RESEARCHREPORT

ANIMAL SCIENCE

Title: Ventilation improvements for controlling swine production systems**, NPB # 13-213**

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Industry Summary: Maintaining acceptable thermal and gas concentration levels during minimum ventilation periods is challenging. The small amount of fresh-air used during cold weather periods needs to be distributed as uniformly as possible through the planned inlet system. Unfortunately, leaks and cracks throughout a barn provide unplanned air inlets at sporadic and unpredictable locations, rendering the ability to uniformly distribute minimum ventilation air nearly impossible. This project focused on quantifying leakage rates from swine finishing barns to characterize the significance of barn leakage, and, to provide guidelines for reducing this leakage. Our results, based on 17 swine finishing barns, indicated that the *as-is* infiltration rate, at an operating static pressure of 0.08 in wc, averaged 5.96±1.49 CFM/pig; with the leakage rates through curtains, fans and other components consisting of 1.49±1.00 CFM/pig (about 25% of *as-is*), 1.52 ±1.38 CFM/pig (about 26% of *as-is*) and 2.90 ±1.42 CFM/pig (about 49% of *as-is*), respectively. These rates apply to finishing barns with 8 ft ceilings and a stocking density of 7.5 ft^2/pig. The *as-is* leakage rate was minimum for rooms from single room barns (5.85 ±1.66 CFM/pig at 0.08 in wc) and rooms having non-metal ceilings aged ≤ 13 years (5.85 ±2.15 CFM/pig at 0.08 in wc). Curtains, pump-outs, and unused cold weather fans are manageable leakage points that can be mitigated with relatively low-cost methods that many producers are presently incorporating. The remaining 50% of the *as-is* leakage, primarily identified from ceiling-to-side/end wall joints and ceiling panel corrosion locations will require significant effort to mitigate, potentially with attic spray foam insulation. If spray foam is used at these targeted locations, a reduction of 80% in overall leakage rate was measured in a controlled test room. If infiltration is not controlled and the barn is operating at the *as-is* leakage rate, a maximum most likely operating pressure (in wc) for delivering 2, 4, and 6 CFM/pig is 0.001, 0.011, and 0.042 in wc, respectively with unplanned leakage openings accounting for 91%, 86%, and 82% of the inlet area required. If infiltration is controlled up through attic foaming, the maximum most likely operating pressure for delivering 2, 4, and 6 CFM/pig increases 0.039, 0.072, and 0.073 in wc, respectively with unplanned leakage openings accounting for 48%, 29%, and 19% of the inlet area required. For more information, please contact Dr. Steve Hoff, Department of Agricultural and Biosystems Engineering, Iowa State University (hoffer@iastate.edu).

Keywords. *Infiltration, ventilation, energy efficiency, comfort*

Introduction: Mechanical ventilation systems are used extensively in swine production facilities to control the inside environment. Good quality indoor air is a necessity for animal health and for maximizing productivity. Continuous release of sensible and latent heat, CO_2 from animals, and NH_3 and H_2S released from manure, are some of the major sources of inside air contamination. Ventilation forces outside air through the barn, which dilutes and removes indoor air contaminates (ASHRAE, 2013). In the mechanical ventilation process, air enters into the barn simultaneously through planned openings and unplanned leakage points. Unplanned air entry into a room (i.e., infiltration) is an integral part of any ventilation process. Zhang and Barber (1995b) summarized infiltration air entering a barn in three categories: 1) Interflow - "contaminated" air from an adjacent interior room leaks into the building, 2) Inflow – outside fresh air leaks into the barn, and 3) Short-circuiting – outside fresh air leaks into the barn from the envelope openings around the exhaust fans and exits through fan without mixing with inside air.

Infiltration negatively affects ventilation control and effectiveness. High infiltration rates reduce the effectiveness of the ventilation air and is an indicator of potentially poor design and/or construction (Jadhav et al., 2015). Zhang and Barber (1995b) highlighted the negative effects of air leakage; 'interflow' reduces air quality; 'inflow' may be the common source of drafts and increase winter heating costs, and 'short-circuiting' causes a reduction in ventilation effectiveness. All three types of infiltration potentially affect the controllability and performance of planned inlets as infiltration reduces the quantity of air coming into the barn through designed and planned inlets. Infiltration develops pockets of non-uniform and undesired environments in a barn (Masse et al., 1994b) and in winter can develop cold drafts around/nearby cracks. Albright (1990) highlighted that air infiltration directly affects air mixing and its distribution. More infiltration from one section of the building compared to low infiltration from another affects the uniform distribution of fresh air in the barn. ASAE standard EP270.5 also cautions that negative pressure ventilation systems may get affected easily due to wind effects and air leaks and may not provide acceptable air distribution at low air flow rates. Air leakage has also been identified as one of the important reasons for the deterioration of building components (Zhang and Barber, 1995a) especially for positive pressure ventilation systems. Water condensation on interior claddings and water accumulation in the ceiling and walls are other ill-effects of infiltration. Water condensation can affect animal comfort and health; whereas, water accumulation can reduce the building durability and energy efficiency.

Masse et al. (1994a) summarized the available methods and tests to determine building air leakage. Along with pressurization methods, tracer gas, acoustic, and thermographic surveys are methods used to determine the leakage rate. The ASHRAE "crack method" has also been used for leakage prediction (ASHRAE, 2013). Albright (1990) questioned ASHRAE's crack method of infiltration quantification and stated that this method has not proved accurate for agricultural structures and suggested the development of methods specific for agricultural structures. During minimum cold-weather ventilation, Munroe (1988) recommended a pressure difference of 15 Pa (0.06 inches water column; in wc) or greater across the planned inlet system to ensure proper fresh air distribution. Zhang and Barber (1995a) stated that ventilation systems for animal barns are operated at a low pressure difference, usually less than 25 Pa (0.10 in wc) and animal barn leakage characteristics at low pressures are more important in ventilation system design than those at high pressure differences. Therefore, precise data on infiltration is very important in the design of animal barn ventilation systems. To increase the effectiveness of a ventilation system, Zhang and Barber (1995a) recommended using air infiltration at 20 Pa (0.08 in wc) when designing ventilation systems for animal barns.

Many researchers commented on the lack of sufficient data on infiltration of agricultural barns (Albright, 1990; Zhang and Barber 1995a, 1995b). Using the pressurization method, Zhang and Barber (1995a) measured and modeled the leakage rates of five new grow/finish swine rooms built for research purposes. Data on the infiltration rate of commonly constructed swine finishing rooms as affected by their age, construction layout, and construction material are missing. A general data set on infiltration of swine finishing rooms that could readily be used in the design of ventilation systems is needed. In the present study, 19 swine finishing rooms were tested for their leakage potential using the pressurization method – an alternate to ASHRAE's crack method. Numerous methods are available for quantification of air infiltration into a building including pressurization, tracer gas, acoustic, and thermographic survey (Masse et al., 1994a). Among all tests, the tracer gas and pressurization methods are most common (Masse et al., 1994b). The pressurization method is relatively easy, quick, inexpensive, and less weather dependent as compared to the tracer gas method (ASHRAE, 2013). The most common method uses pressurization testing (ASHRAE, 2013 and Masse et al., 1994b). Shaw and Tamura (1980), Kronvall (1978), and Hunt (1978) all adopted the pressurization method to measure leakage through buildings.

For a ventilation system to function properly, the major system components, including fans, planned inlets, controllers, and the building itself, must work in harmony. This research project focused on the path fresh-air must take from outside to inside the building. Our swine production ventilation systems, unless filtered for virus control, are negative pressure where fans pull air out of the barn, creating a slight vacuum inside the barn relative to outside thus allowing fresh outside air to enter the barn *through any opening, planned or otherwise*. Ideally, all of the fresh-air that gets pulled into a building should travel to and through planned inlets. The reality however is that a significant amount of this fresh-air is being pulled through unwanted cracks and leakage points throughout the building shell. Curtains, for example, have been installed and used in their current configuration for decades with little or no regard to the seal-ability of this potentially high-leakage area, especially with the low static pressure differences associated with wean-to-finish buildings. Back-draft shutters have been used for years but over time these components warp and crack, losing the ability to reduce back-drafting into the animal occupied zone. Ventilation engineers need to account for infiltration but currently the very best available information for barn leakage rates is from a study conducted over 60 years ago from *two dairy barns* (Millier, 1950). These leakage rates in turn can drastically affect the performance of any ventilation system during the heating season where air distribution suffers from excessive leakage area compromising the performance of the designed and planned fresh-air inlet system. The end result is that fans require a given amount of air and this same amount of air must enter into the barn. If significant enough, unplanned leakage locations can satisfy most all of the inlet area required, rendering the planned inlet system inoperable. This can cause drafts on pigs which impacts effective temperature and acts as a stressor which may create opportunities for disease. It may also impact propane usage and dunging patterns within pens, potentially creating a wet environment which can also act as a stressor. This research project was intended to quantify the extent of infiltration through careful in-field evaluation of barn leakage rates and locations, with follow-up construction techniques to significantly reduce these rates in new and existing barns.

The PI and Co-PI for this research have been involved in swine production system design for a combined 50 years. Problems that existed 25 years ago are still prevalent today requiring a dedicated and focused effort to resolve these building design and climate control flaws and provide recommendations for retrofitting existing buildings. The PI studied (Hoff, 2001) curtain material properties and leakage rates of curtains in a controlled laboratory setting. This research concluded that, assuming no obvious curtain tears, the vast majority of curtain leakage air was entering through improper sealing and overlap at the opening and not through the curtain material itself (unless the curtain was designed and marketed as breathable). From this research, recommendations have been made for specific curtain overlaps and maintenance there-of. These changes are simple and cost effective and more importantly allow the designed fresh-air inlet system to function closer to intended design conditions. Significantly more effort however needs to be placed on in-field whole barn features that contribute to excessive leakage air.

Objectives: The objectives of this research project were to;

1. Provide to the swine production industry a set of building design guidelines for new and retrofitted construction focusing on leakage air control, and,

2. Develop support materials to be used in the ISU Extension swine ventilation workshops to disseminate the newly found information.

Materials & Methods:

Objective 1. Provide to the swine production industry a set of building design guidelines for new and retrofitted construction focusing on leakage air control.

BARNS AND ROOMS TESTED

Nineteen swine finishing rooms in Iowa were tested to quantify their infiltration rates. The rooms tested were typical of Midwest barns where a gable roof with a flat interior ceiling constructed using wooden studs, metal sheeting, concrete, and attic insulation were used. A typical swine finishing room tested consisted of insulated walls and attic/ceiling, slotted concrete floor, underfloor manure pit, and internally reinforced polyethylene curtains on at least one sidewall. The rooms tested were fitted with mechanical ventilation systems typical of intensive swine rearing operations across the Midwest region of the US (figure 1).

(a) Front view.

(b) Internal view.

Figure 1. Typical swine finishing barn room from Central Iowa.

All barns tested for leakage originated from four distinct construction layouts (figure 2) identified as single barns (one large room per barn), double-wide barns (two side-by-side single rooms with one common roof), H-type barns (two end-to-end single rooms per barn with two barns connected by a walkway), and double-wide + H-type barns (two side-by-side single rooms with one common roof per barn with a connecting hallway to an adjacent similar barn).

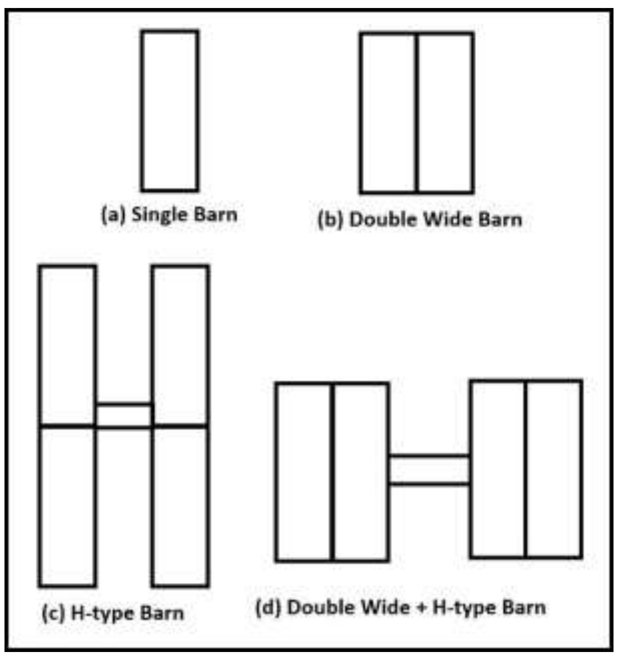


Figure 2. Construction layouts of swine finishing barns.

All the rooms tested used mechanical ventilation systems for periods of cooler weather (minimum-to-mild weather periods). These systems used combinations of variable speed fans, single speed fans, and ceiling inlets. For the hot weather maximum ventilation, rooms either used sidewall ventilation curtains to provide the final ventilation stage naturally or through a series of tunnel fans. Double-wide barns had curtains on the sidewall for emergency ventilation but used fans for all ventilation stages.

TEST PROCEDURE

Nineteen producer cooperators were identified for participation in this research project and site visits were made to each during the summer months of 2014 and 2015. Additional barns were visited during summer 2016 for follow-up work, the purpose of which will be described later in this report. In the present investigation, the pressurization method was used for leakage quantification of all 19 swine finishing rooms. Air infiltration into mechanically ventilated swine finishing rooms was quantified using procedures outlined in standards CGSB 149.15-96 (1996) and ASTM E779-10 (2010). Both the standards are suited for single zone rooms typical of swine finishing. Eighteen of the rooms were tested by following the procedure in standard CGSB 149.15-96. This standard (CGSB 149.15-96) is best to follow when the installed air handling capacity of the room is capable of producing static pressure differences up to 60 Pa (0.24 in wc) or its air handling capacity lies in the range of 1 to 2.5 L/s per square meter of building envelope (CGSB, 1999). All rooms tested, with the exception of one room, satisfied this CGSB 149.15-96 criterion. The exception room was tested by following both the CGSB 149.15-96 and ASTM E779-10 standards. For this exception room, the building's air handing system along with one externally fitted fan (into the barn room entry door) was used to create the desired negative static pressure difference.

During field testing, static pressure differences were generated across the barn envelope by exhausting varied quantities of air from the room. Three pressurization tests – I, II and III were conducted on each room. Test I, called the *as-is* test, was conducted with the primary inlet system sealed while allowing all other building characteristics to remain as in production (figure 3a). For all rooms tested, the primary inlet system consisted of ceiling inlets in 1 to 3 rows along the long-axis of the room, dependent on room width. During Test I, all fans were closed normally using existing back-draft louvers. In situations where louvers were broken/missing/not operating normally, the louvers were sealed using duct tape such that they will act and function like normally closed in-tact louvers. In addition, before Test I was conducted, all pump out covers were checked for their normal closure status and adjusted if required to their normal position. Test II, designed to isolate curtain leakage, was conducted with the primary inlet and all curtain perimeters sealed (top and sides). Test III, designed to isolate fan leakage, was conducted with the primary inlet, curtain perimeter, and all fan and pump-out cover locations sealed. The leakage remaining after Test III was designated as *other* leakage. In all three tests (I, II, III) a minimum of five static pressure differences were generated by exhausting five different air flow rates from the room (CGSB, 1999). The exhaust flow rates were adjusted such that the static pressure difference spanned between 0 to 60 Pa. The difference between leakage rates of Tests I and II was quantified as *curtain* leakage and the difference between Tests II and III was quantified as *fan* leakage. The leakage measured during Test III indicated leakage through *other* building components such as doors, ceiling panel panels, and wall-to-ceiling joints. While performing Tests I, II and III, combinations of duct tape, 6-mil plastic, and reinforced polyethylene sheets were used as sealing material (figure 3).

a

b

Figure 3. Barn (a) inlet primary inlet sealing and (b) curtain and fan sealing required to isolate the curtain and fan contributions to total barn leakage rates.

Along with the leakage test data, data on room characteristics including room age, layout, length, width, height, floor and envelope areas, internal volume, and curtain/fan perimeters were also recorded. Weather data including temperature, relative humidity, wind speed, and altimeter setting was obtained from a weather station closest to each test site. An official calculator provided by the National Weather Service website (http://www.srh.noaa.gov/epz/?n=wxcalc_stationpressure) was used to obtain atmospheric pressure at each test site from altimeter settings. Google earth (https://www.google.com/earth/) was used to retrieve test site elevations.

TESTING EQUIPMENT AND ACCURACY REQUIREMENTS

The precise measurement of exhaust fan air flow rates and static pressure differences across a test room governs the accuracy in infiltration quantification (CGSB, 1986). In this study, the Fan Assessment Numeration System (FANS; figure 4) was used to measure *in-situ* fan air flow rates (Gates et al., 2004). The FANS unit consists of an array of propeller anemometers, which traverse vertically. Velocities by sweep area are integrated to achieve an air flow rate. During actual testing, the FANS unit was placed before the fan in operation. Leakage paths between the frame of the FANS unit and room wall were sealed airtight, so that all the air exhausted by the fan was forced to pass through the FANS unit. For all tests conducted, each individual leakage air flow rate was measured twice. Combinations of inclined manometers with ±0.005 inches water column (in. wc) reading resolution and micro-manometers with ±0.001 in. wc reading resolution were used to measure static pressure difference across the room envelope during testing. A minimum of two manometers were used at opposite sidewalls of the tested room. Infiltration measurement using the pressurization technique is affected by wind pressure around the building, which most of the time is non-uniform (Masse et al., 1994a). To account for wind effects, pressure differences were recorded at least two times for each FANS measurement. Infiltration tests on 17 (out of the 19 total tested) were conducted when the wind speed was less than the recommended 6 Km h^{-1} (Zhang and Barber, 1995a). The wind speeds during testing of two rooms (13 and 19) were observed higher than the recommended 6 Km h^{-1}, hence infiltration data recorded for these two rooms was discarded. Also, all the infiltration tests were conducted when atmospheric air temperatures at barn locations were greater than 5°C (CGSB, 1999).

Figure 4. FANS units installed in-field to assess air leakage rates. In all barns tested, both the 30" and 52" FANS units were installed to assess leakage rates.

DATA CORRECTION AND INFILTRATION PREDICTION

Tests I, II, and III were performed on all 19 swine finishing rooms and at least five data points, exhibiting the relationship between leakage air flow rate and static pressure difference, were generated for each individual test. CGSB standard 149.15-96 (1996) recommends correction of measured infiltration rates for differences in test and calibration temperatures. To minimize the errors due to variation in temperatures from site to site and to maintain uniformity in correction, all the measured infiltration air flow rates were corrected from calibration temperature to standard mean sea level pressure and temperature conditions defined as 101.325 KPa at 15°C. The infiltration rates reported at this standard sea level condition are designated as 'standard' infiltration rates. Two FANS units (FANS Model Numbers 30-0010 and 42-0002) were used for this study, both calibrated at 25.56°C (78°F) at BESS laboratory (http://bess.illinois.edu/). Equation 1 was used to correct all the measured infiltration data from the calibration temperature (25.56°C) to standard sea level temperature (15°C).

$$\mathrm{I}_c = \mathrm{I}_m \left\{\frac{\mathrm{P}_{fan}(t_i + 273)}{\mathrm{P}_{atm}(t_{fan} + 273)}\right\}\left\{\frac{(t_{fan} + 273)}{(t_c + 273)}\right\}^{0.5} \tag{1}$$

Where

I_c = infiltration air flow rate corrected to standard temperature, $m^3 s^{-1}$

I_m = measured on-site infiltration air flow rate, $m^3 s^{-1}$

P_{atm} = standard atmospheric pressure at sea level = 101325 Pa

P_{fan} = barometric pressure at measuring location, Pa = (101325 – static pressure difference across barn envelope for that particular infiltration airflow rate in Pa)

t_c = calibration air temperature for FANS unit calibration (25.56°C)

t_{fan} = air temperature at air flow measuring location (sea level, 15°C)

t_i = indoor air temperature (sea level, 15°C)

Standard infiltration rates ($m^3 s^{-1}$) of each room were then normalized to air changes per hour (ACH) using the internal volume of the barn, excluding the pit and attic volumes. Normalized standard infiltration rates and corresponding pressure difference values were then used for fitting power law equations on all infiltration tests (Walker et al., 1998). Gauss-Newton method was used for fitting power law equations and was executed using SAS statistical software package (SAS, Inc., Cary, NC). The power law equation 2 was used to predict standard infiltration air flow rates at desired pressure differences across the room envelope (ASHRAE, 2013).

$$\mathrm{I}_c = c(\Delta p)^n \tag{2}$$

Where

I_c = predicted standard (sea level) infiltration rate, ACH

c = flow coefficient, $(\mathrm{h}\cdot\mathrm{Pa}^n)^{-1}$

n = pressure exponent, dimensionless

Δp = static pressure difference across barn room envelope, Pa

The predicted standard infiltration rates (using fitted equation 2) at any static pressure difference can be converted from standard ACH unit to standard $m^3 s^{-1}$ unit by using the internal volume (excluding pit and attic volumes) of the room. This standard infiltration rate ($m^3 s^{-1}$) can be converted from standard sea level weather condition to any desired test site weather condition using equation (3). In summary, all the fitted power law equations reported in this study predicts infiltration rates at standard sea level conditions and needs to be corrected to local test site conditions.

$$\mathrm{I}_p = \mathrm{I}_s \left\{\frac{\mathrm{P}_{fan}(t_o + 273)}{\mathrm{P}_{atm}(t_{fan} + 273)}\right\}\left\{\frac{(t_{fan} + 273)}{(t_c + 273)}\right\}^{0.5} \tag{3}$$

Where

I_p = predicted infiltration rate for any specific barn site, $m^3 s^{-1}$
I_s = predicted standard (sea level) infiltration rate, $m^3 s^{-1}$
P_{atm}= atmospheric pressure at barn site, Pa
P_{fan} = barometric pressure inside the barn room, Pa = (atmospheric pressure at barn site location in Pa – desired static pressure difference across barn envelope in Pa)
t_c = standard air temperature at sea level = 15°C
t_{fan} = t_o = outside/atmospheric air temperature at barn site location, °C

INFILTRATION RESISTANCE CALCULATION

Zhang and Barber (1995b) presented an analogy for the infiltration process in comparison to an electric circuit. It was also suggested that the infiltration resistance could be used as a standard parameter to quantify the quality of building materials and construction and building performance during a commissioning process. In this analogy, infiltration was analogous to electric current in a circuit, infiltration resistance (restriction to airflow) was analogous to circuit resistance, and pressure drop across the building envelope was analogous to circuit voltage. An infiltration air flow rate, in mechanically ventilated barns, is a function of leakage area and pressure difference across the envelope. Using this analogy, a formula to calculate infiltration resistance was developed. Infiltration through the barn envelope can be quantified using equation (4).

$$\frac{\mathrm{I}_{ACH}\, X\, V}{3600} \quad \left(\frac{m^3}{s}\right) = A_{eff}\; X \sqrt{\frac{2\Delta P}{\rho}} \quad \left(\frac{m^3}{s}\right) \tag{4}$$

At any constant pressure difference across the envelope, an increasing effective leakage area implies less resistance to infiltration. Hence, A_{eff} can be rewritten as

$$A_{eff} = \frac{1}{R_i} \tag{5}$$

Combining equations (4) and (5), equation (6) can be used to quantify infiltration resistance if infiltration at any pressure differential is known.

$$\frac{\mathrm{I}_{ACH}\, X\, V}{3600} \quad \left(\frac{m^3}{s}\right) = \frac{1}{R_i}\; X \sqrt{\frac{2\Delta P}{\rho}} \quad \left(\frac{m^3}{s}\right) \tag{6}$$

Where

R_i = infiltration resistance, m^{-2}
A_{eff} = effective leakage area in barn envelope, m^2
I_{ACH} = infiltration rate at pressure difference (ΔP), ACH
V = internal volume of the barn (excludes pit and attic volume), m^3
ΔP = pressure difference across barn envelope, Pa
ρ = air density, kg m^{-3}

Objective 2: Develop support materials to be used in the ISU Extension swine ventilation workshops to disseminate the newly found information.

Objective 2 was satisfied using the findings from Objective 1. Educational materials were developed for producers, focused on flyers and PPT slides to be distributed during ventilation workshop sessions. Iowa State University Extension and Outreach currently conducts day-long ventilation workshops for swine producers; a process funded in part by IPPA and directed by Co-PI Dr. Jay Harmon. Information on better barn sealing and inlet management has been frequently requested in post-meeting surveys conducted after the 63 ventilation workshops involving nearly 900 producers managing nearly 700,000 sow spaces and 29 million finishing spaces over the past six years.

Results: Results are summarized by project objective as requested.

Objective 1. Provide to the swine production industry a set of building design guidelines for new and retrofitted construction focusing on leakage air control.

Infiltration tests were carried out during the summer months of 2014 and 2015. The test weather data is presented in table 1. Also, data collected on selected barn characteristics of each test room is shown in table 2.

Table 1. Location specific weather and elevation data obtained from nearest weather stations. Data was obtained for individual tests performed on rooms for that particular day(s) and test time period.

Barn room number	Location	Elevation (m)	Mean Temperature (°C)	Mean Relative Humidity (%)	Mean Altimeter Setting (m Hg)	Mean Atmospheric Pressure (kPa)
1	Manning, Iowa	439.5	14.1 ± 4.0	32.8 ± 11.7	0.77	96.952
2	Schleswig, Iowa	414.5	25.0 ± 2.3	58.8 ± 11.1	0.76	96.115
3	Schleswig, Iowa	414.5	21.8 ± 1.4	44.1 ± 4.1	0.76	96.759
4	Schleswig, Iowa	414.5	25.0 ± 0.3	34.2 ± 2.5	0.76	96.759
5	Creston, Iowa	380.1	24.7 ± 0.8	69.3 ± 4.5	0.76	97.158
6	Creston, Iowa	380.1	24.9 ± 1.7	70.5 ± 5.9	0.76	97.191
7	Storm Lake, Iowa	396.5	21.9 ± 1.1	59.6 ± 5.5	0.76	96.839
8	Storm Lake, Iowa	396.5	20.6 ± 1.5	74.1 ± 14.6	0.76	96.645
9	Storm Lake, Iowa	396.5	23.0 ± 0.7	66.7 ± 3.5	0.76	96.548
10	Manning, Iowa	435.6	25.5 ± 0.5	61.9 ± 5.2	0.76	96.226
11	Mallard, Iowa	361.2	26.9 ± 1.0	68.6 ± 3.9	0.76	97.086
12	Mallard, Iowa	366.7	19.4 ± 3.4	69.8 ± 7.1	0.76	96.731
13	Mallard, Iowa	366.7	17.6 ± 1.9	64.9 ± 7.8	0.76	97.509
14	Mallard, Iowa	366.7	21.1 ± 0.8	47.7 ± 4.1	0.76	97.514
15	Dennison, Iowa	447.1	21.4 ± 0.8	58.5 ± 4.3	0.77	96.960
16	Dennison, Iowa	447.1	22.7 ± 0.7	52.8 ± 3.0	0.77	96.864
17	Melcher-Dallas, Iowa	290.5	22.7 ± 1.0	26.8 ± 3.9	0.77	98.826
18	Melcher-Dallas, Iowa	290.5	23.0 ± 1.7	53.9 ± 9.1	0.76	98.303
19	Manning, Iowa	435.6	32.7 ± 1.9	29.2 ± 4.1	0.76	95.776

Table 2. Selected characteristics of swine finishing rooms tested.

Barn Room number	Barn Age (Years)	Barn Layout	Pit Type	Ceiling Material	Ceiling Height (m)	Room Length (m)	Room Width (m)	Floor Area (m^2)	Envelope Area[a] (m^2)	Internal Volume[b] (m^3)	CP[c] (m)	FP[d] (m)
1	14	DW[e]	DE[i]	M[k]	2.44	61.0	12.2	743	1100	1812	144.7	66.7
2	14	S[f]	SH[j]	M	2.44	58.5	12.2	713	1058	1740	142.3	33.1
3	14	S	SH	M	2.44	58.5	12.2	713	1058	1740	142.3	33.1
4	14	S	SH	M	2.44	58.5	12.2	713	1058	1740	142.3	33.1
5	16	S	DE	M	2.44	58.5	12.2	713	1058	1740	142.3	63.0
6	16	S	DE	M	2.44	58.5	12.2	713	1058	1740	143.1	63.0
7	18	S	DE	M	2.44	43.6	12.2	531	803	1296	175.9	41.7
8	21	S	DE	M	2.44	43.6	12.2	531	803	1296	175.9	42.9
9	9	S	DE	PL[l]	2.44	43.6	15.2	664	951	1620	175.9	34.6
10	22	HT[g]	SH	M	2.29	37.8	12.2	461	705	1124	151.7	21.7
11	2	HT	DE	PL	2.44	52.9	15.2	806	1138	1965	210.3	53.8
12	2	HT	DE	PL	2.44	52.9	15.2	806	1138	1965	210.3	54.1
13	2	HT	DE	PL	2.44	54.0	15.2	822	1160	2005	210.3	54.1
14	2	HT	DE	PL	2.44	52.9	15.2	806	1138	1965	210.3	54.1
15	13	DW	DE	PLY[m]	2.44	62.2	12.2	751	1114	1831	144.1	63.3
16	13	DW	DE	PLY	2.44	62.2	12.2	751	1114	1831	144.1	65.6
17	7	DWH[h]	DE	PL	2.29	72.2	18.4	1327	1741	3032	303.7	102.0
18	7	DWH	DE	PL	2.29	72.2	18.4	1327	1741	3032	298.4	102.0
19	23	HT	SH	M	2.29	37.8	12.2	461	705	1124	151.7	23.9

[a] Includes walls and ceiling area.
[b] Excludes attic and pit volume.
[c] Curtain perimeter.
[d] Fan perimeter (includes pump out cover perimeter).
[e] Double-wide barn.
[f] Single barn.
[g] H-type barn.
[h] Double-wide + H-type barn.
[i] Deep.

[j] Shallow.
[k] Metal.
[l] Plastic.
[m] Polyethylene.

Tests I, II, and III were conducted on each room. The air flow data measured at each test site was assumed to be recorded at calibration temperature (CGSB, 1996) and corrected from calibration temperature to standard sea level temperature. Standard (sea level) infiltration air flow data was again converted from $m^3\ s^{-1}$ to ACH. Infiltration air flow data (ACH) and corresponding pressure differences for Tests I, II, and III were used to fit power law equations (equation 2). Power law equations fitted to standard test data for Tests I and III, can directly predict standard (sea level) *as-is* and *other* infiltration rates, respectively. The predicted standard infiltration rates for Test II were subtracted from Test I rates at the same pressure difference levels. The data on air flow rate differences and corresponding pressure differences was again used to fit a power law model useful to predict standard curtain infiltration rate. Similarly, subtracting Test III infiltration rates from Test II, power law models to predict standard fan infiltration rate was fitted. Standard infiltration prediction curves fitted for an example room (Room 16) are shown in figure 5. Normalizing data to ACH was required to render the results general and applicable to various sized swine finishers. For finishers using 7.5 ft^2/pig stocking density and a ceiling height of 8 ft, 1.0 ACH corresponds exactly to 1.0 CFM/pig. Therefore, as shown in figure 5, the *as-is* leakage at 20 Pa (0.08 in wc) pressure difference is about 4 ACH, or 4 CFM/pig.

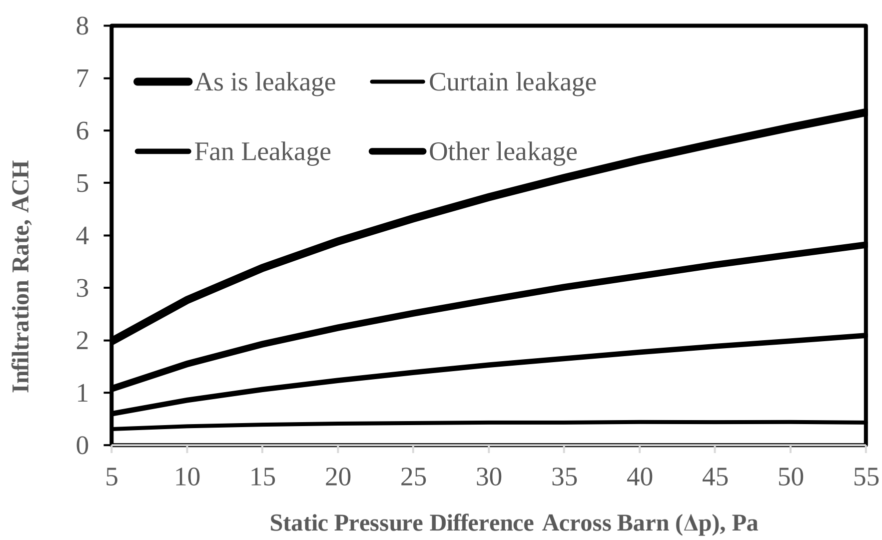


Figure 5. Example infiltration curves generated. Power law curves for room 16 shown.

In order to enhance the end use value of collected leakage data and in keeping the basic objective of leakage prediction in view, the 17 swine finishing rooms were organized in various groups and power law equations were developed for each individual group. The room grouping was done on the basis of major construction characteristics. These characteristics (barn layout, age, ceiling material, and curtain/fan perimeter lengths) were selected such that they will positively reflect the overall leakage status of rooms. To fit power law equations for groups of rooms, data on infiltration rates and corresponding pressure differences for rooms in the group were listed together and a power law equation was fitted for that particular group of rooms.

AS-IS INFILTRATION PREDICTION

The 17 swine finishing rooms, tested for their leakage potential, varied greatly in their characteristics and so was the measured leakage rate. Average values of selected room characteristics for different groups of test rooms (designated as A to K) are listed in table 3. The swine finishing rooms from barns having double wide, H-type, and double wide + H-type layouts were organized together and named 'Multi Room' as those layouts had more than one room in a barn. Also, rooms from a barn with plastic or polyethylene (reinforced fabric) as their ceiling material were grouped as 'Non-metal Ceiling'.

Table 3. Average values of selected characteristics for groups of swine finishing rooms tested.

Room Group Name	Group	NR[g]	Barn Age (Years)	Ceiling Height (m)	Room Length (m)	Room Width (m)	Floor Area (m^2)	Envelope Area[h] (m^2)	Internal Volume[i] (m^3)	CP[e] (m)	FP[f] (m)
All rooms together	A	17	12.0 ±6.1[j]	2.41 ±0.1	55.9 ±9.3	13.6 ±2.1	769 ±225	1104 ±265	1851 ±491	180.0 ±50.8	54.6 ±21.9
Rooms from S[a]	B	8	15.3 ±3.3	2.44 ±0.0	52.9 ±7.2	12.6 ±1.0	661 ±77	981 ±108	1614 ±187	155.0 ±16.2	43.1 ±12.1
Rooms from MR[b]	C	9	9.1 ±6.5	2.38 ±0.1	58.5 ±10.2	14.6 ±2.4	864 ±267	1214 ±310	2061 ±573	202.0 ±60.0	64.8 ±23.5
Rooms from M[c]	D	9	16.5 ±2.9	2.42 ±0.0	53.2 ±8.3	12.2 ±0.0	648 ±101	967 ±142	1581 ±247	151.2 ±13.5	44.3 ±15.3
Rooms from NM[d]	E	8	6.9 ±4.3	2.40 ±0.1	58.9 ±9.5	15.3 ±2.2	905 ±248	1259 ±284	2155 ±518	212.1 ±57.5	66.2 ±22.4
Rooms from barns having age ≤ 13 years	F	8	6.9 ±4.3	2.40 ±0.1	58.9 ±9.5	15.3 ±2.2	905 ±248	1259 ±284	2155 ±518	212.1 ±57.5	66.2 ±22.4
Rooms from barns having age > 13 years	G	9	16.5 ±2.9	2.42 ±0.0	53.2 ±8.3	12.2 ±0.0	648 ±101	967 ±142	1581 ±247	151.2 ±13.5	44.3 ±15.3
Rooms having CP ≤ 150 m	H	8	14.3 ±1.1	2.44 ±0.0	59.7 ±1.6	12.2 ±0.0	726 ±17	1077 ±25	1771 ±41	143.2 ±0.9	52.6 ±15.2
Rooms having CP > 150 m	I	9	10.0 ±7.7	2.39 ±0.1	52.4 ±11.7	14.9 ±2.3	807 ±304	1129 ±361	1922 ±665	212.5 ±51.0	56.3 ±26.4

[a] Single barn.
[b] Multi room barn.
[c] Metal ceiling barns.
[d] Non-metal ceiling barns.
[e] Curtain perimeter.
[f] Fan perimeter (includes pump out cover perimeter).
[g] Number of rooms in the specific group.
[h] Includes walls and ceiling area.
[i] Excludes attic and pit volume.
[j] Standard deviation.

Using the leakage test data of these rooms, the models were fitted for groups of rooms that can be used to predict standard *as-is* leakage rate. These equations are listed in table 4. Rooms in groups E and F (i.e., 'Non-metal Ceiling' and 'Age ≤ 13 Years') and groups D and G (i.e., 'Metal Ceiling' and 'Age >13 Years') were the same and hence their respective infiltration prediction equations are identical. The standard *as-is* leakage rate for all swine finishing rooms (group A) was 5.96±1.49 ACH at 20 Pa (i.e., 5.96±1.49 CFM/pig at 0.08 in wc). This leakage rate was much higher than the leakage rate reported (1.4 ACH at 20 Pa) for five newly constructed finishing rooms intended for research purposes (Zhang and Barber, 1995a). Also, swine finishing barns, during minimum winter ventilation, require the primary inlet system to deliver between approximately 2 and 10 ACH for pigs between 6 and 115 kg, respectively (MWPS, 1987). The standard *as-is* leakage rate reported in this study was about three times the ventilation rate recommended for weaned pigs entering swine finishers in cold weather conditions. This standard *as-is* leakage rate (5.96±1.49 ACH at 20 Pa) was comparable with the leakage rate of dairy buildings reported as 3 to 12 ACH at 15 Pa (Masse et al., 1994b). A study on commercial broiler houses in

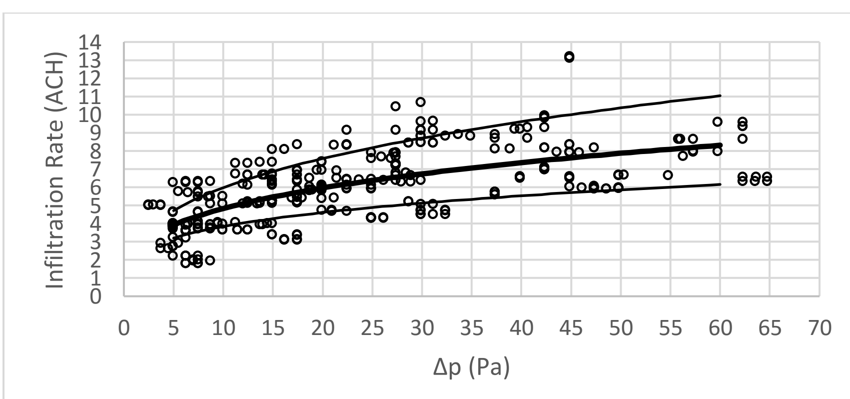
Kentucky (Lopes et al., 2010) reported *as-is* leakage rates between 3.6 and 5.6 ACH at 25 Pa for fourteen Kentucky broiler houses.

Table 4. Power law models for prediction of standard *as-is* infiltration rate (ACH) of swine finishing rooms as a function of building envelope pressure difference (Pa). Rooms are grouped by barn layout, age, and ceiling material.

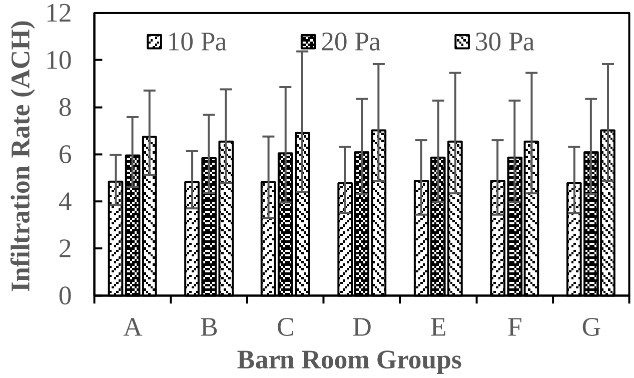
Room Group Name	Group	NR[e]	Model ($I = c \times \Delta p^n$)	Standard Errors		95 % Confidence Limits			
				c	n	Lower		Upper	
						c	N	c	n
All rooms together	A	17	$I = 2.4047 \times \Delta p^{0.3031}$	0.1586	0.0201	2.0926	0.2636	2.7167	0.3425
Rooms from S[a]	B	8	$I = 2.5332 \times \Delta p^{0.2793}$	0.1888	0.0228	2.1601	0.2343	2.9062	0.3244
Rooms from MR[b]	C	9	$I = 2.2748 \times \Delta p^{0.3267}$	0.2416	0.0321	1.7979	0.2632	2.7516	0.3901
Rooms from M[c]	D	9	$I = 2.1332 \times \Delta p^{0.3501}$	0.1855	0.0267	1.7669	0.2974	2.4996	0.4027
Rooms from NM[d]	E	8	$I = 2.6057 \times \Delta p^{0.2701}$	0.2519	0.0292	2.1084	0.2125	3.103	0.3277
Rooms from barns having age ≤ 13 years	F	8	$I = 2.6057 \times \Delta p^{0.2701}$	0.2519	0.0292	2.1084	0.2125	3.103	0.3277
Rooms from barns having age > 13 years	G	9	$I = 2.1332 \times \Delta p^{0.3501}$	0.1855	0.0267	1.7669	0.2974	2.4996	0.4027

[a] Single barn.
[b] Multi room barn.
[c] Metal ceiling barns.
[d] Non-metal ceiling barns.
[e] Number of rooms in the specific group.

The standard *as-is* leakage rate was maximum (6.09 ±2.02 ACH at 20 Pa) for rooms with a combined metal ceiling and an age > 13 years. In metal ceiling rooms, there were more joints as compared to non-metal ceilings. The wear and tear of building components with age and non-rigid/flexible nature of leakage areas in animal buildings (Zhang and Barber, 1995b) might be a cause for higher leakages in these rooms. The predicted standard *as-is* leakage rate was minimum for rooms from single layout barns (5.85 ±1.66 at 20 Pa), rooms having a non-metal ceiling (5.85 ±2.15 at 20 Pa) and room age ≤ 13 years (5.85 ±2.15 at 20 Pa). Rooms having a non-metal ceiling (particularly with polyethylene ceiling) had less joints in the ceiling and ultimately that might have reduced the leakage area. On the contrary, non-metal ceiling and rooms aged ≤ 13 years, had the highest curtain perimeter (212.1 ±57.5) and near to highest fan perimeter (66.2 ±22.4), but still their standard *as-is* leakage rates were found minimum. This highlighted the multi-parameter dependability of leakage rate. Hence, the leakage rates of a particular group of finishing rooms may be treated as an attribute of that particular group. Alternatively, to be more accurate, combinations of barn age, layout, and ceiling material can be used to select an appropriate power law equation to predict standard *as-is* leakage rate for a room (table 5), but the limited number of barns tested in these combinations warrant further investigation.



(a)



(b)

Figure 6. (a) As measured standard *as-is* infiltration rates versus barn static pressure difference (Group A, table 4 regression with 95% confidence intervals) and (b) predicted *as-is* infiltration rates for various barn room groups using power law models from table 5.

Table 5. Power law models for prediction of standard *as-is* infiltration rate (ACH) of a swine finishing barn room as a function of building envelope pressure difference (Pa). Rooms are designated by combination of barn layout, age and ceiling material.

Barn age (Years)	Barn layout	Ceiling material	NR[h]	Model ($I = c \times \Delta p^n$)	Standard Error		95 % Confidence Limits			
							Lower		Upper	
					c	n	c	n	c	n
8 to 15	S[a]	M[e]	3	$I = 1.8173 \times \Delta p^{0.3587}$	0.2639	0.0443	1.2874	0.2699	2.3472	0.4475
> 15	S	M	4	$I = 2.5423 \times \Delta p^{0.3185}$	0.1708	0.0211	2.2017	0.2765	2.8829	0.3605
8 to 15	S	PL[f]	1	$I = 2.5364 \times \Delta p^{0.2247}$	0.1200	0.0134	2.2888	0.1971	2.7841	0.2524
8 to 15	DW[b]	M	1	$I = 1.7330 \times \Delta p^{0.3760}$	0.2281	0.0393	1.2600	0.2945	2.2060	0.4575
8 to 15	DW	PLY[g]	2	$I = 0.7305 \times \Delta p^{0.5391}$	0.0370	0.0146	0.6554	0.5095	0.8056	0.5687
> 15	HT[c]	M	1	$I = 1.4952 \times \Delta p^{0.5777}$	0.2618	0.0507	0.8546	0.4537	2.1359	0.7016
< 8	HT	PL	4	$I = 1.8642 \times \Delta p^{0.3952}$	0.1639	0.0252	1.5360	0.3447	2.1924	0.4458
< 8	DWH[d]	PL	2	$I = 3.4929 \times \Delta p^{0.2669}$	0.1999	0.0195	3.0897	0.2277	3.8962	0.3062

[a] Single barn.
[b] Double-wide barn.
[c] H-type barn.
[d] Double-wide + H-type barn.
[e] Metal ceiling barns.
[f] Plastic ceiling barns.
[g] Polyethylene ceiling barns.
[h] Number of rooms in the specific group.

CURTAIN INFILTRATION PREDICTION

Curtain leakage rates are governed by many parameters like number of curtains, end pocket length, curtain top edge-wall overlap, holes and other leakage areas in and around the curtains. Curtain infiltration is governed not only by a curtain top overlap, but also by how tightly a curtain seals against a wall surface. Curtain perimeter was identified as an indicator parameter to describe curtain leakage rate. The power law equations to predict standard curtain infiltration rates are presented in table 6. These leakage rates are also compared at 10, 20 and 30 Pa in figure 7.

Table 6. Power law models for prediction of standard curtain infiltration rate (ACH) of a swine finishing barn room as a function of building envelope pressure difference (Pa). Rooms are grouped by barn layout and their curtain perimeter.

Room Group Name	Group	NR[b]	Model ($I = c \times \Delta p^n$)	Standard Error		95% Confidence Limits			
						Lower		Upper	
				c	n	c	n	c	n
All rooms together	A	17	$I = 1.2600 \times \Delta p^{0.0555}$	0.2197	0.0524	0.8266	-0.0480	1.6934	0.1589
Rooms having CP[a] ≤ 150 m	H	8	$I = 0.8697 \times \Delta p^{0.1086}$	0.2908	0.0993	0.2916	-0.0888	1.4477	0.3060
Rooms having CP > 150 m	I	9	$I = 1.5235 \times \Delta p^{0.0331}$	0.3122	0.0620	0.9038	-0.0899	2.1432	0.1561

[a] Curtain perimeter.
[b] Number of rooms in the specific group.

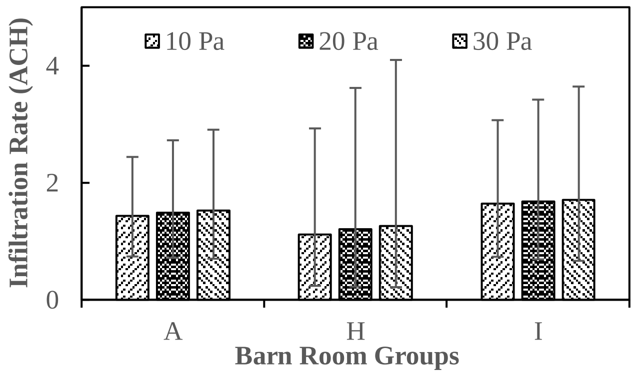


Figure 7. Standard curtain infiltration rates for various barn room groups.

The standard curtain leakage rate for all rooms tested (group A) was 1.49 ±1.00 ACH at 20 Pa. It was minimum (1.20 ±1.70 ACH at 20 Pa) for rooms having a curtain perimeter ≤ 150 m. The standard curtain infiltration rate was 1.68 ±1.37 ACH (at 20 Pa) for rooms having a curtain perimeter > 150 m (212.5 ±51.0 for group I). It was observed that the curtain infiltration rates remained almost constant or increased marginally with pressure difference. This was most likely due to self-sealing action of curtains with increasing pressure differentials. The recommendation, based on the limited number of barns tested, supports using equation 7 for predicting curtain infiltration for barns with total curtain perimeter between 140 and 300 m and curtain overlaps greater than 5 cm.

$$I=1.26(\pm 0.22)\Delta p^{0.056(\pm 0.052)} \quad (7)$$

FAN INFILTRATION PREDICTION

Fan leakage rate depends on many parameters such as number of fans, fan diameter, physical condition of louvers, and installation practices. Barn layout governs the number of fans and manure pump outs. Fan perimeter (including pump out cover perimeter) was identified as an indicator parameter to describe fan leakage rate. The power law equations to predict standard fan infiltration are presented in table 7. These leakage rates are also compared at 10, 20 and 30 Pa in figure 8.

Table 7. Power law models for prediction of standard fan infiltration (ACH) of a swine finishing barn room as a function of building envelope pressure difference (Pa). Rooms are grouped by barn layout and their fan perimeter.

Room Group Name	Group	NR[b]	Model ($I = c \times \Delta p^n$)	Standard Error		95 % Confidence Limits			
						Lower		Upper	
				c	n	c	n	c	n
All rooms together	A	17	$I = 0.6868 \times \Delta p^{0.2652}$	0.1609	0.0675	0.3694	0.1321	1.0041	0.3982
Rooms having BSA[a] ≤ 7.65	J	10	$I = 0.5288 \times \Delta p^{0.3236}$	0.2210	0.1192	0.0907	0.0873	0.9669	0.5599
Rooms having BSA > 7.65	K	7	$I = 0.9390 \times \Delta p^{0.1972}$	0.1559	0.0484	0.6284	0.1007	1.2496	0.2936

[a] Backdraft shutter area.

[b] Number of rooms in the specific group.

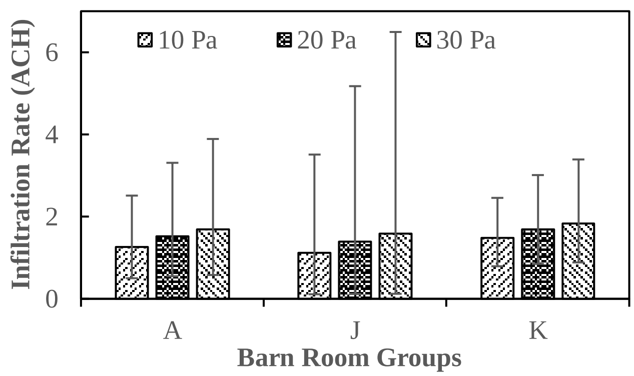


Figure 8. Standard fan infiltration rates for various barn room groups.

The standard fan leakage rate for all rooms tested (group A) was 1.52 ±1.38 at 20 Pa. It was minimum (1.39 ±1.43 ACH at 20 Pa) for rooms from multi-room barns; while, it was maximum (1.66 ±2.68 ACH at 20 Pa) for rooms from single barns. Surprisingly, the fan perimeter was higher (64.8 ±23.5 m) for rooms from multi-room barns as compare to single rooms (43.1±12.1). This highlighted the fact that there may be other fan parameters which affect fan leakage rate. The recommendation, based on the limited number of barns tested, supports using equation 8 for predicting fan infiltration for typical mid-western swine finishing rooms.

$$I=0.687(\pm 0.161)\Delta p^{0.265(\pm 0.068)} \quad (8)$$

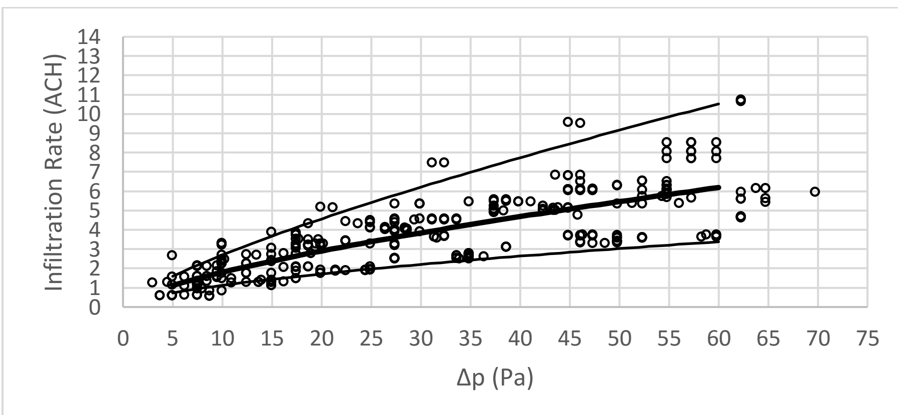
OTHER INFILTRATION PREDICTION

The resulting *other* infiltration is the total infiltration excluding curtain and fan leakage components. The *other* infiltration measured for all rooms tested is shown in Figure 9a. Sources of *other* leakage include doors, ceiling, ceiling panel joints, walls, and joints between walls, floor, and ceiling. It was difficult to measure barn room characteristics closely associated with *other* leakage sources, hence data was summarized using the *as-is* room groupings. The standard *other* leakage rate for all rooms tested (group A) was 2.90 ±1.42 ACH at 20 Pa. The *other* leakage was a major component (about 49%) of *as-is* infiltration rate as compared to curtains (about 25% of *as-is*) and fans (about 26% of *as-is*). The power law equations to predict standard *other* infiltration rates are presented in table 8. These leakage rates are also compared at 10, 20 and 30 Pa in figure 9b.

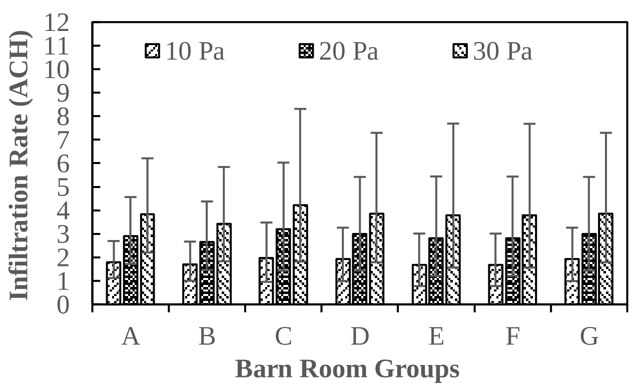
Table 8. Power law models for prediction of standard *other* infiltration (ACH) of a swine finishing room as a function of building envelope pressure difference (Pa). Rooms are grouped by barn layout, age, and ceiling material.

Room Group Name	Group	NR[e]	Model ($I = c \times \Delta p^n$)	Standard Error		95 % Confidence Limits			
						Lower		Upper	
				C	n	c	n	c	n
All rooms together	A	17	$I = 0.3690 \times \Delta p^{0.6887}$	0.0500	0.0365	0.2706	0.6169	0.4675	0.7605
Rooms from S[a]	B	8	$I = 0.3990 \times \Delta p^{0.6321}$	0.0596	0.0410	0.2813	0.551	0.5167	0.7131
Rooms from MR[b]	C	9	$I = 0.4046 \times \Delta p^{0.6893}$	0.0793	0.0522	0.2479	0.5862	0.5613	0.7924
Rooms from M[c]	D	9	$I = 0.4451 \times \Delta p^{0.6356}$	0.0802	0.0491	0.2868	0.5385	0.6035	0.7327
Rooms from NM[d]	E	8	$I = 0.3011 \times \Delta p^{0.7449}$	0.0616	0.0545	0.1794	0.6372	0.4227	0.8528
Rooms from barns having age ≤ 13 years	F	8	$I = 0.3011 \times \Delta p^{0.7449}$	0.0616	0.0545	0.1794	0.6372	0.4227	0.8525
Rooms from barns having age > 13 years	G	9	$I = 0.4451 \times \Delta p^{0.6356}$	0.0802	0.0491	0.2868	0.5385	0.6035	0.7327

[a] Single barn.
[b] Multi room barn.
[c] Metal ceiling barns.
[d] Non-metal ceiling barns.
[e] Number of rooms in the specific group.



(a)



(b)

Figure 9. (a) As measured standard *other* infiltration rate versus room static pressure difference (Group A, table 8 regression with 95% confidence intervals) and (b) predicted *other* infiltration rates for various barn room groups using power law models from table 8.

The standard *other* leakage rate varied greatly among room groups, averaging 2.90 ±1.42 ACH at 20 Pa amongst all rooms tested. It was found maximum (3.19 ±2.30 ACH at 20 Pa) for rooms from multi-room barns; while, it was minimum (2.65 ±1.45 ACH at 20 Pa) for rooms from single barns.

SIGNIFICANCE OF INFILTRATION RESISTANCE

Infiltration resistance represents the envelope resistance to leakage and their standard values were calculated using equation (6). Standard *as-is*, curtain, fan, and *other* infiltration resistances of each room were calculated. Average values are presented in table 9. The resistances were calculated using standard infiltration rates and standard air density (ρ) equal to 1.225 kg m^{-3}. The standard *as-is* leakage resistance of finishing room groups was either almost constant (for many groups) or increased negligibly with increased pressure differences. Therefore, the increase in infiltration resistances of curtains and fans was compensated almost equally by the decrease in *other* infiltration resistance. The standard *as-is* infiltration resistance of rooms remained almost constant and hence could be used as a standard parameter to quantify the quality of building materials, construction, and building performance during a commissioning process as suggested by Zhang and Barber, 1995b. The standard infiltration resistances of different room groups are compared graphically at 20 Pa in figure 10. The error bars in figure 10 indicate standard deviation of infiltration resistance for that group. Among all the resistances, standard curtain resistance of rooms having CP ≤ 150 m was maximum (17.2 ±14.2 m^{-2} at 20 Pa); while, standard *as-is* infiltration resistance for rooms having curtain perimeter > 150 m was minimum (1.8 ±0.6 m^{-2} at 20 Pa). In general, standard infiltration resistance of curtains was highest, followed by fan, *other*, and *as-is* resistances.

For all groups, standard curtain infiltration resistance increases with the pressure difference and this was most likely due to self-sealing, and, as a result did not increase proportionately with increasing pressure difference. The standard *other* infiltration resistance decreased with increased pressure difference. In summary, this study indicated that the leakage areas for curtains, fans, and other sections of rooms were non-solid or flexible. They are changing with barn layout, age, construction material, and pressure difference.

Table 9. Standard infiltration resistances (m^{-2}) reported for various room groups at 10, 20 and 30 Pa.

Room Group Name	Group	N[g]	Standard *As-Is* Infiltration Resistance			Standard Curtain Infiltration Resistance			Standard Fan Infiltration Resistance			Standard *Other* Infiltration Resistance		
			Δp (Pa)			Δp (Pa)			Δp (Pa)			Δp (Pa)		
			10	20	30	10	20	30	10	20	30	10	20	30
All rooms together	A	17	1.9± 0.7[h]	2.0± 0.6	2.1± 0.6	9.7± 9.2	12.1± 11.1	14.3± 13.0	8.6± 5.0	9.5± 5.4	10.5± 6.1	4.9± 2.2	4.3± 1.7	4.0± 1.4
Rooms from S[a]	B	8	2.0± 0.4	2.2± 0.4	2.3± 0.4	6.4± 2.5	8.1± 2.8	9.7± 3.1	7.6± 2.9	8.8± 2.9	9.9± 3.1	6.0± 2.2	5.2± 1.5	4.9± 1.2
Rooms from MR[b]	C	9	1.9± 0.8	1.9± 0.7	2.0± 0.7	12.6± 11.6	15.6± 14.2	18.4± 16.7	9.5± 6.2	10.2 ±6.8	11.0± 7.8	3.9± 1.8	3.5± 1.4	3.3± 1.2
Rooms from M[c]	D	9	2.0± 0.4	2.1± 0.4	2.2± 0.3	9.0± 6.0	10.7± 6.8	12.1± 7.3	7.9± 4.7	9.7± 5.8	11.3± 6.9	5.1± 1.5	4.6± 1.2	4.3± 1.0
Rooms from NM[d]	E	8	1.8± 0.9	1.9± 0.8	2.0± 0.8	10.5± 11.7	13.6± 14.4	16.8± 17.0	9.4± 5.2	9.4± 5.6	9.5± 4.8	4.6± 2.8	4.0± 2.1	3.7± 1.7

Rooms from barns having age ≤ 13 years	F	8	1.8± 0.9	1.9± 0.8	2.0± 0.8	10.5± 11.7	13.6± 14.4	16.8± 17.0	9.4± 5.2	9.4± 5.6	9.5± 4.8	4.6± 2.8	4.0± 2.1	3.7± 1.7
Rooms from barns having age > 13years	G	9	2.0± 0.4	2.1± 0.4	2.2± 0.3	9.0± 6.0	10.7± 6.8	12.1± 7.3	7.9± 4.7	9.7± 5.8	11.3± 6.9	5.1± 1.5	4.6± 1.2	4.3± 1.0
Rooms having CP[e] ≤ 150 m	H	8	2.2± 0.7	2.3± 0.5	2.4± 0.5	14.1± 11.5	17.2± 14.2	20.1± 16.8	6.9± 2.2	8.1± 2.1	9.3± 2.1	5.5± 1.8	4.9± 1.2	4.5± 1.0
Rooms having CP > 150 m	I	9	1.7± 0.6	1.8± 0.6	1.9± 0.6	5.9± 2.9	7.6± 3.3	9.3± 3.8	10.5 ±6.7	11.1 ±7.3	11.8± 8.2	4.4± 2.5	3.9± 1.9	3.6± 1.6

[a] Single barn.
[b] Multi room barn.
[c] Metal ceiling barns.
[d] Non-metal ceiling barns.
[e] Curtain perimeter.
[f] Fan perimeter (includes pump out cover perimeter).
[g] Number of rooms in the specific group.
[h] Standard deviation.

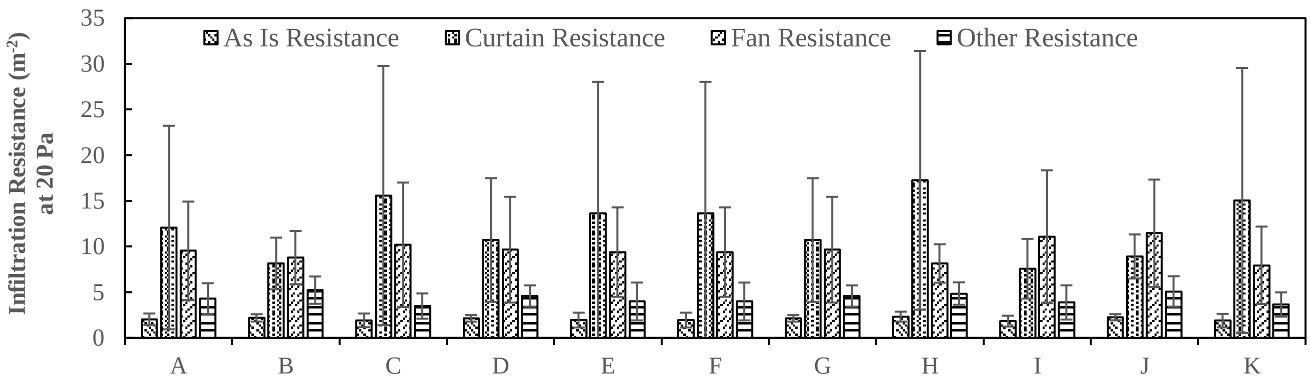


Figure 10. Comparison of standard infiltration resistances for room groups A-K at 20 Pa.

Objective 2: Develop support materials to be used in the ISU Extension swine ventilation workshops to disseminate the newly found information.

From our research we have developed the following general audience material that we have currently implemented in all presentations related to swine house ventilation.

Discussion: The leakage data of 17 swine finishing rooms was used to develop power law models useful to predict standard air infiltration rates of similar rooms. The standard *as-is* leakage rate was minimum for rooms from single layout barns (5.85 ±1.66 at 20 Pa) and from rooms having a non-metal ceiling and aged ≤ 13 years (5.85 ±2.15 at 20 Pa). The standard curtain, fan, and *other* leakage rates were minimum for rooms having a curtain perimeter ≤ 150 m (1.20 ±1.70 ACH at 20 Pa), rooms within multi-room barns (1.39 ±1.43 ACH at 20 Pa), and for single barn rooms (2.65 ±1.45 ACH at 20 Pa). The standard *as-is* leakage rate was 5.96 ±1.49 at 20 Pa. Similarly, the standard curtain, fan, and *other* leakage rates, for all 17 swine finishing rooms tested at 20 Pa, were 1.49 ±1.00 ACH (about 25% of *as-is*), 1.52 ±1.38 ACH (about 26% of *as-is*) and 2.90 ±1.42 ACH (about 49% of *as-is*), respectively. The standard *as-is* leakage rate reported in this study was about three times the ventilation rate recommended for weaned pigs entering swine finishers in cold weather conditions. This fact needs to be to be taken into consideration while designing winter ventilation systems. Additionally, suitable leakage control practices/techniques should be implemented in swine finishing rooms. These measures will help to develop a more congenial environment in swine finishing rooms. This study indicated that the leakage areas for curtains, fans, and other sections of a room were non-solid or flexible, changing with barn layout, age, construction material, and pressure difference. The *as-is* leakage resistance of finishing rooms remained either almost constant (for many groups) or increased negligibly with increased pressure differences. The data presented here could be used, in conjunction with follow-up studies, to develop standard design procedures for incorporating infiltration into ventilation system design practices.

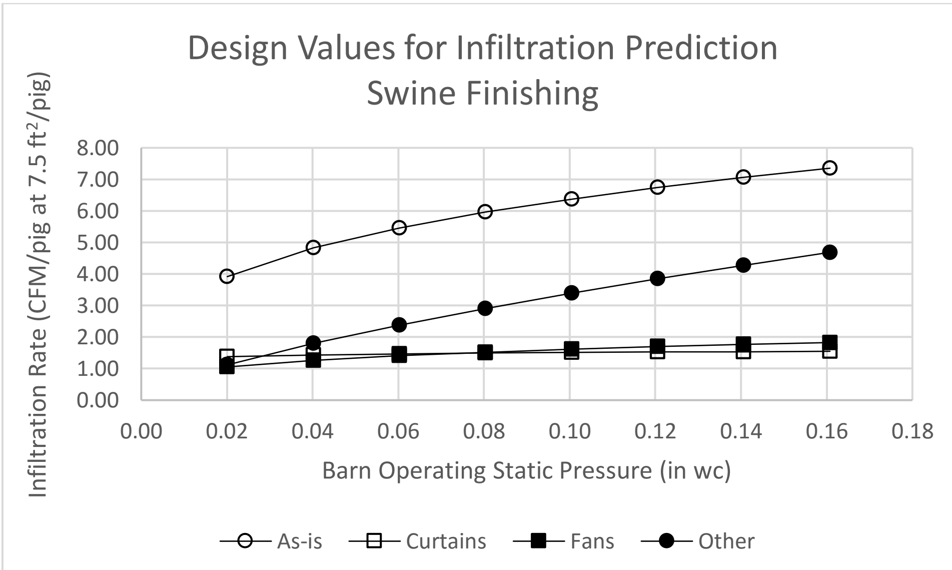


Figure 11. Final design equations suitable in swine finishing for predicting infiltration rate. Data values listed as CFM/pig for barns with a stocking density of 7.5 ft2/pig. In general, the values shown can be interpreted as fresh-air exchanges per hour (ACH; i.e., 1 ACH = 1 CFM/pig if pigs are stocked at 7.5 ft^2/pig).

The implications of the results given in figure 11 are summarized in table 10. Table 10 gives operating conditions expected in a typical 1,000-hd swine finisher with a center-ceiling inlet system. The barn used in this example is 42 ft wide, 180 ft long, with an 8 ft ceiling height. One row of ceiling inlets consisting of 18-biflows, each 3 ft in length is used in this example. Table 10 indicates the influence of infiltration on ventilation performance as summarized in figure 11.

Table 10. Implications of infiltration on cold weather ventilation performance.

CFM/pig	As-is				Other-No Attic Foaming			
	Inlet Opening, in	ΔP, in wc	% infiltration	% planned	Inlet Opening, in	ΔP, in wc	% infiltration	% planned
2	0.25	0.001	91	9	0.25	0.025	58	42
4	0.25	0.011	86	14	0.35	0.059	55	45
6	0.25	0.042	82	18	0.50	0.085	49	51

The example includes three cold-weather rates typical of weaned pigs (2 CFM/pig) up to 100 lb pigs (6 CFM/pig) placed in cold weather. The assumption in table 10 is that the smallest inlet opening height that could be controlled is 0.25 inches. The implications are as follows:

1. If the leakage rate of the barn is at the *as-is* rate (i.e., curtains closed to at least a 2 inch overlap distance and unused fans and pump-outs not sealed beyond normal), then the barn operating static pressures are predicted to be 0.001, 0.011, and 0.042 in wc for 2, 4, and 6 CFM/pig ventilation rates. An operating static pressure of at least 0.05 in wc is required for adequate fresh-air mixing. More troubling however is the fact that at this leakage "state", 91%, 86%, and 82% of the fresh-air will enter through unplanned leakage points for the 2, 4, and 6 CFM/pig ventilation rates.

2. If the leakage rate of the barn is at the *other* rate (i.e., curtains closed to at least a 2 inch overlap distance with added top curtain sealing and unused fans and pump-outs sealed), then the barn operating static pressures are predicted to be 0.025, 0.059, and 0.085 in wc for 2, 4, and 6 CFM/pig ventilation rates. At this leakage "state", 58%, 55%, and 49% of the fresh-air will enter through unplanned leakage points for the 2, 4, and 6 CFM/pig ventilation rates.

3. If the leakage rate of the barn is at the *other* rate with added attic foaming, the barn operating static pressures are predicted to be 0.039, 0.072, and 0.073 in wc for 2, 4, and 6 CFM/pig ventilation rates (table 11). At this leakage "state", 48%, 29%, and 19% of the fresh-air will enter through unplanned leakage points for the 2, 4, and 6 CFM/pig ventilation rates.

Table 11. Ventilation operating conditions if barn is attic-foamed.

CFM/pig	Other-Attic Foamed			
	Inlet Opening, in	ΔP, in wc	% infiltration	% planned
2	0.25	0.039	48	52
4	0.50	0.072	29	71
6	0.85	0.073	19	81

In summary, the leakage rate of swine finishing barns is at a level that is affecting our ability to provide optimal ventilation operating conditions and fresh-air distribution during cold-weather conditions. In addition, the vast majority of ventilation air being delivered to a barn is originating from unplanned leakage locations and not the planned inlet system itself. A change in building construction practices needs to be considered to reverse this situation. These results also point out the extent of sealing required if barns are converted to negative-pressure filtration.

ACKNOWLEDGEMENTS

This project would not have been possible without the support from our cooperating producers. Their willingness to allow us ready access to their barns for testing was invaluable. In addition, the funding support by the National Pork Checkoff on behalf of the Iowa Pork Producers Association is greatly appreciated

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Appendix A. Infiltration Fact Sheet

Considerations for Infiltration Control

Introduction. Infiltration is the entrance of outside air into a barn in locations other than the planned inlet system. Infiltration is a problem in cold weather ventilation control and for negative pressure filtration barns (unfiltered air enters barn directly) or positive pressure filtration barns (exfiltrates through building shell potentially condensing inside structure).

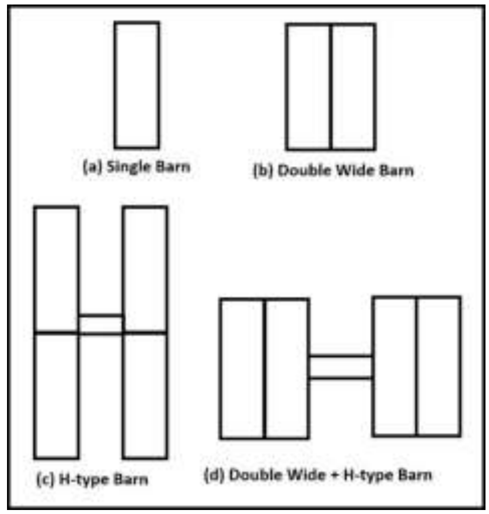


FIGURE 1. BARN STYLES ME… …ION.

FIGURE 2. PRIMARY INLET

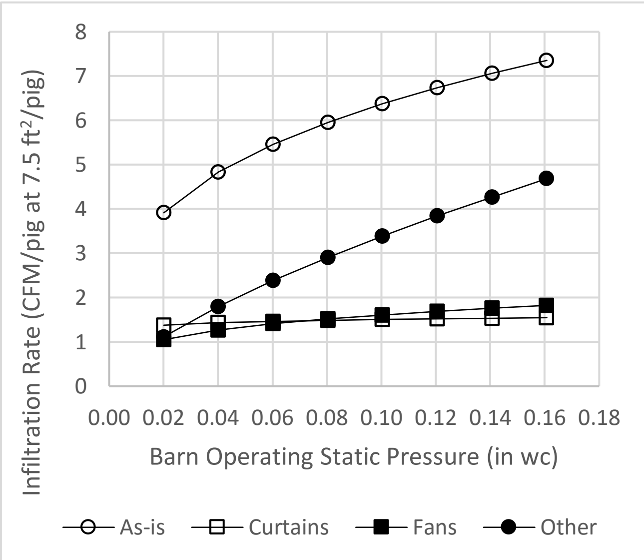
The Study. A study was conducted to test the extent of infiltration in typical swine finishing facilities. Nineteen rooms within four barn styles (figure 1) were investigated. Infiltration was evaluated for each room by conducting three tests. Test I was defined as the *as-is infiltration*. During this test the primary ceiling inlet system was blocked allowing infiltration air to enter barn with no modifications (figure 2). During Test II, all curtains associated with the tested room were sealed at the top opening location and at the sides (figure 3). During Test III, all fans and pump-out covers were sealed (figure 4). The infiltration that remained after Test III was labelled as *other infiltration*. The difference between Tests I and II was *curtain infiltration*, and the difference between Tests III and II was *fan infiltration*.

FIGURE 3. CURTAIN SEALING.

FIGURE 4. FAN AND PUMP-OUT

Results. Our results indicated that the *as-is* infiltration rate, at an operating static pressure of 0.08 in wc, averaged 5.96±1.49 CFM/pig; with the leakage rates through curtains, fans and other components consisting of 1.49±1.00 CFM/pig (about 25% of *as-is*), 1.52 ±1.38 CFM/pig (about 26% of *as-is*) and 2.90 ±1.42 CFM/pig (about 49% of *as-is*), respectively. These rates apply to finishing barns with

8 ft ceilings and a stocking density of 7.5 ft^2/pig. The design curves that are recommended for incorporating infiltration in ventilation design is shown in figure 5.



Implications. If infiltration is not controlled and the barn is operating at the *as-is leakage rate*, a maximum most likely operating pressure (in wc) for delivering 2, 4, and 6 CFM/pig is 0.001, 0.011, and 0.042 in wc, respectively with unplanned leakage openings accounting for 91%, 86%, and 82% of the inlet area required. If infiltration is controlled to the *other infiltration rate*, the maximum most likely operating pressure achievable for delivering 2, 4, and 6 CFM/pig is 0.025, 0.059, and 0.085 in wc, respectively with unplanned leakage openings accounting for 58%, 55%, and 49% of the inlet area required.

FIGURE 5. INFILTRATION VALUES TO CONSIDER FOR VENTILATION

CFM/pig	As-is				Other-No Attic Foaming			
	Inlet Opening, in	ΔP, in wc	% infiltration	% planned	Inlet Opening, in	ΔP, in wc	% infiltration	% planned
2	0.25	0.001	**91**	**9**	0.25	0.025	**58**	**42**
4	0.25	0.011	**86**	**14**	0.35	0.059	**55**	**45**
6	0.25	0.042	**82**	**18**	0.50	0.085	49	51

Curtains, pump-outs, and unused cold weather fans are manageable leakage points that can be mitigated with relatively low-cost methods that many producers are presently incorporating. The remaining 50% of the *as-is* leakage, primarily identified from ceiling-to-side/end wall joints and ceiling panel corrosion locations will require significant effort to mitigate. If spray foam is used at these targeted locations, a reduction of 80% in overall leakage rate was measured in a controlled test room. If infiltration is controlled to this level, the maximum most likely operating pressure achievable for delivering 2, 4, and 6 CFM/pig is 0.039, 0.072, and 0.073 in wc, respectively with unplanned leakage openings accounting for 48%, 29%, and 19% of the inlet area required.

CFM/pig	Other-Attic Foamed			
	Inlet Opening, in	ΔP, in wc	% infiltration	% planned
2	0.25	0.039	48	52
4	0.50	0.072	29	71
6	0.85	0.073	19	81

Funding, wholly or in part, was provided by the National Pork Checkoff on behalf of the Iowa Pork Producers Association. The authors would like to thank the many cooperating producers who made this project possible. For more information, please contact Dr. Steve Hoff, Department of Agricultural and Biosystems Engineering, Iowa State University (hoffer@iastate.edu).

Appendix B. PPT Details Added to Ventilation Workshop Series

Barn Infiltration Summary

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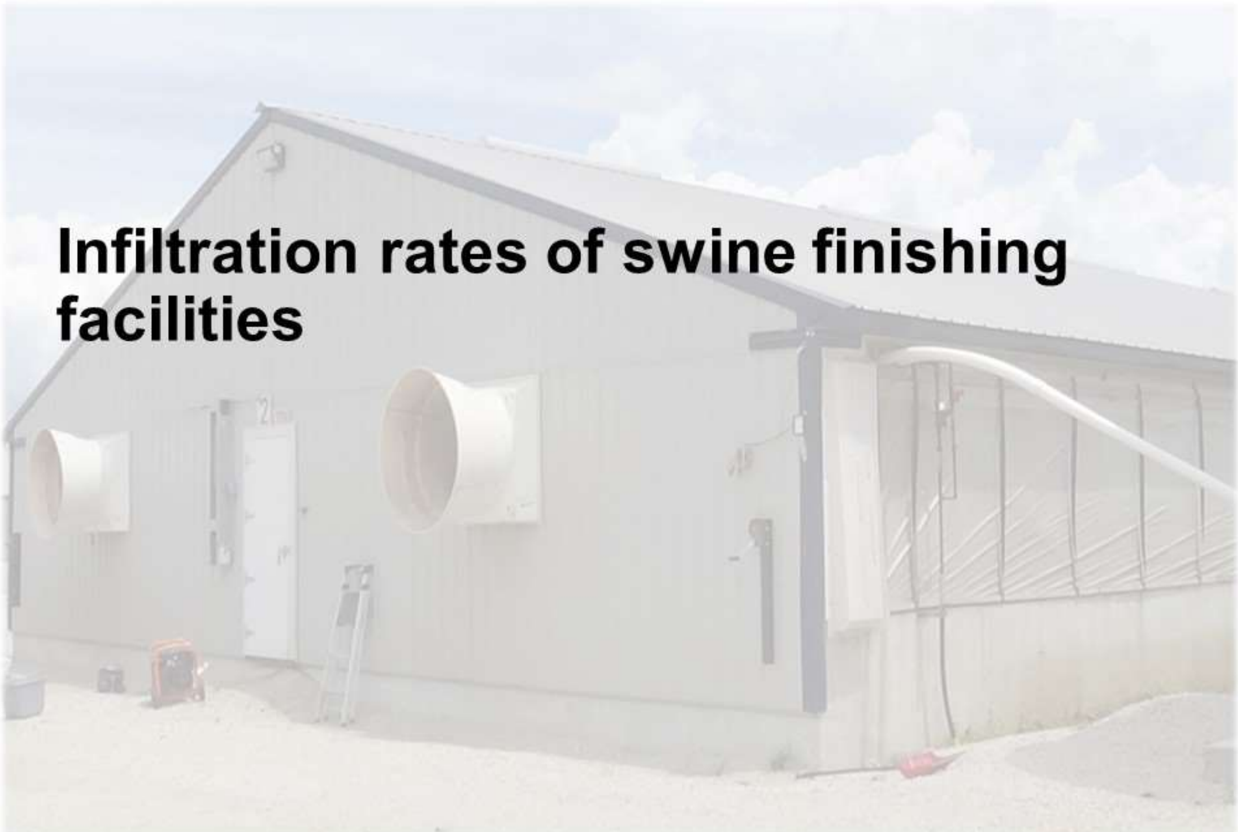
Ventilation Workshop Series
Iowa State University



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What is infiltration?

Fresh-air intake from unplanned inlets (cracks, joints, seams, curtains, shutters, etc)

Goal is to reduce unplanned inlet air and improve planned inlet behavior

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Infiltration (air leakage) rates were measured following a standard procedure to identify and quantify leakage from common perceived locations.

Inclined manometer for static pressure measurement

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51” and 30” FANS units for airflow measurement 4

Four sources of infiltration were quantified:

1) *As-is* or total infiltration
(primary planned inlets sealed)

2) *Curtain* infiltration
(curtain top, end-pockets)

3) *Fan* infiltration
(sidewall fans, pit fans, pump-out covers)

4) *Other* infiltration
(doors, ceiling, ceiling/wall joints, etc.)

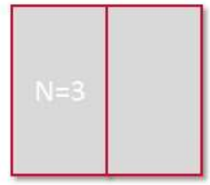
5

19 rooms housed in four different building construction types were tested.

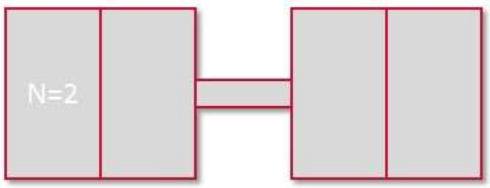
Range of room characteristics:

- Length: 124 to 237 ft
- Width: 40 to 60 ft
- Age: 2 to 23 years old

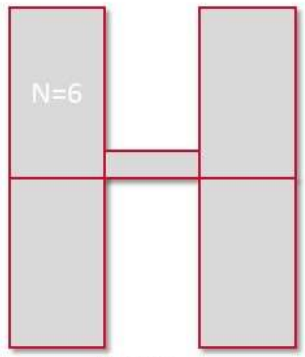
1) Single



2) Double wide



3) Double wide + H-Type



4) H-Type

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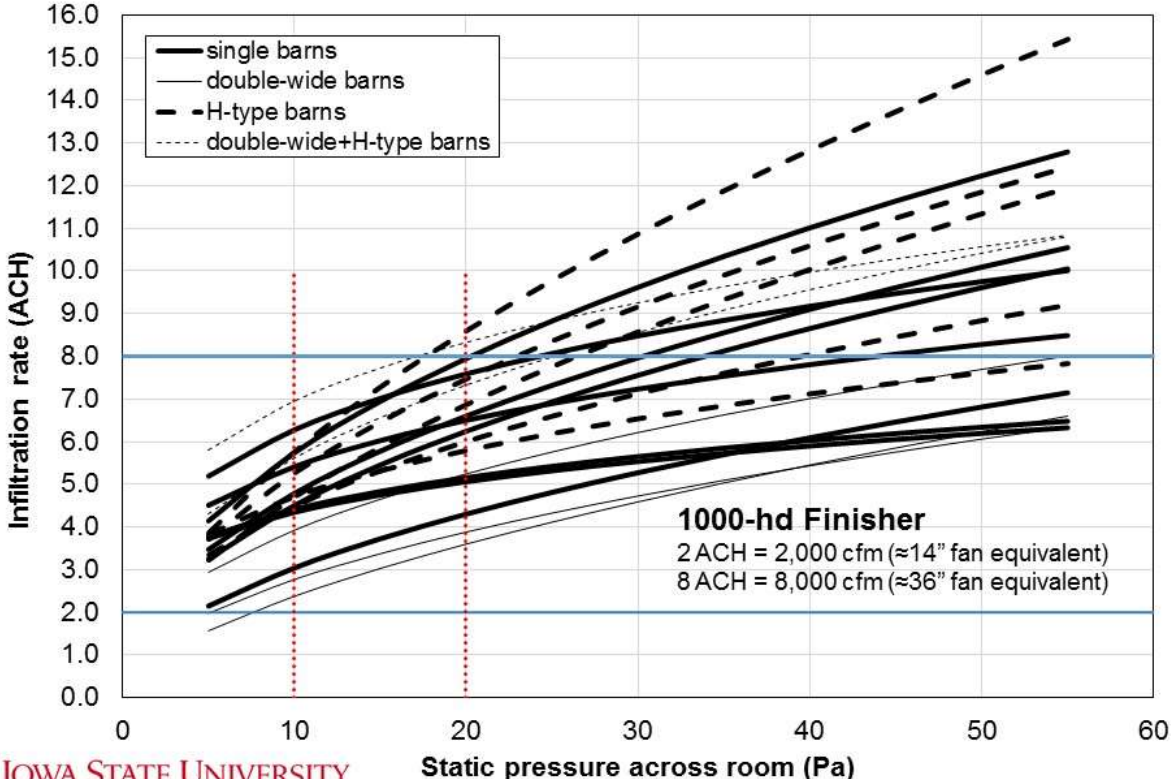
As-is infiltration rates for all 18 finishing rooms tested



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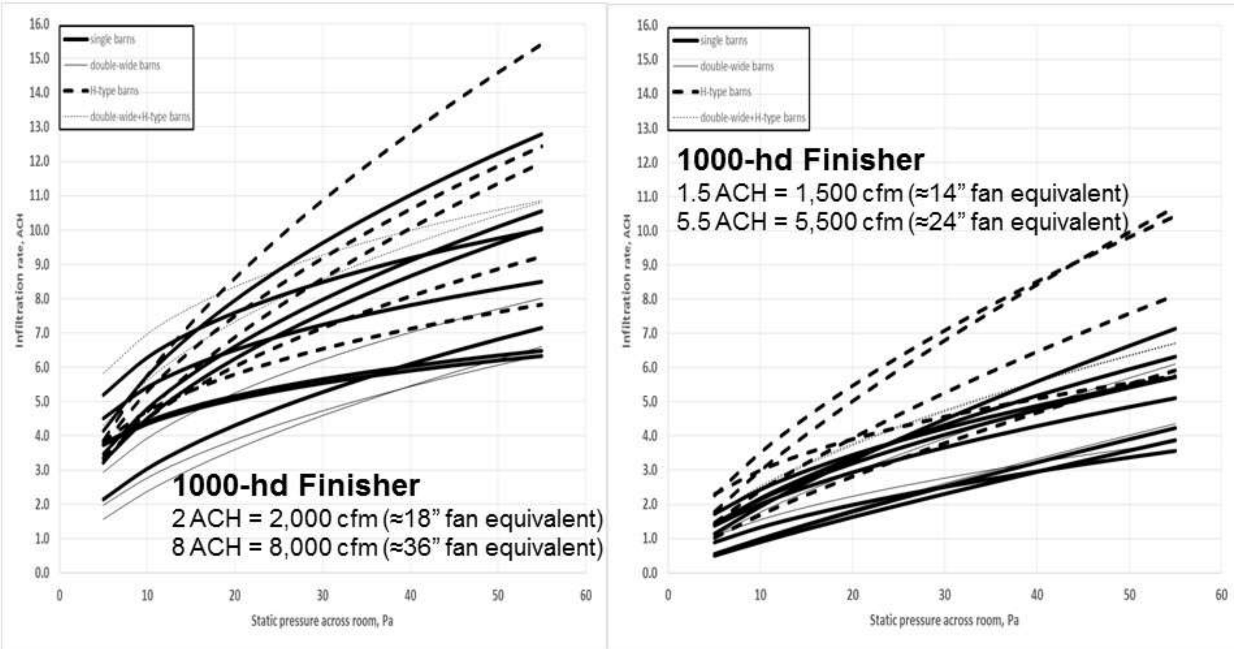
Comparison of *As-is* versus *Other* infiltration rates:



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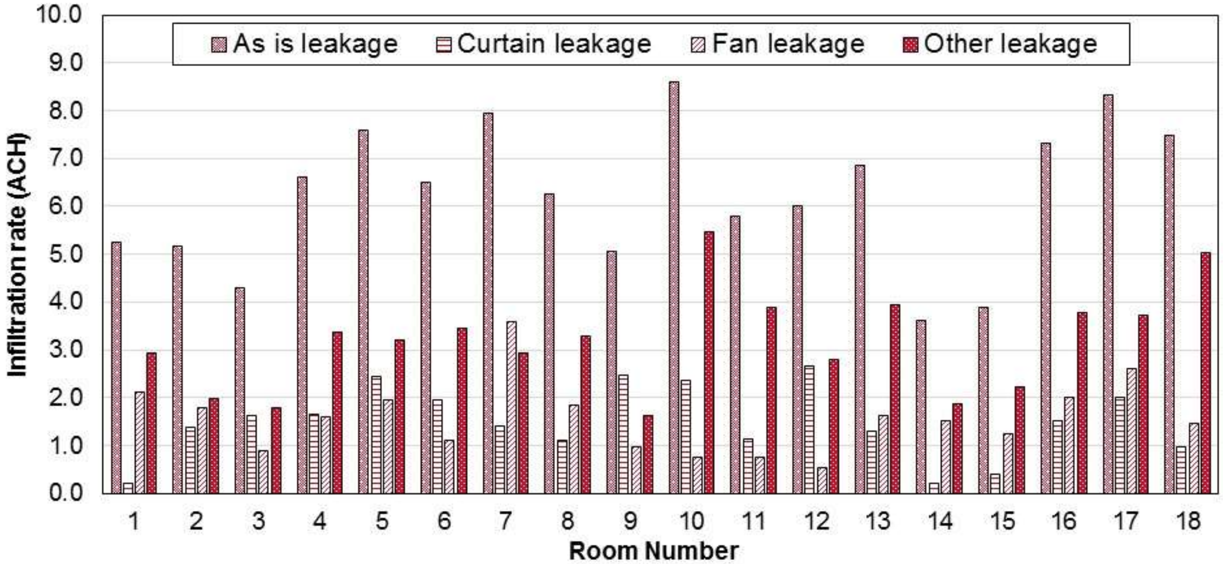
Infiltration rate comparison at ΔP = 0.08 in. wc by room and infiltration source: **Note:** ACH=CFM/pig at 7.5 ft^2/pig



Take Home: *Curtain and fan leakage can be controlled.*
Half of all leakage from obscure locations.

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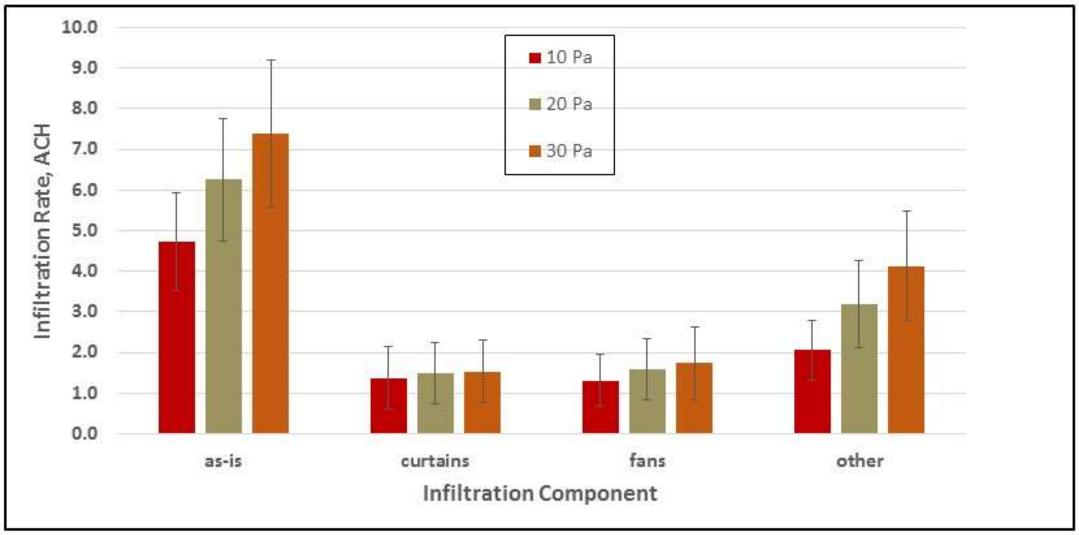
Predicted infiltration rate summary: (ACH or CFM/pig at 7.5 ft^2/pig)



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Infiltration study summary (at ΔP = 0.08 in. wc):

- *As-is* infiltration rate = 5.96±1.49 CFM/pig **(24" fan equivalent[&])**
- *Curtain* infiltration rate = 1.49±1.00 CFM/pig (25%) **(14" fan equivalent)**
- *Fan* infiltration rate = 1.52±1.38 CFM/pig (26%) **(14" fan equivalent)**
- *Other* infiltration rate = 2.90±1.42 CFM/pig (49%) **(20" fan equivalent)**

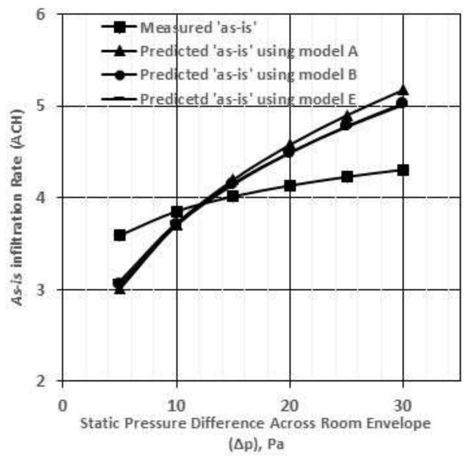
[&] *7.5 ft^2/pig stocked finisher*

***The Challenge**: identify 'other' sources of infiltration and develop practical low-cost retrofit solutions.*

Infiltration model validation:

Validation room details:

- located near Garner, Iowa.
- Single room.
- Plastic ceiling.
- The internal length, width, and floor-to-ceiling height of the validation room was 78.33 m, 15.24 m, and 2.29 m, respectively.
- Infiltration testing done in calm weather and ambient air temperature > than 5°C (CGSB, 1999).



Data compared with models:

Model A (all): $I = 2.4047 \times \Delta p^{0.3031}$
Model B (single): $I = 2.5332 \times \Delta p^{0.2793}$
Model E (plastic): $I = 2.6057 \times \Delta p^{0.2701}$

Percent prediction error over measured Infiltration at 20 Pa:

For Model A : 10.76%
For Model B : 8.65%
For Model E : 8.72%

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Comparison with others:

- *As-is* infiltration rate for five newly constructed (tight) swine barns

  = 1.4 CFM/pig at ΔP = 20 Pa (Zhang and Barber, 1995)

- *As-is* infiltration rate for commercial broiler houses

  = 3.6 to 5.6 ACH at ΔP = 25 Pa (Lopes et al., 2010)

So, what does it all mean…

Infiltration Effect on Barn Operating Conditions		
1,000	pigs	ACH=CFM/pig with 8ft ceiling
7.5	ft^2/pig	
180	ft long	Barn Parameters
42	ft wide	
8	ft ceiling	
18	N inlets	Inlet Parameters
3	L inlet, ft	
6	Biflow L, ft	
0.25	inlet setting, in	
2.25	inlet area, ft^2	
0.21	inlet area, m^2	
0.60	inlet Cd	
12	dP, Pa	Resulting Operating Conditions
0.55	Vinlets, m^3/s	
1.16	Vinlets, cfm/pig	
1.92	Vinfil, cfm/pig	
3.08	Vtotal, cfm/pig	
0.05	in wc	

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Infiltration control:

1. Minimum 3 inch overlap on curtain (worth 1.5 cfm/pig less leakage).

2. Louvers operating as designed. Unused cold weather fans covered. Pump-out covers secured with sill-plate construction foam (worth 1.5 cfm/pig less leakage).

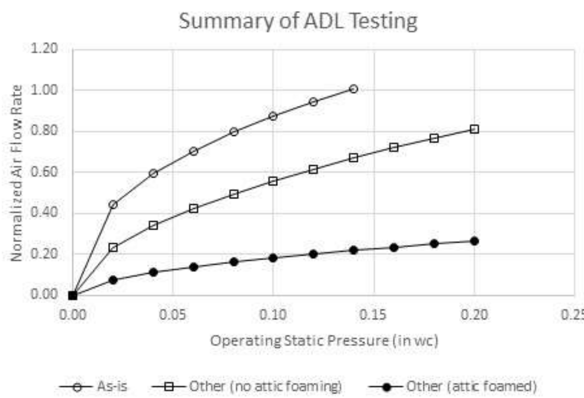
3. Doors, although obvious and fixable, were negligible.

4. 50% of leakage from undefined locations. In-field smoke testing revealed ceiling-to-wall joints significant. If attic is foamed, this balance of 50% is reduced to 9% (83% reduction).

5. Following items 1-4 can reduce as-is infiltration from about 6 cfm/pig to 0.8 cfm/pig resulting in a significant improvement in planned inlet performance and overall cold-weather air distribution.

In-lab infiltration testing:

Infiltration mitigation techniques tested in simulated barn at ISU Air Dispersion Laboratory



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