40 - 55	28.92	-147.49	205.32	
55 - 70	-1271.71	-1452.08	-1091.34	***
55 - 40	-28.92	-205.32	147.49	

The results (Table B-1) also showed that, at 70% MC, there was a significant difference ($p=0.0017$) between the sampling times when a vacuum was pulled on the system. However, there was not a significant diffecnce at 40 or 55% MC when vacuum was pulled. Since pulling a vacuum only had an effect on one of the three MC tested, it was decided that adding a vacuum system to the probes did not warrant the logistical challenges that would occur with field implementation. The data were reanalyzed without the vacuum trials to determine the sampling times. The results of the updated model can be seen in Table B-2 of the appendix. The least squared means (Table 4-3) show that the only set of data that is significantly different ($p=.0001$) was the 70% MC compacted.

Table 4-3: LMS of Sampling Time (s)

moisture	compaction	time LSMEAN	LSMEAN Number
40	Compact	770.00000	1
40	Fluffy	978.33333	2
55	Compact	859.66667	3
55	Fluffy	756.66667	4
70	Compact	3674.00000	5
70	Fluffy	896.00000	6

Least Squares Means for effect moisture*compaction
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: time

i/j	1	2	3	4	5	6
1		0.2609	0.9109	1.0000	<.0001	0.7276
2	0.2609		0.7711	0.2106	<.0001	0.9355
3	0.9109	0.7711		0.8543	<.0001	0.9983
4	1.0000	0.2106	0.8543		<.0001	0.6442
5	<.0001	<.0001	<.0001	<.0001		<.0001
6	0.7276	0.9355	0.9983	0.6442	<.0001	

The sampling times were established by adding two times the standard deviation to the means in order to create a 95% confidence interval. The sampling time for 70% MC compacted was found to be 65 minutes. The sampling time for all other tested conditions was found to be 18 minutes. Based on the initial field test conducted (discussed in chapter 3), the new diffusion head design provided greatly improved sampling times over what was observed in the initial field test (between 40 and 80 minutes). The variability was also greatly reduced. The standard deviation for the initial data were over 19 min compared to 2 min for similar conditions (loose compaction @ ~70% MC).

4.4 Conclusions

A method for determining the sampling time for various compost conditions was devised. Three different moisture contents, two levels of compaction, and two levels of applied vacuum were tested for their effect on the sampling time. The results of the ANOVA indicated that the vacuum only had a significant effect on one moisture content. It was decided that the benefits of pulling a vacuum did not justify modifying the probe.

The data were processed without the vacuum data and it was found that two sampling times where required based on compost conditions, if the compost was ~70% MC and compacted, 65 minutes were required to be 95% confidant that the air was completely diffused. Between 40 and 55% MC at any compaction, and 70% MC at loose compaction, 18 minutes were required to be 95% confidant that the air was completely diffused.

CHAPTER 5: AIR INJECTION DEVOLOPMENT

5.1 Introduction

Compost bedded pack (CBP) barns, like other types of dairy housing, require proper management techniques to ensure that they are working to their full potential; however, proper management techniques are not always easy to establish in new systems. One of the biggest management challenges in CPP barns is aeration. Traditional large scale composting systems place the material in large rows that can be aerated by use of a mechanical turning device (Figure 5-1). In CBP barns, composting takes place in a pack that is simultaneously used as bedding for the animals. The physical constraints of the pack and the covering structure (barn) do not generally allow for conventional aeration tools to be used.

Figure 5-1: Mechanical Windrow Compost Turning Device

Forced aeration is another method that is commonly used in composting operations. In forced aeration operations, the compost is placed over either a slatted floor or perforated tube. A fan or pump is used to either push or pull air though the compost. In the Netherlands, these forced aeration systems are being implemented in CBP barns (Galama 2011). The biggest concern with forced aeration systems is the initial cost and that daily incorporation of fresh manure and urine is still required. A system that could combine daily incorporation and mechanical aeration with forced aeration could help better maintain oxygen levels in CBP barns.

The hybrid tillage tool that was designed (discussed in chapter 1) as a senior design project at the University of Kentucky was used as the platform for the forced air injection system. The mobile vehicle platform required the fan to be either be powered electrically (12 V from the tractor) or hydraulically. A custom-made, hydraulically driven fan was available, however, the fan performance curve was unknown.

Two things were needed to in order to determine if the aeration system would be effective: the fan performance curve and the compost air flow resistance. The goal of this experiment was to create a fan curve that would be used in conjunction with an air flow resistance curve for the compost to approximate the volumetric flow of air that could be added to the compost bedded pack.

5.2 Materials and Methods

The required volumetric air flow per shank was calculated to be 0.00775 m^3/s and was based on the volume of compost disturbed, the velocity of the tractor and the porosity of the compost. Based on field tests with the original hybrid aeration tool, the tractor's velocity while pulling the implement was ~ 0.45 m/s. The volume disturbed was calculated from the width of the shank foot (7.6 cm), the depth the compost was disturbed (45.7 cm), and the distance the tractor traveled in one second (45 cm). The porosity of the compost was assumed to be 50%, based on work by Damasceno (2012).

5.2.1 Fan Performance Curve

The Air Movement and Control Association (AMCA) standard 210:99 (AMCA 1999) was used as the basis for generating the fan performance curve. The Outlet Duct Setup was chosen because it fit the fan installation type of free inlet, ducted outlet. The setup was replicated in the laboratory using 5 cm (2") PVC pipe for the duct with a ball valve as the throttling device. A 10 cm to 5 cm (4" to 2") reducer was used to transition from the fan outlet to the duct. The duct was 102 cm (40") in length and had a Pitot tube placed 15 cm (6") from the valve. Thermocouples (t_{d2}, t_{d3}) were not used but the ambient temperature was maintained at 21° C during testing.

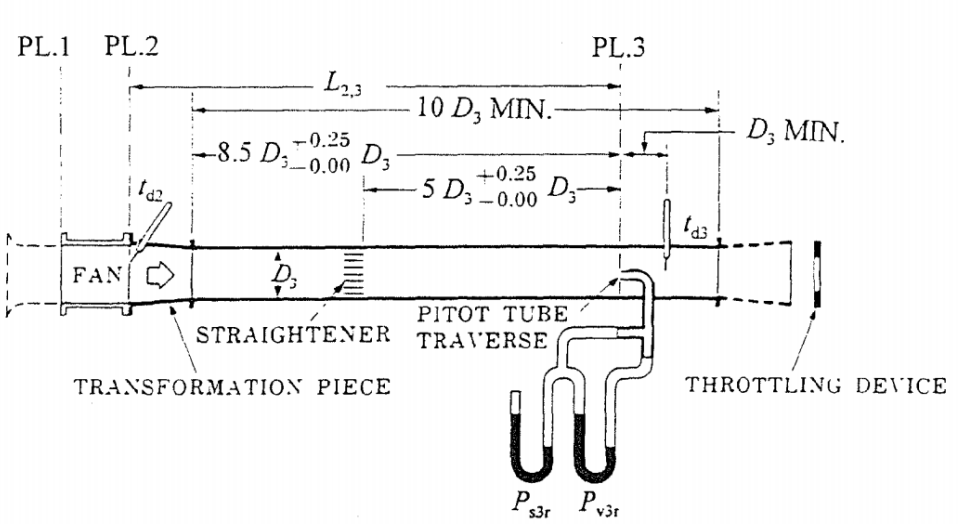

Figure 5-2: Outlet Duct Setup

The hydraulically powered fan was tested at 38 l/min, which was the rated hydraulic flow for the tractor used in the field testing (Massy Ferguson 271xe). The Pitot tube was used to measure the air velocity while a separate manometer was used to measure the static pressure. Air velocities and static pressures were recorded at 10 valve positions between fully open and fully closed.

5.2.2 System Air Resistance

The system air resistance was found by measuring the pressure drop though the compost as well as the piping required to channel the air from the fan to the compost. The aeration system was set up as close as possible to the setup that would be used in the field. Figure 5-3 shows the fan pumping the air into a 10 cm PVC plenum. In field use, the plenum channels the air into three pipes that channel the air to the compost. For the laboratory test, two holes were plugged forcing the entire airflow into one pipe. The pipe and flexible hose were the same length and diameter that were used on the tillage tool.

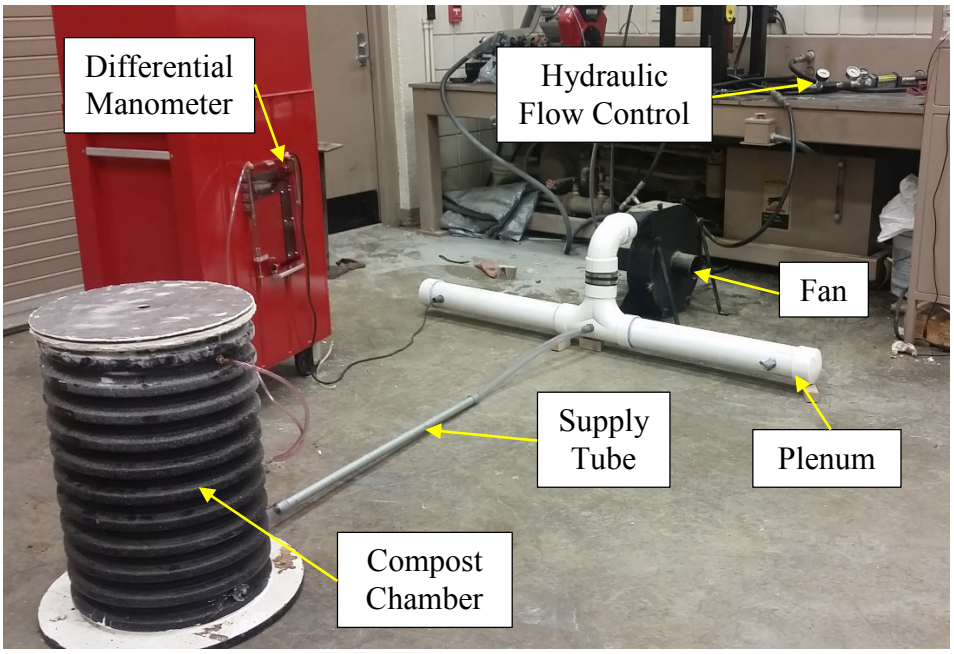

Figure 5-3: System Setup

The air coming out of the pipe entered the plenum at the bottom of the compost chamber (Figure 5-4). A mesh floor kept material from falling into the plenum, but allowed air to freely pass into the material. The compost chamber was filled to a depth of 46 cm with uncompact compost to simulate the desired field aeration depth, post-tillage. The compost was taken from a local dairy and was 65% MC when testing occurred. The air traveled from the plenum though the compost and out through a 2.86 cm orifice centered in the top cover.

A Kestrel 4600 (Nielsen-Kellerman Co., Birmingham, MI) anemometer measured the air velocity exiting the orifice. One Dwyer manometer measured the static pressure in the 10 cm plenum while another measured the static pressure in the top of the compost chamber. The difference in the two pressures was the total system air resistance. The pressure drop across the system was recorded at varying volumetric flows to produce a resistance curve.

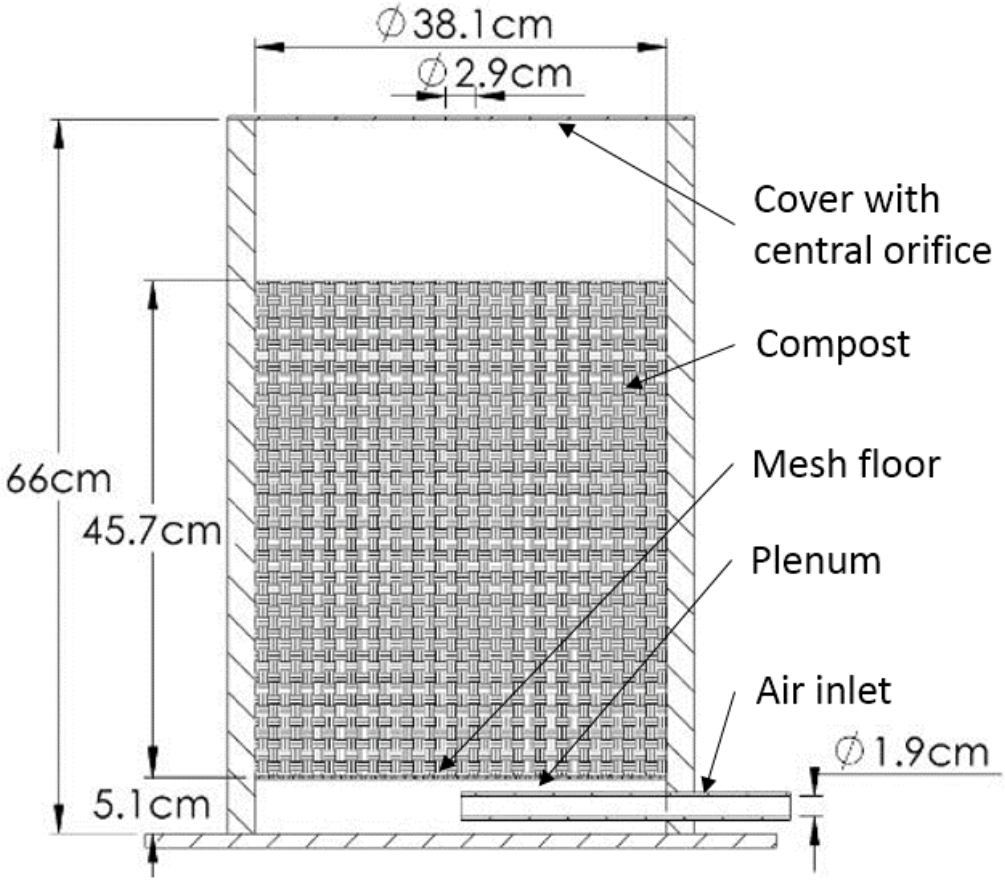

Figure 5-4: Compost Chamber

5.3 Results and Discussion

The results of the both the Fan Performance Curve testing and the System Air Resistance test are presented in (Figure 5-5). The data used to generate the graph are included in Appendix D. The graph shows the intersection of the system resistance curve and the fan curve. This intersection indicates how much volumetric flow the fan can produce though the system when operating at 38 l/min of hydraulic flow, i.e. how much air the tool can inject behind a single shank.

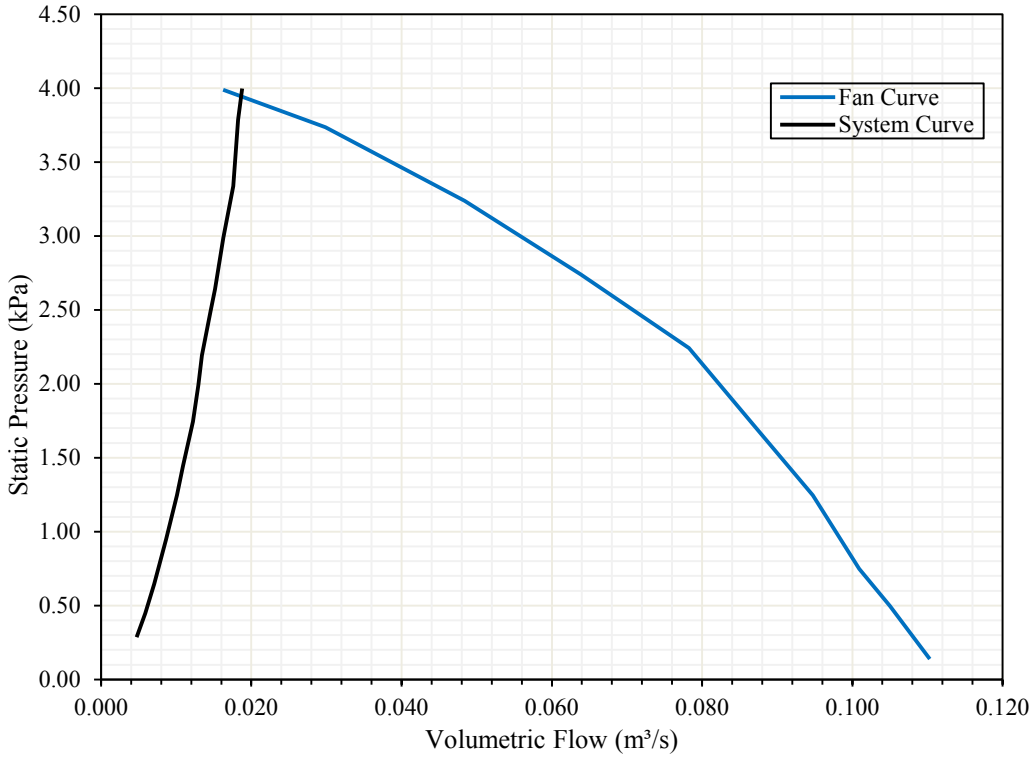

Figure 5-5: Performance Curve

The process for calculating the volumetric flow for multiple shanks (systems) using the single fan is additive. Estimating the volumetric flow per shank when multiple shanks are used is achieved by first finding the static pressure at the intersection of the fan curve and the multiple shank curve. Then the corresponding volumetric flow for the static pressure is found on the single shank performance curve (Brooker et al. 1992). Figure 5-6 shows that using 3 shanks in the system caused the single shank volumetric flow to decrease from ~.0185 m³/s to ~.0170 m³/s.

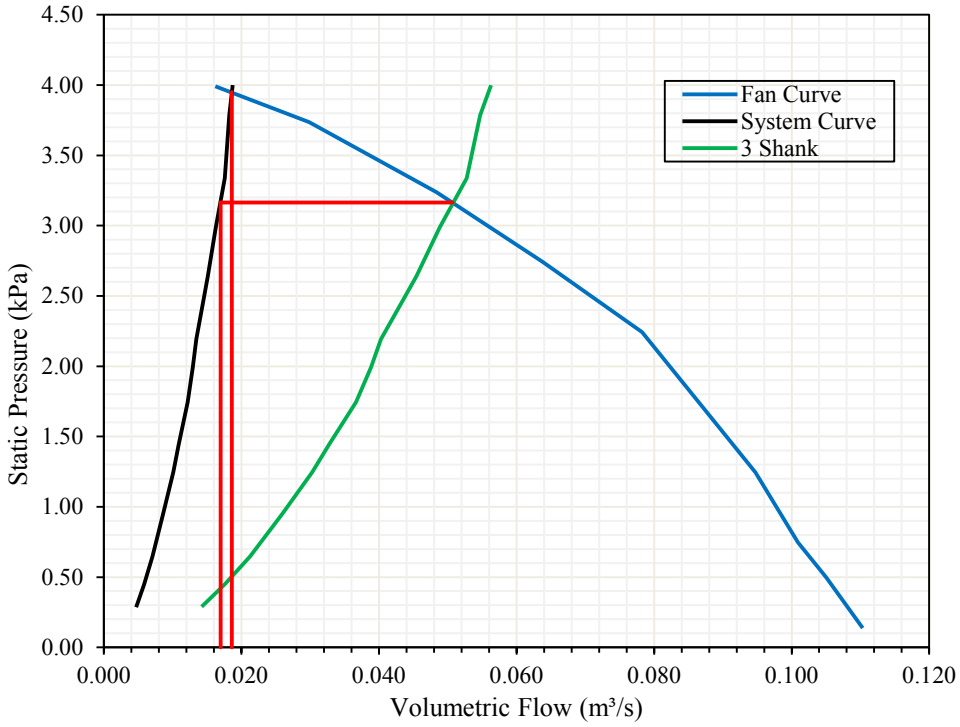

Figure 5-6: Volumetric Flow Estimation

Figure 5-7 shows the forced aeration system as it was implemented in the field.

Figure 5-7: Hybrid Tillage Tool with Forced Aeration

5.4 Conclusions

An aeration attachment for the hybrid tillage tool was designed. A hydraulic fan was used to force air in to the compost as the tool incorporated the waste and loosened the compost. Two tests were performed to determine if the air flow provided by the fan was sufficient to aerate the area disturbed by the hybrid tool. The first test was required to generate a performance curve for the custom made fan. The second test was required to find the system resistance curve. The tests showed that, at an operating speed of ~.45 m/s at a depth of 45.6 cm in 65% MC compost, the system should provide 0.017 m^3/s which is more than the 0.00775 m^3/s required. It should be noted that both the calculated and required air flows were based on a specific set of conditions that were seen in the field, and, if any of those conditions change, then these numbers would no longer be valid.

CHAPTER 6: AERATION COMPARISON

6.1 Introduction

The goal of this experiment was to determine if there were significant differences in the amount oxygen introduced into the CBP between the rototiller, the hybrid tillage/aeration tool, and the hybrid tillage/aeration tool with added aeration injection (discussed in Chapter 5). The hybrid tillage tool consisted of the rototiller combined with deep tillage, while the hybrid tillage tool with air injection added a fan to force air into the compost.

6.2 Materials and Methods

6.2.1 CBP Conditions

All experiments were conducted at Harvest Home Dairy in Crestwood, Kentucky. In order to ensure stable composting conditions, testing was not started until four weeks after the barn was cleaned out (Bewley et al. 2013). Experiments began on November 26, 2014 and were concluded on January 15, 2015. The moisture of the compost was recorded daily before each replication.

6.2.2 Experimental Design

A randomized complete block design was used to compare the effects of the three tillage/aeration methods. The design was necessary because of the high possibility of spatial variability in the barn. The barn was sectioned into three blocks shown in Figure 6-1. The blocks were chosen based on past temperature readings, taken by the producer, which suggested that these areas had the most consistent composting in the barn. Each block was sectioned into three treatment areas. Owing to time constraints, only one tillage/ aeration treatment was tested each day. The order of treatment testing (Table 6-1) was randomized by block and by treatment area within the block.

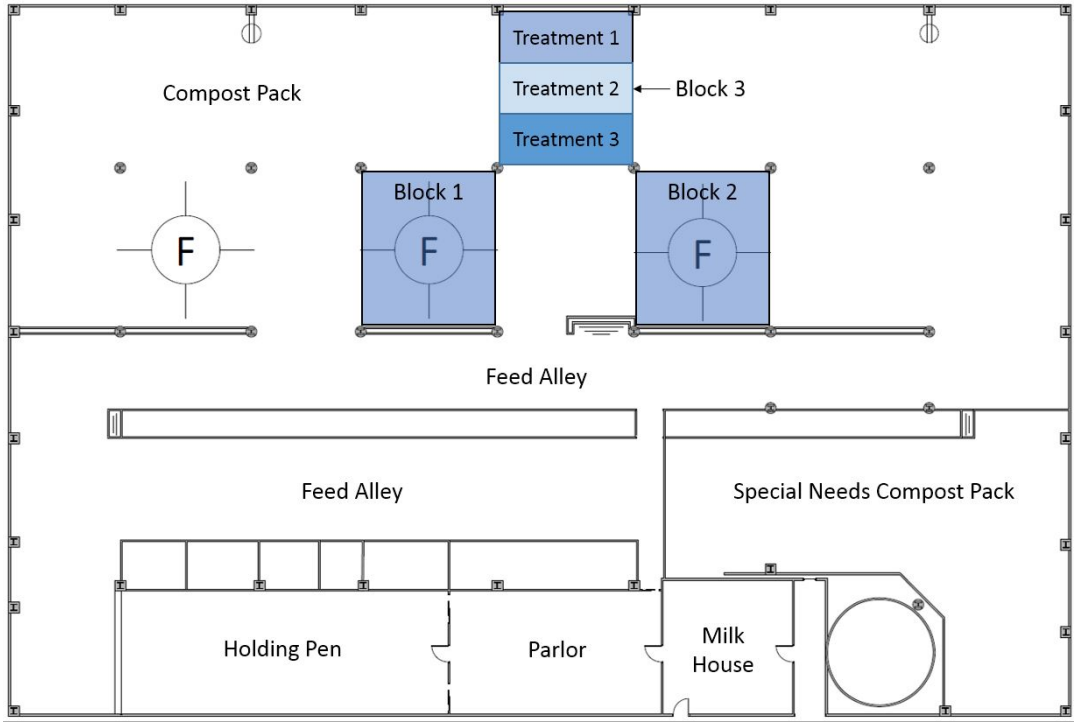

Figure 6-1: Compost Bedded Pack Barn

Table 6-1: Treatment Order

Date	Block	Treatment Zone	Tillage/Aeration Treatment
12/03/2014	2	1	Rototiller & Deep Tillage w/ Air Injection
12/04/2014	2	3	Rototiller
12/05/2014	2	2	Rototiller & Deep Tillage
12/08/2014	1	1	Rototiller & Deep Tillage
12/10/2014	1	3	Rototiller
12/11/2014	1	2	Rototiller & Deep Tillage w/ Air Injection
01/12/2015	3	2	Rototiller & Deep Tillage w/ Air Injection
01/13/2015	3	3	Rototiller
01/14/2015	3	1	Rototiller & Deep Tillage

6.2.3 Test Procedure

Custom probes each containing three Apogee Instruments SO-120 oxygen sensors at depths of 11, 22 and 33 cm, were used to measure the oxygen levels in the CBP. A week

before testing, all sensors were recalibrated to account for any drift that may have occurred. Table A-1 in the Appendix shows the calibration coefficients for Equation 2-1 corresponding to each sensor.

Approximately one hour before milking, the cows were removed from the block that was to be sampled. Three pilot holes were excavated in the randomly selected treatment area using a drill mounted auger. The holes allowed for placement of the probes in the compacted pre-tillage compost. The pilot holes were made slightly larger than the diameter of the probe (5 cm) to prevent compaction of the side walls during probe placement. The holes were evenly spaced along the center of the treatment zone (Figure 6-2). The position of the holes were referenced off the barn poles, allowing for repositioning after tillage. Moisture samples were collected from the material removed from the holes at the approximate depth that each sensor would be located (three samples per hole).

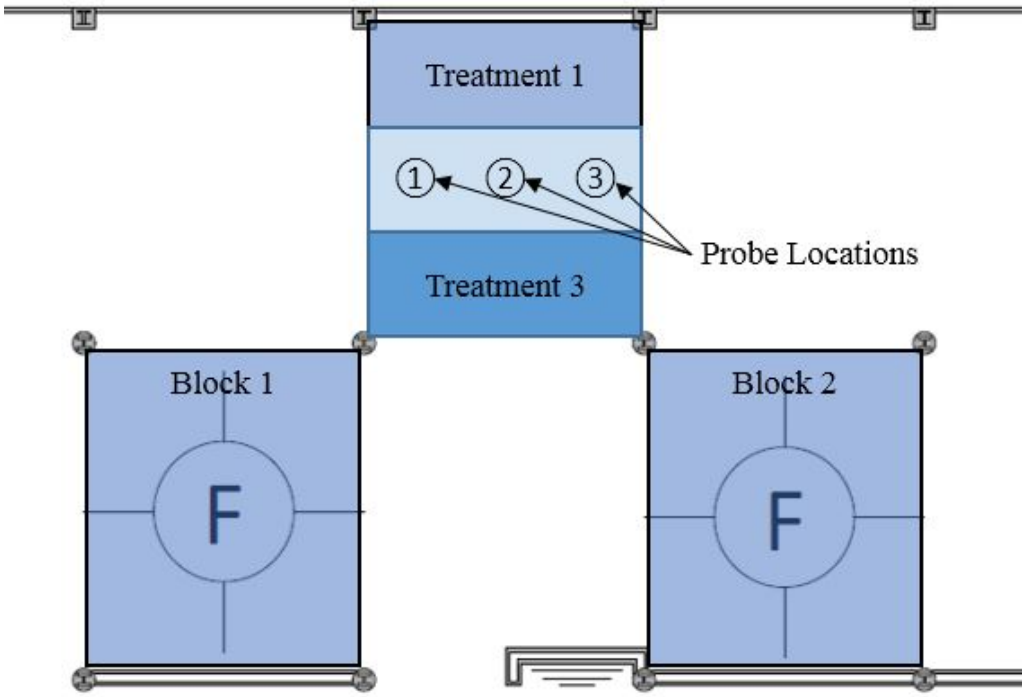

Figure 6-2: Probe Placement for Block 3 Treatment 2

The probes were placed into the holes and the surrounding compost was packed in around the probes to form a loose seal between the compost and outer probe wall. The inner carriage of the probe was turned to expose the porous section of the diffusion chamber to the compost. The logging switch on the data collection box was enabled and measurements from the sensors were collected. Based on the diffusion head testing performed in Chapter 4, and the bed conditions observed during testing, (~70% moisture content and high compaction), the sensors were left in the compost for 65 minutes to achieve full diffusion.

The probes were removed from the compost after the sampling time. Subsequently, the randomly selected tillage/aeration method was performed. The center of the tillage/aeration tool was aligned with the holes during operation. This ensured that, in the case of the rototiller & deep tillage and the rototiller & deep tillage w/ air injection, the probes would be placed in the area disturbed by the deep tillage.

Once the tillage/aeration was complete, the pilot holes were re-drilled using the auger, and the probes were reinserted. According to the diffusion head testing results, the compost, now at a lower bulk density, should have taken 21 minutes to reach full diffusion. However, initial test showed that oxygen levels were still decreasing at that time (Figure 6-3), for 8 out the 9 sensors tested. Since the 21 minute sampling time was not sufficient the decision was made to use the 65 minutes sampling time for both the pre- and post-treatment.

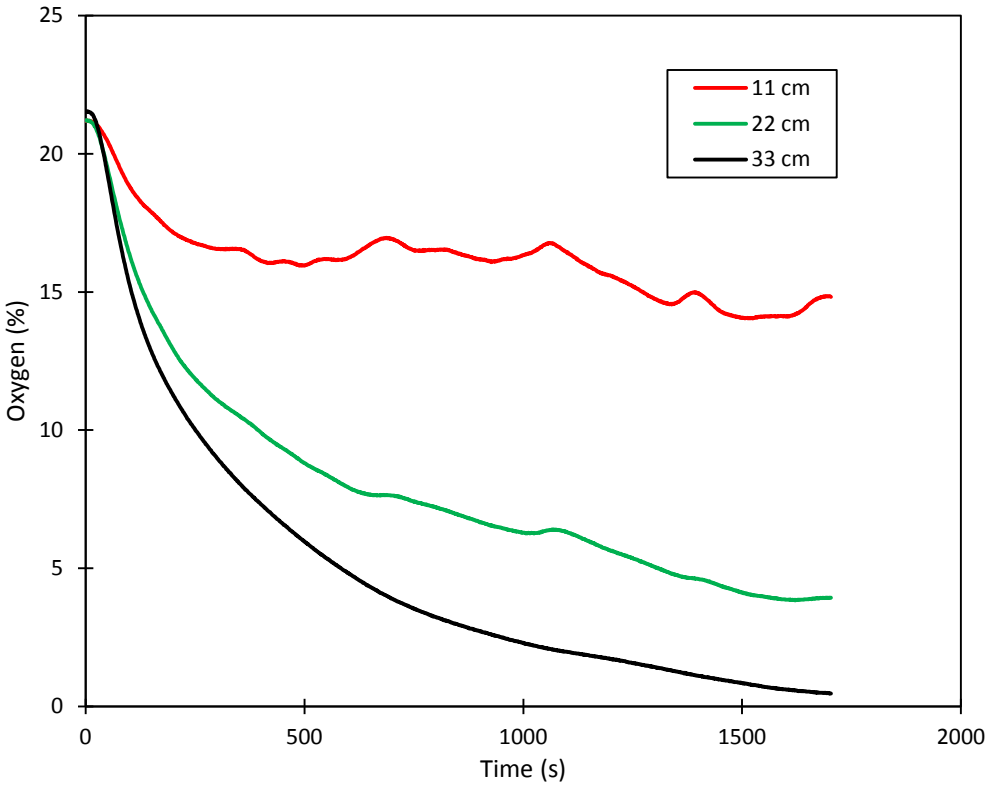

Figure 6-3: Probe 1 Post Tillage Diffusion Profile during the First 21 Minutes

6.2.4 Data Collection

All data were collected and organized using a combination of Microsoft Excel (Microsoft Excel 2010, Microsoft Corporation, Redmond, WA) and MATLAB (MATLAB2013a, The MathWorks Inc. Natick, MA). The data were recorded on a 1 Hz sampling interval, and stored in individual CSV files for each probe using a program written in Microsoft Visual Studio (Microsoft Visual Studio 2012, Microsoft Corporation, Redmond, WA). The data included the system time and date (from the computer), the raw voltage from each of the three sensors, the temperatures from each of the sensors, and the calibrated oxygen concentration from each sensor.

6.2.5 Data Analysis

The statistical analysis was performed using the GLM procedure available within SAS (SAS 9.3, SAS Institute Inc. Cary, NC) and the *ttest()* function available in MATLAB. A t-test was conducted on the last sixty seconds of the before and after treatment to determine if the means of the oxygen levels were significantly different (α=0.05). If the

results of the t-test were not significantly different, then the ΔO2 value, defined as the post-treatment %O2 minus the pre-treatment %O2 was recorded as zero. If the results were significant, the individual prediction interval for each sensor (α=0.05) was applied to the means. If there was an overlap in the prediction intervals (i.e. the sensors were not precise enough to measure the difference), then the ΔO2 value was set to zero. If no overlap occurred then the ΔO2 value was calculated as the difference between the means.

The PROC GLM function of SAS was used to perform an analysis of variance on the resulting data (α=0.05). In cases where a significant interaction was found between variables, the main effects were examined using the Tukey's HSD test.

6.3 Results and Discussion

6.3.1 Aeration Comparison

The moisture of the compost was between 58 and 69% when tested. The results of the tillage/aeration experiments showed that, at all depths tested (11, 22 and 33 cm), the concentration of oxygen in the compost was not significantly different between any of the treatments (Table 6-2). The blocks were also not significantly different. However, the means of the oxygen concentrations were significantly different (p=<.0001) at the varying depths.

Table 6-2: Aeration ANOVA Table

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	2	37.9872667	18.9936333	2.41	0.0984
Trt	2	19.6768963	9.8384481	1.25	0.2944
Trt*Block	4	240.2501259	60.0625315	7.61	<.0001
Sensor_Depth	2	303.3024222	151.6512111	19.23	<.0001
Trt*Sensor_Depth	4	37.0431259	9.2607815	1.17	0.3310
Sensor_Depth*Block	4	26.2404889	6.5601222	0.83	0.5102

It was expected that because all three tillage\aeration methods used the rototiller to aerate the top 20 cm of the compost there would be no significant oxygen concentration difference between them. It was also expected (based on producer feedback) that both the rototiller & deep tillage w/ and w/o air injection treatments would result in elevated post treatment oxygen concentrations at depths of 22 and 33 cm. However, there was no

evidence supporting the assumption that the addition of deep tillage and air injection significantly increased the post treatment oxygen concentrations.

Possible reasons for the lack of effect include:

- tillage/aeration methods did not add oxygen
- tillage/aeration methods added oxygen, but the sensors error caused it to appear as if no oxygen was added
- tillage/aeration methods added oxygen, but sensor deployment method caused it to appear as if no oxygen was added
- tillage/aeration methods added oxygen, but environmental factors masked the effect of the tillage/aeration treatment.

6.3.2 Other Composting Factors

In the weeks following the initial deployment of the rototiller & deep tillage w/o air injection the producer reported higher bed temperatures. The assumption was that the increase in temperature was due to better aeration. However, the composting process has other limiting factors such as C/N ratio, moisture and ambient air temperature. It is possible that no additional aeration was occurring, and one or more of these factors was leading to the temperature rise.

6.3.3 Sensor Deployment Method

Another possible cause of the unexpected results could have been incorrect testing strategy. Oxygen concentrations were taken at the end of the diffusion time (65 minutes), and after only one pass of the tillage/aeration. The effects of the tillage/aeration may have not been apparent when the readings were taken, but hours or even days later after multiple passes. Project timing and logistical issues did not allow for this hypothesis to be fully tested. However, preliminary density testing was conducted. Decreased density at constant moisture causes increased porosity which could better facilitate natural oxygen infiltration after tillage/aeration treatments. The test used a robotic total station (SPS930, Trimble Ltd., Sunnyvale, CA) to create a topographical map before and after each tillage treatment. A 63 m^2 area was sampled before tillage/aeration was conducted using a 0.09 m^2 (1ft^2) grid. The three tillage/aeration methods were then conducted separately in the area. Samples were taken in a 0.09 m^2 (1ft^2) grid were the tillage/aeration methods had been conducted. Using

ArcGIS (ESRI 2009) a surface mesh was created using the 517 samples taken pre tillage/aeration. The post tillage/aeration points (164 total) were then overlaid and the separate treatments were parsed out to obtain the change in the bed height after the individual tillage/aeration methods. The results of the test are shown in Table 6-3.

Table 6-3: Post Tillage/Aeration Average Depth Increase

Treatment	Average Bed Depth Increase (cm)
Rototiller & Deep Tillage w/ Air Injection	9.98
Rototiller & Deep Tillage	8.12
Rototiller	6.60

The preliminary data only consisted on one replication so no statistical analysis was conducted. However, the results show that both of the tillage/aeration treatments with deep tillage had higher average bed depth increases than with rototilling alone. The mass of the material was assumed to be constant between before and after tillage/aeration methods. The tillage/aeration methods were started and stopped well outside the sampled area to prevent any boundary conditions, and the length of the test ensured that any lateral movement of the material into or out of the test area was negligible. Based on Equation 6-1, the greater the increase in volume (without added mass), the lower the density, and at constant MC, the higher the porosity.

$$Density = \frac{Mass}{Volume} \qquad \text{Equation 6-1}$$

6.3.4 Environmental Factors

It is also possible that the tillage/aeration treatments increased the oxygen concentration in the compost, but the results were not seen because of other factors affecting the oxygen levels more than the tillage/aeration. These factors could have included the airflow in the barn, cow movement, or a reaction in the compost.

6.3.4.1 Air Infiltration

The airflow in the barn was the result of a combination of the natural convective forces in the barn, the three fans mounted above the bedded pack, and the ambient wind

speed. The barn was located on top of a ridge and was in close proximity to other buildings which caused ambient wind speed to be highly variable, both in magnitude and direction, over the bedded pack. No wind speed data was recorded, but it was hypothesized that this variability in the air speed over the bedded pack may have contributed to the high variability in many of the oxygen readings. Figure 6-4 shows the probe 2 readings taken pre- and post-rototiller & deep tillage w/o air injection application. The air velocity appears to have an impact on the reading based on a few factors seen in the chart. These factors include the variability in the O2 measurements with respect to time, the fact that the variability occurs predominantly in the post treatment readings, and the fact that the variability is consistent between all three sensors. The variability in the readings was not seen during the calibration process or any subsequent laboratory test, which indicates that the cause was something related to the conditions in the barn. The variability was also seen in different probes and only occurred in a few cases, indicating that it was not cause by a simple instrumentation issue. In almost every test conducted the post-treatment variability was much higher than the pre-treatment variability. This coincides with the hypothesis that the increased porosity due to the tillage/aeration leads to increased air infiltration. The apparent offset between sensors indicated that the variability was not caused by single sensor error. However, the offset between sensors did not occur in any of the trials where the rototiller treatment was used. In the rototiller trials, if high variability occurred it was always in the sensor closest to the surface. This also coincides with the porosity hypothesis, because the sensor closest to the surface is the only sensor affected by the aeration in the rototiller treatment.

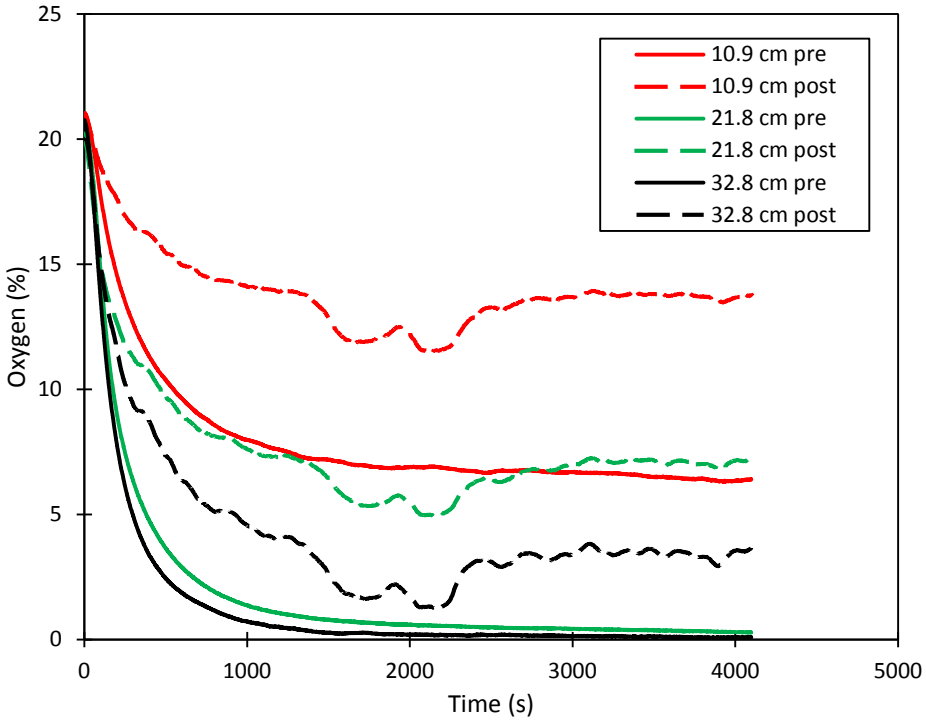

Figure 6-4: Variability in Oxygen Levels During the Sampling Window

6.3.4.2 Compost Reaction

A test was performed in an environmental chamber at the University of Kentucky in order to determine if the source of the variation in the data were caused by a reaction in the compost after aeration. The chamber allowed the response of the compost to be tested without any surface air velocity or cow movement. The chamber was set to maintain a constant temperature of 20°C at 35% relative humidity. The compost was taken from the Harvest Home Dairy in Crestwood, KY. The compost was placed in a 379 liter container inside the chamber (Figure 6-5). The average initial moisture content of the compost was 68%. The compost was mixed by hand and the probes were inserted in to the compost following the same procedure was used in the field testing. The temperature of the compost was approximately 40°C during testing, which indicated that the compost was active. The data were collected in the same manner as the field test with the exception that the data were collected for a full 24 hours, rather than the 65 minutes used in the field study. After 24 hours the probes were removed, the compost was mixed, and the probes were reinserted. This process was repeated 3 times.

Figure 6-5: Compost in Environmental Chamber

Figure 6-5 shows the first 65 minutes of the diffusion profile for probe 1 in the environmental chamber. The complete chart (full day diffusion profile) can be seen in Figure D-2 in the Appendix along with the chart from the other probes and trials. All of the diffusion profiles from the environmental chamber testing were similar. They all showed a very smooth diffusion curve with little variability. This indicates that neither the compost activity nor the probes were likely the cause of the variability observed in field studies.

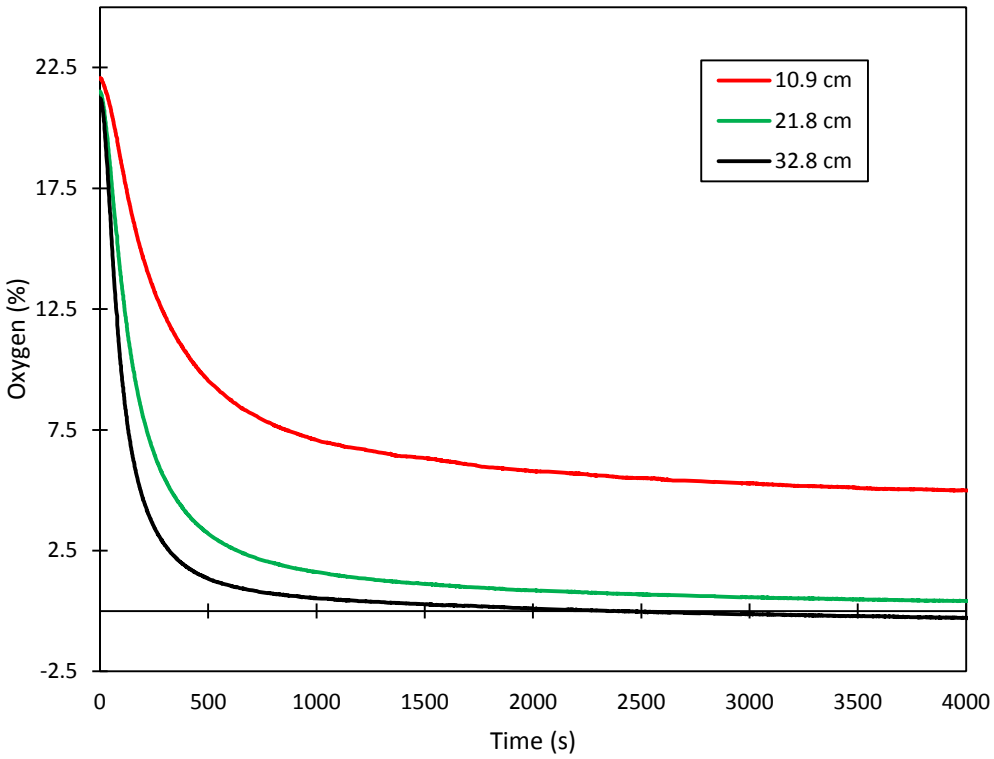

Figure 6-6: Probe 1 Diffusion Profile in an Environmental Chamber (65 min)

6.4 Conclusions

The means of the oxygen concentrations were significantly different (p=<.0001) at the varying depths. However, the data indicated that there was no significant difference between the tillage/aeration methods. Possible reasons for the lack of effect were identified and investigated. Based on the data and subsequent tests, it appears most likely that environmental factors affected the oxygen concentrations more than the tillage/aeration methods making it difficult to determine if the tillage/aeration methods had any statistically significant effect on the oxygen concentrations in the compost, however, more test are needed to fully substantiate this claim. The subsequent laboratory test validated the design of the probes, but revealed the need for more sensors, such as an anemometer to measure external air movement, in order to fully understand the effect of tillage\aeration methods in compost bedded pack barns.

The results also indicate that there is the possibility that the increase in bed depth after tillage could have led to better aeration and explain the increased bed temperatures that were observed by the producer.

CHAPTER 7:SUMMARY AND FUTURE WORK

Commercially available Apogee oxygen sensors were selected and tested for their ability to perform in harsh composting conditions. The sensors were temperature and oxygen dependent, and a second-order polynomial was determined to be the appropriate fit for the calibration. All of the sensors tested were accurate to less than ± 1% O2, in the ranges 10 to 60°C and 0 to 20% O2.

A probe was designed to allow simultaneous *in-situ* testing of oxygen concentrations at different locations and depth in the compost. The probe was capable of measuring oxygen levels at 11, 22, and 33 cm from the surface. Custom instrumentation electronics were designed using a PCB to interface each probe to a single PC using a Zigbee mesh network. The electronics amplified, sampled, and filtered sensor voltages and provided an output data rate of 1 Hz. A Visual Studio program was written to display and log the data from the custom electronics.

A laboratory test was performed to determine the sampling time for the probe under varying moisture and compaction conditions. The effect of pulling a vacuum on the diffusion head when initially introduced to the compost was also tested. The test determined that pulling a vacuum only affected the 70% MC conditions, thus it was determined it was not worth implementing. However, in the later field this moisture did actually occur. The results also showed the required sampling time was 18 minutes for all conditions tested except for the 70% MC compacted. The sampling time at those conditions was found to be 65 minutes.

An aeration attachment for the hybrid tillage tool was designed and implemented. Tests showed that, at an operating speed of ~.45 m/s at a depth of 45.6 cm in 65% MC compost, the system should provide 0.017 m^3/s which is more than the 0.00775 m^3/s required.

The effect of three tillage/aeration methods on oxygen level in the compost was tested. The data indicated that there were no significant differences between using a rototiller, the hybrid tillage tool, or the hybrid tillage tool with forced air injection. Based on the data and subsequent tests, it appeared mostly likely that environmental factors affected the oxygen concentrations more than the tillage/aeration methods, making it

difficult to determine if the tillage/aeration methods had any effect on the oxygen concentrations in the compost.

The next logical step in the research is to determine exactly what is causing the variation in the field data. Preliminary data showed that the probe was capable of measuring oxygen concentrations in the lab with little variation. This indicated the composting process and the sensor were not causing the variation. If the source of the variation can be identified and eliminated, then the effect of different tillage/aeration methods can be quickly determined. This would allow researchers to test various tillage/aeration methods and identify which are most effective in CBP barns. The cumulative effect of the tillage methods would also be of interest, because of the limited disturbance that the deep tillage is capable of in a single pass.

APPENDICES

Appendix A. Oxygen Sensor Calibration

Table A-1: Calibration Equation Coefficients Used in Main Test

Probe	Sensor Depth from Surface (cm)	p00	p10	p01	p11	p02
1	11	2.128	369.4	-0.06685	1.55	0.0003379
	22	4.009	344.5	-0.106	1.326	0.0005202
	33	3.075	359.2	-0.08949	1.338	0.0004533
2	11	4.554	329	-0.1212	1.545	0.0006154
	22	3.007	328	-0.08892	1.631	0.0004652
	33	3.806	315.3	-0.1051	1.501	0.000554
3	11	2.932	336	-0.08417	1.357	0.0004265
	22	2.219	330.8	-0.06924	1.274	0.0003506
	33	3.194	314.9	-0.09028	1.465	0.0004663

Appendix B. Oxygen Probe Design and Testing

Table B-1: Moisture Vacuum Interaction

moisture	vac	time LSMEAN	LSMEAN Number
40	Novac	766.00000	1
40	Vac	727.50000	2
55	Novac	808.16667	3
55	Vac	627.50000	4
70	Novac	2285.00000	5
70	Vac	1913.05769	6

Least Squares Means for effect moisture*vac
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: time

i/j	1	2	3	4	5	6
1		0.7039	0.6773	0.1789	<.0001	<.0001
2	0.7039		0.4282	0.3276	<.0001	<.0001
3	0.6773	0.4282		0.0833	<.0001	<.0001
4	0.1789	0.3276	0.0833		<.0001	<.0001
5	<.0001	<.0001	<.0001	<.0001		0.0017
6	<.0001	<.0001	<.0001	<.0001	0.0017	

Table B-2: GLM Procedure No Vacuum

Source	DF	Type I SS	Mean Square	F Value	Pr > F
moisture	2	8980351.444	4490175.722	400.38	<.0001
compaction	1	3016786.722	3016786.722	269.00	<.0001
moisture*compaction	2	8845565.444	4422782.722	394.37	<.0001

Appendix C. Air Injection Development

Table C-1: Fan Performance Data

Velocity (m/s)	Volumetric Flow (m^3/s)	Static Pressure (kPa)
54.4	1102	0.15
51.8	1050	0.50
49.8	1009	0.75
46.7	947	1.25
42.7	865	1.74
38.6	783	2.24
31.5	638	2.74
23.9	484	3.24
14.7	299	3.74
8.1	165	3.99

Table C-2: System Performance Data

Velocity (m/s)	Volumetric Flow (m^3/s)	Static pressure (kPa)
29.2	187	4.0
28.4	182	3.8
27.4	176	3.3
25.4	163	3.0
23.6	151	2.6
22.7	146	2.5
21.0	134	2.2
20.2	129	2.0
19.1	122	1.7
17.0	109	1.4
15.7	101	1.2
13.5	86	0.9
11.0	71	0.6
9.1	59	0.4
7.5	48	0.3

Appendix D. Aeration Testing

Table D-1: Average Moisture Levels by Depth

Sample Depth	Average Moisture	Standard Deviation
11 cm	63.46%	4.70%
22 cm	62.73%	5.56%
33 cm	64.34%	3.38%

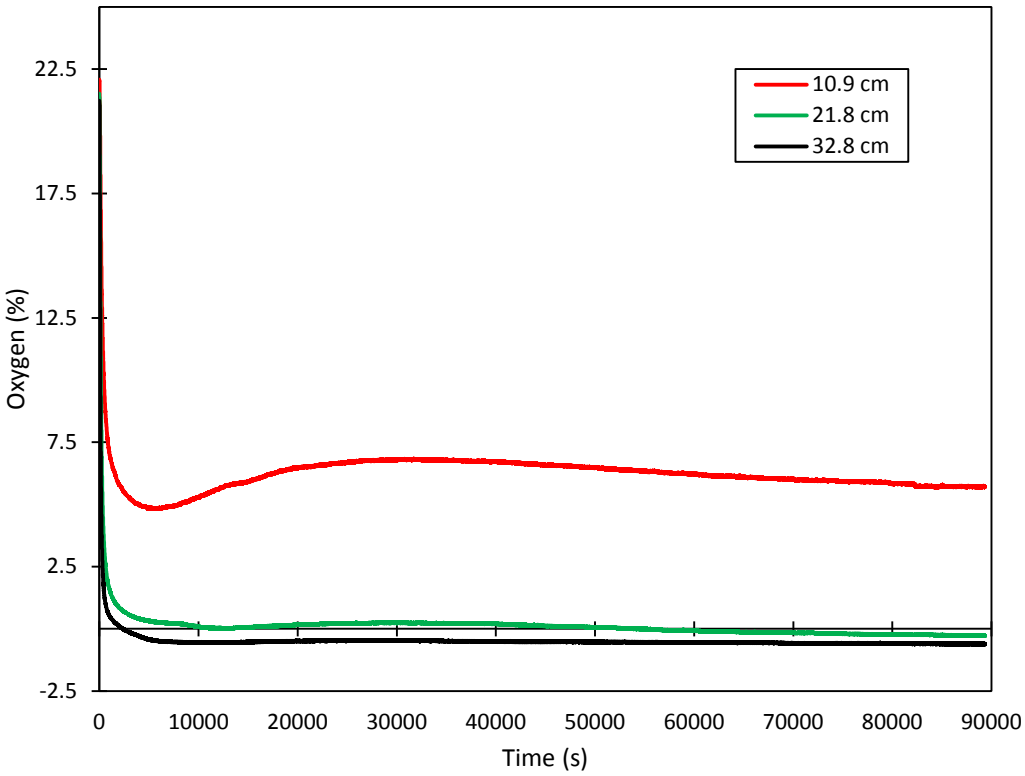

Figure D-2: Probe 1 Diffusion Profile in Environmental Chamber (24 Hour)

Appendix E. Oxygen Logging Program:

```
Public Class main

    Private WithEvents CommPort As New RS232
    Private Csum As New Checksum
    Private ElapsedTime1 As New Stopwatch
    Private ElapsedTime2 As New Stopwatch
    Private ElapsedTime3 As New Stopwatch
    Private CurrentTime1 As Long = 0
    Private CurrentTime2 As Long = 0
    Private CurrentTime3 As Long = 0
    Private PreviousTime1 As Long = 0
    Private PreviousTime2 As Long = 0
    Private PreviousTime3 As Long = 0
    Private SaveFile1 As New SaveFileDialog
    Private SaveFile2 As New SaveFileDialog
    Private SaveFile3 As New SaveFileDialog
    Private SaveImages As New SaveFileDialog
    Private Logging As Boolean = False
    Private Logging2 As Boolean = False
    Private Logging3 As Boolean = False

    Private WithEvents SerialPort1 As New System.IO.Ports.SerialPort

    Private Sub Main_Load(ByVal sender As System.Object, ByVal e As System.Eve
ntArgs) Handles MyBase.Load
        CheckForIllegalCrossThreadCalls = False
        For Each Port In CommPort.GetComPortNames
            CommPorts.Items.Add(Port)
        Next
        CommPorts.SelectedIndex = My.Settings.DefaultCommPort
        FolderTextBox.Text = My.Settings.DefaultFolder
        FileTextBox.Text = My.Settings.DefaultFilename
        FolderTextBox2.Text = My.Settings.DefaultFolder2
        FileTextBox2.Text = My.Settings.DefaultFilename2
        FolderTextBox3.Text = My.Settings.DefaultFolder3
        FileTextBox3.Text = My.Settings.DefaultFilename3

        ConnectButton.PerformClick()
    End Sub
    Private Sub SerialMessage() Handles CommPort.NewMessage
        Dim Data As String = CommPort.GetMessage
        If Csum.CheckChecksum(Data) Then
            'Probe 1
            If Data.Chars(4) = "1" Then
                Terminal.Text = Data    'display the data string in the termin
al text box
                ChecksumTextBox.Text = Csum.GetChecksum(Terminal.Text)  'displ
ay the checksum

                Dim DataItems As String() = Split(Data, ",")
                ' Probe 1 Battery voltage
                Dim battvolt As Single = (DataItems(10) * 5 / 4095) / 0.099011
 + 0.291
```

```
                Tp1battvolt.Text = Format(battvolt, "#.00")
                If battvolt < 12 Then
                    Tp1battvolt.BackColor = Color.Red
                Else
                    Tp1battvolt.BackColor = Color.White
                End If
                ' Probe 1 cold junction
                Dim tcold As Single = (DataItems(11) * 5 / 4095) * 100 - 75
                p1cold.Text = Format(tcold, "#.00")
                ' Probe 1 top sensor values
                Dim p1topvol As Single = (DataItems(3) * 5 / 4095 - 2.5) / 40.
22
                Dim p1toptemp As Single = (DataItems(4) * 5 / 4095 - 2.5) * 10
0 + tcold
                Dim p1topo2 As Single = 2.128 + 369.4 * p1topvol - 0.06685 * p
1toptemp + 1.55 * p1topvol * p1toptemp + 0.0003379 * p1toptemp ^ 2
                ' Probe 1 top sensor output
                Tp1topvol.Text = Format(p1topvol, "#.00000")
                Tp1toptemp.Text = Format(p1toptemp, "#.00")
                Tp1topo2.Text = Format(p1topo2, "#.00")
                ' Probe 1 middle sensor values
                Dim p1middlevol As Single = (DataItems(5) * 5 / 4095 - 2.5) /
40.22
                Dim p1middletemp As Single = (DataItems(6) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p1middleo2 As Single = 4.009 + 344.5 * p1middlevol - 0.106
 * p1middletemp + 1.326 * p1middlevol * p1middletemp + 0.0005202 * p1middletem
p ^ 2
                ' Probe 1 middle sensor output
                Tp1middlevol.Text = Format(p1middlevol, "#.00000")
                Tp1middletemp.Text = Format(p1middletemp, "#.00")
                Tp1middleo2.Text = Format(p1middleo2, "#.00")
                ' Probe 1 bottom sensor values
                Dim p1bottomvol As Single = (DataItems(7) * 5 / 4095 - 2.5) /
40.22
                Dim p1bottomtemp As Single = (DataItems(8) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p1bottomo2 As Single = 3.075 + 359.2 * p1bottomvol - 0.089
19 * p1bottomtemp + 1.338 * p1bottomvol * p1bottomtemp + 0.0004533 * p1bottomt
emp ^ 2
                ' Probe 1 bottom sensor output
                Tp1bottomvol.Text = Format(p1bottomvol, "#.00000")
                Tp1bottomtemp.Text = Format(p1bottomtemp, "#.00")
                Tp1bottomo2.Text = Format(p1bottomo2, "#.00")
                'Logging
                If DataItems(2) = "0" Then
                    Logging = True
                    If P1LogButton.Text = "Disable Logging" Then
                        ElapsedTime1.Start()
                        CurrentTime1 = ElapsedTime1.ElapsedMilliseconds
                        TextBox5.Text = Format(CurrentTime1 / 1000, "#.00")
                        If (CurrentTime1 / 1000) > 3926 Then
                            TextBox5.BackColor = Color.Red
                        Else
```

```
                        TextBox5.BackColor = Color.White
                    End If
                    TextBox3.Text = Format(1000 / (CurrentTime1 - Previous
Time1), "#.0")
                    PreviousTime1 = CurrentTime1
                End If

            Else
                Logging = False
                ElapsedTime1.Stop()
            End If
            If Logging Then
                Try
                    Dim Settings As String = My.Computer.Clock.LocalTime.T
oString & "," & "," & p1topvol.ToString & "," & p1toptemp.ToString & "," & p1t
opo2.ToString & "," & "," & p1middlevol.ToString & "," & p1middletemp.ToString
 & "," & p1middleo2.ToString & "," & "," & p1bottomvol.ToString & "," & p1bott
omtemp.ToString & "," & p1bottomo2.ToString & "," & vbCrLf
                    My.Computer.FileSystem.WriteAllText(SaveFile1.FileName
, Settings, True)
                Catch ex As Exception
                End Try
            End If

        End If
        'Probe 2
        If Data.Chars(4) = "2" Then
            Terminal2.Text = Data    'display the data string in the termi
nal text box
            ChecksumTextBox2.Text = Csum.GetChecksum(Terminal2.Text)  'dis
play the checksum
            Dim DataItems As String() = Split(Data, ",")
            ' Probe 2 Battery voltage
            Dim battvolt As Single = (DataItems(10) * 5 / 4095) / 0.099011
 + 0.291
            Tp2battvolt.Text = Format(battvolt, "#.00")
            If battvolt < 12 Then
                Tp2battvolt.BackColor = Color.Red
            Else
                Tp2battvolt.BackColor = Color.White
            End If
            ' Probe 2 cold junction
            Dim tcold As Single = (DataItems(11) * 5 / 4095) * 100 - 75
            Tp2cold.Text = Format(tcold, "#.00")
            ' Probe 2 top sensor values
            Dim p2topvol As Single = (DataItems(3) * 5 / 4095 - 2.5) / 40.
22
            Dim p2toptemp As Single = (DataItems(4) * 5 / 4095 - 2.5) * 10
0 + tcold
            Dim p2topo2 As Single = 4.554 + 329 * p2topvol - 0.1212 * p2to
ptemp + 1.545 * p2topvol * p2toptemp + 0.0006154 * p2toptemp ^ 2
            ' Probe 2 top sensor output
            Tp2topvol.Text = Format(p2topvol, "#.00000")
            Tp2toptemp.Text = Format(p2toptemp, "#.00")
```

```
                Tp2topo2.Text = Format(p2topo2, "#.00")
                ' Probe 2 bottom sensor values
                Dim p2bottomvol As Single = (DataItems(7) * 5 / 4095 - 2.5) /
40.22
                Dim p2bottomtemp As Single = (DataItems(8) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p2bottomo2 As Single = 3.806 + 315.3 * p2bottomvol - 0.105
1 * p2bottomtemp + 1.501 * p2bottomvol * p2bottomtemp + 0.0005453 * p2bottomte
mp ^ 2
                ' Probe 2 bottom sensor output
                Tp2bottomvol.Text = Format(p2bottomvol, "#.00000")
                Tp2bottomtemp.Text = Format(p2bottomtemp, "#.00")
                Tp2bottomo2.Text = Format(p2bottomo2, "#.00")
                ' Probe 2 middle sensor values
                Dim p2middlevol As Single = (DataItems(5) * 5 / 4095 - 2.5) /
40.22
                Dim p2middletemp As Single = (DataItems(6) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p2middleadjtemp As Single = ((p2toptemp - p2bottomtemp) /
2 + p2bottomtemp)
                Dim p2middleo2 As Single = 3.007 + 328 * p2middlevol - 0.08892
 * p2middleadjtemp + 1.632 * p2middlevol * p2middleadjtemp + 0.0004652 * p2mid
dleadjtemp ^ 2
                ' Probe 2 middle sensor output
                Tp2middlevol.Text = Format(p2middlevol, "#.00000")
                Tp2middletemp.Text = Format(p2middleadjtemp, "#.00")
                Tp2middleo2.Text = Format(p2middleo2, "#.00")

                'Logging
                If DataItems(2) = "0" Then
                    Logging2 = True
                    If P2LogButton.Text = "Disable Logging" Then
                        ElapsedTime2.Start()
                        CurrentTime2 = ElapsedTime2.ElapsedMilliseconds
                        TextBox2.Text = Format(CurrentTime2 / 1000, "#.00")
                        If (CurrentTime2 / 1000) > 3926 Then
                            TextBox2.BackColor = Color.Red
                        Else
                            TextBox2.BackColor = Color.White
                        End If
                        TextBox4.Text = Format(1000 / (CurrentTime2 - Previous
Time2), "#.0")
                        PreviousTime2 = CurrentTime2
                    End If
                Else
                    Logging2 = False
                    ElapsedTime2.Stop()
                End If
                If Logging2 Then

                    Try
                        Dim Settings As String = My.Computer.Clock.LocalTime.T
oString & "," & "," & p2topvol.ToString & "," & p2toptemp.ToString & "," & p2t
opo2.ToString & "," & "," & p2middlevol.ToString & "," & p2middletemp.ToString
```

```
 & "," & p2middleo2.ToString & "," & "," & p2bottomvol.ToString & "," & p2bott
omtemp.ToString & "," & p2bottomo2.ToString & "," & vbCrLf
                        My.Computer.FileSystem.WriteAllText(SaveFile2.FileName
, Settings, True)
                    Catch ex As Exception
                    End Try
                End If
            End If
            'Probe 3
            If Data.Chars(4) = "3" Then
                Terminal3.Text = Data    'display the data string in the termi
nal text box
                ChecksumTextBox3.Text = Csum.GetChecksum(Terminal3.Text)  'dis
play the checksum
                Dim DataItems As String() = Split(Data, ",")
                ' Probe 3 Battery voltage
                Dim battvolt As Single = (DataItems(10) * 5 / 4095) / 0.099011
 + 0.291
                Tp3battvolt.Text = Format(battvolt, "#.00")
                If battvolt < 12 Then
                    Tp3battvolt.BackColor = Color.Red
                Else
                    Tp3battvolt.BackColor = Color.White
                End If
                ' Probe 3 cold junction
                Dim tcold As Single = (DataItems(11) * 5 / 4095) * 100 - 75
                Tp3cold.Text = Format(tcold, "#.00")
                ' Probe 3 top sensor values
                Dim p3topvol As Single = (DataItems(3) * 5 / 4095 - 2.5) / 40.
22
                Dim p3toptemp As Single = (DataItems(4) * 5 / 4095 - 2.5) * 10
0 + tcold
                Dim p3topo2 As Single = 2.932 + 336 * p3topvol - 0.08417 * p3t
optemp + 1.357 * p3topvol * p3toptemp + 0.0004265 * p3toptemp ^ 2
                ' Probe 3 top sensor output
                Tp3topvol.Text = Format(p3topvol, "#.00000")
                Tp3toptemp.Text = Format(p3toptemp, "#.00")
                Tp3topo2.Text = Format(p3topo2, "#.00")
                ' Probe 3 middle sensor values
                Dim p3middlevol As Single = (DataItems(5) * 5 / 4095 - 2.5) /
40.22
                Dim p3middletemp As Single = (DataItems(6) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p3middleo2 As Single = 2.219 + 330.8 * p3middlevol - 0.069
24 * p3middletemp + 1.274 * p3middlevol * p3middletemp + 0.0003506 * p3middlet
emp ^ 2
                ' Probe 3 middle sensor output
                Tp3middlevol.Text = Format(p3middlevol, "#.00000")
                Tp3middletemp.Text = Format(p3middletemp, "#.00")
                Tp3middleo2.Text = Format(p3middleo2, "#.00")
                ' Probe 3 bottom sensor values
                Dim p3bottomvol As Single = (DataItems(7) * 5 / 4095 - 2.5) /
40.22
```

```
                Dim p3bottomtemp As Single = (DataItems(8) * 5 / 4095 - 2.5) *
 100 + tcold
                Dim p3bottomo2 As Single = 3.194 + 314.9 * p3bottomvol - 0.090
28 * p3bottomtemp + 1.465 * p3bottomvol * p3bottomtemp + 0.0004663 * p3bottomt
emp ^ 2
                ' Probe 3 bottom sensor output
                Tp3bottomvol.Text = Format(p3bottomvol, "#.00000")
                Tp3bottomtemp.Text = Format(p3bottomtemp, "#.00")
                Tp3bottomo2.Text = Format(p3bottomo2, "#.00")
                If DataItems(2) = "0" Then
                    Logging3 = True
                    If P3LogButton.Text = "Disable Logging" Then
                        ElapsedTime3.Start()
                        CurrentTime3 = ElapsedTime3.ElapsedMilliseconds
                        TextBox6.Text = Format(CurrentTime3 / 1000, "#.00")
                        If (CurrentTime3 / 1000) > 3926 Then
                            TextBox6.BackColor = Color.Red
                        Else
                            TextBox6.BackColor = Color.White
                        End If
                        TextBox7.Text = Format(1000 / (CurrentTime3 - Previous
Time3), "#.0")
                        PreviousTime3 = CurrentTime3
                    End If
                Else
                    Logging3 = False
                    ElapsedTime3.Stop()

                End If
                If Logging3 Then
                    Try
                        Dim Settings As String = My.Computer.Clock.LocalTime.T
oString & "," & "," & p3topvol.ToString & "," & p3toptemp.ToString & "," & p3t
opo2.ToString & "," & "," & p3middlevol.ToString & "," & p3middletemp.ToString
 & "," & p3middleo2.ToString & "," & "," & p3bottomvol.ToString & "," & p3bott
omtemp.ToString & "," & p3bottomo2.ToString & "," & vbCrLf
                        My.Computer.FileSystem.WriteAllText(SaveFile3.FileName
, Settings, True)
                    Catch ex As Exception
                    End Try
                End If
            End If
        End If



    End Sub
    Private Sub CommPorts_SelectedIndexChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles CommPorts.SelectedIndexChanged
        My.Settings.DefaultCommPort = CommPorts.SelectedIndex
    End Sub
    Private Sub FolderTextBox_TextChanged(ByVal sender As System.Object, ByVal
 e As System.EventArgs) Handles FolderTextBox.TextChanged
        My.Settings.DefaultFolder = FolderTextBox.Text
```

```
    End Sub
    Private Sub FolderTextBox2_TextChanged(ByVal sender As System.Object, ByVa
l e As System.EventArgs) Handles FolderTextBox2.TextChanged
        My.Settings.DefaultFolder2 = FolderTextBox2.Text
    End Sub
    Private Sub FolderTextBox3_TextChanged(ByVal sender As System.Object, ByVa
l e As System.EventArgs) Handles FolderTextBox3.TextChanged
        My.Settings.DefaultFolder3 = FolderTextBox.Text
    End Sub
    Private Sub FileTextBox_TextChanged(ByVal sender As System.Object, ByVal e
 As System.EventArgs) Handles FileTextBox.TextChanged
        My.Settings.DefaultFilename = FileTextBox.Text
    End Sub
    Private Sub FileTextBox2_TextChanged(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles FileTextBox2.TextChanged
        My.Settings.DefaultFilename2 = FileTextBox2.Text
    End Sub
    Private Sub FileTextBox3_TextChanged(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles FileTextBox3.TextChanged
        My.Settings.DefaultFilename3 = FileTextBox3.Text
    End Sub
    Private Sub ConnectButton_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles ConnectButton.Click
        If ConnectButton.Text = "Connect" Then
            If CommPort.OpenPort(CommPorts.SelectedItem, 19200, 8, "n", 1) The
n
                P1LogButton.Enabled = True
                ConnectButton.Text = "Disconnect"

            End If
        Else
            If CommPort.ClosePort Then
                P1LogButton.Enabled = False
                ConnectButton.Text = "Connect"
            End If
        End If
    End Sub


    Private Sub LogButton_Click(sender As Object, e As EventArgs) Handles P1Lo
gButton.Click
        If P1LogButton.Text = "Enable Logging" Then
            ElapsedTime1.Reset()
            SaveFile1.FileName = FolderTextBox.Text & "\" & FileTextBox.Text &
 "-1.csv"
            If System.IO.Directory.Exists(FolderTextBox.Text) Then
                GroupBox1.BackColor = Color.Green
                While System.IO.File.Exists(SaveFile1.FileName)
                    Dim Split1 As String() = Split(SaveFile1.FileName, "-")
                    Dim Split2 As String() = Split(Split1(1), ".")
                    Dim FileNumber As Short = CShort(Split2(0))
                    FileNumber = FileNumber + 1
                    SaveFile1.FileName = FolderTextBox.Text & "\" & FileTextBo
x.Text & "-" & CStr(FileNumber) & ".csv"
```

```
                End While
                Try
                    Dim settings As String = ",,,Top Sensor,,,,Middle Sensor ,
,,,Bottom Sensor" & vbCrLf & "Time,,O2 Voltage,Tempature (C),O2%,,O2 Voltage,T
empature (C),O2%,,O2 Voltage,Tempature (C),O2%" & vbCrLf
                    My.Computer.FileSystem.WriteAllText(SaveFile1.FileName, se
ttings, False)
                    P1LogButton.Text = "Disable Logging"
                    'Logging = True
                Catch ex As Exception

                End Try

            Else
                MessageBox.Show("Folder Does Not Exist")
                GroupBox1.BackColor = Color.Gray
            End If

        Else
            P1LogButton.Text = "Enable Logging"
            GroupBox1.BackColor = Color.Gray

        End If
    End Sub

    Private Sub P2LogButton_Click(sender As Object, e As EventArgs) Handles P2
LogButton.Click
        If P2LogButton.Text = "Enable Logging" Then
            ElapsedTime2.Reset()
            SaveFile2.FileName = FolderTextBox2.Text & "\" & FileTextBox2.Text
 & "-1.csv"
            If System.IO.Directory.Exists(FolderTextBox2.Text) Then
                GroupBox5.BackColor = Color.Green
                While System.IO.File.Exists(SaveFile2.FileName)
                    Dim Split1 As String() = Split(SaveFile2.FileName, "-")
                    Dim Split2 As String() = Split(Split1(1), ".")
                    Dim FileNumber As Short = CShort(Split2(0))
                    FileNumber = FileNumber + 1
                    SaveFile2.FileName = FolderTextBox2.Text & "\" & FileTextB
ox2.Text & "-" & CStr(FileNumber) & ".csv"
                End While
                Try
                    Dim settings As String = ",,,Top Sensor,,,,Middle Sensor ,
,,,Bottom Sensor" & vbCrLf & "Time,,O2 Voltage,Tempature (C),O2%,,O2 Voltage,T
empature (C),O2%,,O2 Voltage,Tempature (C),O2%" & vbCrLf
                    My.Computer.FileSystem.WriteAllText(SaveFile2.FileName, se
ttings, False)
                    P2LogButton.Text = "Disable Logging"

                Catch ex As Exception

                End Try

            Else
```

```
                MessageBox.Show("Folder Does Not Exist")
                GroupBox5.BackColor = Color.Gray
            End If

        Else
            P2LogButton.Text = "Enable Logging"
            GroupBox5.BackColor = Color.Gray

        End If
    End Sub
    Private Sub P3LogButton_Click(sender As Object, e As EventArgs) Handles P3
LogButton.Click
        If P3LogButton.Text = "Enable Logging" Then
            ElapsedTime3.Reset()
            SaveFile3.FileName = FolderTextBox3.Text & "\" & FileTextBox3.Text
 & "-1.csv"
            If System.IO.Directory.Exists(FolderTextBox3.Text) Then
                GroupBox9.BackColor = Color.Green
                While System.IO.File.Exists(SaveFile3.FileName)
                    Dim Split1 As String() = Split(SaveFile3.FileName, "-")
                    Dim Split2 As String() = Split(Split1(1), ".")
                    Dim FileNumber As Short = CShort(Split2(0))
                    FileNumber = FileNumber + 1
                    SaveFile3.FileName = FolderTextBox3.Text & "\" & FileTextB
ox3.Text & "-" & CStr(FileNumber) & ".csv"
                End While
                Try
                    Dim settings As String = ",,,Top Sensor,,,,Middle Sensor ,
,,,Bottom Sensor" & vbCrLf & "Time,,O2 Voltage,Tempature (C),O2%,,O2 Voltage,T
empature (C),O2%,,O2 Voltage,Tempature (C),O2%" & vbCrLf
                    My.Computer.FileSystem.WriteAllText(SaveFile3.FileName, se
ttings, False)
                    P3LogButton.Text = "Disable Logging"
                    'Logging = True
                Catch ex As Exception

                End Try

            Else
                MessageBox.Show("Folder Does Not Exist")
                GroupBox9.BackColor = Color.Gray
            End If

        Else
            P3LogButton.Text = "Enable Logging"
            GroupBox9.BackColor = Color.Gray
            'Logging = False
        End If
    End Sub
    Private Sub MasterLogButton_Click(sender As Object, e As EventArgs) Handle
s MasterLogButton.Click
        P1LogButton.PerformClick()
        P2LogButton.PerformClick()
        P3LogButton.PerformClick()
```

```
        If P1LogButton.Text = "Enable Logging" Then
            MasterLogButton.Text = "Enable All Logging"
        Else
            MasterLogButton.Text = "Disable All Logging"
        End If

    End Sub


End Class
```

Figure E-1: O2 Logging Program Code

Appendix F. Main Test Diffusion Profiles

A.1. Rototiller Only

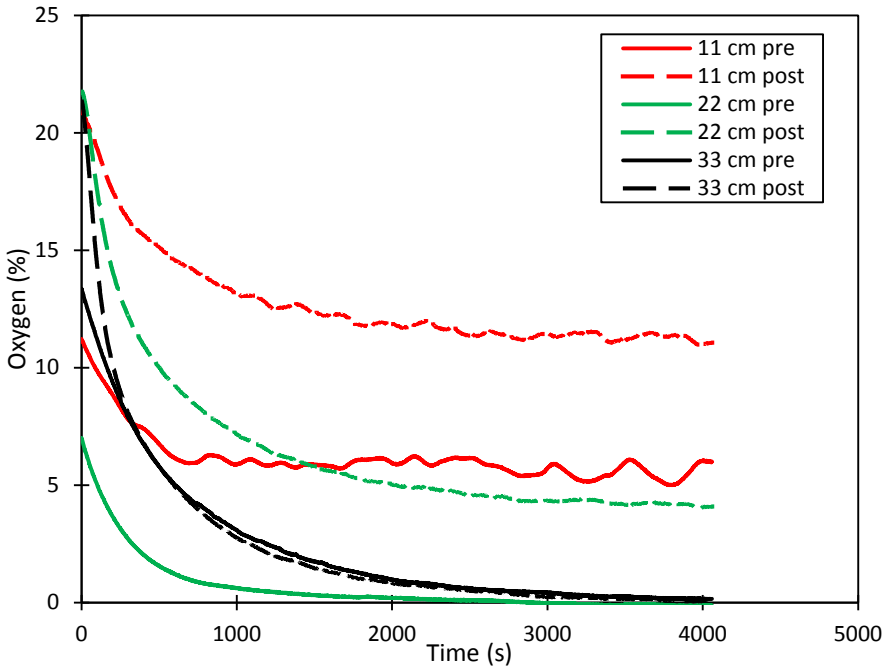

Figure F-1: Probe 1 Trial 1

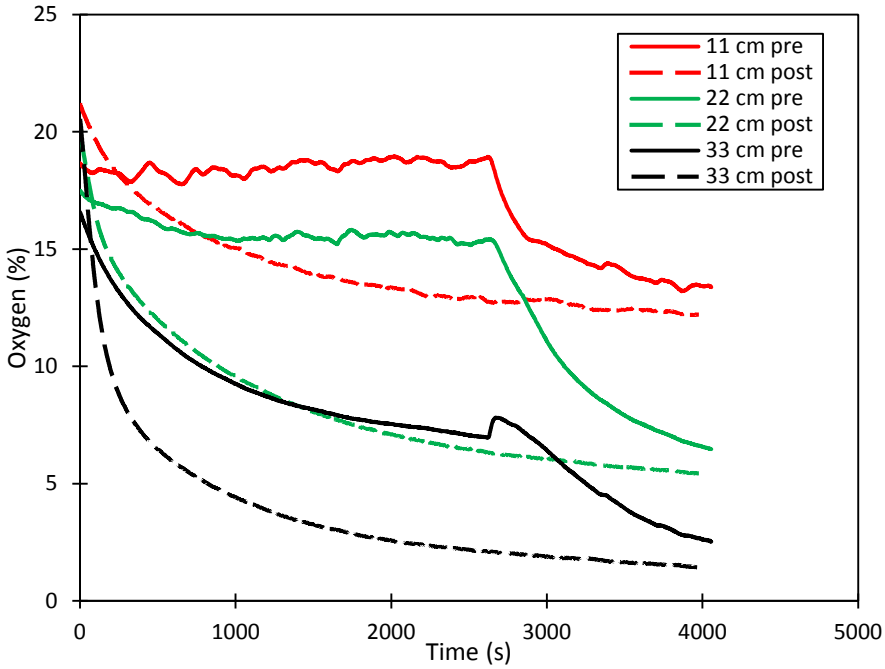

Figure F-2: Probe 2 Trial 1

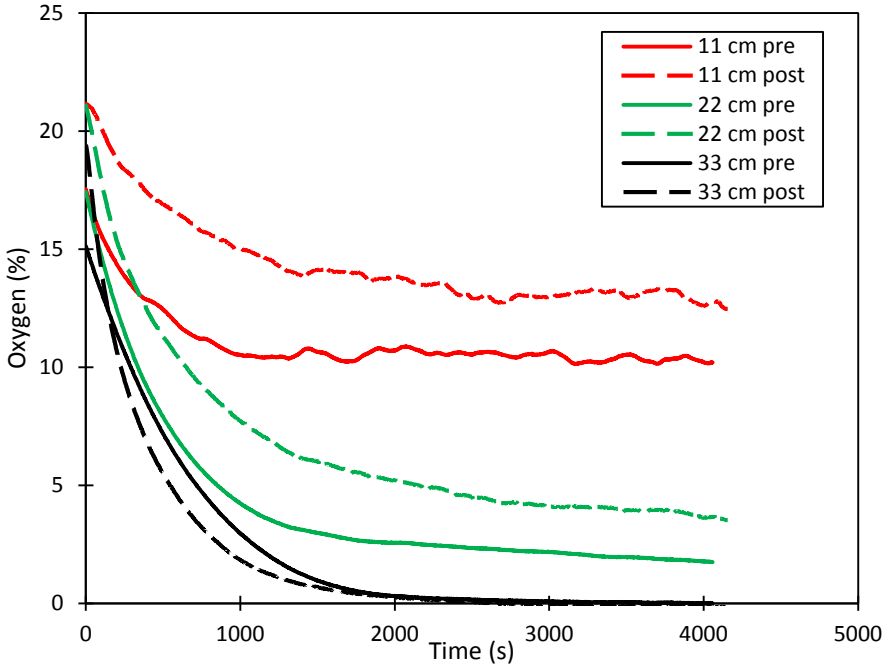

Figure F-3: Probe 3 Trial 1

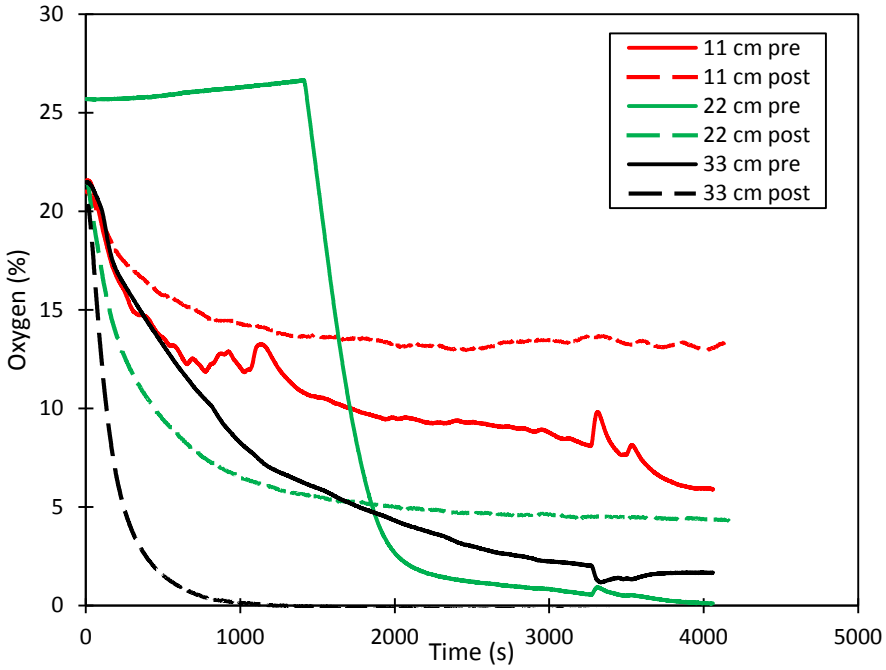

Figure F-4: Probe 1 Trial 2

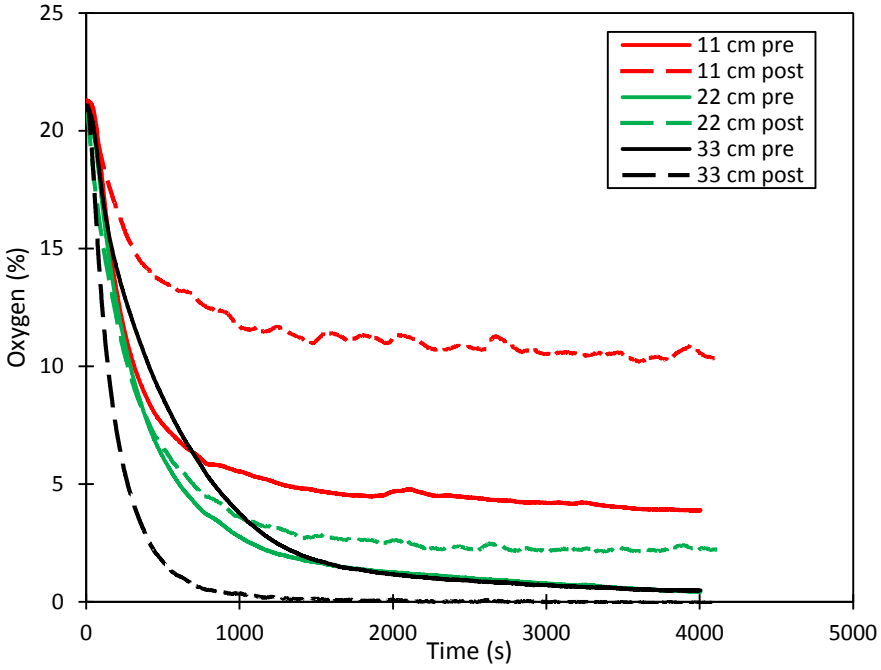

Figure F-5: Probe 2 Trial 2

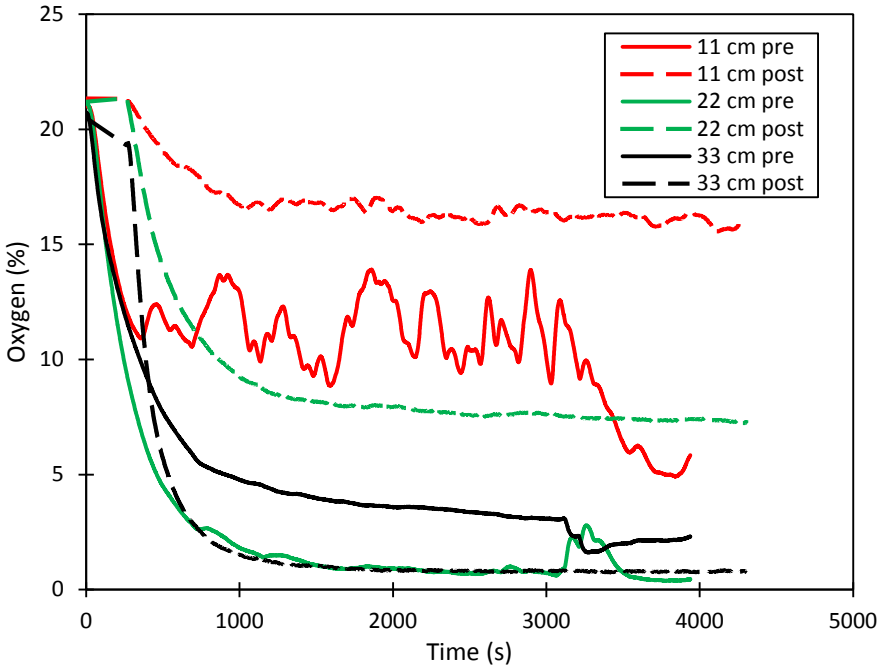

Figure F-6: Probe 3 Trial 2

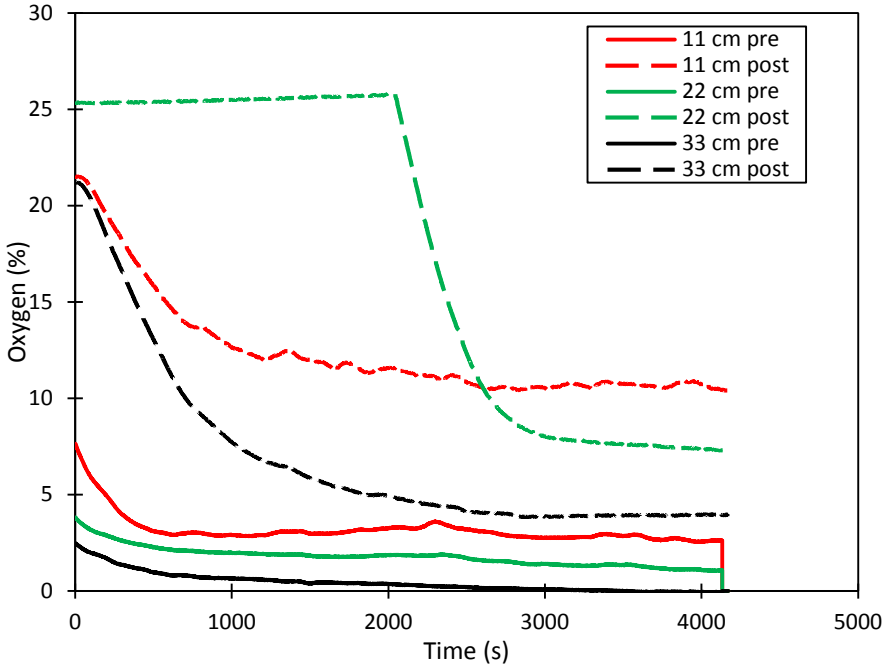

Figure F-7: Probe 1 Trial 3

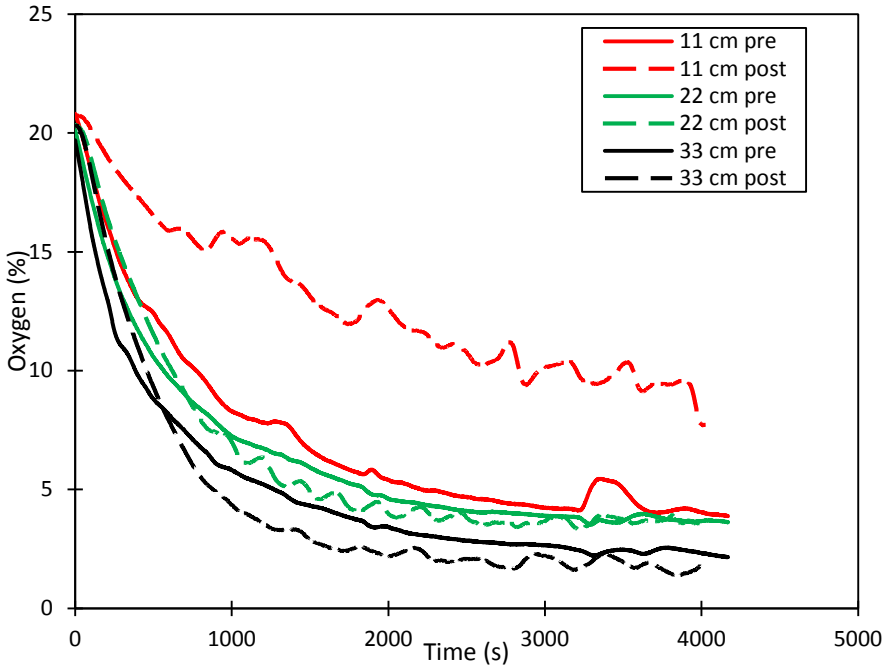

Figure F-8: Probe 2 Trial 3

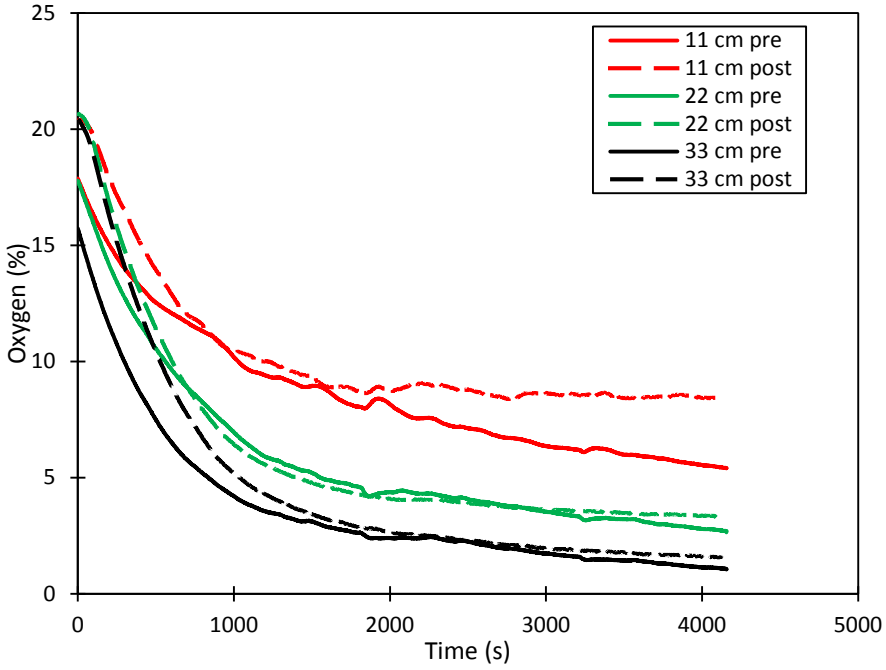

Figure F-9: Probe 3 Trail 3

A.2. Hybrid Tillage/Aeration Tool

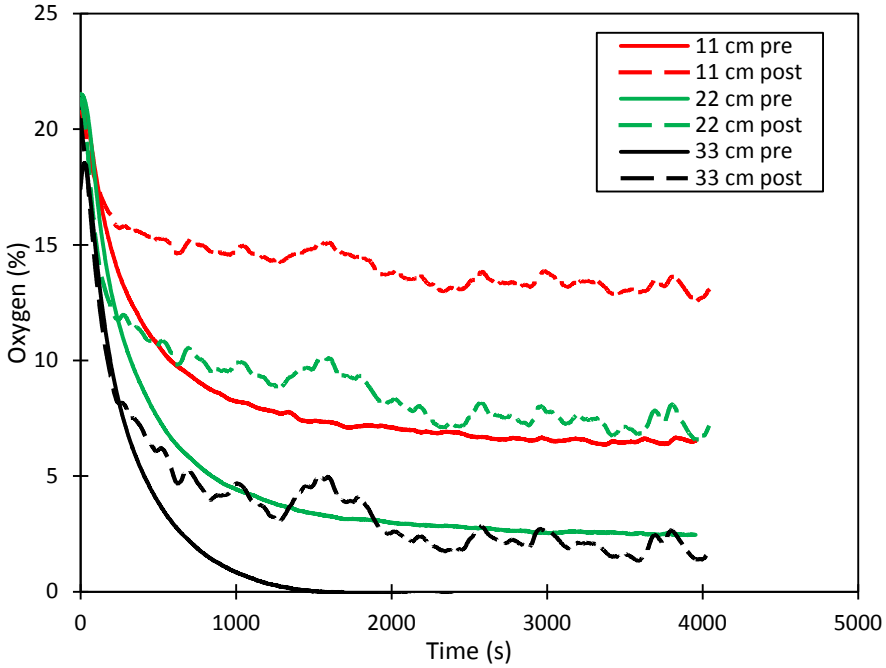

Figure F-10: Probe 1 Trial 1

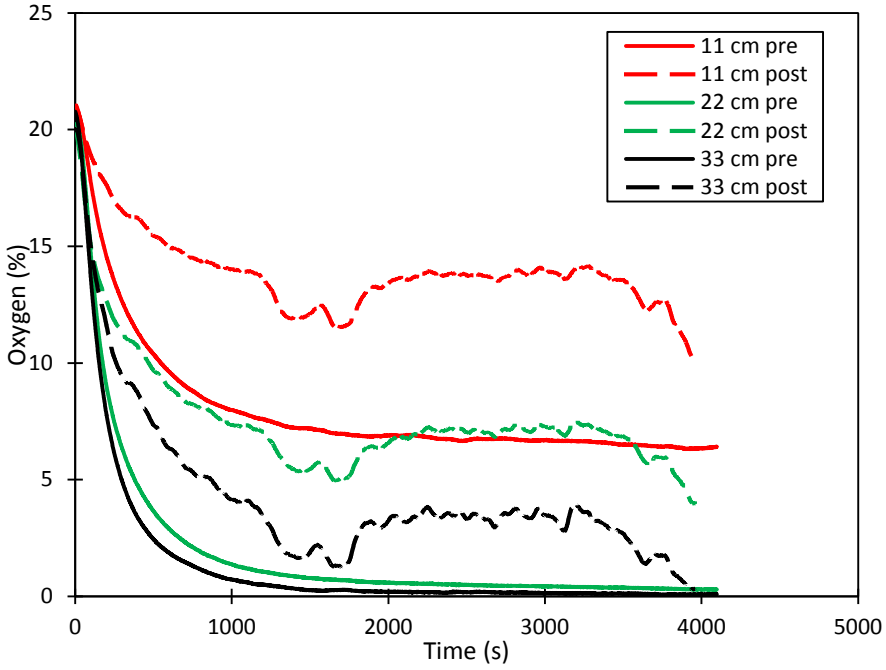

Figure F-11: Probe 2 Trial 1

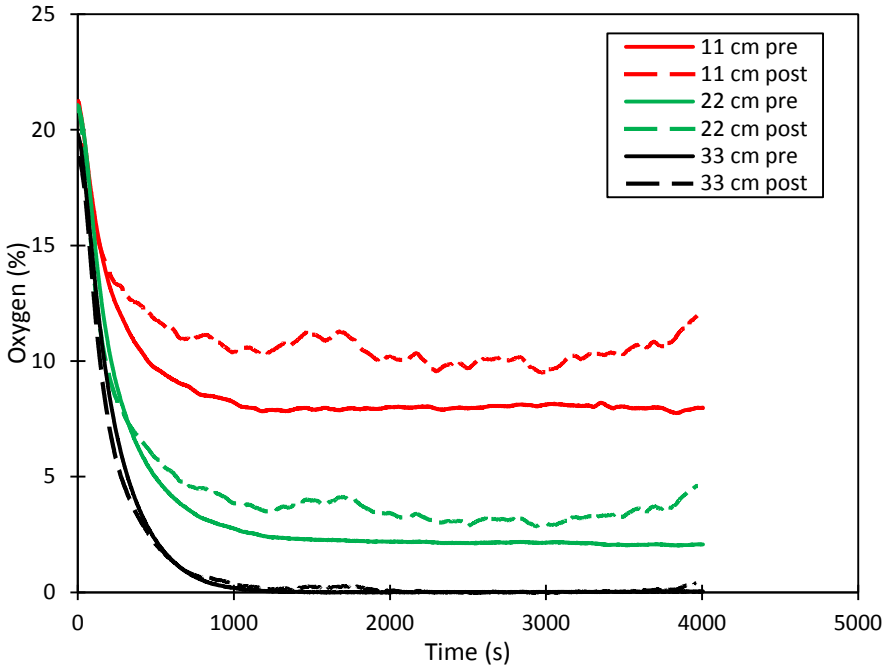

Figure F-12: Probe 3 Trial 1

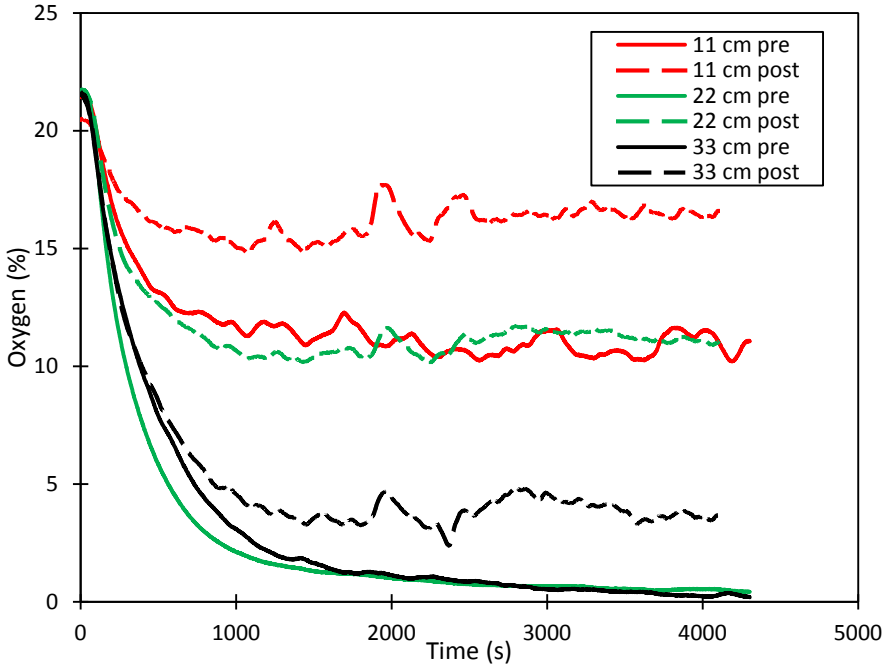

Figure F-13: Probe 1 Trial 2

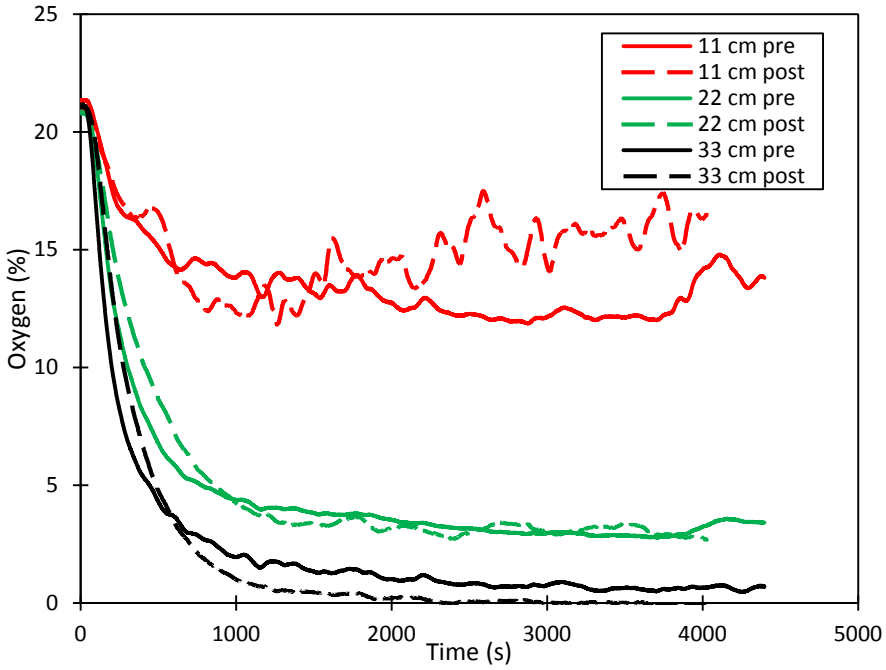

Figure F-14: Probe 2 Trail 2

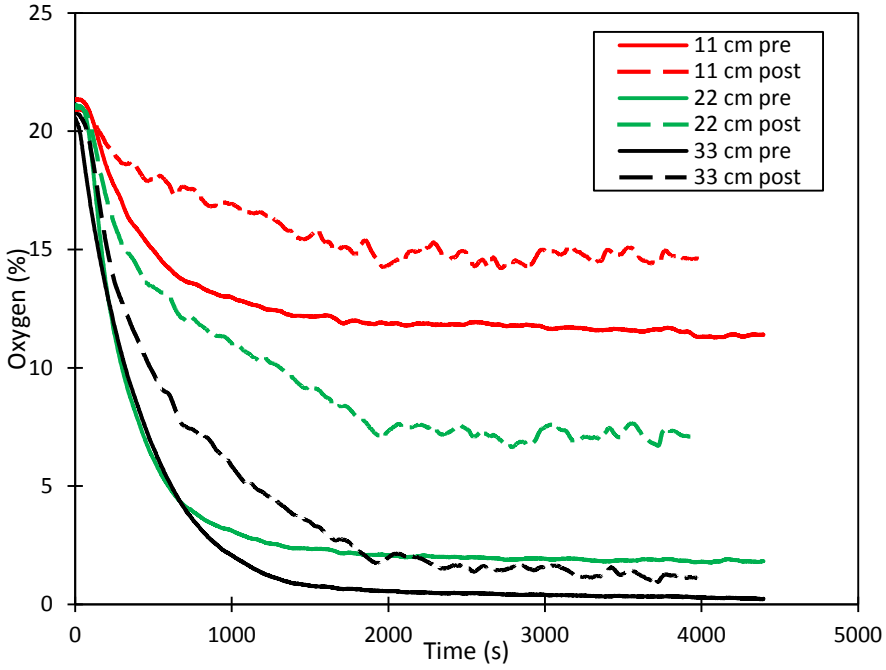

Figure F-15: Probe 3 Trail 2

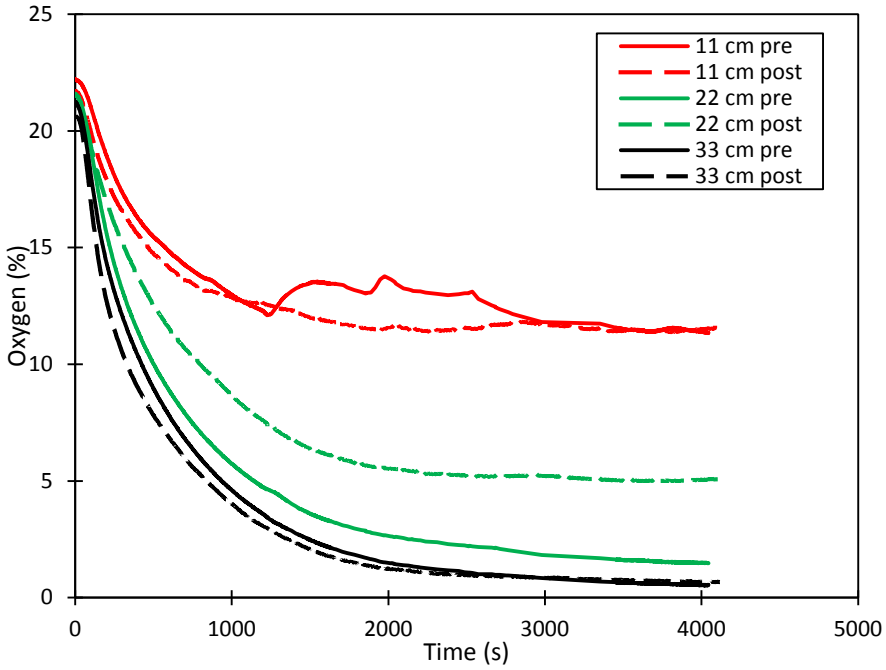

Figure F-16: Probe 1 Trial 3

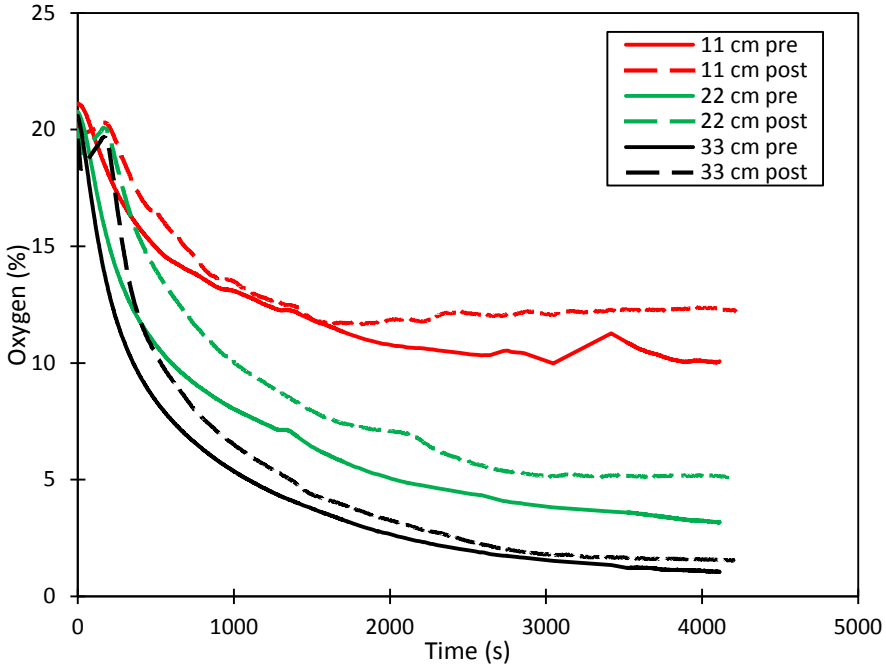

Figure F-17: Probe 2 Trial 3

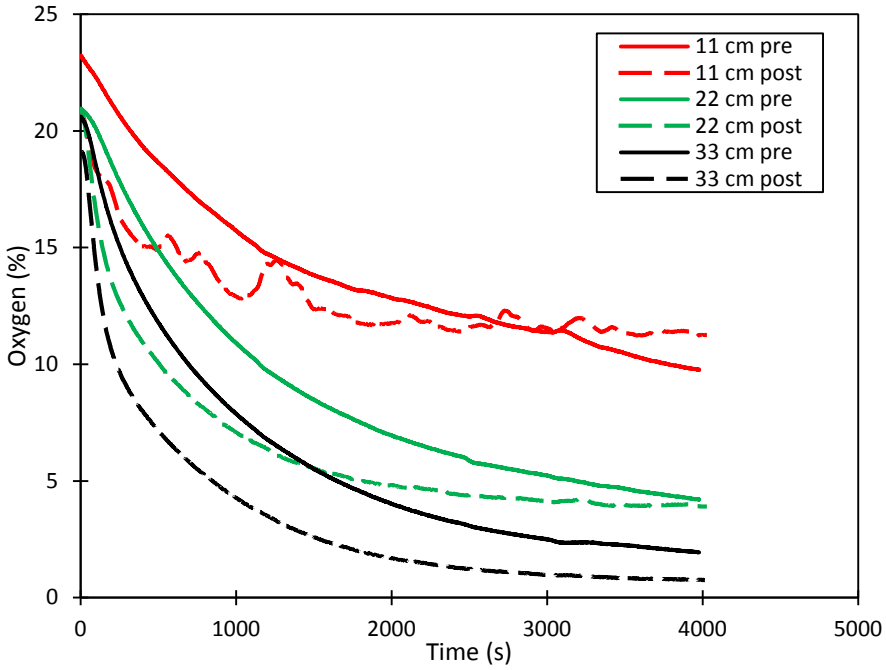

Figure F-18: Probe 3 Trial 3

A.3. Hybrid Tillage/Aeration Tool + Forced Air Injection

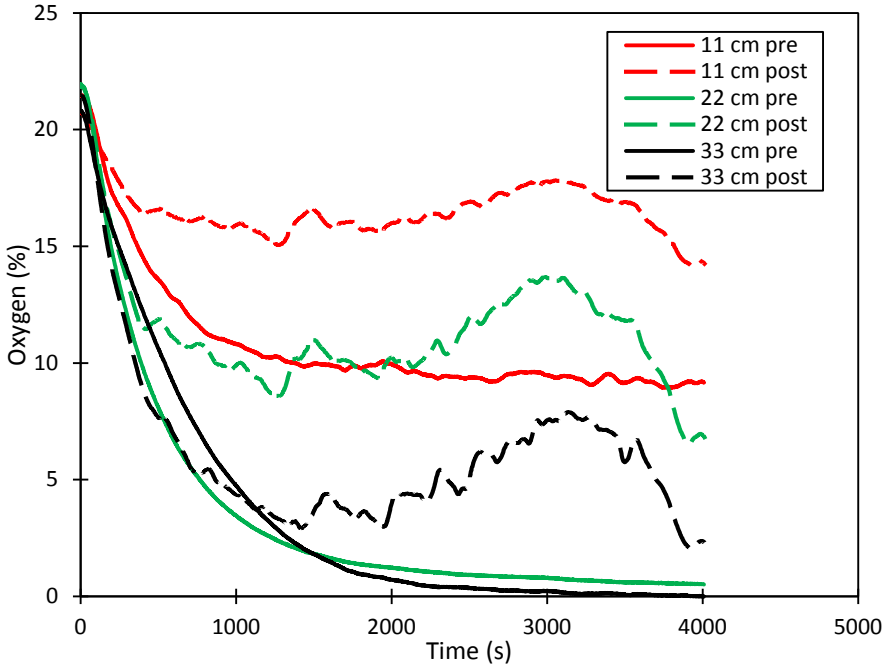

Figure F-19: Probe 1 Trial 1

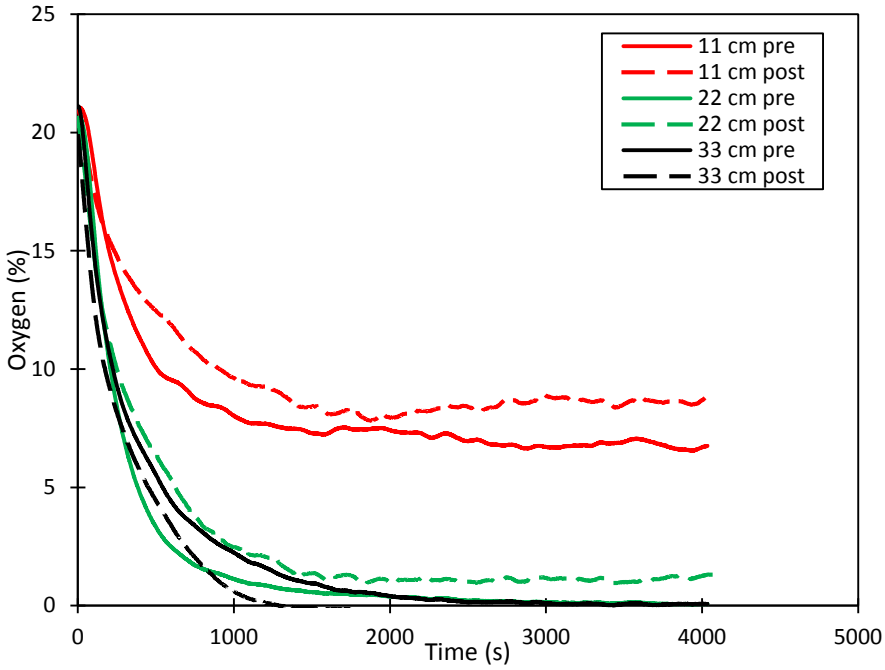

Figure F-20: Probe 2 Trial 1

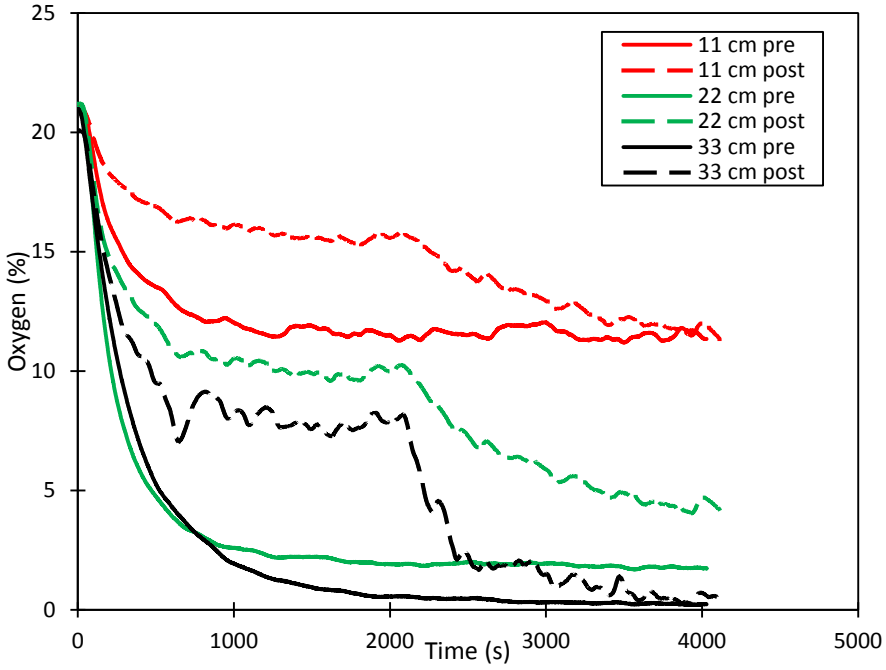

Figure F-21: Probe 3 Trial 1

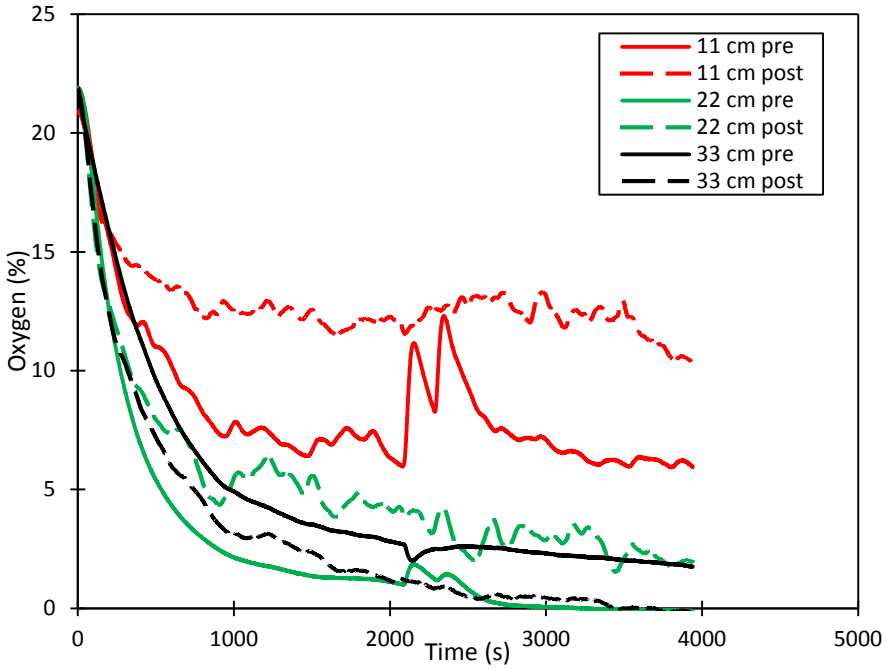

Figure F-22: Probe 1 Trial 2

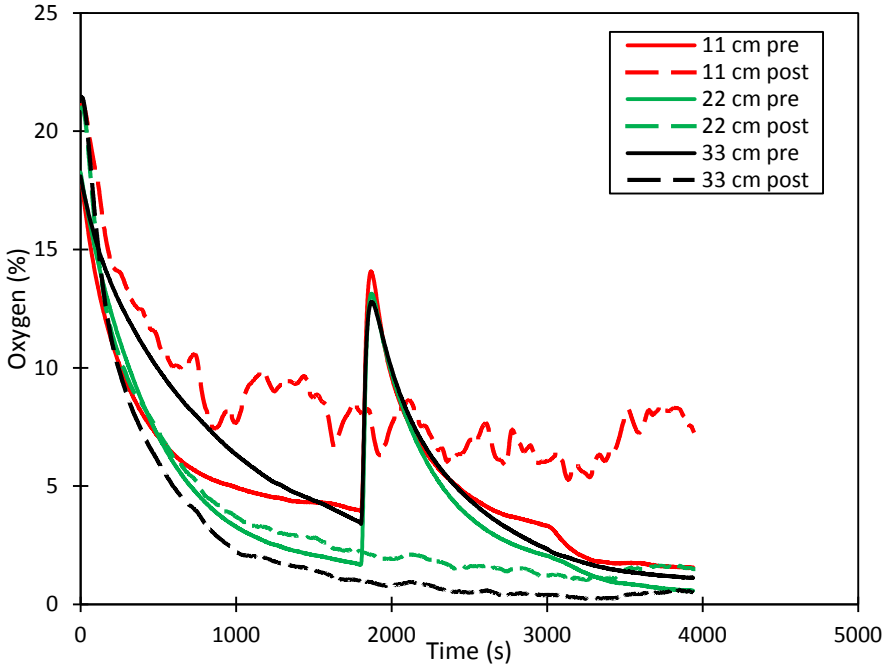

Figure F-23: Probe 2 Trial 2

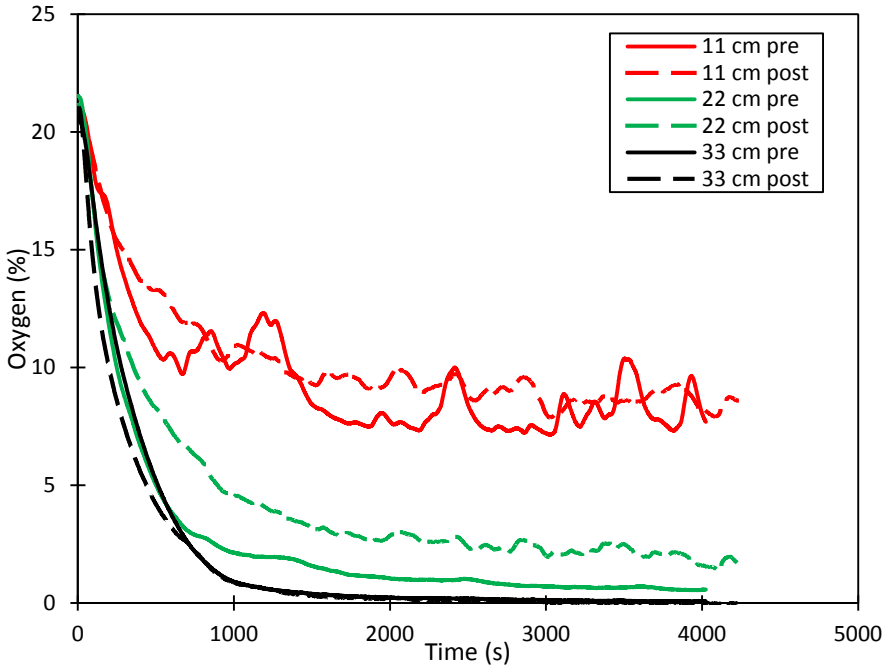

Figure F-24: Probe 3 Trial 2

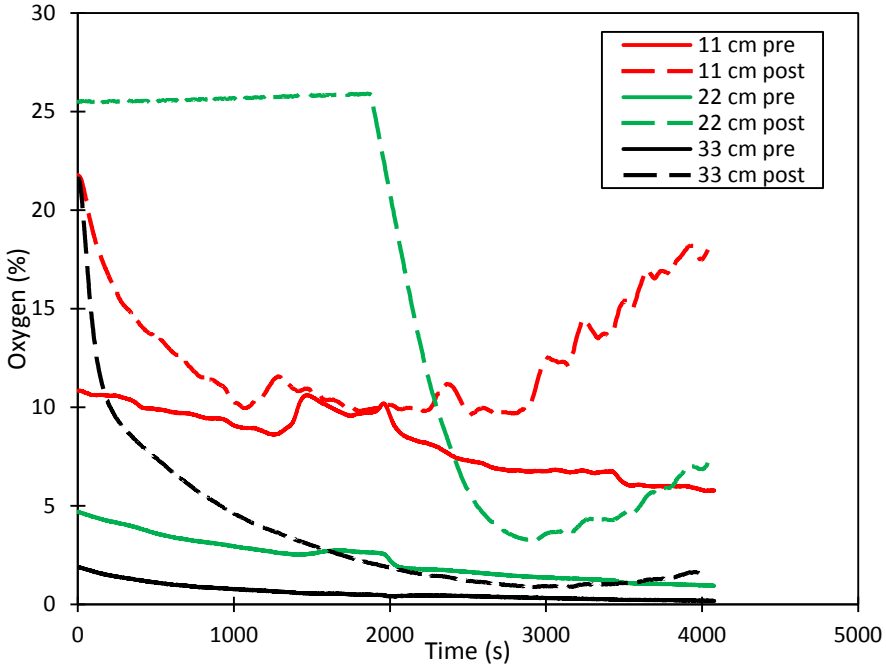

Figure F-25: Probe 1 Trial 3

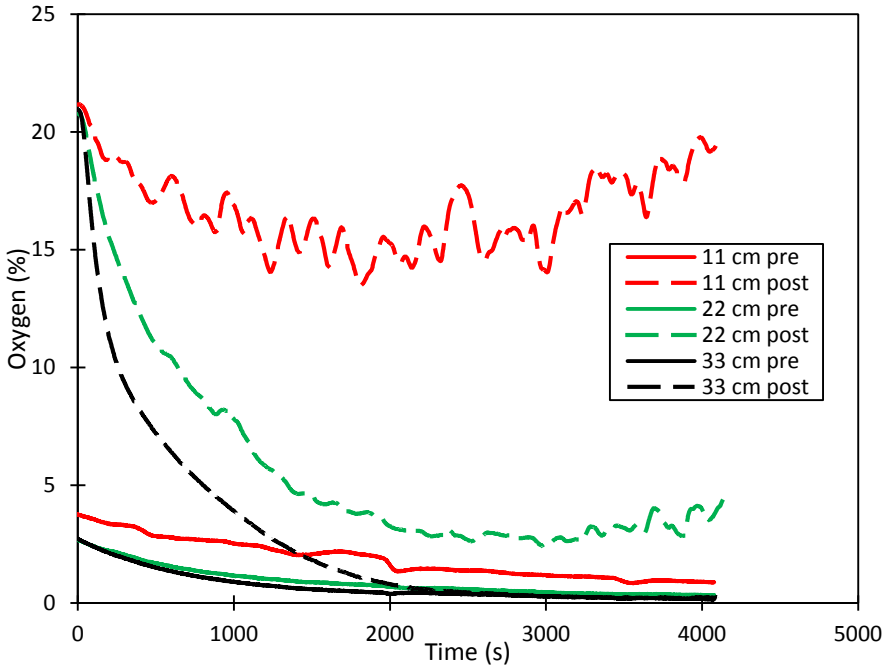

Figure F-26: Probe 2 Trial 3

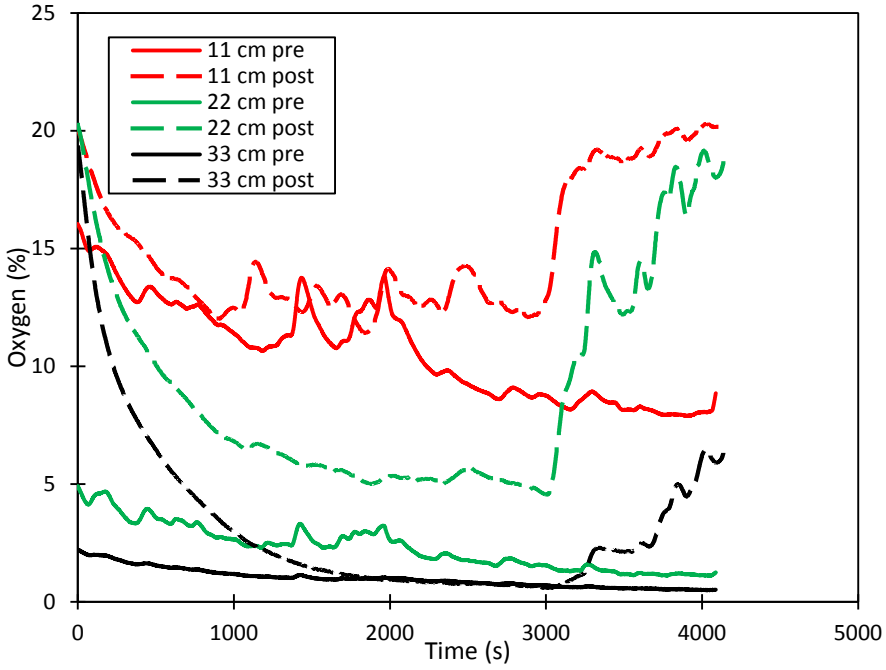

Figure F-27: Probe 3 Trial 3

Appendix G. O2 Probe Instrumentation:

Table G-1: PCB Controller Components

Components	Description	Manufacturer Part Number	Manufacturer
UC1	Digital Signal Processor	DSPIC30F4013-30I/PT	Microchip Technology
IA1 - IA9	Instrumentation Amplifier	INA333AIDGKR	Texas Instruments
CAN1	Male D-SUB 9 Connector	5747840-3	TE Connectivity
C21 - C25, C27 - C32	1 uF Capacitor (Ceramic 0603)	GRM188F51E105ZA12D	Murata Electronics North America
R1, R11 - R19, R21, R22, R26 -R29, R32 - R35, R38 - R41, R44, R45	10 K Resistor (Thick Film 0603	CRCW060310K0FKEA	Vishay Dale
R3, R5, R7, R8 - R10	412 Resistor (Thick Film 0603)	RC0603FR-07412RL	Yageo
R2, R4, R6	2.55 K Resistor (Thick Film 0603)	RC0603FR-072K55L	Yageo
D1	2A 40V Shottky Diode	CD1206-B240	Bournes Inc.
STAT	Blue LED (1206 3.3V)	LTST-C150TBKT	Lite-On Inc
SW1	SPST NO Tactile Switch	EVQ-PJJ04T	Lite-On Inc
J1 - J11	2 Position Jumper	382811-8	TE Connectivity
T1, T2, T3,T4,T5	3 Position Terminal Block	284392-3	TE Connectivity
T6, T7	2 Position Terminal Block	284392-2	TE Connectivity
T7	10 Position Terminal Block	1-284392-0	TE Connectivity
VR1	5.0V Linear Voltage Regulator	LM1084IS-5.0/NOPB	Texas Instruments
VR2	2.5V Linear Voltage Regulator	LM1086CS-2.5/NOPB	Texas Instruments
IC2	CAN Transceiver	MCP2551T-I/SN	Microchip Technology
IC1	RS-232 Level Shifter	MAX232DR	Texas Instruments
Q1 - Q12	PNP Transistor	MMBT3906	Fairchild Semiconductor
XTAL	15 Mhz Crystal Oscillator	HC49US-15.000MABJB	Citizen Finetech Miyota
COM1, COM2	Female D-SUB 9 Connector	1734354-1	TE Connectivity
ICSP	6P6C RJ-11 Jack	5520470-3	TE Connectivity
C1, C3	10 uF Capacitor (Tantalum 1210)	F931A106MBA	Nichicon
C2, C4	10 uF Capacitor (Tantalum 2312)	F931V106MCC	Nichicon
C5 - C17, C26	0.1 uF Capacitor (Ceramic 0603)	C1608X7R1H104K080AA	TDK Corporation
C19, C20	22 pF Capacitor (Ceramic 0603)	06035A220JAT2A	AVX Corporation
R24, R25, R30, R31, R36, R37, R42, R43	470 Resistor (Thick Film 0603)	CRCW0603470RJNEAHP	Vishay Dale
R23	120 Resistor (Thick Film 0603)	CRCW0603120RFKEA	Vishay Dale
R46, R47	4.7 K Resistor (Thick Film 0603)	CRCW06034K70FKEA	Vishay Dale
PWR	Red LED (1206 2V)	LTST-C150KRKT	Lite-On Inc
U1TX, U2TX, C1TX	Green LED (1206 2V)	LTST-C150KGKT	Lite-On Inc
U1RX, U2RX, C1RX	Yellow LED (1206 2.1V)	LTST-C150KSKT	Lite-On Inc

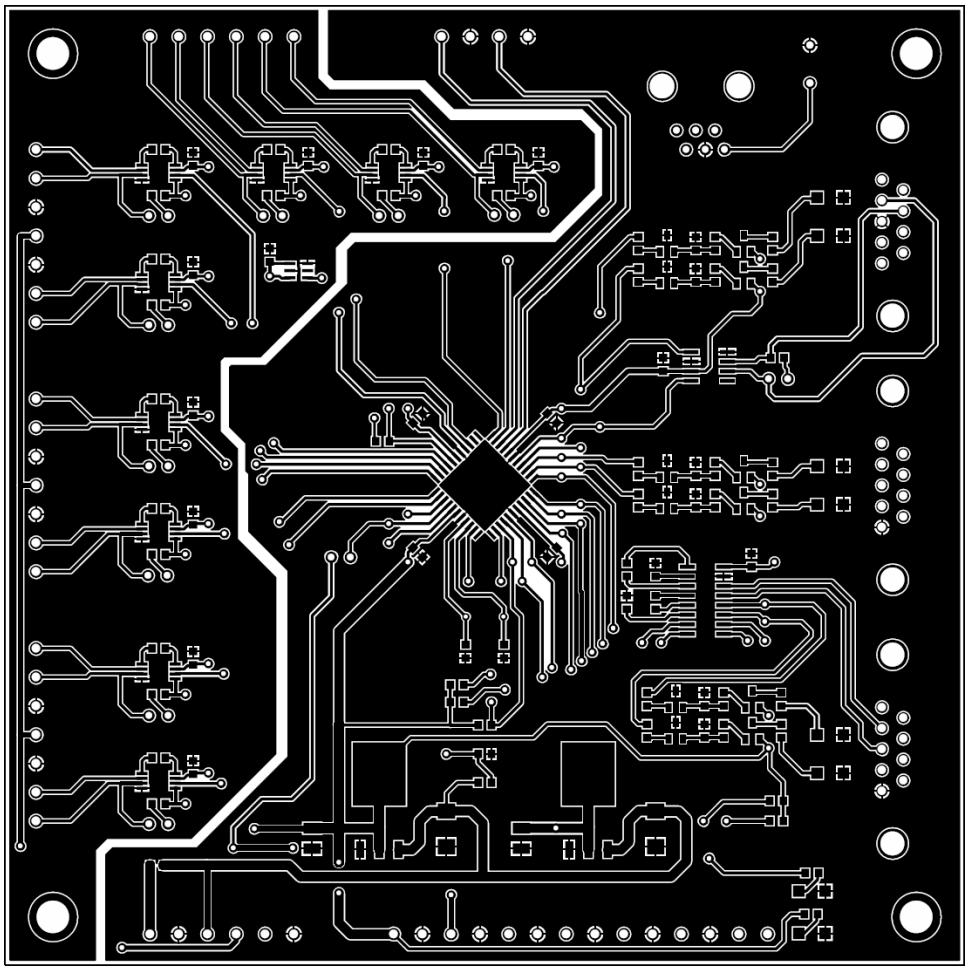

Figure G-1: PCB Top Copper Layer (Scale = 1:1)

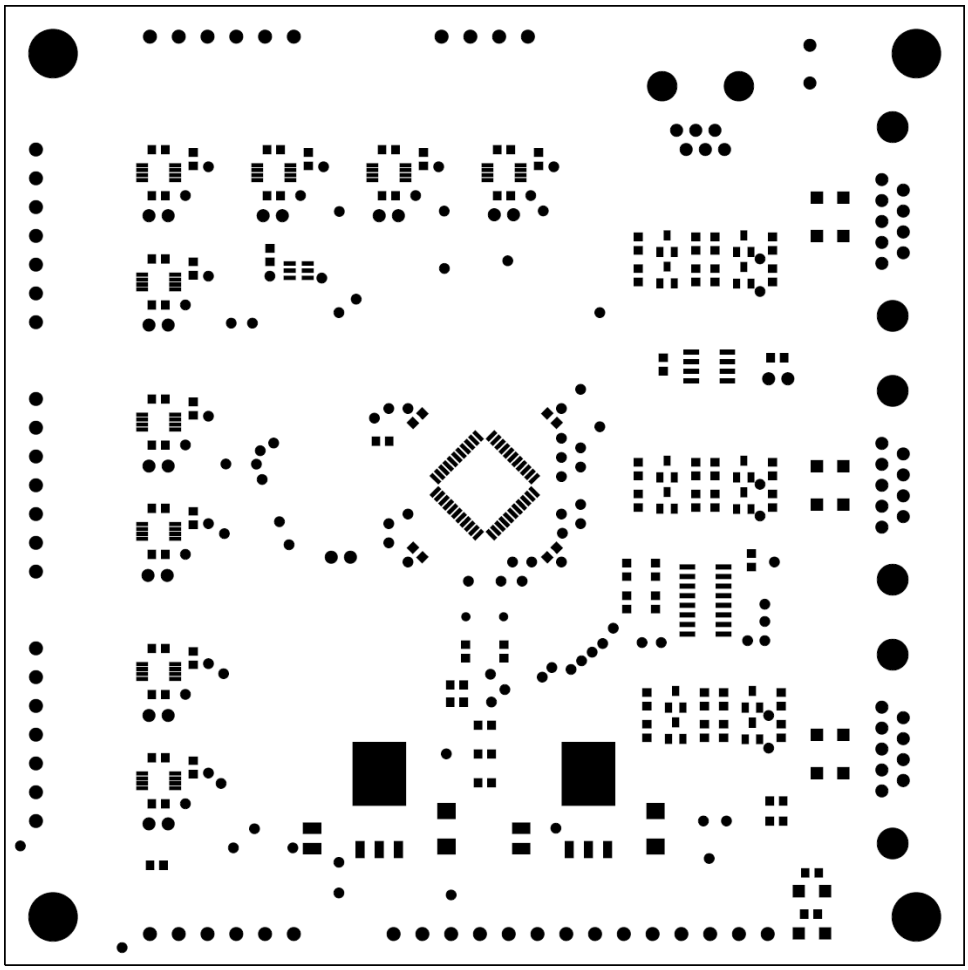

Figure G-2: PCB Top Solder Mask (Scale = 1:1)

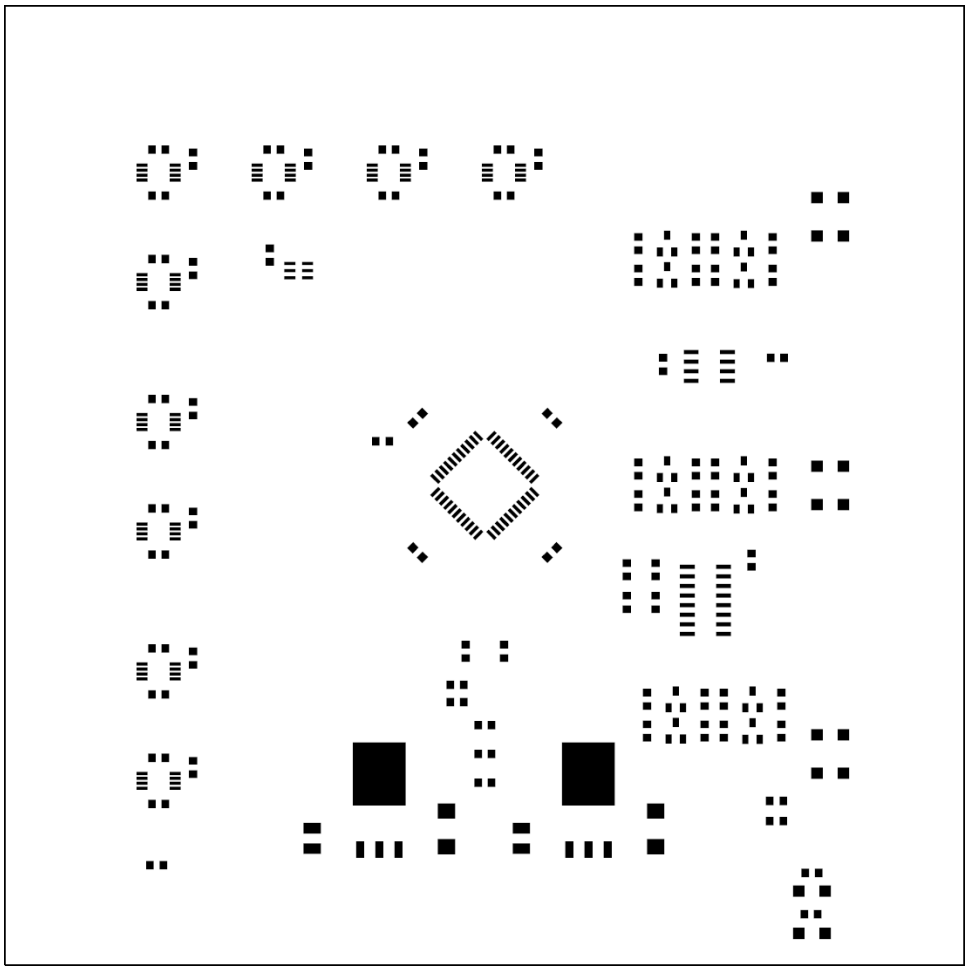

Figure G-3: PCB Top Paste Mask (Scale = 1:1)

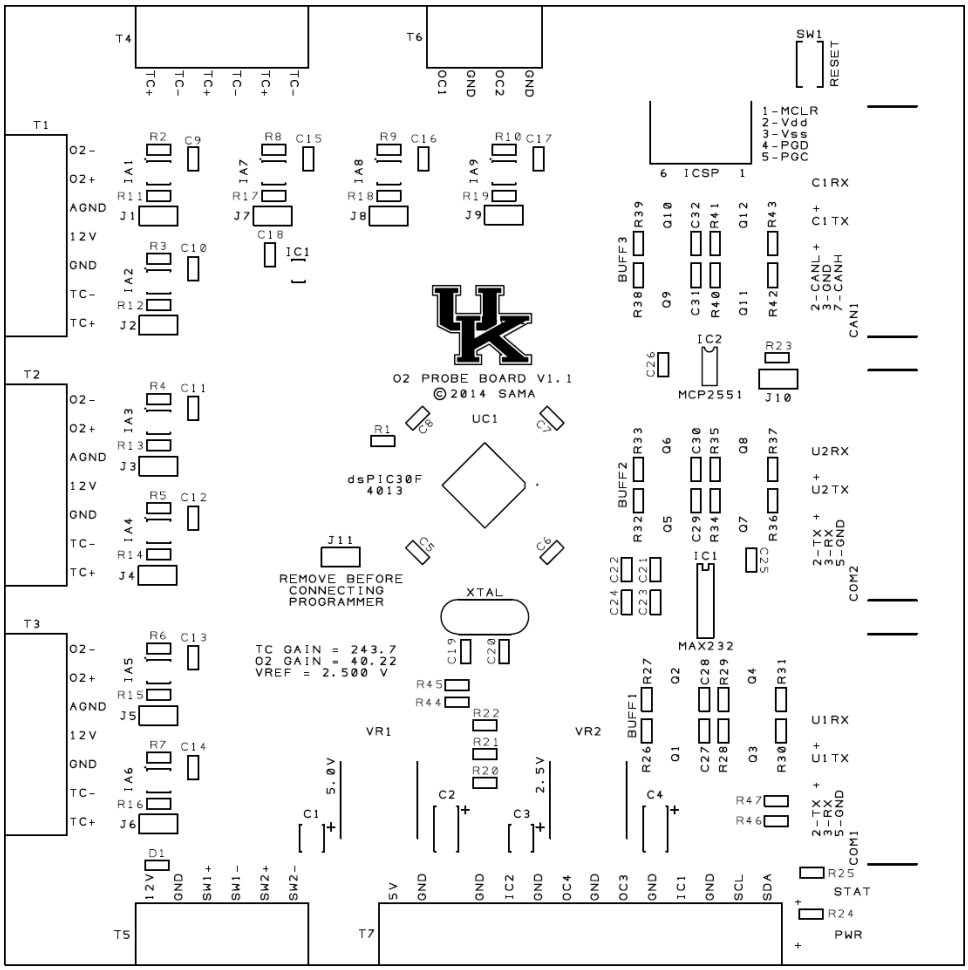

Figure G-4: PCB Top Silkscreen (Scale = 1:1)

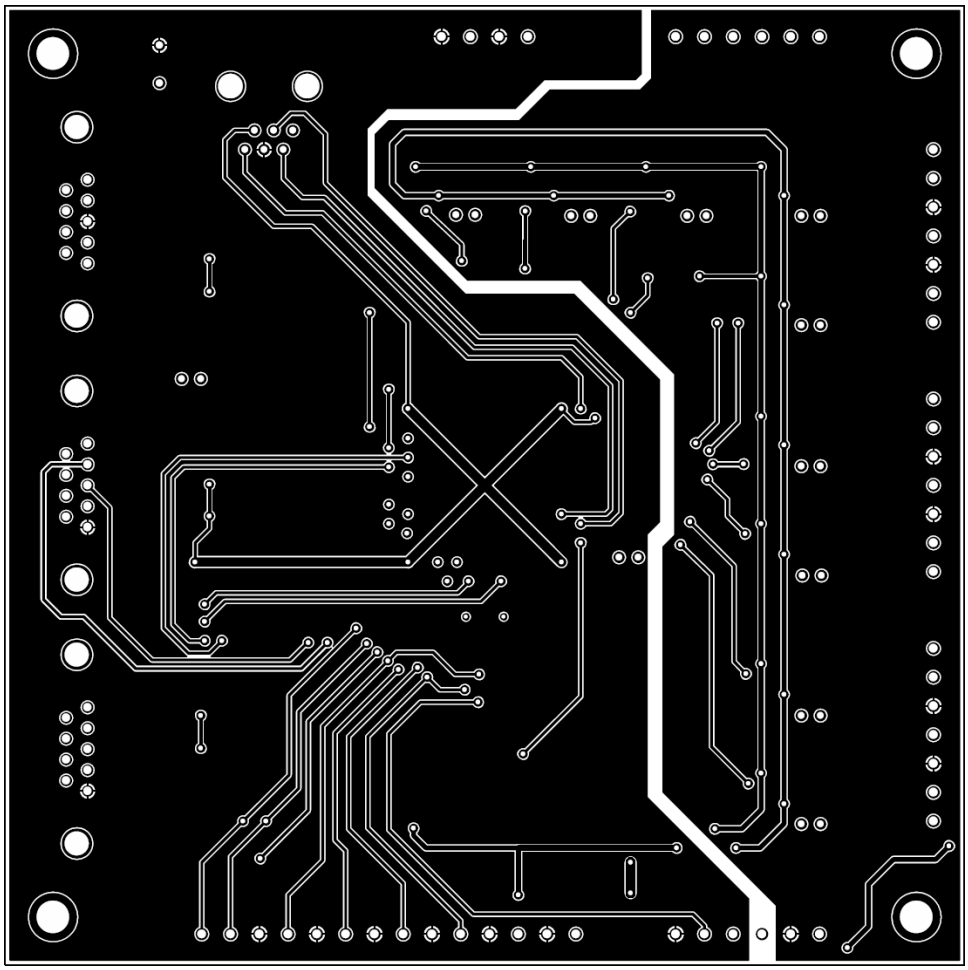

Figure G-5: PCB Bottom Copper Layer (Scale = 1:1)

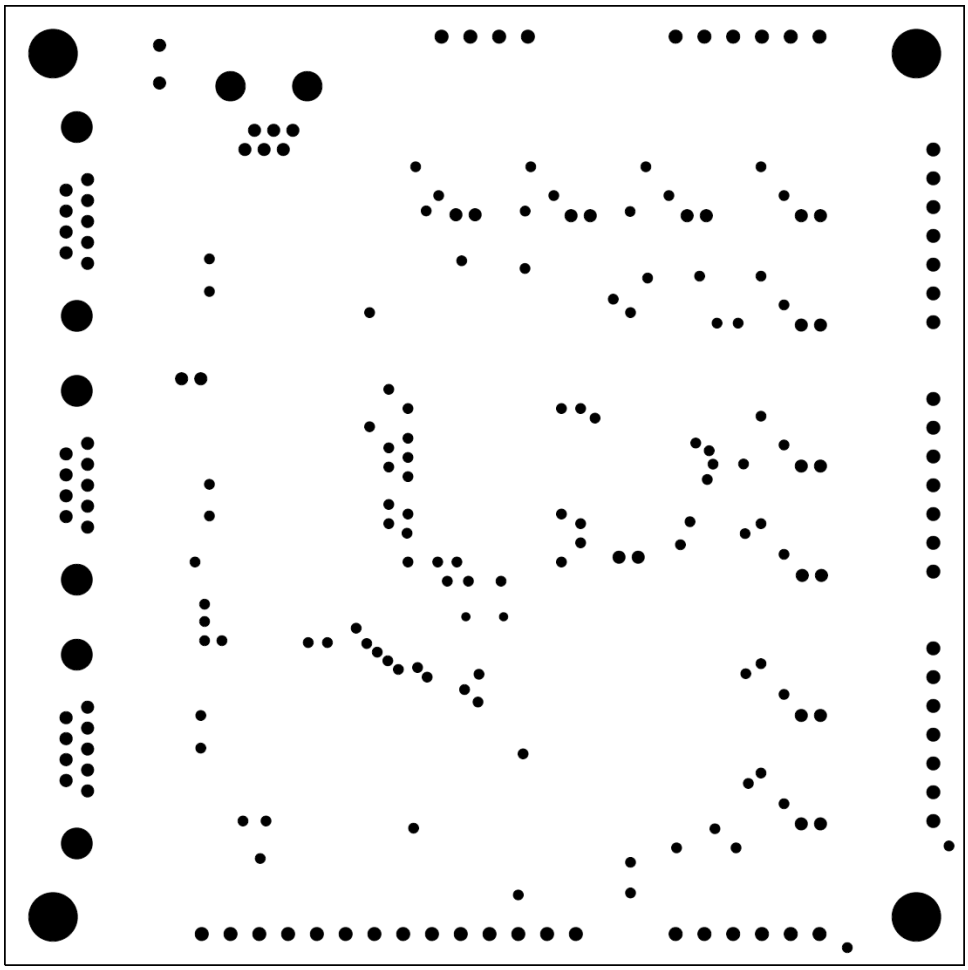

Figure G-6: PCB Bottom Solder Mask (Scale = 1:1)

Appendix F. O2 Controller Program

```
////////////////////////////////////////////////////
//    Title: main.c                                //
//    Author: Michael P. Sama, John T. Evans       //
//    Date: 09/15/2014                             //
////////////////////////////////////////////////////

#define SYSCLK    15000000UL  //Define the system clock speed as 15 MHz
#define FCY 3750000UL         //Define the instruction clock speed as
3.75 MHz

//Pin aliases
#define LED PORTFbits.RF6
#define SW  PORTAbits.RA11

//Include the following libraries
#include <p30fxxxx.h>         //Base library for the dsPIC30F4013
#include <libpic30.h>         //General c30 Functions (delays, etc.)
#include <uart.h>       //Universal Asynchronous Receiver/Transmiter
#include <stdio.h>            //Standard Input/Output
#include <string.h>           //String Manipulation
#include <math.h>             //Math Functions
#include "ANALOG.h"           //Custom A/D Conversion Class
#include "CHECKSUM.h"         //Custom Checksum Class

_FOSC(HS)   //Set the oscillator to external high speed crystal /2*16
(FOSC = 120 MHz, FCY = 30 MHz)
_FWDT(WDT_OFF)          //Turn off the watch dog timer

//Global Variables
char TXdata[128];       //data transmit string for RS-232
char RXdata[128];       //data receive string for RS-232
unsigned int res, REF;  //analog input temp variables
unsigned int A0,A1,A2,A3,A4,A5,A7,A8,A9,A10,A11,A12;  //analog input
variables
```

```
//Interrupt handler function prototypes
void __attribute__((__interrupt__)) _T1Interrupt(void);     //declare
the interrupt handler for Timer1

//Timer1 Interrupt Handler (1Hz)
void __attribute__((interrupt, no_auto_psv)) _T1Interrupt(void)
{
      IFS0bits.T1IF = 0;    /* Clear Timer interrupt flag */
      unsigned int n = 32;
      A0 = Samples(0,n);
      A1 = Samples(1,n);
      A2 = Samples(2,n);
      A3 = Samples(3,n);
      A4 = Samples(4,n);
      A5 = Samples(5,n);
      A7 = Samples(7,n);
      A8 = Samples(8,n);
      A9 = Samples(9,n);
      A10 = Samples(10,n);
      A11 = Samples(11,n);
      A12 = Samples(12,n);

      A7 = 2040; //Comment this line out after testing is done.

      sprintf(TXdata,"O2,1,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u",SW,A
0,A1,A2,A3,A4,A5,A7,A8,A9,A10,A11,A12);
      unsigned char Csum = CreateChecksum(TXdata);
      sprintf(TXdata,"$O2,1,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u,%u*%02X
\n\r",SW,A0,A1,A2,A3,A4,A5,A7,A8,A9,A10,A11,A12,Csum);
      putsUART1((unsigned int *) TXdata);
}

//Main Function
int main (void)
{

      TRISF = 0b0111111;          //Configure PORTF pin directions
```

```
//TRISD = 0b1111111111; //Configure PORTD pin directions:
TRISB = 0b1111111111111111;
ADPCFG = 0b0000000000000000;


//Open UART1 19200 8-N-1
OpenUART1 ( UART_EN &
                  UART_IDLE_CON &
                  UART_DIS_WAKE &
                  UART_DIS_LOOPBACK &
                  UART_DIS_ABAUD &
                  UART_NO_PAR_8BIT &
                  UART_1STOPBIT,
                  UART_INT_TX_BUF_EMPTY &
                  UART_TX_PIN_NORMAL &
                  UART_TX_ENABLE &
                  UART_INT_RX_CHAR &
                  UART_ADR_DETECT_DIS &
                  UART_RX_OVERRUN_CLEAR,
                  11);

U1MODEbits.ALTIO = 1;   //Set UART1 to the default pins

//Open UART2 115200 8-N-1
OpenUART2 ( UART_EN &
                  UART_IDLE_CON &
                  UART_DIS_WAKE &
                  UART_DIS_LOOPBACK &
                  UART_DIS_ABAUD &
                  UART_NO_PAR_8BIT &
                  UART_1STOPBIT,
                  UART_INT_TX_BUF_EMPTY &
                  UART_TX_PIN_NORMAL &
                  UART_TX_ENABLE &
                  UART_INT_RX_CHAR &
                  UART_ADR_DETECT_DIS &
                  UART_RX_OVERRUN_CLEAR,
                  11);
```

```
      //Configure Timer 1
      T1CONbits.TSIDL = 0;
      T1CONbits.TGATE = 0;
      T1CONbits.TCKPS = 2;    //Timer Input Clock Prescale bits set to
1:64
      T1CONbits.TSYNC = 0;
      T1CONbits.TCS = 0;            //Internal timer clock (FOSC/4)
      T1CONbits.TON = 1;

      PR1 = 58594;
      TMR1 = 0;
      IEC0bits.T1IE = 1;

      INTCON1     = 0b0000000000000000;   //Global interrupt settings
      INTCON2 = 0b0000000000000000;

      while(1)
      {
            LED = ~SW;
    }
      return 0;
}

////////////////////////////////////////////////////
//    Title: ANALOG.c                             //
//    Author: Michael P. Sama, John T. Evans      //
//    Date: 09/15/2014                            //
////////////////////////////////////////////////////

#include <p30fxxxx.h>
#include "ANALOG.h"
#include <libpic30.h>

unsigned int Sample(unsigned char channel)
{
      unsigned int result;
      ADCON3 = 0b0000001100010011;
```

```
      ADCON2 = 0b1000000000000000;
      ADCON1 = 0b1000000011100000;
      ADCHS = channel;
      ADCON1bits.SAMP = 1;
      while(ADCON1bits.DONE == 0);
      result = ADCBUF0;
      return result;
}

unsigned int Samples(unsigned char channel,unsigned int n)
{
      unsigned long results = 0;
      unsigned int result;
      unsigned int i;
      ADCON3 = 0b0000001100010011;
      ADCON2 = 0b0000000000000000;
      ADCON1 = 0b1000000011100000;
      ADCHS = channel;
      for (i=0; i<n; i++)
    {
            ADCON1bits.SAMP = 1;
            while(ADCON1bits.DONE == 0);
            results += (unsigned long) ADCBUF0;
      }
      result = (unsigned int)(results / (unsigned long) n);
      return result;

}

unsigned int DelayedSamples(unsigned char channel,unsigned int n,
unsigned long t)
{
      unsigned long results = 0;
      unsigned int result;
      unsigned int i;
      ADCON3 = 0b0000001100010011;
      ADCON2 = 0b0000000000000000;
      ADCON1 = 0b1000000011100000;
```

```
      ADCHS = channel;
      for (i=0; i<n; i++)
    {
            ADCON1bits.SAMP = 1;
            while(ADCON1bits.DONE == 0);
            results += (unsigned long) ADCBUF0;
            __delay32(t);
      }
      result = (unsigned int)(results / (unsigned long) n);
      return result;

}

////////////////////////////////////////////////////
//    Title: CHECKSUM.c                           //
//    Author: Michael P. Sama, John T. Evans      //
//    Date: 09/15/2014                            //
////////////////////////////////////////////////////

#include <p30fxxxx.h>
#include "CHECKSUM.h"
#include <stdio.h>
#include <string.h>

unsigned char CreateChecksum(char *message)
{
      char len = strlen(message);
      unsigned int i = 0;
      unsigned char TheChecksum = 0;
      for (i=0;i<len;i++)
      {
            TheChecksum ^= (unsigned char) message[i];
      }
      return TheChecksum;
}
////////////////////////////////////////////////////
//    Title: ANALOG.h                             //
//    Author: Michael P. Sama, John T. Evans      //
```

```
//    Date: 09/15/2014                                //
//////////////////////////////////////////////////////

//#ifndef __ANALOG_H
//#define __ANALOG_H

unsigned int Sample(unsigned char channel);
unsigned int Samples(unsigned char channel,unsigned int n);
unsigned int DelayedSamples(unsigned char channel,unsigned int
n,unsigned long t);

//////////////////////////////////////////////////////
//    Title: CHECKSUM.h                               //
//    Author: Michael P. Sama, John T. Evans          //
//    Date: 09/15/2014                                //
//////////////////////////////////////////////////////

//#ifndef __CHECKSUM_H
//#define __CHECKSUM_H

unsigned char CreateChecksum(char *message);
```

Figure G-7: Micro-Controller Code

BIBLIOGRAPHY

AMCA (1999). 210-99: Laboratory Methods of Testing Fans for Aerodynamic Performance Rating, AMCA.

ANSI/ASAE (2012). Moisture Measurement - Forages **S358.3**.

Baratieri, M., P. Baggio, L. Fiori and M. Grigiante (2008). "Biomass as an energy source: Thermodynamic constraints on the performance of the conversion process." Bioresource Technology **99**(15): 7063-7073.

Barberg, A. E., M. I. Endres and K. A. Janni (2007). "Compost dairy barns in Minnesota: A descriptive study." Applied Engineering in Agriculture **23**(2): 231-238.

Barberg, A. E., M. I. Endres, J. A. Salfer and J. K. Reneau (2007). "Performance and Welfare of Dairy Cows in an Alternative Housing System in Minnesota." Journal of Dairy Science **90**(3): 1575-1583.

Bewley, J. and J. Taraba (2013). "Guidelines for Managing Compost Bedded-Pack Barns." THE DAIRY PRACTICES COUNCIL.

Bewley, J., J. Taraba, G. Day and F. Damasceno (2010). "Compost Bedded Pack Barn Design ".

Black, R., J. Bewley, J. Taraba, G. Day and F. Damasceno (2013). "Kentucky compost-bedded pack barn project." Cooperative extension service, University of Kentucky, College of agriculture, Lexington, KY, USA.

Black, R. A. (2013). Compost Bedded Pack Barns: Management Practices and Economic Implications, Universtiy of Kentucky

Brooker, D. B., F. W. Bakker-Arkema and C. W. Hall (1992). Drying and Storage of Grains and Oilseeds

Cha, E., J. A. Hertl, D. Bar and Y. T. Gröhn (2010). "The cost of different types of lameness in dairy cows calculated by dynamic programming." Preventive Veterinary Medicine **97**(1): 1-8.

Clarkson, M., D. Downham, W. Faull, J. Hughes, F. Manson, J. Merritt, R. Murray, W. Russell, J. Sutherst and W. Ward (1996). "Incidence and prevalence of lameness in dairy cattle." The veterinary record **138**(23): 563-567.

Cook, N. B. (2003). "Prevalence of lameness among dairy cattle in Wisconsin as a function of housing type and stall surface." Journal of the American Veterinary Medical Association **223**(9): 1324-1328.

Damasceno, F. A. (2012). Compost bedded pack barns system and computational simulation of airflow through naturally ventilated reduced model., University of Kentucky.

Das, K. and H. M. Keener (1997). "Moisture effect on compaction and permeability in composts." Journal of environmental engineering **123**(3): 275-281.

Eckelkamp, E. (2014). COMPOST BEDDED PACK BARNS FOR DAIRY CATTLE: BEDDING PERFORMANCE AND MASTITIS AS COMPARED TO SAND FREESTALLS, University of Kentucky.

El Kader, N. A., P. Robin, J.-M. Paillat and P. Leterme (2007). "Turning, compacting and the addition of water as factors affecting gaseous emissions in farm manure composting." Bioresource Technology **98**(14): 2619-2628.

ESRI (2009). ArcGIS. Redlands, California., ESRI (Environmental Systems Resource Institute). .

Galama, P. (2011). Prospects for bedded pack barns for dairy cattle.

Green, L. E., V. J. Hedges, Y. H. Schukken, R. W. Blowey and A. J. Packington (2002). "The Impact of Clinical Lameness on the Milk Yield of Dairy Cows." Journal of Dairy Science **85**(9): 2250-2256.

Haug, R. T. (1995). The Practical Handbook of Compost Engineering, Lewis Publishers.

Hogan, J., F. Miller and M. Finstein (1989). "Physical modeling of the composting ecosystem." Applied and Environmental Microbiology **55**(5): 1082-1092.

Janni, K. A., M. I. Endres, J. K. Reneau and W. W. Schoper (2007). "Compost dairy barn layout and management recommendations." Applied Engineering in Agriculture **23**(1): 97-102.

Kashmanian, R. M. and R. F. Rynk (1996). "Agricultural composting in the United States: Trends and driving forces." Journal of soil and water conservation **51**(3): 194-201.

Kleinman, P. J. and A. N. Sharpley (2003). "Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events." Journal of Environmental Quality **32**(3): 1072-1081.

Kuter, G., H. Hoitink and L. Rossman (1985). "Effects of aeration and temperature on composting of municipal sludge in a full-scale vessel system." Journal (Water Pollution Control Federation): 309-315.

Liang, D. (2013). Estimating the economic losses from diseases and extended days open with a farm-level stochastic model, University of Kentucky.

Lobeck, K. M., M. I. Endres, E. M. Shane and S. M. Godden (2011). "Animal welfare in cross-ventilated, compost-bedded pack, and naturally ventilated dairy barns in the upper Midwest."

Michel, F. C., J. A. Pecchia, J. Rigot and H. M. Keener (2004). "Mass and nutrient losses during the composting of dairy manure amended with sawdust or straw." Compost science & utilization **12**(4): 323-334.

Oppenheimer, J. R., A. G. Martin and L. P. Walker (1997). "Measurements of air-filled porosity in unsaturated organic matrices using a pycnometer." Bioresource Technology **59**(2–3): 241-247.

Popescu, S., C. Borda, E. A. Diugan, M. Spinu, I. S. Groza and C. D. Sandru (2013). "Dairy cows welfare quality in tie-stall housing system with or without access to exercise." Acta Veterinaria Scandinavica **55**(1): 43.

Rynk, R. (1992). "On-farm composting handbook."

Shane, E., M. Endres, D. Johnson and J. Reneau (2010). "Bedding options for an alternative housing system for dairy cows: A descriptive study." Applied engineering in agriculture.

Shane, E. M., M. I. Endres, D. G. Johnson and J. K. Reneau (2010). "BEDDING OPTIONS FOR AN ALTERNATIVE HOUSING SYSTEM FOR DAIRY COWS: A DESCRIPTIVE STUDY." Applied Engineering in Agriculture **26**(4): 659-666.

USDA (2007). Part I: Reference of Dairy Cattle Health and Management Practices in the United States, 2007.

USDA (2007). "Part IV: Reference of Dairy Cattle Health andManagement Practices in the United States."

Van Ginkel, J. T., I. A. Van Haneghem and P. A. C. Raats (2002). "SE–Structures and Environment: Physical Properties of Composting Material: Gas Permeability, Oxygen Diffusion Coefficient and Thermal Conductivity." Biosystems Engineering **81**(1): 113-125.

Wagner, P. E. (2002). " Bedded Pack Shelters." Lancaster Farming **47(20)**(36).

Warnick, L. D., D. Janssen, C. L. Guard and Y. T. Gröhn (2001). "The Effect of Lameness on Milk Production in Dairy Cows." Journal of Dairy Science **84**(9): 1988-1997.

Wiederholt, R., S. Rahman and A. Ehni (2011). "Calculating Energy Efficiency of Applying Fresh and Composted Manure to Soil." GIS Applications in Agriculture, Volume Two: Nutrient Management for Energy Efficiency **2**: 265.

VITA

PLACE OF BIRTH

Lexington, KY

EDUCATION

B.S. 2013: University of Kentucky – Biosystems and Agricultural Engineering

ADVISING

Advisor, UK Quarter Scale Tractor Team, 2013 – Current

PROFESSIONAL MEMBERSHIP

American Society of Agricultural and Biological Engineers

Alpha Epsilon: The Honor Society of Agricultural, Food, and Biological Engineering