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PIT VENTILATION SYSTEMS PERFORMANCE IN A MODEL SWINE BUILDING

BY

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A thesis submitted
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1975

PIT VENTILATION SYSTEMS PERFORMANCE
IN A MODEL SWINE BUILDING

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor Date

Head, Agricultural Engineering Date
Department

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INTRODUCTION

The removal of noxious gases and odors from swine confinement buildings with slotted floors over manure storage tanks is an important aspect of environmental control. One of the functions of the ventilation system is the removal of the gases. Ventilation systems have traditionally been designed to remove moisture at the same rate as it has been produced within the structure and to provide air movement for animal comfort. If efficient removal of gases is to be achieved, ventilation systems designs must be specifically developed for those confinement buildings with slotted floors and underfloor manure storage.

The opportunity for reducing labor, land, and bedding costs, and realizing the benefits of better management are major factors in the continuing trend toward increased use of confinement swine housing systems. The environmental advantages associated with these systems in many climatic regions are also stimulating the turn toward increased confinement. The improvements created by a proper ventilation design on environmental conditions and subsequently on swine production are of important economic value to the swine producer.

A potential method of achieving an environment that is conducive both to livestock and workers is the utilization of a pit ventilation system. A properly designed and managed pit ventilation system should remove gases and odors from the space above the liquid manure surface before natural convection currents or mechanical air movement above the slotted floor transfers the gases into the livestock's environment. This is particularly important during winter operation when minimum ventilation rates are employed, and during manure agitation, prior to pumping the pit, which often creates an environment with a high concentration of gases and odors that cannot be controlled effectively by conventional ventilation systems. Various types of underfloor or manure pit ventilation systems have been employed, but many have had limited success.

The evaluation of pit ventilation systems performance by comparing air flow velocities, air currents, and evacuation times is needed to develop the information needed for proper engineering design. Therefore, a research project employing scale models of five pit ventilation systems and employing the principles of similitude and dimensional analysis was initiated with the following objectives:

1) To determine the influence of manure pit ventilation system geometry on air removal from a swine building and
2) To evaluate the effects of pit ventilation system geometry on swine building ventilation characteristics.

REVIEW OF LITERATURE

Confinement Environment

Optimum environmental conditions in a total confinement swine building are dependent upon proper ventilation design and management. The American Society of Agricultural Engineers Yearbook (2)[1] defines ventilation as a system of air exchanges which accomplishes one or more of the following:

1) Provides desired amounts of fresh air without drafts to all parts of the shelter.
2) Maintains temperatures in the shelter within desired limits.
3) Maintains relative humidity in the shelter within desired limits.

According to the Midwest Plan Service (26) an adequately designed and managed ventilation system provides: 1) proper air movement, 2) adequate working conditions, 3) increased feed efficiency, 4) longer building life, 5) fewer odors, 6) increased capacity, and 7) no drafts or sudden temperature changes. According to Hellickson, et al. (19), the ventilation system should be designed to remove excess moisture and noxious and corrosive gases without creating drafts on the animal. David (6) stated that the goal of

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[1] Numbers in parenthesis refer to literature cited.

ventilation in a swine confinement structure is that all pigs receive the correct amount of air continually and without drafts.

Overall, uniformity of air distribution depends primarily on location, design, and adjustment of the air inlet, Midwest Plan Service (26). Claybaugh (3) stated that optimum air movement can be obtained by correct placement and control of the air intakes, and that proper air movement can be obtained through maintaining correct static pressure and by proper design of the intake air. Furthermore, the Midwest Plan Service (26) recommends that in a building where manure is stored below the floor, there should be ventilation of the space between the liquid and the floor.

Odor control becomes important where low ventilation rates or summer cooling with mechanical refrigeration are employed stated Hazen and Mangold (18). Muehling (27) indicated that under normal conditions in an adequately ventilated confinement unit, no noxious gases will reach lethal concentrations for pigs or human beings. Muehling (27) concluded that dangerous levels of gases would be reached only under special conditions such as ventilation failure or vigorous agitation of the manure in the pit. However, Karknak and Aldrich (23) report that when propeller fans for exhaust and a perimeter slot inlet were employed a manure pit odor was quite noticeable. The reason for this was that air from the inlet was following the wall down and constantly passing over the liquid stored in the pit before entering the occupied area.

Gunnarson et al. (17) studied the effect of air velocity, air temperature, and mean radiant temperature on the performance of 97- to 216-lb (44- to 88-kg) finishing swine from January 6, 1966 to March 16, 1966. When air velocity inside the building was 30 fpm (9.1 m/min), the average daily gain equaled 1.5-lb (0.68-kg)/day/hog and at 10 fpm (3 m/min) the average daily gain was 2.15-lb (0.98-kg)/day/hog. Gunnarson et al. (17) concluded that the average daily gain of swine of both sexes was significantly affected by air velocity, with average daily gain related inversely to air velocity.

The Midwest Plan Service (26) states that finishing pigs will grow faster with the least amount of feed, if temperatures and relative humidity are maintained at 55°F (12.8°C) and 50 to 80 percent, respectively. Jensen et al. (22) found in a study of different housing environments for growing and finishing of swine that rate and efficiency of gain decreased with a drop in temperature. The gain-to-feed ratios were 18 percent and 13 percent greater for the growing and finishing periods, respectively, in the heated building than in the open-front building. Mangold et al. (24) reported that growing and finishing pigs raised at air temperatures below 50°F (10°C) were less efficient than pigs raised at 60°F (15.6°C). The decrease in efficiency for heavy weight pigs as the temperature dropped below 50°F (10°C) of 0.002 lb (0.91 grams) of gain per pound of feed intake for each degree Fahrenheit was highly significant.

Manure Pit Gases and Effects on Swine and Humans

Day et al. (7) identified gases in a totally slotted floor building with under-floor pits as being carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), and possibly ammonia (NH_3). Merkel et al. (25) assessed swine odors as complex mixtures of amines, whose odors resemble ammonia and sulfur-containing compounds, which may be characterized as the hydrogen sulfide or decomposing sewage odor. Merkel et al. (25) found that the intermediate products of anaerobic manure decomposition include organic acids, amines, amides, alcohols, carbonlys, and sulfides of which the intermediates are important in the characteristic odor resulting from the storage of manure. Elliot et al. (11) reported that average CO_2 concentrations (737 ppm) were highest 1 foot (.3 meters) above the floor, which is approximately the level at which air is inspired by swine. Day et al. (7) also found that H_2S and CO_2 accumulate in the lower part of the building where the pigs breathe. Elliot et al. (11) found that carbon dioxide was higher in the pit (907 ppm) and 1 foot (.3 meters) above the floor (877 ppm) during pumpout than during weekly samplings. From tests at the 1 foot level, Elliot (11) noted that there were no extremely high H_2S values, but stated that it should not be assumed that higher values did not occur. Muehling (27) reported that CO_2 normally makes up 10 to 40 percent of the gas in a bubble coming from the liquid manure pits, and ammonia odors can reach high levels in swine buildings with heated floors, since high temperatures promote ammonia odor. Taiganides et al. (38) concluded that during pit stirring, when low ventilation rates are employed, the gases from manure will not mix fast enough with the air, and animals that keep their noses to the floor could inhale oxygen-deficient gases.

Merkel et al. (25) stated that three specific problems stem from confinement feeding of swine:

1) Odor control for the sake of the producer and his neighbors.
2) Possible toxic effects of the individual gases and gas combinations on the animals or manager.
3) Potential damage to structural components of the confinement building.

Cramer et al. (4) noted that odors of an enclosed house were frequently objectionable to humans and may have an adverse effect on the welfare of the hog as compared to a hog raised in an open-front building. In a study of pigs raised in confinement, Anderson (1) observed chronic coughing and reduced growth rates in buildings with odor problems, but there was no evidence of pneumonia. Curtis et al. (5) suggested that there is a possibility that lung disease in pigs may be related to the stress caused by irritating air pollutants such as ammonia. Muehling (27) reports that inhalation of air containing 40,000 ppm of CO_2 will increase inhalation depth and rate while concentrations of 100 to 200 ppm NH_3 will cause swine to lose their appetite, sneeze, and salivate.

Preuschen (33) observed healthy workers who were exposed, over a long period of time, to odor and dust-laden air and found that the odors from confinement housing were not only unpleasant, but health damaging. Workers would experience irritation of the respiratory tract, dizziness, shortness of breath, and fatigue. Fletcher (14) cited several accidents due to gases from liquid manure pits and animal losses that have occurred during manure agitation. These accidents and losses generally occur during winter conditions when lower ventilation rates are employed. Fletcher (14) noted that numerous workers, including agricultural engineers, have experienced temporary illness after exposure to gases in confinement buildings, with the effects lasting for several days. Fletcher (14) concluded that to assure optimum conditions for livestock, the levels of gas accumulation would have to be lower than humans could tolerate because of 24-hour exposure to gases, not the standard 8-hour exposure set up by the industrial hygienists.

Under-Slat Ventilator Systems Design

Numerous researchers have indicated the need for pit ventilation systems and others have evaluated performance of specific systems. However, no information exists on the comparative performance of various systems and there is little agreement on the optimum system for use in swine buildings.

Ross et al. (34) raised several questions concerning pit ventilation systems:

1) Can odor control be effective if only minimum ventilation is exhausted through the pit?
2) Does all the air need to be exhausted through the pit?

3) What kind of ducting is required to get acceptable air distribution in the occupied zone and the pit?

4) What is the minimum air flow through the pit for acceptable odor control?

Driggers (9) stated that odors are a serious obstacle to the acceptance of totally enclosed buildings, but can be eliminated with proper ventilation.

Driggers (9) noted that lack of ventilation in livestock buildings during winter operation is a common mistake. Ross et al. (34) found that tapered exhaust ducts equipped with a variable speed fan rated from 1490 cfm (42.2 m^3/min) to 4000 cfm (113.3 m^3/min) resulted in acceptable air distribution and temperature control, but unsatisfactory odor control in a swine structure. The poor odor control was due to the variable speed fan dropping to the minimum speed during cold periods; thus the airflow through the pits was not enough to prevent pit odors from moving into the occupied zone. However, Driggers (9) concluded that no more than the normal ventilation air flow should be exhausted from the manure pit because the ventilation system becomes less effective in providing air distribution during prolonged cold periods.

According to Oatway (30), all ventilation air should be forced to pass down through the slots and exhausted from the pits. Oatway (30) achieved satisfactory odor control in a fully slatted, 500 head swine unit by ventilating all the exhaust air from beneath the slatted floor. The exhaust air was transferred from the pit space up to a 2- by 2-foot (0.6- by 0.6-meter) duct. Ventilation rates of 750 cfm (21.2 m^3/min), continuous, and 10,500 cfm (297.2 m^3/min), thermostatically controlled, provided air movement in the duct. Grub et al. (16) noted continuous removal of gas from the pit area with a pit ventilation design consisting of one exhaust fan rated at 4100 cfm (1250 m^3/min) located 5 feet (1.5 meters) above the slatted floor, and a continuously operating exhaust fan rated at 1600 cfm (488 m^3/min) for each pit. The fan in each pit was connected to a 10-inch (25.4 cm) diameter perforated duct, which extended the length of the pit. Grub et al. (16) concluded that an accumlation of H_2S, NH_3, CO_2, and CH_4 was prevented by the pit ventilation system. Fisher and DeShazer (13) found that pit exhaust fans placed over manure pit annexes must be supplemented by wall exhaust fans, when high levels of the lighter than air gases are being generated. From a study of a pressurized system in a beef confinement unit, Feddes and McQuitty (12) reported that higher concentrations of NH_3 were removed, when the exhaust air was vented below the slatted floor. Overall, Ross et al. (34) concluded that a system in which air must be exhausted through the pits is more easily designed than one that exhausts only part of the air in that manner.

A pit ventilation system needs to provide uniform air distribution the entire length of the structure. Ross et al. (34) studied the performance of 6- and 8-inch (15.2- and 20.3-cm) plastic pipe with orifices spaced 12 inches (30.5 cm) apart, and found for both ducts tested, the air flow decreased with distance, but the average air volume was above the minimum design volume of 4 cfm (0.11 m^3/min) per foot. Driggers (8) obtained uniform exhaust air from one end of a farrowing house to the other by employing a plenum or duct along the manure pit. The duct had small openings connecting the pit and plenum and air flows were provided by a variable speed fan located at one or both ends of the duct. Driggers (8) balanced the system by partially restricting the openings nearest the fan until the velocity furthest from the fans reached 500 to 600 fpm (152.4 to 182.9 m/min). Driggers (8) concluded that when duct length is greater than 100 feet (30.5 meters), a fan should be provided on each end to achieve better air flow distribution through the connecting openings to the pit and also to minimize the size of the duct.

One criterion for satisfactory control of odors with a pit ventilation system is to obtain downward air movement through the slots. In a study of a beef confinement facility without a pit ventilation system, Nabben (29) noted that the upward movement of gases, from the liquid manure pit, varied from a few feet per minute to 15 fpm (4.6 m/min), and did not reach zero velocity until it reached a point 30 inches (0.76 meters) above the slats. At this height, the gases mixed with the ventilation air. Sallvik (35) reported that a theoretical velocity of 40 fpm (12 m/min) would ensure downward movement of exhaust air. Furthermore, Grub et al. (16) concluded that the most positive ventilation of the pit occurred when air was exhausted downward through the slots at a velocity greater than 16 fpm (4.9 m/min)

Model Ventilation Studies

Model studies of various ventilation systems have been performed using dimensional analysis and the principles of similitude. For many design and operating conditions the ventilation data obtained from the model studies are similar to those observed in prototype units.

Pattie and Milne (31) theorized that ventilation air flow is governed by viscous effects. Therefore, air velocities in model studies may be increased as size of the model decreases without appreciably altering air flow patterns or velocity distributions. Model studies of air movement in a one-tenth size scale model of a 40- by 240-foot broiler house substantiate this concept as air flow patterns were essentially the same in the model and prototype, and velocity distributions in the model and prototype were in good agreement. Further investigation at Reynolds numbers of 0.20, 0.65, and 0.95 that of the prototype indicated no significant changes in flow patterns or velocity distributions. Pattie and Milne (31) concluded that ventilation air flow patterns and velocity distributions were governed by the configuration of the air inlet. In a similitude study of ventilation inlet configuration, Smith and Hazen (37) found that models of air inlets successfully predicted the prototype air flow characteristics. Wilson and Bishop (39) noted that high inlet velocities, 660 fpm (201.2 m/min) as compared to 440 fpm (131.1 m/min), did little to improve the distribution of air for a given fan and inlet arrangement in a one-thirteenth size, plexiglass model of a broiler house. Wilson et al. (40) concluded from a model study of non-isothermal jet velocities and temperature profiles, that buoyancy force effects were found to be negligible at velocities above 800 fpm (243.8 m/min) and temperature differences larger than 50°F (10°C). Below this velocity and at the same temperature differences, some buoyance force effects were noted.

Effects of ridge vent design on air flow characteristics in a one-twentieth size scale model of a 72- by 96-foot (21.3-by 27.4-meter) open-front beef confinement building subjected to a north wind were evaluated by Dybwad et al. (10). Dybwad et al. (10) concluded that ridge vent design had a highly significant effect on outlet velocity, with the greatest air flow occurring with an open-front ridge vent and the least occurring with a covered ridge vent. It was concluded that the most desirable ventilation rates and temperature conditions were obtained, when the open ridge vent was employed.

Schulte et al. (36) studied air flow patterns with titanium tetrachloride in a one-twelfth scale model of a swine confinement unit. Dynamic similarity between the prototype and model was maintained by holding Reynolds number constant. Schulte et al. (36) noted that, when titanium tetrachloride was introduced into the pit, the gas was drawn or forced up through the slots into the animal's environment. Schulte et al. (36) concluded that odors and gases may be forced from the manure pit into the animal's environment as a result of above-floor inlets and an exhaust ventilation system.

Also, Schulte et al. (36) found that mean air velocities in the model were generally higher when air entered through a baffled eave inlet than when it entered through non-baffled inlets. Overall, mean velocities were higher near the floor, ceiling and exhaust locations and were a function of the horizontal distance from the side wall. Employing a similar model, Ifeadi and DeShazer (20) reported that as more air is exhausted below the slatted floor, the concentration of NH_3 above the floor decreases. Ifeadi and DeShazer (20) found that when all exhausts were located above the floor, the relative ammonia index was 2.1 times greater than any of the other exhaust conditions.

Furry and Hazen (15) applied the principles of similitude to obtain a constant temperature model of a ventilation-dilution situation. Carbon dioxide was introduced into three models, one prototype and two others that had length scales of 2 and 3. Ventilation flow rates, as determined by the number of air-changes per hour, were modeled on the basis of both Reynolds and Froude numbers. Flow rate scaling on the basis of N_{RE} and N_{FR} did not appear to impose any contradictory requirements for modeling the ventilation-dilution phenomenon, therefore, allowing modeling on the basis of either design parameter. However, Furry and Hazen (15) stated that it would be more convenient to find air-change numbers using low-magnitude time scales (N_{FR}), because of limitations of the measuring equipment.

DETERMINATION OF PERTINENT VARIABLES

The purpose of this study was to evaluate and compare ventilation characteristics and evacuation times of under-slat ventilation systems. A 24- by 90-foot (7.3- by 27.4-meter) swine finishing building (Figures 1 and 2) located on the South Dakota State University Swine Research Farm was selected as the prototype for this study. Model studies were performed to obtain better control of the variables and to limit expenses.

The air flow rate, air patterns, and system performance of under-slat ventilation are affected by fluid properties, such as the ratio of inertia forces to viscous forces and the ratio of inertia forces to gravitational forces. Building geometry factors, such as length and diameter of ducts, area of slot inlets, and length, width, and height of the building also influence air flow rates and patterns and system performance. Assuming that the same phenomenon govern performance in the model and prototype, a list of pertinent variables affecting the ventilation characteristics was compiled (Table 1). The selection of pertinent variables was based on the assumptions that fluid flow is incompressible, the building atmosphere will be without manure gases and added moisture, and there will be no significant internal heat source present.

The functional relationships between pertinent variables can be expressed as $T = f\,(l, w, h_p, h_c, s, w_s, w_o, h_s, h_o, L_p, D_p, W_{sp}, B_w, A_v, V, \rho, g, r, \mu)$. Employing dimensional analysis and the

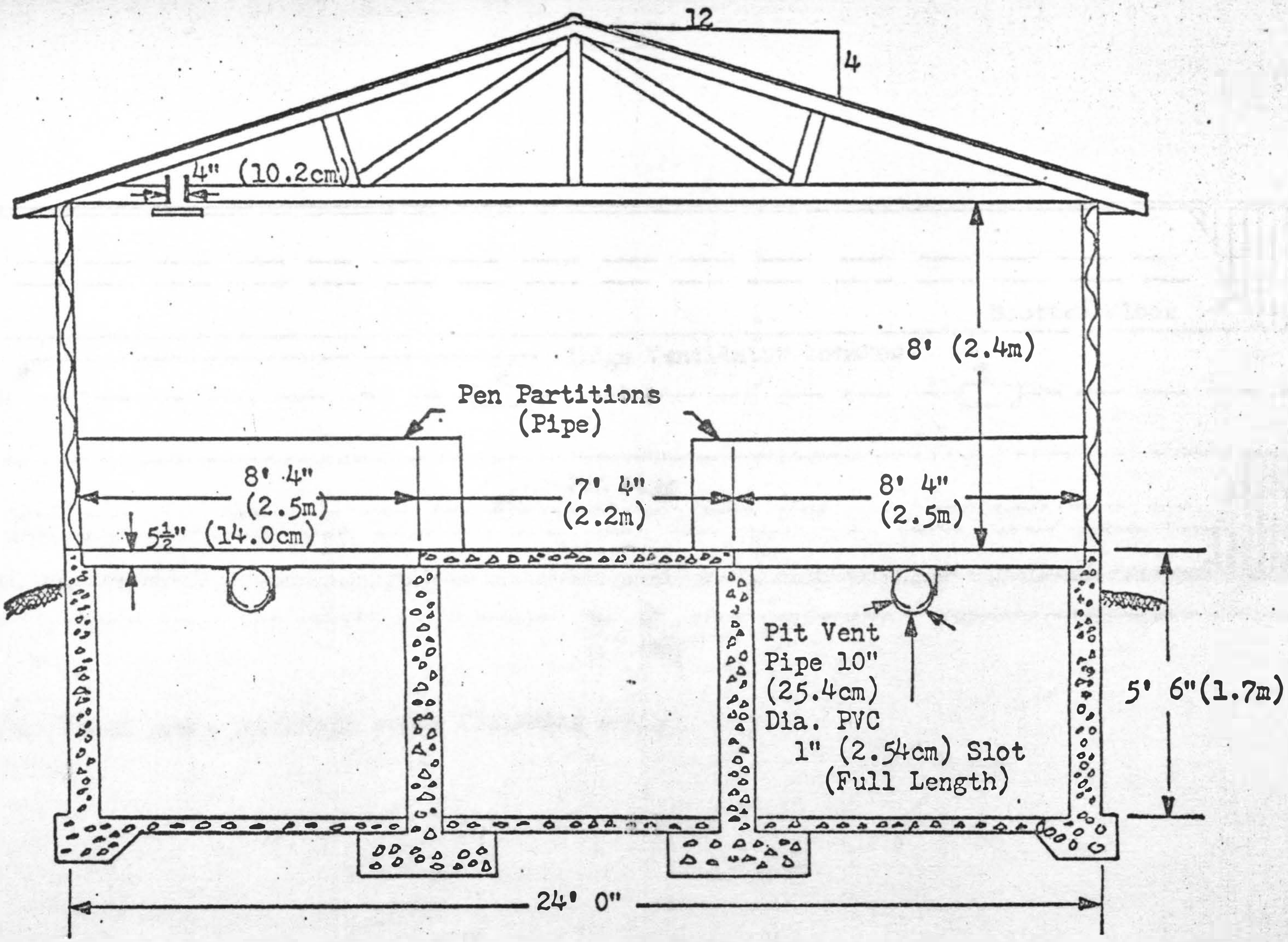


Figure 1. Front view, prototype swine finishing unit.

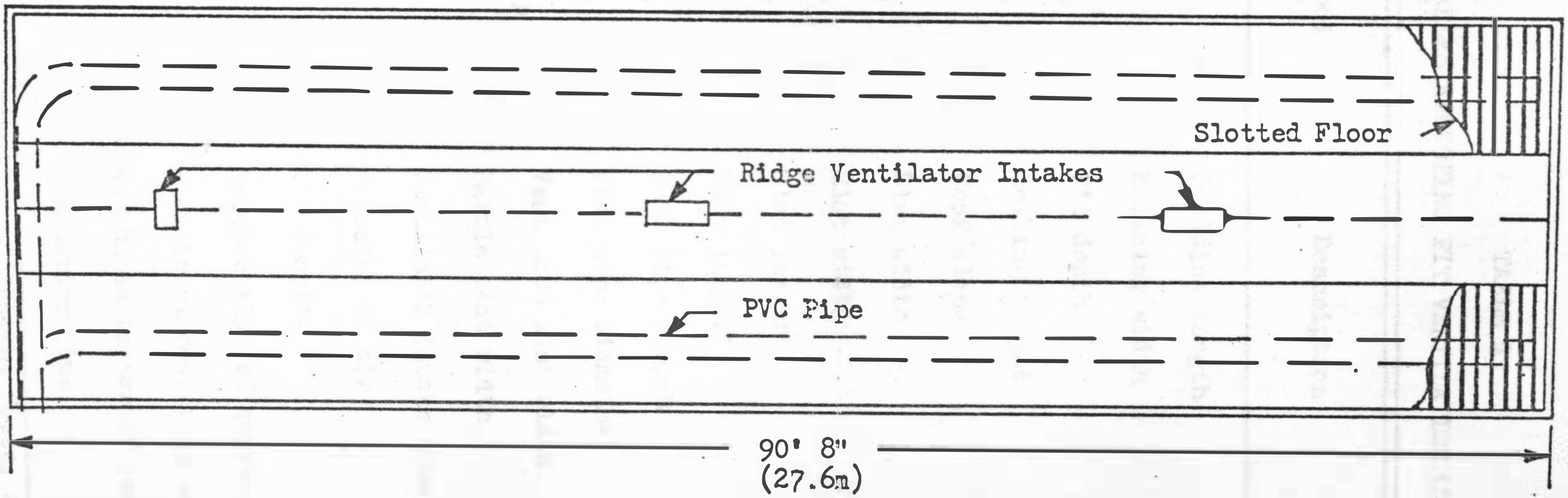


Figure 2. Floor plan, prototype swine finishing unit.

TABLE 1

VARIABLES AFFECTING PIT VENTILATION CHARACTERISTICS

Variable No.	Symbol	Description	Dimensional Symbol*
1.	l	Building length	L
2.	w	Building width	L
3.	h_p	Pit depth	L
4.	h_c	Ceiling height	L
5.	s	Roof slope	-
6.	w_s	Slat width	L
7.	w_o	Slot width	L
8.	L_s	Slat length	L
9.	L_o	Slot length	L
10.	L_p	Vent pipe length	L
11.	D_p	Vent pipe diameter	L
12.	W_{sp}	Vent pipe slot width	L
13.	B_w	Baffle slot width	L
14.	A_v	Ventilator intake area	L^2
15.	V	Velocity of air	LT^{-1}
16.	ρ	Air density	$FL^{-4}T^2$
17.	g	Acceleration of gravity	LT^{-2}
18.	μ	Dynamic viscosity of inside air	$FL^{-2}T$
19.	r	Roughness factor of vent pipe	-
20.	T	Evacuation time	T

*L,F,T are the basic dimensions of length, force, and time, respectively.

Buckingham Pi Theorem, (28), a set of 17 independent and dimensionless groups, π terms, (Table 2), were derived (20 variables minus the 3 basic dimensions of force, length, and time). The dimensionless form can be expressed as

$$\frac{gT^2}{L} = F\left(\frac{w}{l}, \frac{h_p}{l}, \frac{h_c}{l}, \frac{w_s}{l}, \frac{w_o}{l}, \frac{L_s}{l}, \frac{L_o}{l}, \frac{L_p}{l}, \frac{D_p}{l}, \frac{W_{sp}}{l}, \frac{B_w}{l}, \frac{A_v}{l^2}, s, r, \frac{\rho V D_p}{\mu}, \frac{V^2}{gl}\right) \qquad \text{Equation 1}$$

When establishing the dimensionless groups, commonly used Pi terms were derived whenever possible and appropriate. These Pi terms include Reynold's Number (N_{RE}), which relates the inertia forces to viscous forces, and Froude Number (N_{FR}), which relates the inertia forces to gravitational forces.

The relationships expressed in Equation 1 are general and can be applied to any other system, if the same parameters are involved. Therefore, these relationships can represent a model system and can be written as

$$\frac{gT^2}{l}\,m = F\left(\frac{w}{l}, \frac{h_p}{l}, \frac{h_c}{l}, \frac{w_s}{l}, \frac{w_o}{l}, \frac{L_s}{l}, \frac{L_o}{l}, \frac{L_p}{l}, \frac{D_p}{l}, \frac{W_{sp}}{l}, \frac{B_w}{l}, \frac{A_v}{l^2}, s, r, \frac{\rho V D_p}{\mu}, \frac{V^2}{gl}\right)m \qquad \text{Equation 2}$$

(subscript m refers to the model). In accordance with the theory of models, (28), π_1 equals π_{1m}, if the corresponding independent Pi terms for the model and the prototype are equal. From Equations 1 and 2 $\pi_{1m} = \pi_1$, or $\left(\frac{gT^2}{l}\right)m = \frac{gT^2}{l}$, if the design conditions listed in Table 3 are satisfied.

TABLE 3

(continued)

No.	Basic Equation	Design Conditions
11.	$\left(\frac{W_{sp}}{l}\right)_m = \frac{W_{sp}}{l}$	$\frac{W_{sp}}{W_{spm}} = n$
12.	$\left(\frac{B_w}{l}\right)_m = \frac{B_w}{l}$	$\frac{B_w}{B_{wm}} = n$
13.	$\left(\frac{A_v}{l^2}\right)_m = \frac{A_v}{l^2}$	$\frac{A_v}{A_{vm}} = n^2$
14.	$s_m = s$	$s_m = s$
15.	$r_m = r$	$r_m = r$
16.	$\left(\frac{\rho V D_p}{\mu}\right)_m = \frac{\rho V D_p}{\mu}$	$\frac{V}{V_m} = \frac{1}{n}$ or $V_m = nV$
17.	$\left(\frac{V^2}{gl}\right)_m = \frac{V^2}{gl}$	$\frac{V}{V_m} = n^{\frac{1}{2}}$ or $V_m = \frac{V}{n^{\frac{1}{2}}}$

Design condition 1, the dependent Pi term, determines the evacuation time scale between model and prototype. Since the acceleration of gravity is the same in model and prototype, the time scale $\frac{T}{T_m} = n^{\frac{1}{2}}$ can be obtained from the dependent Pi term. $\frac{T}{T_m} = n^{\frac{1}{2}}$ indicates that for length scales greater than unity, the evacuation time for the model will be less than the evacuation time for the prototype.

Design conditions 2 through 13 (Table 3) indicate the requirements of geometric similarity between the model and prototype with $n = l/l_m$ being the geometric length scale. The roof slope, design condition 14, will be the same for model and prototype. Design condition 15, the roughness factor of the under-slat ventilators, is also equal in model and prototype.

The air flow velocity can be obtained from either design condition 16 or design condition 17, $\frac{V}{V_m} = \frac{1}{n}$ or $\frac{V}{V_m} = n^{\frac{1}{2}}$, respectively. Design condition 16 is determined from Reynolds Number (N_{RE}) and design condition 17 is based on Froude Number (N_{FR}). Previous research has indicated that the velocity scale derived from Reynold's Number has given the best relationships between air flows and patterns in the model and prototype. Which Pi term will have the greatest influence on evacuation times cannot be determined before tests are conducted. Therefore, the velocity scale for determining air flows and patterns was generated from Reynold's number and for evacuation times, velocity scales based on both Reynold's and Froude numbers were evaluated.

PROCEDURE

The construction of the model (Figures 3 and 4) is based on a geometric length scale of 12, design conditions 2 through 8 and 12 through 14 (Table 3) and the assumption that the same fluid and material would be used in the model and prototype. The one-twelfth size model is a scaled reproduction of the swine finishing structure (Figures 1 and 2) cited in the determination of pertinent variables.

The model was constructed with a 3/8-inch (0.95 cm) plywood ceiling, slatted floor, and roof, 1/2-inch (1.3 cm) plywood sides, and a 3/4-inch (91.9 cm) plywood base. The ends were built of 1/4-inch (0.64 cm) plexiglass, which aided in visual observations of air flow patterns as did the 4 plexiglass windows located below the slatted floor on one side wall. The slatted floor was constructed with 1/12-inch (0.21 cm) slats. Air entered the building through ridge ventilator intakes that were scaled to 1/144th the actual area of the prototype ridge ventilator intakes. Air was transferred into the swine's environment from the attic through either a side- or center-baffle, 1/3-inch (0.85 cm), ceiling inlet and was exhausted below the slatted floor.

Comparisons of the ventilation characteristics and evacuation times were conducted with five manure pit ventilation systems. The pit ventilation systems were constructed, depending on the specific system, of PVC (Poly-Vinyl-Chloride) pipe, plywood, and plexiglass tubing, and reduced in accordance with design conditions 9, 10, and

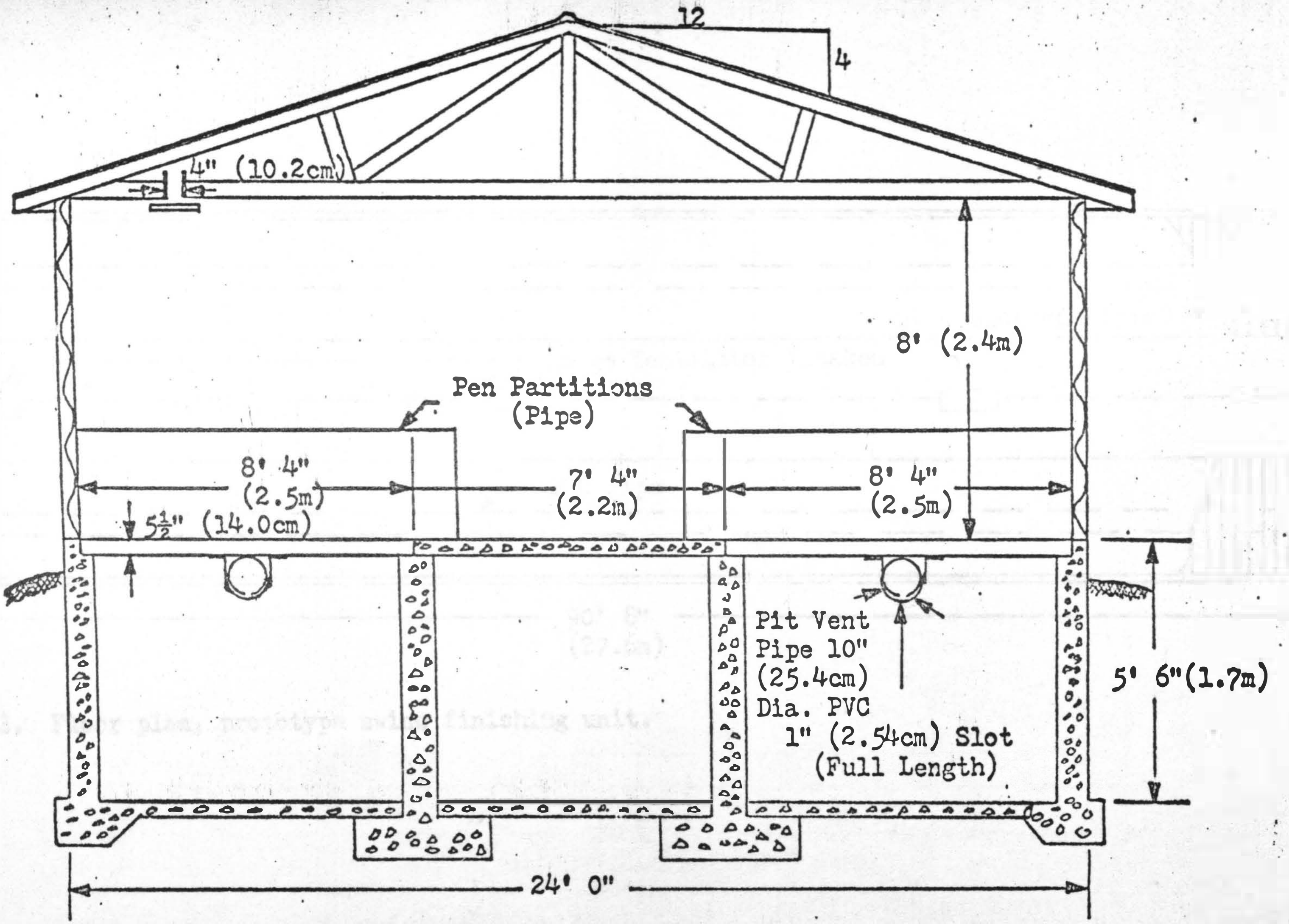


Figure 1. Front view, prototype swine finishing unit.

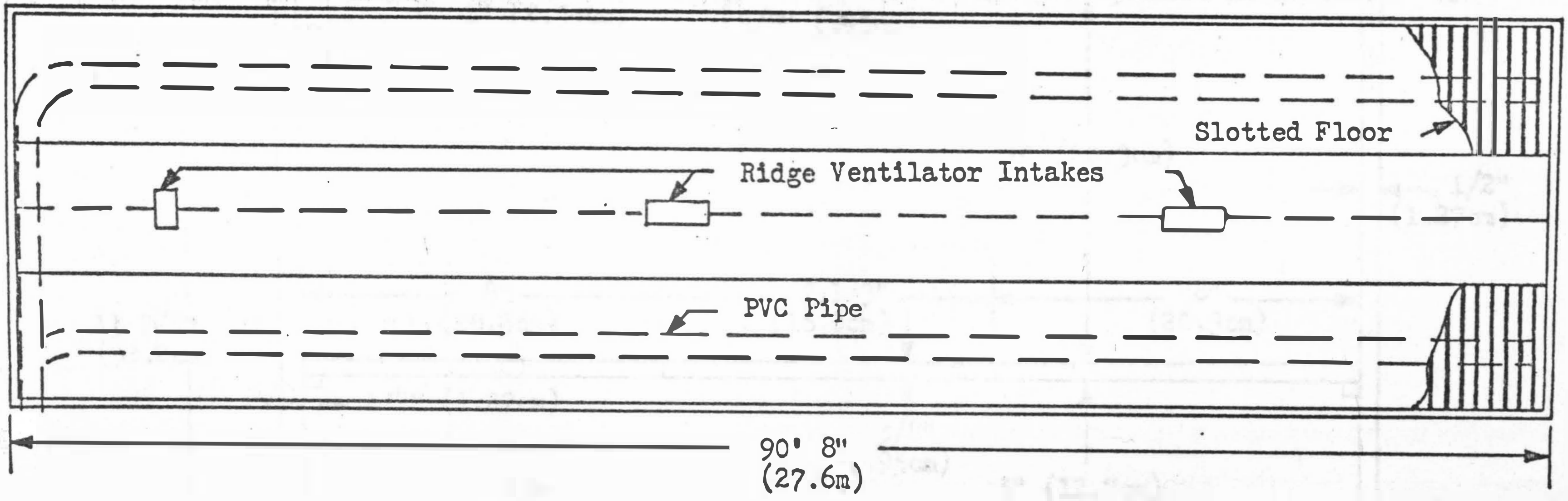


Figure 2. Floor plan, prototype swine finishing unit.

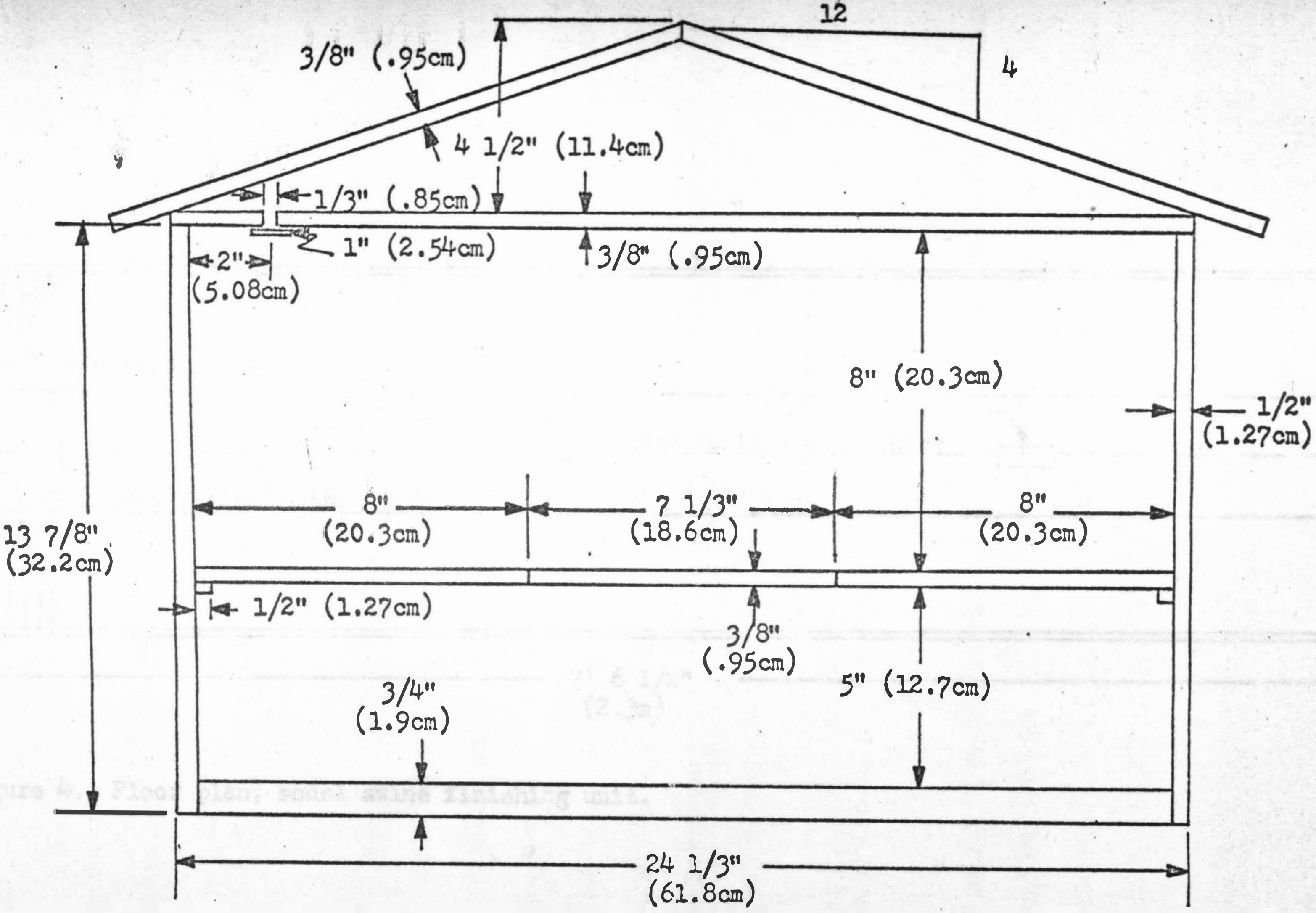


Figure 3. Front view, model swine unit.

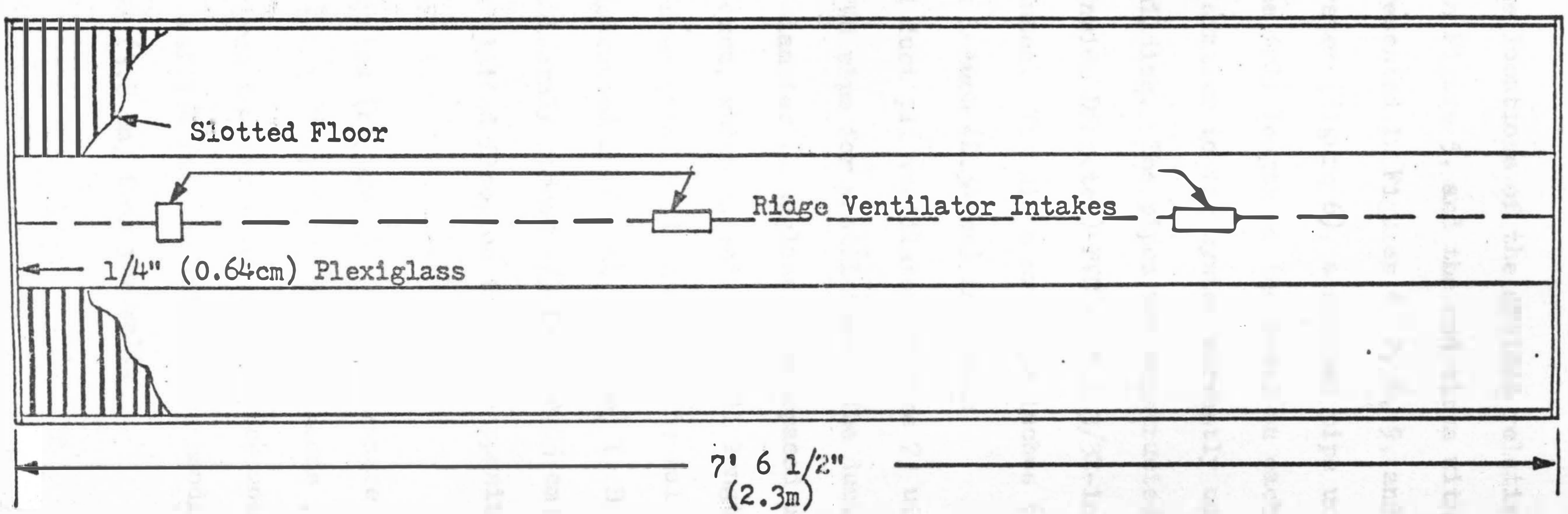


Figure 4. Floor plan, model swine finishing unit.

11 (Table 3). The locations of the systems relative to the model are illustrated in Figure 5, and the end views with related dimensions are presented in Figures 6, 7, 8, 9, and 10.

The first system (Figure 6), a slotted pipe under-slat ventilator, extends the full length of the model on each side underneath the slats and is similar to the system currently used in the SDSU Swine Research Building. The pipes are constructed of 1 1/2-inch (3.8 cm) I. D. (Inside Diameter) PVC with a 3/32-inch (0.24 cm) wide slot cut in the tubes. The slots are 9/32 inches (0.72 cm) long and are spaced at 1 inch (2.54 cm) intervals.

The centered duct pit ventilator (Figure 7) utilizes a 2-inch (5.08 cm) I. D. PVC pipe for ventilation. The duct has 18 1/3-inch (0.85 cm) inside diameter plexiglass tubes spaced uniformly along each side of the duct, which extends the full length of the model.

The third system (Figure 8) is an outside wall pit ventilator. This unit was constructed of 2-inch (5.08 cm) I. D. PVC pipe connected to 36 uniformly spaced 1/3-inch (0.85 cm) plexiglass tubes located below the slatted floor on the wall opposite the side-baffled ceiling inlet.

The fourth system (Figure 9), a hooded manure pit exhaust system, included two 12-inch (30.5 cm) long hoods placed 22 1/2-inches (57.2 cm) from the front and rear of the model along the wall opposite the side-baffled ceiling inlet. The hoods covered an air space 1 1/2 inches (3.8 cm) from the wall.

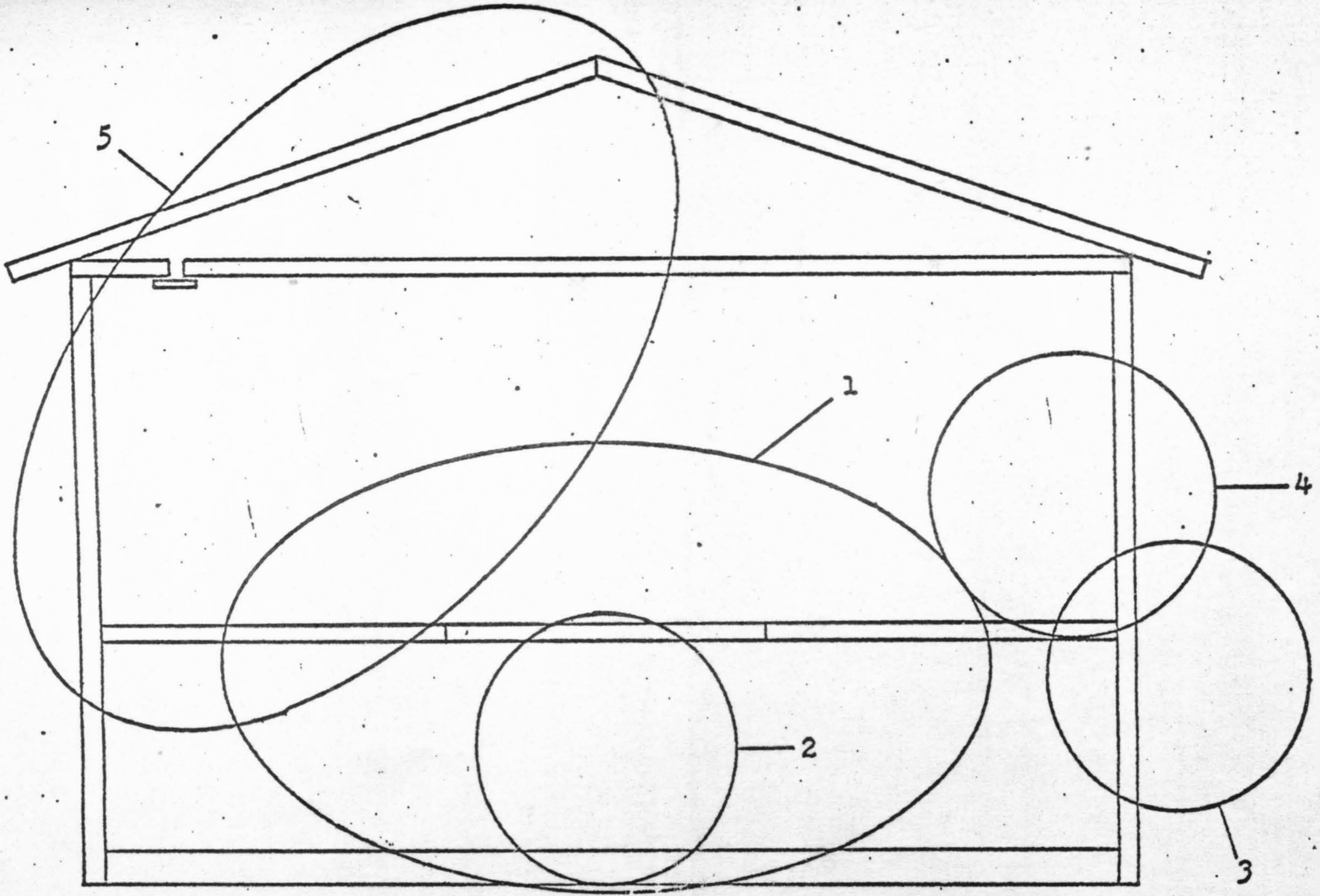


Figure 5. Location of detail sections of the manure pit ventilation systems. (Note figures 6, 7, 8, 9, and 10.)

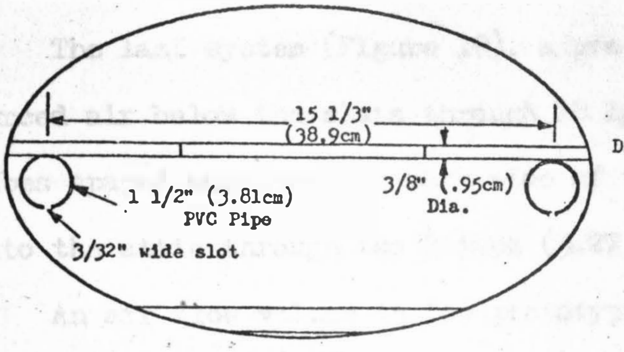
Figure 6. No. 1, Slotted pipe under-slat ventilator.

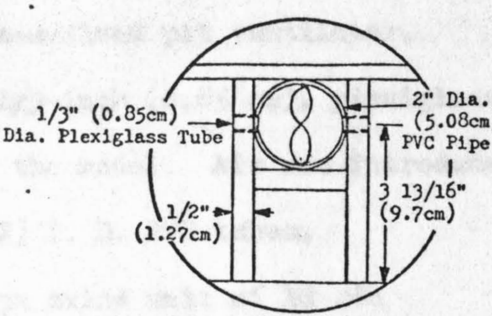
Figure 7. No. 2, Centered duct pit ventilator.

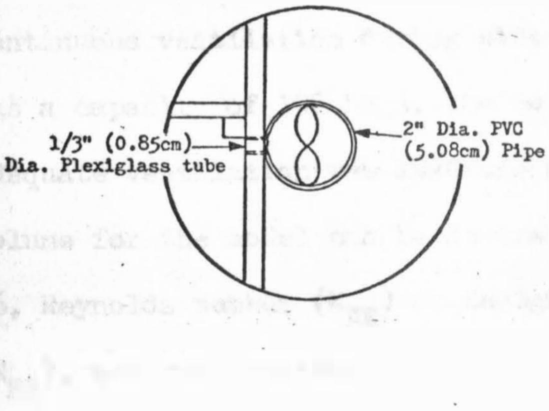
Figure 8. No. 3, Outside wall pit ventilator.

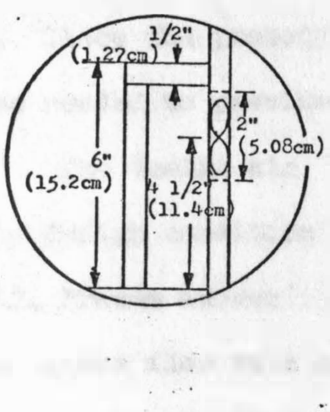
Figure 9. No. 4, Hooded manure pit exhaust system.

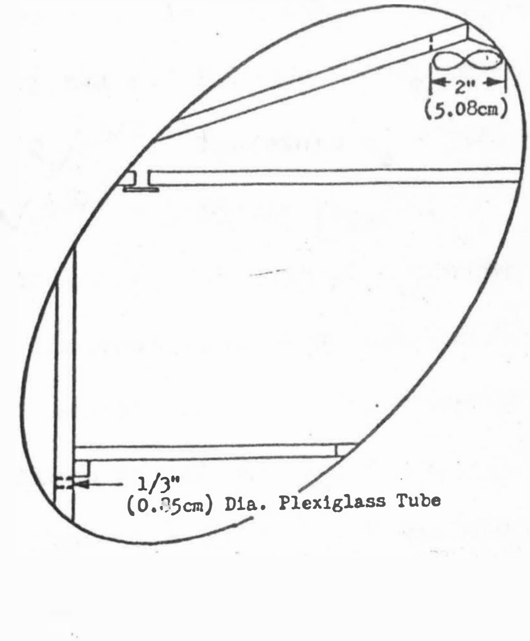
Figure 10. No. 5, Pressurized pit ventilator system.


15 1/3"
(38.9cm)
3/8" (.95cm)
Dia.
1 1/2" (3.81cm)
PVC Pipe
3/32" wide slot


1/3" (0.85cm)
Dia. Plexiglass Tube
2" Dia.
(5.08cm)
PVC Pipe
1/2"
(1.27cm)
3 13/16"
(9.7cm)


1/3" (0.85cm)
Dia. Plexiglass tube
2" Dia. PVC
(5.08cm) Pipe


1/2"
(1.27cm)
6"
(15.2cm)
2"
(5.08cm)
4 1/2"
(11.4cm)


2"
(5.08cm)
1/3"
(0.85cm) Dia. Plexiglass Tube

The last system (Figure 10), a pressurized pit ventilator, forced air below the slats through 18 1/3-inch (0.85 cm), plexiglass tubes spaced uniformly on each side of the model. Air was introduced into the attic through two 2-inch (5.27) I. D. PVC tubes.

An air flow volume in the prototype swine unit of 10 cfm (0.28 m^3/min) per 150- to 210-lb. (68.1 to 95.3 kg) hog was selected from the Midwest Plan Service (26) recommendation for minimum continuous ventilation during winter operation. Since the prototype has a capacity of 192 hogs, the total air volume needed to provide adequate ventilation was 1920 cfm (54.4 m^3/min). The design air volume for the model can be determined either by design condition 16, Reynolds number (N_{RE}) or design condition 17, Froude number (N_{FR}), and the continuity equation $Q = AV$. The volume flow rate of the model (Q_m) equals the volume flow rate of the prototype (Q_p) divided by the geometric length scale (n), $Q_m = Q_p/n$ if N_{RE} determines the velocity scale. However, if N_{FR} determines the velocity scale, then $Q_m = Q_p/n^{5/2}$. Therefore Q_m = 1920 cfm/12 = 160 cfm (N_{RE}) or Q_m = 1920 cfm/$12^{5/2}$ = 3.85 cfm (N_{FR}).

An initial inlet air velocity of approximately 575 fpm (175.3 m/min) in the prototype swine was based on Midwest Plan Service (26) recommendations. The N_{RE} velocity scale will increase air flow rate n times in the model and the N_{FR} velocity scale will decrease the air flow rate by $n^{1/2}$. Thus, the initial air velocity in the model equals 6900 fpm (2103 m/min) or 166 fpm (50.6 m/min) depending on whether N_{RE} or N_{FR} determines the design velocity. Air flows were provided by centrifugal fans and were varied by adjusting the opening area in a plexiglass tube mounted between the fan and the model.

All the experiments were performed in the laboratories of the South Dakota State University Agricultural Engineering Building. Air flow patterns and velocities were taken at two levels (pit and swine), three positions (front, center, and rear), and 8 points across the model, Figures 11 and 12. Air velocities (Appendix B) were measured with a hotwire anenometer, and titanium tetrachloride was used to detect the direction of air movement.

Evacuation time studies were conducted by placing an infrared heat lamp 2 feet (0.61 meter) from the end of the model and letting the light pass through above the slatted floor to the spectroradiometer sensor that was positioned 3/4 inches (1.9 cm) away from the opposite end of the model. Smoke was then introduced into the model through the ridge ventilator intakes, while the exhausting or pressurizing fan was operating, until a zero reading was noted on the spectroradiometer. The evacuation time was recorded as that time required for the spectroradiometer reading to change by a predetermined amount. A total of three replications (Appendix C) was performed on each pit ventilation system with the side baffled inlet for velocity scales determined from both Reynolds and Froude numbers.

Analyses of variance were used to determine if pit ventilation system design, side and centered baffling, and position within the

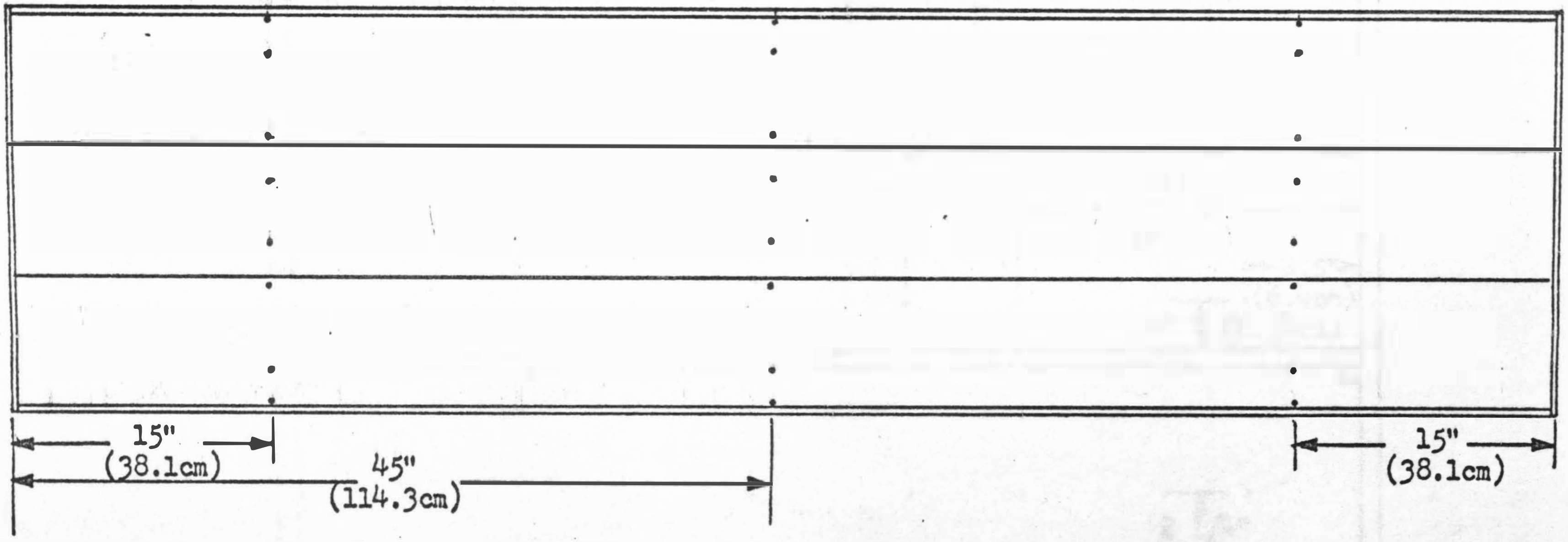


Figure 11. The 24 locations where air velocities and patterns were obtained. Top view

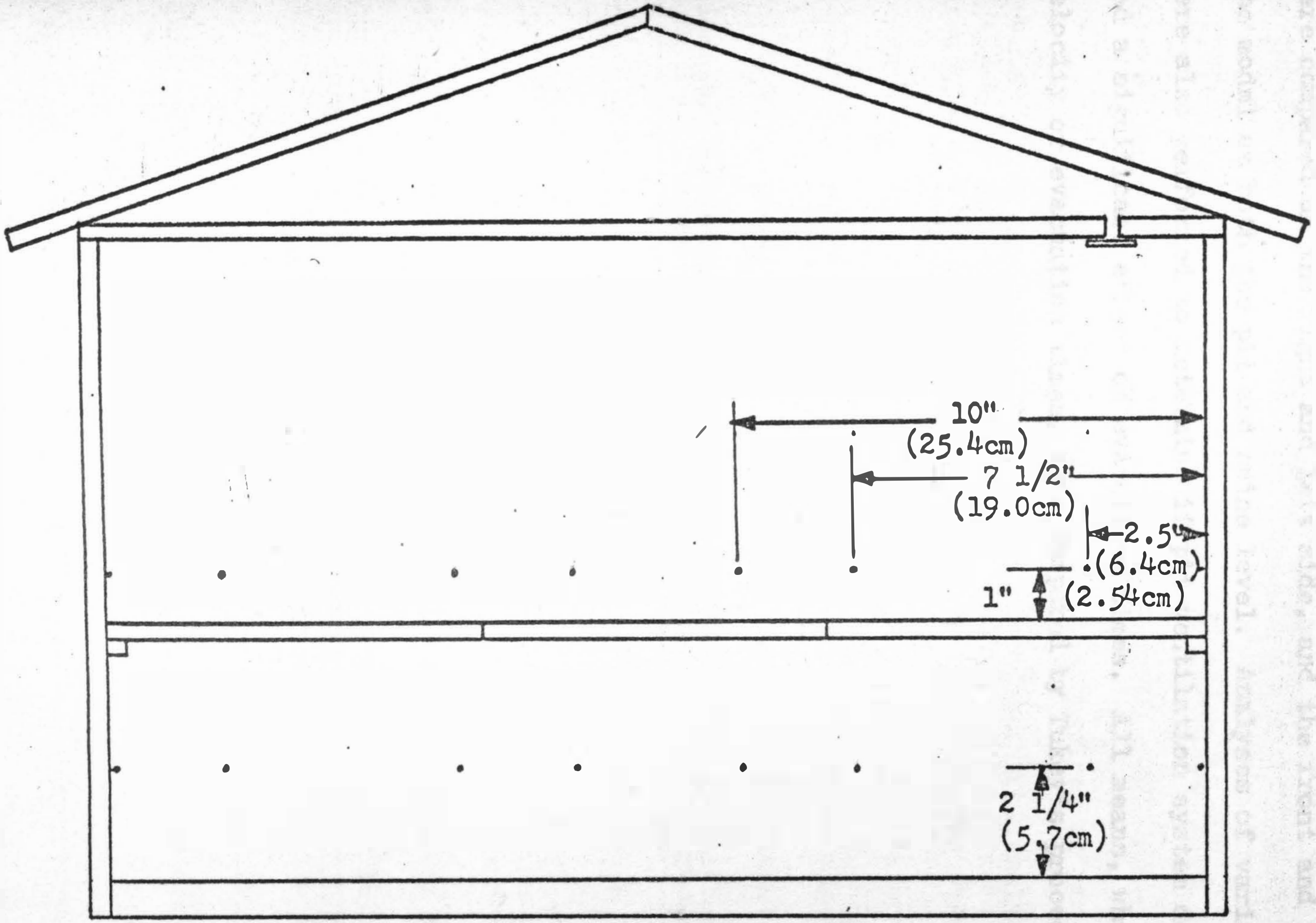


Figure 12. Locations where air velocities and patterns were obtained. End view.

building had significant effects on velocities. The velocities were compared on the right and left side, and the front and rear of the model at both the pit and swine level. Analyses of variance were also performed to determine if pit ventilation system design had a significant effect on evacuation times. All means, whether velocity or evacuation times, were compared by Tukey's procedure.

RESULTS AND DISCUSSION

The results of this investigation include aspects of air movement in terms of both velocity and distribution. Also, to be considered are the relative amounts of time required to move given quantities of air through the model. Therefore, the results will be presented under the following general headings: 1) Air Flow Velocities, 2) Air Flow Patterns, 3) Evacuation Times, and 4) Overall Ventilation Performance. In several instances aspects from one heading have been used to enhance and clarify the results discussed in another heading.

Air Flow Velocities

Pit ventilation system design has a significant effect on average air flow velocities taken 2.5 inches (6.4 cm) from the right and left walls at the front, center, and rear locations of the pit, (Appendix D, Table 7). The average velocity means were 11.7 fpm (3.6 m/min), 74.6 fpm (22.7 m/min), 77.5 fpm (23.6 m/min), 79.2 fpm (24.1 m/min) and 107.1 fpm (32.6 m/min) for the pressurized ventilator system (S_5), centered duct pit ventilator (S_2), outside wall pit ventilator (S_3), hooded manure pit exhaust system (S_4), and slotted pipe under-slat ventilator (S_1) systems, respectively. The average velocity in the manure pit is significantly lower for the pressurized ventilation system as compared with the four exhaust systems studies (Table 4). This is due to initial air movement being provided by fans in the ceiling for the pressurized system, while the exhaust fans located in the pit generate initial air movement in the manure pit area. Systems also had a significant effect on velocities studied 2.5 and 7.5 inches (6.4 and 19.0 cm) away from each wall in the front and rear of the pit. Similar behavior was noted for these locations as was noted previously for air velocities studied 2.5 inches (6.4 cm) from the right and left walls in that the pressurized ventilator system produced significantly lower velocities than did the four exhaust systems (Table 5). However, for all systems air velocities were lower at the ends of the building as contrasted with air velocities along the length of the building. This is believed to be due to increased air movement directed by the ceiling baffles along the walls in the swine confinement area.

TABLE 4

TUKEY'S PROCEDURE COMPARING AVERAGE VELOCITY
MEANS IN THE PIT, (RIGHT AND LEFT)

Source	Identification				
System	S_5	S_2	S_3	S_4	S_1
	11.7	74.6	77.5	79.2	107.1

5% Level

Results from Tables 4 and 5 indicate that the exhaust systems as compared to a pressurized system generate higher air flows in the pit. However, pit ventilation systems did not have a significant effect on air velocity means above the slatted floor at the simulated level of swine occupation. The average velocity means for the five systems ranged from 129.6 to 166.7 fpm (39.5 to 50.8 m/min) and from 101.2 to 125.6 fpm (30.8 to 38.3 m/min) for the right and left sides and the front and back of the model, respectively.

TABLE 5

TUKEY'S PROCEDURE COMPARING AVERAGE VELOCITY MEANS IN THE PIT, (FRONT AND BACK)

Source	Identification				
System	S_5	S_4	S_2	S_3	S_1
	9.2	44.4	45.0	49.7	65.9

5% Level

Average air velocity data for the right and left side and the front and rear of the model at both swine and pit levels using the side- and center-baffled ceiling inlets are presented in Appendix D, Tables 7, 8, 9, and 10. No significant differences were noted at the pit or swine levels for velocity means as influenced by ceiling baffle location. However, significant differences were noted between the interaction of ventilation system and baffle position at the swine level based on data obtained from the right and left sides of the model. The comparisons of velocity means for the interaction between systems and baffle (side, B_1; center, B_2) are presented in Table 6. Average air flow ranged from 95.8 fpm

(29.2 m/min) for the pressurized ventilation system with the side-baffled ceiling inlet to 184.2 fpm (56.1 m/min) for the hooded manure pit exhaust system with the side-baffled ceiling inlet. These were the only velocity means significantly different from the means of the remaining system by baffled ceiling inlet interactions. No significant effects were found as produced by the five ventilation systems and the center-baffled ceiling inlet because of the small differences between velocity means, which ranged from 134.2 to 164.2 fpm (40.9 to 50.0 m/min). The range of velocity means is greater for a ventilation system with a side-baffled ceiling inlet indicating that ventilation system location with respect to a side-baffled ceiling inlet results in a wider variation of velocity means. The significant difference noted in the effects of systems by baffled ceiling inlet interactions indicates the need for considering these factors in design of swine ventilation systems, if predicted and desired ventilation characteristics are to be obtained.

Velocity means were significantly higher (175.2 fpm versus 124.5 fpm) (53.4 m/min versus 37.9 m/min) along the right side of the model than along the left side at swine level, (Appendix D, Table 8). This unequal ventilation distribution is attributed to the use of a side-baffled ceiling inlet located on the right side of the model. Also, a significant difference in velocity means was noted for the baffle by position interaction, (Appendix D, Table 8). The velocity means equaled 102.0 fpm (31.1 m/min), 147.0 fpm (44.8 m/min), 159.0 fpm (48.5 m/min), and 191.3 fpm (58.3 m/min)

TABLE 6

TUKEY'S PROCEDURE COMPARING AVERAGE SYSTEM BY BAFFLE VELOCITY MEANS AT SWINE LEVEL, (RIGHT AND LEFT)

Source	Identification									
S X B	S_5B_1	S_3B_1	S_4B_2	S_2B_1	S_2B_2	S_1B_2	S_5B_2	S_3B_2	S_1B_1	S_4B_1
	95.8	127.5	134.2	144.2	151.7	151.7	163.3	164.2	181.7	184.2

5% Level

for the side-baffle, left position (B_1P_2), center-baffle, left position (B_2P_2) center-baffle, right position (B_2P_1), and side-baffle, right position (B_1P_1), respectively. Results (Table 7) indicate that the side-baffled ceiling inlet generated a significantly lower velocity mean of 102.0 fpm (31.1 m/min) on the left side as compared to 191.3 fpm (58.3 m/min) on the right side. The velocity mean on the left side for the side-baffled ceiling inlet was also significantly lower than the velocity means obtained on either the left or right sides of the model, when a center-baffled ceiling inlet was used. However, there were no significant differences between velocity means of 147.0 fpm (44.8 m/min) and 159.0 fpm (48.5 m/min) on the right and left positions, respectively, for the center-baffled ceiling inlet. This would indicate that uniform air distribution was accomplished on the right and left sides of the model with a center-baffled ceiling inlet. Furthermore, no significant baffle by

TABLE 7

TUKEY'S PROCEDURE COMPARING BAFFLE BY POSITION AVERAGE VELOCITY MEANS AT SWINE LEVEL, (RIGHT AND LEFT)

Source	Identification			
B X P	B_1P_2	B_2P_2	B_2P_1	B_1P_1
	102.0	147.0	159.0	191.3

5% Level

position interactions were noted in the pit velocity means from the right and left sides or from the front and back of the model. Velocity means from the front and back were also non-significantly affected by baffle, position, or baffle by position interactions. Overall, evidence provided by the analysis of the velocity means at both pit and swine levels indicates that the paramount effect of location of the baffled ceiling inlet is to influence the amount of air flow along the walls above the slatted floor.

Average air velocity data for the system by position and system by baffle by position interaction effects are included in Appendix D, Tables 7, 8, 9, and 10. Even though no significant effects were found, there are several noteworthy trends that should be discussed.

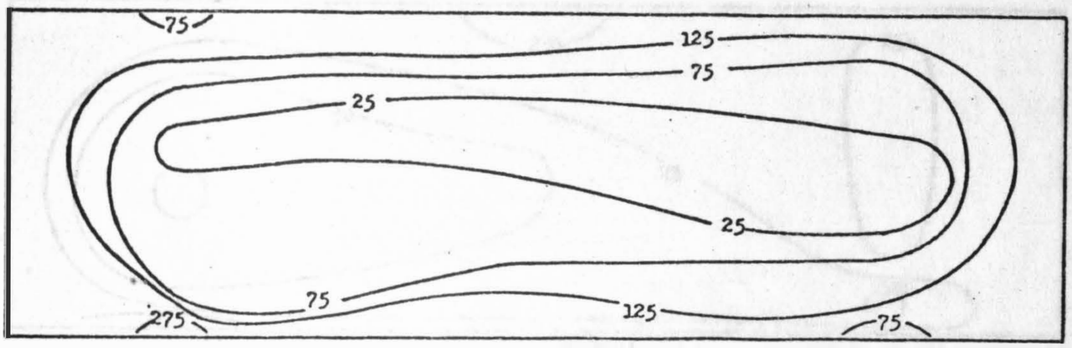
Considering the system by position interaction, velocity means tended to be higher on the right side as compared to the left side of the model at the swine level, when either the outside wall pit ventilator or the hooded manure pit exhaust system provided ventilation of the model. However, the velocity means in the pit were lower on the right side as compared to the left side for the same two systems. The velocity means in the pit for the outside wall pit ventilator were 51.5 and 103.0 fpm (15.7 and 31.4 m/min) for the right and left sides, respectively. At swine level the velocity means equaled 188.3 fpm (57.4 m/min) for the right side and 103.0 fpm (31.4 m/min) on the left side with an outside wall pit ventilator. The hooded manure exhaust system had velocity means equaling 74.0 and 121.0 fpm (22.6 and 36.9 m/min) 195.0 and 123.0

fpm (59.4 and 37.5/m/min) for the right and left sides in the pit and at the swine level, respectively. The distribution of velocity means was the same for both systems. The velocity means in the pit were lower for both systems on the right side of the model opposite the ventilation exhausts. However, above the slatted floor the velocity means were higher on the right side as compared to the left side. This is due to the movement of the ventilation air from the side-baffled ceiling inlet toward the exhaust inlets located on the opposite side of the model. The other three systems had relatively equal velocity means on the right and left sides of the model at both the pit and swine levels. Also, equivalent air flows were noted from the front to the rear of the model for all systems, with the exception of the outside wall pit ventilator, in which system velocity means in the pit decreased from 70.6 fpm (21.5 m/min) in the front to 28.7 fpm (8.7 m/min) at the rear of the model. These uniform air velocities indicate satisfactory ventilation air distribution may be achieved without varying inlet opening area along the ventilation ducts.

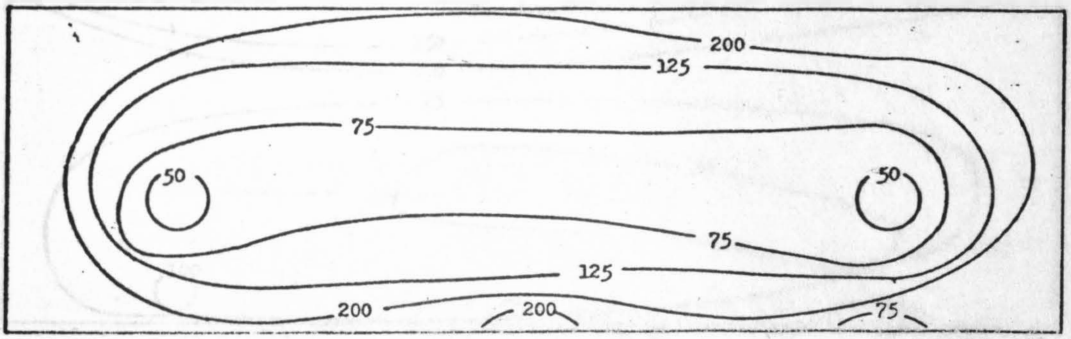
Similar velocity mean patterns were obtained for the system by baffle by position interactions as were found for the system by position interactions. The outside wall pit ventilator and the hooded manure pit exhaust system with a side-baffled ceiling inlet had velocity means in the pits ranging from 48.3 to 100.0 fpm (14.7 to 30.5 m/min) and 84.3 to 143.3 fpm (25.7 to 43.7 m/min) for the right and left sides, respectively. When a center-baffled ceiling inlet was utilized, the velocity means in the pit for the right and left sides equaled 55.0 fpm (16.8 m/min) and 106.7 fpm (32.5 m/min) for the outside wall pit ventilator, and 65.0 (19.8 m/min) and 100.0 fpm (30.5 m/min) for the hooded manure pit exhaust system. At swine level the velocity means were considerably higher on the right side than the left side. These results correspond well with the results from the system by position interactions which indicated that velocity means in the pit were much lower on the right side as compared to the left side, while above the slatted floor the velocity means were higher on the right side of the model. Unequal velocity means of 200.0 fpm versus 88.3 fpm (61.0 m/min versus 26.9 m/min) were noted for the right and left sides at the swine level, when the centered duct pit ventilator with a side-baffled ceiling inlet provided air movement within the model. However, distribution of velocity means was approximately equal on the right and left sides at both pit and swine levels, when a center-baffled ceiling inlet was used instead of the side-baffled ceiling inlet. Velocity means between the front and rear of the model were quite consistent for all systems with the exception of the outside wall pit ventilator used with the center-baffled ceiling inlet. For this combination velocity means decreased from 93.7 fpm (28.6 m/min) to 27.5 fpm (8.4 m/min) from the front to the back of the model. This indicates that the outside wall pit ventilator should have a variable inlet area if adequate air flow distribution from the front to the rear of the model is to be achieved.

Iso-velocity lines for the five systems, using side- and center-baffled ceiling inlets, at the pit and swine levels are illustrated in Figures 13 through 17. The iso-velocity lines are presented to help indicate which system and baffle arrangement produced the most desirable air velocity distributions in the model.

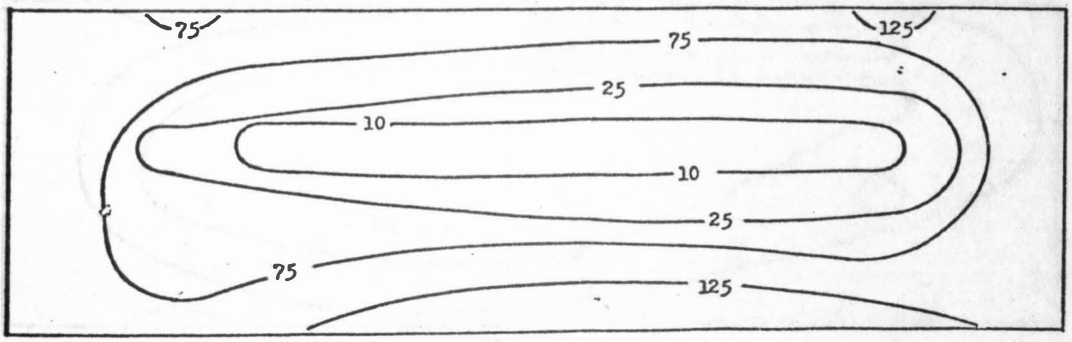
Unequal air distribution was noted above the slatted floor, when a side-baffled ceiling inlet was combined with either a centered duct pit ventilator, outside wall pit ventilator, hooded manure pit exhaust, or pressurized ventilator systems, Figures 14b, 15b, 16b, and 17b, respectively. Air velocities tended to be higher for these systems along the side wall adjacent to the side-baffled ceiling inlets. The slotted pipe under-slat ventilator with a side-baffled ceiling inlet (Figure 13b) generated quite uniform air velocity patterns. Velocities tended to range from 200 fpm (61.0 m/min) along each side wall to 75 fpm (23.9 m/min) near the center of the model. The center-baffled ceiling inlet combined with either a slotted pipe under-slat ventilator (Figure 13d) or a centered duct pit ventilator (Figure 14d) system achieved relatively even velocity distribution above the slatted floor. The velocities equaled 150 fpm (45.7 m/min) along the walls and decreased quite uniformly to 75 fpm (22.9 m/min) at the center of the model for the slotted pipe under-slat ventilator. Correspondingly, the velocities along the wall were 175 fpm (53.3 m/min) for the centered duct pit ventilator and the velocities near the center of the model were 75 fpm (22.9 m/min). Iso-velocity lines at swine level for the outside wall pit ventilator (Figure 15d) and



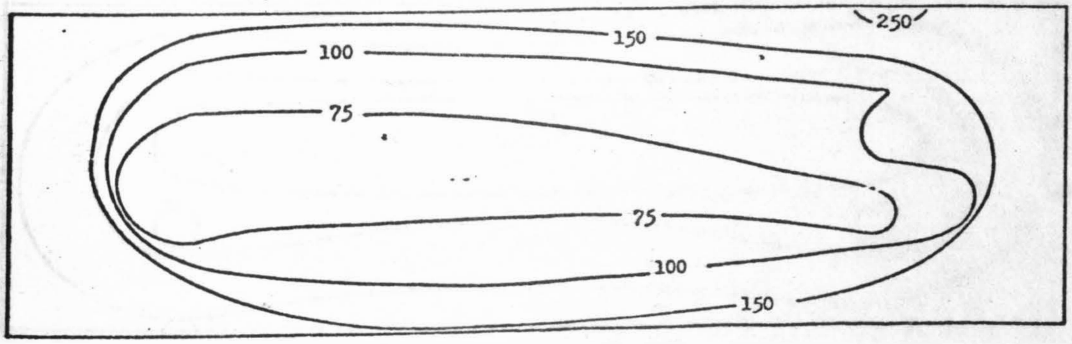
a. Pit level (Side Baffle)



b. Swine level (Side Baffle)

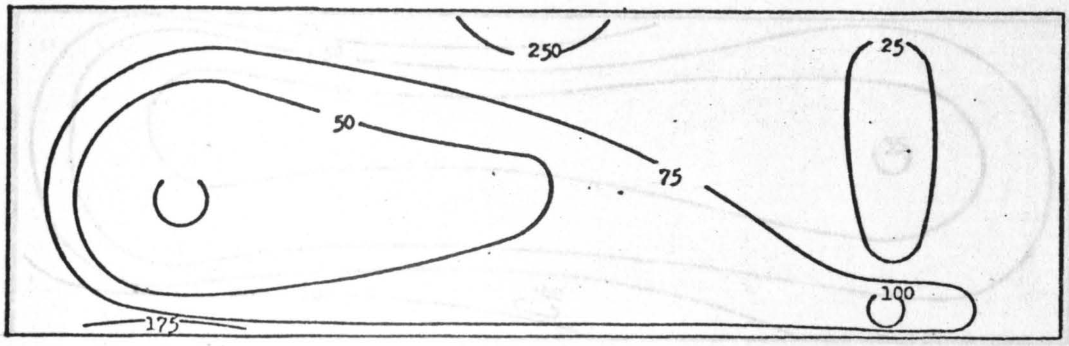


c. Pit level (Center Baffle)

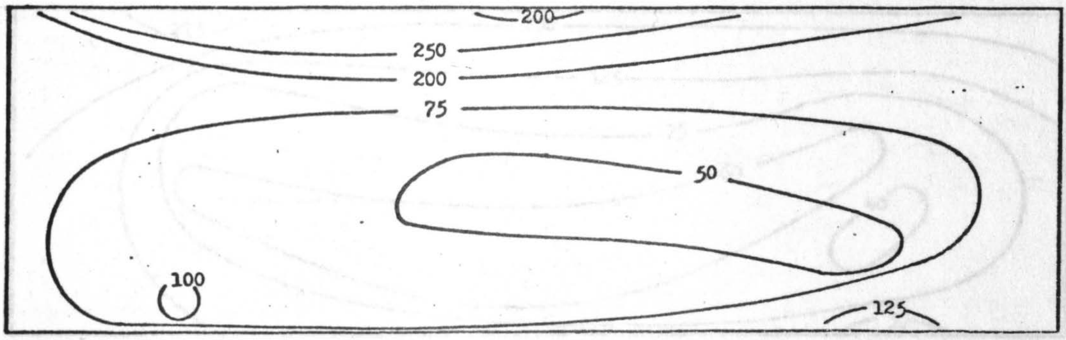


d. Swine level (Center Baffle)

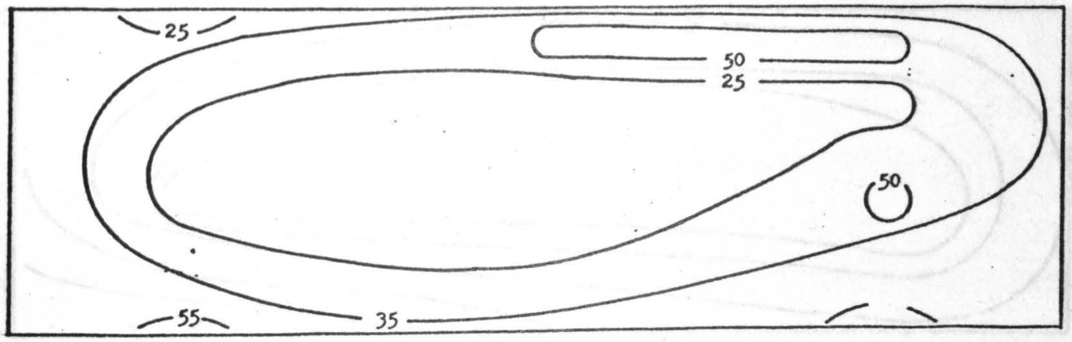
Figure 13. Iso-velocity lines for slotted pipe under-slat ventilator (velocities in fpm).



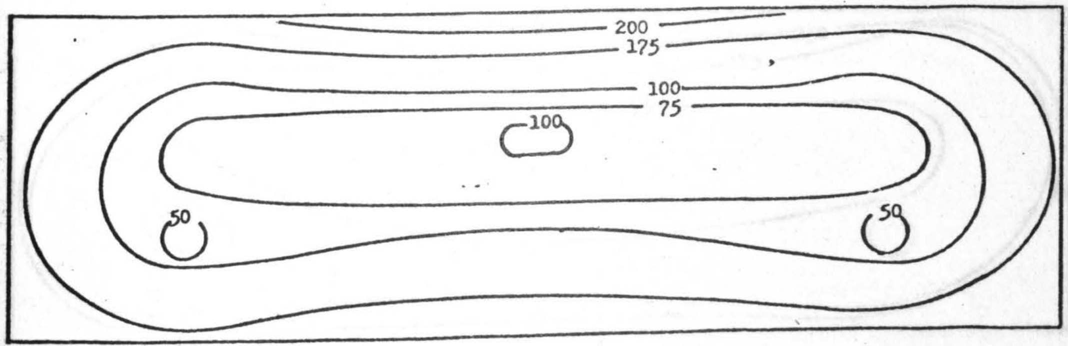
a. Pit level (Side Baffle)



b. Swine level (Side Baffle)

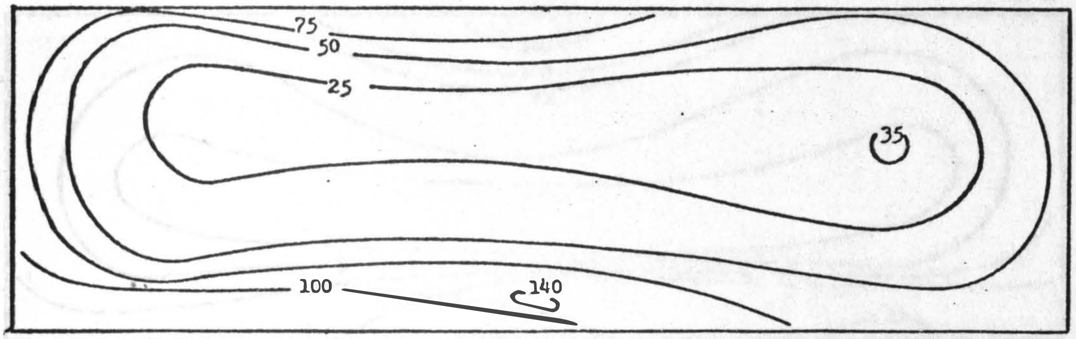


c. Pit level (Center Baffle)

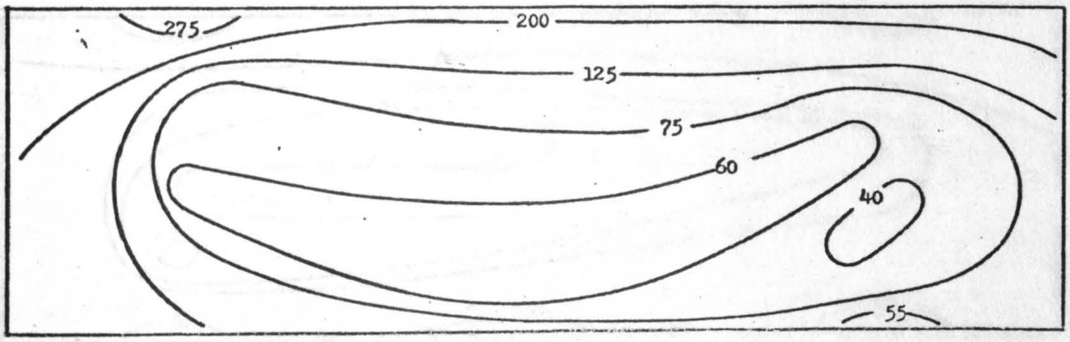


d. Swine level (Center Baffle)

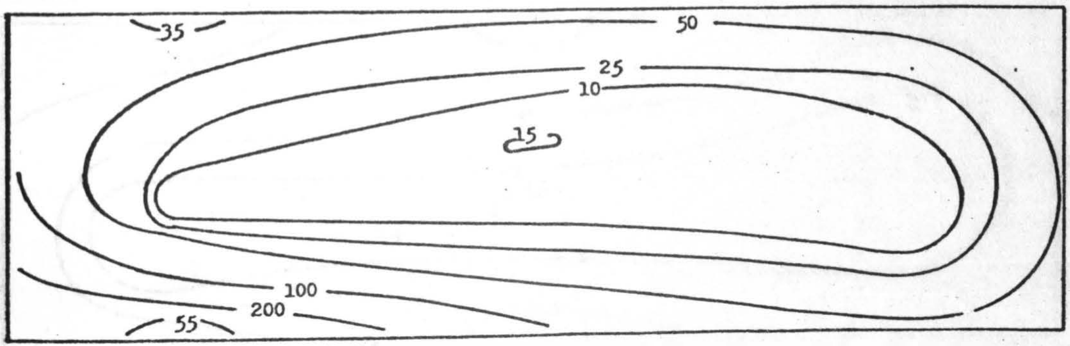
Figure 14. Iso-velocity lines for centered duct pit ventilator (velocities in fpm).



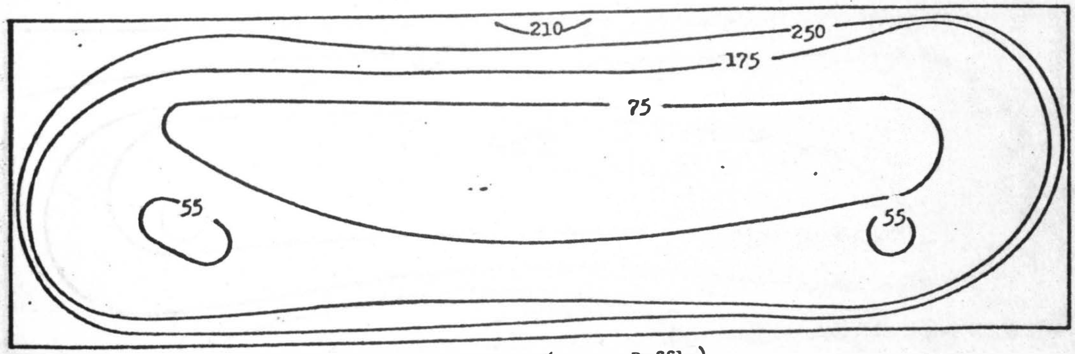
a. Pit level (Side Baffle)



b. Swine level (Side Baffle)

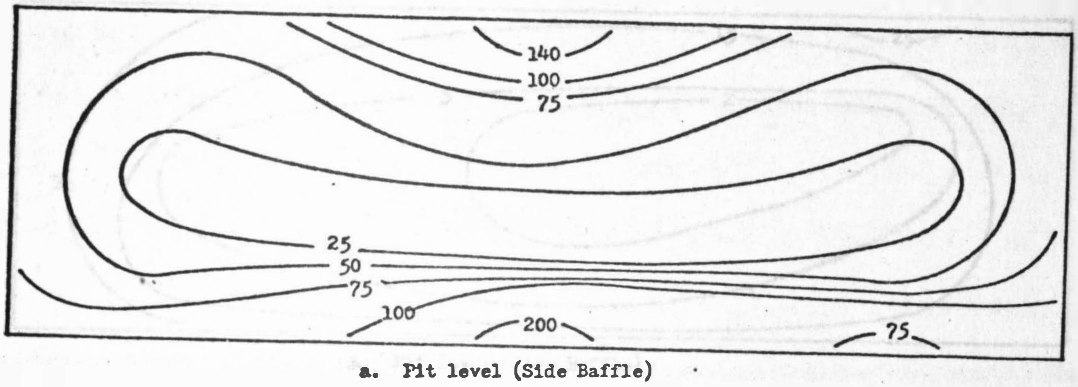


c. Pit level (Center Baffle)

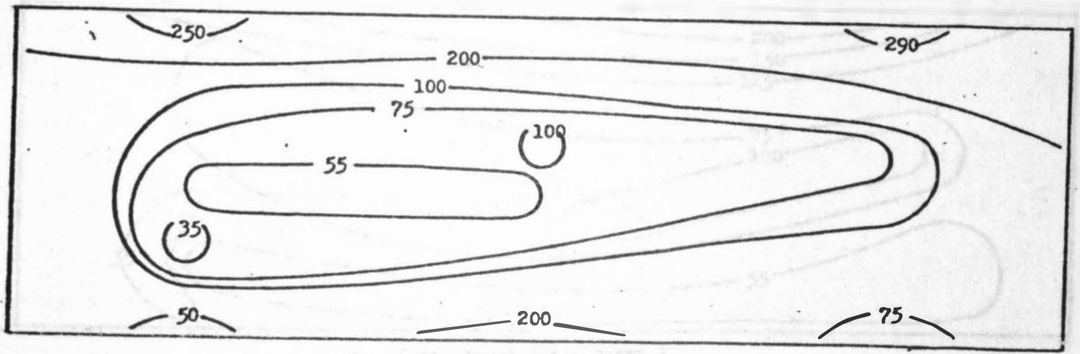


d. Swine level (Center Baffle)

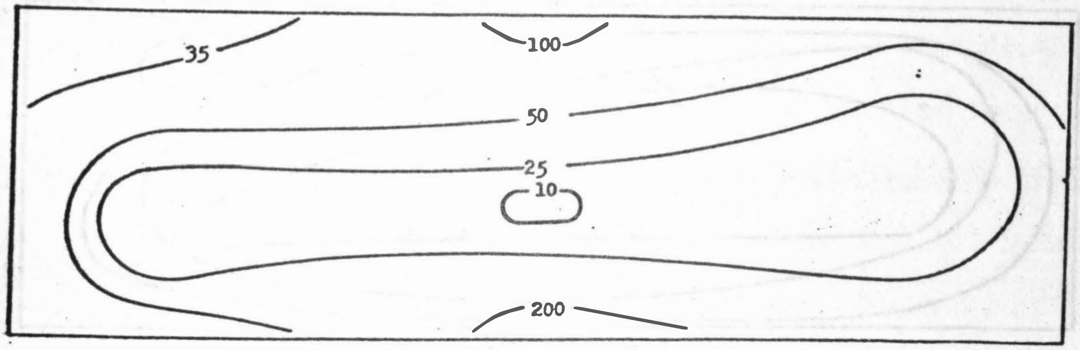
Figure 15. Iso-velocity lines for outside wall pit ventilator (velocities in fpm).



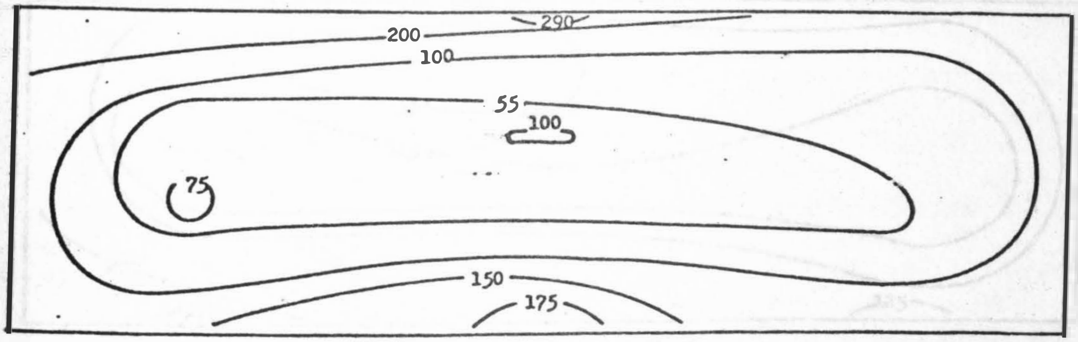
a. Pit level (Side Baffle)



b. Swine level (Side Baffle)

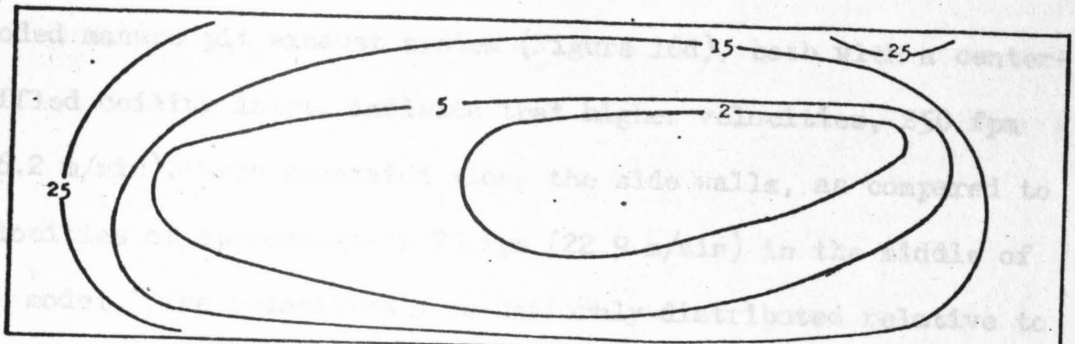


c. Pit level (Center Baffle)

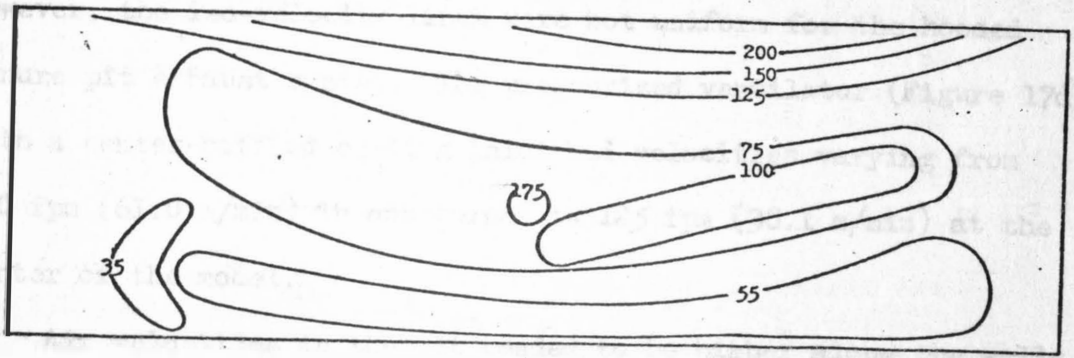


d. Swine level (Center Baffle)

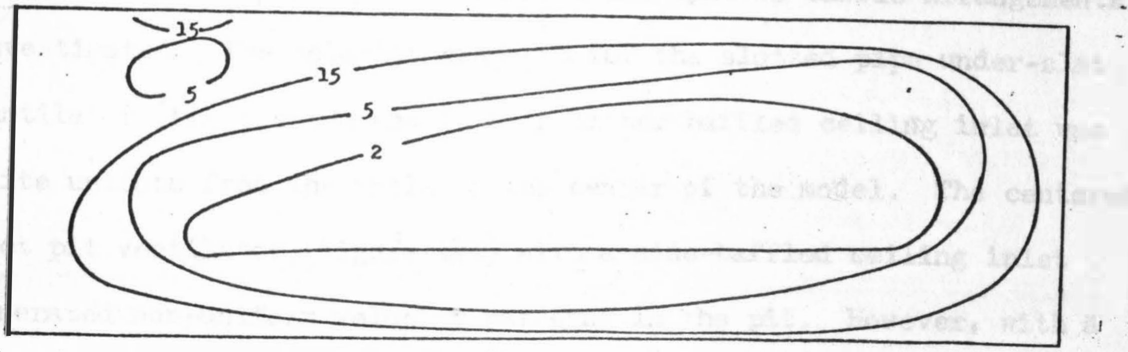
Figure 16. Iso-velocity lines for hooded manure pit exhaust system (velocities in fpm).



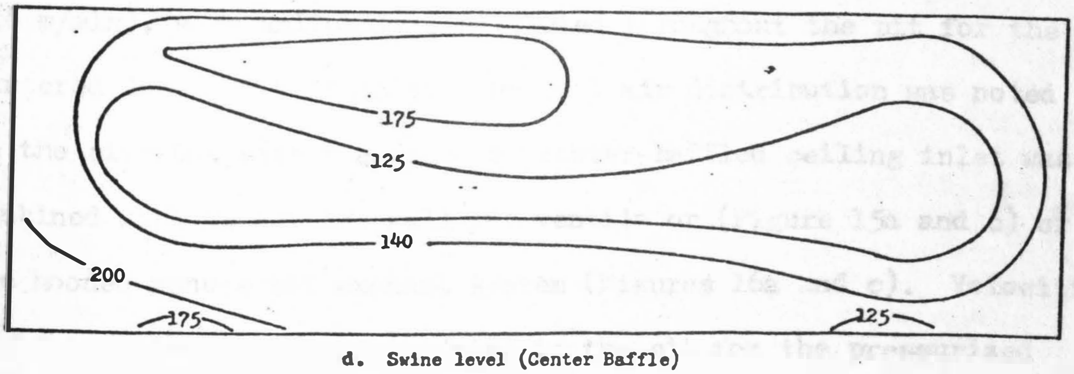
a. Pit level (Side Baffle)



b. Swine level (Side Baffle)



c. Pit level (Center Baffle)



d. Swine level (Center Baffle)

Figure 17. Iso-velocity lines for pressurized ventilator system (velocities in fpm).

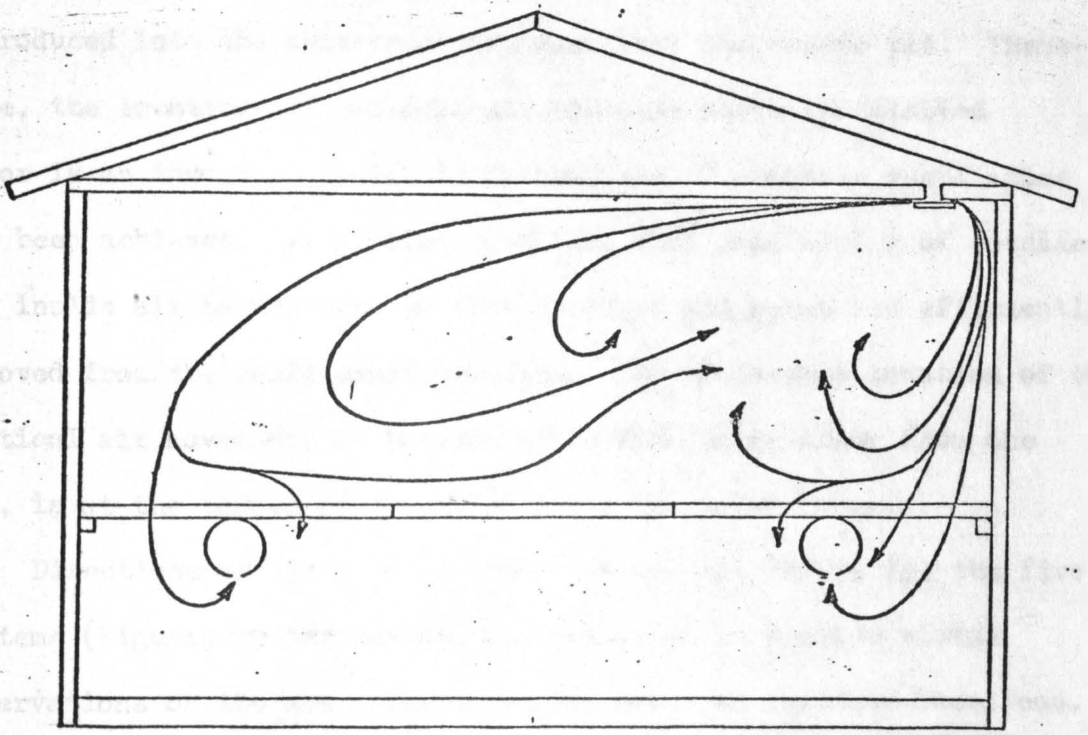
hooded manure pit exhaust system (Figure 16d), both with a center-baffled ceiling inlet, indicate that higher velocities, 250 fpm (76.2 m/min), were generated along the side walls, as compared to velocities of approximately 75 fpm (22.9 m/min) in the middle of the model. The velocities were uniformly distributed relative to location above the slatted floor for the outside wall pit ventilator. However, the iso-velocity lines were not uniform for the hooded manure pit exhaust system. The pressurized ventilator (Figure 17d) with a center-baffled ceiling inlet had velocities varying from 200 fpm (61.0 m/min) in one corner to 125 fpm (38.1 m/min) at the center of the model.

Air velocities in the pit tended to be higher along the walls than near the center of the model for all systems baffle arrangements investigated. The velocity gradient for the slotted pipe under-slat ventilator (Figures 13a and c) with either baffled ceiling inlet was quite uniform from the walls to the center of the model. The centered duct pit ventilator (Figure 14a) with a side-baffled ceiling inlet generated non-uniform velocity patterns in the pit. However, with a center-baffled ceiling inlet the velocities, (50 to 25 fpm) (15.2 to 7.6 m/min), were uniformly distributed throughout the pit for the centered duct pit ventilator. Unequal air distribution was noted in the pit when either a side- or center-baffled ceiling inlet was combined with an outside wall pit ventilator (Figure 15a and c) or the hooded manure pit exhaust system (Figures 16a and c). Velocities of 15 to 2 fpm (4.6 to 0.6 m/min) in the pit for the pressurized ventilator system were quite low as compared to the velocities for the other four systems, but the velocity distribution was relatively uniform throughout the pit.

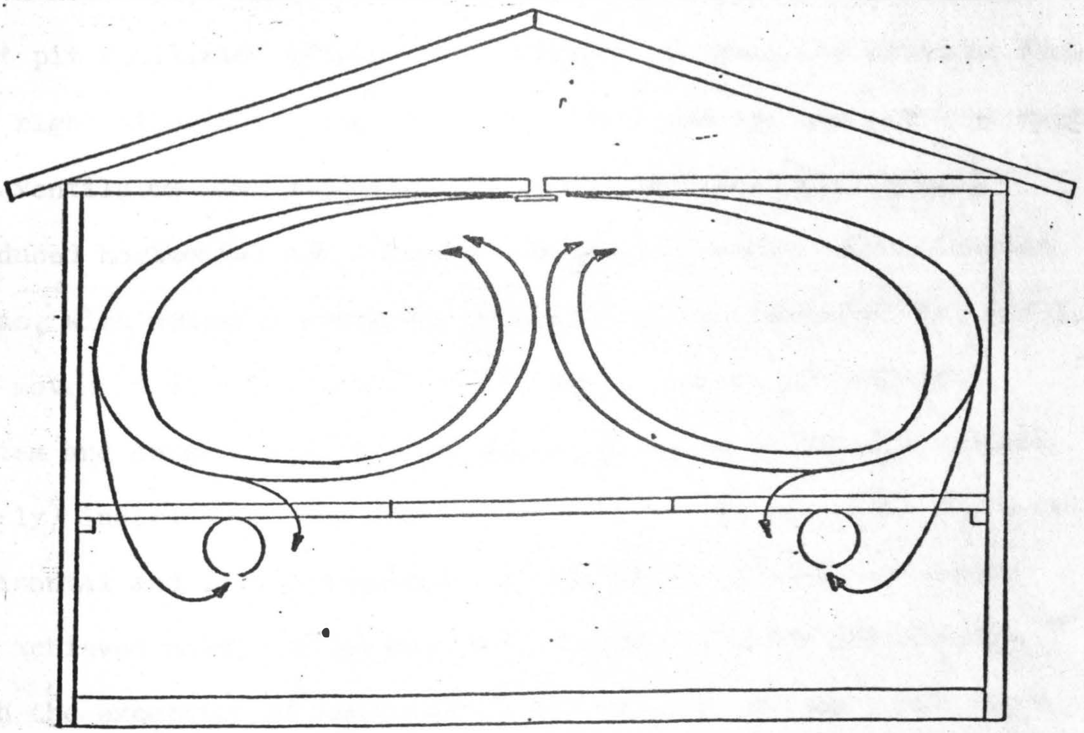
Overall, for all systems and levels investigated, the air flow velocities were higher along the side walls than near the center of the model. The slotted pipe under-slat ventilator and the centered duct pit ventilator, along with a center-baffled ceiling inlet, had the most uniform air flows relative to location throughout the model. Unequal air velocity distribution was noted for the outside wall pit ventilator and hooded manure pit exhaust system with either baffle at both pit and swine levels. Also, the pressurized ventilator system with a side-baffled ceiling inlet had relatively unequal velocity distribution at the swine level.

Air Flow Patterns

Air flow patterns illustrating air movement above and through the slatted floor in the model with the slotted pipe under-slat ventilator and both baffled ceiling inlet arrangements are presented in Figure 18. These illustrations (Figure 18) are representative of air patterns observed in the other four systems. Air was directed horizontally along the ceiling from the baffled inlet, down the side wall, across the slatted floor until it encountered the air from the opposite side and then air movement was upwards toward the ceiling. This vertical movement of air was noted at several locations along the length of the model. Horizontal or downward movement of air is essential to insure that gases and odors are not



a. Side Baffle



b. Center Baffle

Figure 18. Air flow patterns comparing side and center baffles for slotted pipe under-slat ventilator.

introduced into the swine's environment from the manure pit. Therefore, the locations of vertical air movement above the slatted floor is an important factor in determining if adequate ventilation has been achieved. It is also essential that good mixing of outside and inside air be achieved so that moisture and gases are efficiently removed from the confinement building. The preferable location of the vertical air movement, to prevent gases from being drawn from the pit, is at the center of the model above the solid floor.

Directions of air flow at the swine and pit levels for the five systems (Figures 19 through 26) are presented to provide visual observations of the air movement in the model at selected locations. Upward air movement was noted for all locations at swine level for the slotted pipe under-slat ventilator (Figure 19). The centered duct pit ventilator (Figure 20) generated vertical air movement from the right side to the center of the model. However, a centered duct pit ventilator with a center-baffled ceiling inlet (not shown) produced horizontal and downward air movement across both occupied areas, with updrafts occurring primarily at the center of the model. Air movement at swine level for the hooded manure pit exhaust system and outside wall pit ventilator (Figures 21 and 23, respectively) indicate vertical movement of air at the center of the model. Horizontal and downward movement of air across the slatted floor was achieved using the pressurized ventilator system (Figure 22), with the exception of some slight, but vertical air movement above the slatted floor on the left side.

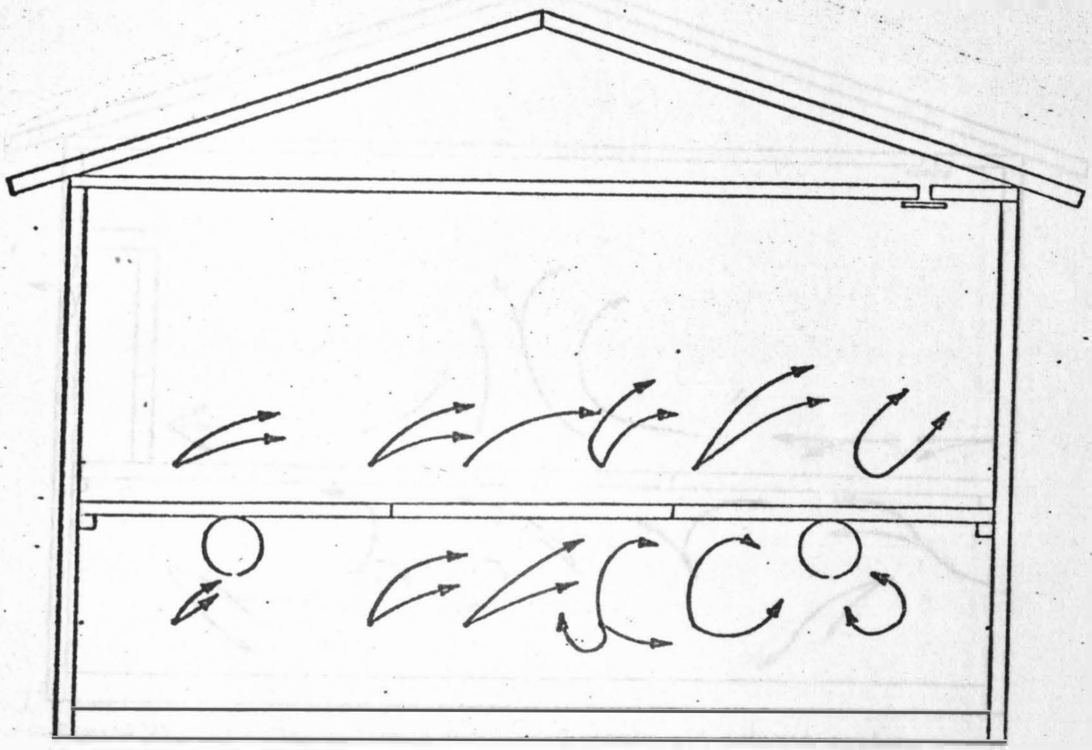


Figure 19. Air flow patterns for slotted pipe under-slat ventilator, center location.

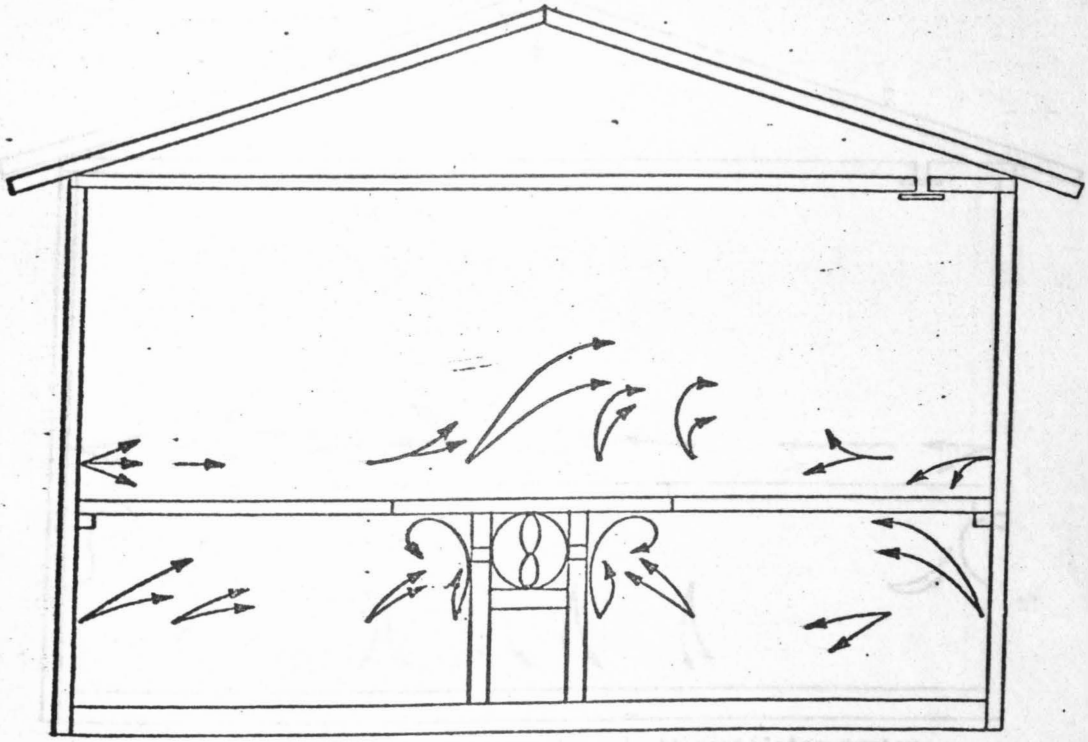


Figure 20. Air flow patterns for centered duct pit ventilator, center location.

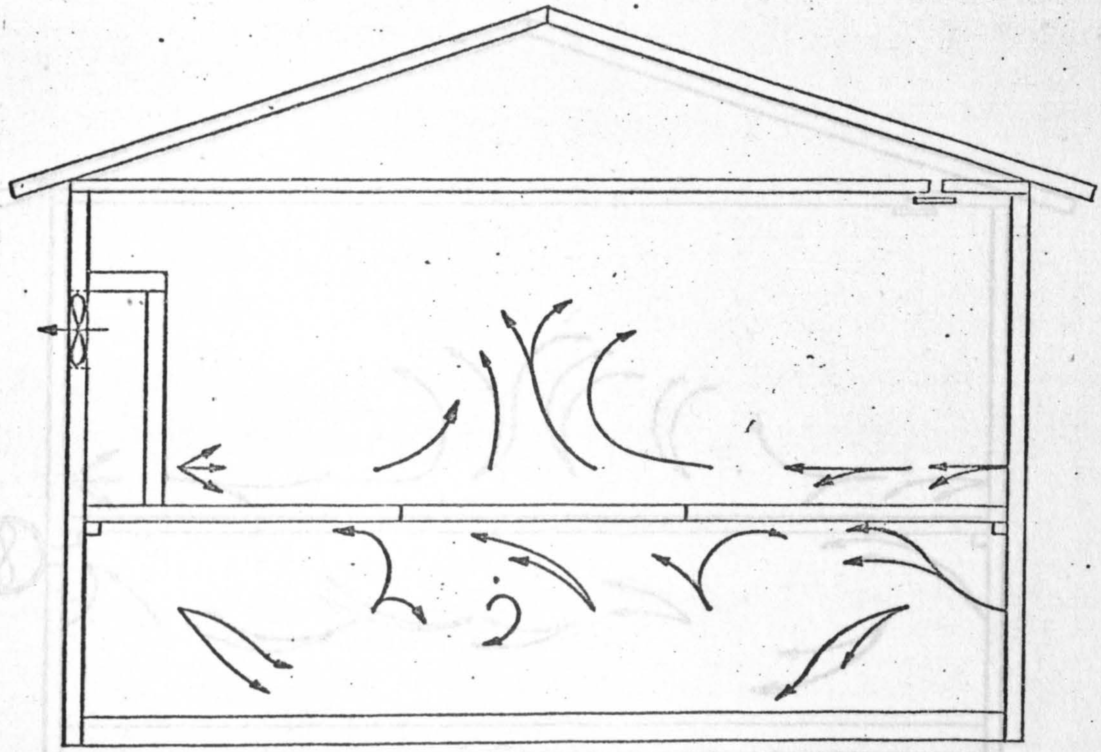


Figure 21. Air flow patterns for hooded manure pit exhaust system, center location.

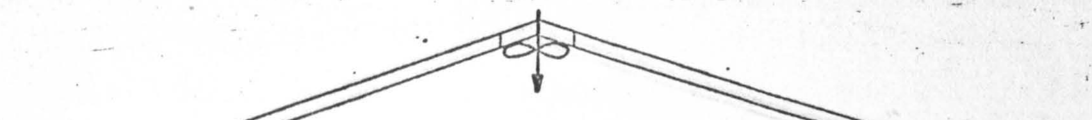


Figure 22. Air flow patterns for pressurized pit ventilator system, center location.

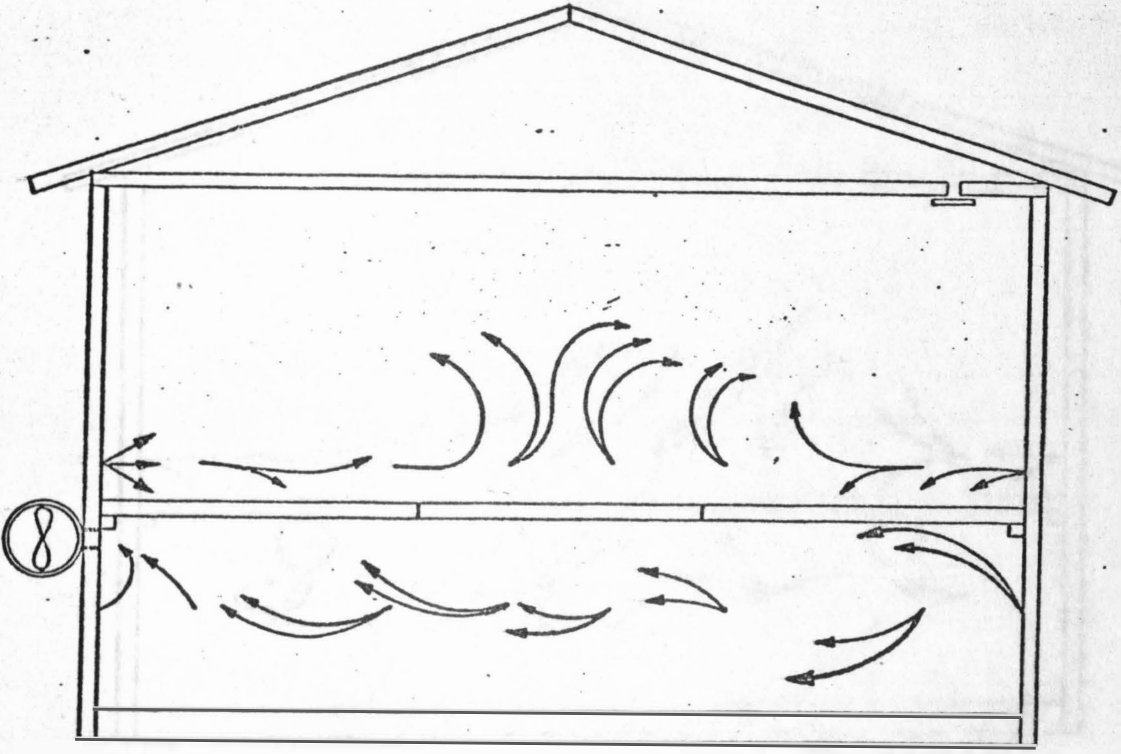


Figure 23. Air flow patterns for outside wall pit ventilator system, side baffle, center location.

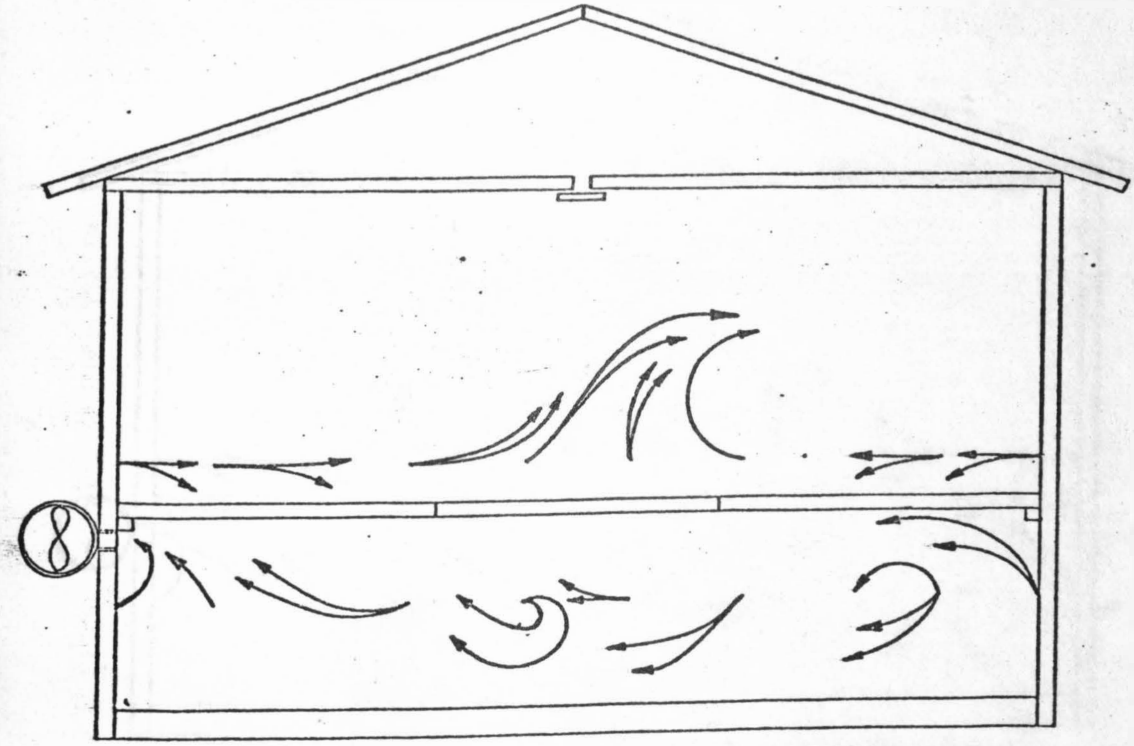


Figure 24. Air flow patterns for outside wall pit ventilator system, center baffle, center location.

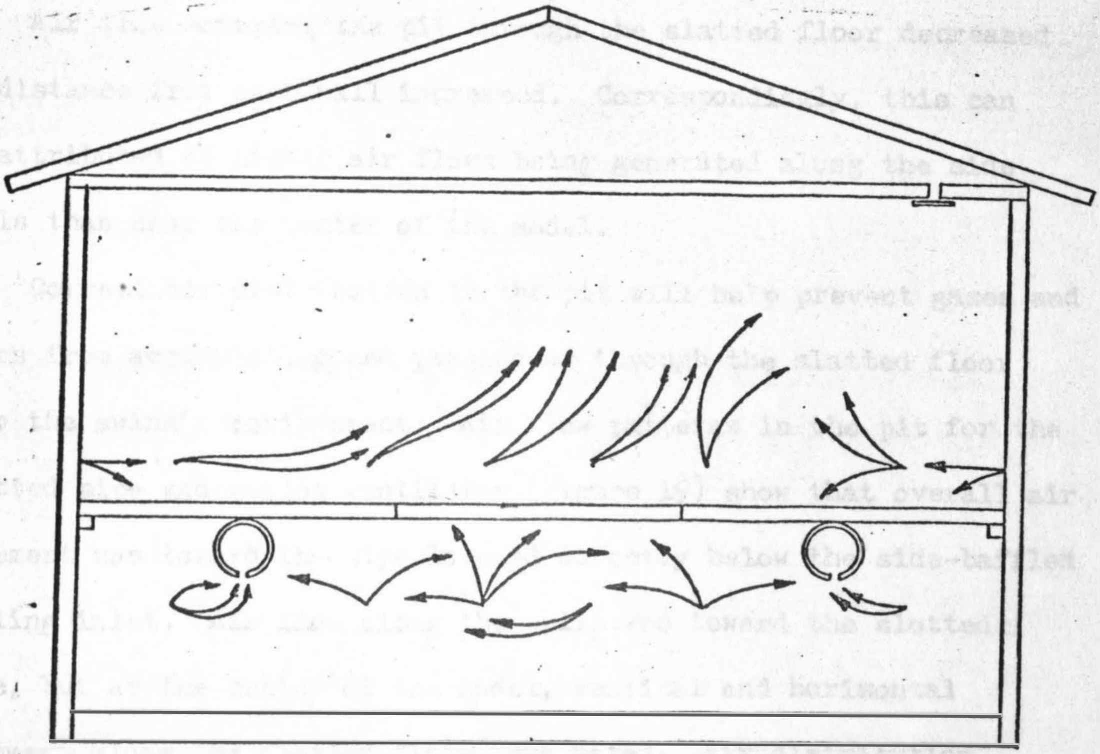


Figure 25. Air flow patterns for slotted pipe under-slat ventilator, rear location.

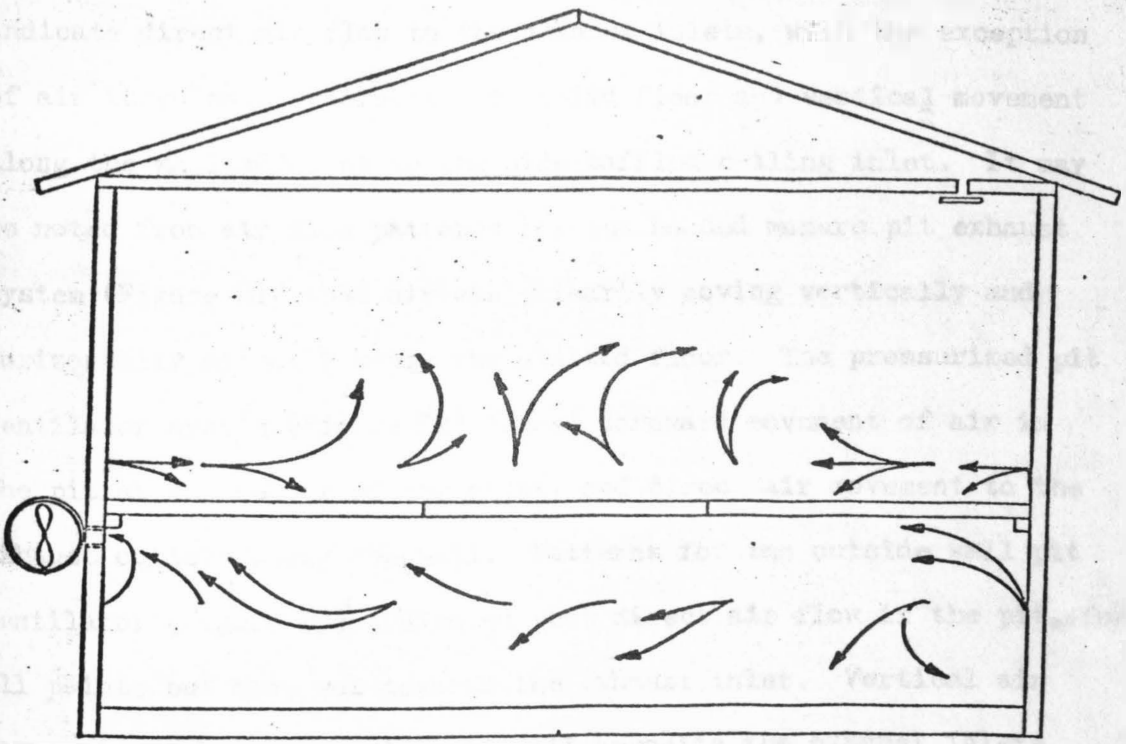


Figure 26. Air flow patterns for outside wall pit ventilator, rear location.

Air flow entering the pit through the slatted floor decreased as distance from each wall increased. Correspondingly, this can be attributed to higher air flows being generated along the side walls than near the center of the model.

Correct air distribution in the pit will help prevent gases and odors from accumulating and passing up through the slatted floor into the swine's environment. Air flow patterns in the pit for the slotted pipe under-slat ventilator (Figure 19) show that overall air movement was toward the pipe located directly below the side-baffled ceiling inlet. Air flow along the walls was toward the slotted pipe, but at the center of the model, vertical and horizontal movement along the slatted floor were noted. Air distribution patterns in the pit for the centered duct pit ventilator (Figure 20) indicate direct air flow to the exhaust inlets, with the exception of air turbulence underneath the solid floor and vertical movement along the wall adjacent to the side-baffled ceiling inlet. It may be noted from air flow patterns for the hooded manure pit exhaust system (Figure 21) that air was primarily moving vertically and horizontally directly below the slatted floor. The pressurized pit ventilator system (Figure 22) forced downward movement of air in the pit at the center of the model, and direct air movement to the exhaust outlets along the wall. Patterns for the outside wall pit ventilator (Figure 23) indicated that direct air flow in the pit, for all points but one, was towards the exhaust inlet. Vertical air movement was noted near the pit wall opposite the exhaust inlets.

Comparisons between the side- and center-baffled ceiling inlets (Figures 23 and 24) for the outside wall pit ventilator indicates a minimal amount of difference between air flow patterns. Also, comparisons of air flow patterns between the center and the rear of the model for the slotted pipe under-slat ventilator and outside wall pit ventilator (Figures 19 and 25) and (Figures 23 and 26), respectively, showed little difference, with the exception that more turbulence was generated at the rear of the model for the slotted pipe under-slat ventilator.

Evacuation Time

Evacuation times (Appendix D, Tables 11 and 12) were determined using model ventilation flow rates based on both Reynolds Number (high air flow) and Froude Number (low air flow). For both flow rates pit ventilator design significantly affected the time required to produce an air change in the model. The results will be presented for evacuation times determined using flow rates based on N_{RE} and for evacuation times based on N_{FR}.

The average evacuation time means were 11.5, 12.6, 13.3, 14.3, and 15.8 seconds for the pressurized ventilator system (S_5), outside wall pit ventilator (S_3), centered duct pit ventilator (S_2), hooded manure pit exhaust system (S_4) and the slotted pipe under-slat ventilator (S_1) systems, respectively, when Reynolds number determined the velocity scale. The average evacuation time for the pressurized ventilator system was significantly lower than the evacuation times obtained from either the hooded manure pit exhaust system or the slotted pipe under-slat ventilator (Table 8). Also, the slotted pipe under-slat ventilator produced significantly higher evacuation times than those recorded for the outside wall pit ventilator and the centered duct pit ventilator.

TABLE 8

TUKEY'S PROCEDURE COMPARING AVERAGE EVACUATION TIME MEANS, (REYNOLDS NUMBER)

Source	Identification				
Evacuation Times (Sec.)	S_5	S_3	S_2	S_4	S_1
	11.4	12.6	13.3	14.3	15.8
				———	———
		———	———	———	
	———	———	———		

5% Level

Average evacuation times obtained when Froude number was used to determine the velocity scale were 201.3, 207.3, 215.0, 229.0, and 231.7 seconds for the hooded manure pit exhaust system (S_4), pressurized ventilator system (S_5), centered duct pit ventilator (S_2), slotted pipe under-slat ventilator (S_1), and outside wall pit ventilator (S_3) systems, respectively. Results (Table 9) indicated that the hooded manure pit exhaust system and the pressurized ventilator system had significantly lower average evacuation times than the slotted pipe under-slat ventilator and the outside wall pit ventilator.

TABLE 9

TUKEY'S PROCEDURE COMPARING AVERAGE EVACUATION TIME MEANS, (FROUDE NUMBER)

Source	Identification				
Evacuation Times (Sec.)	S_4	S_5	S_2	S_1	S_3
	201.3	207.3	215.0	229.0	231.7

5% Level

Dissimilar mean rankings were obtained for evacuation times determined using Reynolds and Froude numbers for establishing the air flow rates. The pressurized ventilator system provided the fastest and most desirable evacuation time at the high air flow rate (N_{RE}), while the hooded manure pit exhaust system provided the fastest evacuation time of low air flow rate (N_{FR}). Correspondingly, the slowest evacuation times were recorded for the slotted pipe under-slat ventilator system at high air flow and for the outside wall pit ventilator system at low air flow. The centered duct pit ventilator system had the intermediate evacuation time for both air flow rates. Difficulties were encountered in accurately introducing a constant amount of smoke at the lower flow rate. Therefore, more confidence is associated with the accuracy of the data based on Reynolds Number.

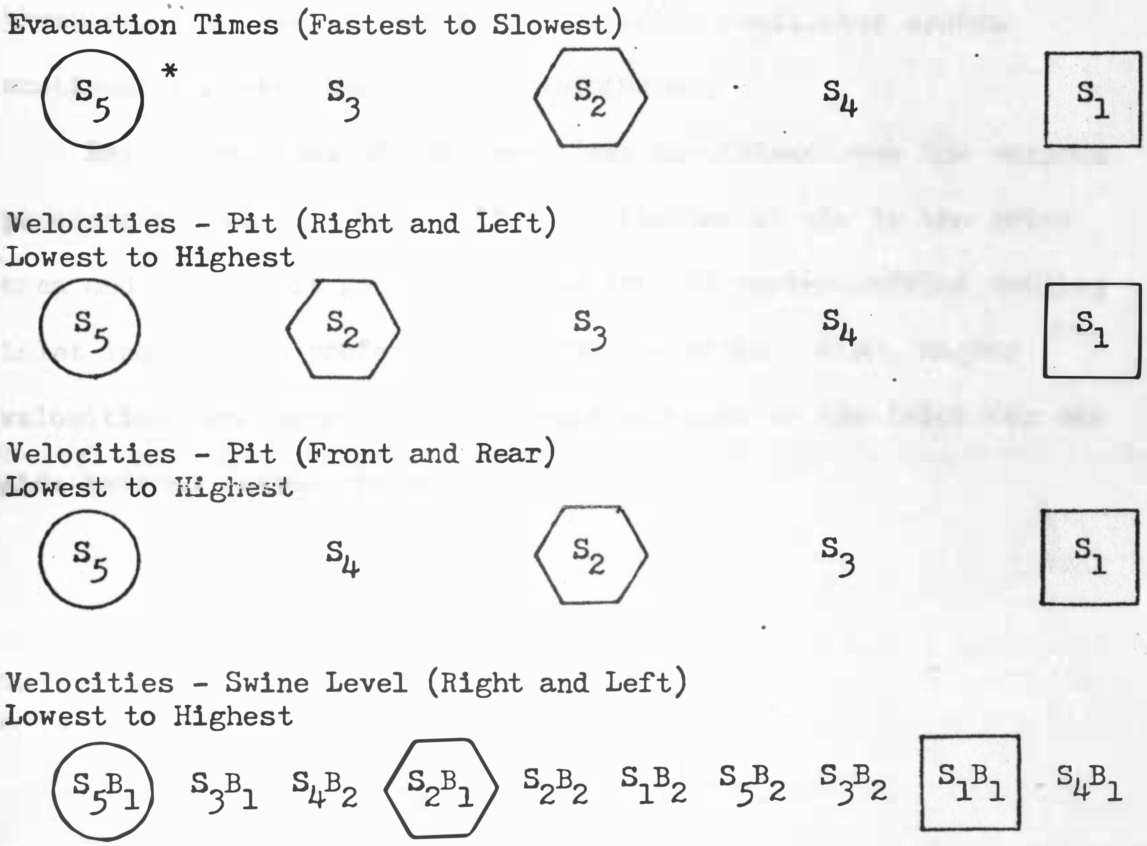
Overall Ventilation Performance

Research results have been presented for several of the individual performance criteria normally used to evaluate ventilation system performance. However, it is the composite of factors such as air flow velocities and patterns and evacuation time that establish the ventilation characteristics of a particular system. The results presented under the various headings and at the various points within the structure do not provide a clear indication of which is the optimum system. Several of the most important characteristics in terms of proper engineering design are evident, when the individual ventilation performance criteria are evaluated as an integral unit. It is emphasized that the results presented are for a model and do reflect the limitations of no heat and moisture production in the building as was established in the original design of the study.

Table 10 illustrates the ranking of the following ventilation performance means: evacuation time, air velocities in the pit (front and left sides), air velocities in the pit (front and back of the building) and air velocities (front and back) for selected ventilation system designs. Assuming that a fast evacuation time, combined with low air flow rates at swine level and in the pit, are desirable, the pressurized ventilator system (S_5) gave the best response. This system also had very good air flow patterns in that there was little existence of air being moved from the pit into the livestock confinement area. The centered duct pit ventilator ranked second best based on these criteria: air velocity distribution was

TABLE 10

RANKING OF VENTILATION CHARACTERISTIC MEANS



Evacuation Times (Fastest to Slowest)

S_5 * S_3 S_2 S_4 S_1

Velocities - Pit (Right and Left)
Lowest to Highest

S_5 S_2 S_3 S_4 S_1

Velocities - Pit (Front and Rear)
Lowest to Highest

S_5 S_4 S_2 S_3 S_1

Velocities - Swine Level (Right and Left)
Lowest to Highest

S_5B_1 S_3B_1 S_4B_2 S_2B_1 S_2B_2 S_1B_2 S_5B_2 S_3B_2 S_1B_1 S_4B_1

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*Individual ventilator systems enclosed with like geometric patterns.

quite uniform throughout the model and the air flow patterns indicated that proper ventilation was achieved. High evacuation time and poor air flow patterns were obtained when a slotted pipe under-slat ventilator (S_1) provided ventilation of the model. For these criteria the slotted pipe under-slat ventilator system continually showed the poorest performance. .

Baffle position effects were less consistent over the various parameters studied. The better distribution of air in the swine area and in the pit generally noted for the center-baffled ceiling inlet indicates a preference for that location. Also, higher velocities were noted along the wall adjacent to the inlet for the side-baffled ceiling inlet.

CONCLUSIONS

The following conclusions were indicated by this study:

1. Pit ventilation system design has a significant effect on average air flow velocities in the pit, with the pressurized pit ventilator system consistently generating lower velocities in the pit than those generated by the other four systems.
2. Pit ventilation system geometry has no significant effect on average air flow velocities above the slatted floor.
3. The significant differences noted in velocity means indicate a need for considering the placement of the baffled ceiling inlet with respect to ventilation system location, if proper ventilation characteristics are to be obtained.
4. The location of the baffled ceiling inlet influences the amount of air flow along the walls above the slatted floor.
5. Uniform air velocities from the front to the rear of the model were obtained for all systems tested with the exception of the outside wall pit ventilator. This indicates that satisfactory ventilation air distribution may be accomplished without varying inlet opening area along the ventilation ducts.
6. Air velocity distribution was relatively uniform at pit and swine levels for the slotted pipe under-slat ventilator, the centered duct pit ventilator, and pressurized pit ventilator

system, used with the center-baffled ceiling inlets. However, non-uniform air flows were noted for the outside wall pit ventilator and hooded manure pit exhaust system with either baffle position at both pit and swine levels.

7. Air flow patterns were adequate at both levels for the centered duct pit ventilator, pressurized ventilator system, and the outside wall pit ventilator, and inadequate for the slotted pipe under-slat ventilator and hooded manure pit exhaust system.
8. Ventilation system design significantly affected the time required to produce an air change in the model.
9. The pressurized ventilator system and the hooded manure pit exhaust system had the shortest evacuation times at air flow rates derived from Reynolds and Froude numbers, respectively. The highest evacuation times were recorded for the slotted pipe under-slat ventilator and outside wall pit ventilator for Reynolds and Froude numbers, respectively.
10. Results obtained, when Reynolds number determined air flow rate are considered to be more accurate than those from Froude number, because of difficulties in trying to introduce a constant amount of smoke into the model at the lower air flow rate.
11. The composite results of the data obtained from air flow velocities and patterns and evacuation times indicate that

the pressurized ventilator system and the centered duct pit ventilator provided the best ventilation characteristics in the model, with the slotted pipe under-slat ventilator producing the poorest ventilation characteristics.

SUMMARY

The trend in swine production is toward increased use of confinement buildings to improve environmental conditions, reduce labor, land, and bedding costs, and broaden the producer's management capabilities. An aspect of environmental control is the removal of gases and odors from the manure storage tanks located underneath the slatted floor. A number of manure pit ventilation systems have been employed, but have had limited success. Therefore, a model study of pit ventilation system design on ventilation characteristics was conducted.

Employing the principles of similitude, 17 dimensionless groups (Pi terms) were established describing the fluid properties and the building geometry of a model of a total confinement swine finishing unit. Comparisons of winter ventilation characteristics and evacuation times were conducted with five manure pit ventilation systems. Analyses of variance and Tukey's procedure were used to analyze air flow velocities and evacuation times. Air flow velocity distribution and air flow patterns were analyzed with iso-velocity lines and visual observations, respectively.

Results indicated that pit ventilation system design has a significant effect on average air flow velocities in the pit, but not at swine level. Also, pit ventilation system location with respect to baffle ceiling inlet arrangement is important in developing proper ventilation design.

Satisfactory air velocity distribution was achieved from the front to the back of the model for all pit ventilation systems with the exception of the outside wall pit ventilator. Relatively uniform air velocity flows were found in the model for the pressurized pit ventilator system, the centered duct pit ventilator, and the slotted pipe under-slat ventilator, when used with a center-baffled ceiling inlet. The centered duct pit ventilator and pressurized pit ventilator system also generated suitable air flow patterns in the model.

The fastest evacuation times were recorded using the pressurized pit ventilator system and the hooded manure pit exhaust system based on ventilation rates established by Reynolds and Froude numbers, respectively. However, evacuation times were considered to be more accurate, when air flow rates were determined by Reynolds number.

The pressurized pit ventilator system had the best overall ventilation performance of all models tested, with the centered duct pit ventilator also providing adequate ventilation characteristics. Poor ventilation characteristics were noted for the slotted pipe under-slat ventilator.

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APPENDIXES

APPENDIX A

LIST OF SYMBOLS

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A_v = Ventilator intake area
B_i = Baffle positioning
B_w = Baffle slot width
cfm = Cubic feet per minute
cm = Centimeter
D_p = Vent pipe diameter
fpm = Feet per minutes
g = Acceleration of gravity
h_c = Ceiling height
h_p = Pit depth, ft.
I. D. = Inside diameter
l = Building length
L_o = Slot length
L_p = Vent pipe length
L_s = Slat length
m = Subscript, designates the model system
m/min = Meters per minute
m^3/min = Cubic meters per minute
N_{FR} = Froude number
N_{RE} = Reynolds number
n = Geometric length scale
P_i = Position relative to model location
Q_m = Volume flow rate of model, cfm

Q_p = Volume flow rate of prototype, cfm

r = Roughness factor of vent pipe

S_i = Ventilation system

s = Roof slope

T = Evacuation time

V = Velocity of air

w = Building width

w_o = Slot width

w_s = Slat width

W_{sp} = Vent pipe slot width

μ = Dynamic viscosity of inside air

π_i = i^{th} pi term (dimensionless group)

ρ = Air density

APPENDIX B

AIR FLOW VELOCITIES

TABLE 1

SLOTTED PIPE UNDER-SLAT VENTILATOR

Level	Wall	Distance From Wall (In.)	Velocities (Side Baffle) Front (Ft/Min)	Velocities (Side Baffle) Center (Ft/Min)	Velocities (Side Baffle) Rear (Ft/Min)	Velocities (Center Baffle) Front (Ft/Min)	Velocities (Center Baffle) Center (Ft/Min)	Velocities (Center Baffle) Rear (Ft/Min)
Manure Pit	Right	0.0	75.0	140.0	175.0	55.0	55.0	140.0
		2.5	140.0	140.0	75.0	105.0	75.0	75.0
		7.5	35.0	15.0	55.0	35.0	15.0	15.0
		10.0	15.0	15.0	15.0	15.0	5.0	5.0
	Left	10.0	35.0	35.0	15.0	35.0	15.0	15.0
		7.5	35.0	55.0	55.0	35.0	75.0	35.0
		2.5	75.0	175.0	105.0	75.0	140.0	105.0
		0.0	290.0	210.0	75.0	55.0	140.0	140.0
Swine Level	Right	0.0	250.0	210.0	290.0	210.0	210.0	250.0
		2.5	210.0	140.0	250.0	105.0	105.0	210.0
		7.5	55.0	105.0	75.0	75.0	75.0	105.0
		10.0	75.0	75.0	75.0	105.0	75.0	140.0
	Left	10.0	35.0	75.0	35.0	55.0	75.0	75.0
		7.5	55.0	75.0	55.0	75.0	75.0	75.0
		2.5	140.0	210.0	140.0	210.0	105.0	175.0
		0.0	290.0	175.0	75.0	290.0	105.0	210.0

TABLE 2

CENTERED DUCT PIT VENTILATOR

Level	Wall	Distance From Wall (In.)	Velocities (Side Baffle)			Velocities (Center Baffle)		
			Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)	Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)
Manure Pit	Right	0.0	105.0	210.0	35.0	15.0	35.0	35.0
		2.5	75.0	250.0	15.0	35.0	55.0	75.0
		7.5	35.0	75.0	15.0	35.0	15.0	15.0
		10.0	35.0	55.0	35.0	15.0	15.0	35.0
	Left	10.0	15.0	35.0	15.0	15.0	15.0	55.0
		7.5	35.0	55.0	15.0	35.0	15.0	35.0
		2.5	55.0	55.0	105.0	35.0	35.0	105.0
		0.0	175.0	75.0	75.0	55.0	35.0	75.0
Swine Level	Right	0.0	290.0	210.0	210.0	210.0	210.0	210.0
		2.5	210.0	250.0	140.0	140.0	175.0	140.0
		7.5	75.0	75.0	75.0	75.0	75.0	75.0
		10.0	75.0	55.0	75.0	75.0	105.0	75.0
	Left	10.0	55.0	35.0	55.0	75.0	75.0	75.0
		7.5	55.0	55.0	35.0	55.0	105.0	55.0
		2.5	105.0	55.0	105.0	140.0	175.0	140.0
		0.0	75.0	75.0	140.0	175.0	175.0	175.0

TABLE 3

OUTSIDE WALL PIT VENTILATOR

Level	Wall	Distance From Wall (In.)	Velocities (Side Baffle) Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)	Velocities (Center Baffle) Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)
Manure Pit	Right	0.0	75.0	35.0	35.0	35.0	35.0	15.0
		2.5	35.0	75.0	35.0	75.0	35.0	55.0
		7.5	15.0	15.0	15.0	35.0	5.0	15.0
		10.0	15.0	15.0	35.0	15.0	15.0	5.0
	Left	10.0	35.0	35.0	15.0	5.0	5.0	5.0
		7.5	35.0	35.0	15.0	55.0	15.0	5.0
		2.5	105.0	140.0	55.0	210.0	75.0	35.0
		0.0	105.0	105.0	55.0	55.0	105.0	55.0
Swine Level	Right	0.0	290.0	210.0	250.0	250.0	210.0	290.0
		2.5	250.0	140.0	140.0	210.0	250.0	140.0
		7.5	75.0	75.0	75.0	75.0	75.0	75.0
		10.0	75.0	75.0	55.0	75.0	75.0	75.0
	Left	10.0	55.0	55.0	35.0	55.0	75.0	75.0
		7.5	75.0	55.0	35.0	55.0	75.0	55.0
		2.5	105.0	55.0	75.0	55.0	75.0	55.0
		0.0	140.0	75.0	55.0	210.0	210.0	250.0

TABLE 4

HOODED MANURE PIT EXHAUST SYSTEM

Level	Wall	Distance From Wall (In.)	Velocities (Side Baffle)			Velocities (Center Baffle)		
			Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)	Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)
Manure Pit	Right	0.0	35.0	15.0	35.0	35.0	55.0	35.0
		2.5	55.0	140.0	55.0	35.0	105.0	55.0
		7.5	55.0	55.0	35.0	35.0	55.0	15.0
		10.0	15.0	55.0	15.0	55.0	35.0	15.0
	Left	10.0	15.0	15.0	15.0	15.0	5.0	15.0
		7.5	35.0	15.0	35.0	15.0	15.0	15.0
		2.5	75.0	250.0	105.0	55.0	210.0	35.0
		0.0	55.0	250.0	55.0	35.0	105.0	15.0
Swine Level	Right	0.0	250.0	210.0	290.0	175.0	290.0	140.0
		2.5	250.0	210.0	290.0	210.0	105.0	105.0
		7.5	55.0	75.0	105.0	55.0	55.0	75.0
		10.0	75.0	105.0	75.0	55.0	105.0	75.0
	Left	10.0	55.0	55.0	105.0	75.0	55.0	55.0
		7.5	35.0	75.0	35.0	55.0	55.0	55.0
		2.5	105.0	175.0	75.0	105.0	175.0	105.0
		0.0	35.0	210.0	55.0	140.0	175.0	105.0

TABLE 5

PRESSURIZED PIT VENTILATOR SYSTEM

Level	Wall	Distance From Wall (In.)	Velocities (Side Baffle)			Velocities (Center Baffle)		
			Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)	Front (Ft/Min)	Center (Ft/Min)	Rear (Ft/Min)
Manure Pit	Right	0.0	35.0	15.0	35.0	15.0	15.0	35.0
		2.5	15.0	15.0	15.0	5.0	15.0	5.0
		7.5	15.0	2.0	2.0	15.0	2.0	2.0
		10.0	5.0	2.0	2.0	5.0	2.0	2.0
	Left	10.0	15.0	2.0	5.0	5.0	2.0	2.0
		7.5	5.0	2.0	5.0	2.0	2.0	2.0
		2.5	15.0	5.0	15.0	15.0	5.0	15.0
		0.0	35.0	15.0	15.0	35.0	15.0	35.0
Swine Level	Right	0.0	140.0	210.0	210.0	140.0	140.0	140.0
		2.5	75.0	175.0	140.0	175.0	175.0	140.0
		7.5	75.0	105.0	75.0	105.0	175.0	105.0
		10.0	75.0	75.0	75.0	105.0	140.0	105.0
	Left	10.0	35.0	175.0	75.0	105.0	105.0	105.0
		7.5	55.0	105.0	55.0	140.0	140.0	105.0
		2.5	55.0	55.0	75.0	210.0	140.0	140.0
		0.0	35.0	55.0	55.0	175.0	140.0	105.0

APPENDIX C

EVACUATION TIMES

TABLE 6

EVACUATION TIMES

System	Evacuation Times Employing Reynolds Number (Sec.)	Froude Number (Sec.)
Slotted Pipe Under-Slat Ventilator	15.2	225.0
	16.8	230.0
	15.0	232.0
Centered Duct Pit Ventilator	13.2	222.0
	14.4	212.0
	12.4	211.0
Outside Wall Pit Ventilator	12.5	230.0
	12.9	232.0
	12.5	233.0
Hooded Manure Pit Exhaust System	15.1	190.0
	14.7	198.0
	13.0	216.0
Pressurized Pit Ventilator System	12.1	209.0
	11.2	200.0
	11.3	213.0

APPENDIX D

STATISTICAL ANALYSIS

TABLE 7

ANALYSIS OF VARIANCE, COMPARING VELOCITIES ON RIGHT AND LEFT SIDE AT PIT LEVEL

Source	D.F.	Mean Square	F
System (S)	4	16,692.7	5.95**
Baffle (B)	1	4,420.4	1.57
Position (P)	1	4,950.4	1.76
S X B	4	992.3	0.35
S X P	4	2,820.2	1.01
B X P	1	350.4	0.12
S X B X P	4	505.6	0.18
Error	40	2,804.2	

**Significant at the 1% level.

TABLE 8

ANALYSIS OF VARIANCE, COMPARING VELOCITIES ON RIGHT AND LEFT SIDE AT SWINE LEVEL

Source	D.F.	Mean Square	F
System (S)	4	2,400.6	1.21
Baffle (B)	1	601.7	0.30
Position (P)	1	38,506.7	19.39**
S X B	4	6,867.3	3.46*
S X P	4	2,891.0	1.46
B X P	1	22,426.7	11.30**
S X B X P	4	1,115.2	0.56
Error	40	1,985.4	

*Significant at the 5% level.

**Significant at the 1% level.

TABLE 9

ANALYSIS OF VARIANCE, COMPARING VELOCITIES FOR FRONT AND REAR OF BUILDING AT PIT LEVEL

Source	D.F.	Mean Square	F
System (S)	4	6,862.8	6.65**
Baffle (B)	1	168.2	0.16
Position (P)	1	1,496.4	1.45
S X B	4	1,158.4	1.12
S X P	4	1,420.0	1.38
B X P	1	151.2	0.15
S X B X P	4	886.4	0.86
Error	60	1,032.5	

**Significant at the 1% level.

TABLE 10

ANALYSIS OF VARIANCE, COMPARING VELOCITIES FOR FRONT AND REAR OF BUILDING AT SWINE LEVEL

Source	D.F.	Mean Square	F
System (S)	4	1,502.7	0.38
Baffle (B)	1	1,901.2	0.48
Position (P)	1	845.0	0.21
S X B	4	4,250.5	1.08
S X P	4	1,348.9	0.34
B X P	1	211.2	0.01
S X B X P	4	1,407.3	0.36
Error	60	3,950.4	

TABLE 11

ANALYSIS OF VARIANCE, COMPARING EVACUATION TIMES EMPLOYING REYNOLDS NUMBER

Source	D.F.	Mean Square	F
System	4	7.90	11.8**
Error	10	0.67	

**Significant at the 1% level.

TABLE 12

ANALYSIS OF VARIANCE, COMPARING EVACUATION TIMES EMPLOYING FROUDE NUMBER

Source	D.F.	Mean Square	F
System	4	526.0	9.56**
Error	10	55.0	

**Significant at the 1% level.