PAYNE, C.G. (1966). in *Proc. British Egg Marketing Board Symp. No.3*, Ed. T.C. Carter

SAINSBURY, D. (1967). *Animal Health and Housing*, Balliere, Tindall

SAINSBURY, D. (1970). *Pig Housing*, Farming Press

4813

19

VENTILATION OF BUILDINGS FOR INTENSIVELY HOUSED LIVESTOCK

G. A. CARPENTER

National Institute of Agricultural Engineering, Silsoe, Bedford

INTRODUCTION

Because ventilation systems affect the air temperature and air speed around intensively housed farm stock, they play an important part in controlling animal heat loss. The role of a ventilation system is very complex partly because of the large number of climatic factors that it can influence, partly because of the complex interaction between climate and factors such as nutrition, disease, building structure and group effects (Baxter, 1969), and partly because of the ways in which the design of the ventilation system can offer a choice of air temperatures and air speeds around the stock. Thus, there are at least sixteen factors that can be modified (but not controlled) by a ventilation system (see *Figure 19.1*). Usually, only one factor, namely air temperature, is actually controlled, others being merely limited. In this context, the phrase 'controlled environment' is inappropriate, 'temperature controlled' being preferable.

The ventilation system itself has the following three main design aspects:

1. Its basic configuration or layout, that is the positions of the vents in relation to the building and the stock.

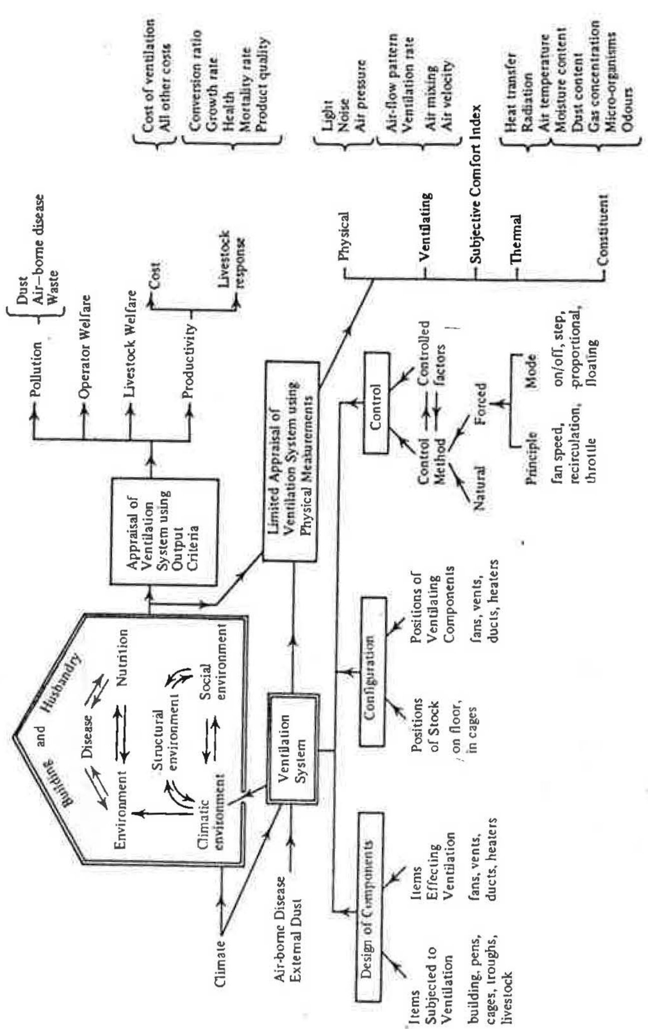

Figure 19.1 The ventilation of livestock buildings: its scope and its relationships to output and other factors

2. The controls, in other words the methods and mode of control and the factors to be controlled.
3. The characteristics of the components, namely the detailed design of the stock enclosure, air vents and so on.

The performance of the ventilation system is affected by external factors beyond its control, such as dust, air-borne disease, wind and climate and power failure.

The effects of the ventilation system can be measured in two ways: in a limited way, by making physical measurements of the environment, or comprehensively, using various output criteria such as pollution, operator and livestock welfare and productivity.

THE CHARACTERISTICS OF INTENSIVE LIVESTOCK BUILDINGS

Specifically excluding buildings for adult cattle, a large proportion of intensive livestock buildings have five characteristics which determine both the basis for controlling temperature in an economic manner and important aspects of the design of the system of ventilation.

1. They have a high level of heat generation per unit floor area, typically 150 W m^{-2}.
2. A high standard of thermal insulation is employed.
3. The buildings are single storey, detached and of a length much greater than their width. This form results in an absence of inherent resistance to air movement which enables propeller fans to be used but also makes the buildings susceptible to wind effects.
4. Normally there is a fairly uniform distribution of stock over the floor area and so there is need for ventilation over all parts of the building.
5. The rapid ventilation rates required to remove heat in summer can be 20 times the corresponding figure for offices. This requirement, combined with the high ratio of length to width means that air movement along the long axis of the building would involve undesirably high air speeds, so the predominant air movement is transverse.

TEMPERATURE CONTROL

The first two characteristics - high levels of heat production and insulation - enable buildings for adult stock, to be kept close to the optimum temperature for most of the year without using artificial heating or cooling but by merely varying the rate of fresh air intake. In this context the economic thickness of insulation for pig fattening houses has been studied (Fuller, 1970).

Figure 19.2 shows how the mean temperature in a fully stocked insulated Danish-type pig fattening house depends on ventilation rate for various outside ambient temperatures. In such a building, where the conducted heat loss is always kept small, most of the heat is dissipated by the ventilating air. In winter, approximately 80% of the total heat is removed in this way but in summer the proportion is much higher than this, depending on factors such as solar radiation. A typical layer house with 3 rows of double 3-tier battery cages has almost identical height and width, thickness of insulation and heat release per unit floor area, and the same curves apply to such a house using units of ventilation rate based on unit floor area of building.

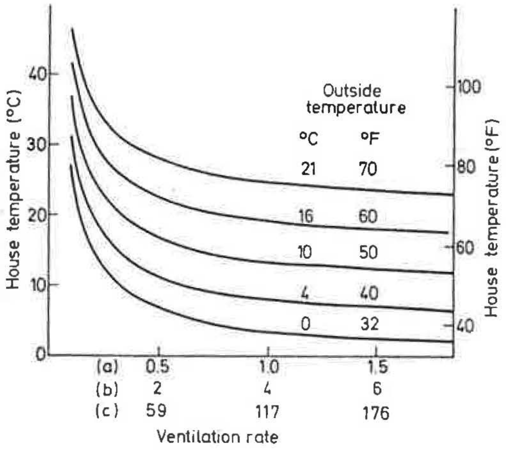

Figure 19.2 The effect of ventilation rate on house temperature for a range of outside temperatures. (a) pigs per unit live weight (m^3 h^{-1} kg^{-1})*, (b) laying hens per unit live weight* (m^3 h^{-1} kg^{-1})*, (c) either 90 kg pigs or 1.8 kg battery hens both per unit live weight* (m^3 h^{-1} kg^{-1})

Several important facts are illustrated by Figure 19.2 for pigs and poultry. Three points relate to pigs:

1. The frequently recommended winter rate 0.38 m^3 h^{-1} per kg live weight (0.1 ft^3 min^{-1} lb^{-1}) appears to be unduly fast for a system that uses the ventilating air efficiently. In practice, this higher value may be necessary if some of the ventilating air bypasses the stock.
2. House temperature becomes increasingly sensitive to ventilation rate as the rate is reduced, especially below 0.56 m^3 h^{-1} kg^{-1}.
3. House temperature becomes increasingly insensitive to ventilation rate above 1.5 m^3 h^{-1} kg^{-1}.

The practical implications are that existing methods of controlling ventilation in winter are inadequate both as regards the manner in which the air intake rate is controlled and as regards the elimination of uncontrolled ventilation by wind and leaks in the building. In addition, no purpose is served by providing a massive increase in fan capacity to improve temperature control in hot weather. A more promising approach would be to effect local cooling by modifying the air distribution system, so that the air velocity over the stock can be increased when required.

DESIGN OF VENTILATION SYSTEM

The low resistance of livestock buildings to air movement and the use of propeller fans enables ventilation costs to be kept very low both as regards power consumption and overheads (see below). However, because they work at very low pressures they are very susceptible to wind, particularly at low fan speeds. Therefore, either wind-proof vents must be provided or systems must be selected that lend themselves to wind-proofing. In practice, wind baffles fitted to the commonly occurring eaves inlet are seldom adequate and the ultimate solution may be to have all vents feeding into a limited number of chimneys raised above roof level. These considerations on wind, together with the need to provide ventilating air over all parts of buildings that are frequently long and narrow, lend support to the adoption of ducted systems, especially for supplying the air.

THE EFFECT OF DESIGN OF VENTILATION SYSTEM ON TEMPERATURE AND VELOCITY AT STOCK LEVEL

Figure 19.2 relates the mean temperature of the air in the building to the overall ventilation rate, assuming complete mixing of the supply air with the air in the building. In practice, complete mixing never occurs and gradients of temperature occur within the building space. Further, the air speed varies throughout the building both in direction and in magnitude due to the ventilating and thermal forces. The word 'distribution', often used to describe how air passes through the building, has two important aspects. One can be called the 'air flow pattern', which is a map of the dominant air paths; and the other is 'path distribution' - a quantitative measurement of how the air divides when a single path splits into two (or conversely when two paths combine). The extremes of path distribution are (a) laminar flow which consists of a series of parallel paths with zero mixing and (b) highly turbulent flow which has no readily identifiable paths and gives complete mixing. Real systems lie between these extremes with air flow patterns that are reasonably defined and invariably consist of one or more rotary motions. Using a full scale section of a building, a technique has been developed for visualising such patterns using bubbles and for recording them photographically by interrupted exposure to indicate both direction and speed (Carpenter, Moulsley and Randall, 1972).

FACTORS AFFECTING AIR FLOW PATTERN

The air velocity and air temperature components of the environment of stock are determined by the air flow pattern and the path distribution. *Figure 19.3* shows how the air flow pattern depends on the entry conditions of the supply air and the factors causing change of direction after entry. The entry conditions are defined by the position, direction, area and air speed of the supply vent and the factors causing change of direction

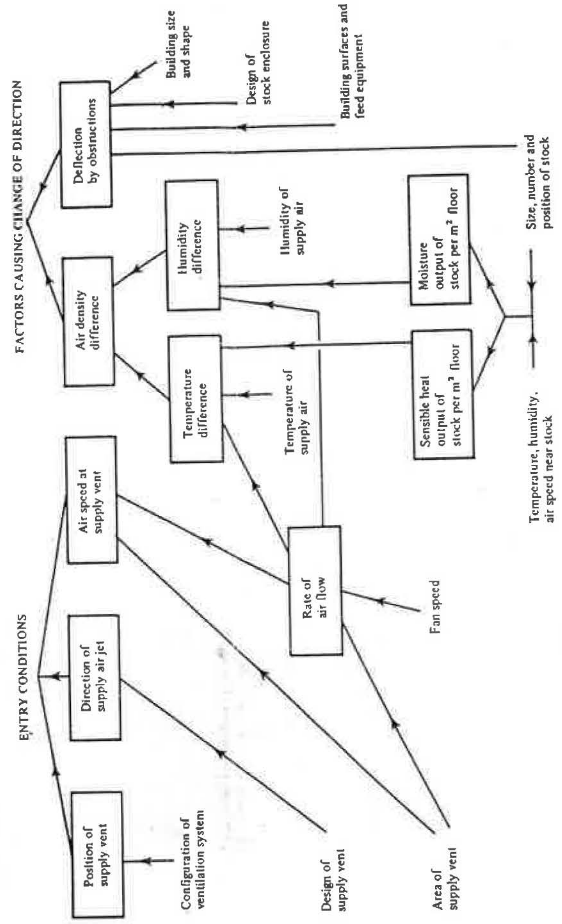

Figure 19.3 Factors affecting airflow pattern

are differences of air density and obstructions. Some of the factors are fixed parameters of the ventilation system and of the building and its equipment. Examples are the position, direction and area of supply vents, the shape, size and details of the building and the characteristics of the stock enclosure. The number and size of stock are constant over the short term, but for untethered animals in pens, their position, although restricted, is not fixed. The temperature and humidity of the supply air is affected by climate and so is the rate of air flow by wind, even when fans are used.

In two respects, control of the air flow pattern is further complicated by the existence of closed loops. For example, any controlling thermostatic device can control fan speed which in turn affects the pattern which will affect the temperature sensed by the thermostat. Again, the heat and moisture loss from the stock depend on the environmental temperature and air velocity, and yet these losses influence the air flow patterns that produce this environment.

EFFECT OF VENT AND STOCK POSITIONS

One possible way of classifying fan-ventilated systems is to base them on the relative positions of the vents disposed in the main components of the building. The six possible relative positions are shown in *Figure 19.4*.

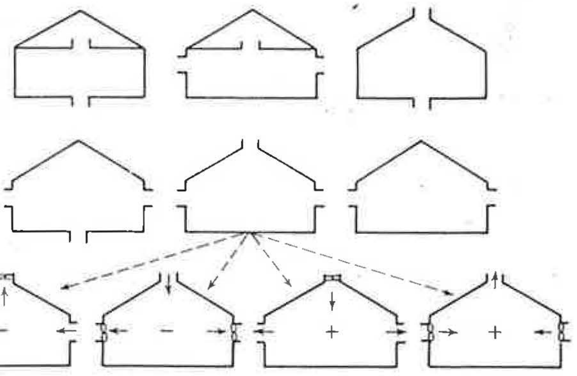

Figure 19.4 Principal configurations of air vents

Except for wall-to-wall ventilation the inlet and outlet can be reversed and in all cases the fan can be upstream of an inlet (pressurised system) or downstream of an outlet (an exhausted system). In practice, only some of these arrangements are practicable because of the need to keep stock away from supply vents.

Figure 19.5 emphasises the dramatically different characteristics of supply and exhaust vents. Air is discharged from a supply vent as a jet, but enters an exhaust vent from all directions hemispherically. For example, for an air speed of 10 m s^{-1} through a 0.62 m diameter vent, the exhausted air speeds are 5%, 1.2% and 0.3% of the supply air speed at distances of 1 m, 2 m and 4 m respectively.

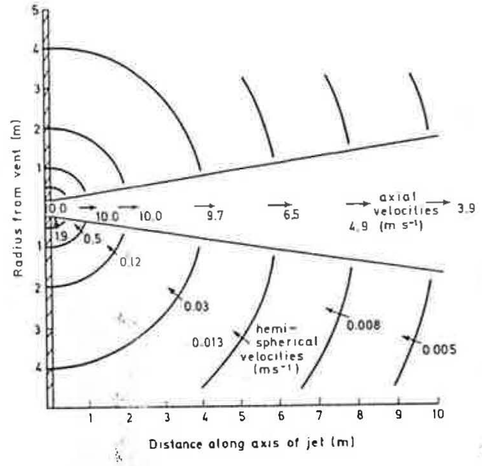

Figure 19.5 Comparison between air speeds adjacent to supply and exhaust vents for a vent of 0.62 m diameter and a vent air speed of 10 m s^{-1}

Another important aspect of the relative positions of vents and animals is whether livestock are adjacent to a wall, on the floor or in a cage in the centre part of the air space. In the latter instance, high-speed air circulating around the walls, floor and roof (or ceiling) can often be acceptable, but if stock are penned on the floor or in cages against a wall, then a different type of air circulation or protection from draughts may be necessary.

VENT DESIGN

Vents can be of the following three main types:

1. Direct vents: a direct connection to the outside of a building such as ridge- or wall-mounted fans or ridge or eaves slots.
2. Ducted vents: rigid ducts for pressurised or exhausted systems and inflatable ducts for pressurised systems.
3. Plenum vents: a permeable area over a large part of a wall or ceiling.

The most important aspects of the design of supply vents are the direction of discharge, the discharge velocity and the aperture size.

Figure 19.6 shows for an exhausted or pressurised building and a pressurised polythene duct how air throughput and vent discharge velocity vary with the total vent area. For vent areas that are greater than three times that of the fan area, vent velocity is inversely proportional to the vent area. For smaller vent areas, the relationship is approximately linear due to the throttling effect on the fan. Because polythene ducts will not remain inflated above a certain total area of holes, typical discharge velocities (Carpenter, 1972a) are of the order of 5 m s^{-1}. For conventional exhausted systems, velocities as low as 1.0 m s^{-1} are recommended although under these circumstances ventilation of the building can be affected by wind. By using fine-pore materials such as calico or glass fibre matting over a large area of supply vent, discharge velocities as low as 0.1 m s^{-1} can be achieved (Charles and King, 1969; Carpenter, 1972).

Established equations exist for relating the throw of a jet to the dimensions of the aperture for a given discharge velocity (Becher, 1966). For example, *Figure 19.7* shows how calculated air velocities vary with distance from the aperture for circular holes in the range 6.4 to 51 mm diameter. Thus, a given rate of discharge can often be achieved in a number of ways by selecting the position of the duct in the building, the size of the holes and the directions in which the holes are pointing.

SUPPLY TEMPERATURE

For non-recirculatory systems, fresh air close to the external air temperature enters the ventilated space. In a system using ridge extraction and eaves supply vents of fixed area, Randall (unpublished) has observed that, provided ambient temperature is below 14°C, the air passes over simulated stock in a direction from supply to exhaust, but goes in the reverse direction for temperatures above 14°C. The causes of this reversal are the effects of the different air temperature and the different discharge velocity interacting with the convected heat. The relevant meteorological data imply that this reversal of direction of flow will take place during at least a third of the days in the year. If such reversals are eventually shown to be associated with undesirable changes in air velocity and temperature, then either a design must be evolved that avoids them or a recirculation system must be adopted in which the ambient fresh air is mixed with house air before being discharged into the ventilated space thereby discharging both at a constant temperature and at a constant velocity. Whether or not a recirculatory system is used,

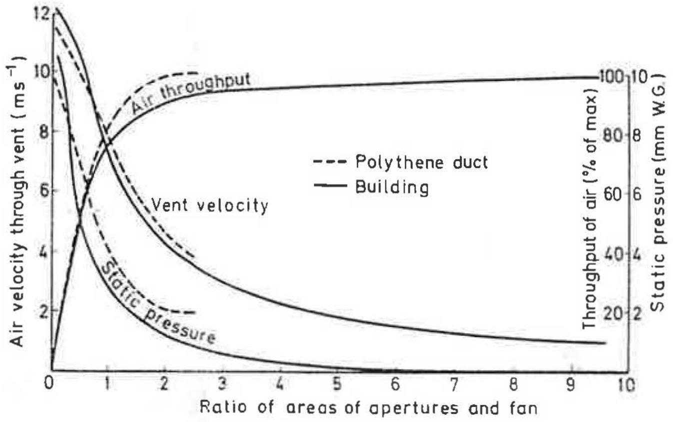

Figure 19.6 Effect of aperture area on air throughput, aperture air velocity and static pressure for a pressurised polythene duct and an exhausted or pressurised building

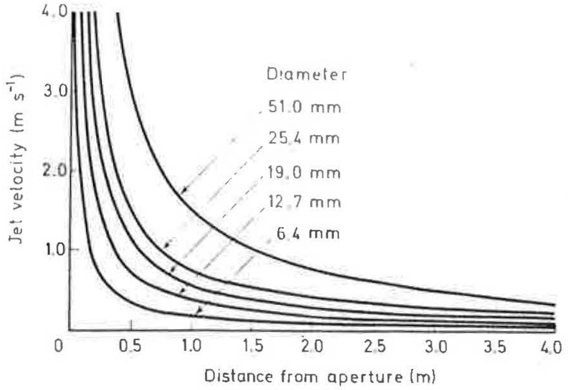

Figure 19.7 Theoretical variation of jet velocity with distance from aperture for different aperture diameters with 5.6 m s^{-1} discharge velocity

however, due regard must be paid to the velocity and direction of the discharged air. Systems using supply and exhaust ducts, for example, are probably superior to those using supply and discharge at a single point in the centre of the building because the latter are inevitably based on a square or circular module whereas ducts are based on a linear one that is more appropriate to the proportions of the buildings described earlier.

THE COST OF FAN VENTILATION

Whilst it is generally accepted that forced ventilation using fans is necessary in intensively stocked buildings, the fact that naturally ventilated systems persist and continue to be built for semi-intensive buildings may be partly a matter of husbandry, but also implies a reluctance to adopt force-ventilated systems. This reluctance may be due to the desire to be independent of mechanical breakdowns or power failure, to uncertainty of the relative performance of livestock in the forced and naturally ventilated systems, or to the desire to avoid the installation and running costs of a fan-powered system. Overall assessment of natural and fan-ventilated systems involves the consideration of considerable biological, climatological and engineering data. It is possible, however, to calculate orders of magnitude of costs in order to establish whether there is justification for opting against fan ventilation on these grounds alone (Carpenter, 1972b).

From the results of a pig management scheme taken over 110 farms (Ridgeon, 1972), production figures can be quoted which are typical enough of pig production to form a basis for the comparison of ventilation with other costs. For an average breeding and fattening unit based on a sow herd size of 82, costs for producing bacon pigs in 1971 were £12·27 per pig for fattening costs and £18·32 for total costs (including weaner production) for a net selling price (including bonus) of £21·36, leaving a margin of £3·04.

An 80 sow herd will typically have 1375 progeny per annum, and with a 9½ week fattening period from 36 kg to 90 kg, the number of fatteners housed at any one time would be 252 with an average weight of 63 kg (140 lb). The volume of ventilating air required in such a fattening house under summer conditions would be 30,000 m^3 h^{-1} (17,700 ft^3 min^{-1}). Assuming a resistance of 4 mm (0.15 in) W.G., *Table 19.1* shows the various combinations of size and number of propeller fans that will provide this ventilation rate. Further, if the speeds of these fans were controlled by proportional solid-state devices in order to control the temperature in the fattening house, the mean annual power consumption would be approximately 40% of the full-load consumption (Owen, 1969). Assuming a cost of electricity of 1 p per unit, installation costs of 20% of the fan and controller capital cost, depreciation and interest each of 10% and a maintenance of 5% of the capital plus installation cost, then *Table 19.1* gives the costs per pig of fan ventilation.

Since these costs are less than half the average mortality cost, or 3.0% of the average margin, or 0.7% of the fattening costs, or 0.5% of the total costs, it appears that fan costs are not normally critical and that there is no question of selecting natural ventilation rather than fan ventilation on account of fan costs alone.

Further, if fan costs are related to the economics of food conversion, then, because every 0.1 gain in conversion ratio saves 5.4 kg of food per pig (assuming 54 kg liveweight gain) and has a value of about 20 p

Table 19.1 Total costs of provision and operation of propeller fans

Fan diameter (mm)	(in)	Fan speed (rev min^{-1})	Number of fans required	Costs, new pence per pig fattened[1]			
				Electrical power	Maintenance	Overheads	Total
381	15	1400	20	4.1	1.3	5.3	10.7
457	18	1400	11	4.7	1.0	3.9	9.6
610	24	940	7	4.2	0.8	3.2	8.2
761	30	700	5	3.0	0.8	3.1	6.9
Mean				4.0	1.0	3.9	8.9

[1] To convert to costs per pig place multiply by 5.46

per pig (food at 3.74 p per kg or £1·90 per cwt), any ventilation system cost of the order of 9 p per pig, as in *Table 19.1*, pays for itself if it can effect an improvement in conversion ratio of 0.05.

The use of alternative designs such as aerofoil, centrifugal or tangential fans incurs a capital cost of the order of 2½ times that of propeller fans with the effect of increasing total costs by 40%. The use of recirculatory systems, which maintain the fan at full speed continuously, would increase power costs to 10 p and thus the total cost to 14.9 p per pig, an increase of 67%.

CONCLUSION

By paying due regard to the special characteristics of intensive livestock buildings, it should be possible to select appropriate designs of ventilating equipment and techniques and thus go some way towards achieving better control of temperature and air velocity close to stock. This objective can be achieved at relatively low cost in relation to the economics of intensive livestock enterprises.

Complete control is probably possible only by using recirculatory systems which incur a 67% higher fan ventilation cost, though costs of the extra ducting and dampers might readily be offset by a simplified arrangement of exterior vents.

REFERENCES

BAXTER, S. (1969). *Scottish Farm Buildings Investigation unit Report No. 4*

BECHER, P. (1966). *J. Instn Heat. Vent. Engrs*, Oct., 219

CARPENTER, G.A. (1972a). *J. agric. Engng Res.*, 17, 219

CARPENTER, G.A. (1972b). Dep. Note FB/291/3020, National Institute of Agricultural Engineering

CARPENTER, G.A., MOULSLEY, L.J. and RANDALL, J.M. (1972), *J. agric. Engng Res.*, 17, 323

CHARLES, D.R. and KING, A.W.M. (1969). Proc. Filtration Society Symposium: Filtration in Medical and Health Engineering, London, 70

FULLER, M. (1970). *Pig Farming*, Nov., 38

OWEN, V.M. (1969). *Power Farming*, April, 49

RIDGEON, R.F. (1972). Results of pig management scheme, 1971. Agricultural Economics Unit, Dept. of Land Economy, Univ. of Cambridge