Development and assessment of unconventional mortality management for swine

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

A foreign animal disease outbreak or other catastrophic event impacting the swine industry may require the need to depopulate facilities, resulting in large numbers of mortalities. If these mass mortalities are responded to improperly, an economic burden and threat to biosecurity will be created. Current methods to dispose of swine mortalities include composting bins for routine carcass disposal, composting windrows, shallow burial, landfill disposal, rendering for non-infected carcasses, and incineration. However, these existing methods pose a risk to biosecurity if the animals were diseased with a highly pathogenic virus. Removing carcasses from an infected facility poses an immediate threat to biosecurity because of the exposure of the pathogen to the environment via air, water, soil, vegetation, or fomites (i.e., people, vehicles, and carcass handling equipment); therefore, more biosecure methods of mortality management strategies are needed for swine. The goals of this thesis research were to create a novel mobile test facility replicating a typical swine finishing barn, validate the facility performance, and execute tests for in-barn carcass management strategies to characterize carcass response. This thesis describes the design, construction, and validation of a mobile two-room swine production discovery lab with an instrumentation room. The laboratory featured a concrete slatted floor with a pit and ventilation system comprised of an unvented forced air combustion furnace, exhaust fan, and bi-flow actuated attic inlet in each discovery room. The discovery rooms were remotely monitored and controlled by a building automation controller in the instrumentation room of the laboratory. Validation and quantification of discovery room characteristics demonstrates functional performance and capability of the laboratory to conduct varying types of experimentation and under a range of operating conditions. The inclusion of environmental sensing equipment allows thermal and other environmental parameters to be

monitored. This data allowed comparison of environmental effects seen in each discovery room based on carcass treatment for mortalities. Knowledge of environmental impacts on building construction and gas and odor production of carcass management in-barn will help inform future research for in-barn carcass management strategies. Additionally, knowledge of carcass decomposition rates and internal carcass temperature will help gauge when mortalities can be removed from group-housed confinements to continue decomposing using an established carcass management method. This research will assist the swine industry by providing more biosecure in-barn alternatives to carcass management than existing methods in the event of a disease outbreak or other mass mortality event. This thesis will advance the existing knowledge of in-barn strategies for swine and, if adopted, will aid in reducing potential disease spread due to poor carcass management.

CHAPTER 1. GENERAL INTRODUCTION

As the global population continues to rise, demand for animal protein increases as well, specifically, with the demand for pork products projected to rise 0.8% annually until 2030 (FAO, 2003). To meet these demands under additional consumer pressure for sustainably and enhanced animal welfare, it is critical that all inputs to the animal agriculture system result in usable outputs. Animal diseases which lead to mass mortality are an immense detriment to food security and economic prosperity of animal agriculture. Additionally, as animal production facilities become increasingly intensified, the risk of disease spread to nearby operations rises. The inventory of pigs in Iowa is 23 million, or about 30% of the total US inventory (NASS, 2017). With this type of intensive production, a foreign animal disease (FAD) outbreak or other disruptive event in animal agriculture will affect swine dense regions more severely. Resulting mortalities of the event will accumulate in large numbers in a concentrated region, causing stress on the resources of the area and making a FAD more difficult to control.

In the event of a FAD outbreak, it is important to eliminate the disease before it spreads to other operations. While limiting disease spread often requires depopulation and results in a loss of usable animal protein, it is a proven method for controlling the spread of FADs. For FADs without treatment or vaccine, depopulation can protect surrounding operations. Depopulation, or other types of “stamping out” approaches, is often the recommended form of disease control by the USDA (DeOtte Jr. & DeOtte III, 2010), and is the defined response strategy for African Swine Fever (ASF; USDA, 2020). Defined and approved methods for swine depopulation include electrocution, captive bolt, gunshot, and chemical or injectable euthanasia agents (USDA, 2015). Regardless of technique, carcasses must be properly managed to ensure complete virus inactivation.

If animal mortalities resulting from depopulation are managed improperly, the FAD can be exposed to the environment, including soil and water, and nearby swine populations; thereby rapidly becoming difficult to control and immediately having negative implications for trade, and soon followed by consequences for domestic prices and consumer perception (Harper, DeRouchey, Glanville, Meeker, & Straw). Hence, economical and biosecure carcass management methods are needed. Mortality disposal via composting, burial, and incineration all present challenges and pose a risk to biosecurity in the event of dealing with a FAD such as ASF (USDA, 2020). Blood, tissues, and excretions from living or deceased animals can be a source of ASF and other FADs, which can be spread via biological vectors such as ticks, or fomites such as people, vehicles, implements, and wildlife (OIE, 2019). Therefore, achieving inactivation is critical before allowing carcasses or leachate to be exposed to transmissive agents. For this reason, methods for in-barn carcass-management to improve biosecurity are worth additional exploration.

Management, control practices, and preparedness in the US were recently tested during outbreaks of highly pathogenic avian influenza and Newcastle disease, and areas where planning and research for in-barn carcass management response are still needed were emphasized (Hagerman & Marshall, 2020). Lessons learned from these outbreaks can be applied to the swine industry to identify where areas of planning and information can be enhanced. Improvements ahead of a FAD outbreak will allow producers to make informed decisions for carcass management. Some aspects of carcass management are already well established, such as critical temperatures for virus inactivation, but some unexplored, or undefined, factors of managing carcasses in-barn exist. These include odor levels, gas production, the rate at which carcasses

decompose, the amount of leachate than can be expected, and the feasibility of managing carcasses on concrete slats with a pit.

Objectives

The overall goal of this thesis is to characterize carcass response and environmental conditions of in-barn carcass management for swine in the event of a mass mortality event. The specific objectives of the research were to 1) design and construct a mobile, swine finishing lab with concrete slats and a pit, capable of heating and ventilation, and validate the function of the lab and components; and 2) perform high-temperature trials with swine carcasses in the mobile lab, collecting leachate from individual animals and monitoring tissue temperatures, supplemental heat, and air quality.

Thesis Organization

Chapter 1 provides a brief introduction and rational for the research. Chapter 2 summarizes past literature regarding risks associated with mortality management in response to swine disease outbreaks, discusses criteria needed for pathogen inactivation, reviews current carcass disposal methods, discusses methods for modeling decomposition rates for pigs, and summarizes construction of typical swine buildings. Chapter 3 discusses design and construction of a general-purpose laboratory for small-scale in-barn swine production discoveries, which was submitted to Applied Engineering in Agriculture. Chapter 4 documents finishing pig carcass response during a 16-day study in January 2021. Finally, Chapter 5 provides a summary of the thesis and suggestions for future work.

CHAPTER 2. LITERATURE REVIEW

Disease Outbreaks and Risks

Animal disease outbreaks have increased in recent years and this trend is expected to continue in the future. Risks such as increased global travel, movements of animals and meat, wildlife interactions, growth of small-scale operations, and survivability of some viruses contribute to the rise of FAD outbreaks (Hagerman & Marshall, 2020). This jeopardizes animal health, food safety, the economy, and environment. Additionally, intensified livestock production facilities impact the ways diseases are spread because of concentrated animal populations; therefore, to limit further disease spread, definition of the way dead and diseased animals are managed is needed (Wilkinson, et al., 2011). Common traditional approaches for carcass management include composting, incineration, and burial but some diseases may require more biosecure methods to control. For example, failure to control ASF in the US could result in pork industry revenue losses of $50 billion and 140,000 jobs nationwide, while proper controlling of the virus after two years will result in losses of $15 billion and almost no permanent job loss (Carriquiry, Elobeid, Swenson, & Hayes, 2020).

Catastrophic mortality events will have economic consequences and the disposal of carcasses may threaten public health and the environment, including air and water resources (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005). During the ASF outbreak in China beginning in 2018, the virus was difficult to kill in the environment, even post-euthanasia and after removal of infected pigs (Hagerman & Marshall, 2020). In the scenario of an ASF outbreak or other highly infectious diseases, it will be imperative to dispose of carcasses in a timely, cost-effective, environmentally conscience, and biosecure manner (Tablante & Malone, 2005). Valuable lessons can be learned from the poultry industry after experiencing the worst disease

outbreak in US history. Prior to the 2014 to 2015 outbreak of HPAI in the US, the US government and poultry industry stockpiled equipment and supplies and created response plans. Although the poultry industry was challenged with these outbreaks, the preparedness allowed the response strategies to be successful and no disease re-introductions occurred on restocked farms (Hagerman & Marshall, 2020).

Pathogen Inactivation

Following a disease outbreak and depopulation, containment and treatment of carcasses by subjection to heat or disinfecting agents to control pathogen and viral populations are critical to minimize the risk of disease transmission to other populations. The long-standing policy of the USDA regarding an outbreak of a highly infectious animal disease has been "stamping out," which entails depopulation of infected animals as well those that have been exposed (USDA, 2015). Additionally, this approach incurs massive costs to the industry, including costs for disposal of large numbers of animals and cleaning and disinfection of equipment used for disposal, as well as placing a strain on resources in an area (DeOtte Jr. & DeOtte III, 2010).

ASF is resistant to low temperatures but is inactivated at temperatures of 56°C for 70 minutes or 60°C for 20 minutes (OIE, 2019). A pH less than 3.9 or greater than 11.5 will also inactivate ASF (OIE, 2019). The US Environmental Protection Agency (EPA) defines standards for pathogen reduction in biosolids as Class A and Class B criteria. To meet criteria for Class B pathogen reduction during composting, a windrow compost pile must be maintained at 40°C for five consecutive days, with 4 hours during that period reaching 55°C (US EPA, 2003). If a virus becomes aerosolized, it remains relatively unaffected during dispersion because inactivation is unlikely to occur at temperatures below 33°C and relative humidity above 60% (Daggupaty & Sellers, 1990). Additionally, a disease like ASF remains viable in blood, feces, and tissues in alive and deceased animals with the potential to multiply if not properly managed or inactivated

(OIE, 2019). Considering the mechanics of disease transmission and the extent the virus remains viable, vectors such as vehicles, implements, and clothes pose a threat to further disease spread. For this reason, the potential to inactivate pathogens in carcasses before exposure to fomites is desirable in mortality management.

Carcass Disposal Methods

Many carcass disposal methods currently exist for swine mortalities. However, each presents challenges associated with logistics, cost, availability, and biosecurity of containing pathogens during disposal. The most common methods currently used for swine mortalities include composting, burial, rendering, incineration, and landfill disposal. In-house strategies were widely used for recent poultry mass mortality events but remain relatively unexplored for swine. This chapter will discuss current methods of swine carcass disposal and compare with examples from the poultry industry for in-house mortality management.

Burial

While it is one of the simplest approaches, disposing of carcasses via burial presents enormous costs for land, excavation equipment rental and operation, transporting those pieces of equipment to the site, and the amount of time required to bury animal mortalities (DeOtte Jr. & DeOtte III, 2010). Additionally, burial could have long-term impacts on groundwater as carcasses decay and nitrogen percolates to the water table with a potential of 10 kg (22 lb) of nitrogen per 455 kg (1,000 lb) of carcasses (Harper, DeRouchey, Glanville, Meeker, & Straw; Glanville, 2009). In Iowa, about 40% of land is poorly suited for mass burial because of ground water or other environmental restrictions, and often requires prior approval by the Department of Natural Resources (DNR; Glanville, et al., 2005). Burial can also be significantly delayed by frozen soil or muddy conditions, and carcasses buried in wet soils can take more than 10 years to decompose (Glanville, 2009). Furthermore, in the late 1990s, a trench burial site in Virginia was

uncovered after 15 years and poultry carcasses still infected with avian influenza were found (Malone, 2005).

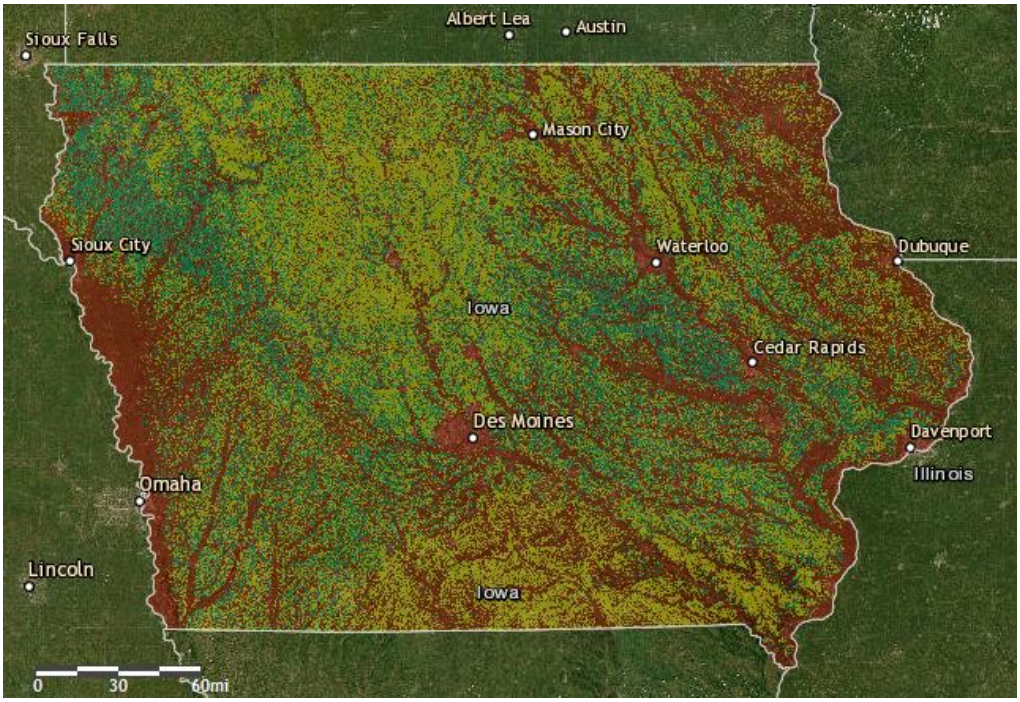

Figure 2.1. Map of acceptable burial sites in Iowa. Red color indicates the area is high risk for soil and water contamination, yellow is moderate risk, and green is low risk (Iowa DNR, 2021).

Rendering

While it is a relatively cost-effective option, rendering is only viable for non-diseased, residue-free carcasses (Malone, 2005; Bendfeldt, Peer, & Flory, 2006). It is mainly hindered by site proximity to rendering plants and lack of capacity, especially in an emergency (DeOtte Jr. & DeOtte III, 2010; Glanville, 2009). Many rendering plants are operating near capacity during normal business so surges in demand may not be met during a catastrophic event (USDA, 2012). Finally, a plan for final disposal of the rendered product needs to be developed (Malone, 2005; Bendfeldt, Peer, & Flory, 2006).

Sanitary Landfill

Sanitary landfills have been used for livestock carcass disposal, especially when chemical residues may be present. However, not all landfills accept carcasses and logistical challenges of transporting and coordinating movements of large amounts of mortalities in biosecure dump trailers is a challenge (USDA, 2012). Additionally, this option removes carcasses from the infected premises and inherently poses a potential threat to biosecurity of other farms (Malone, 2005). The cost associated with landfilling carcasses can be much greater than other disposal options; transportation and tipping costs can be up to three times more expensive than an in-house composting option (Bendfeldt, Peer, & Flory, 2006). Additionally, public perception is an issue, and environmental impact, such as odors and the ability of the landfill to process an increased leachate production resulting from carcasses, must all be considered (Bendfeldt, Peer, & Flory, 2006).

Incineration

The biggest advantage of incineration is the extreme heat to inactivate pathogens. However, during FAD mortality events, the capacity of incineration is inadequate, difficult to expand, and overloading the incinerator will also lead to serious odor problems (Glanville, 2009). Problems associated with incineration of carcasses include its limited scale, the need for incineration units to be transported to the location of use, smoke and odor produced during the process, and the 0.3 tons of ash produced per ton of carcass (Malone, 2005).

Composting

A less expensive alternative to incineration and rendering and more biosecure than burial and landfill disposal, carcass composting for animal mortalities began in the US in the poultry industry during the early 1980s and the approach was quickly adopted by other animal industries (Wilkinson, 2006). It can be defined as burying carcasses above ground temporarily in a mound

of supplemental carbon and allowing microorganisms to heat the pile, inactivate pathogens, and degrade carcasses. Primary goals of composting include prevention of disease transmission; minimizing opportunities for contamination of air, soil, water; and converting carcasses to beneficial end-products. There are two typical approaches to composting: piles or bins for a small number of routine mortalities, or a windrow system for catastrophic mortality events. Regardless of approach, carcasses are ideally placed in the composting system within 48 hours postmortem (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005). When managed properly, composting mortalities has many advantages, including reducing the volume of the carcasses, prevention of many nuisance problems such as predators and odors, and pathogens are destroyed.

A proven pathogen reduction strategy, composting is known to control almost all pathogens through thermal inactivation, including viruses, bacteria, fungi, and protozoa with the exceptions of endospore-forming bacteria and prions (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005). However, if a compost pile is turned before completion of the primary stage of composting when viral inactivation has been reached, biosecurity is at risk and it is not advisable to turn the pile (Wilkinson, 2006). For this reason, compost must be continually monitored, maintained, and managed for a prolonged period to retain the proper conditions. Key factors to control for optimal compost conditions include moisture, porosity, temperature, material mix or carbon to nitrogen ratio, and pH. For example, moisture greater than 60% in the compost material removes oxygen from small pores and can create problems including inhibition of aerobic activity, increased odor production, risk of leachate runoff, and restriction in temperature rise (Flynn & Hagevoort, 2013).

A loss of heat and inability to retain heat in compost hinders achieving maximum biosecurity through pathogen inactivation and is an obstacle with traditional composting systems.

Glanville (2005) determined that corn silage is the best option for material selection for mass mortality composting if pathogen inactivation is the primary goal because it is readily available in large quantities, and produced higher internal temperatures compared to the other materials tested (i.e., ground cornstalks and ground straw). Additionally, pathogen-inactivating-temperatures were reached quickly in corn silage, although it did not result in shorter carcass decay times (Glanville, et al., 2005). Furthermore, improper sizing of composting piles and windrows can impact heat retention and substantial heat loss can occur on the perimeter, especially in cold climates because of a low volume and high surface area of the pile (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005). An additional layer of cover material of 30.5 to 45.7 cm (12 to 18 in.) thickness helps serve as an insulating material to maintain high temperatures that support pathogen inactivation throughout the active compost (Glanville, et al., 2005). Glanville et al. (2005) also showed that placing an additional layer of cover material over the carcasses also reduced odor from the piles. Approximately 25% of the samples were comparative to a secondary manure lagoon (1,000 to 2,000 dilutions to threshold), while the remaining samples yielded results of approximately the same odor level as the cover materials (<500 dilutions to threshold; Glanville, et al., 2005).

Although it is a more ideal strategy than burial for areas with a shallow water table, a concern surrounding traditional composting systems is the potential for soil and water contamination. Leachate from carcasses during composting was found to have a high pollution potential (Glanville, et al., 2005). For example, ammonia concentration in the uppermost 15 cm (6 in.) of topsoil beneath windrows has been shown to increase 40 to 160 times; a 70 cm (24 in.) carbon source base can mitigate this consequence, but ammonia deposits can still pollute the soil during periods of high precipitation (USDA, 2012). Therefore, construction of composting piles

and windrows with sufficient material to retain and evaporate water from within the composting system and precipitation is critical (Glanville, et al., 2005). Minimizing pooling of water at the composting site will aid in maintaining maximum levels of biosecurity (Wilkinson, 2006). It is suggested that bales of hay or straw can be placed around the perimeter of the pile to absorb excess runoff from the pile and deter pests (Flynn & Hagevoort, 2013). However, in a catastrophic animal mortality event when favorable composting materials may be in short supply or not readily available, the inability to supply adequate amounts of material for active compost, absorbent, and leachate collection will threaten biosecurity. For each 454 kg (1,000 lb) of carcasses, 6.1 to 9.2 m^3 (8 to 12 yd^3) of cover material are required so acquisition can be difficult on short notice (Glanville, 2009). Off-site carbon sources may pose a biosecurity risk because one of the primary mechanisms for virus spread is vehicle traffic; therefore, limiting the number of vehicles entering the diseased premise is imperative (Flory & Peer, 2010).

Additional considerations for composting exist such as additional equipment required for efficient handling of mortality events on a catastrophic scale. Although the process is expedited by using equipment such as grinders, shredders, mixers, screeners, bucket loaders, and windrow turners, additional costs incur from rental and operation, and regular and frequent sanitation is required (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005; Wilkinson, 2006). The time of year the compost is finished and when it can be utilized or if additional storage time and space is required should be considered (Keener, Elwell, & Monnin, 2000). Finally, site selection for composting can be challenging. Some have advised to keep composting and production sites separate to minimize hazards of composting (Wilkinson, 2006), but moving carcasses poses a risk to biosecurity and a site where hazards to soil and water will be minimal should be selected.

Plastic Wrapped Composting

Modified plastic wrapped and passively aerated composting systems were tested under lab-scale conditions by Glanville et al. (2009). This method was explored for swine after it was successful in decomposing poultry mortalities in composting windrows while reducing the risk of pathogen spread caused by wind or leachate release (Glanville, Ahn, Crawford, Koziel, & Akdeniz, 2009). Akdeniz et al. (2010) found that volatile organic compounds (VOCs) can be used to estimate the completion of carcass degradation in this type of composting system. This plastic wrapped composting system did not result in excess moisture retention or accumulation of leachate, and carcasses placed in corn silage met criteria for US EPA Class B pathogen reduction (Glanville, Ahn, Crawford, Koziel, & Akdeniz, 2009). Although this strategy has only been tested for a small number of mortalities, it avoids challenges present with traditional composting systems such as leachate runoff leading to soil and water contamination.

Ag-Bags

An alternative to traditional composting, Ag-Bag composting systems have been used on a limited scale for poultry mortalities or where carbon sources are limited. The system uses a plastic tube up to 61 m (200 ft) long with a 1.5 to 3.7 m (5 to 12 ft) diameter and features positive forced aeration during composting. These systems have many advantages including odor and leachate control, vector control for diseased composts, reduced site area, reduced cycle time, and eliminates the need for turning piles or windrows (Ag-Bag Forage Solutions, 2020). However, the system is prohibitive for large carcasses (swine and cattle) unless they are ground and mixed with a bulking agent in the right proportions (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005). Malone (2005) suggests that due to logistical constraints of associated equipment for grinding and bagging, it may be more feasible to transport carcasses to a centralized location for composting with this system; however, transporting carcasses poses a

biosecurity risk. If the specialized equipment can be obtained, there are still additional challenges, such as, moving and sanitizing the equipment, coordinating supplies and personnel, and managing moisture content and adequately blending feedstocks (Bendfeldt, Peer, & Flory, 2006).

In-House Strategies

With the biosecurity issues associated with existing management strategies for mass mortalities, every effort should be made to inactive the virus prior to carcass removal from the facility. Although there has been minimal research conducted in the swine industry for in-barn mortality management strategies, it has been explored for poultry mortalities. In a study by Flory and Peer (2010), five carcass management and disposal methods were tested for layer flocks and turkeys. Of the strategies tested, it was found that in-house composting was the most effective at confining the virus to the infected house and provided the greatest level of disease containment by minimizing transmission pathways such as vehicles and aerosolization. The labor requirement was also more than 50% less than traditional carcass management methods, thereby limiting human exposure and risk of disease transfer to other operations. However, the researchers also noted that the poultry industry did not view this as a viable option because of the potential loss of production. One set of researchers credited in-barn composting as the reason an Avian Influenza outbreak on the Delmarva Peninsula in 2004 was limited to three farms, despite high farm density in the region (Tablante & Malone, 2006). Tablante and Malone (2006) also noted that the procedure was well received by government agencies, the public, and the poultry industry after proving successful in limiting disease spread. The researchers credited the ability to heat the house to 100°F for three days after forming and turning the compost windrows to the speed and effectiveness of the procedure at inactivating a heat-sensitive virus.

The greatest benefits to in-house carcass management strategies are the high temperatures generated in a composting situation or maintainable by the house heating system, the avoidance of transport of infected carcasses, circumvention of potential ground water pollution from burial, prevention of air pollution from incineration, and avoiding high costs from landfill disposal (Tablante & Malone, 2006). However, in-barn composting requires site evaluation to determine if composting is a feasible option based on door size and location, ceiling height, floor construction, and accessibility for a skid-steer to turn piles and remove compost (Tablante & Malone, 2005). This may be more challenging in swine facilities because of the fixed nature of gating, feeding, and watering equipment.

Other Methods

Other methods of carcass management exist, but are typically less available, more expensive, or have limited scale. Alkaline Hydrolysis uses high temperature, pressure, and pH to process carcasses; however, it is limited by its low capacity and hazardous liquid wastes, so it is unsuitable for large-scale mortalities. Gasification is a process which uses slow heating to reach temperatures between 537°C and 1,037°C (1,100°F and 1,900°F) and converts carcasses into carbon dioxide, carbon monoxide, methane, hydrogen, and some ash. It is not readily available, and the process takes up to 12 hours to complete. Plasma vitrification, a relatively new technology, uses temperatures 7,000°C (12,630°F) or greater to vaporize water, pyrolyze organic materials, and vitrifies inorganic materials. It is a proven method to destroy all pathogens, including prions, and reduces the original carcass by 97%. However, the technology currently requires mortalities to be transported to a facility and it is unable to process carcasses larger than 45 kg (100 lb) (USDA, 2012).

Decomposition Rates for Pig Carcasses

Swine carcasses can contain between 48% water for fat market pigs and 77% water for newborn piglets (de Lange, Morel, & Birkett, 2003). The bone content for growing finishing pigs is approximately 12% (Kuhn, et al., 1997). Factors such as these are important when considering carcass degradation rates when exposed to varying carcass management systems. Decomposition rates can vary with carcass size, disposal method, cover material, and other factors. For example, Ahn et al. (2007) observed carcass mass changes in a composting system for 16 weeks and found that the carcasses underwent the most significant mass reduction during the first 6 weeks of composting, while only a slight loss was observed during the remainder of the trial. They also found that cover materials with greater porosity were more conducive for desiccation of the carcasses, having overall losses of 70% or greater after 16 weeks (Ahn, Glanville, Crawford, Koziel, & Akdeniz, 2007). Other studies of carcass decomposition rates in compost have yielded results of an Approximate Composting Rate (ACR) of 1 kg d^{-1} (Kalbasi, Mukhtar, Hawkins, & Auvermann, 2005).

Keener et al. (2000) defined equations to calculate time (days) for completion of the composting primary and secondary cycles (before and after turning) for carcasses of mass 2 to 650 kg (4.4 to 1433 lb) as shown by equations 2.1 and 2.2, respectively. The equations were developed based on studies from poultry, dairy calves, and swine and the minimum of 10 days was obtained from poultry composting work (Keener, Elwell, & Monnin, 2000).

$$T_1 = 7.42 \times {W_1}^{0.5} \geq 10\ days \qquad (2.1)$$

$$T_2 = \frac{1}{3} \times T_1 \geq 10\ days \qquad (2.2)$$

where

T_1 = time to complete primary composting cycle (d)

T_2 = time to complete secondary composting cycle (d)

W_1 = the largest body mass of mortality (kg).

Keener (2000) defined compost volume equations during the primary and secondary phases as well. Knowing the volume of compost during the primary stage will aid in site selection and pile construction. After turning, the volume during the secondary stage should be less than the volume of the primary stage in mass mortality situations. However, in routine mortality composting systems, compost at the completion of the primary phase may be continually added to the pile, resulting in a greater secondary compost volume than primary volume. Primary and secondary phase volume can be calculated using equations 2.3 and 2.4, respectively (Keener, Elwell, & Monnin, 2000):

$$V_1 \geq 0.0125 \times ADL \times T_1 \qquad (2.3)$$

$$V_2 \geq 0.0125 \times ADL \times T_2 \qquad (2.4)$$

where

ADL = the average daily loss ($kg_{mortality}$ d^{-1})

T_1 = the primary composting time (d)

T_2 = the secondary composting time (d).

Although the research from Keener (2000) directly addresses routine animal mortalities rather than mass mortality management, carcass decomposition times are still applicable to composting of mortalities on a catastrophic scale.

Choi et al. (2017) used a modified Gompertz equation (eq. 2.5) to describe the cumulative leachate production from swine carcasses during burial. Researchers placed sampling ports for leachate in a bed of gravel followed by soil before layering whole swine carcasses and

backfilling with soil. Temperature was not controlled but was recorded and the initial water content of each sample was varied, but the volume of leachate produced by the carcasses was calculated by excluding initial water content in the burying medium. It was shown that the model for leachate production fit the recorded data well (Choi, Han, & Lee, 2017).

$$M = P \times exp\left[-exp\left\{\frac{R_m \times e}{P}(\lambda - t) + 1\right\}\right] \quad (2.5)$$

where

M =cumulative leachate production (L $kg_{volatile\ solids}^{-1}$)

P =maximum production (L $kg_{volatile\ solids}^{-1}$)

R_m = maximum production rate (L $kg_{volatile\ solids}^{-1} d^{-1}$)

λ = lag phase (d)

t = time (d).

Gompertz models are commonly used to fit biological data for growth. An "s-shaped" curve, a Gompertz equation has a lower asymptote which indicates beginning value (0 for leachate production) and an upper asymptote indicating the upper limit of the data being modeled (maximum mass of water in a carcass for leachate production). It is similar to logistic growth models in shape, but the Gompertz curve is asymmetrical about the point of inflection while the logistic growth curve has symmetry.

Logistic growth could be considered to model carcass decay if the data is considered in terms of carcass mass reduction. This model would indicate an initial value of nearly 0, followed by a shallow convex curve representing a slow rate of mass reduction, then a steep portion which indicates the rate of maximum mass reduction and is the point of inflection, and finally becoming a concave curve and leveling out to a limiting value, which would correspond to the amount of water in the pig's body. It can be modeled by equation 2.6:

$$f(x) = \frac{c}{1 + ae^{-bt}} \quad (2.6)$$

where

$\frac{c}{1+a}$ = initial mass value (kg)

c = carrying capacity or limiting value (kg)

b = constant rate of growth (kg d^{-1})

t = time (d).

Another decay model that could be considered for decay of pig carcasses is a first-order decay model. A first order decay model could be considered appropriate for decomposition rates of pigs because the value of carcass mass will fall towards the dry carcass mass, but the rate of loss will decrease each day. However, the first order decay model indicates a rapid decline over the first few days, which may not accurately fit a model for a decaying carcass. It can be modeled by equation 2.7:

$$y = A_0 e^{kt} \qquad (2.7)$$

where

A_0 = starting mass value (kg)

k = constant rate of decay (kg d^{-1})

t = time (d).

Modeling carcass rate of decay and leachate production allows characterization of mortality decomposition. Factors such as time required for mortalities to reach maximum mass reduction or be fully desiccated, volume of leachate that can be expected from carcasses, and remaining dry mass of carcasses after desiccation will aid in planning for in-barn mortality responses. For this reason, carcass response to a barn environment during decomposition is a useful exercise, and interaction of the carcass and barn environment should be assessed. Availability of space in the pit to accommodate leachate production and effects of in-barn carcass management on the barn and equipment should be assessed.

Construction of Typical Swine Buildings

In Iowa and the rest of the US, the standard construction practice for swine buildings is a conventional wood framed structure with slatted concrete floor and liquid manure storage system (Lammers, Honeyman, Harmon, Kliebenstein, & Helmers, 2009). Swine confinements are typically constructed with a poured concrete stem-wall 0 to 1.2 m (0 to 4 ft) tall with anchor bolts to attach a treated lumber base plate. The remainder of the structure is wood-framed with prefabricated trusses set atop a stud wall with a double top plate and fastened using a continuous load path approach with truss clips, strapping, and hurricane ties. Headers with double studs are used around doors, fans, and other required openings. Durable and waterproof wall materials and concrete slatted floors are recommended as well as pen partitions a minimum of 81 cm (32 in.) high for finishing spaces (MWPS, 1987). Although swine confinements are primarily wood construction, steel elements may be used such as moment frames or exterior buttresses for larger facilities. Because of the nature of conventionally built swine barns, there are some challenges presented such as wood being a material of variable strength and the thermal properties and consequences of concrete slats.

Typical Wood Frame Structures

As with all structural design, loads combinations are required to be calculated for dead loads, live loads, snow, wind, and seismic, although seismic is typically negligible in the Midwest. The American Society of Civil Engineers (ASCE, 2016) provides details on determining these loads, as well as load combination equations to determine the design conditions. Two methods for load determination are defined: load combinations for design strength (LRFD) and allowable stress design (ASD). Using LRFD, structures are designed so their strength equals or exceeds the effects of factored loads using load combinations. ASD compares the actual stresses the structure will undergo to the allowable stress before the building

materials fail. Both are acceptable approaches to determining load combinations, but their respective procedures must be followed for each.

Dead loads consist of structural members and the weight of finishes and equipment inside; this could include feed and water lines, heaters, and other equipment suspended from a ceiling for a swine finishing barn. Live loads account for the weight of stored products and occupants; the weight of growing pigs and feed moving through a feed line would be considered this type of load. Snow loads are calculated using a procedure outlined in ASCE 7-16. Exposure factor is selected based on surrounding terrain, slope factor is determined based on roof slope, a thermal factor is identified based on temperature of the interior space, and an importance factor is selected (agricultural buildings are typically Category I buildings because failure poses a minimal risk to human life). Ground snow load for the area is obtained from snow loading maps (ASCE, 2016) and a flat roof and sloped roof snow load can then be calculated. An unbalanced snow load may result on hip and gable roofs from drifting and aerodynamic shading (snowdrifts formed on lower roofs of the same structure, adjacent structure, or terrain) may occur. ASCE 7-16 outlines procedures for calculating snow loads for drifting, aerodynamic shading, sliding snow, rain-on-snow surcharges, intersecting roofs, and unconventional roof shapes. For conventional swine finishing barns, the snow loading factors most commonly influencing structure design are drifting for gable type roofs, aerodynamic shading for offices or loadouts, and sliding snow.

Wind pressures on a structure can be determined using two methods: main wind force resisting system (MWFRS) or components and cladding (CC). Either approach is appropriate as long as specific procedures are adhered to. Regardless of method, basic wind speed at 10 m (32.8 ft) above the ground is identified from wind speed maps based on building importance category

(Category I for swine confinements; ASCE, 2016). The structure is determined to be classified as "enclosed," "open," "partially enclosed," or "partially open" to assign an internal pressure coefficient; most swine confinement buildings are considered "enclosed" type buildings, although curtain sided buildings may be considered "partially open." However, the ASCE 7-16 should be consulted for accurate classification. An exposure factor based on terrain, and a wind directionality factor are identified. Topographic factors, gust effects, and a ground elevation factor to adjust for air density can be included, although they are typically ignored for swine confinement design. Once all factors are identified, wind velocity pressure on predefined zones of the building can be calculated using MWFRS or CC procedures. After all loads and combinations are determined, structural members can begin to be designed.

Wood structure conventional grow-finish buildings are typically constructed of dimensioned lumber of sizes 2 x 4 or 2 x 6, nominal 3.8 x 8.9 cm (1.5 x 3.5 in.) and 3.8 x 14.0 cm (1.5 x 5.5 in.), for the main frames. Treated lumber, typically Southern Yellow Pine (SYP) is used in locations exposed to excessive moisture such as sill or base plates, in curtain wall openings, and cool-cell framing. Untreated spruce-pine-fir (SPF) lumber is used in locations which will not be exposed to weather. SYP has higher strengths than SPF, including greater strengths for bending, tension parallel to the grain, shear parallel to grain, and compression perpendicular and parallel to grain, but it is a more expensive material, so it is rarely used in locations where SPF will suffice (American Wood Council, 2018).

For sawn lumber, there are several factors that contribute to the uncertainty of the strength of wood. To account for this uncertainty, adjustment factors are defined for things such as moisture, temperature, size, beam stability depending on load distribution, flat use for lumber loaded on the wide face, incising for chemical treatment, repetitive members, buckling stiffness,

and bearing area. The ASD method also includes a factor for load duration and LRFD includes factors for resistance, time effect, and a format conversion factor. The inclusion of these factors is intended to remove some uncertainty from the variable strength of wood products. Engineered lumber such as parallel strand lumber (PSL), laminated veneer lumber (LVL), or engineered joists are often used for long beams, headers, or columns because of higher material strength and ability to resist bending without an increase in size. Engineered wood products allow reduction factors in wood member selection to be eliminated because much of the uncertainty of the strength of the wood product is removed with an engineered material. Additionally, engineered products are tested under lab conditions to establish exact loading values that will cause the member to fail.

Similar to design of wood members, connections also have adjustment factors to account for the uncertainty in the strength of wood. There are four varieties of connection yielding modes outlined for threaded fasteners, nails, and dowel type fasteners: (I) yielding of wood fibers, (II) pivoting of the fastener at the shear plane with localized wood fiber crushing, (III) fastener yield to a plastic hinge point at one point per shear plane, and (IV) fastener yield to a plastic hinge at two points per shear plane (fig. 2.2).

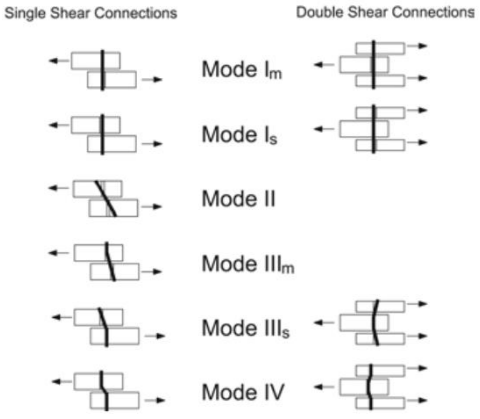

Figure 2.2. Connection yield modes for solid cross section members in single and double shear (American Wood Council, 2018).

Each mode of yielding needs to be considered when selecting type and number of fasteners (American Wood Council, 2018). Additionally, it is important to consider specialty connectors, such as hurricane ties, truss/joist hangers, and strapping. Manufacturer specifications will provide strengths of each connector. However, the designer must ensure that a continuous load path exists from the ridge of the structure, through the trusses, to the top plate, through the studs, to the sill plate, and to the foundation.

Most structures require a unique truss design depending on building width, loading combinations, eave overhangs, and desired heel heights. However, to aid in calculating dead loads, truss weight can be estimated in pounds per square foot (psf) by knowing top and bottom chord length (MWPS, 1987). In swine grow-finish buildings, trusses are most commonly placed 1.2 m (4 ft) on center with a pitch of 3/12, unless height is restricted, in which a shallower pitch may be used. Confinement buildings often have an eave overhang and truss heel height larger than typical wood-framed structures to allow for ventilation air to enter the attic through the eaves.

Stud wall construction is covered with interior sheathing to protect the wall from damage and provide some shear strength for the structure (American Wood Council, 2018). Outer sheathing, often ribbed steel, prevents damage to the structure but provides minimal strength. Wall cavities are filled with insulation such as mineral fiber (fiberglass), closed or open cell spray foam, or foam board, which are all commonly used in livestock facilities (Albright, 1990). A wood framed wall and its components can be modeled as a combination of series and parallel thermal circuits to determine an overall R-value (h ft^2 °F BTU^{-1} or m^2 °C W^{-1}). Values for the area of wood in a typical 2 x 6 framed wall is 15% while a typical 2 x 4 framed wall can be as much as 20% wood (Albright, 1990). Material properties for common building materials, as well

as surface conductance and resistance data for still and moving air can be found in the ASHRAE Handbook of Fundamentals (ASHRAE, 2013). An overall heat transfer coefficient, U (W m^{-2} $°C^{-1}$) can be defined for the structure to quantify heat lost through the building shell. Minimum R-values recommended for environmentally controlled livestock housing are 2.5 m^2 °C W^{-1} (14 h ft^2 °F BTU^{-1}) for walls and 3.9 m^2 °C W^{-1} (22 h ft^2 °F BTU^{-1}) for ceilings (MWPS, 1987).

Flooring

Concrete slats are used commonly in swine housing because of the low investment cost, benefits for foot traction of the animals, and a longer lifespan than other materials (Timmerman, Hoofs, & van Wagenberg, 2003). Typical slats are 12.7 to 20.3 cm (5 to 8 in.) wide with 2.5 cm (1 in.) slots and a trapezoidal shape (MWPS, 1987), but some research has examined alternate slat shapes to decrease ammonia emissions from finishing barns using concrete slats (Hamelin, Godbout, Theriault, Lemay, & Pelletier, 2007). Additionally, research has been done on slat degradation and it was found that after only nine months of use, all slats had observable degradation around wet feeders, except those slats treated with epoxy resin or with cement-bound surface layers (De Belie, 1997). Slats are typically reinforced with grade 400 steel rebars and have a compressive strength of 60 MPa (Hamelin, Godbout, Theriault, Lemay, & Pelletier, 2007).

Although concrete slats have many benefits such as low-cost, durability, and high compressive strength, there is a potential challenge with the concrete serving as a thermal heat sink, or thermal mass. Materials with high specific heat capacity, conductivity, and high emissivity are candidates for thermal masses (Hoes, Trcka, Hensen, & Hoekstra Bonnema, 2010). With specific heat capacity (c_p) = 0.75 kJ kg^{-1} K^{-1}, thermal conductivity (k) = 1.0 to 1.8 W m^{-1} K^{-1} for dense concrete, and an emissivity (ε) = 0.85, concrete fits this category (Concrete-Properties, 2020). While thermal masses can positively increase energy efficiency of buildings,

in some cases during specific operating conditions and configurations, a thermal mass can have a negative effect on energy demand (Hoes, Trcka, Hensen, & Hoekstra Bonnema, 2010).

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CHAPTER 3. A GENERAL PURPOSE LABORATORY FOR SMALL-SCALE IN-BARN SWINE DISCOVERIES

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Abstract

Specialized animal environment experiments needing swine facilities calls for novel technology creation to enable unique experimentation without the drawbacks of traditional swine facilities. In a full-scale swine facility, there are challenges with cost, increased travel time to sites, additional labor is required, the facility cannot be fully controlled, and biosecurity becomes a risk. A small-scale, mobile swine confinement laboratory was designed and built to mitigate the challenges faced in a full-scale barn. The mobility of the laboratory enables it to travel to swine farms to obtain fresh animal specimens, which allows the experiments and data collected to be more representative of an in-barn application. The model facility, built on a flat-bed trailer, has two identical, fully instrumented rooms (L × W × H) of 2.24 × 2.29 × 2.05 m (88.0 × 90.0 × 80.5 in.) with a 0.46 m (18 in.) shallow pit, replicating typical swine finishing rooms. Walls were composed of typical wood-frame construction with interior paneling and metal clad on the exterior. Instrumentation allows the environment and air quality of the rooms, along with other parameters, to be controlled and monitored. The rear portion of the trailer includes an instrumentation room to house necessary computers, controllers, and associated equipment. Commissioning of components and verifying function of equipment were performed, which included quantifying infiltration and performing a thermal analysis for each room. Analysis showed that the infiltration equation was distinct for each room. The use of this laboratory for

qualitative and quantitative evaluation of in-barn experimentation on a controlled, small-scale will mitigate the challenges presented in a typical barn.

Keywords. building, commissioning, facility, heat transfer, mobile, pig

Highlights.

- Design and construction of mobile swine facility on a flat decked trailer for experimentation
- Air infiltration evaluation for an experimental building
- Theoretical building shell thermal analysis and heat transfer determination

Introduction

Conducting field research in swine production facilities is desirable over artificial laboratory settings because field research integrates the complexity of real environments and is subject to relevant management practices that influence results and implications. However, executing field research presents many challenges. Production facilities are frequently outside of the desired region of travel and are not entirely customizable to conduct experiments with satisfactory and consistent control. Additionally, the cost associated with equipping the facility and the necessary research personnel to successfully execute an experiment in an entire barn can be prohibitive. Moreover, as animal disease outbreaks become a greater concern, experimentation on farms poses an increased biosecurity risk. Therefore, a custom designed small facility with the ability to be isolated will address the challenges of control, cost, labor, and biosecurity.

This paper will discuss the design, construction, and operation of a mobile laboratory that replicates two swine finishing rooms for small-scale experimentation. The structure was stick-built atop a flat-bed trailer and constructed in style of a typical, modern swine finishing facility.

The laboratory includes two identical discovery rooms, with heating and ventilation capabilities, as well as an instrumentation room located at the rear of the trailer.

The purpose of this mobile laboratory is to provide a space to conduct an assortment of trials in a near-production setting, with live pigs or carcasses. This laboratory will be particularly useful for experimentation focusing on the animal environment and housing where only a small number or no animals are required. Additionally, this laboratory is ideal for extreme environmental experimentation (temperatures of up to 60°C, RH=100%), and for monitoring parameters that would be otherwise difficult in a swine finishing barn, such as internal slat temperature. There are limitations of long-term housing of pigs in the laboratory because of the lack of a feeding and watering system, as well a limitation of space to house a large number of animals. Mobility of the laboratory offers both isolation and relocation of the laboratory to satisfy potential logistical constraints. By scaling down the size of the facility it allows for greater environmental control than a large, commercial production facility, and presents fewer challenges in labor, time, and cost. Two discovery rooms with full heating and ventilation capabilities provide the opportunity for simultaneous experimentation of a range of environmental conditions.

Objectives of the project were (1) design and construct a mobile small-scale typical swine facility with an instrumentation room, (2) commission components and verify the function of the ventilation system and quantify infiltration for each room, and (3) perform a theoretical shell thermal analysis and quantify heat transfer from each room.

Materials and Methods

Criteria and Constraints

The operation of the mobile laboratory shall be contained to a flat-bed trailer of a nominal length of 7.32 m (24.0 ft) to maintain ease of transportation to a field site and to have

the capability for isolation of experiments. Criteria of the mobile laboratory included containment of the discovery rooms, instrumentation, and office space to the area of the trailer and a total structure weight of less than 6.35 Mg (7.0 ton) to adhere to the constraint of two 3.40 Mg (3.5 ton) axels. Additionally, overall height was not to exceed 4.12 m (13.5 ft) to comply with transportation regulations. The structure should withstand wind and snow loading for Iowa, along with additional wind pressures from towing. The laboratory should be capable of maintaining a range of environmental conditions with an environmental control system to support a variety of experiments.

Concept

A primary structure with a center wall divides the space into two identical discovery rooms towards the front of the trailer, each of nominal size 2.44 × 2.44 m (8.0 × 8.0 ft). The remainder of the space was a single office with instrumentation housing, desk, chair, computer, etc. The discovery rooms were built on a base of four 1.22 × 2.44 m (4.0 × 8.0 ft) concrete swine slats to stay within the allowed width of the structure. Each room included an oversized door for ease of access into the rooms. A manure pit with a depth of 0.46 m (1.5 ft) allowed liquid and leachate to collect beneath the slats. The pit of each room was separated by an interior wall, sealed, and lined with a vinyl insert. Ball-valves made of PVC affixed to the bottom of the trailer deck serve as the drain for each pit.

A fully functioning environmental control system was required to enable the room to be heated and ventilated. Air enters the attic through an eave intake in the heel of the truss and rafter system, and then a bi-flow ceiling inlet disperses air into the room. An actuator controls the opening and closing of the inlet, and a Ø46 cm (18 in.) variable speed fan draws air through the room. The variable speed fan exhaust and eave intake should be on opposite sidewalls to prevent

stale air entrainment into the rooms. A forced air unvented combustion furnace sized to maintain a room temperature of 60°C was included.

Structural Load Design

Structural components were designed using procedures outlined in the Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE, 2016) and National Design Specification for Wood Construction (NDS, 2018). A custom design spreadsheet was built and used to calculate structural loads and size members and connections. The structure was assumed to remain within the state of Iowa; therefore, all loads were calculated based on worst-case conditions for Iowa. Loads were obtained from the ASCE, along with topographic and duration factors. The building was determined to be an enclosed structure in a region with exposure category C (flat, open area with scattered obstructions) with a fully exposed roof. Assumed to be unheated during the worst-case snow-loading scenario, the building with a roof slope factor of the main structure (1.25/12) was used to determine the roof slope factor for the entirety of the building. A risk category of I (typical agricultural structure) was assumed during snow events, while a risk category of II was assumed during wind events for an additional factor of safety during towing. The snow load was the maximum ground snow load for Iowa, 1.92 kPa (40 lb_f ft^{-2}), and the wind load for Iowa for structures in category II was 51 m s^{-1} (115 mile h^{-1}; ASCE, 2016). The flat-roof snow load was calculated from the procedure outlined by the ASCE (eq. 3.1), and unbalanced snow loading was determined as a function of roof width and slope (ASCE, 2016). The maximum wind pressure in the building was determined by using the velocity pressure equation from the ASCE (eq. 3.2).

$$p_f = 0.7 C_e C_t I_s p_g \quad (3.1)$$

where

p_f = flat roof snow load

C_e = exposure factor

C_t = thermal factor

I_s = importance factor

p_g = ground snow load.

$$q_z = 0.00256\, K_z K_{zt} K_d K_e V^2 \quad (3.2)$$

where

q_z = velocity pressure at height z

K_z = velocity pressure exposure coefficient

K_{zt} = topographic factor

K_d = wind direction factor

K_e = ground elevation factor

V = basic wind speed.

Using equations from the ASCE, the design wind pressure was 3.16 kPa (66 $lb_f\ ft^{-2}$) using the non-simplified components and cladding method, and the unbalanced snow load was 1.53 kPa (32 $lb_f\ ft^{-2}$).

From calculated wind pressures and snow-loads, combinations using the load and resistance factor design method (LRFD) were determined. Knowing the load cases for LRFD, beams, columns, fasteners, and beam-columns were sized for flexure, tension, shear, compression, bearing area, and deflection using equations from the National Design Specification (NDS, 2018) for wood construction to size all members.

Section properties were taken from the section properties of standard dressed sawn lumber in NDS (NDS, 2018). Physical properties for spruce-pine-fir grade No. 2 (SPF#2) and southern yellow pine No. 2 (SYP#2) wood species were obtained from the reference design values for visually graded dimension lumber in the NDS.

Connections for bolts, wood screws, nails, and lag screws were designed using the dowel-type fasteners section of the NDS. Loads were calculated for withdrawal, lateral loads, single and double shear cases, bearing strength, and shear strength.

The weight of the structure was estimated from the material densities and calculated using the estimated quantity of each. Material densities were obtained from manufacturer specifications, and lumber weights were acquired from the NDS.

Construction

Two discovery rooms with interior dimensions (L × W × H) of 2.24 × 2.29 × 2.05 m (88.0 × 90.0 × 80.5 in.) were constructed atop a 6.71 × 2.59 m (22.0 × 8.5 ft; L × W) flat-bed trailer. An office space measuring 1.54 × 2.22 × 2.30 m (60.5 × 87.5 × 90.5 in.; L × W × H) was built at the back of the trailer. All connections were made with wood construction screws for the most strength possible during transportation.

The pit walls were built of treated nominal 2 × 6 in. (actual 3.8 × 14.0 cm; 1.5 × 5.5 in.) lumber spaced 30.5 cm (12 in.) center-to-center with custom welded steel frames between every two or three studs in critical locations to prevent shifting during transportation. Treated plywood 1.9 cm (0.75 in.) thickness fully lined the interior of the pit stud wall and added additional shear strength to the sidewalls of the pit. Bolts of Ø1.6 cm (0.63 in) and 10.2 cm (4.0 in.) length fastened the bottom plate to the trailer decking and served as the anchors for the entire structure. The wall cavity was filled with R=2.29 m^2 °C W^{-1} (R-13 h ft^2 °F BTU^{-1}) fiberglass-batt insulation and sheathed exteriorly with 28-gauge (0.37 mm) green ribbed steel siding. A vinyl

liner of thickness 0.08 cm (0.03 in.) wrapped the inside of the pit, and two 15.2 cm (6.0 in.) diameter ball valves on the underside of the trailer decking allowed draining of the pits.

Due to width restrictions for roadway vehicles, the building was positioned directly atop the concrete slats. The structure of the rooms was built of a treated SYP#2, nominal 2 × 4 in. (actual 2.8 × 8.9 cm; 1.5 × 3.5 in.), base plate and SPF#2 nominal 2 × 4 in. studs, spaced 30.5 cm (12 in.) center-to-center with bracing between each for additional support to resist wind pressures from highway towing. The base plate was attached to the top plate of the pit wall with 16-gauge steel strapping for wood structure applications. Additionally, 0.61 × 0.46 m (2.0 × 1.5 ft) steel plates were placed at each slat corner and junction, then screwed through the studs in the pit and room walls to lock the slats into place and tie the structures above and below the slats together. The ceiling joists were also SPF#2 nominal 2 × 4 in. with the broad face resting on a single top plate, which was designed to minimize the overall height of the structure. The ceiling beams and rafters were affixed directly above wall studs to reduce bending stress on the top plate, and the truss system of pitch 1.25:12 allowed for water and snowmelt runoff while minimizing overall height. The room interiors were finished with Delphi wall panels (0.25 in. thick; #181023; QC Supply, Schuyler, NE) to provide high shear strength, durability, and a cleanable surface required inside the rooms, and the ceiling clad in 28-gauge (0.37 mm) ribbed steel. The end-walls were additionally sheathed beneath the ribbed steel with 1.3 cm (0.50 in.) plywood continuously from the pit wall to room wall to provide extra shear strength against any wind or highway gusts perpendicular to the sidewalls. Each room included a 1.52 × 1.83 m (5.0 × 6.0 ft; W × H) door (DuraDoor, EPS, Graettinger, IA) for ease of access into the rooms.

The office walls were SPF#2 nominal 2 × 4 in. stud construction with an SYP#2 nominal 2 × 4 in. baseplate. A flat ceiling with a mono-slope roof of pitch 1.4:12 allowed the attic to be

insulated. Walls and attic were filled with fiberglass-batt insulation (2.29 m^2 °C W^{-1}; 13 h ft^2 °F BTU^{-1}), lined in the interior with 0.95 cm (0.38 in.) thick plywood and fiber-reinforced plastic (FRP) paneling, and sheathed on the exterior with 28-gauge ribbed steel siding. A L14-20R male plug in weatherproof housing for 240-V, 30-A split-phase service was placed on the rear exterior wall and routed into the office to supply the main breaker panel. From the breaker panel, branch circuits were routed to each room through conduit for all fans, forced air unvented combustion furnaces, inlet actuators, lights, and power outlets. Folding, removable steps attached to the rear of the trailer allowed ease of access into the office through a 0.91 × 2.03 m (3.0 × 6.7 ft.; W × H) insulated, exterior door with a window.

During construction, care was taken to avoid adding unnecessary components that would contribute excessive weight to the structure. To the extent possible, the materials added to the trailer were previously factored into the weight estimation to avoid overloading the trailer.

Table 3.1. Descriptions and dimensions for labels defined in figures 3.1-3.3.

Label	Description	Dimension
A	Ridge height	3.90 m (153.5 in.)
B	Office roof height and eave height	3.53 m (139 in.)
C	Structure length	6.63 m (261 in.)
D	Trailer deck length	6.71 m (264 in.)
E	Trailer overall length	8.54 m (336 in.)
F	Room door height	1.83 m (72 in.)
G	Ground to room floor height	1.40 m (55 in.)
H	Deck height	0.84 m (33 in.)
I	Ball valve clearance	0.46 m (18 in.)
J	Trailer width	2.55 m (100.5 in.)
K	Structure width	2.50 m (98.25 in.)
L	Office interior width	2.22 m (87.5 in.)
M	Office interior length	1.54 m (60.5 in.)
N	Room interior width	2.24 m (88 in.)
O	Room interior length	2.34 m (90 in.)
P	Room door width	1.52 m (60 in.)
Q	Room interior height	2.05 m (80.5 in.)
R	Pit depth	0.46 m (18 in.)
S	Eave secondary inlet opening	0.13 m (5 in.)

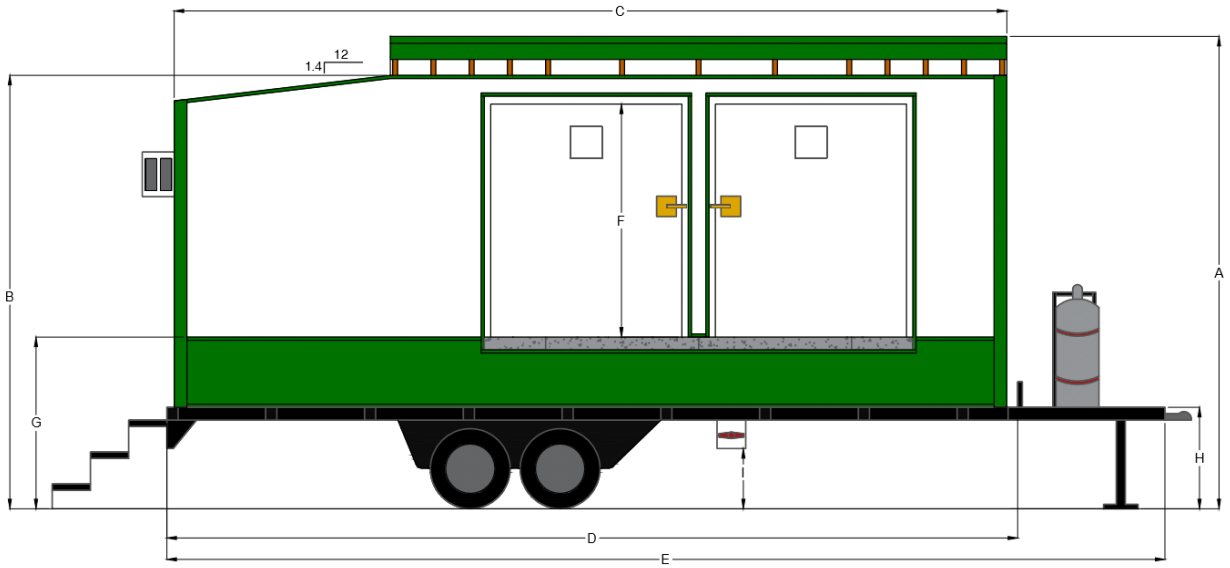

Figure 3.1. Trailer design with labels A-I, as defined in table 3.1.

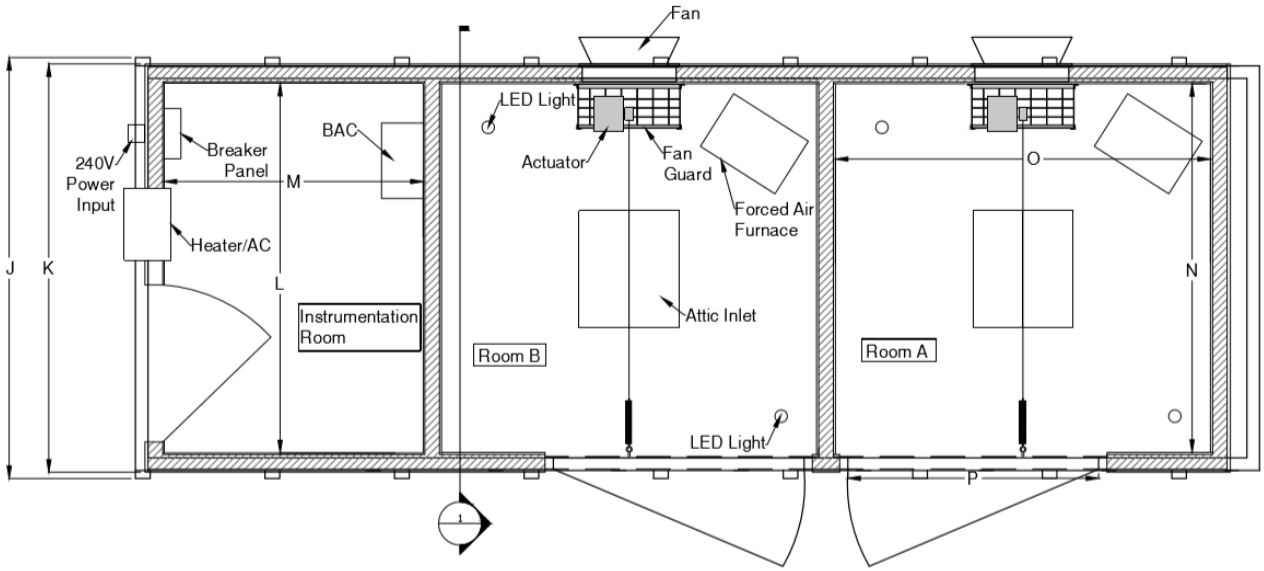

Figure 3.2. Trailer plan-view with labels J-P, as defined in table 3.1.

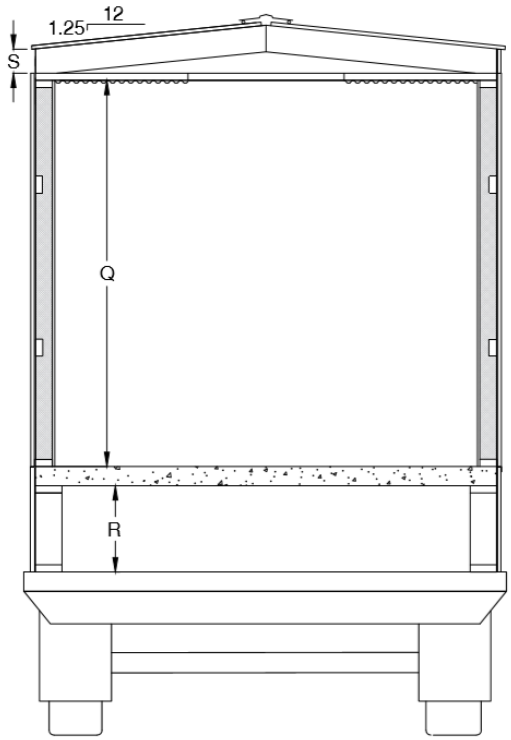

Figure 3.3. Room cross-section with labels Q-S, as defined in table 3.1.

Environmental Control

Each room included an inlet actuator (iM.60 + CPS, Fancom B.V., Pannigen, The Netherlands), a 0.71 m (28 in.) bi-flow attic inlet (1.56 $m^3\ s^{-1}$; 3,300 $ft^3\ min^{-1}$ at 37.4 Pa; 0.15 in. H_2O, BI28, Munters Corporation, Lansing, MI, USA), hot plate ignition forced air unvented liquid propane (LP) combustion furnace (17,600 W; 60,000 BTU hr^{-1}, Guardian, L.B. White Inc., Onalaska, WI, USA) and a Ø46 cm fan (1.49 $m^3\ s^{-1}$; 3166 $ft^3\ min^{-1}$ at 37.4 Pa; 0.15 in. H_2O, I-Fan Complete IF 18inch Xtra, Fancom B.V., Pannigen, The Netherlands). The fans were centered in the sidewall directly opposite the door and included custom fan guards on the interior and hinged doors on the exterior to completely close off the room during heating. The inlet was centered in the room with the center hinge perpendicular to the long axis of the trailer. The actuator was ceiling-mounted directly above the fan, in line with the inlets, with a tensioning

spring fastened using a cable above the door. The forced air unvented combustion furnace, adjustable in height, was located in the front corner opposite the door. It was sized for room temperature maintenance of 60°C (140°F) on the coldest temperature central Iowa experiences (-24°C) using equation 3.3 (Albright, 1990). Hence, each room required supplemental heating of 17,700 W (60,400 BTU hr^{-1}).

$$W = \rho\, c_p\, \Delta T\, \dot{V} + UA\, \Delta T \qquad (3.3)$$

where

W = supplemental heat (J s^{-1})

ρ = density of air (kg m^{-3})

c_p = specific heat of air (J kg^{-1} K^{-1})

ΔT = temperature difference of average room temperature and T_{out} (°C)

$\dot{V}$ = ventilation rate due to infiltration (m^3 s^{-1})

UA = theoretical building resistance to heat transfer (W $°C^{-1}$).

The tongue of the trailer featured space for two 45.5 kg (100 lb) LP tanks. An air conditioner/forced air resistance heater furnace combination system (2,200 W; 7,500 BTU/hr cooling, 1,100 W; 3,850 BTU hr^{-1} heating, LW8016HR, LG Electronics U.S.A. Inc., Englewood Cliffs, NJ, USA) was installed in the office for increased thermal comfort for the operator.

Instrumentation

A building automation and control (BAC) system (Fusion, ControlTech, Bondurant, IA, USA) measured and recorded environmental conditions inside each room. Static pressure (accuracy: ±10 Pa, ±0.05 in. H_2O; range: -1,000 to 1,000 PA, -5 to 5 in. H_2O; Model MRGSD, Setra Systems Inc., Boxborough, MA) was measured inside Room A (P_A) and Room B (P_B), and a combination probe (accuracy: ±1.5°C, ±3% RH; range: -40°C to 60°C, 0 to 100% RH; Model 114, Dol Sensors A/S, Aarhus, Denmark) measured dry bulb temperature (T_A and T_B) and

relative humidity (RH_A and RH_B). Two additional dry bulb temperature probes (°F Temp, ControlTech, Bondurant, IA, USA), placed in Room A (T1 and T2) and Room B (T3 and T4), served as the feedback for the BAC. An additional combination probe (T_{out} and RH_{out}) was placed in a radiation shield on the exterior of the rear office wall to obtain ambient air conditions. In the future, a gas sampling system will be added, and cameras in each room will allow conditions inside the rooms to be visually monitored via remote access.

Operation

The BAC system allowed for remote environmental control of the discovery rooms. Temperature sensors (T1, T2, T3, and T4) were integrated with the BAC as feedback for control decisions to adjust fans, inlet machines, and forced air unvented combustion furnaces. Each component was adjusted or turned on or off based on programmed offsets for each device and temperature from the rooms.

During transportation, ceiling inlets are closed to maintain the integrity of the inlet spring and machine and forced air unvented combustion furnaces are removed from the hanging position to prevent jostling of the unit and damage from swinging. All removable components of the laboratory, including the power cord and office stairs, are stored and secured in the office during transportation. Once on-site, any removed components are re-installed, and the laboratory is powered via on-site 240-V service or generator.

Operational Performance

Operational performance data was processed using Microsoft Excel and MATLAB. The ability of the discovery rooms to maintain a temperature above ambient conditions was tested by heating the rooms to a setpoint of 60°C (140°F) for a minimum of 2 hours to allow the system to reach steady state. The BAC recorded static pressure, RH, fan power, inlet opening, and forced air unvented combustion furnace state using a sparse sampling method. The minimum threshold

of change was 0.23°C, 0.5% RH, or 0.5 A for each respective sensor, or a 5 min interval if the minimum threshold had not occurred. Sensors T1 and T2 in Room A and T3 and T4 in Room B were averaged by the BAC to calculate mean room temperature, and the reference temperature probes T_A and T_B were recorded for post-processing purposes. Collected data allowed a building thermal analysis to be conducted, in addition to calculating a time constant for heating each discovery room. Time to reach steady state was estimated by 3τ, assuming first-order system behavior (equation 3.4).

$$T_s(t) = T_{s,0} + \Delta T_s \left(1 - e^{\frac{-t+t_0}{\tau}}\right) \quad (3.4)$$

where

$T_s(t)$ = room temperature as a function of time (°C)

$T_{s,0}$ = initial T_s at time t_0 (°C)

ΔT_s = difference between $T_{s,0}$ and T_s at steady state (°C)

t = time (min)

t_0 = initial time (min)

τ = time constant (min).

Additionally, apparent power usage for the laboratory was estimated using an ammeter (accuracy: ±8 A; range: 0-400 A; Model 323; Fluke; Everett, WA, USA) on each of 120 V legs of the split phase 240 V supplied to the breaker panel. Operational states that the laboratory was identified to operate in commonly were established, considering a combination of operational states in the office and the discovery rooms. The apparent power consumption of the system allows researchers to assess what additional equipment can be added to the electrical loads for new experiments.

Room Infiltration Analysis

The infiltration rate of each room was quantified using the Fan Assessment Numeration System (FANS; S/N: 30-0010; Gates, Casey, Xin, Wheeler, & Simmons, 2004) placed on the intake of each fan 20 cm (8 in.) from the wall and sealed using rigid insulation board. Prior to testing, pit valves were closed, room doors shut, and inlets closed. The testing took place in an enclosed building, so wind effects and temperature variations were negligible. Differential pressures ranging from 12.5 to 75 Pa were recorded using a vertical-inclined manometer (accuracy: ±22 Pa, ±0.09 in. H_2O; range: 0-746 Pa, 0-3 in. H_2O; Mark II; Dwyer Instruments, Inc.; Michigan City, IN, USA), and data were recorded for increasing (n=8) and decreasing (n=8) airflows.

Infiltration rates and corresponding differential pressure were used to fit a power-law equation for the room envelope, having parallel and series leaks (Walker, Wilson, & Sherman, 1997). The infiltration regression (eq. 3.5) was fitted for each room using statistical curve fitting tools (MATLAB, 2018).

$$I = c\Delta P^n \qquad (3.5)$$

where

I = predicted infiltration (air changes per hour; ACH)

ΔP = pressure differential across the room envelope (Pa)

c = pressure coefficient

n = power-law exponent of pressure.

Volumetric flow rates ($m^3\ h^{-1}$) recorded from the FANS unit were converted to ACH using the nominal room volume (10.6 m^3), assessed as the internal L × W × H dimensions (excluding attic and pit volumes).

Thermal Analysis

A theoretical building thermal transmittance, U (W m^{-2} °C^{-1}), was calculated using known material properties and wall construction. The theoretical value was used to size the forced air unvented combustion furnace, estimating approximate run-time as a function of outdoor temperature.

Results and Discussion

The results presented quantify the performance of the mobile laboratory during heating, air infiltration of each room, and thermal analysis for each room.

Structure Validation

The performance of the structure was qualitatively validated when towing the laboratory at highway speeds of 88 km h^{-1} (55 mile h^{-1}). Additionally, the structure withstood perpendicular wind gusts of 102 km h^{-1} (63.3 mile h^{-1}) during a derecho storm in central Iowa (Boone County) in August of 2020 with no damages, suggesting the loads calculated and designed for were appropriate (Iowa Environmental Mesonet, 2020). The weight estimate of the structure was validated by a truck scale, in which the final weight of the trailer with structure was 6,180 kg (13,600 lb).

Operational Performance

A time constant for heating each room was calculated for heating the rooms from an ambient temperature to a set point of 60°C (140°F). Time constants for each trial are recorded in table 3.2. After reaching steady-state, the average of each parameter (table 3.3) was calculated from the remaining time in the two-hour data collection period. The temperatures and relative humidity recorded in each room showed a cyclical pattern varying with the operational state of the forced air unvented combustion furnace (fig. 3.4). Using Chauvenet's criterion with a maximum allowable deviation of 2.807, no outliers were detected for any measurements during

the testing period after reaching steady-state. Knowledge of the time to reach steady-state will guide future experimentation conducted in the laboratory.

Table 3.2. Nonlinear regression coefficients to determine the time to reach steady-state (3τ) for heating the discovery rooms to 60°C.

Test	Ambient Temperature (°C)	Room	$T_{x,0}$ (°C)	ΔT	R^2	RMSE (°C)	Time to Reach Steady-State (min)
1	37.32	A	30.24	29.76	0.91	2.13	23.19
		B	31.35	28.65	0.92	2.07	23.96
2	33.71	A	25.63	34.37	0.95	1.83	25.22
		B	27.27	32.73	0.96	1.56	28.91
3	35.21	A	29.13	30.87	0.91	2.37	23.80
		B	29.63	30.37	0.93	2.14	24.44
4	12.14	A	9.62	50.38	0.97	2.19	39.57
		B	15.34	44.66	0.97	2.86	30.33

Table 3.3. Summary of average (±standard deviation) steady-state conditions during temperature maintenance tests with a setpoint of 60°C.

Parameter	Test 1	Test 2	Test 3	Test 4
T1 (°C)	59.52 ± 1.55	59.58 ± 1.70	59.80 ± 1.68	58.39 ± 1.93
T2 (°C)	60.42 ± 1.45	60.58 ± 1.58	60.57 ± 1.60	60.43 ± 1.93
T_A (°C)	59.64 ± 0.35	59.69 ± 0.25	59.53 ± 0.41	57.80 ± 1.47
T3 (°C)	57.24 ± 1.26	57.28 ± 1.23	57.40 ± 1.17	55.83 ± 1.41
T4 (°C)	62.23 ± 2.01	62.04 ± 2.11	62.24 ± 1.17	61.05 ± 2.16
T_B (°C)	59.66 ± 0.29	59.80 ± 0.00	59.80 ± 0.00	59.29 ± 0.54
RH_A (%)	24.65 ± 1.38	18.42 ± 2.19	21.14 ± 1.47	22.55 ± 2.58
RH_B (%)	18.48 ± 1.07	17.25 ± 0.98	20.28 ± 1.33	15.98 ± 3.43
P_A (Pa)	17.20 ± 3.06	11.78 ± 3.46	14.49 ± 2.34	14.59 ± 1.14
P_B (Pa)	9.92 ± 2.19	5.79 ± 2.32	6.81 ± 1.68	11.02 ± 1.23

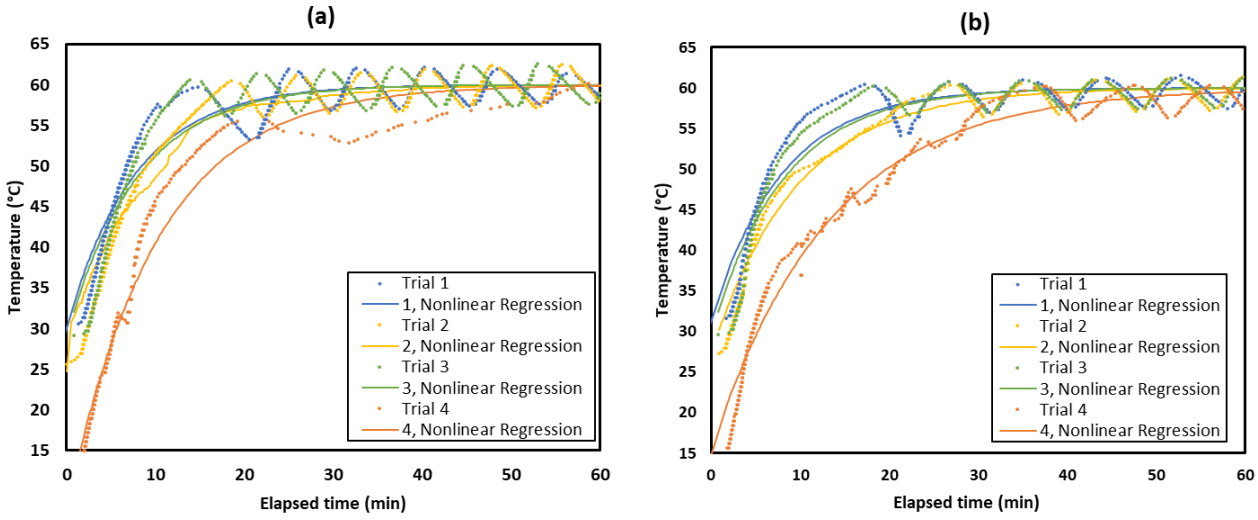

Figure 3.4. (a) Nonlinear regressions to determine time constants for heating room A and (b) Nonlinear regressions to determine time constants for heating room B.

All individual temperature measurements, including T_A and T_B, were significantly different from the set point of 60°C ($p<0.001$). However, when T1 and T2 were averaged for Room A, and T3 and T4 were averaged for Room B, it was found that the temperature was approximately equal to 60°C for Room A ($p=0.343$) and Room B ($p=0.214$), suggesting that the BAC is operating satisfactorily.

Apparent power for multiple operational states was measured and recorded. The maximum apparent power for any identified state was with the office cooled while the rooms were cooled at 1,224 W, or a current of 10.2 A. During the minimum power state with only the BAC running, the current draw was 1.5 A, or a minimum apparent power consumption of 180 W. With a 240 V, 30 A power supply, the laboratory will be able to sustain the electrical loads permanently within the system, as well as additional equipment such as computers and other small equipment.

Infiltration

A unique infiltration calibration for each room was developed using a power-law equation. The coefficient of determination (R^2) for both rooms exceeded 0.97 (table 3.4, fig. 3.5). The RMSE for Room A was 1.740 and Room B was 1.193. The static pressure coefficient and pressure exponent for each room were found to be significantly different from each other (both $p<0.001$), suggesting that infiltration characterization for individual rooms was justified and necessary. A t-test against coefficients for metal ceiling barns (Jadhav, et al., 2018) found the infiltration for rooms A and B to be significantly different ($p<0.001$) from the established values.

Table 3.4. Power law models for predicting infiltration (*I*; ACH) for each room as a function of building envelope pressure differential (*P*; Pa).

Room	Model ($I = c \times \Delta P^n$)	RMSE (ACH)	Standard Error		95% Confidence Interval			
					Lower		Upper	
			c	n	c	n	c	n
A	$I = 0.141 \times \Delta P^{1.287}$	1.740	2.99E-2	5.09E-2	0.080	1.183	0.202	1.392
B	$I = 0.031 \times \Delta P^{1.517}$	1.193	9.28E-3	7.19E-2	0.012	1.370	0.050	1.664

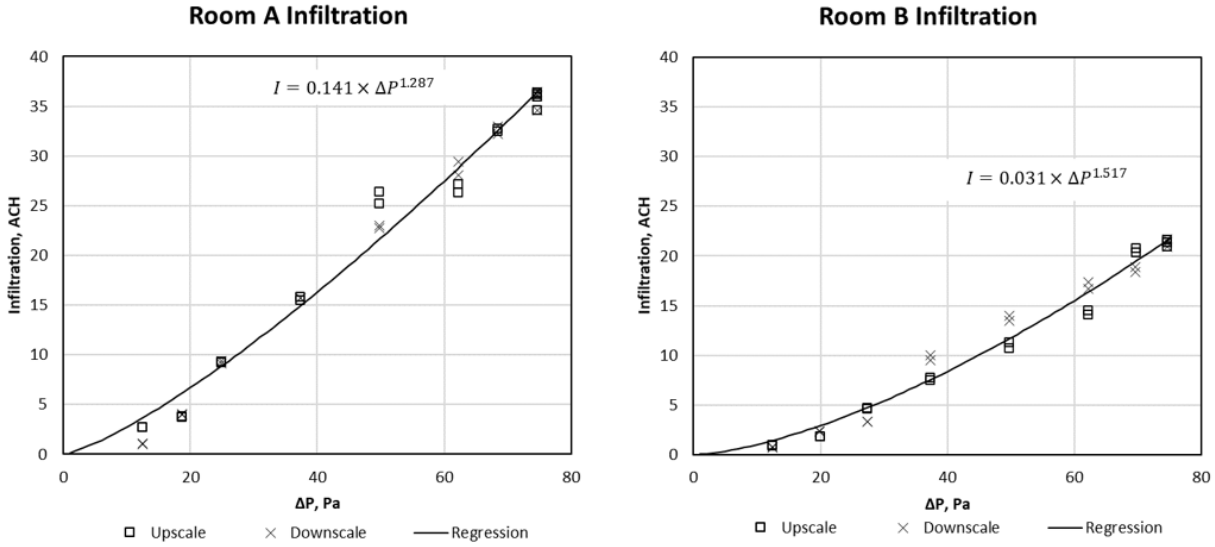

Figure 3.5 Predicted infiltration for Rooms A and B using the power law models from table 3.4.

The infiltration regressions for these rooms do not exhibit the same shape as established infiltration curves for livestock housing. However, because the model shapes for both rooms are similar, and the equations fit the data well (R^2>0.97 for each; $RMSE_A$=1.740; $RMSE_B$=1.193), it is reasonable to attribute the shape of the infiltration characteristic curve, which differs from a standard swine finishing barn, to the size and nature of the rooms. It can be assumed that the anomaly causing the irregularly shaped curve is present in both rooms.

The infiltration rate is greater in these rooms than typical metal ceiling swine finishing facilities, but the perimeter to volume ratio in these rooms is much larger than in a standard swine finishing facility, allowing a full air exchange at a faster rate than a traditional facility. In a typical finishing facility, if the perimeter is considered as the sum of the edges at the floor,

ceiling, and corners (not including fan and curtain openings), the ratio of perimeter to volume is 1:5.57 to 1:6.00 (Jadhav, et al., 2018). For the mobile lab, the ratio of perimeter to room volume is 1:0.4, which explains the increase in air changes per hour compared to typical metal ceiling facilities. Hysteresis was observed for both rooms, where $s_{hysteresis,\ A}$ = 0.33 ACH and $s_{hysteresis,\ B}$ = 0.66 ACH.

Thermal Analysis

A separate analytical thermal analysis for each room was performed to determine a unique thermal transmittance, U, theoretically. The theoretical value determined by using physical properties of the building materials was U=1.12 W m^{-2} °C^{-1}.

Conclusions

A mobile, general-purpose laboratory replicating a typical swine production setting equipped with full instrumentation was designed and constructed for small-scale in-barn experimentation. The laboratory is built in style of a typical swine finishing building but allows more control than a full-scale barn and requires less labor and other monetary inputs. The mobility of the laboratory makes it ideal for testing in remote locations and isolation if necessary. Many useful features such as cameras, environmental monitoring, and remote ventilation control make the laboratory a preferred space to carry out a variety of studies on a small-scale. Verification of laboratory function and quantification of parameters such as infiltration have been documented and recorded in this paper.

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CHAPTER 4. CHARACTERIZATION OF UNDEVELOPED RESPONSES OF DESICCATION AND IN-HOUSE ALTERNATIVES FOR MORTALITIES (CURED HAM) IN SWINE

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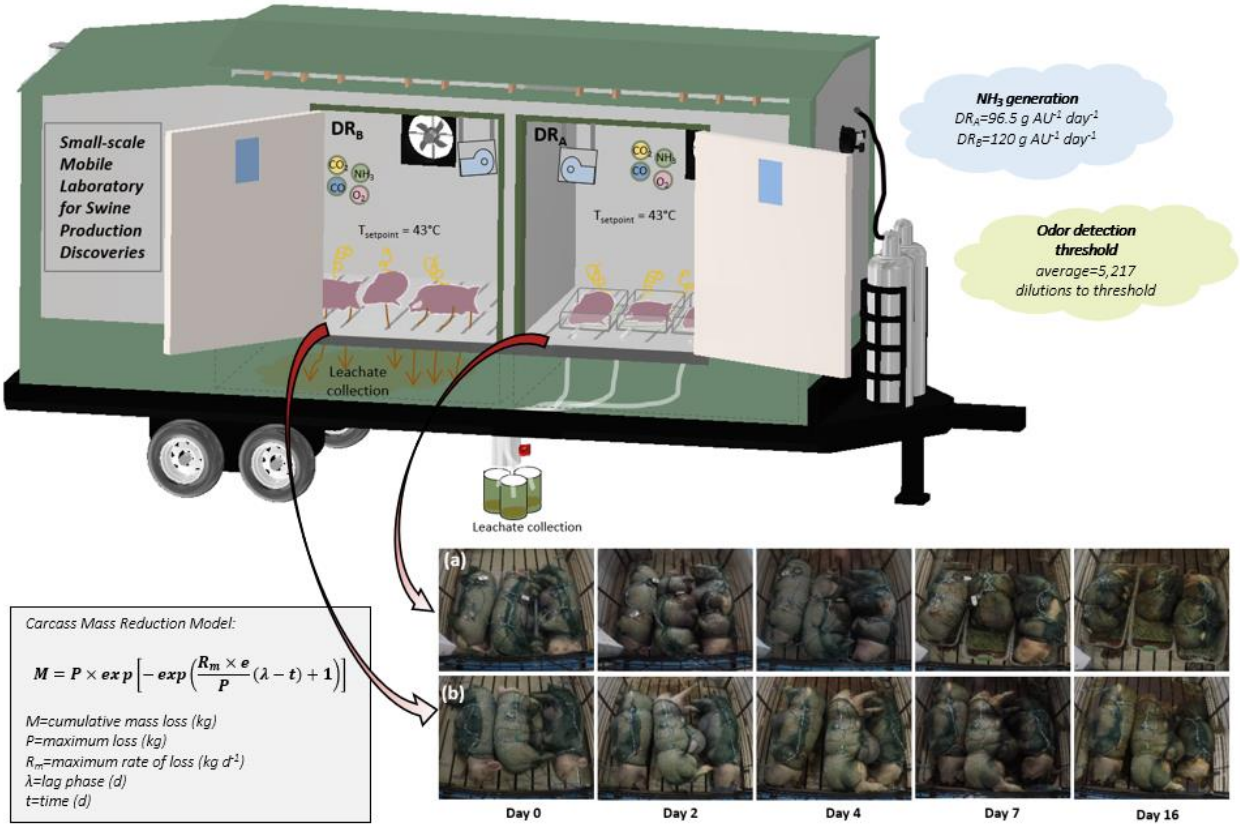
Abstract

A catastrophic mortality event for swine would present numerous challenges with management and disposal of infected carcasses. This study explored a new strategy for biosecure in-barn processing of swine carcasses as an alternative to traditional management and disposal approaches. A small-scale, mobile laboratory with two discovery rooms (DRs), replicating a swine finishing facility, was constructed to execute tests of in-barn disposal methods. Carcasses were desiccated by subjection to heat at a room air temperature of 43°C (110°F) for 16 days. Three carcasses (average=82 kg, SE=1.27 kg) were elevated over individual leachate collection systems in DR_A, thereby removing leachate from the room. Three carcasses in DR_B were placed on concrete slats with cumulative leachate collection in the pit below. Environmental data were collected for DR, outdoor, and slat temperatures; CO_2, CO, O_2, and NH_3 gas concentrations; and odor samples. Carcasses were characterized by rectal and shoulder temperature monitoring and daily weighing of carcasses and leachate in DR_A. Air exchange rate for this unventilated system was quantified based on wind and thermal driven infiltration. Room environments were compared for thermal performance and air quality. Carcass temperatures were compared, and data suggested there was no significant impact of flooring material on internal carcass temperature. Gompertz and logistic models were fit to leachate production data and carcass mass reduction data. Ammonia generation rates were found to have a peak production rate of 96.5 g

AU^{-1} day^{-1} (15.8 g $animal^{-1}$ day^{-1}) in DR_A and 120 g AU^{-1} day^{-1} (19.7 g $animal^{-1}$ day^{-1}) in DR_B. Over the entirety of the study, generation of NH_3 in DR_B (360 g) was nearly twice that of DR_A (182 g) due to the removal of leachate. Olfactometry panel results concluded no significant difference between odor emission of the DRs and an average dilution to threshold level of 5,217. Further quantification and qualification of in-barn management strategies will result in better definition of biosecure disposal approaches in the event of a catastrophic mortality event.

Keywords. ammonia, carcass, disposal, in-barn, odor, pig

Graphical Abstract.



Highlights.

- Carcass characterization of pig mortalities exposed to an in-barn desiccation environment
- Wind pressure and stack effect driven infiltration for an experimental building
- Ammonia production of pig mortalities and leachate managed in-barn

Introduction

Proper management of swine mortalities in response to a Foreign Animal Disease (FAD) outbreak is imperative to mitigate disease spread to other pig populations. If infected carcasses are improperly managed, the pathogen can remain in the environment and severely inhibit recovery efforts from FAD outbreaks. Existing mortality management options for swine include composting, shallow burial, landfill disposal, rendering, and incineration. However, all existing carcass management approaches challenge biosecurity and threaten pathogen spread via air, water, soil, vegetation, or fomites (USDA, 2020). Therefore, if pathogen inactivation can be achieved before carcass removal from the barn, a reduction in the exposure of mortalities or leachate to transmissive agents is possible.

Composting has been the preferred method for catastrophic mortality events because of the potential for the pile to reach elevated temperatures to inactivate pathogens, the wide availability of carbon sources near animal production facilities, and the creation of a usable end product (Glanville et al., 2005; Wilkinson, 2006; Kalbasi, Mukhtar, Hawkings, & Auvermann, 2005). However, composting systems managed improperly can quickly become a biosecurity hazard if a pile is turned before completion of the primary inactivation stage, windrows are sized improperly, or an inappropriate site is selected where soil and water contamination is a risk (Wilkinson, 2006; Kalbasi, Mukhtar, Hawkings, & Auvermann, 2005; USDA, 2012). Modified Ag-Bag composting systems mitigate many of the biosecurity risks associated with traditional composting, but are not ideal for large carcasses such as swine, and specialized carcass-handling equipment is required for the system (Ag-Bag Forage Solutions, 2020; Kalbasi, Mukhtar, Hawkings, & Auvermann, 2005).

Alternatively, carcass burial is a simple approach but presents many challenges: it can be cost-prohibitive due to land prices and equipment rental, suitable land is difficult to secure in

many regions of the US, and the potential for long-term impacts on ground water exists (DeOtte Jr. & DeOtte III, 2010; Harper, DeRouchey, Glanville, Meeker, & Straw; Glanville, et al., 2005). Additionally, burial is not a biosecure option and in one case, poultry carcasses still infected with avian influenza were unearthed after 15 years (Malone, 2005). Rendering is only a viable carcass management option for non-diseased mortalities and is hindered by lack of capacity (DeOtte Jr. & DeOtte III, 2010; USDA, 2012). Landfill disposal of carcasses can incur costs of up to three times that of other options, and the ability of the landfill to contain and process leachate from carcasses is often challenged (Bendfeldt, Peer, & Flory, 2006). Finally, incineration commonly has inadequate capacity and odor problems can become a serious issue (Glanville, 2009).

Due to the biosecurity issues associated with existing management strategies for mass swine mortalities, efforts should be made to inactivate pathogens prior to removal from the facility. In-barn mortality management strategies have been tested and deployed for catastrophic poultry mortality events with success. As little as 50% of the labor is required for in-barn methods of disposal compared to traditional carcass disposal methods, limiting risk of disease transfer by workers (Tablante & Malone, 2006). Additionally, it is a relatively cost-effective option, high temperatures can easily be generated and maintained for pathogen inactivation, and exposure of pathogens to the environment is avoided (Tablante & Malone, 2006). For these reasons, in-barn mortality management strategies for swine should be explored and quantification of carcass responses are needed to determine feasibility of managing swine moralities in-barn.

A general-purpose laboratory for small-scale in-barn swine discoveries with ventilation and environmental instrumentation and control was previously constructed and validated. This laboratory was built to replicate a typical swine finishing facility with concrete slats, pit, and

construction finishes. Both Discovery Rooms (DRs) were utilized to house three carcasses each for the duration of a 16-day trial in January 2021. A desiccation environment was created by heating each DR to 43°C (110°F) with minimal air changes. Carcasses and leachate were weighed daily, along with continuous recording of carcass temperatures, gas concentrations, and other environmental data. Characterization of Unconventional Responses of Desiccation and In-House Alternatives for Mortalities (CUReD HAM) is necessary to prepare for FAD outbreaks. The objectives of this study of CUReD HAM were to 1) measure and quantify production of ammonia from in-barn carcasses; 2) weigh carcasses and leachate to determine a model appropriate for decomposition modeling; and 3) assess odor from in-barn carcass decomposition using an olfactometry panel.

Materials and Methods

The trial occurred in a general-purpose lab for small-scale in-barn swine discoveries (described in Chapter 3) during January of 2021. Two DRs (DR_A and DR_B) were utilized for different treatment of carcasses. Each room was set to 43°C (110°F) air temperature for the duration of the study and was maintained by a direct gas-fired circulating heater. Rooms were preheated to the set point temperature 24 hours prior to the start of the trial. A circulation fan was placed inside the room to increase convection across the surface of the slats.

Air Exchange

Determination of air exchange is necessary for quantification of gas production during the study. Air exchange in buildings is a function of thermal infiltration due to the stack effect, wind pressure infiltration, and infiltration due to mechanical ventilation (Awbi, 2003). Although mechanical infiltration was defined as a function of pressure in Chapter 3, the DRs were not mechanically ventilated during this study; hence, thermal and wind pressure infiltration required quantification. The DRs cannot be considered closed systems; therefore, infiltration due to wind

and stack pressure were considered independently of mechanical ventilation. Stack pressure typically has little effect on low-rise buildings compared to high-rise structures, but it was calculated because of the large temperature gradient between indoor and outdoor temperatures. Because DR_A and DR_B were warmer than the outdoor temperature, the base of each room was depressurized, causing infiltration at lower levels, and the top of each room was pressurized, causing exfiltration to occur at upper levels. Although temperature stratification occurred in each room, the average vertical distribution of temperature was more appropriate to use compared to localized temperatures at the opening of interest for exfiltration and infiltration (ASHRAE, 2013). Each room was modeled as having no internal separations and average carcass temperature was used as the average room temperature, meaning each DR was modeled as a single equivalent space for the stack effect (ASHRAE, 2013; Sherman, 1992a).

Wind pressure on a building is a function of wind direction, wind speed, air density, building orientation, and surrounding obstructions. Wind speed and direction data were obtained from a weather station approximately 12 km (7.5 miles) from the testing site (Iowa Environmental Mesonet, 2021). Wind speed was corrected from a 10 m (33 ft) measurement height to a single-story building height. Building surrounding conditions were assessed by defining a shelter factor (eq. 4.1) for the structure (ASHRAE, 2013).

$$s = \frac{1}{2}\{[s_1 + s_2]\, cos^2\varphi + [s_1 - s_2]cos\varphi + [s_3 + s_4]sin^2\varphi + [s_3 - s_4]sin\varphi\} \quad (4.1)$$

where

s = shelter factor for wind direction

φ = wind direction (radians)

s_i = shelter factor for when wind is normal to wall.

Shelter factors for walls are defined as Class 1) no obstructions or local shielding; Class 2) typical shelter for an isolated rural structure; Class 3) typical shelter caused by other buildings from across a street; Class 4) typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away; and Class 5) typical shelter produced by buildings or other structures immediately adjacent and less than one building height away (ASHRAE, 2013). Shelter factors for walls of the laboratory were defined based on surrounding obstructions (fig. 4.1).

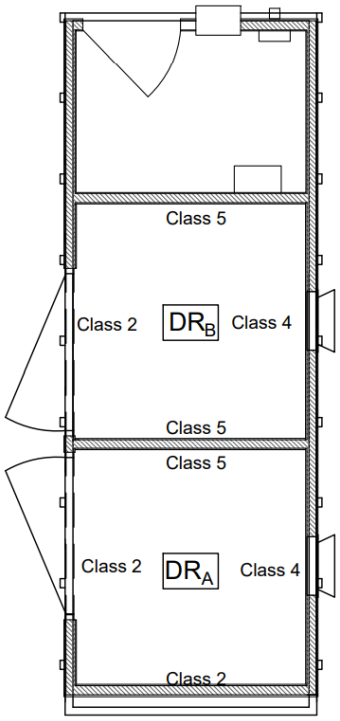


Figure 4.1. DR_A and DR_B with wall classification shelter classes defined.

Because infiltration was caused by both stack effect and wind pressure, the air exchange of each driving force cannot be considered independently. Superposition of wind and stack effects was necessary to create an enhanced infiltration model because internal and external pressures were affected by each of these parameters and caused interaction. An exact solution is impossible to achieve, but summation in quadrature has been found to be a robust superposition

technique for combining wind and stack effects (Sherman, 1992b; Walker & Wilson, 1993; Awbi, 2003). For an enhanced infiltration model, the airflow rates were calculated by equations 4.2 to 4.4 (ASHRAE, 2013):

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{4.2}$$

$$Q_s = cC_s\Delta T^n \tag{4.3}$$

$$Q_w = cC_w(sGU)^{2n} \tag{4.4}$$

where

Q = total airflow rate ($m^3\ s^{-1}$)

Q_s = airflow rate due to stack infiltration ($m^3\ s^{-1}$)

Q_w = airflow rate due to wind infiltration ($m^3\ s^{-1}$)

c = flow coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

C_s = stack coefficient $(Pa\ K^{-1})^n$

C_w = wind coefficient $(Pa\ s^2\ m^{-2})^n$

G = wind speed multiplier

U = measured wind speed ($m\ s^{-1}$)

s = shelter factor

ΔT = indoor-outdoor temperature difference (K)

n = pressure exponent.

Stack coefficient (C_s=0.069), wind coefficient (C_w=0.128), wind speed multiplier (G=0.48), and shelter factor inputs (DR_A: s_1=0.54; s_2=0.70; s_3=1.02; s_4=1.02; DR_B: s_1=0.54; s_2=0.70; s_3=0.54; s_4=1.02) were chosen based on a one-story building with a flue. Flow coefficients (c=0.051) and pressure exponents (n=0.67) were chosen based on typical values for a standard rectangular building (ASHRAE, 2013; Awbi, 2003).

Instrumentation

The instrumentation systems described in Chapter 3 were used for room and ambient temperature, relative humidity (RH), and static pressure. The building automation controller (BAC) remotely monitored and controlled the heating and ventilation system. However, some additional instrumentation systems were added for this study.

Thermal

Slat temperatures were monitored during the trial using thermocouples embedded into the slats and data were logged on 30 second intervals using a 4-channel thermocouple data logger (Type K; accuracy: ±0.7°C; range: -260°C to 1,370°C; resolution: 0.04°C; UX120-014M, Onset, Bourne, MA, USA). Air temperatures inside the DRs were recorded using sensors already integrated in the laboratory. Outliers were removed using Chauvenet's criterion and data was averaged hourly and daily. Temperatures were compared using a statistical package to assess differences in room environment (SAS Institute, Inc., 2018). A t-test (α=0.05, df=30) assessed if daily mean DR temperatures were different from one another. Room conditions of slat and DR air temperatures comparison aided in evaluating carcass response.

Air Quality

The custom gas sampling system measured oxygen (O_2), carbon monoxide (CO), ammonia (NH_3), and carbon dioxide (CO_2; table 4.1). All gas sensors were housed in a 0.8 × 1.0 × 03 m (32 × 40 × 12 in.; W × H × D) cabinet with a plexiglass window for viewing and heater to maintain cabinet airspace at 40°C. Each sensor used a transmitter with LCD screen to display current measurement values and a 4-20 mA signal output was interfaced with a 4 channel datalogger recording at 10 second intervals (accuracy: ±0.001 mA or ±0.2% of reading; range: 0-20.1 mA; resolution: 0.3μA; UX120-006M, Onset, Bourne, MA, USA).

Table 4.1. Gas sampling system transmitter and sensor model, range, and uncertainty.

Gas	Transmitter	Sensor	Range	Uncertainty
CO_2	Draeger Polytron 5720 IR	Draeger PIR 7200	0-10% volume	±0.1% measured value
CO	Draeger Polytron 5100 EC	Draeger CO- 68 09 605	5-1,000 ppm	±2.0 ppm or ±1% measured value
O_2	Draeger Polytron 5100 EC	Draeger O_2 LS – 68 09 630	0.5-25% volume	±1% measured value
NH_3	Draeger Polytron 5100 EC	Draeger NH_3 LC – 68 09 680	5-300 ppm	±1.5 ppm or ±5% measured value

Air was sampled from three locations at six-minute intervals programmed into the BAC: outdoor, DR_A, and DR_B. The outdoor air sample was taken near the rear of the trailer by the office on the opposite side of the lab exterior from the room exhaust fans. The DR air samples were drawn from an array of four sampling tubes Ø 0.318 cm (Ø 0.125 in.) in the center of each quadrant of the DRs which combined at a manifold into a single tube Ø 0.635 cm (Ø 0.25 in.) before being routed to the gas analyzers in the office. A small in-line fuel filter (40 micron, Briggs & Stratton, Wauwatosa, WI, USA) was attached at the end of each sampling line to mitigate dust and particulate build up in the sampling lines or gas analyzers. Samples were drawn to the office from each of the locations with a diaphragm pump (19.5 L min^{-1} at 0 Pa; Model No. 107CAB18 7; Rietschle Thomas; Slidell, LA, USA) and leaks were detected on the outflow of the pumps using a solution of soapy water. For each sampling location, a flow rate of 0.5 L min^{-1} was required for the gas sensors, so rotameters (2.5 L min^{-1} capacity, Dwyer, Michigan City, IN, USA) were added to each sampling line and adjusted on the outflow of the pumps in the office to achieve this. Additionally, rotameters were temporarily placed at the end of each of the four sampling lines in the rooms to verify uniform sampling. All four lines in the DR_A were verified to have the same flow rate as one another (~0.6 L min^{-1}) as well as DR_B (~1.0 L min^{-1}) so uniform sampling within each room was achieved. Finally, heating wire (9.8 W m^{-1}; Model

H311 WinterGard; Raychem; Menlo Park, CA, USA) was added to all sample line tubing in the office to prevent condensation when sampling at high temperature and high humidity.

After sampling integrity was confirmed, six compressed gasses (GASCO, Oldsmar, FL, USA) of known concentrations were used to calibrate the gas sensors and check for leaks within the system (400 ±8 ppm CO_2 with O_2 and N_2 air balance; 3500 ±70 ppm CO_2 with O_2 and N_2 air balance; 20.8% ±0.42% O_2 with N_2 balance; 50 ±1 ppm CO, 18% ±0.36% O_2, with N_2 balance; 15% ±0.3% O_2 with N_2 balance; and 25 ±1 ppm NH_3 with O_2 and N_2 air balance). Gas flowing constantly at 0.5 L min^{-1} was supplied directly to the sensors through the cabinet for calibration. Next, the same gas cylinder flowing at 0.5 L min^{-1} was connected to the end of a sampling line (outdoor, DR_A, and DR_B) to verify there were no leaks on the inflow sampling lines to the pumps. If the gas sensor failed to measure the same value as the cylinder (within the range of uncertainty of the sensor), adjustments in fittings were made to remove points of leakage.

Visual

Waterproof cameras (Hero5 Black, GoPro, San Mateo, CA, USA) were set up in each DR to record a time lapse of progress of decay. Still images were captured every hour and later combined into a continuous time lapse video for each room. Additionally, an outdoor surveillance camera (KC200 Kasa Cam Outdoor, TP-Link, San Jose, CA, USA) was installed for remote viewing and monitoring.

Carcasses Management and Characterization

Six pigs (average: 82 kg, 180 lb; SE: 1.27 kg, 2.80 lb) which were culled because of umbilical hernias were obtained from a nearby cooperator. Carcasses were euthanized by electrocution and were free of punctures or ruptures. Each carcass was fully encased in plastic landscape netting to contain carcasses during decomposition (1.3 × 1.3 cm; 0.5 × 0.5 in. mesh size) and then wrapped in a chain secured with carabineers to aid in moving the carcasses for

daily weighing. Carcasses in DR_A were placed in a leachate collection system while DR_B carcasses were placed directly on concrete slats for the duration of the study. The leachate collection system in DR_A consisted of plastic slatted flooring placed inside a plastic bin (1.12 × 0.50 × 0.17 m; 44 × 19.75 × 6.5 in.) and Ø1.6 cm (Ø0.63 in.) tubing routed through DR_A pit and drain valve to accumulate leachate in collection buckets outside the mobile laboratory (fig. 4.2b, 4.2c). Collection lines were periodically cleared using a plumbing drain snake to avoid build-up of solids. Leachate from DR_B was collected and stored in the pit for the duration of the study. Carcasses in each room and leachate from DR_A were weighed daily (fig. 4.2a) using a hanging scale (accuracy: ±0.91 kg, 2 lb; range: 0 to 250 kg, 0 to 550 lb; Tool Shop Model #8386, Menards, Eau Claire, WI, USA). At the completion of the trial, carcasses were weighed one final time before being removed from the DR and placed in a corn stover compost pile to complete decomposition.

Figure 4.2. (a) Daily carcass weighing in the rooms using a hanging scale. (b) Daily leachate weighing from leachate collection systems. (c) Leachate collection buckets routed from each carcass bin and through the pit and leachate release valve.

Temperature

Carcass rectal and shoulder temperatures were logged on 60 s intervals using a battery-powered two-channel datalogger (accuracy: ±0.2°C from 0°C to 70°C; range: -40°C to 100°C; resolution: 0.04°C; MX2303, Onset, Bourne, MA, USA). Dataloggers were contained and taped to each carcass for portability when carcasses were weighed. Temperature probes were inserted through a small incision (1 cm long) in the shoulder and secured using tape and epoxy. Temperature probes were secured in a similar way rectally, and the datalogger was affixed to the carcass. Carcass rectal and shoulder (n=6) temperatures were averaged in each room hourly and daily. Hourly temperatures for DR_A and DR_B were compared using a statistical package to assess differences in room environment (SAS Institute, Inc., 2018). A t-test (α=0.05, df=799) assessed if mean hourly DR temperatures were different from one another.

Carcass Decay Models

Several decay models were considered to model carcass mass reduction and leachate production to predict carcass mass change during exposure to an in-barn decomposition environment. A first order decay model was considered for carcass decay and is defined in equation 4.5:

$$y = A_0 e^{-k/t} \qquad (4.5)$$

where

A_0 = starting mass (kg)

k = constant rate of decay (kg d^{-1})

t = time (d).

Choi et al. (2017) used a modified Gompertz equation to model leachate production from buried carcasses by collecting leachate in individual collection systems. Although the model was

used only for leachate production, it could also be applied to carcass decomposition when written in terms of cumulative mass reduction. The modified Gompertz equation is show in equation 4.6:

$$M = P \times exp\left[-exp\left(\frac{R_m \times e}{P}(\lambda - t) + 1\right)\right] \quad (4.6)$$

where

M = cumulative leachate production (L $kg_{volatile\ solids}^{-1}$)

P = maximum production (L $kg_{volatile\ solids}^{-1}$)

R_m = maximum production rate (L $kg_{volatile\ solids}^{-1}$ d^{-1})

λ = lag phase (d)

t = time (d).

Similar to the Gompertz model, a logistic decay model has an S-shaped curvature which is symmetrical about the point of inflection, whereas the Gompertz model is not. A logistic model can be defined by equation 4.7:

$$y = \frac{c}{1+ae^{-bt}} \quad (4.7)$$

where

y = cumulative production (kg)

$\frac{c}{1+a}$ = initial mass value (kg)

c = carrying capacity or limiting value (kg)

b = constant rate of growth (kg d^{-1})

t = time (d).

Ammonia Production

Using infiltration rate from wind and stack pressure and recorded concentrations, NH_3 production was calculated using equations 4.8 and 4.9.

$$\dot{m}_{NH3\ produced} = Q \times \rho \times (\beta_{A,B} - \beta_O) \quad (4.8)$$

$$\beta = \frac{C}{10^6}\frac{R_a}{R_{NH3}} \quad (4.9)$$

where

$\dot{m}_{NH3}$ = mass of NH_3 produced (kg_{NH3} h^{-1})

Q = total airflow rate (m^3 h^{-1})

ρ = density of room air (kg m^{-3})

β = mass fraction (kg_{NH3} kg_a^{-1})

C = concentration of NH_3 (ppm)

R_a = 287 J kg^{-1} K^{-1} (gas constant for air)

R_{NH3} = 487.9 J kg^{-1} K^{-1} (gas constant for NH_3).

Olfactometry

Odor samples from each DR were collected every two days in inert Tedlar sampling bags. Samples were stored for less than four days before being assessed by odor panelists in the Olfactometry Lab at Iowa State University. Four panelists who would remain isolated from the vicinity of the DRs during the entire study were selected to assess the odor samples to avoid developing insensitivity to the odor. The panelists remained the same during each session and assessed the samples in the same sequence during each meeting. Because the panelists remained the same, a qualification test was not necessary. A triangular forced choice (TFC) method was used for the olfactometry panel; hence, panelists were delivered three stimuli of air for three seconds each. Two of the stimuli were clean air while the third was the diluted, odorous sample air. Panelists could return to any of the stimuli an unlimited number of times before selecting which they believed was the odorous air sample. The olfactometer could deliver 14 levels of dilution corresponding to dilution ratios between 2^3 and 2^{16}. Samples were delivered to the panelists initially at a dilution level of 2 (dilution of 2^{15}) and the dilution level was increased

(i.e., sample became less dilute), until the panelist correctly identified the odorous sample of air in two consecutive dilution levels. Average odor detection threshold (ODT) and dilutions to threshold for each sample were determined by a geometric average of the four panelists. Differences in ODT_A and ODT_B were assessed using a statistical package (SAS Institute, Inc., 2018) and t-test (α=0.05, df=14).

Results and Discussion

Air Exchange

Air exchange due to wind and stack pressures was determined based on the enhanced model for infiltration procedure (ASHRAE, 2013). Infiltration values in each DR were approximately equal for most of the study (fig. 4.3). Differences in infiltration can be attributed to slight average temperature and shelter class differences between the rooms (DR_B having only two exterior walls, whereas DR_A has three).

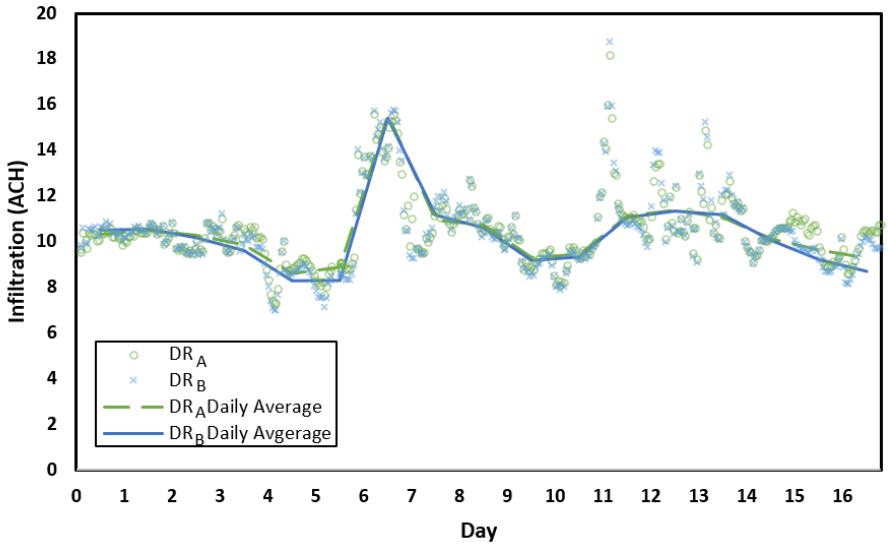


Figure 4.3. Infiltration as defined by ASHRAE Handbook of Fundamentals for wind driven and thermal driven infiltration.

Room Environment

Thermal

Outdoor, DR_A, and DR_B temperatures were averaged on hourly and daily intervals, and room temperatures were found to be significantly different from each other ($p<0.01$). Average temperature of DR_A = 45.7°C (σ = 3.3°C) and DR_B = 44.2°C (σ = 2.9°C). Slat temperature was colder than DR temperatures throughout the trial with an average temperature of 23.7°C (σ = 2.1°C). The decrease in room temperatures on day 9 was caused by an empty propane tank, resulting in no heating for approximately four hours (fig. 4.4).

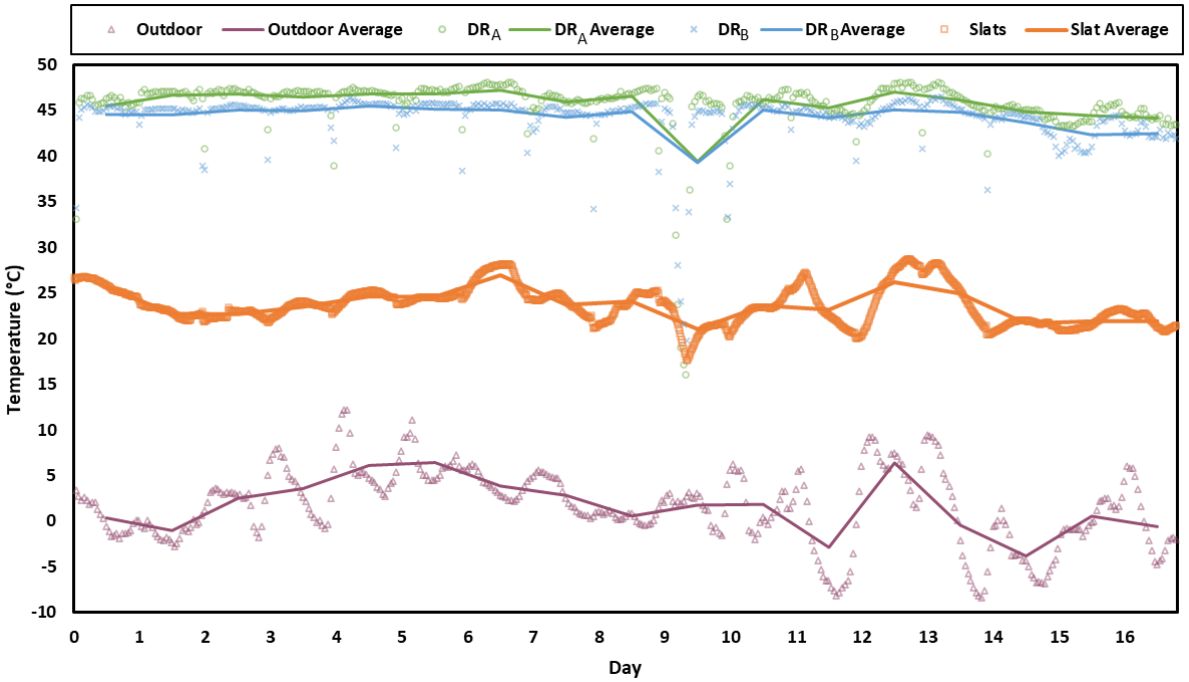


Figure 4.4. Outdoor, DR_A, DR_B, and slat temperatures shown by one hour increments and daily averages.

Air Quality

Gas concentration data was averaged daily and compared between rooms. On day 13, a solenoid on the outdoor sampling line malfunctioned and did not fully open. From day 13 forward, outdoor gas concentrations cannot be considered accurate because the gas measurement

resulted from stale DR air in the sampling line with minimal outdoor air entering the sampling line through the broken solenoid. However, outdoor concentrations did not deviate significantly during the first 12 days of the trial, so an average value can be assumed from day 13 forward. For CO, the average outdoor concentration before day 13 was 7.5 ppm. Considering the uncertainty of the sensor (±2 ppm or ±1% of the measured value), a measured CO standard deviation of 0.74 ppm for the first 12 days falls well within the range of uncertainty of the sensor; therefore, outdoor CO can be considered constant from day 13 forward (fig. 4.5).

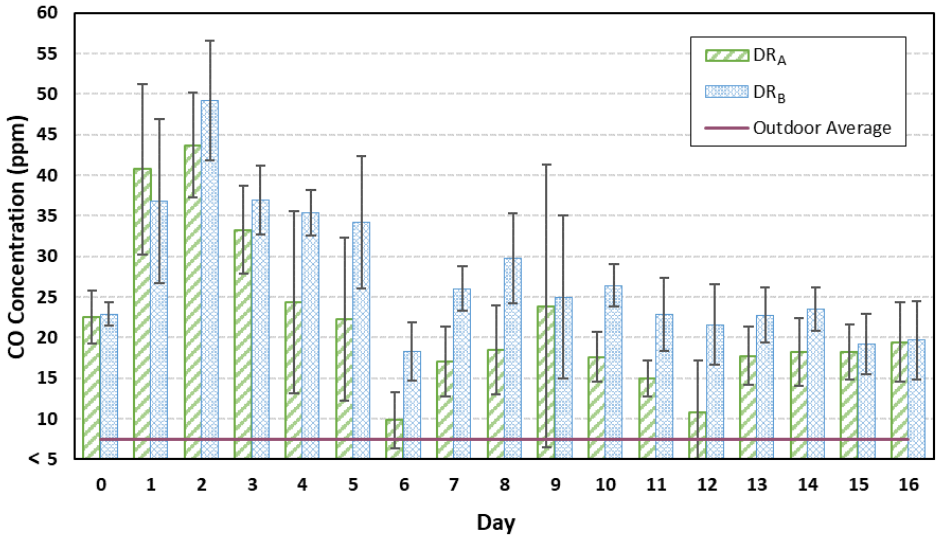


Figure 4.5. Daily average CO concentration by location with standard deviation uncertainty.

Likewise, the daily average outdoor O_2 prior to day 13 was 20.87% with a standard deviation of 0.07%. The uncertainty of the sensor is ±1% of the measured value, so the standard deviation for the first 12 days of measurements falls within this range and an average value for outdoor O_2 was assumed for the duration of the study (fig 4.6).

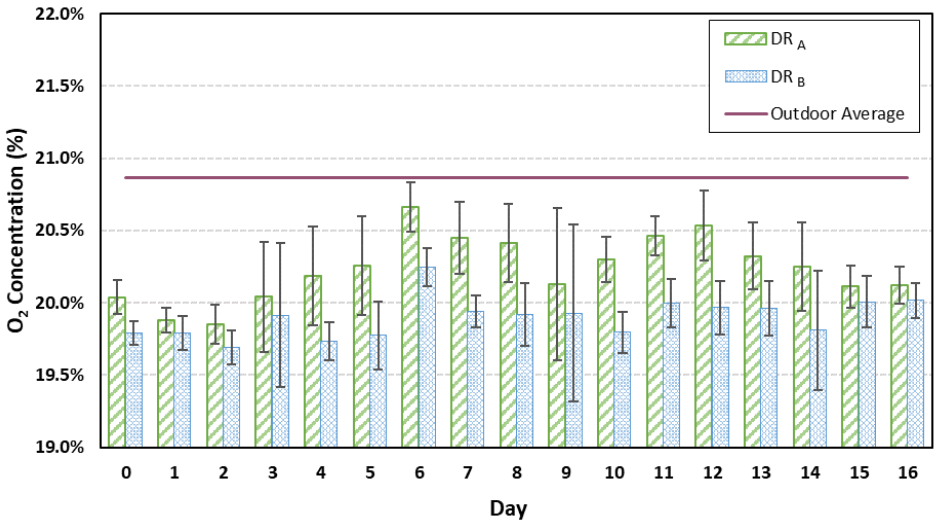


Figure 4.6. Daily average O_2 concentration by location with standard deviation uncertainty.

The daily average of outdoor CO_2 prior to day 13 was 903 ppm with a standard deviation of 146 ppm. With a sensor uncertainty of ±0.1% of the measured value, this does not fall within the uncertainty of the sensor, but it was unreasonable to assume that the values for outdoor CO_2 after day 13 were valid. Therefore, the outdoor average CO_2 concentration was considered constant after day 13 (fig. 4.7).

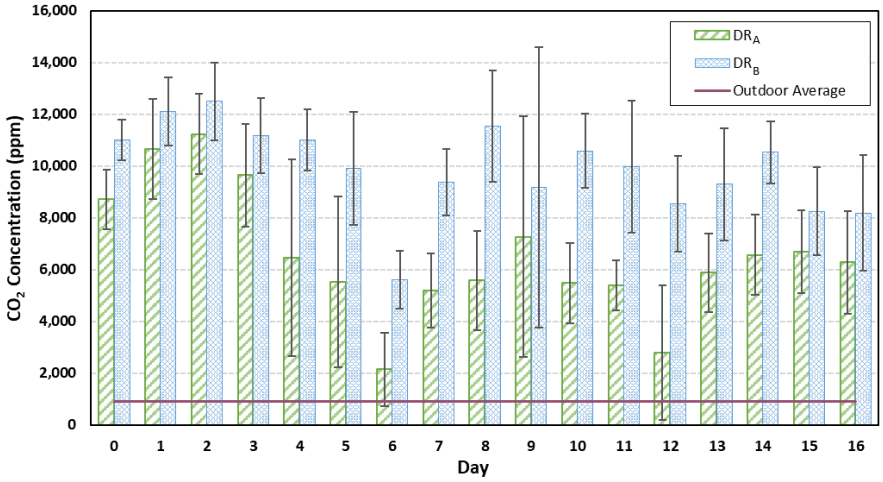


Figure 4.7. Daily average CO_2 concentration by location with standard deviation uncertainty.

Differences in CO, O_2, and CO_2 concentrations between rooms can be explained by varying room air exchange rate and heater runtimes (DR_A average = 4.9 h d^{-1} and DR_B average = 5.1 h d^{-1}) and subsequent consumption of O_2 and production of CO and CO_2 during combustion.

Unlike the other gasses, outdoor NH_3 was not averaged for the length of the study for several reasons. First, the lower detection limit of the sensor was 5 ppm and any value below this threshold cannot be considered accurate; therefore, values less than 5 ppm were considered 0 ppm with the caution that there was some uncertainty in the measurement. For all sampling locations including each DR, the NH_3 measured concentration was less than 5 ppm during the last several days of the study. Second, an average outdoor concentration of NH_3 was not used because NH_3 occurs naturally in the atmosphere from sources such as fertilizers, livestock operations, biomass burning, and fossil fuel combustion and can vary based on proximity to production sources (Behera, Sharma, Aneja, & Balasubramanian, 2013; NOAA, 2000). Based on nearby activities, outdoor NH_3 concentration is more likely to vary between days than other gasses measured. Outdoor NH_3 concentrations during days 1 through 3 were greater than typical atmospheric levels of 3 ppb because the production source (decaying carcasses) was in proximity and emitting high concentrations of NH_3 during this time. The desired NH_3 measurement was mass production, so the measured concentration at any given time was used in the mass balance calculation (fig 4.8).

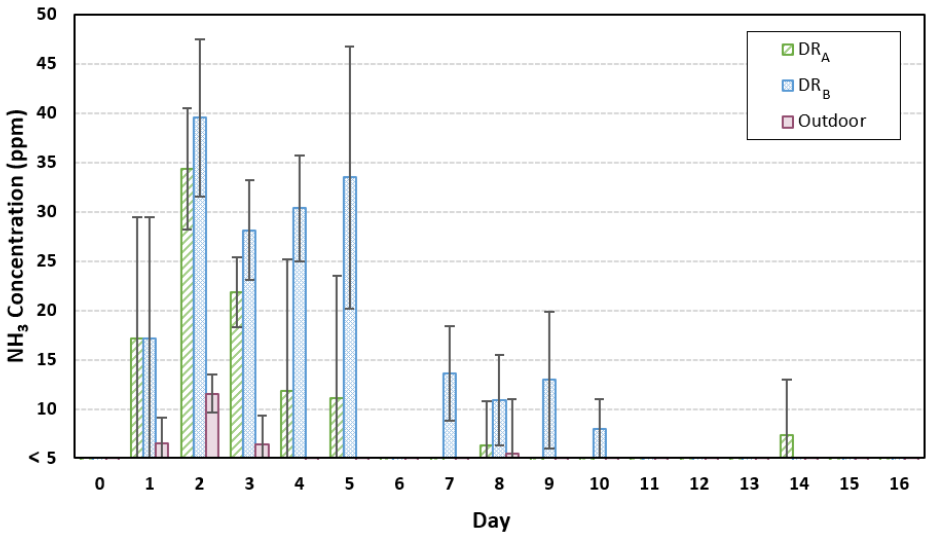


Figure 4.8. Daily average NH_3 concentration by location with standard deviation uncertainty.

Carcass Management and Characterization

Measured parameters of air exchange rate, gas concentrations, carcass mass, and odor were analyzed to characterize response of six carcasses exposed to air temperatures of 43°C. Carcass decay was modeled, NH_3 production was quantified, and ODT was measured to characterize carcass response to a desiccation environment.

Temperature

In each DR, carcass rectal and shoulder temperatures were averaged hourly and daily (fig. 4.9). Carcasses housed on concrete slats in DR_B had significantly lower temperatures than carcasses housed on elevated plastic slatted flooring in DR_A ($p<0.01$), suggesting that the flooring material may have an impact on carcass thermal response. However, when the differences in carcass and air temperatures were compared, DR_A was found to have a greater difference between carcass and air temperature than DR_B. Although DR_B carcass temperatures were colder and suggest flooring material may have an impact on carcass temperature, the later test conflicts the initial observation and suggests flooring material has no impact. More research

is needed to determine if managing carcasses on flooring materials with a lower thermal mass than concrete, or placing carcasses on solid surfaces to minimize convection with cooler air from the pit may aid in reaching elevated carcass temperatures.

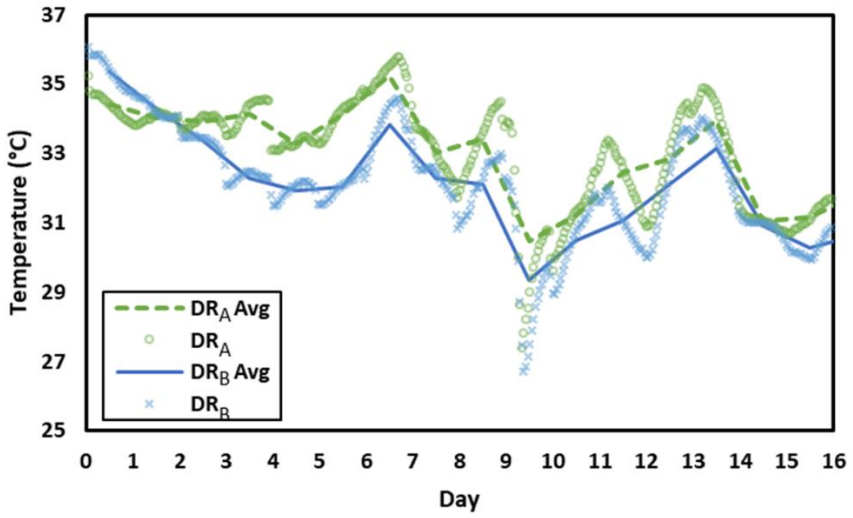


Figure 4.9. Carcass thermal response on one-hour intervals and daily average carcass temperatures.

Carcass Decay Models

Carcass condition was recorded by visual inspection from the researchers daily. They observed carcass swelling until days 2 to 3 for the smaller carcasses (<80 kg;177 lb) before rupture followed by deflation. Carcasses most often ruptured in the posterior ventral region as abdominal pressure exceeded the strength of the skin, with intestines being the first exposed organs. Because the larger carcasses did not rupture, it was hypothesized that as carcass mass increases, skin thickness also increases and is able to withstand the pressure exerted by swelling of abdominal organs post-mortem. Time lapse images displayed noticeable swelling of carcasses during the first days, followed by rupture, then deflation. Still images of the time lapse are recorded in figure 4.10 to depict decay and state of the carcasses at various points in the study.

Figure 4.10. (a) DR_A and (b) DR_B carcass decay selected still photos from time-lapse recording.

Daily weights of carcasses indicated a gradual decrease in weight the first 2 days of the study. From days 3 to 9, a more drastic decrease in weight occurred daily, with peak day-to-day loss occurring between days 4 and 5 (fig. 4.11). The same trends can be observed in daily leachate production. At the end of the study, some leachate remained in each of the collection bins. The remaining leachate was weighed, and the average (kg d^{-1}) was added to the leachate weights from each day.

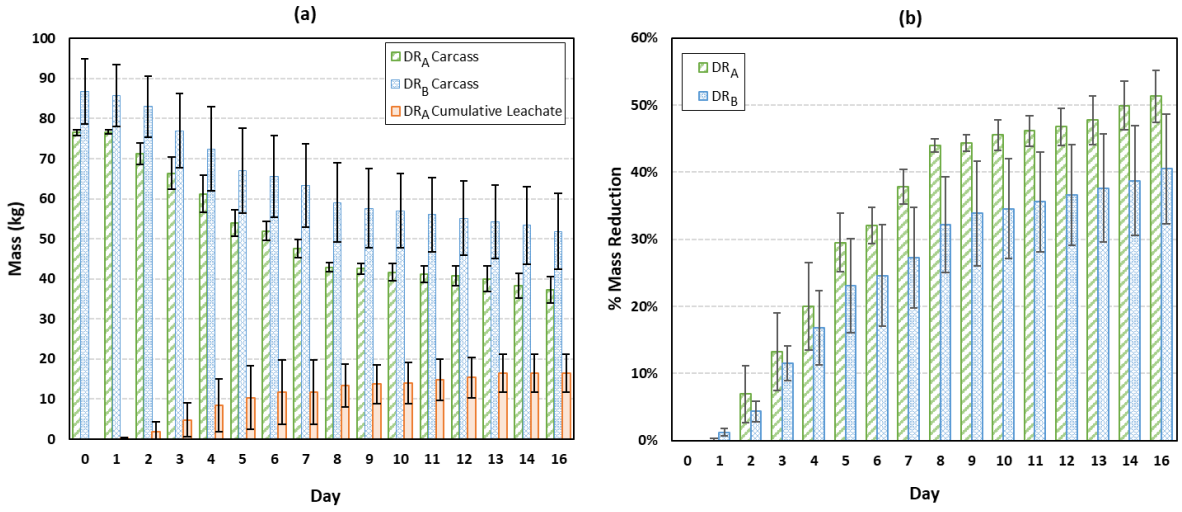


Figure 4.11. (a) Daily carcass weights and leachate weights by room with standard deviation uncertainty, and (b) daily average carcass percent mass reduction with standard deviation uncertainty. Remaining leachate in collection bins was averaged and added to daily leachate totals. Carcass and leachate were not weighed on day 15 of the trial.

Modified Gompertz and logistic models were used to fit data for leachate production (fig. 4.12) and carcass mass reduction (fig. 4.13) using statistical curve fitting tools (MATLAB, 2018). A first order decay model was fit for carcass mass but did not fit the data as well as the logistic and Gompertz models (table 4.2). Although both Gompertz and logistic models fit the data well, additional research is needed to assess applicability of a model to a range of carcass sizes under varying environmental conditions such as temperature and air exchange rate.

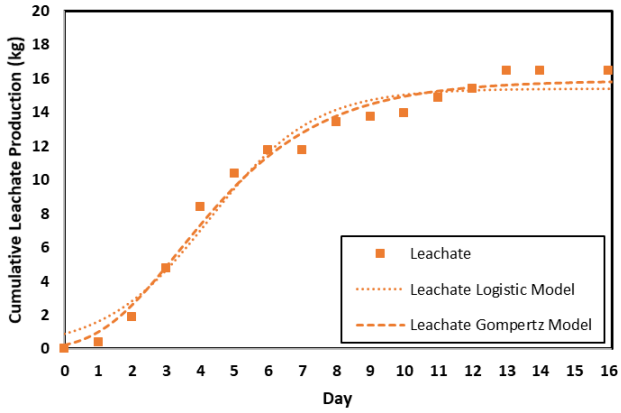


Figure 4.12. Gompertz and logistic models for cumulative leachate production.

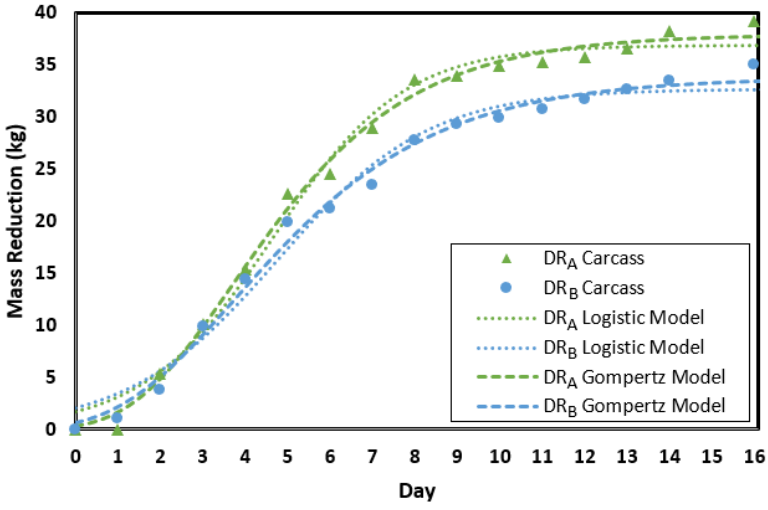


Figure 4.13. Gompertz and Logistic models for carcass mass reduction by day.

Table 4.2. First order decay, logistic model, and Gompertz model summaries with coefficient values, 95% confidence intervals, R^2 and root mean square error (RMSE).

Model	Source	Coefficients (95% CI)			R^2	RMSE (kg)
		t				
First Order Decay	DR_A	17.8 (16.2, 19.4)			0.94	3.49
	DR_B	25.34 (23.3, 27.4)			0.94	2.94
		a	b	c		
Logistic Model	DR_A	20.7 (9.0, 32.5)	0.7 (0.5, 0.8)	36.9 (35.3, 38.4)	0.99	1.60
	DR_B	14.9 (6.2, 23.5)	0.6 (0.4, 0.7)	32.7 (30.9, 34.4)	0.98	1.69
	Leachate	16.2 (2.8, 29.6)	0.7 (0.5, 0.8)	15.4 (14.4, 16.4)	0.97	1.05
		P	R	λ		
Gompertz Model	DR_A	37.9 (36.7, 39.2)	5.9 (5.2, 6.5)	1.3 (1.0, 1.7)	0.99	1.07
	DR_B	33.8 (32.4, 35.2)	4.6 (4.0, 5.2)	1.0 (0.6, 1.5)	0.99	1.07
	Leachate	15.9 (15.0, 16.7)	2.5 (2.0, 3.0)	1.0 (0.4, 1.7)	0.99	0.76

Ammonia Production

The NH_3 production from DR_B was greater than DR_A production. This can be explained by the removal of leachate from DR_A through the leachate collection system and accumulation of leachate in the pit of DR_B. This aligns with previous research for NH_3 generation from leachate research. Aarnink et al. (1995) showed that the removal of leachate from under-floor slurry storage for finishing pigs resulted in an NH_3 reduction of 20%. Osada et al. (1998) showed that removing under-floor slurry weekly resulted in a slight decline in NH_3 generation rates. However, with the daily removal of leachate from DR_A, it was expected that the rate would be significantly less than DR_B based on previous research. At the completion of this study, cumulative production of $NH_{3,A}$=182 g from carcasses alone, while cumulative production of $NH_{3,B}$=360 g from carcasses and leachate. Total NH_3 generation in DR_A was approximately 50% of the total generation in DR_B, indicating that removing leachate significantly reduces NH_3 generation from inside the barn during carcass decomposition.

Both carcass treatments resulted in increasing daily NH_3 production until day 2 followed by a decline for the remainder of the study, but DR_A daily production decreased more quickly than DR_B. Peak NH_3 production, measured in g AU^{-1} day^{-1} (where AU is animal unit and equivalent to 500 kg body mass) was 120 g AU^{-1} day^{-1} (19.7 g $animal^{-1}$ day^{-1}) for DR_B, while maximum rate for DR_A was 96.5 g AU^{-1} day^{-1} (15.8 g $animal^{-1}$ day^{-1}.) Although the range of NH_3 generation rates is broad and the majority of previous studies of NH_3 production have focused only on emissions from swine production facilities and not carcass NH_3 production, the rates of maximum production fall within previous extremes of NH_3 production, but outside of the standard range. Hoff et al. (2006) identified the average and most dominating range to be 300 to 500 mg NH_3 m^{-2} h^{-1} from swine finishing pigs. Aarnink et al. (1995) found generation rates for finishing pigs were in the range of 5.7 to 5.9 g NH_3 pig^{-1} d^{-1} (331 mg NH_3 m^{-2} h^{-1}.) Generation rate for DR_A fell below 5 g $animal^{-1}$ day^{-1} after day 5, but DR_B generation rates did not reduce as quickly, with a rate of less than 10 g $animal^{-1}$ day^{-1} not occurring until day 6, and generation rates of less than 5 g $animal^{-1}$ day^{-1} not occurring until day 11. However, it is important to note the uncertainty in the NH_3 production measurement. Because NH_3 emission rate is a function of air exchange rate, uncertainty in infiltration calculations will impact calculations. In figure 4.14, the developing trend seen from approximately days 2 to 11 was broken on day 6; infiltration on day 6 (figure 4.3) also increased due to wind pressure. However, an underestimation in air change rate would result in an apparent decrease in NH_3 production. It was hypothesized that this was what caused an apparent lower level of NH_3 production on day 6.

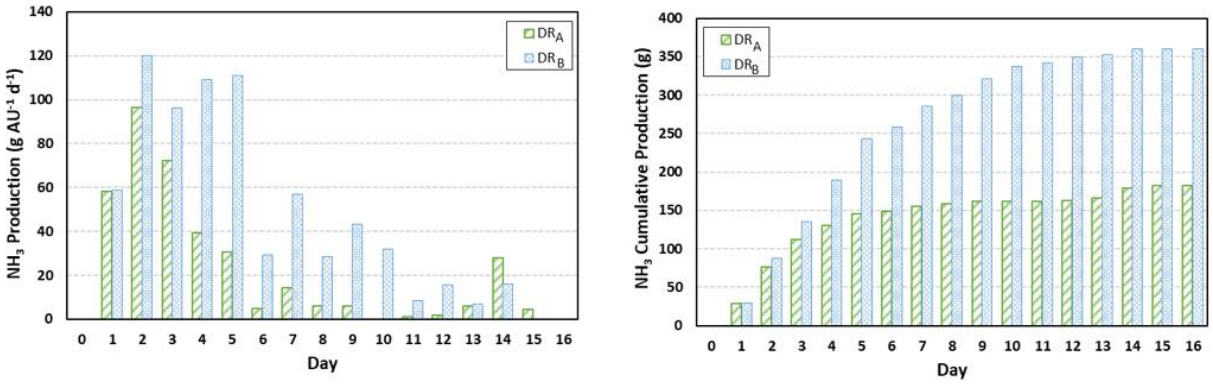


Figure 4.14. (a) Daily NH_3 production (g AU^{-1} day^{-1}) by room. (b) Cumulative total NH_3 production (g) by room.

Olfactometry

From daily observatory assessment, the researchers noticed a sharp increase in odor on approximately day 3 of the study. The olfactometry panel results indicated a similar observation with an increase in odor noted on day 3, with ODT_{avg}=5,793 compared to ODT_{avg}=1,942 on day 1 (fig. 4.15). There was no significant difference in ODT_A and ODT_B through the duration of the study (p=0.5), and ODT_{avg}=5,217 for the entire study after day 3.

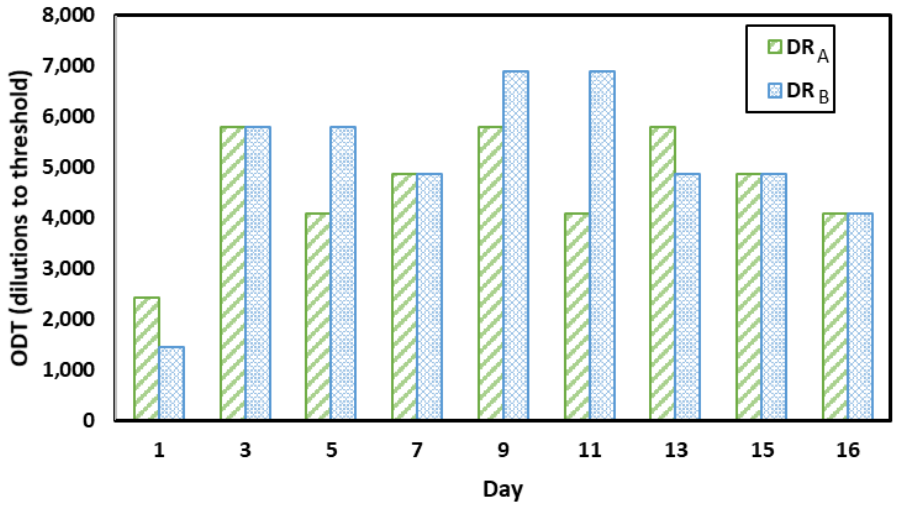


Figure 4.15. Geometric average odor detection threshold level by sample.

Conclusions

Six swine carcasses were exposed to a desiccation environment for 16 days in a small-scale swine production laboratory. Carcass and room temperatures, CO, CO_2, O_2, and NH_3 were continuously monitored, and carcasses and leachate were weighed daily. Infiltration was quantified as a function of wind and stack pressures and used to determine NH_3 production. Release of NH_3 by carcasses and leachate during in-barn swine carcass desiccation was found to be approximately twice that of desiccation in which leachate was removed. Gompertz and logistic models were found to fit data well for carcass mass reduction and leachate production, with a Gompertz model having a slightly better fit. No significant differences in ODT_A and ODT_B were observed by an olfactometry panel for the study. The parameters assessed aid in preliminary characterization of carcasses during in-barn carcass management for swine. Additional data collection may lead to creation of an accurate model for swine carcass decomposition under controlled conditions based on initial carcass mass and varying environmental factors.

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CHAPTER 5. GENERAL CONCLUSIONS

Key results of the two manuscripts presented in this thesis are, first, the development and commissioning of a mobile swine production facility and second, the results of a 16-day trial in the production facility to characterize carcass response to an in-barn desiccation environment. The development of the mobile laboratory allowed carcass management and response approaches to be conducted in a near-production setting for an extended length of time. In-barn mortality management strategies for swine are relatively undeveloped and this thesis advanced knowledge of carcass response to an in-barn environment and provided beginning framework for characterization of mortalities in a controlled environment. Areas where future research is needed will also be highlighted.

Research in swine production facilities presents many challenges with time required to travel to the site, labor required to set up site instrumentation, and cost of modification and additions to existing production systems for research purposes. In many cases, the degree of control and customization desired is not attainable when working in production facilities. The creation of a general-purpose laboratory for small-scale in-barn swine discoveries mitigated many of these challenges, and provided an opportunity to create a customized system for unique experimentation.

The lab was designed in style of a typical swine production facility from construction style and finishes to heating and ventilation equipment. Two discovery rooms (DRs) with concrete slats and pit beneath replicated conditions of a typical barn. The laboratory was instrumented with a building automation controller (BAC) which remotely monitored and controlled the heating and ventilation system, and also served as the data acquisition system for sensors permanently integrated into the lab (i.e., air temperature, relative humidity, static

pressure). The mobility of the laboratory enables its use at a variety of sites, and geographical isolation if necessary.

The laboratory can be used for a variety of experimentation because of its capability of environmental control for a range of ambient conditions and desired DR temperature setpoints. Although there are currently no provisions for a feeding or watering system, the objective of the lab was to provide a space for observation of environmental response of animals or carcasses; therefore, studies requiring live pigs to be housed for several days or weeks could be conducted in the laboratory with hand feeding and watering. Additionally, the quantification of laboratory parameters such as air exchange rate and thermal transmittance enable researchers to more accurately quantify and model results from studies conducted in the laboratory.

In summary, the creation of small-scale laboratories for animal production has many advantages including the ability to customize the facility to the needs of the research, a lower cost for labor and materials, and quantification of many factors that are otherwise unknown in traditional production settings. More control is achievable with small-scale facilities and factors that contribute to uncertainties in production settings are reduced. Furthermore, it is possible to conduct research in such a laboratory that may be infeasible in traditional facilities. For example, in-barn mortality management strategies are impractical to conduct in a commercial facility because of the loss of production space and enormous scale for preliminary studies. The use of this general purpose swine discovery laboratory for characterization of carcass response to in-barn mortality management strategies is one example of use for the laboratory.

With the threat of a Foreign Animal Disease (FAD) outbreak on the horizon, definition for more biosecure methods of carcass disposal is called for. A strategy of desiccation mitigates many problems associated with existing carcass disposal methods. During desiccation, carcasses

are not removed from the production facility until they have reached critical times and temperatures for thermal inactivation of pathogens, thereby reducing the risk of virus spread by avoiding exposure of diseased carcasses to transmissive agents. Additionally, carcasses undergo a significant mass reduction, meaning less carbon material will be required for further composting outside of the barn. Burial after desiccation may also become a more feasible option because pathogen inactivation temperatures have already been reached, and the majority of moisture in the carcass has evaporated or leached into the pit. Hence, potential for groundwater pollution is substantially reduced and risk of pathogen survival in buried carcasses is negated. The main opposition of in-barn carcass management strategies would be a loss of usable production space during the period of carcass treatment. However, in the event of a FAD, in-barn approaches of mortality management will be the most biosecure and if implemented properly, could mitigate much of the pathogen spread that would have occurred with traditional strategies.

There is a great need for definition of strategies for in-barn carcass mortality management, but this thesis aims to begin characterization of carcass response to an in-barn desiccation environment. This study compared three carcasses housed on concrete slats with cumulative leachate collection in a pit below, and three carcasses housed on plastic flooring elevated above individual leachate collection systems. All six carcasses were exposed to a desiccation environment for 16 days. Although it was expected that concrete slatted floors would negatively impact carcass ability to reach elevated temperatures, it was found that flooring material had no impact on carcass temperature during the study. Daily weighing of carcass and leachate quantified carcass rate of decay and Gompertz and logistic models were fit to the data. All carcasses in this study were approximately the same mass, but future studies with varying carcass masses and varying environmental parameters may allow a model to be created to predict

carcass desiccation time as a function of mass and environmental conditions. Ammonia generation rate in the DR with leachate removal was approximately half that of leachate collection beneath the slats, indicating that leachate contributes significantly to ammonia emission rates. Finally, odor for each treatment was compared and was not found to be significantly different from one another. However, odor levels were relatively high and may become a nuisance, so additional research for odor reduction strategies for in-barn carcass treatment may be warranted.

Overall, this study will help the swine industry by providing new information for more biosecure methods of carcass management though in-barn strategies. While additional work is needed to garner more information and refine a procedure to use in practice when needed, this research provides a foundation to build from.

Future Work

There are many opportunities to extend the research presented in this thesis. The following is not an exhaustive list of potential opportunities, but a mere start to enhancing the knowledge of the research presented.

- Refinement of the general-purpose laboratory for small-scale in-barn swine discoveries to reduce uncertainty in environmental measurements (i.e. nonmechanical infiltration) and improve function of the laboratory for a variety of experiments.
- Additional replications of CUReD HAM over prolonged testing periods with a range of carcass sizes and varying environmental conditions (i.e., air exchange rate, air temperature).
- Creation of a model for carcass desiccation time as a function of air temperature, air exchange rate, and beginning carcass mass.

- Evaluation of an in-barn composting approach for swine carcasses, determination of feasibility, and assessment of carcass response.
- Appraisal of long-term impacts of in-barn carcass management strategies on building construction, equipment performance, and system integrity.
- Development of a computer model with flexible parameters (i.e., building size, ambient conditions, carcass size and number, and air infiltration rates) to assess carcass response and time to reach pathogen inactivation temperatures for in-barn mortality management strategies on a catastrophic scale.