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A LIVESTOCK MODEL FOR WASTE HEAT UTILIZATION ASSESSMENT*

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ABSTRACT

Thermal effluents from power plants can be used to accelerate the growth of farm animals. Livestock operations can be made more profitable by raising animals under controlled temperature conditions to obtain maximum food conversion efficiency. In order to evaluate whether the benefits of increased productivity outweigh the costs of temperature control, it is necessary to simulate the operation of livestock facilities. The livestock simulation model presented here has two parts. First, a materials balance approach is used to estimate the growth of animals at various temperatures. Second, a heat balance enables us to determine how much heat must be supplied to the buildings under anticipated weather conditions in order to maintain the desired temperature. In turn, this is used to compute the mass flow rate of heated water needed to provide the required heat.

Considerable amounts of low grade heat are rejected annually to the environment [1]. The temperature of this low grade heat is too low for most industrial processes, but it is ideal for living organisms. Fish, livestock, and plants grow faster at optimum temperatures, and require less nutrients. Biological waste treatment is accelerated, so a greater volume of wastes can be handled. Air flow requirements for crop drying can be reduced if the temperature of the air is elevated.

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* This is the fourth in a series of articles on the utilization of waste heat from power plants. The first article presented our method for site specific assessment of technology options, and a summary of our findings. The other articles describe models for simulating the aquaculture, greenhouse, crop drying, and wastewater treatment components of an integrated waste heat utilization complex.

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Further efficiency improvements may be obtained by linking together several operations into a single integrated complex. This mimics the natural cycling of nutrients among plants and animals, thereby minimizing both waste disposal and feed costs. Consider the arrangement shown in Figure 1. The waste-laden effluent of the aquaculture facilities passes through a series of waste treatment ponds. The fish waste provides nutrients for water hyacinth and algae production. The water hyacinths are harvested mechanically and fermented into ethanol, while the algae are filtered biologically by clams in the clam and crayfish pond. The renovated water is aerated and returned to the aquaculture facility. Livestock shelters for broiler chickens and swine litters provide ample manure for the anaerobic digesters. Municipal sewage and refuse can be added as necessary to achieve the proper moisture content and chemical composition. The anaerobic digestion process yields methane gas, which can be burned to provide backup heating whenever waste heat supplies are inadequate. The liquid by-product supernatant is treated in the algae pond, while the solid sludge portion becomes fertilizer for the greenhouses. This complex produces fish, shellfish, livestock, vegetables, flowers, ethanol, and methane for wholesale markets, and also provides waste treatment and crop drying services.

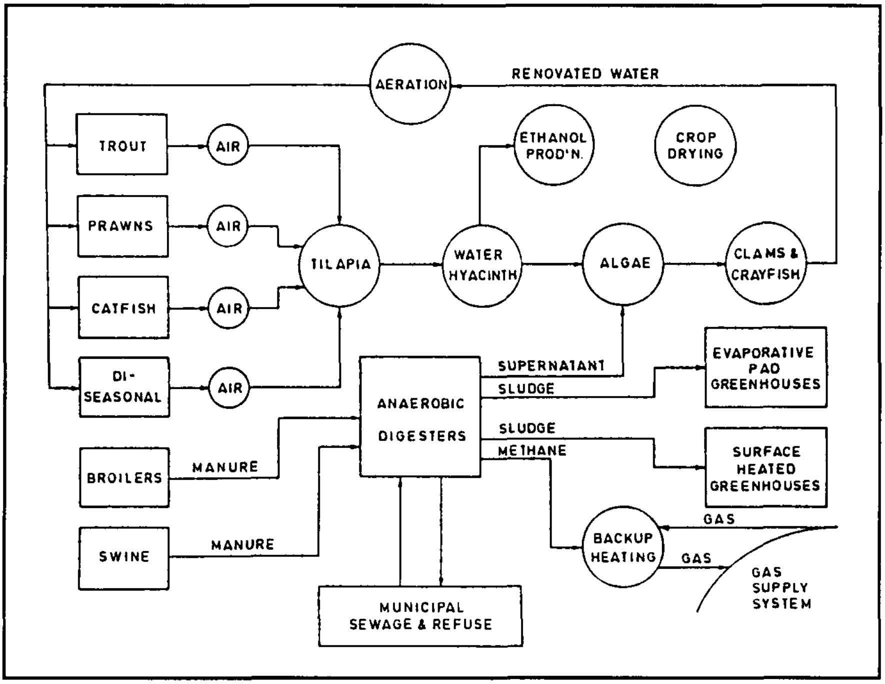

Figure 1. Integration of waste heat utilization options.

By varying the proportion of the complex which is devoted to each particular technology, we can adapt this arrangement to a specific site. We are faced with a bewildering array of power plant operating data, local market prices, anticipated weather conditions, biological production functions, and interconnections among diverse production facilities. Perhaps the only way to analyze such a complicated system is to simulate its performance under numerous sets of conditions, and then use optimization techniques to select the best configuration for each specific site [2, 3].

In this article, we describe a model for simulating livestock production facilities. This model can be combined with others to aid in the design of integrated waste heat utilization complexes.

ENVIRONMENTAL CONTROL OF LIVESTOCK SHELTER

The principal food animals in modern agriculture are swine, cattle, and poultry. Swine (sometimes called "pigs" or "hogs") provide ham, pork, and bacon. Cattle may be used to produce milk ("dairy cows") or slaughtered to produce beef. Poultry may be raised primarily for their eggs ("layers") or they may be intended for roasting ("broilers").

Most of these animals need only simple shelters to survive. It is most important to provide adequate ventilation, keep the animals dry, and block the winds. It is also essential to maintain sanitary conditions. Temperature and humidity control greatly improve performance by relieving physiological stress.

Animals frequently have different temperature requirements for their reproductive and growing-out stages. Poultry do not need high temperatures in order to lay eggs, but their weight gain is significantly accelerated by supplemental heat as they are grown to broiler size [4]. Conversely, swine do not require supplemental heat to grow at an acceptable pace, but can not brood their young ("care for newborns") in uncontrolled environments [5]. Therefore, environmental control is advisable for broiler growing and swine brooding, but not for broiler brooding and swine growing. Cattle generally do not need any supplemental heating at all [6].

About 17 x 10^{12} Btu are consumed each year in the United States to produce 2.7 billion broilers [7]. An additional 3 x 10^{12} Btu are required annually for nine million litters in swine brooding operations [8]. The need for temperature control, and the magnitude of potential energy savings, make swine brooding and broiler growing the most promising candidates for waste heat utilization in livestock operations.

Swine Brooding

An eight-week cycle is common in swine brooding. The sow is given two weeks to settle into her new stall before giving birth to her litter. Newborn piglets require temperatures near 86°F. A gradual decrease of 5°F per week over a period of five weeks enables the litter to adjust to the 60°F which is normal for the sow [9]. One more week is allotted for a thorough cleaning of the stall before the next sow is brought in to farrow (give birth).

A typical farrowing building is divided into eight rooms which are assigned on a rotating basis (see Figure 2). Each room has its brooding cycle begin on a different week so that births will occur in only one room at a time.

Each of the eight rooms has five stalls. A farrowing stall has dimensions of five feet by seven feet (see Figure 3). The sow is confined at the center of the stall to prevent her from crushing the piglets. The sides of the stall, known as the "creep area," are heated from below the floor, since the piglets need supplemental heat. The floor beneath the stall slopes towards a slotted grate. Beneath the grate is a pit which runs the length of the row of stalls. Wastes collect in these pits for easy cleaning [10]. The sow and litter remain in the same stall during their entire stay, but the creep area heating requirements rotate from room to room in an eight week cycle. In any given week, two rooms contain pregnant sows, five rooms contain nursing litters, and one room is being thoroughly cleaned.

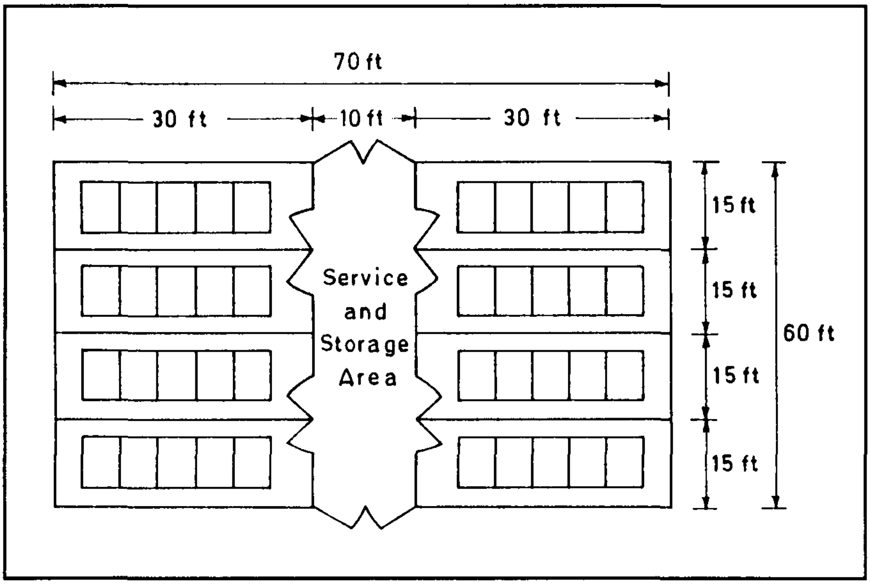

Figure 2. Schematic of typical swine farrowing building.

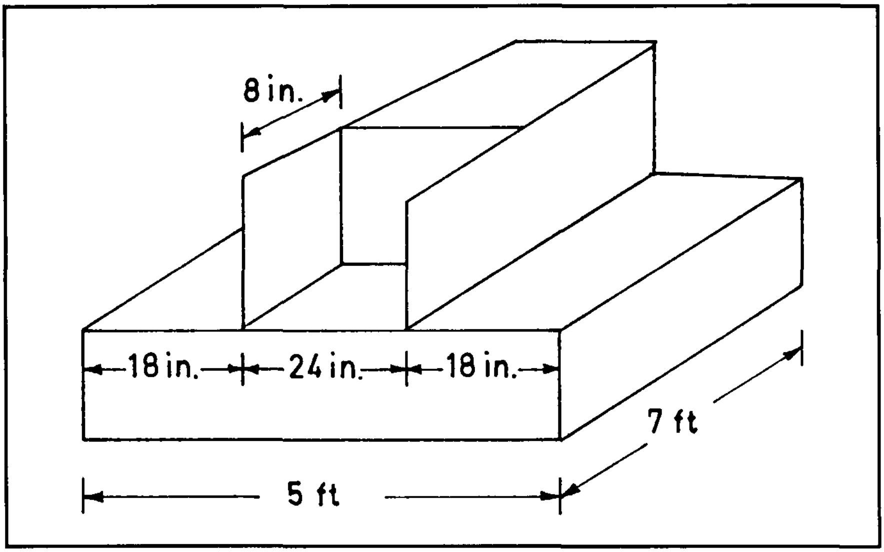

Figure 3. Schematic of farrowing stall.

Broiler Growing

Broiler operations are described in detail by North [11]. Day-old chicks may be ordered from commercial hatcheries, which deliver them by the truckload. These chicks weigh approximately 0.125 pounds; the aim is to raise them to a market weight of four pounds. This takes approximately sixty days (eight weeks).

Initially the chicks are confined in the center of the growing room, at an areal packing density of 0.35ft^2/chick. The partitions are gradually shifted to allow more space as the chicks grow. Generally the partitions are completely removed after three weeks, and the chicks may roam about the entire floor, at an areal density of 0.8ft^2/chick. About three inches of space per bird is required along the automatic feeding and watering machines; these machines are about forty feet long. No more than 2500 birds should be raised on a single floor, and the lighting should be kept dim to reduce movement and cannibalism [11].

Figure 4 shows a typical broiler house with a capacity of 4000 birds (2000 birds per room). We will assume that the entire floor of the house contains one inch polyethylene pipes embedded in concrete, spaced one foot apart. Warm water flows through them to heat the building.

Although the temperature of the floor may be uneven, this is desirable. According to North, poultry houses with heated concrete floors should have different temperature regimes to allow birds to select their own individual comfort level and to promote the normal development of feathers [11]. Best results

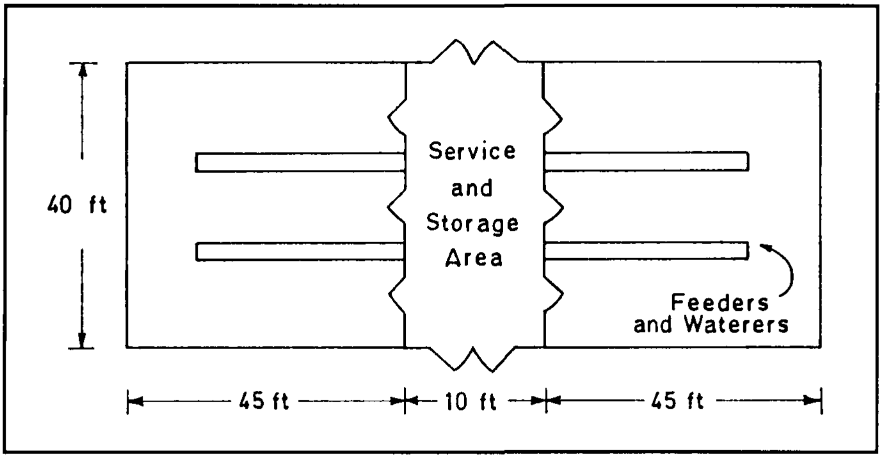

Figure 4. Schematic of broiler growing building.

are obtained when chicks are started at about 90°F, and lowered in 5°F per week increments, but not to below 70°F [10].

MATERIALS BALANCE

A homeothermic (warm-blooded) animal maintains a nearly constant body temperature regardless of the temperature of its environment, T. In order to maintain the most basic body functions, it must consume energy through food at or above some minimum rate, E_m. Unless it is starving, it will actually consume food energy at some higher rate, E_{intake}.

Meanwhile, the animal is losing heat to its environment. Below some critical temperature, T', this is predominantly sensible heat loss, S. Above the critical temperature, latent heat loss, L, will dominate.

The energy which remains is available for gain, and some is converted into flesh. How much energy is available in a pound of feed, E_f, is a property of the feed. The maximum amount of feed which can be consumed by the animal, E_{max}, is obviously a function of its size and hence its weight, W. Most of the other operational characteristics are also functions of weight.

Figure 5 is a graphical representation of this model. At this level of abstraction, broilers and swine function in the same way. To apply this model, one merely fits equations to data gathered by experimentation with live animals at various weights and temperatures.

A modified form of the operational model for swine which was developed by Teter, DeShazer, and Thompson is presented here [12].

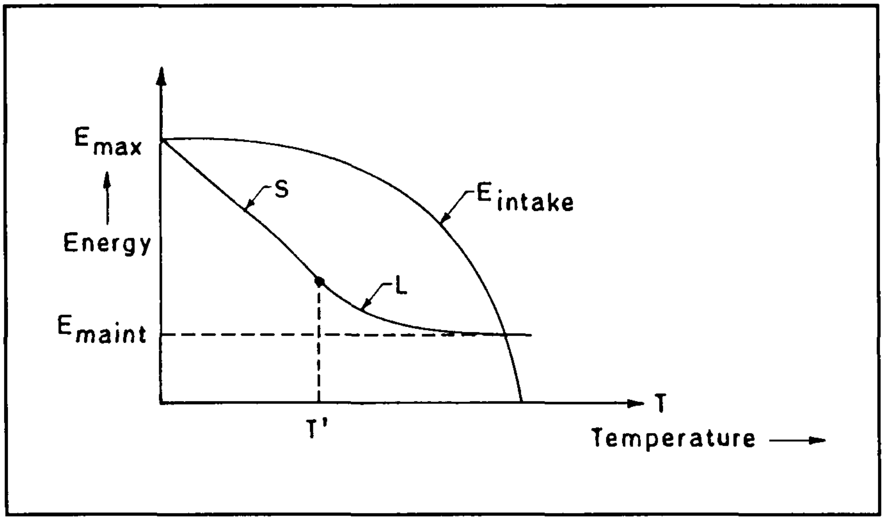

Figure 5. Operational characteristics of homeothermic animals [12].

$$K = 0.06 - 0.00005W \tag{1}$$

$$E_M = 22000 \text{ arcsinh } \frac{W}{49} \text{ [radians]} \tag{2}$$

$$E_m = 260W^{0.75} \tag{3}$$

$$E_i = E_M - (E_M - E_m)e^{K(T+(W/25)-116)} \tag{4}$$

$$S = (142 + 0.88W)(103 - T)[1 - e^{-0.045(W+5.5)}] \tag{5}$$

$$L = [7000 + 70W^{0.96} - T^{(1.51+0.001W)}](1 - e^{-0.33W}) \tag{6}$$

$$E_f = 3584 + 2016[1 - e^{-0.0019W^{1.9}}] \tag{7}$$

$$E_g = 1330W^{0.436} \tag{8}$$

where

T = temperature of environment, °F
W = weight of animal, lb
K = intake factor, dimensionless
E_M = maximum energy intake, Btu/day
E_m = maintenance energy, Btu/day
E_i = metabolizable energy intake, Btu/day
S = heat loss from animal below critical temperature T', Btu/day
L = heat loss from animal above critical temperature T', Btu/day

E_g = energy for gain, Btu/lb
E_f = metabolizable feed energy, Btu/lb

The animal gains weight according to:

$$G = \begin{cases} \dfrac{E_i - S}{E_g} & \text{for } T < T' \\ \dfrac{E_i - L}{E_g} & \text{for } T \geq T' \end{cases} \tag{9}$$

where G is expressed in pounds per day, and will consume feed according to:

$$F = \frac{E_i}{E_f} \tag{10}$$

where F is measured in pounds per day.

The original form of this model applied only to swine from forty-five pounds to 240 pounds. The exponential terms in equations (5), (6), and (7) were added later to extend this model to include newborn piglets [13]. Readers may consult Kleiber for an in-depth discussion of animal energetics [14]..

In practice, applying this type of model to broilers has been more complicated. Broilers change considerably as they mature, passing through feathering stages which affect their heat transfer properties. This results in equations which are less elegant in appearance, but still reliable.

Teter, DeShazer, and Thompson give the following operational model for broilers [15]:

$$E_M = 135 + 730\, W^{0.69} \tag{11}$$

$$E_M = 216\, W^{0.64} \tag{12}$$

$$\begin{aligned} E_i = E_M \sin^{0.5} [\, T\, (1.61 - 0.56\, (\sin^{0.4} (22.5(W - 0.1)))) \\ + 71.8 \sin^{0.292} (18.5\, (W - 0.092))\,] \end{aligned} \tag{13}$$

$$S = (107.6 - T)\, [\, 21.6 \sin^{0.57} (19\, (W - 0.07)^{0.79})\,] \tag{14}$$

$$L = E_m + 14.4\, [\, \sin^{0.56} (13.2(W - 0.06))\,]\, (100 - T) \tag{15}$$

$$E_g = \begin{cases} 4886 + 2846^{-4W} & \text{for } W < 2.5 \\ 4770 + 9.49e^{W} & \text{for } W \geq 2.5 \end{cases} \tag{16}$$

$$E_f = \begin{cases} 5670 & \text{for } W < 1.7 \\ 5870 & \text{for } W \geq 1.7 \end{cases} \tag{17}$$

The equations for broiler weight gain and feed requirements are the same as for swine (equations (9) and (10)). The symbols and units are the same for both models.

Manure production is dependent upon environmental factors and diet which make it very difficult to predict. Water is a major constituent, and the moisture content varies considerably. A good rule-of-thumb is [16]:

$$M = 2(F - G) \tag{18}$$

where manure is measured in pounds per day. This relationship also works for swine, if manure is defined to include both solid and liquid wastes. Poultry excrete both simultaneously. Calculations of manure production are necessary to link the livestock and waste treatment components of an integrated waste heat utilization complex (Figure 1).

The equations presented in this section provide a growth model for swine and broilers which depends solely on the set temperature, T_i, and the weight of the animal, W. These equations describe the growth of livestock given a particular temperature and starting weight. The model is used to predict feed requirements and manure production. Additionally, animal heat loss is determined and used in the heat balance discussed below.

HEAT BALANCE

We begin with the standard formula for building heat loss calculations:

$$Q = UA(T_i - T_e) \tag{19}$$

where

Q = rate of heat flow, Btu/hr
U = heat transfer coefficient, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
A = area of exposed surface, ft^2
T_i = interior temperature, °F
T_e = exterior temperature, °F

The swine farrowing building heat losses are summarized in Table 1, and the broiler growing building heat losses are summarized in Table 2. The insulation and ventilation levels meet the recommendations of Whitaker [10]. Since these buildings are heated by warm water circulating through pipes embedded in the concrete floors, we will consider heat losses to the ground below, in "Flow Requirements."

There are three sources of internal heat gains: the light bulbs, the heating system, and the bodies of the animals. At thermal equilibrium, the heat lost to the surroundings equals the heat gained from within.

Livestock shelters are cheaper to build and need less heat if there are no windows. Low levels of lighting reduce animal movement, which increases weight gain and decreases injuries. Each twenty-five watt incandescant light bulb gives

Table 1. Swine Farrowing Building Heat Losses

	U, Btu-hr^{-1}-ft^{-2}-°F^{-1}	A, ft^2	UA, Btu-hr^{-1}-°F^{-1}
Ceiling	0.0555	4200	233
Doors	0.4900	84	41
Walls	0.0769	1996	154
Ventilation	(20 cfm/sow) (35 sows) (60 min/hr (0.018 Btu-cfm^{-1}-°F^{-1}) =		756
Total			1184

Table 2. Broiler Growing Building Heat Losses

	U, Btu-hr^{-1}-ft^{2}-°F^{-1}	A, ft^2	UA, Btu-hr^{-1}-°F^{-1}
Ceiling	0.0833	4000	333
Doors	0.4900	84	41
Walls	0.1250	2156	270
Ventilation	(0.2 cfm/bird) (4000 birds) (60 min/hr) (0.018 Btu-cfm^{-1}-°F^{-1}) =		864
Total			1508

off 85.325 Btu per hour. We need to have one light bulb per stall in the swine farrowing house [10], and one light bulb for every 100 ft^2 of growing space in the broiler growing building [11]. These lights burn almost continuously so that feeding is not interrupted. They contribute 3413 Btu per hour in the swine farrowing house, and 3072 Btu per hour in the broiler growing building.

The heat lost by the bodies of the animals can be calculated using equations (5) and (6) for the swine, and equations (14) and (15) for the broilers. We calculate both S and L but use only the larger of the two in each case. This will ensure that S is used below the critical temperature T' and that L is used above the critical temperature T'.

At any given time, seven rooms of the farrowing building are occupied by sows. Five of these rooms also have litters. The average litter size is eight [9]. The simplest method is to calculate the heat lost by a single sow and multiply by seven; then add the heat lost by a single piglet multiplied by forty. A typical sow weighs 200 pounds and a newborn piglet weighs four pounds [13]. A more precise method is to make individual calculations for each room, because each week the piglets gain some weight and are kept at a lower temperature.

Likewise, for the broilers, we can calculate the heat lost by the body of a single bird. We can multiply this by 4000, the number of birds per house, to figure out the heat gain from the birds in each house. All of the birds in a given house will be the same age and therefore approximately the same weight. This is because the houses are staggered in their growing schedules, which enables the complex to produce a steady supply of broilers. Each house is set at a different temperature, which falls every week as the chicks mature.

The supplemental heating needed by the swine farrowing building is:

$$H_s = 1184(T_i - T_e) - \left[3413 + \sum_{W\,T} \frac{\max(S, L)}{24}\right] \tag{20}$$

where S and L are given by equations (5) and (6). We sum over the weights and temperatures experienced by each sow and piglet. The sows are standing and react to the temperature of the air inside the building, T_i. The piglets are lying and react to the temperature of the concrete in their creep area, T_n. We will elaborate on this in the next section. Note that we divide by 24 to convert the time units from day to hr.

The supplemental heating needed by the broiler growing building is:

$$H_B = 1508(T_i - T_e) - \left[3072 + 4000\left(\frac{\max(S, L)}{24}\right)\right] \tag{21}$$

where S and L are given by equations (14) and (15). Although all of the birds in any one building are at the same age and temperature, the conditions in different buildings are not identical. The buildings do not receive newly-hatched chicks simultaneously. Therefore, each building is at a different point in the eight-week growing-out cycle. One simplification is to divide the buildings into eight groups, spaced one week apart.

To summarize, the amount of supplemental heat required is found by figuring out how much heat escapes from each building and then subtracting the heat which is replenished by the hot light bulbs and the warm animal bodies. Swine brooding and broiler growing both follow eight-week schedules. Swine age groups are assigned to different rooms; broiler age groups are assigned to different buildings. The younger animals weigh less and are kept warmer. This makes it important to consider the age groups separately, since body heat loss is affected by weight and temperature. In practice, the heat given off by the animals is quite substantial, and can even heat the house unaided on some cool days.

FLOW REQUIREMENTS

Now that we are able to calculate the amount of heat which is needed to supplement the internal gains, we would like to be able to translate this into the rate of flow of warm water which must be delivered to each livestock shelter from the power plant. We begin by analyzing the creep area heating system of the swine farrowing building.

According to Manning and Mears, a dry concrete floor embedded with one inch polyethylene pipes spaced one foot apart transfers heat at 0.6 Btu- hr^{-1}-ft^{-2}-°F^{-1} [17]. This estimate is consistent with values given by Whitaker [10]. Whitaker discusses a method for heating the creep area floors to no more than 90°F to benefit the litter while maintaining the air temperature at 60°F to avoid stress on the sow. Figure 6 shows the arrangement which will keep both the sow and the litter within their comfort ranges.

Beneath the creep areas on either side of the sow, where warm floors are desired, the pipes are uninsulated. However, they rest upon two inches of polystyrene insulation which prevents the heat from going into the ground. Two inches of concrete cover these pipes. The pipes beneath the sow are wrapped in two inches of polystyrene insulation, and then buried in four inches of concrete. The sow's floor stays cool.

We need to know what temperature of water will keep the creep area floors at their prescribed temperatures. Figure 7 represents the following equation:

$$T_n = T_i + \frac{R_a + R_c}{R_a} (T_w - T_i) \tag{22}$$

where

T_w = temperature of water in the pipe, °F
R_a = thermal resistance of film of air, hr-ft^2-°F-Btu^{-1}
R_c = thermal resistance of concrete, hr-ft^2-°F-Btu^{-1}
T_n = temperature of concrete, °F, in room n
n = room number subscript (1, 2, . . . , 8)

Using the values of T_i = 60°F and T_n = 89°F suggested in Figure 7, we can perform a sample calculation:

$$T_w = 60 + \frac{0.61 + 1.06}{0.61} (89 - 60) = 139°F \tag{23}$$

Thus, if the room air if 60°F and we want the creep area floor heated to 89°F, we must supply water at 139°F. This formula enables us to adjust the water temperature as the litter matures, and to respond to warm weather. There must be a control system to administer the correct temperature water to each room. The warm

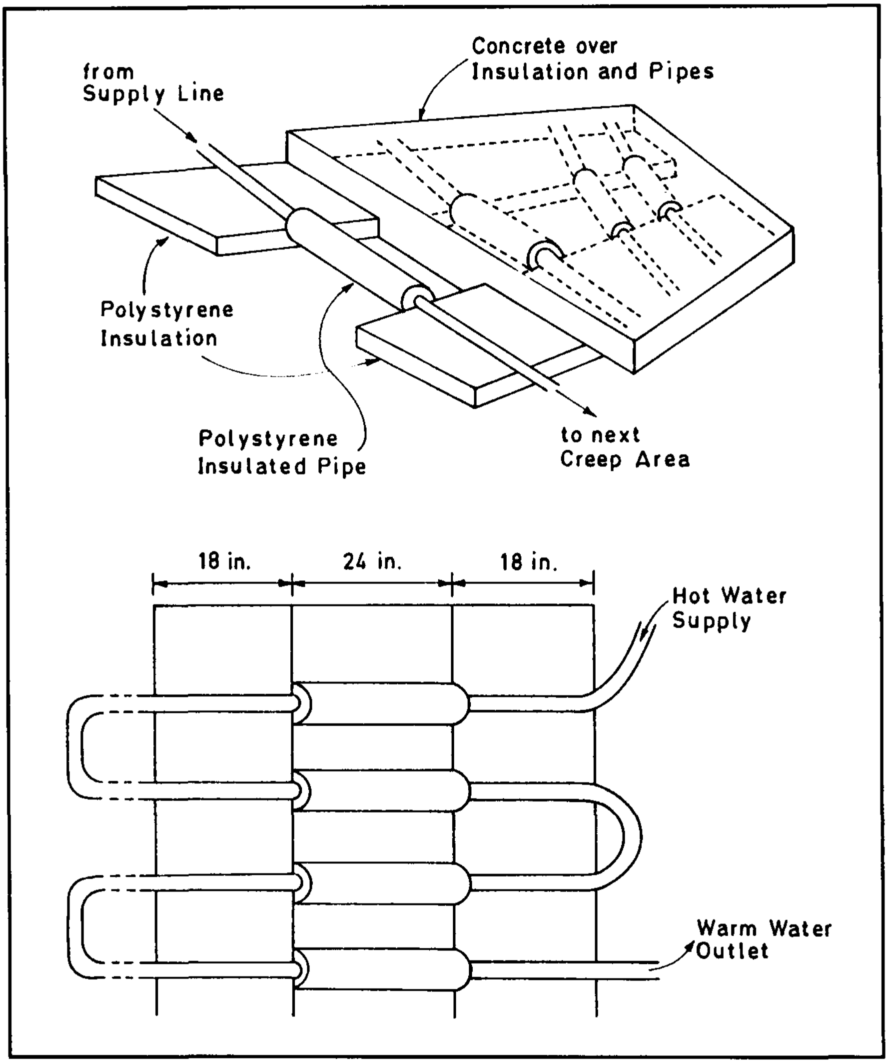

Figure 6. Schematic of creep area heating system.

water from the power plant won't necessarily be at the right temperature, so some extra heating or mixing with cool water may be needed.

Given any schedule of thermostat settings for the creep areas in the eight rooms (T_1, T_2, . . . , T_8) we can use equation (22) to calculate the corresponding temperatures for the water circulating inside the floor (T_{w1}, T_{w2}, . . . , T_{w8}). The temperature of the air inside the building, T_i, is controlled by a separate thermostat. The temperature of the ground, T_g, can be estimated from weather data.

These temperature differences, along with the heat transfer data presented in Table 3, enable us to calculate the water flow requirements. We simply divide the Btu/hr transferred to the house and the ground by the Btu/lb lost from the water as it travels through the pipes:

$$m = \frac{\sum_{n=1}^{8} \left[(U_u A_u + U_c A_c)(T_{wn} - T_i) + (U_g A_g)(T_{wn} - T_g)\right]}{C_w(T_{w1} - T_{w8})} \tag{24}$$

where

m = mass flow rate of water, lb/hr
C_w = specific heat of water, Btu-lb^{-1}-°F^{-1}
T_{w1} = water temperature for warmest room, °F
T_{w8} = water temperature for coolest room, °F

U_u, A_u, U_c, A_c, U_g, and A_g are defined in Table 3.

We have assumed that all of the water enters at the temperature needed by the warmest room, and leaves at the temperature needed by the coolest room. This makes sense if the water passes through the rooms in order of descending temperature, and if the flow rates are carefully controlled for each individual

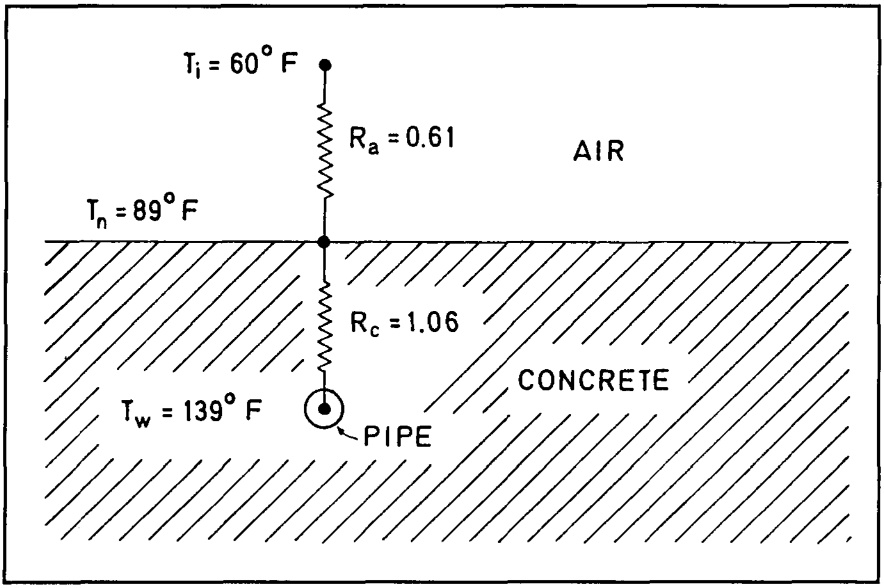

Figure 7. Calculation of circulating water temperature.

Table 3. Heat Transfer Data for Creep Area Heating [2]

Surface	*U*	*A*	*Subscript*
Floor of creep area - pipes uninsulated	0.6000	105	u
Floor beneath sow and outside stalls–pipes insulated	0.0857	345	c
Underside of slab in contact with ground–pipes insulated	0.0475	450	g

room. It should be mentioned that this is only an approximate technique, but its simplicity makes it desirable for our purposes.

The heat gain from the creep area heating is:

$$h = \sum_{n=1}^{8} (U_u A_u + U_c A_c)(T_{wn} - T_i) \tag{25}$$

This should be compared with the supplemental heating needs of the swine farrowing building (equation (20)). If these heat gains are inadequate, we can send additional water through uninsulated pipes in the floor of the service and storage area. The analysis is the same as we are about to describe for the broiler growing building.

The floor of the broiler growing building is not divided into small, separate creep areas. Rather, the entire floor functions as a single heating unit. This makes the temperature drop along the length of the pipes significant and calls for a different method of analysis.

We know that at equilibrium:

$$H_B = mC_W (T_{in} - T_{out}) = U_f A_f (LMTD) \tag{26}$$

where

H_B = heat required (from equation (21)), Btu/hr
U_f = heat transfer coefficient of the floor, 0.60 Btu-hr^{-1}-ft^{-2}-°F^{-1}
A_f = area of the floor, 4000 ft^2
T_{in} = temperature of water entering building, °F
T_{out} = temperature of water exiting building, °F
LMTD = log mean temperature difference, °F

The log mean temperature difference is defined as:

$$\mathrm{LMTD} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in} - T_i}{T_{out} - T_i}\right)} \qquad (27)$$

We know T_{in} because that's the temperature of the water being supplied by the power plant. The simplest method is to assume some reasonable value for T_{out}, such as the temperature inside the building, i.e., let $T_{out} = T_i$. We know T_i from our schedule of thermostat settings. Our flow requirements would be:

$$m = \frac{H_B}{C_w\,(T_{in} - T_{out})} \qquad (28)$$

A more precise method is to solve the following equation by iteration [2]:

$$\mathrm{LMTD} = \frac{H_B}{U_f A_f} \qquad (29)$$

This will yield a more exact value for T_{out} to use in equation (28). We could have a second set of iterations to account for the heat losses to the ground. However, the temperature of the water is dominated by the temperature, T_i, of the building. Therefore, we can approximate the additional water flow necessary to compensate for heat losses to the ground by:

$$m_g = \frac{U_g A_g\,((T_i + \mathrm{LMTD}) - T_g)}{C_W\,(T_{in} - T_{out})} \qquad (30)$$

The total mass flow rate of water required to maintain the desired interior temperature is determined by summing the results of equations (28) and (30). The exit water temperature, T_{out}, is developed from the iteration scheme described above.

SUMMARY AND CONCLUSIONS

The beneficial use of thermal effluents has an intuitive appeal. Rather than increasing ecosystem stress in the form of thermal pollution, we are able to derive tangible benefits in the form of increased food production. However, quantifying these benefits has proved elusive. This livestock model provides a means for predicting the feed consumption, animal growth, waste disposal, and heating requirements of specific livestock facilities. We have identified swine brooding and broiler growing as being particularly well suited for waste heat projects, based on their need for temperature control, and the magnitude of potential energy savings.

The materials balance uses an operational model which accounts for the transformation of feed energy into weight gain, body heat losses, and waste products.

The net heat loss from the buildings is found by a heat balance, which includes the substantial heat given off by the bodies of the animals. The rest of the heat is replenished by pumping warm water from the power plant through pipes buried in the concrete floors.

NOMENCLATURE

The following is a list of the nomenclature used throughout this article.

A =Area of exposed surface, ft^2
A_c = Area of floor of beneath sow and outside stalls, ft^2
A_f = Area of floor, Ft^2
A_g = Area of slab in contact with ground, ft^2
A_u = Area of floor of creep area, ft^2
C_w = Specific heat of water, Btu-lb^{-1}-°F^{-1}
E_M = Maximum energy intake, Btu/day
E_f = Metabolizable feed energy, Btu/lb
E_g = Energy for gain, Btu/lb
E_i = Metabolizable energy intake, Btu/day
E_{intake} = Feed energy intake, Btu/day
E_m = Maintenance energy, Btu/day
E_{max} = Maximum consumption of feed energy, Btu/day
F = Feed required, lb/day
G = Weight gain, lb/day
H_B = Supplemental heating for broiler growing building, Btu/hr
H_S = Supplemental heating for swine farrowing building, Btu/hr
K = Intake factor, dimensionless
L = Latent heat loss, Btu/day
LMTD = Log mean temperature difference, °F
M = Manure produced, lb/day
Q = Rate of heat flow, Btu/hr
R_a = Thermal resistance of film of air, hr-ft^2-°F-Btu^{-1}
R_c = Thermal resistance of concrete, hr-ft^2-°F-Btu^{-1}
S = Sensible heat loss, Btu/day
T = Temperature of environment, °F
T' = Critical temperature, °F
T_e = Exterior temperature, °F
T_g = Temperature of the ground, °F
T_i = Interior temperature, °F
T_{in} = Water temperature entering building, °F
T_n = Temperature of concrete in creep area of room n, °F
T_{out} = Water temperature exiting building, °F

T_w = Temperature of circulating water, °F
T_{wn} = Temperature of water supplied to floor of room n, °F
U = Heat transfer coefficient, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
U_f = Heat transfer coefficient for floor of broiler building, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
U_u = Heat transfer coefficient for floor of creep area, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
U_c = Heat transfer coefficient for floor beneath sow, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
U_g = Heat transfer coefficient for underside of slab, $\text{Btu-hr}^{-1}\text{-ft}^{-2}\text{-°F}^{-1}$
W = Weight, lb
h = Heat gain from the creep area, Btu/hr
m = Mass flow rate of water, lb/hr
m_g = Mass flow rate of water needed to compensate for heat losses to ground, lb/hr

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