THE SCOTTISH FARM BUILDINGS INVESTIGATION UNIT SF

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J M Bruce

Natural ventilation is frequently found to be unsatisfactory in practice due to poor design or inappropriate application. The physics of natural ventilation is discussed mathematically. The application for natural ventilation, it is argued, should be decided through analysis of bio-climatic systems. A case for cattle is considered in detail.

9 CONDUCTIVE HEAT LOSS FROM THE RECUMBENT ANIMAL

J M Bruce

A mathematical model is proposed for heat transfer from a recumbent animal. A thermal simulation of a pig is described and the results of heat lost to various floors is interpreted as a floor thermal resistance. Predictions from the model are made and compared with the experimental results of others.

In 1974 a programme of work titled Climatic Influences was begun at SFBIU. At that time it was argued that the methods and concepts of systems analysis would be ideally suited to study the effect of climatic influences on specifications for farm buildings. The high degree of interaction in bio-climatic systems necessitates such an organised and disciplined approach.
Since then various projects have been undertaken and the results published. Some reports however, because of their initial purpose do not reach a wide audience. This edition of *Farm Building R & D Studies* brings together two such reports. Although the reports treat different bio-entities, cattle and pigs, they are both concerned, each in its way, with the quantitative analysis of thermal components of bio-climatic systems.

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The investigational programme is directed by a Joint Advisory Committe which is chaired by Maitland Mackie CBE LLD and on which the three Scottish Agricultural Colleges, the Department of Agriculture and Fisheries for Scotland, the Scottish Agricultural Development Council, and the Agricultural Research Council are represented.

In addition to *'Farm Building R & D Studies'* SFBIU also publishes a quarterly *'Farm Building Progress'* which features items of current interest, details of new developments in farm buildings and short research reports. *'Farm Building Cost Guide'*, published each February, gives up-to-date prices and price forecasts for buildings, materials, equipment and labour in agricultural construction work. *'Farm Building R & D Index'* lists and indexes current farm building research and development work and recent publications of organisations throughout Europe. A full list of these and other publications available from SFBIU is given inside the back cover of the current issue of *Farm Building Progress*, or is available on request.

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NOTATION

A	area
C	conductance
C_p	pressure coefficient
g	acceleration due to gravity
H	height
ΔP	pressure difference
Q	heat generation
Q_e	evaporative heat loss
Q_m	total metabolic heat production for thermoneutrality
R	gas constant
R_a	external thermal resistance
R_t	tissue thermal resistance
S	specific heat
T	absolute temperature
t	temperature
ΔT	temperature difference
U	velocity
V	ventilation rate
W	weight
ρ	density

Subscripts

in	at an inlet
int	internal
out	at an outlet
e	external
$_1$	inside
$_2$	outside
$_{10}$	at the standard meteorological height
crit	refers to lower critical temperature
b	deep body

WHAT IS NATURAL VENTILATION?

There is no implied difference in quality between air admitted to a building by natural and mechanical ventilation. The difference is principally associated with the type of motive power harnessed. Generally, electrical power is converted in a mechanical system whereas the motive power in a natural system is provided from two distinct sources, thermal buoyancy and wind.

Thermal buoyancy or stack effect

Air which is heated with respect to surrounding air is less dense and experiences an upthrust due to thermal buoyancy. Whenever a building contains livestock the production of sensible metabolic energy is always available to warm the air entering from outside. Provided there are two apertures with a height differential, the heated, less dense air will be forced out of the upper aperture to be replaced by an equal volume of cooler, denser air from outside. The primary source of motive power for ventilation by thermal buoyancy or 'stack effect' can be regarded as the livestock. In other words we have bio-ventilation

The hydrostatic pressure due to this gravitational effect of buoyancy may be written:

$$\Delta P = gH(\rho_1 - \rho_2) \qquad [1]$$

and this pressure is converted in part to kinetic head, the remainder being used to overcome pressure losses. The pressure losses generally take place at sudden expansions although in certain cases frictional drag at the walls of ducts may be present. For the situation in Figure 2 we may write:

$$\Delta P = \text{kinetic pressure} + \text{pressure losses}$$

$$= \tfrac{1}{2}\rho_2 U_2^2 + \tfrac{1}{2}\rho_1 U_1^2 \qquad [2]$$

For steady flow conditions:

$$\rho_1 A_1 U_1 = \rho_2 A_2 U_2 = \rho_2 V$$

which gives:

$$U_1 = \frac{\rho_2 A_2 U_2}{\rho_1 A_1} \qquad [3]$$

Substituting in Equation 2 gives:

$$\Delta P = \tfrac{1}{2}\rho_2 U_2^2 \, [1 + (A_2/A_1)^2] \qquad [4]$$

Eliminating ΔP between Equations 1 and 4 and re-arranging gives:

$$U_2 = \left[\frac{2gH(\rho_1/\rho_2 - 1)}{1 + (A_2/A_1)^2}\right]^{1/2} \qquad [5]$$

Treating air as a perfect gas Equation 5 can be simplified to give:

$$U_2 = \left[\frac{2gH\Delta T}{T_1 \, [1 + (A_2/A_1)^2]}\right]^{1/2} \qquad [6]$$

which is in the form commonly quoted as describing the

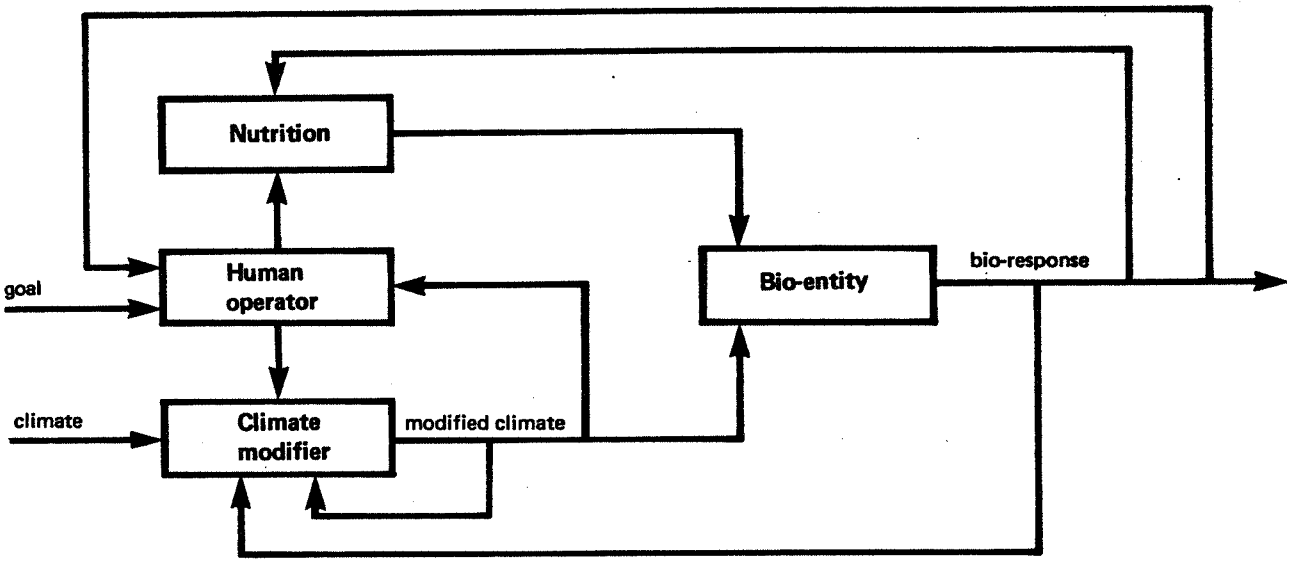

Figure 1 *A possible bio-climatic system*

stack effect and used for design calculations.

However, Equation 6 is not very useful unless the temperature difference, ΔT, is known. The temperature difference is not generally known as it depends on the heat transfer characteristics of the building, the ventilation rate, and the magnitude of the heat source. These quantities are related by:

$$Q = (\rho_2 SV + C)\,\Delta T \qquad [7]$$

Eliminating ΔT between Equations 6 and 7 gives:

$$\frac{1}{A_1^2} + \frac{1}{A_2^2} = \frac{2gHQ}{T_1\,(\rho_2 SV + C)V^2} \qquad [8]$$

In SI units we can more simply write the numerical form:

$$\frac{1}{A_1^2} + \frac{1}{A_2^2} = \frac{0.07HQ}{(1200V + C)V^2}\ \mathrm{m}^{-4} \qquad [9]$$

Equation 9 expresses the inlet and outlet ventilation areas as a function of Q, V, H and C which are independent of each other. Figure 3 is a design aid for the graphical solution and calculation of the ventilation apertures.

Ventilation due to wind

As the wind passes around an obstacle such as a building, accelerations and decelerations are experienced and associated with these are regions of low and high pressure. However the velocity at any point is not generally known and it is convenient to express the action of the wind using the concept of a pressure coefficient, C_p. The pressure on an external surface of a building is given by:

$$P_e = C_{pe}\tfrac{1}{2}\rho U_{10}^2 \qquad [10]$$

which defines C_{pe}. The external pressure coefficient, C_{pe}, is then that fraction of the kinetic pressure of the free wind, at the standard meteorological height of 10 m, acting on the building; it may be positive or negative. An internal pressure coefficient, C_{pi}, may be defined in a similar way and can be regarded as constant throughout the air volume at a given time for a building with no internal partitions.

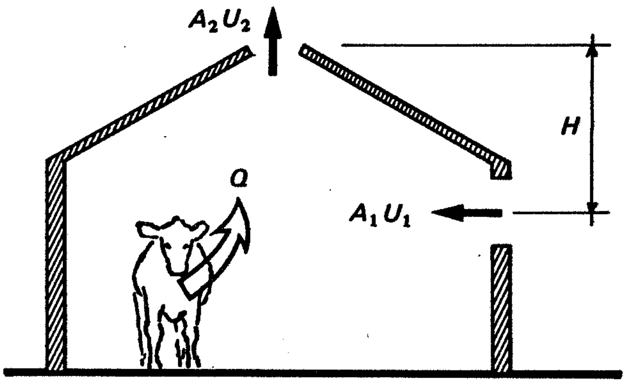

Figure 2 *Animal heat will produce thermal buoyancy*

Where openings occur in a building shell any pressure head developed by wind action will induce air to flow in and out of the building. As stated previously this pressure head is equal to the rate of change of momentum plus pressure losses so that for two openings:

$$\Delta P = \tfrac{1}{2}\rho U_{in}^2 + \tfrac{1}{2}\rho U_{out}^2 \qquad [11]$$

assuming a sudden expansion at inlet with a corresponding loss of velocity head.

From continuity, assuming negligible density change:

$$V = A_{in}U_{in} = A_{out}U_{out} \qquad [12]$$

so that:

$$\Delta P = \tfrac{1}{2}\rho U_{in}^2\,[1 + (A_{in}/A_{out})^2] \qquad [13]$$

Using Equation 10 we may write:

$$\Delta P = (C_{pe,in} - C_{pe,out})\,\tfrac{1}{2}\rho U_{10}^2 \qquad [14]$$

so that:

$$U_{in} = U_{10}\left[\frac{C_{pe,in} - C_{pe,out}}{1 + (A_{in}/A_{out})^2}\right]^{1/2} \qquad [15]$$

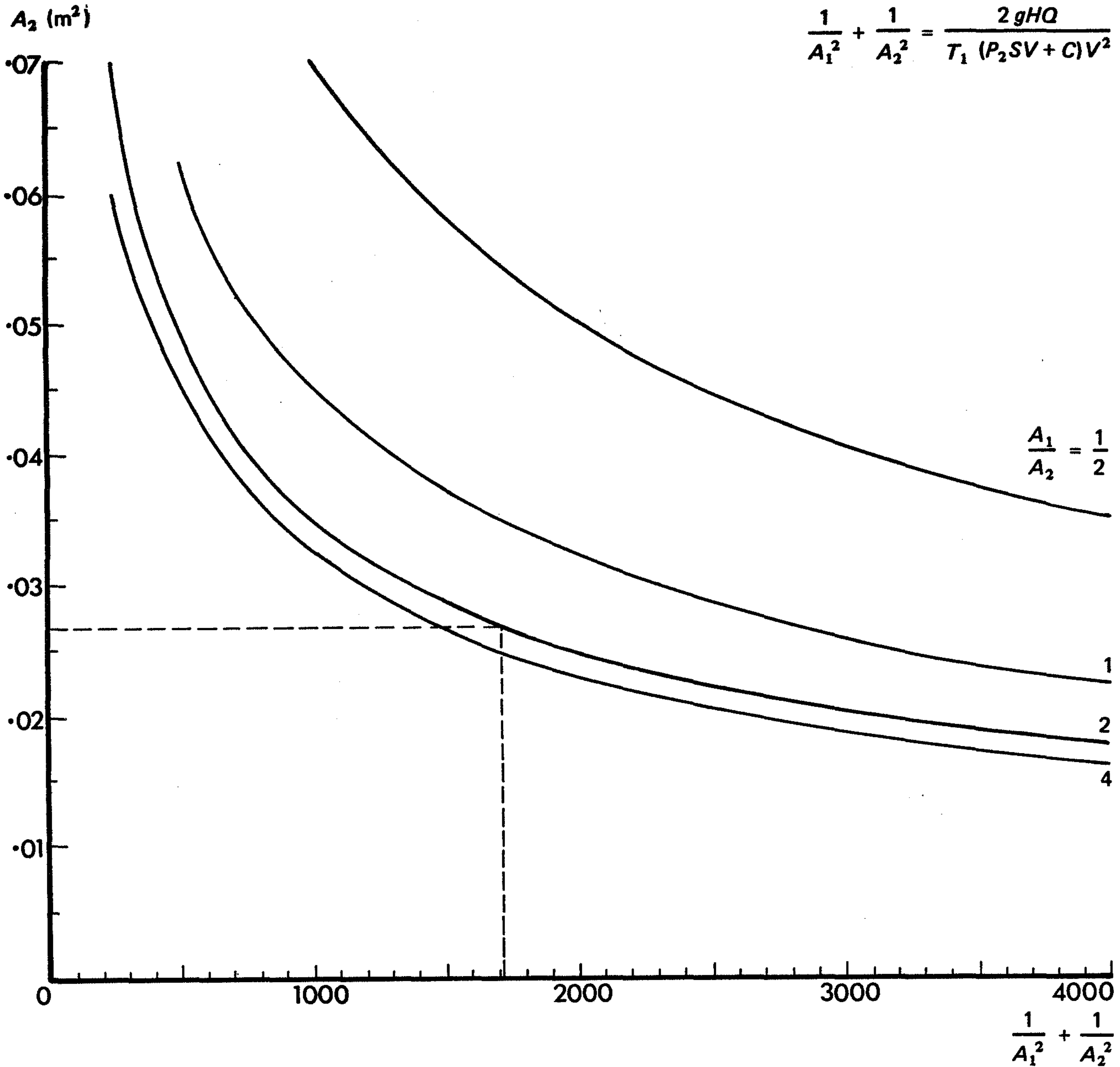

Figure 3 *Design aid for stack effect*

Strictly we ought to consider any number of inlets and outlets each having a local external pressure coefficient. How this is done is considered elsewhere (1) and for a complex case is better handled as an iterative calculation by a digital computer. A program is now available at SFBIU which will calculate ventilation rate due to wind for a building with up to two hundred openings (7).

Natural ventilation

It has been shown that natural ventilation is amenable to analysis. There is no denying the complexity and anyone who wishes to design or compare natural ventilation systems must be prepared to understand and carry out the calculations.

There are two distinct mechanisms for natural ventilation. The first depends on the heat of metabolism altering the climatic variable, temperature. The second depends on the climatic factor, wind. Natural ventilation in this light could be thought of as bio-climatic or simply climatic ventilation.

Quite a separate issue from the complexity of the calculations required is the unpredictability of uncontrolled natural ventilation due to its inherent dependence on climate. Our weather is highly variable on a day to day basis, therefore we must expect a corresponding variability in a natural ventilation system. This factor must be borne in mind when a particular application is considered. Some statistical measures of climate would seem appropriate when predictability is to be considered.

APPLICABILITY OF NATURAL VENTILATION

Natural ventilation is often degraded, quite wrongly, in preference to mechanical systems because of so-called lack of control. There is of course no reason why natural ventilation could not be controlled simply by applying established control techniques were it so desired. This is an area of application of control technology that has not been extensively studied and will undoubtedly receive more attention in the future.

Generally, however, we find that natural ventilation systems in livestock buildings are either not controlled or simply controlled manually by the stockman. This has given rise to practical problems largely due to uncertainty and even mis-direction regarding animals' climatic requirements. It is essential that the animals' requirements be established and the ventilation system matched to suit those requirements.

There is to be no attempt to explore all the possible bio-climatic systems for the application of natural ventilation within this paper. Experiential evidence exists which indicates the applicability of natural ventilation to the winter housing of cattle. Nevertheless there is an abundance of problems which crop up every winter. Because this is an important application of natural ventilation with pressing problems it is proposed, rather than continue in a general vein, to concentrate in this area.

The animals' requirement

Two important limits to ventilation rate can be identified for winter housed cattle:

(a) A minimum ventilation rate which must be maintained for health or physical reasons such as moisture removal.

(b) A maximum ventilation rate with associated high air velocities which, if exceeded, would lead to cold stress and subsequent depressed production.

If we consider the minimum ventilation rate first we come face to face with the problem of establishing or defining this rate. It is not too difficult to define a minimum ventilation rate based on a maximum acceptable relative humidity, but what is this relative humidity to be? If we were considering warm conditions then we could consider the point of onset of heat stress. If, as is more common, we were interested in winter operation then we find that there is virtually no significant effects of humidity documented at typical winter temperatures. However it is as well to bear in mind that densely stocked cattle with a high energy intake may be subject to heat stress at temperatures which may feel cool to man. More information is required in this area.

It is readily accepted that low ventilation rates could lead to high concentrations of airborne organisms. We do not know what is a critical concentration in any circumstance and we do not have the data to enable us to calculate the concentration even if we did have some estimate of what the limit might be. It is these difficulties which have given rise to empirical recommendations being made with regard to minimum ventilation rates by Sainsbury (2) and others.

On the other hand it appears possible to examine the conditions leading to cold stress with a little more certainty. The physiological data for beef cattle given for example by Webster (3, 4) can be processed using the following equation which mathematically models a part of the bio-climatic system considered:

$$t_{crit} = t_b - Q_m (R_a + R_t) + Q_e R_a \qquad [16]$$

The curves marked with the weight of the animal on Figures 4 and 5 represent Equation 16. For example a 250 kg fattening animal will have a critical temperature of -3°C at a wind speed of 5 m/s.

The climograph illustrates the climatic resources and the variables are chosen as monthly mean temperature less two standard deviations and the wind speed at 1.2 m height which is not exceeded for 90% of the time. The climograph merely illustrates the use of climatic data and it is not implied that the variables are in any way optimal. The capital letters around the climograph represent the months of the year. The growth curves trace out the age-weight relationship for spring-born and autumn-born calves. The thickened segments of these growth curves indicate the periods of cold stress, i.e. excess wind or temperature deficit. For example spring-born calves could be subject to cold stress until the first week in June or thereabout and again between the beginning of December and the latter period of February. This bio-climatic assessment of wind and temperature indicates that beef cattle housing which reduces the wind speed by about 40% will ensure that the cattle are never cold stressed even when there is negligible temperature difference between inside and out.

This quantitative statement on the wind reduction characteristics required of a cattle building allows the design of a natural ventilation system to be carried out on the basis of a maximum air movement criterion. It would also be a fair guess purely on the basis of this assessment that natural ventilation should be eminently suitable for beef cattle.

A PRACTICAL APPLICATION

Let us suppose that beef cattle are to be winter housed on slats in a 9.00 m wide building with a central feed pass. Ration feeding will be practised so that 600 mm of trough space is allowed per head. The construction is to be 150 mm concrete block walls with a single skin asbestos roof.

Stack effect

The minimum winter ventilation rate suggested by Sainsbury (2) is 5×10^{-5} m^3/s kg liveweight (0.05 ft^3/min lb). Since cattle of 450 kg may be housed in this building the ventilation rate per head could be:

$$V = 0.022 \text{ m}^3\text{/s head}$$

We will anticipate space boarding about 1.00 m deep at the eaves and an open ridge so that the effective height will be:

$$H = 0.5 + 4.5 \tan 22.5^\circ = 2.30 \text{ m}$$

From standard *'U'* values the building conductance per head is calculated:

$$C = 18.4 \text{ W/}^\circ\text{C head}$$

Very approximately the sensible heat output from a single beef animal in a calorimeter may be estimated as follows:

$$Q = 0.17\,(45 - t)W^{0.67}$$

but to allow for increased latent heat production at the expense of sensible heat production, due to floor contact and proximity, this is reduced arbitrarily by 30%. Assuming an internal temperature of 10°C then $Q = 245$ W/head.

Substituting these values into Equation 9 gives:

$$\frac{1}{A_1^2} + \frac{1}{A_2^2} = 1720 \text{ m}^{-4}$$

Using Figure 3 it is found that $A_2 = 0.027$ m^2 for an

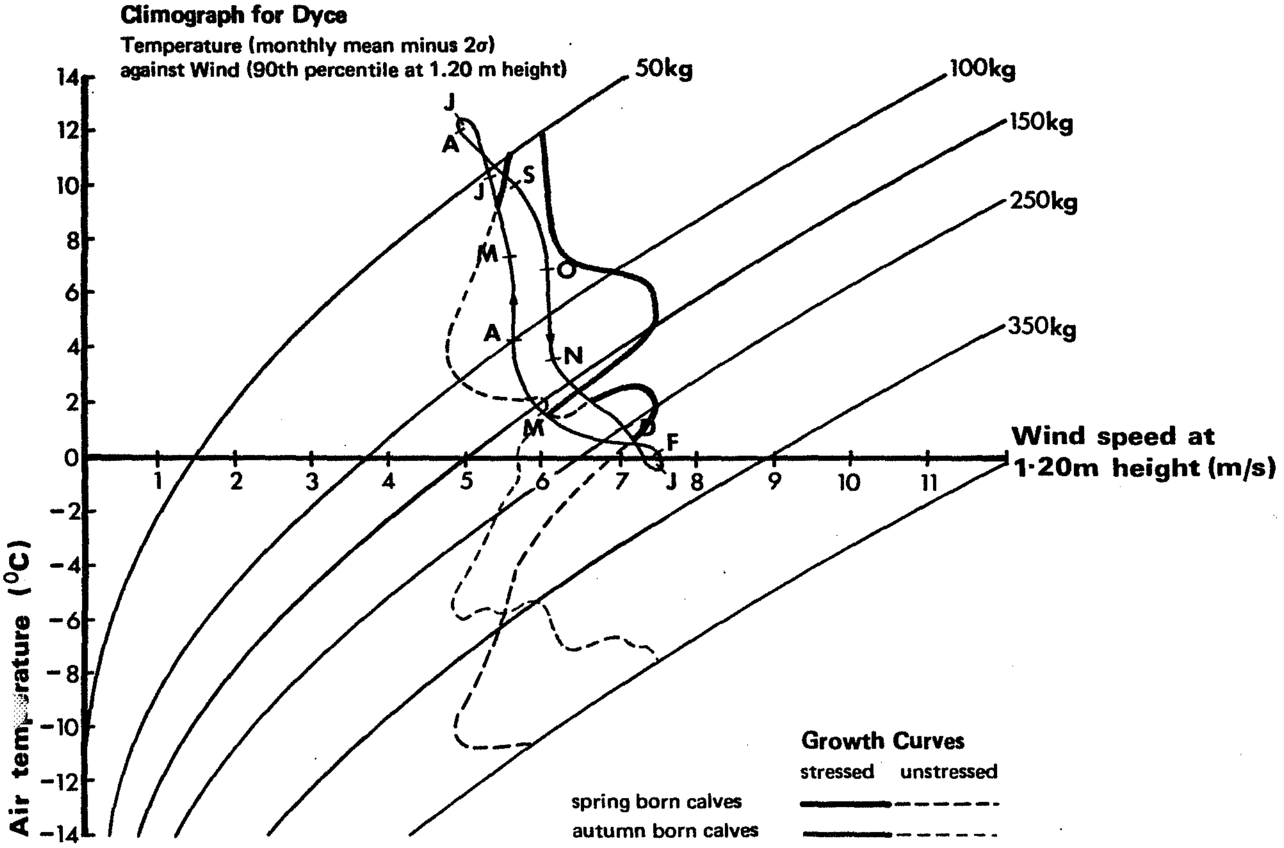

Figure 4 *Bio-climatic assessment of temperature for beef cattle*

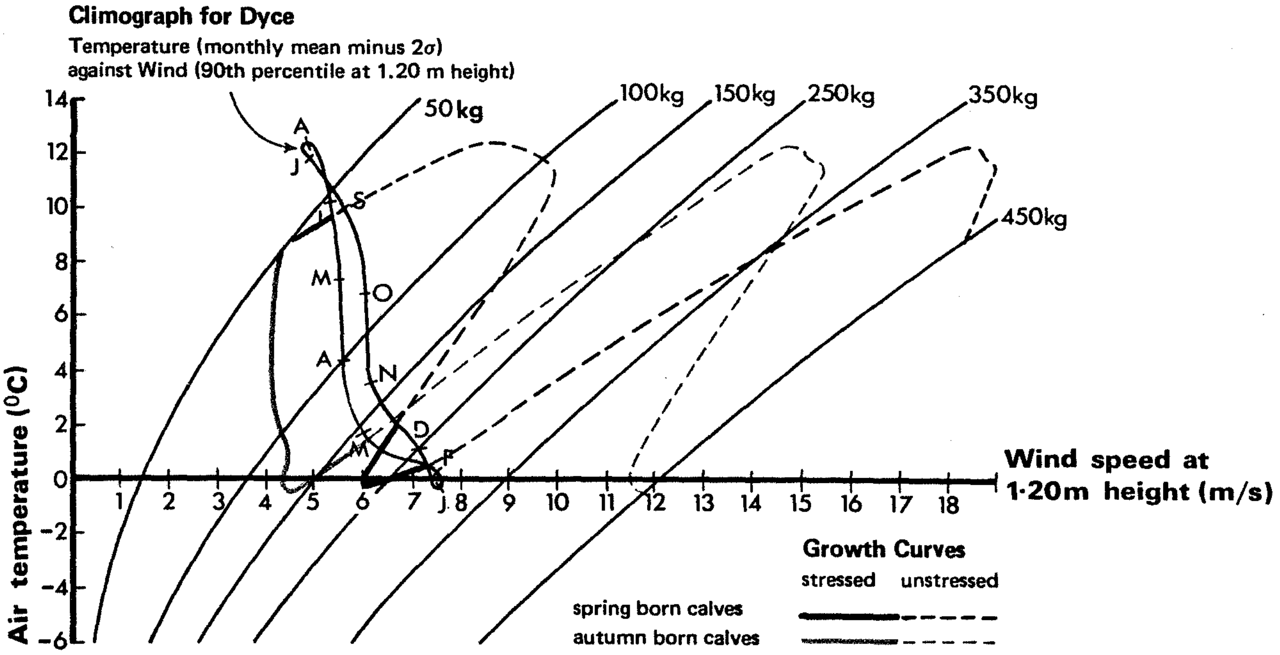

Figure 5 *Bio-climatic assessment of wind speed for beef cattle*

inlet to outlet area ratio of two. However we must bear in mind the hydrodynamic phenomenon of flow area contraction at an opening. For a sharp-edged orifice, which is the extreme case, the area available for flow may be only 60% of the open area. Making allowance for this the outlet area becomes 0.027/0.6 = 0.045 m^2/head. Since there are two animals every 600 mm of building length we require an open ridge of 0.045/0.3 = 150 mm. The opening at each eaves could be achieved using 100 x 18 mm space boarding 1.00 m deep.

Wind

From Figure 6 we see that the external pressure coefficients do not show much variation along the axis of the building. Further, the coefficient at the ridge is identical to that at the eaves on the leeward side. Specifically we find that $C_{pe,in}$ = +0.45 and

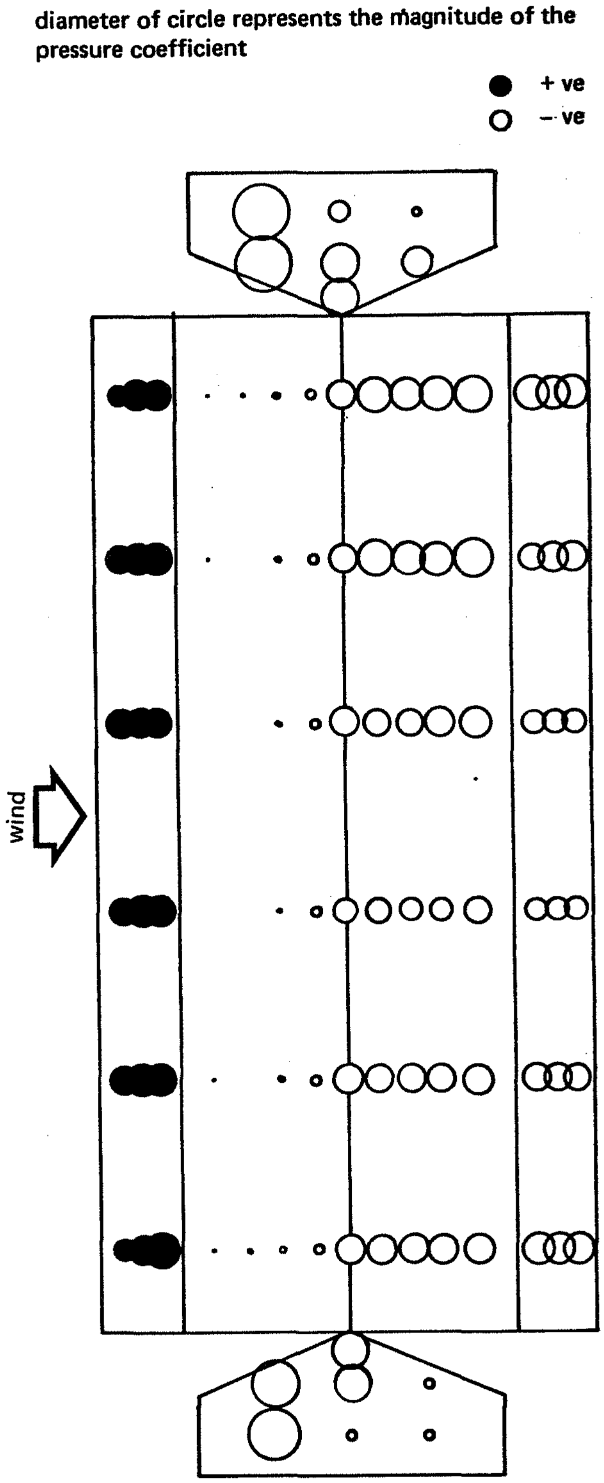

Figure 6 *Wind pressure coefficient distribution measured on a model of a 9 m wide building*

$C_{pe,out} = -0.37$. The windward eaves space boarding will act as an inlet and the leeward eaves and open ridge are outlets so that $A_{in} = 0.045$ m^2 and $A_{out} = 0.09$m^2. Using Equation 15:

$$U_{in} = 0.81 U_{10} \text{ m/s}$$

With an effective inlet area = 0.027 m^2 the ventilation rate due to wind will be:

$$V = 0.022 U_{10} \text{ m}^3\text{/s head}$$

The required minimum winter ventilation rate of 0.022 m^3/s head will then be achieved with a wind speed of 1 m/s.

When air passes through the slots in space boarding small jets are formed, these however rapidly lose their momentum and a more general air movement takes place. Since the effective void fraction of the space boarding is:

$$\frac{0.6 \times 0.045}{0.3 \times 1.0} = 0.09$$

the velocity, averaged over the area of space boarding, inside the building would be given by:

$$U_{int} = 0.073 U_{10} \text{ m/s}$$

This would imply an internal velocity of 1.37 m/s in a fresh gale (Beaufort No. 8), which would lie between a light air and a light breeze (Beaufort No. 1–2).

Beaufort No.	mile/hr	
1	2	direction of wind shown by smoke drift but not by wind vanes
2	5	wind felt on face; leaves rustle; ordinary vane moves
8	42	breaks off twigs; impedes progress

From Figures 4 and 5 it would seem unlikely that deterioration in performance due to cold stress will be experienced by beef cattle, in the building considered, under a combination of air velocity and temperature likely to be encountered in the United Kingdom. The accusation that the building is 'over-ventilated' could not be levelled at the present design. In fact larger openings than these minima would not be objectionable from this viewpoint. Furthermore we have calculated for the most exposed condition, a wind perpendicular to the axis of a free standing building—not a situation we would meet in every case.

The wind shelter factor, based on wind at 1.2 m height, for the building under discussion can be calculated as:

$$0.073 \times (10/1.2)^{1/6} = 0.10$$

i.e. a reduction in wind velocity of 90%. The 1/6 power correction factor allows for the vertical wind velocity profile developed over fairly open rural countryside. It would seem that we could afford to increase our ventilation areas by a factor of four or five and still be within the maximum air movement criterion. This would give rise to a corresponding increase in the minimum ventilation rate due to thermal buoyancy. No one would argue that this would be anything other than desirable in combating respiratory disease which so often appears linked with periods of low wind and low ventilation rates.

DISCUSSION

The preceding sections have attempted to demonstrate that there are methods, using bio-climatic data, which can be used to decide if natural ventilation is suitable for a given application. The theory of natural ventilation has been presented and a sample calculation carried out. That this approach has not been extensively used in the past is quite evident when we come to examine the performance of existing buildings. It is historically interesting to note that in 1891 Buchan (5) recommended 60–70 in^2/head (0.039–0.046 m^2/head) of outlet area for the natural ventilation of stables and byres. This figure is in excellent agreement with the value calculated in the example and also with the empirical figure of 0.045 m^2/head currently recommended as a minimum by SFBIU.

It is known that there does exist today a strong resistance to cold and draughty cattle buildings. There is no question that a properly naturally ventilated cattle building will feel cold and draughty to a man in winter, but to assume the same for cattle must be regarded as sentiment arising from an anthropocentric view or an adherence to a tradition which is not upheld by modern research on the physiology of ruminants (3, 4, 6). If farmers are to be expected to accept well-ventilated cattle buildings then they must be convinced that cold buildings with abundant air movement are good for cattle and desirable in preference to the warm, humid conditions so admired in old-style byres.

There are other factors which apparently limit the acceptability of well-ventilated cattle buildings. The ingress of rain and snow is almost unavoidable and this possibility appears to raise uncertainty and apprehension in the minds of farmers who have no experience of well-ventilated buildings although it is not always entirely clear why. Certainly the quantity of liquid introduced in this way through an open ridge or space boarding is quite negligible in comparison to the liquid in the faeces and urine deposited within the building by the cattle themselves. A wet pass under an open ridge is said to be slippery and often used in argument against natural ventilation, but this is confusing the purpose with the means of achieving it. It is a fault of the designer to specify an open ridge where rain will lead to inconvenience or damage, it is not the fault of natural ventilation. In contrast however it should be noted that farmers operating buildings with open ridges generally have no complaint regarding rain or snow.

It is clear then that there is a barrier to acceptance of well naturally ventilated cattle buildings which must be surmounted partly by education and communication and partly by design of building details.

The importance of the building

Given an acceptance of and a requirement for well-ventilated cattle buildings the remaining problem to be solved is how to incorporate the inlets and outlets in the building shell. The main purposes of the cattle building shell are to keep the cattle in one place, so that feeding and observation is simplified, and to keep the wind, rain and snow off the cattle and off the waste, whether slurry or solid. There is a clear conflict in that certain elements of the external climate are desired to be totally or partially excluded, while large quantities of fresh air are admitted. To resolve this conflict satisfactorily, provision for natural ventilation should be integrated into the building concept functionally, structurally, financially and aesthetically at the design stage.

Natural ventilation should receive a high priority in the list of design criteria. So far as the cattle are concerned the ventilation performance is much more important than, say, the roof construction or the colour, type and position of doors. Too often, because of the low priority assigned, we find the design of a natural ventilation system dictated by a building form rather than the building form reflecting the needs of an efficient natural ventilation system. We can, for example, regard the open ridge as an initial design concept or as a curative measure which can rescue an unsuitable building from failure. The point being made here is that we must free our minds from forming bonds such as 'natural ventilation = open ridge'. There are building forms with no ridge which are very suitable for natural ventilation. Integrated design is an area requiring investigation and should result in more efficient systems.

CONCLUSIONS

The appropriate selection of natural ventilation can only be made through bio-climatic analyses. The methodology of designing for natural ventilation on a quantitative basis has been described. The predictability for uncontrolled natural ventilation can only be as good as the statistical information available for climate.

The problem of inefficient natural ventilation has been around and recorded since the last century. Progress has not been rapid due partly to poor communication, low acceptability and inefficient design. The basic solution so far as the physical requirements are concerned is available; however, it still needs to be given a high enough priority by the buildings designer and incorporated into a scheme at an early stage. More data is required that the designer may judge the effect his decisions may have on the natural ventilation of a building.

Although the technical problems may be overcome there will still remain a barrier to acceptability and implementation. This must be overcome by communication and education.

REFERENCES

1 **Bruce J M** Wind tunnel investigation of a model livestock building The Scottish Farm Buildings Investigation Unit *Internal report* April 1974

2 **Sainsbury D W B** Animal health and housing London Bailliere Tindall & Cassell 1967

3 **Webster A J F** Environmental requirements of beef cattle Beef cattle housing Proceedings of the specialist farm buildings staffs seminar Craibstone Bucksburn 27–29 March 1973 E1–E7

4 **Webster A J F** Physiological effects of cold exposure MTP International review of science Physiology Series One Volume 7 Environmental Physiology London Butterworths 1974

5 **Buchan W P** Ventilation London Crosby Lockwood 1891

6 **Young B A** A practical means for estimating cold stress in cattle University of Alberta feeders' day 1971 12–14

7 **Bruce J M** A computer program for the calculation of natural ventilation due to wind The Scottish Farm Buildings Investigation Unit *Farm Building R & D Studies* 7 November 1975

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Conductive heat loss from the recumbent animal*

J M Bruce The Scottish Farm Buildings Investigation Unit

Essentia non sunt multiplicanda praeter necessitatem (Occam's Razor) .... William of Occam (d. *c.* 1349)

INTRODUCTION

Farm animals under intensive husbandry systems spend a large amount of time lying down. With the trend towards reduced use of litter for economic reasons there is an awareness that there is a significant effect of conductive heat loss on the energy balance for animals. The two ways of controlling the energy balance of an animal are by manipulating the feed intake and by manipulating the thermal environment. However, without the knowledge to predict the effects caused by any change, advance must be to a great extent slow and haphazard.

This paper proposes a model for conductive heat transfer from the recumbent animal. The application of the model is demonstrated using experimental data specifically obtained for the purpose.

THEORETICAL DEVELOPMENT

Figure 1 shows schematically the steady-state heat flow from a recumbent animal.

There is a practical difficulty in defining and measuring a temperature of the heat sink associated with Q_g. However a major simplification is made if it is assumed that $Q_g = 0$ and that all heat lost to the floor is assigned to Q_f. Justification is given for this assumption in an Appendix. Radiant exchange to temperatures other than air temperature is not considered.

The heat balance for the recumbent animal may be written as:

heat produced within the body = heat lost from the body

$$Q = Q_f + Q_a + Q_e \qquad [1]$$

NOTATION

A	total surface area of an animal
A_a	surface area of animal exposed to air
A_f	surface area of animal in contact with floor
F_f	floor factor
L	characteristic length of animal
Q	total rate of energy production of an animal
Q_a	rate of energy loss across A_a due to convection and radiation to a heat sink at air temperature
Q_e	rate of energy loss due to evaporation
Q_f	rate of energy loss through the floor to the air
Q_g	rate of energy loss to the ground
q	total rate of energy loss per m^2 of animal surface
q_e	rate of energy loss by evaporation per m^2 of animal surface
R_a	thermal resistance of air interface
R_f	effective thermal resistance of a floor
R_{f45}	effective thermal resistance of a floor as measured for a 45 kg pig
R_t	whole body thermal resistance of an animal's tissue
t_a	air temperature
t_b	deep body temperature
t_{cr}	critical air temperature
t_f	temperature at the animal-floor interface
t_s	skin temperature
W	weight of an animal

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*This paper was first presented at the Working Session of the 2nd Technical Section of CIGR within the 4th Conference on Rural Building of the Scientific Society for Building at Budapest, Hungary 21–24 September 1976

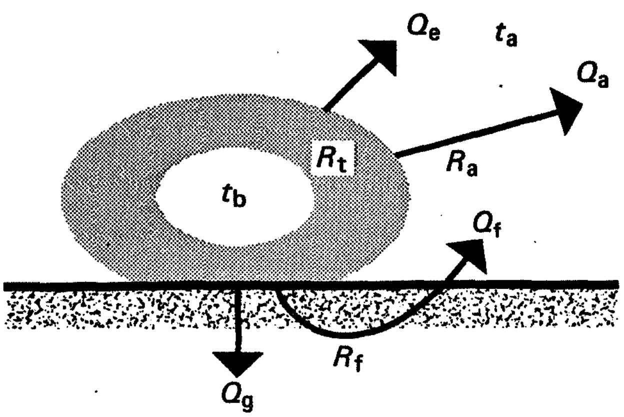

Figure 1 *Thermal pathways from the recumbent animal*

where Q_f is given by:

$$Q_f = \frac{A_f\,(t_b - t_a)}{R_f + R_t} = \frac{A_f\,(t_f - t_a)}{R_f} = \frac{A_f\,(t_b - t_f)}{R_t} \qquad [2]$$

Since evaporation occurs directly from the skin and negligible resistance is assumed due to evaporation:

$$Q_a + Q_e = \frac{A_a\,(t_b - t_s)}{R_t} \qquad [3]$$

and

$$Q_a = \frac{A_a\,(t_s - t_a)}{R_a} \qquad [4]$$

Substituting t_s from Equation 4 into Equation 3 and rearranging gives:

$$Q_a = \frac{A_a\,(t_b - t_a) - Q_e\,R_t}{R_t + R_a} \qquad [5]$$

Substituting Equations 2 and 5 into Equation 1 gives:

$$Q = \frac{A_f\,(t_b - t_a)}{R_f + R_t} + \frac{A_a\,(t_b - t_a)}{R_a + R_t} + \frac{R_a\,Q_e}{R_a + R_t} \qquad [6]$$

rearranging and substituting $A_a = A - A_f$ gives:

$$t_b - t_a = \frac{Q - \dfrac{R_a\,Q_e}{R_a + R_t}}{\dfrac{A}{R_a + R_t}\left[1 + \dfrac{A_f}{A}\left(\dfrac{R_a + R_t}{R_f + R_t} - 1\right)\right]} \qquad [7]$$

writing $q_i = Q_i/A$ gives:

$$t_a = t_b - \frac{q\,(R_a + R_t) - q_e\,R_a}{1 + \dfrac{A_f}{A}\left(\dfrac{R_a + R_t}{R_f + R_t} - 1\right)} \qquad [8]$$

If q is the thermoneutral heat production and q_e is taken as the minimum evaporative heat loss then the air temperature given by Equation 8 is the critical temperature for the animal, i.e. the air temperature below which the animal must increase its heat production so that deep body temperature is maintained.

$$t_{cr} = t_b - [q\,(R_a + R_t) - q_e\,R_a]/F_f \qquad [9]$$

where the floor factor F_f is given by:

$$F_f = 1 + \frac{A_f}{A}\left(\frac{R_a + R_t}{R_f + R_t} - 1\right) \qquad [10]$$

A_f/A is of course simply the proportion of the animal's surface in contact with the floor so that $F_f = 1$ when the animal is standing. Also $F_f = 1$ if $R_f = R_a$ regardless of A_f/A. It is interesting to note that F_f for a given floor is dependent on the external insulation (which is determined by coat length, air speed and wetness), the tissue insulation (which is determined by condition and age), the recumbent posture, and the floor thermal resistance as defined in Equation 2.

EXPERIMENTAL

The apparatus designed to measure the conductive heat loss to floors is illustrated in Figure 2. The contact area and length/breadth ratio is meant to represent a 45 kg pig. The electrical energy required to maintain the internal temperature at 39.6°C was continuously measured. Allowance was made for the heat loss through the insulated top and sides.

The skin temperature was measured by thermocouples so that the 'tissue' insulation could be calculated.

Values were measured only after a steady state had been attained, which could require up to two hours after initial contact with a floor. More than 20 floors have been tested. These include straw and woodchip littered floors, wooden slats, expanded metal, rubber mats, metal slats, concrete slats, dry concrete and slurry-covered concrete in a cattle building.

RESULTS

It is important that the measuring apparatus should conform to some particular animal both in physical size, temperature levels and heat flux. That the temperature levels and heat flux closely simulate those of light pigs is confirmed by the skin temperature data of Kelly, Heitman and Morris (1). If the tissue insulation of a pig and the external insulation are constant then:

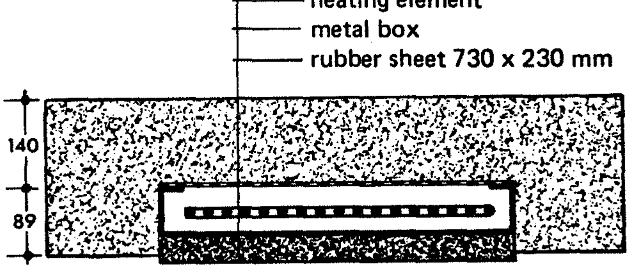

Figure 2 *Section through simulated pig*

$$t_s \approx \frac{R_t}{R_t + R_a} t_a + (1 - \frac{R_t}{R_t + R_a}) t_b \qquad [11]$$

The 'tissue' insulation (R_t) was found to be 0.053°Cm²/W and the external insulation (R_a) was found to be 0.12°Cm²/W which is in good agreement with published values for hairless animals (2). With these values Equation 11 becomes:

$$t_s = 0.31\ t_a + 27.3 \qquad [12]$$

Kelly *et al* (1) give the relationship for measurements on light pigs as:

$$t_s = 0.31\ t_a + 27.6 \qquad [13]$$

If Kelly's pigs had similar external insulation values to that normally measured then the 'tissue' insulation of the simulated pig must also be similar to that of Kelly's pigs.

The effective thermal resistance of a floor referred to the area of contact is calculated from Equation 2. Table 1 shows a range of floor types with their effective thermal resistances as measured with the simulated pig.

Table 1 *Effective thermal resistances of floors as measured with the simulated 45 kg pig with a contact ratio of 0.2*

Floor type	Thermal resistance R_{f45} (°Cm²/W)
38 mm dry redwood chips on concrete	0.71
17 mm dry straw on concrete	0.46
17 mm wet straw on concrete	0.23
Wooden slats 58 mm wide, 10 mm gap, 70 mm deep	0.23
250 mm growing grass after heavy rain	0.13
Expanded metal	0.12
16 mm rubber cow mat on concrete	0.11
12 mm K board (polystyrene and cellulose fibre) on concrete	0.078
T-metal slats 24 mm wide, 12 mm gap	0.067
Concrete slats 100 mm wide, 19 mm gap, 75 mm deep	
pig lying parallel	0.055
pig lying across	0.049
Muddy ground	0.044
Dry concrete	0.039
Concrete covered with cow slurry	0.031

The effective thermal resistances of the various floors tested cover a range from 0.031 to 0.71°Cm²/W i.e. a 23-fold variation. Such a great variation could however have been expected from a knowledge of the thermal resistivities of the floor materials. The following indicate a 20-fold variation (3):

Concrete	0.71°Cm/W
Wet loam	0.83°Cm/W
Hardwood	6.7 °Cm/W
Loose sawdust	12.5 °Cm/W
Straw thatch	14.3 °Cm/W

The simple model adopted for solid floor conduction implies that the effective thermal resistance should be proportional to the thermal resistivity of the floor material. This may well be true in which case it is possible to consider an equivalent thickness of floor material. For example, using the concrete data, the equivalent thickness would be 0.039/0.71 m or 55 mm. For the concrete slats the equivalent thickness would be 69–77 mm; the slat depth was 75 mm.

Scaling factor for other animal weights

If all the heat is lost laterally from an animal on a solid floor then the distance the heat must flow for a similar posture will be proportional to a characteristic length. Therefore $R_f \propto L$ and for animals it can be roughly stated that a characteristic length is proportional to $W^{1/3}$. So as a first approximation $R_f \propto W^{1/3}$ which gives:

$$R_f = R_{f45}(W/45)^{1/3} \qquad [14]$$

where R_{f45} is the thermal resistance given in Table 1 for solid floors.

For a perforated floor such as expanded metal no such scaling factor would be required as the heat loss from below the animal is more dependent on the resistance to convection. Slatted floors would appear to have some of the characteristics of solid and perforated floors so that the scaling factor should perhaps be less powerful than given above for large animals but more powerful for very small animals. Small animals would be those whose body was on a scale similar to that of the slat width.

Scaling factor for posture

Just as the solid floor thermal resistance needs scaling for animal size there is a need to scale for the change in size of the contact area due to postural behaviour. Consider, for simplicity, that the animal alters the contact ratio mainly by reducing the width of the contact area, and that the main heat loss is perpendicular to the long axis of the contact area: the thermal resistance is then proportional to the contact area. The scaling factor for the quoted values is then the actual contact ratio divided by 0.2. Similar considerations apply to perforated and slatted floors as discussed in the preceding paragraph.

The predicted effect of floors on critical temperature

Figure 3, shows the predicted critical temperatures for 1.5, 45 and 180 kg pigs respectively. A few floor descriptions have been located along the axis to provide a practical frame of reference. Contact area ratios 0.0 to 0.3 have been plotted. A_f/A is a function of the shape of the animal and its recumbent postural behaviour. It would seem logical that an animal in the cold would attempt to minimise its contact area when $R_f < R_a$. On the other hand when $R_f > R_a$ the animal would attempt to maximise its contact area. Observations

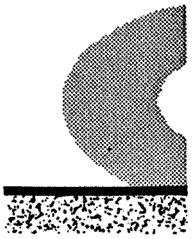

Figure 1 *Therm*

where Q_f is given

$$Q_f = \frac{A_f (t_b - t_a}{R_f + R_t}$$

Since evaporatior
negligible resistar

$$Q_a + Q_e = \frac{A_a (t}{R}$$

and

$$Q_a = \frac{A_a (t_s - t_a)}{R_a}$$

Substituting t_s fr
rearranging gives:

$$Q_a = \frac{A_a (t_b - t_a}{R_t +}$$

Substituting Equ

$$Q = \frac{A_f (t_b - t_a)}{R_f + R_t}$$

rearranging and s

$$t_b - t_a = \frac{}{\frac{A}{R_a + R}}$$

writing $q_i = Q_i/A$

$$t_a = t_b - \frac{q (R_a +}{1 + \frac{A_f}{A}(}$$

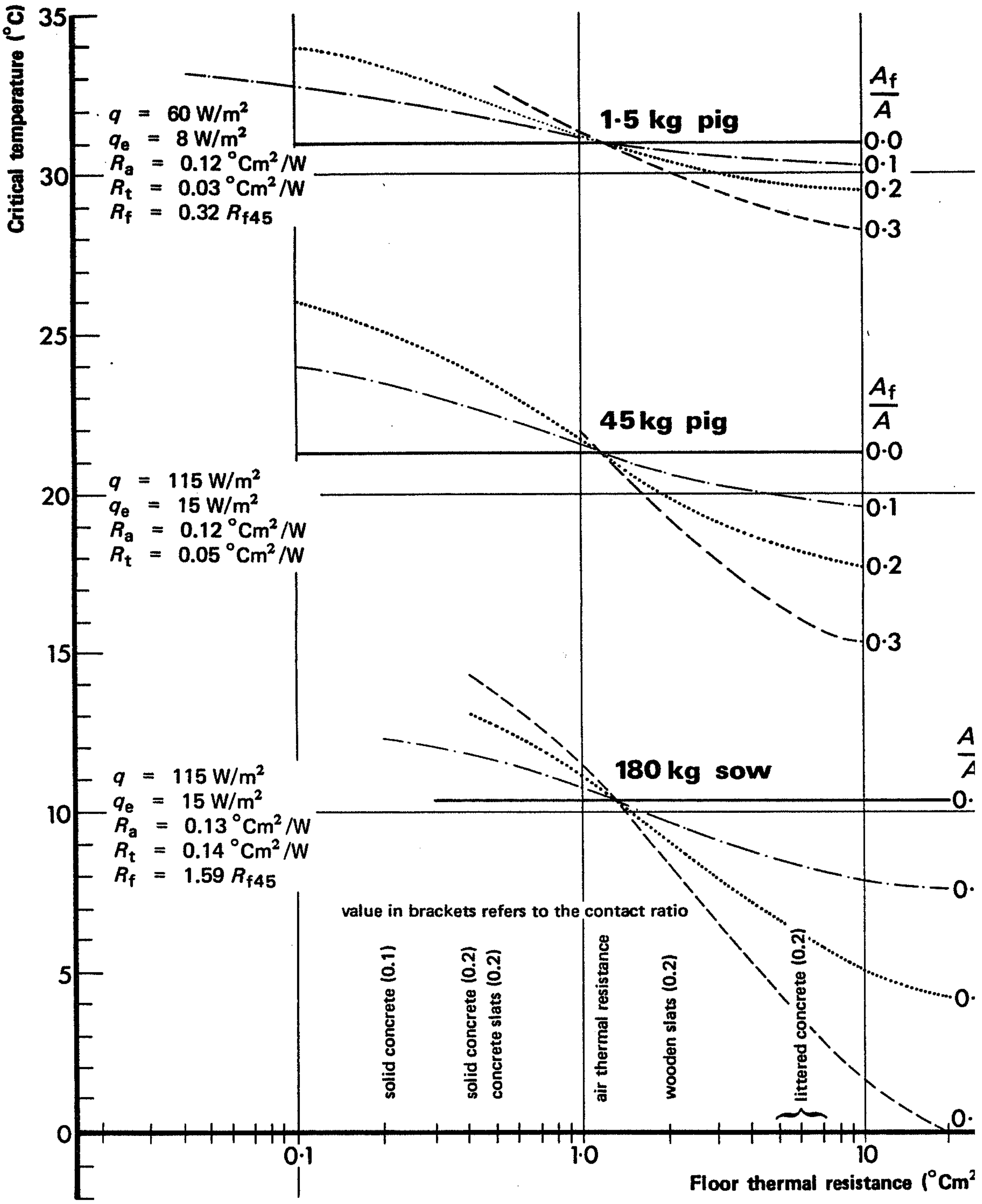

Figure 3 *Critical temperatures for 1.5 kg, 45 kg and 180 kg pigs*

suggest that on a cold floor a pig can have 10% or less of its body in contact with a rigid floor while it can have up to 20% in contact in a comfortable environment (4). Where deep litter is available there is the possibility of burrowing so that the whole body is covered.

Following the graphs $A_f/A = 0.1$ for $R_f < R_a$ and $A_f/A = 0.2$ for $R_f > R_a$ it is seen that the predicted ranges of critical temperatures going from littered concrete to bare concrete allowing for postural scaling would be about:

30.5–33.0°C for 1.5 kg
18.0–23.5°C for 45 kg
5.5–12.0°C for 180 kg

DISCUSSION

Stephens (5) states that savings in energy
and 22% could be made at 10, 20 and 30°C
for piglets less than 24 hours old by moving
concrete onto straw. For piglets between 2
the corresponding savings were 18, 27 and 1
the 1.5 kg pig R_f (concrete) =

$$0.039\ (1.5/45)^{1/3} \times 0.5 = 0.007°\mathrm{Cm^2/W}\ \mathrm{a}$$

$$R_f\ (\mathrm{straw}) = 0.46\ (1.5/45)^{1/3} = 0.147$$

The contact ratio is assumed to be 0.1 on c
and 0.2 on straw. The ratio of heat loss on s
loss on concrete can be calculated from:

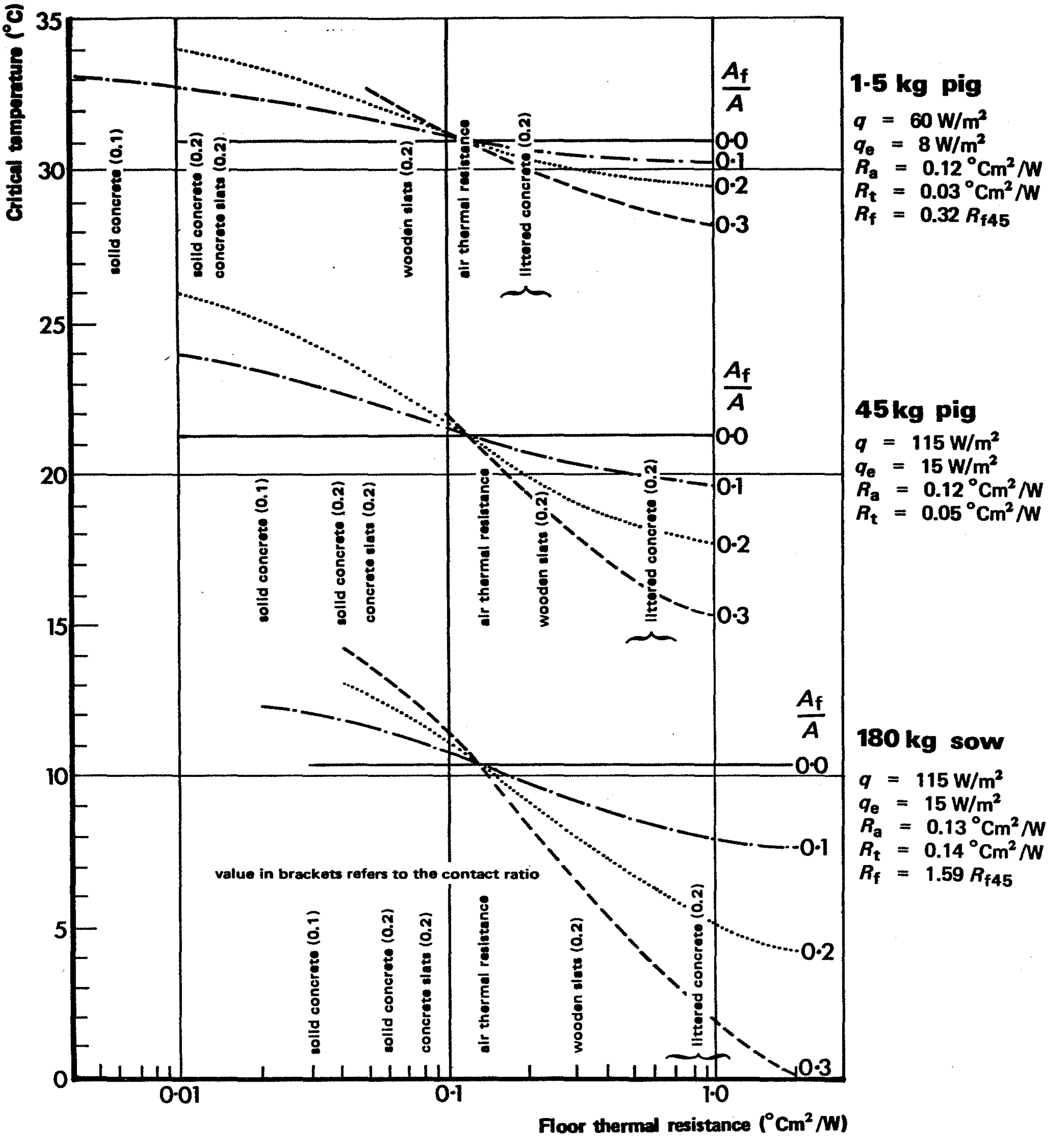

Figure 3 *Critical temperatures for 1.5 kg, 45 kg and 180 kg pigs*

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18.0–23.5°C for 45 kg
5.5–12.0°C for 180 kg

DISCUSSION

Stephens (5) states that savings in energy of 17, 27 and 22% could be made at 10, 20 and 30°C respectively for piglets less than 24 hours old by moving them from concrete onto straw. For piglets between 2 and 9 days the corresponding savings were 18, 27 and 12%. For the 1.5 kg pig R_f (concrete) =

$$0.039\ (1.5/45)^{1/3} \times 0.5 = 0.007\,°\mathrm{Cm^2/W}\ \text{and}$$

$$R_f\ (\text{straw}) = 0.46\ (1.5/45)^{1/3} = 0.147$$

The contact ratio is assumed to be 0.1 on concrete and 0.2 on straw. The ratio of heat loss on straw to the loss on concrete can be calculated from:

$$\frac{(t_b - t_a)\left[\dfrac{A_f}{A\,[R_t + R_f\,(\text{straw})]} + (1 - \dfrac{A_f}{A})\,\dfrac{1}{R_t + R_a}\right] + q_e}{(t_b - t_a)\left[\dfrac{A_f}{A\,[R_t + R_f\,(\text{conc})]} + (1 - \dfrac{A_f}{A})\,\dfrac{1}{R_t + R_a}\right] + q_e}$$

which gives:

$$\frac{(39 - t_a)\left[\dfrac{0.2}{0.03 + 0.147} + \dfrac{0.8}{0.03 + 0.12}\right] + 8}{(39 - t_a)\left[\dfrac{0.1}{0.03 + 0.007} + \dfrac{0.9}{0.03 + 0.12}\right] + 8}$$

The reduction in heat loss in going from concrete to straw is then calculated to be 25, 25 and 23% at 10, 20 and 30°C respectively. These values are of similar magnitude to the values given by Stephens. Stephens also states that the energy losses were similar for piglets kept on straw at 10°C and concrete at 18°C. Setting the ratio above to unity gives the corresponding temperatures as 10°C and 17.5°C which is in good agreement with Stephens.

The effective critical temperatures for groups of 40 kg pigs was given by Verstegen and Van der Hel (6) as 11.5—13.0°C on straw and 19.0—20.0°C on concrete slats which gives a temperature difference of 7°C. This compares with a predicted difference of 5°C for a single 45 kg pig allowing for postural effects.

From Figure 3 it is seen that it is not possible to compensate for low air temperatures to any great extent for the 1.5 kg pig by using straw. The calculations confirm that even with straw supplementary heating would still be required in the UK to eliminate chilling in very young pigs. For the 45 kg pig however straw can compensate for temperature deficit to an extent which can make unheated buildings with straw bedding a practical proposition. The use of straw gives an even greater effect in reducing the critical temperature below the standing value for a 180 kg sow. Lying on concrete, on the other hand, does not increase the critical temperature very much above the standing value. These conclusions are borne out in the husbandry systems which have evolved in the UK; piglets are supplied with heat regardless of flooring, both heated and unheated buildings are used for weaned and growing pigs, and in recent years the practice of tethering sows on concrete has increased.

The main importance of this work is however not that it confirms practice, but that by means of the model and calculations it is possible to understand why the various systems are possible. Further, it allows the biothermal analysis of proposed designs before they are put into practice.

An extensive review of published studies on the heat loss to floors from livestock indicate that most experimenters have not postulated a physical statement to describe the process. This inhibits the use of the data. Data collection in the absence of any methodology to process it and make predictions often results in ineffective research. A simple theoretical approach can lead to a mathematical model which provides at once a framework for experimental work and a basis for prediction. In technology effective prediction must be the aim; this is not the same as accurate prediction. The value of accuracy is not always equal to the cost of achievement.

CONCLUSIONS

1. A simple theory for the conductive heat loss from the recumbent animal has been developed and justified.

2. Values for the effective thermal resistance of a variety of floors have been given. They require to be scaled according to the size of the animal and its posture.

3. Predictions of the critical air temperatures have been made for 1.5, 45 and 180 kg pigs for a range of floors. These predictions are in agreement with experimental results.

APPENDIX

Justification of the model for conductive heat loss

Mount (7) used a gradient layer mat to measure the conducted heat from new-born pigs to various floors. If for each combination of floor and posture the tissue insulation and the proportion of body area in contact with the floor were constant then Equation 2 implies that the ratio of the conducted heat loss to the rectal—ambient temperature difference should be independent of ambient temperature for constant floor thermal resistance. Given the variability inherent in biological specimens the data of Mount confirms this.

Kelly, Heitman and Morris (1) also measured the conductive heat flux from recumbent pigs. They give a least squares regression which relates the interface temperature to air temperature* thus:

$$t_f = 0.67\,t_a + 11.4 \qquad [15]$$

From Equation 2 the interface temperature can be written:

$$t_f = \left(\frac{R_t}{R_f + R_t}\right) t_a + \left(1 - \frac{R_t}{R_f + R_t}\right) t_b \qquad [16]$$

which has the same form as Equation 15. If the proposed model for conductive heat loss is correct then:

$$\frac{R_t}{R_f + R_t} = 0.67 \text{ so that } R_t = 2R_f$$

this would give an intercept (1 − 0.67) 39 = 13°C This is very close to 11.4°C so that the model is verified.

Graee (8) used a simulated cow to measure conductive heat loss to slatted floors. It would seem most reasonable to apply Equation 2 to a slatted floor and this is upheld by his data. His heat loss data show a linear dependence on air temperature with the intercept at 30°C, his controlled temperature, this verifies that for a slatted floor the effective thermal resistance was constant.

From a different but related field of heat transfer (9) there is also a strong indication that Q_g can be neglected

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*There is a misprint in their original paper in comparison to Q_f for small floors. Billington (9) emphasises throughout his paper the dominance of the peripheral heat loss for small floors (< 10 m wide).

An empirical formula given by Billington for heat loss through the long edges of a rectangular floor gives R_f = 0.078°Cm^2/W for a floor the same size as the simulated pig. The peripheral/ground heat loss ratio is calculated to be 9.0 so that no gross error is involved in ignoring the ground heat loss.

It appears that Q_g, the ground heat loss, is a small part of the total conductive heat loss to a floor and the available data can be interpreted without considering Q_g. There seems therefore to be no technological value in its retention in a theory for conductive heat loss from recumbent animals at this stage. The simplicity of Equation 2 is no recommendation in itself. However since it does appear to agree with the available data there is no cause to reject it at present. Time and data will supply the test.

REFERENCES

1 **Kelly C F Heitman H Morris J R** Effect of environment on heat loss from swine *Agricultural Engineering* **29** (12) December 1948 525–529

2 **Blaxter K L** The energy metabolism of ruminants London Hutchinson 1962 130

3 **IHVE** Guide book A London The Institution of Heating and Ventilating Engineers 1971

4 **Hsia L** Observations of the recumbent postural behaviour of pigs The Scottish Farm Buildings Investigation Unit 1977 (in press)

5 **Stephens D B** The metabolic rates of new-born pigs in relation to floor insulation and ambient temperature *Animal Production* **13** 1971 303–313

6 **Verstegen M W A van der Hel W** The effects of temperature and type of floor on metabolic rate and effective critical temperature in groups of growing pigs *Animal Production* **18** 1974 1–11

7 **Mount L E** The heat loss from new-born pigs to the floor *Research in Veterinary Science* **8** 1967 175–186

8 **Graee T** Heat exchange through animal/floor interface *International Journal of Farm Building Research* **6** September 1971 1–13

9 **Billington N S** Heat loss through solid ground floors *Journal of the Institution of Heating and Ventilating Engineers* **19** November 1951 351–372

ADDENDUM

Since the writing of the previous paper further advances have been made in quantifying the interaction of pigs' nutrition and environment. By making what is hoped to be appropriate assumptions regarding, for example, the maintenance requirements and efficiency of utilisation of metabolisable energy, the analysis of the feed:floor:air temperature interaction is possible.

Figures A1, A2 and A3 show this relationship for 40 kg, 65 kg and 180 kg pigs. The major points to note are that both feed intake (kg of meal/day at 12.5 MJ/kg) and floor type affect the appropriate air temperature for pigs and that changing from straw to concrete can have a more significant effect than changing feed level.

With this sort of quantitative information the time is closer when the analysis, on an economic basis, can be carried out for bio-climatic systems which include the nutritional and structural elements.

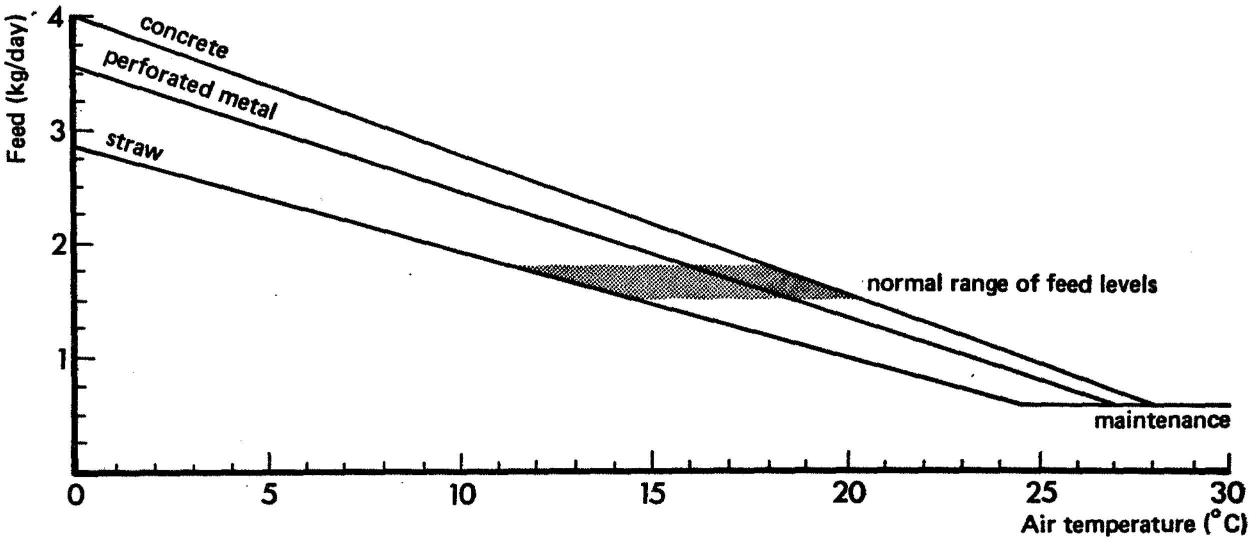

Figure A1 *Feed–floor–air-temperature relationship for 40 kg pig*

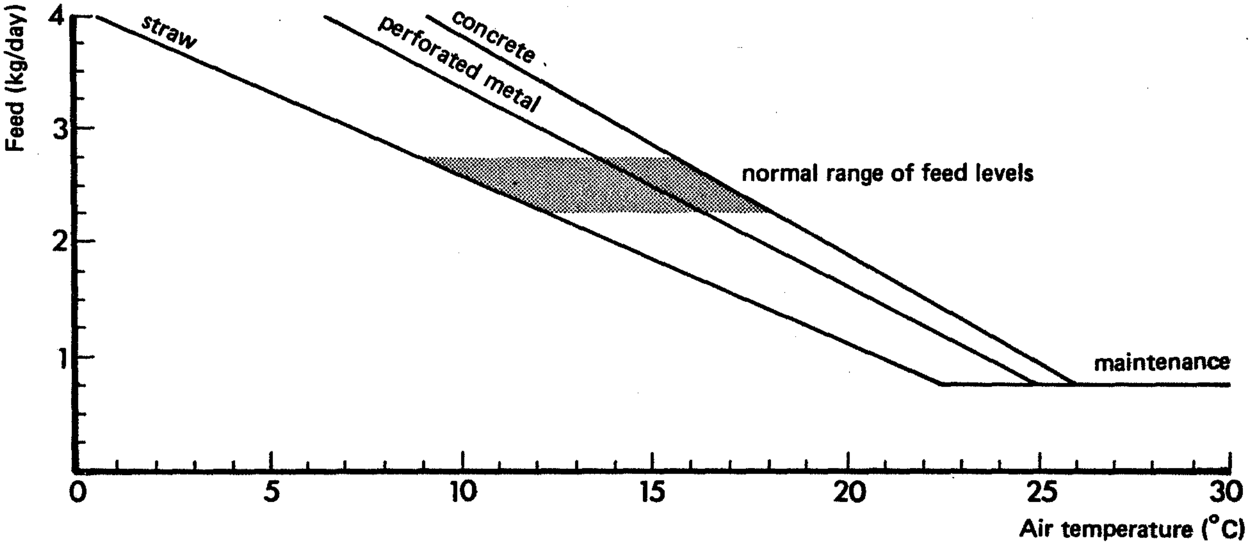

Figure A2 *Feed–floor–air-temperature relationship for 65 kg pig*

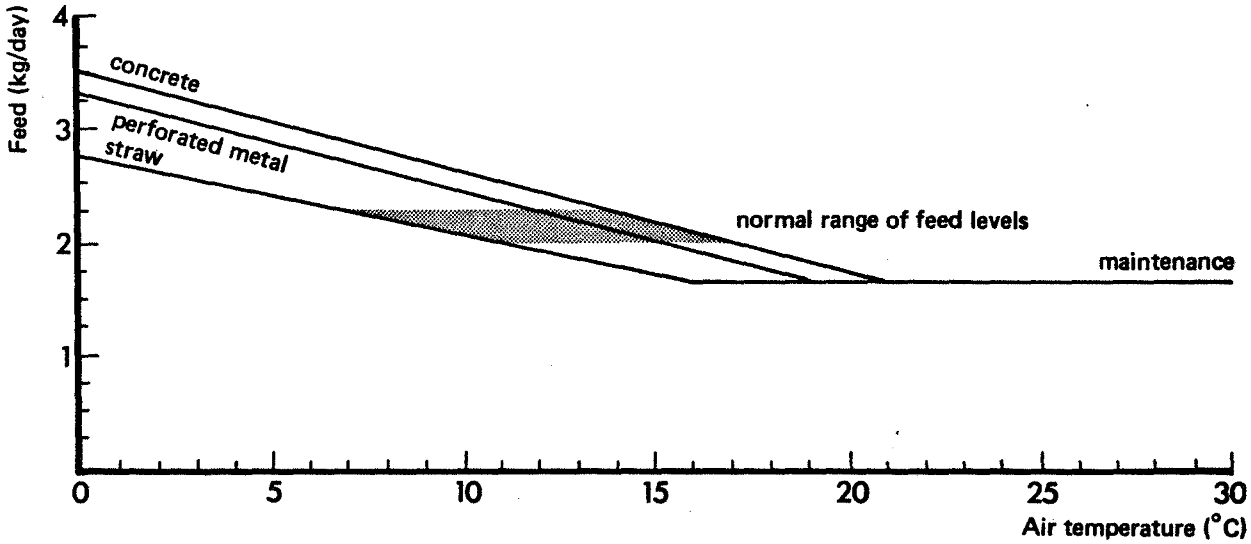

Figure A3 *Feed–floor–air-temperature relationship for 180 kg pig*

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