Simulation of a Swine Nursery to Facilitate Economical Management

by

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(ABSTRACT)

Two deterministic simulation models were developed to assess the economics of swine nurseries. The first model assessed the emergency needs of swine nurseries by simulating the temperature response during a short term power failure. The failure model accounted for heat exchange by conduction, convection, radiation, and air infiltration. An existing sub-model was used to predict swine heat and moisture loss.

The failure model was validated using a nursery constructed of concrete block. It performed well for cases with constant solar load, but tended to overpredict temperature changes during periods of no solar load. Validation indicated accurate wall-characteristic and wind velocity estimations were crucial to obtain accurate model results.

The second model was developed to describe the normal operation of swine nurseries by predicting pig growth and feed consumption, building fuel consumption, and cost per unit of gain produced. It was based on an existing swine model that was converted to an hourly basis. An optimization option was incorporated into the operational model to allow minimization of the cost per unit of gain.

The operational model was validated and found to accurately predict feed consumption and growth during a one week time frame. Fuel consumption was less accurate. The optimization mode predicted considerable cost savings for operation at lower temperatures.

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I wish to dedicate this work to my grandparents, , who shaped my life more than they will ever know.

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Chapter 1

Introduction

Swine production systems in the United States are highly variable. A large percentage of producers have completely changed to confinement production buildings. These buildings are managed in many different ways, some merely by tradition, but many by gambling on innovation. To understand the entire management picture, individual components of a swine facility (construction, ventilation, heating, animals) should be examined carefully. Then, components can be combined to facilitate evaluation of managerial decisions before they are implemented, saving both time and money.

As a consequence of metabolism, pigs produce waste heat. Within a certain range of exposure temperatures, the amount of heat production depends upon the size of the animal and the amount of metabolizable energy consumed. This range, referred to as the thermoneutral zone, is considered the range of optimal growth. Esmay and Dixon (1986) gave four conditions that define animal thermal behavior within the thermoneutral zone: 1) blood vessels in the skin are neither all dilated nor all constricted; 2) moisture evaporation from the skin and respiratory tract is at a minimum level; 3) hair follicles are not erect (minimum piloerection); and 4) behavioral response to heat or cold is not evident. The precise limits of this zone has been the subject of many studies.

The lower limit of the thermoneutral zone is called the lower critical temperature, t_{cl}. Below this temperature there is greater demand for heat due to an increased temperature differential between the animal's core temperature of 39°C and the environmental temperature. Bruce (1982) stated that below t_{cl}, either heat production or thermal resistance is increased, or sometimes both are increased. Esmay and Dixon (1986) indicated that feed consumption, metabolism and heat production must all increase to compensate for increased thermal losses. Increased heat losses rob the body of energy that would normally be utilized for growth, while increased feed consumption means an increased feed-to-gain ratio, which is economically undesirable.

The upper limit of the zone, called the upper critical temperature, t_{cu}, is the temperature at which heat production is greater than the amount that can be lost to the environment. To reduce the amount of heat produced, feed consumption is reduced, and as a result, the amount of energy available for growth is also reduced.

Locating the limits of the thermoneutral zone is important for determining an optimal housing temperature. In Virginia, and regions further north, wintertime production requires intensive house management to minimize the effect of cold weather. The lower critical temperature and the response of swine to cold temperatures become particularly important. During cold weather, ventilation is generally based on moisture removal or on recommended minimum rates for odor and gas control. As a result, fresh air is required for proper ventilation and supplemental heat is required to maintain a desired building temperature. The question arises, what is the desired temperature? If the temperature is set too high, excessive fuel is required. If the temperature is set too low, excessive feed is consumed and less weight is produced per unit of feed.

Close (1982) outlined several factors which influence the position of the thermoneutral zone, and thus the position of t_{cl}. These include: animal factors, such as body weight, animal thermal insulation, group size and condition of the animal; nutritional factors (the higher the level of feeding, the lower the t_{cl}); thermal factors, such as air movement, air and structure temperatures, bedding and flooring type; and relative humidity, which affects latent heat losses and respiration rate. All factors that are involved with management or fixed costs, such as group size or flooring type, can be utilized to the producer's benefit with little added cost. Other factors are not as easily utilized for production management.

To further maximize profit, the unit cost of feed and heating energy should be considered to minimize variable costs. For example, if feed were cheap relative to fuel, it might be more efficient to reduce building temperature to conserve fuel while allowing feed consumption to increase. The feed bill would increase, but there would be overall savings due to a larger reduction in heating cost.

This problem appears to be appropriate for a computer simulation model. Detailed management schemes such as diurnal temperature variation could be evaluated without the risk of bold management choices, which could be costly and time consuming. A model is also efficient for research purposes. Experimenting using enough swine for statistical evaluation would be costly and could require many years. A model can be developed and evaluated which could be utilized, in combination with field data, to minimize experiment cost and time.

Mechanically ventilated buildings are capable of providing ideal situations for animal production; however, the environment is strongly dependent on fans and heaters to exchange and condition the air. In the event of a power interruption there is no means to condition the air, and the environment deteriorates rapidly. Veit et al. (1985) measured temperature, relative humidity, ammonia and carbon dioxide changes during a one hour ventilation failure in a triple deck nursery. They found that temperature increased 12 °C, relative humidity increased from 75 to 98 percent, ammonia increased from 10 to 48 ppm, and carbon dioxide increased from 0.08 to 0.9 percent of the indoor air. They concluded that life threatening situations were created during a power outage, and that alarm systems are necessary in such housing in mild to hot climates.

Many large producers have telephone alarms within their buildings. When a power failure occurs, a recorded message is sent by telephone to designated people, who must then respond accordingly. In many cases reaction time is adequate, but a model of building performance during a power outage would aid producers in planning emergency strategies based on the required response time, and in assessing risk involved with outages. A simulation model would provide an inexpensive method of determining temperature changes during power outages without exposing animals to actual adverse conditions, and without performing repetitive tests.

Objectives

This study had the following objectives:

1. To develop a deterministic model to simulate temperature responses to power interruptions in a swine nursery.

2. To validate the power interruption model using data collected from the Virginia Tech Swine Center.

3. To develop a deterministic model to simulate the normal operation of a swine nursery, accurately assessing feed and fuel usage and growth.

4. To validate the operational model using data collected from the Virginia Tech Swine Center.

5. To develop a routine to optimize profit (minimize total feed and fuel expenditures per unit of gain produced) by changing thermostatic settings in a swine nursery.

Chapter 2

Literature Review

Many models have been developed to describe different aspects of swine production. These include models of the pig (such as heat and moisture models, growth models, and feed consumption models) and models of the building (which include ventilation, heating, and solar energy gain). This chapter contains a review of literature related to the North Central Region Committee (NCR) 179 swine model which was chosen for use in this research. Literature contributing to development of the thermal building model will also be discussed.

2.1 Swine Models

2.1.1 Introduction

Through the years, many experiments have been conducted in order to understand the interaction of swine environmental factors (temperature, moisture, nutrition and other factors) upon the performance of swine. In many of these studies, one factor, such as temperature, was varied, and one criterion, such as heat production, was evaluated. A relationship was then developed. These individual relationships, while illuminating, should not be considered conclusive. Factors affecting swine production are interactive and should be treated as such in experimentation.

In the early 1970's researchers began modeling swine as a complex interactive system. The NCR swine model being used in this research is a compilation of work done by researchers over the last two decades. Work related to the development of the NCR swine model will be reviewed here.

2.1.2 Heat and Moisture Production

Many calorimetry studies have been done over the years to evaluate the quantity and modes of heat transfer from swine. Kelly et al. (1948) used a calorimetric chamber to evaluate convection and radiation losses from a group of pigs. Bond et al. (1952) measured heat loss from a group and graphically presented partitioned heat loss as conduction, convection, radiation, and evaporation. Bond et al. (1959) studied the effect of temperature on heat and moisture loss, and gave approximate percentages of total heat for each of three modes of heat transfer. Later, Butchbaker and Shanklin (1964) evaluated modes of heat transfer and evaporation for a single newborn pig. The data from these experiments, as well as others, have been used by other researchers searching for a way to relate heat and moisture production to measurable parameters. More recent models have been based on data from many experiments to get a good response for a group of animals that have an inherently high variability.

Teter et al. (1973) developed empirical equations using an animal physiological framework for swine ranging in size from 20 to 110 kg (45 to 240 lbs). They used a theory that divided the heat loss curve into two separate curves, shown as S and L in Figure 1. In the L range of heat loss, the animal controls its deep body temperature through physical reactions such as water evaporation and vasomotor control. This range includes the thermoneutral zone and temperatures above. The S range of heat loss depends upon age, size, hair coat, and type of feed, and lies below the lower critical temperature. In this region the animal uses chemical reactions to control its deep body temperature. The S portion is nearly linear with respect to temperature. Teter et al. (1973) used the animal's surface area, the overall heat transfer coefficient, and the temperature difference between the body temperature and the effective environmental temperature to determine the following equation:

$$S = (142 + 0.88\,W)(103 - X) \qquad [2.1]$$

$$L = 7000 + 70\,W^{0.96} - X^{(1.51+0.001\,W)} \qquad [2.2]$$

where

S = heat loss below the lower critical temperature (btu/day)
W = weight (lbs)
X = temperature (°F)
L = heat loss above the lower critical temperature (btu/day)

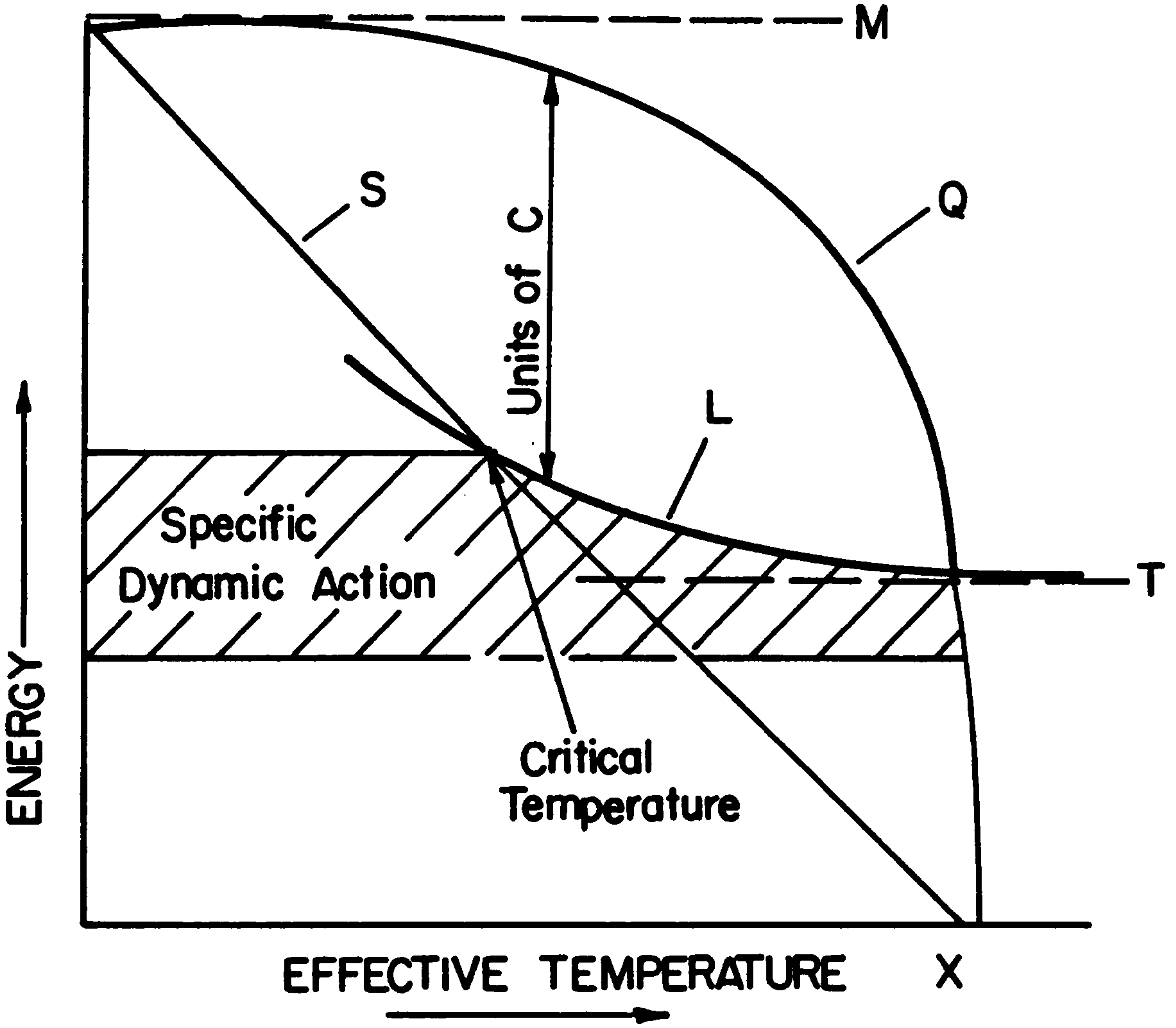

Figure 1. Metabolizable energy intake and energy loss versus effective temperature, Teter et al. (1973).

The larger calculated value, S or L, is the appropriate value for heat loss. If S is larger than L, then the temperature used was below the lower critical temperature. Conversely, temperatures above the lower critical temperature will yield L larger than S. The point of intersection is the lower critical temperature. At this temperature, heat loss from the animal surface and respiratory passages equals heat production inherent to the energy required for respiration, circulation, digestion and other biological functions.

DeShazer and Teter (1974) made adjustments to the Teter et al. (1973) equations. These adjustments simulated baby pigs through multiplying by an exponential term that becomes negligible as animals become large. Other aspects of this model will be discussed in a later section, but the altered heat loss was described as follows:

$$S = (142 + 0.88\,W)(103 - X)\,[1 - \exp\{-0.045(W + 5.5)\}] \qquad [2.3]$$

$$L = 7000 + 70\,W^{0.96} - X^{(1.51+0.001\,W)}\,[1 - \exp(-0.33W)] \qquad [2.4]$$

Whittemore and Fawcett (1976) used an energy balance to calculate heat production. The rates at which energy was used for protein synthesis, protein deamination, and fat accretion were calculated. These rates were then subtracted from the rate of digestible energy intake to yield the heat loss rate for temperatures above the lower critical temperature, t_{cl}. Whittemore (1976) further refined their equation by exchanging digestible energy intake and protein deamination for metabolizable energy intake:

$$H_1 = ME - (23.6\,Pr + 39.3\,Lr) \qquad [2.5]$$

where

H_l = heat output from body above t_{cl} (MJ/day)
ME = metabolizable energy (MJ/day)
Pr = rate of protein accretion (kg/day)
Lr = rate of lipid accretion (kg/day)

When the temperature was below t_{cl} , another component of heat loss was calculated to account for thermogenesis and was then added to equation [2.5]. Thermogenesis is defined as additional heat loss when the animal is exposed to temperatures below t_{cl}, and is based on temperature difference between ambient and t_{cl}, and also on the metabolic animal size. Discussion of the calculation of t_{cl} appears in a later section.

$$H = H_l + 0.016\,LW^{0.75}\,(t_{cl} - t) \qquad [2.6]$$

where

H = total heat output below t_{cl} (MJ/day)
H_l = heat output from body above t_{cl} (MJ/day)
LW = live weight (kg)
t_{cl} = lower critical temperature (°C)
t = environmental temperature (°C)

Whittemore (1976) used published data to validate his model. He concluded that: "Not only is it apparent that temperature has a significant effect upon growth and efficiency, but also that temperature is an inadequate description of the environment for commercial pigs. Information on group size, air speed, and floor insulation markedly improves the situation, but the total environment is more complex than can be described quantitatively by data presently available.".

All the approaches to heat loss discussed thus far have used an energy balance approach. Heat was merely a leftover by-product after growth and other biological processes were completed.

Bruce and Clark (1979) also approached heat loss within the thermoneutral zone in this manner for pigs between 20 and 100 kg, producing the equations:

$$Q_n = m + (1 - k)(F - m) \qquad [2.7]$$

$$k = 0.625 + 0.00142\,M \qquad [2.8]$$

$$m = 0.44\,M^{0.75} \qquad [2.9]$$

where

Q_n = thermoneutral heat production (MJ/day)
m = maintenance energy requirement (MJ/day)
k = efficiency of utilization of metabolizable energy for growth
F = metabolizable energy intake (MJ/day)
M = liveweight (kg)

Below the thermoneutral zone, Bruce and Clark (1979) utilized a thermal resistance method for determining heat loss from the animal. The resistance to heat loss included: tissue resistance between the deep body and body surface; the effective thermal resistance of the floor; and an external thermal resistance at the skin for radiation and convection losses. Evaporative heat loss was considered to take place solely through the skin surface. Figure 2 shows the resistance analogy for heat loss. The total loss is partitioned into:

$$Q = Q_r + Q_c + Q_e + Q_f \qquad [2.10]$$

where

Q = heat loss below the lower critical temperature (W)
Q_r = radiant heat loss (W)
Q_c = convective heat loss (W)
Q_e = evaporative heat loss (W)
Q_f = heat loss through the floor (W)

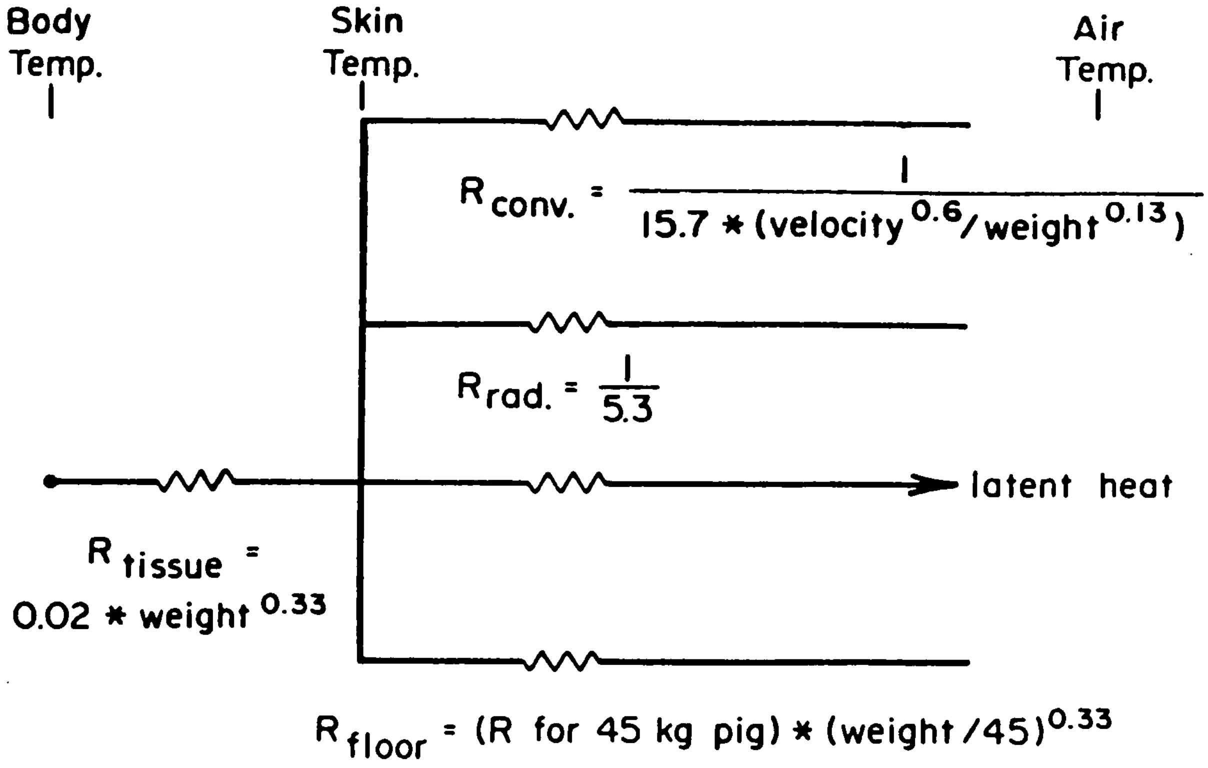

Figure 2. Heat loss resistances used by Bruce and Clark (1979).

It was assumed that the mode of transfer within the tissue between the deep core and skin temperatures was primarily conduction. It was also assumed that the characteristic thickness of subcutaneous tissue is proportional to the characteristic body length, $M^{0.33}$. This yields an empirical equation to represent the tissue:

$$R_t = 0.02\,M^{0.33} \qquad [2.11]$$

where

R_t = tissue resistance (°C m^2/W)
M = liveweight (kg)

The convective resistance was derived from Newton's law of cooling, and assumed Reynold's number to lie between 1000 and 50,000. Equation [2.12] defines the resistance due to convection.

$$R_c = 1 / [15.7(V^{0.6}/M^{0.13})] \qquad [2.12]$$

where

R_c = convective resistance (°C m^2/W)
V = air velocity (m/s)
M = liveweight (kg)

The radiant component was derived from the Stefan-Boltzman law with assumed values for emissivity of 0.99 for a pig's skin and 0.9 for interior building surfaces. Assumptions were also made to simplify the quadratic temperature differences involved in radiant calculations:

$$R_r = 1 / 5.3 \qquad [2.13]$$

where

R_r = radiant resistance (°C m²/W)

The thermal resistance value of an animal on the floor is an ever dynamic quantity due to postural changes by the animal to achieve thermal comfort. Bruce and Clark (1979) created an equation based on data which Bruce (1977) had collected using 45 kg pigs on different flooring types, as shown in Table 1. Bruce (1977) gave resistances for three different flooring types: solid concrete, slatted concrete, and concrete with bedding. A fourth type, metal mesh, was assumed to possess no conduction properties, and the surface of the animal was assumed to be a convective surface only. These factors can be scaled for animal size, percent of animal surface in contact with the floor, and the group size. It is generally assumed that 20 percent of a pig's body surface is in contact with the floor 80 percent of the time, so that:

$$R_f = R_{f45} (M/45)^{0.33} (A_f/0.2A)\, N^{0.5} \qquad [2.14]$$

where

R_f = effective thermal resistances of the floor (°C m²/W)
R_{f45} = effective thermal resistances of the floor for a 45 kg pig (°C m²/W)
M = liveweight (kg)
A_f = area of skin in contact with the floor (m²)
A = total animal surface (m²)
N = number of pigs in a group

This relationship was combined with the tissue resistance to yield the heat loss to the floor:

$$Q_f = A_f(t_b - t_a) / (R_t + R_f) \qquad [2.15]$$

Table 1. Effective thermal resistances of floors as measured with the simulated 45 kg pig with a contact ratio of 0.2, Bruce (1977)

Floor Type	Thermal Resistance R_{f45} (°Cm^2/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 fiber) 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

where

Q_f = thermal loss to the floor (W)
A_f = area of skin in contact with the floor (m_2)
t_b = body temperature (°C)
t_a = air temperature (°C)
R_t = tissue resistance (°C m^2/W)
R_f = effective thermal resistances of the floor (°C m^2/W)

The final component of equation [2.10] is the latent heat loss. Latent heat production is not only an important element of the total animal heat loss; it also adds moisture to a facility thereby requiring elevated ventilation rates to avoid condensation and animal respiratory problems. Bruce and Clark (1979) utilized data collected by other researchers to form a regression model of latent heat loss based on animal weight:

$$Q_e = 0.09(8.0 + 0.07\,M)M^{0.67} \qquad [2.16]$$

where

Q_e = evaporative heat loss (W)
M = live weight (kg)

Thermal resistances as well as the latent heat loss can be combined using equation [2.10] and Figure 2. In Figure 2 the combination of resistances becomes more obvious. Tissue resistance is combined in series with all heat loss paths. Convection and radiation resistances may be combined into an air resistance factor, R_a, because they occur in parallel over the same area of the animal's body:

$$Q = \frac{[A\{1 + A_f/A\,(R_a - R_f)/(R_t + R_f) - A_c/A\}(t_b - t_a) + Q_e R_a]}{(R_a + R_t)} \qquad [2.17]$$

where

Q = total heat loss below the critical temperature (W)
A = total surface area of the pig (m^2)
A_f = area of skin in contact with the floor (m^2)
R_a = external thermal resistance of skin exposed to air (°C m^2/W)
R_f = effective thermal resistance of the floor (°C m^2/W)
R_t = tissue thermal resistance (°C m^2/W)
A_c = average area of skin in contact with other pigs (m^2)
t_b = deep-body temperature (°C)
t_a = air temperature (°C)
Q_e = evaporative heat loss (W)

Bruce and Clark (1979) used data collected from previous research to validate their model. They noted an apparent 20 to 40 percent error when low level feeding at low temperatures occurred. However, they stated that this was not a practical management scheme for growing pigs so the error was ignored. Using other data to test the model for heat production below the critical temperature yielded satisfactory results with a mean square error of 0.77 MJ/day, or 5.6 percent. The model for thermoneutral heat production (equations 2.7-9) resulted in a mean square error of 0.49 MJ/day, or 3.2 percent.

The Bruce and Clark (1979) model was incorporated into the Whittemore framework by Jacobson (1983). This model was extended to include pigs in the 5 to 20 kg range as well as the 20 to 100 kg range, and allowed pigs to lose weight for the first week after weaning. Validation attempts failed because the model overpredicted heat production by 50 percent in young pigs. Jacobson (1983) proposed several adjustments to the resistance values. Since the Bruce and Clark (1979) model approximated the pig as a hairless cylinder, Jacobson (1983) proposed an equation for thermal resistance of the hair coat (equation 2.18) to be added in series with the convective resistance term (Figure 3). The new equation accounted for the sparse hair coat of baby pigs, and is described as follows:

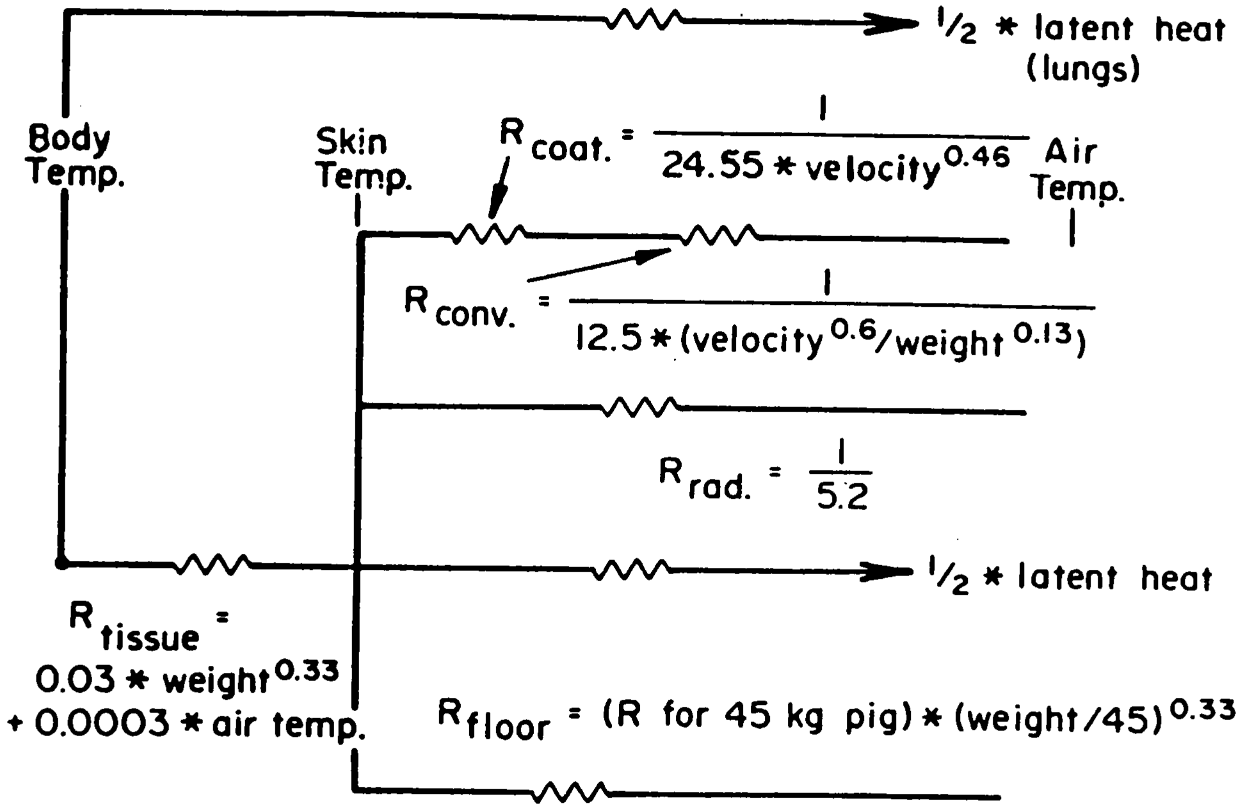

Figure 3. Modified heat loss scheme used by Jacobson (1983).

$$R_{hc} = \frac{1}{(24.55\,V^{0.46})} \qquad [2.18]$$

where

R_{hc} = thermal resistance of the hair coat (°C m^2 /W)
V = air velocity (m/s)

Jacobson (1983) stated that the Bruce and Clark (1979) model for tissue resistance tended to underestimate the value for conditions below the thermoneutral zone. Compiling data from other experiments, a new relationship was proposed using regression:

$$R_t = 0.03\,W^{0.33} + 0.0003\,t \qquad [2.19]$$

where

R_t = tissue thermal resistance (°C m^2 /W)
W = live weight (kg)
t = air temperature (°C)

Bruce and Clark (1979) assumed that during cold thermogenesis, all latent heat is lost from the pig in the form of evaporation of moisture from the skin. Based on other data, Jacobson (1983) assumed that the latent heat loss is equally distributed between the lungs and the skin (Figure 3). Research by Jacobson (1983) was summarized and reported by Jacobson et al. (1989).

The Jacobson (1983) model was incorporated into a PC-based model that was developed by the North Central Region Committee 179, (NCR). The NCR (1987) model was converted to FORTRAN and was utilized for the research reported herein.

2.1.3 Lower Critical Temperature

Within the thermoneutral zone, heat production is a function of animal size, metabolizable energy intake, and efficiency of energy usage, among others. By definition, temperature can vary within the thermoneutral zone without changing the rate of heat production. The lower critical temperature, t_d, for any animal can be determined by reducing the ambient temperature until the heat production of the animal starts to increase. That ambient air temperature is then considered to be the t_d .

Mount (1960) examined the effect of huddling on metabolic rates of newborn pigs. He concluded that the lower critical temperature occurred in the range of 25 to 30°C (77 to 86°F) for a group of 4 to 6 pigs, and 34 to 35°C (93.2 to 95°F) for single pigs, illustrating that the t_d cannot always be determined by pig size. NRC (1981) and Bruce (1982) gave tables of t_d values for different size pigs. Each gave a separate entry for single animals and groups of animals. Both also gave feeding level as a variable. Bruce (1982) gave t_d values as a function of floor type as well. According to Kleiber (1961), total efficiency for a pig is maximum at the lower critical temperature.

Several researchers through the years have expressed t_d in similar ways. It is generally accepted that heat production can be modeled with one equation within the thermoneutral zone and another equation in the cold thermogenesis zone. The junction of these equations must be the boundary between the two regions, and lies at the t_d.

Teter et al. (1973) modeled heat production with two lines, heat below t_d, and heat above t_d (see section 2.1.2). The temperature at which these two lines intersected was taken as the lower critical temperature.

Whittemore and Fawcett (1976) developed regression equations based on data from other experiments. Equation [2.20a] was used for a single pig. Thermoneutral heat production was the independent variable. Equation [2.20b] was used for pigs in groups and was based on animal weight. The data used for the regression were for pigs between 20 and 120 kg that were fed approximately twice the required maintenance diet. Thermoneutral heat production was calculated from equation [2.5].

$$t_{cl} = 26.6 - 0.59H_l \qquad [2.20a]$$

$$t_{cl} = 23.8 - 0.15W \qquad [2.20b]$$

where

t_{cl} = lower critical temperature (°C)
H_l = heat output within thermoneutral zone (MJ/day)
W = animal weight (kg)

Bruce and Clark (1979) derived a much more complex model using the body core temperature, the level of thermoneutral heat loss, insulation, and body surface area values. They based this equation (equation [2.21]) on a theoretical approach that includes heat exchange with the floor and other pigs, along with the heat lost through evaporation. Equations [2.7] and [2.17] for thermoneutral and cold thermogenesis heat production were set equal to each other, and the equations were solved for t_a, which is the intersection of the two equations and therefore t_{cl}. This equation is theoretically based and therefore has more physical meaning than equations [2.20a] and [2.20b].

$$t_{cl} = t_b - \frac{\{Q_n(R_a + R_t) - Q_eR_a\}}{\{A[1 + A_f/A(R_a - R_f)/(R_t + R_f) - A_c/A]\}} \qquad [2.21]$$

where

t_{cl} = lower critical temperature (°C)
t_b = deep body temperature (°C)
Q_n = thermoneutral heat production (W)
R_a = external resistance of skin exposed to air (°C m^2 /W)
R_t = tissue thermal resistance (°C m^2 /W)
Q_e = evaporative heat loss (W)
A = surface area of the pig (m^2)
A_f = area of skin in contact with the floor (m^2)
R_f = effective thermal resistance of the floor (°C m^2 /W)
A_c = area of skin in contact with other pigs (m^2)

The Bruce and Clark (1979) method of determining the lower critical temperature was utilized in the NCR swine model.

2.1.4 Feed Intake

Perhaps one of the most significant factors in swine production is the required feed intake to supply adequate energy for growth and body maintenance. The proper amount of feed is difficult to determine since it is an ever-changing parameter. To alleviate this critical decision, most producers rely on the pig to determine its own feed needs through ad libitum feeding. This method, while labor saving and practical for farm use, prevents accurate knowledge of the rate at which feed is consumed.

DeShazer and Teter (1974) developed a set of empirical equations to estimate metabolizable energy intake. These equations were based on data to develop an intake curve similar to the one in Figure 1, and consisted of an intake factor, K, the maximum energy intake at maturity, M, and the required maintenance energy, T. An energy intake adjustment factor was added later to provide a better fit during validation. The modified equation is:

$$K = 0.06 - 0.00005\,W \qquad [2.22]$$

$$M = 22{,}000 \text{ arc } \sinh\left(\frac{W}{49}\right) \qquad [2.23]$$

$$T = 260\,W^{0.75} \qquad [2.24]$$

$$Q = A\left[M - (M - T)\exp\left\{K\left(X + \frac{W}{25} - 116\right)\right\}\right] \qquad [2.25]$$

where

K = intake factor
W = animal weight (lbs)
Q = metabolizable energy intake (btu/day)
A = energy intake adjustment (0.9)
M = maximum energy intake (btu/day)
T = maintenance energy requirement (btu/day)
X = air temperature (°F)

Feed intake has been treated as a known input by many researchers. Much of the data presented on swine experiments specified feed intake as a multiple of maintenance requirement. NRC (1986) published information on determining voluntary feed intake for several species of food-producing animals. This approach started with an equation for voluntary digestible energy intake within the thermoneutral region. Consumption was then adjusted for physiological, environmental, and nutritional factors. Two basic equations for thermoneutral consumption were used. Equation [2.26a] was meant for pigs between 5 and 20 kg. Equation [2.26b] was designed for pigs between 20 and 120 kg, and was based on an asymptotic relationship with maximum intake occurring at mature body weight:

$$DE = 462\,BW - 9.72\,BW^2 - 1529 \qquad [2.26a]$$

$$DE = 13{,}162[1 - \exp(-0.0176\,BW)] \qquad [2.26b]$$

where

DE = digestible energy intake (kcal/day)
BW = body weight (kg)

A physiological adjustment factor allowed adjustments to be made when the sexual make-up of the group is something other than half gilts and half barrows. Barrows alone have been shown to consume 4.9 percent more feed than a barrow-gilt group. The adjustment is added to the calculated digestible energy intake for barrows and subtracted for gilts. The digestible energy intake for the group may then be determined by weighting it according to the sexual composition of the group. This equation is limited to body weights exceeding 25 kg. NRC (1986) reported the following equation to adjust for sexual makeup of a group:

$$PD = 0.2142\,BW - 0.00133\,BW^2 - 4.42 \qquad [2.27]$$

where

PD = DE deviation due to physiological make-up (percent)
BW = body weight (kg)

NRC (1986) also reported environment adjustments which were made for temperature, space allotment, and the number of pigs per pen. The adjustment for temperature was based on an optimal temperature and an effective ambient temperature. This equation is limited to effective ambient temperatures between 5 and 30 °C:

$$t_o = 26 - 0.0614\,BW \qquad [2.28]$$

$$TD = 0.0165(t_o - EAT) \qquad [2.29]$$

where

t_o = optimal temperature (°C)
BW = body weight (kg)
TD = DE deviation due to temperature (percent)
EAT = effective ambient temperature (°C)

The adjustment for space allotment for pigs was based on the size of the pigs. Equation [2.30a] is for weanling pigs (5 to 20 kg). Equation [2.30b] is for growing pigs (20 to 50 kg), and equation [2.30c] is for finishing pigs (50 to 100 kg), [NRC (1986)]:

$$SD = 72.27 + 132.40\,S - 159.54\,S^2 \qquad [2.30a]$$

$$SD = 77.25 + 42.93\,S - 20.25\,S^2 \qquad [2.30b]$$

$$SD = 61.55 + 70.0\,S - 32.0\,S^2 \qquad [2.30c]$$

where

SD = DE deviation due to space (percent)
S = space per pig (m^2/pig)

There is also an adjustment for the number of pigs per pen. Each additional pig per pen decreases feed intake by 0.92 percent for weanling pigs, and 0.25 percent for growing pigs. The adjustment to feed intake for finishing pigs was a 0.32 percent increase for each additional pig.

The NRC (1986) nutritional adjustments included those for addition of antibiotics, for pelletized feed, and for the energy density level. The adjustment to the digestible energy intake (DE) when antibiotics were used is 8 percent from weaning to 16 kg, 6 percent from 16 to 57 kg, and 2 percent from 57 kg to market weight. The adjustment to the DE when pelletized feed was used is -9 percent from weaning to 20 kg, and -3.1 percent from 20 kg to market weight.

Adjustments were also made to feed intake for energy density of the feed. For pigs from weanling to 30 kg, DE is decreased by 1388 kcal per day for every kcal that the energy density of the feed is below 3.3 kcal per gram. The DE is increased by 183 kcal per day for every kcal that energy density is above 3.6 kcal per gram. For pigs above 30 kg, DE is decreased by 2733 kcal per day for every kcal that energy density is below 3.3 kcal per gram.

The NCR (1987) model utilizes all of the feed adjustment factors recommended by NRC (1986). These factors are assumed to have an additive effect upon digestible energy intake. The NCR swine model has one significant change from the NRC recommendations. Equation [2.26b] was used for pigs weighing more than 18 kg, rather than 20 kg. For a weight range of 5 to 18 kg, equation [2.31a] was used; however, when pigs were weaned at three weeks of age, equation [2.31b] was used to simulate the growth check which occurs during this time. Equation [2.31b] was used until DE was equal or greater than the result of equation [2.31a]:

$$DE = 456\,BW - 9.46\,BW^2 - 1531 \qquad [2.31a]$$

$$DE = 108\,DPW - 101 \qquad [2.31b]$$

where

DE = digestible energy intake (kcal/day)
BW = body weight (kg)
DPW = days post-weaning (days)

2.1.5 Body Composition and Growth

The task of calculating the growth rate of swine is important but difficult. Many factors influence the quantity as well as the quality of growth in swine. An accurate model of the amounts of different body gains, such as fat and lean, would enable producers to produce a leaner and more marketable product.

Teter et al. (1973) presented an over-simplification of growth modeling which seemed to work well in their experiments. Metabolizable energy intake and heat loss, as discussed in earlier sections, were used to calculate gain. They theorized that the difference between intake and heat production (S or L, whichever was larger) yielded energy available for growth. This quantity was converted to gain using a value for energy required per pound of gain:

$$G = \frac{(Q - \text{S or L})}{C} \qquad [2.32]$$

$$C = 1330\,W^{0.436} \qquad [2.33]$$

where

G = gain (lb/day)
Q = metabolizable energy intake (btu/day)
S = heat loss below the t_d (btu/day)
L = heat loss above the t_d (btu/day)
C = energy required for growth (btu/lb)
W = body weight (lb)

A more theoretically based approach was provided by the Whittemore pig model which was developed and described by Whittemore (1976, 1980, 1983), and Whittemore and Fawcett (1974, 1976). This method was developed by examining the path of different intake constituents, accounting for losses and inefficiencies, and then calculating the rate of body constituent increase. The NCR (1987) swine model used a great deal of the Whittemore framework. To expedite this discussion, only the NCR model is discussed with other appropriate authors acknowledged.

In order to begin the growth portion of the model, it was necessary to know the initial composition of the pig. NCR (1987) used the following equations, which were developed using data from slaughtered pigs and were particular to given size ranges:

BW less than 7.5 kg [Ewan (1982)]:

$$PT = 0.155\,BW - 0.004 \qquad [2.34a]$$

$$FAT = 0.092\,BW - 0.160 \qquad [2.35a]$$

$$AT = 0.029\,BW + 0.016 \qquad [2.36a]$$

$$EBW = 0.928\,BW + 0.123 \qquad [2.37a]$$

$$ET = 1.70\,BW - 1364 \qquad [2.38a]$$

BW between 7.5 kg and 15 kg [Ewan (1982)]:

$$PT = 0.149\,BW + 0.089 \qquad [2.34b]$$

$$FAT = 0.0764\,BW + 0.0013\,BW^2 - 0.371 \qquad [2.35b]$$

$$AT = 0.021\,BW + 0.096 \qquad [2.36b]$$

$$EBW = 0.926\,BW + 0.176 \qquad [2.37b]$$

$$ET = 1.777\,BW - 3946 \qquad [2.38b]$$

BW greater than 35 kg [Whittemore (1976)]:

$$PT = 0.154\,BW - 0.212 \qquad [2.34c]$$

$$FAT = 0.192\,BW - 0.288 \qquad [2.35c]$$

$$AT = 0.032\,BW - 0.073 \qquad [2.36c]$$

$$EBW = 0.952\,BW \qquad [2.37c]$$

$$ET = 5640\,PT + 9400\,FAT \qquad [2.38c]$$

For all BW: Whittemore (1976)

$$ALT = PT(5.1 - 0.009\,BW) \qquad [2.39]$$

$$FT = FAT\,1.1 \qquad [2.40]$$

where

PT = body protein (kg)
BW = body weight (kg)
FAT = chemical fat content (kg)
AT = ash content (kg)
EBW = empty body weight (kg)
ET = body energy content (kcal)
ALT = total body protein (kg)
FT = total body fat (kg)

Jacobson et al. (1989) discussed an addition to the NCR model which allowed an animal to lose weight when the energy intake was less than 1.5 times the maintenance requirement. Weight loss was assumed to occur when the pig catabolized stored lipid and protein to meet energy needs for maintenance. Lipid was catabolized exclusively until 90 percent of the body fat was lost, then protein was catobolized until 40 percent of the lean mass was lost. If at this point growth was still limited by energy intake, death occurred. Gain was reduced by the amount of energy due to cold thermogenesis. The following equations were used to calculate the amount of catabolized energy needed from the pig when intake was less than 1.5 times maintenance:

$$PX = 50\,PT \tag{2.41}$$

$$PR = 0.156\,PI - 26.78 \tag{2.42}$$

$$PM = PI - PR \tag{2.43}$$

$$EU = 1.72\,PM \tag{2.44}$$

$$AME = EI - EU \tag{2.45}$$

$$EPR = 5.64\,PR \tag{2.46}$$

$$ALR = \frac{(Q - EM - H1 - EPR)}{9.4} \tag{2.47}$$

$$E = ALR + EPR \tag{2.48}$$

where

PX = protein synthesis (gm/day)
PT = protein mass in body (kg)
PR = protein retention (gm/day)
PI = protein intake (gm/day)
PM = protein deamination (gm/day)
EU = energy loss in urine (kcal/day)
AME = available metabolizable energy (kcal/day)
EI = digestible energy intake (kcal/day)
EPR = energy cost of protein accretion (kcal/day)
ALR = lipid retention (kcal/day)
Q = net energy intake (kcal/day)
EM = energy cost of required maintenance (kcal/day)
= $85\ W^{0.75}$
H1 = energy cost of cold thermogenesis (kcal/day)
E = energy retention (kcal)

2.1.6 The NCR Swine Model

A copy of the NCR (1987) swine model was obtained through personal communications with Richard Ewan at Iowa State University. The model was developed as a menu-driven BASIC computer program for use on an IBM-PC. It operates on a daily basis. Input is read into the program through three main arrays: one with feed composition, one with characteristics of the swine house, and one with physiological data. Table 2 lists the array components. The floor type is designated "1" through "4" and defined as: 1, solid concrete; 2, concrete slats; 3, bedded concrete; and 4, metal wire mesh.

Two different approaches were used for calculation of heat production. The Whittemore method utilizes energy balances and metabolic rates to calculate heat loss. The other method incorporates the Bruce and Clark (1979) methodology along with the Jacobson (1983) adaptations. The second method was also utilized by DeShazer et al. (1988). Heat production values from the two methods generally vary less than 10 percent.

Feed intake was calculated using the guidelines published by NRC (1986) where growth was modelled using the Whittemore model with adaptations based on Ewan (1982). Ewan and DeShazer (1988) validated the growth portion of this model and concluded that it provided reasonable estimates of growth performance.

The output of the NCR model includes either daily nutritional or daily environmental information (depending on user preference). Table 3 summarizes the daily output information. At the end of the simulation, summaries are displayed on carcass composition, environment, or financial information. Table 4 gives a sample of this display.

Table 2. Input arrays for the NCR (1987) swine model.

No.	Item	Units
	Feed Composition	
1	Crude Protein	Percent
2	Digestible Crude Protein	Percent
3	Crude Protein Biological Value	Percent
4	Digestible Energy	kJ/g
5	Net Energy	kJ/g
6	Lysine	Percent
7	Tryptophan	Percent
8	Threonine	Percent
9	Cost	$/kg
10	Wastage	Percent
11	Pelleted (1 = yes)	----
12	Antibiotics (1 = yes)	----
	House Characteristics	
1	Outside Temperature	°C
2	Inside Temperature	°C
3	Air Movement	m/s
4	Floor Type (1 to 4)	----
5	Floor Condition	----
6	Drafts	----
7	Insulation R	----
8	Pen Length	m
9	Pen Width	m
10	Feeder Length	m
	Physiological Characteristics	
1	Gilts/pen	Number
2	Gilt Maximum Protein Deposition	g/day
3	Barrows/pen	Number
4	Barrow Maximum Protein Deposition	g/day
5	Boars/pen	Number
6	Boar Maximum Protein Deposition	g/day

Table 3. Daily output from the NCR (1987) swine model.

Item	Description
	Nutritional
Day	Day of the simulation
Age	Age of the pig
Limit	The limiting growth factor, if any
Energy	Energy gain
Lean	Lean gain
Fat	Fat gain
Ash	Ash gain
Weight	Daily weight gain
Body Weight	Current body weight
HP2	Heat production from the Whittemore method
ME	Metabolizable energy intake
Feed	Daily feed intake
Gain-Feed	Gain-to-Feed ratio
	Environmental
Day	Day of the simulation
Age	Age of the pig
Limit	The limiting growth factor, if any
Body Weight	Current body weight
ADG	Average daily gain
ADF	Average daily feed intake
Gain-Feed	Gain-to-Feed ratio
HP	Heat production from the Bruce and Clark method
Latent:Total	Ratio of latent heat production to the total
AEFT	Effective temperature
ELT	Lower critical air temperature
ALCET	Lower critical effective temperature
HP2	Heat production from the Whittemore method

Table 4. Sample summary output from the NCR (1987) swine model.

```
************* CARCASS COMPOSITION SUMMARY ***************

FINAL BODY WEIGHT        40.2 KG
EMPTY BODY WEIGHT        38.3 KG          95.22 % BODY WEIGHT
DRY MATTER CONTENT       14.9 KG          38.92 % EMPTY BODY WEIGHT
WATER CONTENT            23.4 KG          61.08 % EMPTY BODY WEIGHT
NITROGEN CONTENT         0.9 KG           2.37 % EMPTY BODY WEIGHT
PROTEIN CONTENT          5.7 KG           14.81 % EMPTY BODY WEIGHT
FAT CONTENT              8.1 KG           21.05 % EMPTY BODY WEIGHT
ASH CONTENT              1.2 KG           3.06 % EMPTY BODY WEIGHT
ENERGY CONTENT           107739. KCAL     2814.2 KCAL/KG EBW
LEAN TISSUE CONTENT      28.9 KG          75.53 % EMPTY BODY WEIGHT
FAT TISSUE CONTENT       8.9 KG           23.16% EMPTY BODY WEIGHT
BACKFAT                  7.8 MM

************** ENVIRONMENTAL SUMMARY ***************

AVG TOTAL HEAT PRODUCTION                          112.0 WATTS
AVG LATENT HEAT PRODUCTION                         58.4 WATTS
LATENT TO TOTAL HEAT RATIO                         0.522
AVG EFFECTIVE TEMPERATURE                          24.7 C
AVG LOWER CRITICAL AIR TEMPERATURE                 11.1 C
AVG LOWER CRITICAL EFFECTIVE TEMPERATURE           11.3 C
AVG COLD THERMOGENSIS                              0. KCAL

************** FINANCIAL SUMMARY ***************

AVG DAILY FEED COST                                $ 0.14
TOTAL FEED COST                                    $ 3.84
```

2.2 Thermal Load Calculation Methods

2.2.1 Introduction

When considering a thermal model of a building, many factors such as conduction, convection, radiation, evaporation, infiltration, and ventilation come into play. In livestock housing facilities, ventilation rates are high enough so that as much as 80 to 90 percent of the building heat loss can be attributed to ventilation losses, thereby greatly overshadowing all other modes of heat loss. This situation is in contrast to losses occurring in a building during a power interruption in which conduction losses dominate but other modes also contribute a noteworthy amount.

In order to develop models for normal operation as well as power interruption situations, reasonable methods for estimating modes of heat loss need to be examined. The following sections contain a review of information on methods of estimating conduction, convection, lighting load, and infiltration rates. A review of models developed to simulate thermal building performance using these estimation methods is located in section 2.3.

2.2.2 Conduction

In agricultural buildings, conduction is usually treated as a one-dimensional, steady state process. The method, as illustrated by MWPS (1983), is quite simple. The areas of specific building components over their respective insulation values (R values) are summed. Within each R value is lumped characteristic insulation values for a film of air on either side of the building component. This incorporates convection and allows ambient temperatures on either side of the wall to be used rather than solving for surface temperatures. The A over R summation is then multiplied by the temperature difference, yielding the equation:

$$q_w = \sum_{i=1} \left(\frac{A_i}{R_i} \right) \Delta t \qquad [2.49]$$

where

q_w = conduction loss through walls (W)
A_i = area of component i (m^2)
R_i = insulation value of component i ($m^2 °C/W$)
Δt = temperature difference across wall (°C)

The heat loss through the building foundation is similarly solved using the perimeter length instead of the area:

$$q_p = \sum_{i=1} \left(\frac{P_i}{R_i} \right) \Delta t \qquad [2.50]$$

where

q_p = conduction loss through the perimeter (W)
P_i = area of component i (m)
R_i = insulation value of component i (m°C/W)
Δt = temperature difference across wall (°C)

The above equations, while effective for situations of worst-case design, are strictly for steady state situations. A method described by ASHRAE (1989) called the Transfer Function Method (TRFM) was designed to better accommodate dynamic temperature situations. TRFM is based on the one-dimensional transient heat conduction equation and uses superposition to solve for multi-layer conduction surfaces. It utilizes response factors which weight temperatures and heat fluxes from previous times.

$$q_n(\tau) = \sum_{m=1}^{k} (-1)^{m+1} J_m q_n(\tau - m)$$

$$+ \sum_{m=1} [Y_m t_1(\tau - m + 1) - Z_m t_n(\tau - m + 1)] \qquad [2.51]$$

$$q_1(\tau) = \sum_{m=1}^{k} (-1)^{m+1} J_m q_1(\tau - m)$$

$$+ \sum_{m=1} [X_m t_1(\tau - m + 1) - Y_m t_n(\tau - m + 1)] \qquad [2.52]$$

where

q_n = flux at the outer surface (W/m²)
τ = time step number
J_m = flux response factors
X,Y,Z = temperature response factors (W/m²°C)
t_1 = inner surface temperature (°C)
t_n = outer surface temperature (°C)
q_1 = flux at the inner surface (W/m²)

Stephenson and Mitalas (1967), and Mitalas and Stephenson (1967) first introduced TRFM for design calculations. Using LaPlace transforms and superposition, this method reduced computational time and matrix storage requirements over the finite difference techniques used previously.

Mitalas (1968) later extended the TRFM method to include non-linear boundary conditions. Kusuda (1969) illustrated the development of TRFM for various geometries such as cylindrical and spherical surfaces, as well as for a semi-infinite medium. He concluded that results using the TRFM compared favorably with those from classical analytical solution techniques. Peavy (1978a and b) introduced higher order response factors, thereby reducing the required number of factors to one third of those originally required.

Boufadel (1987) developed a computer program to calculate TRFM response factors. Input to this program included the time step (taken as one hour in most applications), the thermal diffusivity (α), the conductance (k), and the specific heat (c_p) for each wall component. The output included 15 of each of the temperature response factors and 5 of the flux factors. It also included a check to be sure the program was working properly for the case at hand. Theory states that the sum of the X factors, the sum of the Y factors, and the sum of the Z factors should each equal the wall conductance value (U). These values were all printed to be checked by the user. This program was written for use in English units and was used in the research reported herein. A copy of the program, along with inputs and outputs, is in Appendix A.

ASHRAE (1989) gives tables of response factors for various walls and roofs. The walls and roofs described all contain components to account for convection on the two wall faces, so t_1 was replaced by the room temperature in equations [2.51-2]. ASHRAE (1989) also advised using sol-air temperatures for exterior wall temperatures. This allows incorporation of solar heat loads. In this situation, t_n in equations [2.51-2] would be replaced by t_e , where t_e is defined as:

$$t_e = t_o + \frac{(\alpha I_t)}{h_o} - \frac{(\varepsilon\, \delta R)}{h_o} \qquad [2.53]$$

where

t_e = sol-air temperature (°C)

t_o = outdoor air temperature (°C)
α = absorptance of the wall surface
I_t = total incident solar radiation upon the surface (W/m²)
h_o = convective heat transfer coefficient of the outer surface (W/m²-°C)
ε = emittance of the outer surface
δR = difference between the long wavelength radiation incident on the surface from the sky and the radiation emitted from a blackbody at outdoor air temperature (W/m²)

Another method used with TRFM was given by Boufadel (1987). Rather than use the sol-air temperature as described above, he performed energy balances on each face of the wall. In this manner convection and radiation could be incorporated directly. Equation [2.54] was used for exterior surfaces and equation [2.55] was used on inner surfaces. This method is more fully explained in the model development chapter of this dissertation.

$$q_s + q_{conv} + q_{emis} + q_{cond} = 0 \qquad [2.54]$$

$$q_{conv} + q_{cond} = 0 \qquad [2.55]$$

where

q_s = solar flux
q_{conv} = surface convection flux
q_{emis} = longwave emission flux
q_{cond} = conduction flux from TRFM

2.2.3 Convection

Convective heat loss is given by:

$$q_{conv} = h_m (t_s - t_\infty) \qquad [2.56]$$

where

q_{conv} = surface convection flux (W/m^2)
h_m = mean convective coefficient ($W/m^2\ K$)
t_s = surface temperature (°C)
t_∞ = surrounding air temperature (°C)

The difficulty in calculation of convective losses comes in finding the mean convective coefficient (h_m).

The two main modes of convection are natural and forced. Natural convection is driven by thermal buoyancy effects while forced convection results from air movement by wind or mechanical means.

Incropera and DeWitt (1981) gave empirical relationships for natural convection based on the Rayleigh and Prandtl numbers:

$$Ra_L = \frac{\{g\beta(t_s - t_\infty)L^3\}}{(\nu\alpha)} \qquad [2.57]$$

$$Pr = \frac{\nu}{\alpha} \qquad [2.58]$$

where

Ra_L = Rayleigh number based on a characteristic length
g = gravitational acceleration (9.8 m/s^2)
β = inverse of the film temperature (°C)
t_s = surface temperature (°C)
t_∞ = surrounding air temperature (°C)

L = characteristic length (m)
ν = kinematic viscosity (m^2/s)
α = thermal diffusivity (m^2/s)
Pr = Prandtl number

Incropera and DeWitt (1981) state that for most engineering calculations, the following equation is suitable for vertical surfaces:

$$h_m = \frac{k}{L}\left\{0.825 + \frac{\left[0.387 Ra_L^{\left(\frac{1}{6}\right)}\right]}{\left[1 + (0.492/Pr)^{\left(\frac{9}{16}\right)}\right]^{\left(\frac{8}{27}\right)}}\right\}^2 \qquad [2.59]$$

where

h_m = mean convective coefficient ($W/m^2\ K$)
k = conductivity of air ($W/m\ K$)
L = characteristic length (m)
Ra_L = Rayleigh number based on a characteristic length
Pr = Prandtl number

Horizontal surfaces are treated differently, depending on the orientation of the convective surface. Equation [2.60] is for a upper surface being heated or a lower surface being cooled. Equation [2.61] is for a lower surface being heated or an upper surface being cooled:

$$h_m = 0.15\,\frac{k}{L}\,Ra_L^{\left(\frac{1}{3}\right)} \qquad [2.60]$$

$$h_m = 0.27\,\frac{k}{L}\,Ra_L^{\left(\frac{1}{4}\right)} \qquad [2.61]$$

where

h_m = mean convective coefficient (W/m² K)
k = conductivity of air (W/m K)
L = characteristic length (m)
Ra_L = Rayleigh number based on a characteristic length
Pr = Prandtl number

Forced convection is based on the Reynolds number (Re_x) and the Prandtl number, thus giving a velocity dependency to the relationship. For moderate Prandtl numbers, Kays and Crawford (1980) gave the following relationship for laminar flow (Re_x less than 500,000) on flat plates:

$$h_x = 0.332 \frac{k}{x} Pr^{0.33} Re_x^{0.5} \qquad [2.62]$$

$$Re_x = u_\infty \frac{x}{\nu} \qquad [2.63]$$

where

h_x = local convective coefficient (W/m² K)
k = conductivity of air (W/m K)
x = distance from the leading edge (m)
Pr = Prandtl number
Re_x = Reynolds number at a point x
u_∞ = free stream velocity (m/s)
ν = kinematic viscosity (m²/s)

For turbulent flow (Re_x greater than 500,000) Kays and Crawford reported:

$$h_x = 0.0287 \frac{k}{x} Pr^{0.6} Re_x^{0.8} \qquad [2.64]$$

where

h_x = local convective coefficient (W/m² K)
k = conductivity of air (W/m K)
x = distance from the leading edge (m)
Pr = Prandtl number
Re_x = Reynolds number at a point x

The local convective coefficient can be converted to a mean convective coefficient for a surface by integrating h_x over the unknown surface and then dividing by the surface length.

2.2.4 Lighting Load

Lights can contribute a significant amount of additional heat to a room. The instantaneous rate of heat addition to a conditioned space is somewhat different from the rated wattage on bulbs. ASHRAE (1989) gives the following equation:

$$Q_{lights} = W\, F_{ul}\, F_{sa} \qquad [2.65]$$

where

Q_{lights} = heat gain due to lights (W)
W = total light wattage (W)
F_{ul} = lighting use factor
F_{sa} = lighting special allowance factor

The total light wattage can be obtained from the ratings on the lamps installed. The use factor is the ratio of the wattage in use to the total wattage installed. The special allowance factor is for fluorescent fixtures. This added factor accounts primarily for ballast losses. For general applications, F_{sa} of 1.20 is recommended.

2.2.5 Infiltration

Infiltration losses are important in calculating residential heating and cooling loads. Livestock buildings are ventilated at relatively high rates so infiltration is not considered under normal circumstances. However, during a power interruption, infiltration is the sole means of air exchange; therefore, it becomes important. Grimsrud et al. (1982) developed a model for predicting infiltration based on stack and wind effects:

$$Q_{inf} = L\,(f_s^2\,\Delta T + f_w^2\,V^2)^{0.5} \qquad [2.66]$$

where

Q_{inf} = infiltration (m^3/s)
L = effective leakage area (m^2)
f_s = stack parameter ($m/s\text{-}K^{0.5}$)
ΔT = indoor - outdoor temperature difference (K)
f_w = wind parameter
V = wind speed (m/s)

The leakage area is measured using a fan pressurization method. The wind and stack parameters f_w and f_s convert temperature difference and wind speed to equivalent pressures. The wind parameter (equation [2.67]) utilizes shielding coefficients found in Table 5.

$$f_w = C'\left[(1 - R)^{0.333}\right]\left\{\frac{\left[\delta(\frac{H}{10})^{\gamma}\right]}{\left[\delta'(\frac{H'}{10})^{\gamma'}\right]}\right\} \qquad [2.67]$$

where

f_w = wind parameter

Table 5. Generalized shielding coefficient for local shielding (Grimsrud et al., 1982).

Shielding Class	C′	Description
I	0.32	No obstructions (trees, fences, nearby houses) whatsoever
II	0.28	Light local shielding with few obstructions
III	0.24	Some obstructions within two house heights
IV	0.18	Obstructions around most of perimeter
V	0.10	Large obstructions surrounding perimeter within two house heights

C' = generalized shielding coefficient
R = fraction of leakage in the floor and ceiling
δ, γ = terrain parameters of the structure
H = height of the structure (m)
δ', γ' = terrain parameters at the wind measurement site
H' = height of the wind measurement (m)

The stack parameter is given by equation [2.68] and utilizes the terrain parameters in Table 6.

$$f_s = \frac{(1 + \frac{R}{2})}{3}\left[1 - \frac{X^2}{(2 - R)^2}\right]^{1.5}\left[\frac{(g\,H)}{T}\right]^{0.5} \qquad [2.68]$$

where

f_s = stack parameter
R = fraction of leakage in the floor and ceiling
X = ratio of the difference between floor and ceiling leakage to total leakage area
g = acceleration of gravity (9.8 m/s^2)
H = height of the structure (m)
T = inside temperature (K)
total leakage area

Grimsrud et al.. (1982) stated that the values for R and X may be approximated by observing major leakage areas and selecting an estimate. The infiltration model was insensitive to these values; therefore, approximation is adequate. The model was said to have a weekly accuracy within 20 percent of actual infiltration.

Table 6. Terrain parameters for standard terrain classes (Grimsrud et al., 1982)

Class	γ	δ	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles (e.g., buildings or trees, well separated from each other)
III	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban,industrial or forest areas
V	0.35	0.47	Center of large city

2.3 Building Models

The models for swine as growing heat and moisture producing creatures have been examined in previous sections. The ambient indoor temperature played a significant role in many of the swine model components. The environment maintained in a controlled building is a function of the environment to which the building is exposed. Since the reaction of swine is modeled as a function of the building temperature, it is important to model the reaction of the building to the outdoor ambient temperature. Using a building model, a more complete picture of how production and production costs are affected by the outdoor environment can be obtained.

Hinkle and Good (1970) adapted steady state energy and moisture balance equations normally used for design [MWPS (1983)] to form a transient scheme. They formed equations balanced over a duration of one minute assuming no heat storage in the building, complete mixing of air, and constant heat and moisture production from the animals. The purpose was to compare three ventilation schemes: one fan, variable speed control; one fan, time clock control; and two fans, thermostat control. The simulation was performed using actual weather data.

The Hinkle and Good (1970) model was one of the most simple applications of a model. Comparison of systems took a fraction of the time and cost of typical field tests. At each time step the model calculated the total energy and moisture within the specified room. Fluxes were then calculated for the present time step. The addition of energy and moisture were then added to the totals for the previous time step. These values were easily converted to temperature and relative humidity using psychrometric equations. The balances were performed using:

$$Q_{new} = Q_{old} + \Delta Q \qquad [2.69]$$

$$W_{new} = W_{old} + \Delta W \qquad [2.70]$$

where

Q_{new} = energy content in the building at the present time (kJ)
Q_{old} = energy content in the building at the previous time (kJ)
ΔQ = change in the energy content (kJ)
W_{new} = moisture content in the building at the present time (kg)
W_{old} = moisture content in the building at the previous time (kg)
ΔW = change in the moisture content (kg)

Feddes et al. (1973) developed a model that contained algorithms for calculation of the solar heat load on the building surfaces, and the thermal resistance of the attic space. The transfer function method with sol-air temperatures was used to calculate conduction losses. The five basic functions of the model were: 1) determination of solar position and intensity of solar radiation on outer surfaces of the confinement unit at hourly intervals; 2) calculation of the response factors and heat fluxes for the individual structural components of the unit; 3) calculation of the thermal resistance of the attic space in the pitched roof; 4) calculation of the resultant heat load for the unit; and 5) calculation of ventilation rates at hourly intervals based on psychrometric and physiological data. The ventilation rate was based on standard equations for heat and moisture removal.

Fourier series were employed by Albright and Scott (1974a) to simulate temperature changes in a livestock building. Parameters considered were: the ventilation rate, the mass of air in the building, and building construction characteristics. The outside temperature was modeled with a Fourier series. The inside and sol-air temperatures were then derived, using an energy balance, as a Fourier series with a different amplitude and possibly a phase lag with the outside temperature. Animal heat production was simulated by a simple linear expression to temperature.

Albright and Scott (1974b) went on to validate the model. They stated that the model accurately predicted changes of temperature within the building. It was concluded that the series could be truncated after five terms with little loss of accuracy, and that using the sol-air temperature does a better job of predicting inside temperature than merely using outside air temperature.

Christianson and Hellickson (1977) developed a model that included empirical estimations of infiltration heat loss. A straight-forward energy balance, including solar energy, was used to determine the supplemental heat required. Simulations were run to evaluate insulation requirements. Costs were incorporated to determine optimal insulation need as a function of insulation and heating cost.

Cole (1980) derived equations to describe the building air temperature. Four models were derived by making various assumptions concerning constant properties. These models described the rate of change within a control volume surrounding the outlet as a function of mass flow rates, current temperatures, specific heat, and net heat transfer. Accuracy of all four models was greater than the typical measurement capabilities for building temperature, so all four were adequate predictors.

A transient model, employing the transfer function method and sol-air temperatures, was developed by Buffington (1981). Albright (1981) used complex Fourier series to describe boundary conditions which were shown to be accurate within 1°C in most cases. Bruce (1982) graphically depicted the relationship between inside temperature, outside temperature, and ventilation rate.

Timmons (1984) appears to have been the first researcher to combine a weather model, building thermal model, and broiler growth model to simulate a poultry facility. Calculations were based on temperatures of 15.5, 21.1, and 26.7 °C (60, 70 and 80 °F), which are typical brooding and growout temperatures. Daily calculations were made using mean values of outdoor temperature and solar radiation values. Bird weight, feed required, and supplemental heat were then updated and tabulated on a daily basis.

Timmons (1984) reported accuracy of fuel consumption predictions to be within 10 percent of those reported by the cooperating integrator. Predicted feed to gain ratios were within 1.5 percent of the average reported by the growers involved. These numbers indicate that possible errors were within tolerable limits and suggest that combining models may be a very practical tool.

Zhang et al. (1988) used a GASP IV computer model to simulate the dynamic thermal response of a ventilated air-space. They found good agreement between actual and simulated temperature, relative humidity, and supplemental heat requirements for farrowing rooms. From the study they concluded that ventilation rates are greatly effected by fluctuations in static pressure when propeller fans are used, and that the GASP IV simulation program is a good tool for analyzing dynamic thermal responses.

Two models incorporated economic parameters. The first was developed by Timmons and Gates (1986), and determined on a continuous basis the inside temperature which optimized economic return for a broiler production facility. The optimization was affected by bird market value; feed, fuel and electric costs; house thermal characteristics; outside air temperature; and current bird weight. The optimization equation was:

$$\begin{aligned} \text{net} = {} & \text{growth}\,(\$/\text{kg}_{\text{meat}}) - \text{feed}\,(\$/\text{kg}_{\text{feed}}) - \text{fuel}\,(\$/\text{L}_{\text{fuel}}) \\ & - \text{electric}\,(\$/\text{kWh}) - \text{fixed} \end{aligned} \qquad [2.71]$$

where

net = net return per bird per time ($/bird-day)
growth = rate of bodyweight gain (kg/day)
$\$/\text{kg}_{\text{meat}}$ = unit price of meat (liveweight basis)
feed = rate of feed consumption to support growth rate (kg/day)
$\$/\text{kg}_{\text{feed}}$ = unit price of feed ($/kg)
fuel = rate of fuel use necessary to maintain house at specific temperature (L/day)
$\$/\text{L}_{\text{fuel}}$ = unit cost of fuel ($/L)
electric = rate of electric use for fans and lights (kWh/day)

\$/kWh = unit cost of electricity (\$/kWh)
fixed = amount of fixed costs (per unit time and bird) associated with production (\$/bird/day)

To maximize return per kg, the above equation was divided by the growth rate per bird per unit time. Timmons and Gates (1986) concluded there was significant potential for savings based upon the predictions of the model. Gates and Timmons (1987) used the optimization program with a microprocessor controller to evaluate the controllers effectiveness. They found a significant advantage over traditionally controlled houses.

The second type of optimizer program was developed by Gates et al. (1988) to optimize the diet formulation for a given turkey production facility. This model utilized growth and building models to select economically optimal feed energy levels. It was concluded that significant potential for improved profit was available through the use of this model.

Chapter 3

Model Development

3.1 Introduction

Two models were developed in the course of this project. The first was a model to simulate the response to a power interruption in a swine nursery and is referred to as the failure model. This model calculates the nursery room temperature and humidity ratio in increments of ten minutes from the point at which ventilation and heating fail due to a power interruption.

The second model simulates the hourly operation of a swine nursery and is referred to as the operational model. This model estimates feed consumption, fuel usage, and pig growth as the main outputs. A routine calculates the economically optimal temperature at which the least cost per unit of gain produced can be attained.

Both models were developed using similar principles. In the following section, the principles which were common to both models are discussed. Principles which were unique to each individual model are discussed in their respective sections. The failure model was developed first because of its reliance upon the conduction subroutine. It therefore was a better test of the conduction principles and allowed ease in development of the operational model. The failure model is, therefore, presented before the operational model.

3.2 General

Portions of the development common to the two models were limited to conduction, solar load, and psychrometric aspects. The conduction submodel was developed using the transfer function method (TRFM) and followed closely the development of the Boufadel (1987) model. The solar subroutine converted collected solar measurements to solar loads upon each surface. The psychrometric subroutine converted wet and dry bulb measurements to a humidity ratio.

3.2.1 Conduction

The conduction submodel consisted of three parts. The first part initialized the TRFM by calculating q_n and q_i (see equations [2.51] and [2.52]) for one hundred time steps. ASHRAE (1989) stated that approximately 72 time steps are needed to initialize the TRFM when using hourly steps. One hundred steps were chosen after experimentation with the method using a reduced time step.

The second portion of the conduction submodel calculated the surface temperatures (t_i and t_n) for each conduction surface. This was done using a heat balance equation for each surface. For the outer surfaces:

$$q_n + q_{emis} + q_s + q_{conv} = 0 \qquad [3.1]$$

where

q_n = conduction flux at the outer surface (W/m²)
q_{emis} = longwave emission flux (W/m²)
q_s = solar flux (W/m²)
q_{conv} = surface convective flux (W/m²)

Figure 4 illustrates the heat balance. The terms in the above expression were replaced with the appropriate equation or value. The q_n term was replaced by equation [2.51],and q_s was replaced by the solar load as calculated using the method described in a later section.

The q_{emis} term is based on a quadratic equation and represents longwave radiation exchange between the exterior of the wall and its surroundings. For an exchange between a horizontal surface and the sky:

$$q_{emis,sky} = F\,\varepsilon\,\sigma(T_{sky}^4 - T_n^4) \qquad [3.2]$$

where

q_{emis} = longwave emission flux (W/m²)
F = view factor
ε = surface emissivity
σ = Stefan-Boltzmann constant (5.669E-08 W/m² K⁴)
T_{sky} = effective sky temperature (K)
T_n = exterior surface temperature (K)

In actuality, T_{sky} was replaced with a term to encompass the view factor associated with each surface. Equation [3.2] represents a horizontal surface if F equals one. However, for a vertical surface this equation would be multiplied by a view factor of 0.5, because the surface views the sky

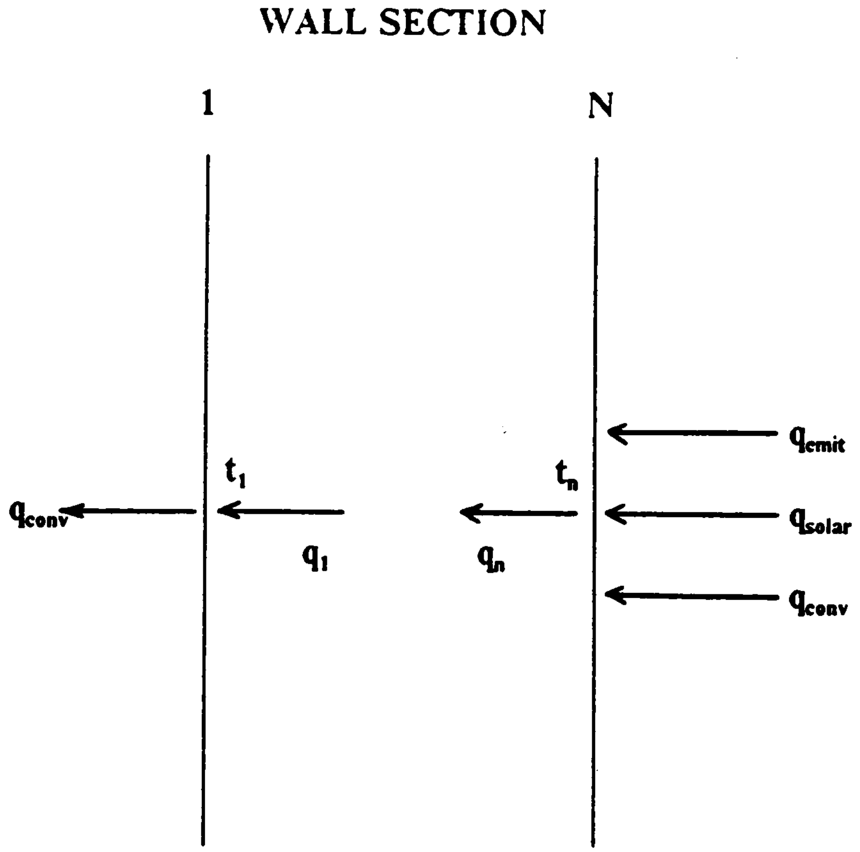

Figure 4. Heat flow through the wall and appropriate balances.

and the terrestrial surroundings equally. The remainder of the longwave emission is associated with a loss to the surroundings assumed to be at the exterior air temperature:

$$q_{emis,sur} = F\,\varepsilon\,\sigma(T_{sur}^4 - T_n^4) \qquad [3.3]$$

where

q_{emis} = longwave emission flux (W/m^2)
F = view factor for a vertical wall (0.5)
ε = surface emissivity
σ = Stefan-Boltzmann constant (5.669E-08 W/m^2 K^4)
T_{sur} = effective surrounding temperature (K)
T_n = exterior surface temperature (K)

Combining equations [3.2] and [3.3], assuming surface emissivity was near one, approximately yields:

$$q_{emis} = 0.5\,\varepsilon\,\sigma(T_{sky}^4 + T_{sur}^4 - 2\,T_n^4) \qquad [3.4a]$$

$$q_{emis} = \varepsilon\,\sigma\left\{\frac{(T_{sky}^4 + T_{sur}^4)}{2} - T_n^4\right\} \qquad [3.4b]$$

Therefore

$$T_{emis} = \left\{\frac{(T_{sky}^4 + T_{sur}^4)}{2}\right\}^{0.25} \qquad [3.4c]$$

and

$$q_{emis} = \varepsilon\,\sigma(T^4_{emis} - T^4_n) \qquad [3.4d]$$

where

q_{emis} = longwave emission flux (W/m²)
ε = surface emissivity
σ = Stefan-Boltzmann constant (5.669E-08 W/m² K⁴)
T_{sky} = effective sky temperature (K)
T_{sur} = effective surrounding temperature (K)
T_n = exterior surface temperature (K)
T_{emis} = effective longwave temperature (K)

Equation [3.4d] was linearized as follows:

$$q_{emis} = \varepsilon\,\sigma(T^2_{emis} + T^2_n)\,(T_{emis} + T_n)\,(T_{emis} - T_n) \qquad [3.5a]$$

$$q_{emis} = h_r\,(T_{emis} - T_n) = h_r\,(t_{emis} - t_n) \qquad [3.5b]$$

where

q_{emis} = longwave emission flux (W/m²)
ε = surface emissivity
σ = Stefan-Boltzmann constant (5.669E-08 W/m² K⁴)
T_{emis} = effective longwave temperature (K)
T_n = exterior surface temperature (K)
h_r = linearized radiant coefficient (W/m² K)
t_{emis} = effective longwave temperature (°C)
t_n = exterior surface temperature (°C)

This allows t_n to be calculated more expediently by iteration. The q_{conv} term was derived using basic convection equations as found in Chapter 2, Section 2.2.3. Local convection coefficients were integrated to determine the mean convection coefficient:

$$h_m = \frac{1}{(x_2 - x_1)} \int_{x_1}^{x_2} h_x \, dx \qquad [3.6]$$

where

h_m = mean convection coefficient (W/m² K)
x_2 = distance from the wall leading edge to the end of the convective surface (m)
x_1 = distance from the wall leading edge to the beginning of the convective surface (m)
h_x = local convection coefficient (W/m² K)

In the case of turbulent flow, equation [2.64] becomes:

$$h_m = \frac{(0.037 \, k \, Pr^{0.33})}{(x_2 - x_1)} (Re_{x2}^{0.8} - Re_{x1}^{0.8}) \qquad [3.7]$$

where

h_m = mean convection coefficient (W/m² K)
k = conductivity of air (W/m K)
Pr = Prandtl number
x_2 = distance from the wall leading edge to the end of the convective surface (m)
x_1 = distance from the wall leading edge to the beginning of the convective surface (m)
Re = Reynolds number (greater than 500,000)

If the flow becomes turbulent within the area of interest, equations [2.62] and [2.64] are integrated over respective wall lengths and become:

$$h_m = \frac{1}{(x_2 - x_1)} \left\{ 0.664\, k\, Re_c^{0.5}\, Pr^{0.33} + 0.037\, k\, Pr^{0.33} (Re_{x2}^{0.8} - Re_c^{0.8}) \right\} \qquad [3.8]$$

where

h_m = mean convection coefficient (W/m² K)
x_2 = distance from the wall leading edge to the end of the convective surface (m)
x_1 = distance from the wall leading edge to the beginning of the convective surface (m)
k = conductivity of air (W/m K)
Re_c = Reynolds number at the critical point (500,000)
Pr = Prandtl number
Re = Reynolds number at some point along the surface

The coefficient, h_m, was then substituted into the standard convection equation (equation [2.56]).

Both models were designed to calculate h_m and were programmed to be sensitive to wind direction. Standard properties for air were used in this calculation. Building dimensions for validation were programmed into the model for this calculation rather than read in by the program. More complex input programming would be necessary to allow more flexibility for use of the model with other facilities.

All components of equation [3.1] were therefore determined or expressed as a function of the surface temperature, t_n. The equation was then solved for t_n:

$$A = \sum_{m=1}^{k} (-1)^{m+1} J_m q_n(\tau - m)$$

$$+ \sum_{m=2} \{Y_m t_1(\tau - m + 1) - Z_m t_n(\tau - m + 1)\} \qquad [3.9a]$$

$$t_n(\tau) = \frac{\{A + Y_1 t_1(\tau) + h_r t_{emis}(\tau) + h_{m,n} t_a + q_s\}}{(Z_1 + h_r + h_{m,n})} \qquad [3.9b]$$

where

A = intermediate value
J_m = flux factor
q_n = flux at the exterior surface (W/m^2)
τ = time step number
Y,Z = temperature factors
t_1 = interior surface temperature (°C)
t_n = exterior surface temperature (°C)
h_r = radiant coefficient (W/m^2 K)
t_{emis} = effective longwave temperature (°C)
$h_{m,n}$ = mean convection coefficient for the outer surface (W/m^2 K)
t_a = external air temperature (°C)
q_s = solar load (W/m^2)

The above equations do not yield an explicit solution for t_n . The term h_r was based on an assumed value of t_n and, therefore, required iteration to find a precise solution for t_n. Furthermore, the inside surface temperature, t_1 , was an assumed value while calculating t_n. In order to solve for t_1, a heat balance was performed on the interior building surfaces:

$$q_1 + q_{conv} = 0 \qquad [3.10]$$

where

q_1 = flux at the interior surface (W/m^2)
q_{conv} = convective heat flux (W/m^2)

The q_1 term was determined from the TRFM, equation [2.52]. The convective flux was calculated assuming still air on interior surfaces and, therefore, natural convection. For walls, equation [2.59] was used to calculate the convection coefficient. For the ceiling, equations [2.60] and [2.61] were used. The upper, as well as the lower surface were assumed to be solely convective surfaces.

Once t_n and h_r were found, t_1 was calculated. Substituting the appropriate values into equation [3.10] and solving for t_1 yields:

$$B = \sum_{m=1}^{k} (-1)^{m+1} J_m q_1(\tau - m)$$

$$+ \sum_{m=2} \{X_m t_1(\tau - m + 1) - Y_m t_n(\tau - m + 1)\} \qquad [3.11a]$$

$$t_1(\tau) = \frac{\{Y_1 t_n(\tau) + h_{m,1} t_r(\tau) - B\}}{(X_1 + h_{m,1})} \qquad [3.11b]$$

where

B = intermediate value
J_m = flux factor
q_1 = flux at the interior surface (W/m²)
τ = time step number
X,Y = temperature factors
t_1 = interior surface temperature (°C)
t_n = exterior surface temperature (°C)
$h_{m,1}$ = mean convection coefficient for the inner surface (W/m² K)
t_r = room temperature (°C)

At this point the assumed value for t_1 , which was used in equation [3.9b], was checked. If the difference between the values was not within a specified range, then the model assumed a value between the new and old value of t_1, and calculated t_n and h_r again. This iteration procedure continued until all three variables (t_1, t_n, and h_r) converged for each wall.

The third portion of the conduction submodel determined heat loss through the concrete slab floor of the building. The slab was assumed to have a shallow manure pit over it, thereby complicating heat flow. Figure 5 illustrates the slab configuration. The earth one meter below the slab was assumed to have a constant temperature, t_g. At the upper slab surface the balance appears as:

$$q_f + q_g = 0 \qquad [3.12]$$

where

q_f = convective flux within the fluid (W/m^2)
q_g = conductive flux at the slab surface (W/m^2)

The TRFM was used to determine the heat flux from the ground. Pit liquids were considered to be a convecting fluid. The heat balance shown in Figure 5, at the slab surface, becomes:

$$C = \sum_{m=1}^{k} (-1)^{m+1} J_m q_g(\tau - m) + \sum_{m=2} \{X_m t_s(\tau - m + 1) - Y_m t_g\} \qquad [3.13a]$$

$$t_s(\tau) = \frac{\{Y_1 t_g(\tau) + h_f t_f(\tau) - C\}}{(X_1 + h_f)} \qquad [3.13b]$$

where

C = intermediate value
J_m = flux factor
q_g = flux at the slab surface (W/m^2)

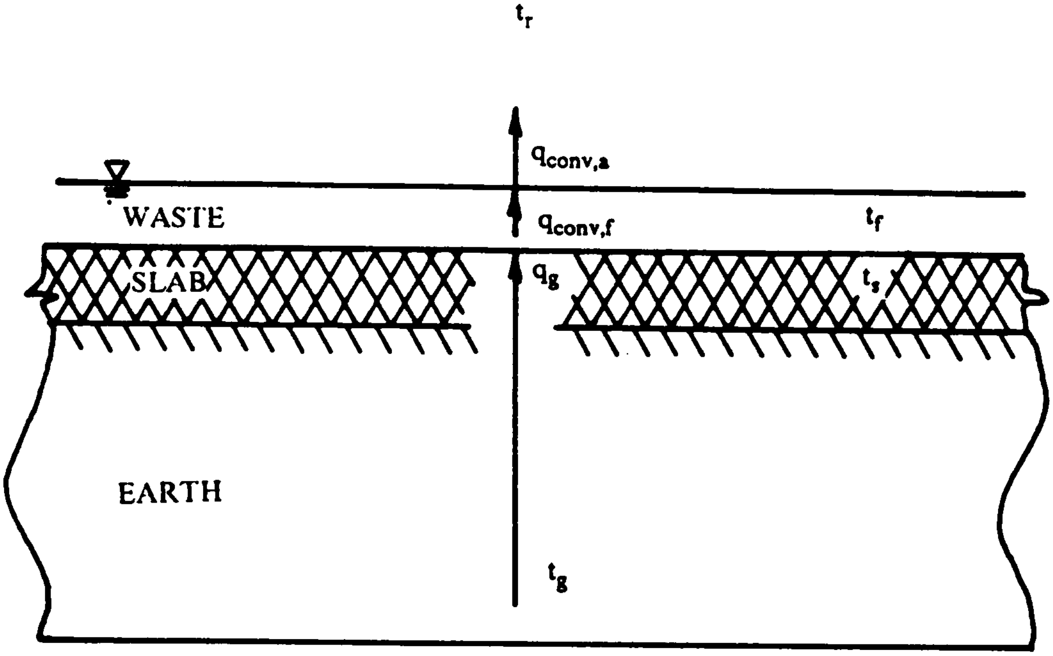

Figure 5. Heat flow through the floor slab and overlying fluid.

τ = time step number
X,Y = temperature factors
t_s = slab surface temperature (°C)
t_g = deep ground temperature (°C)
h_f = mean convection coefficient for the fluid to slab surface (W/m² K)
t_f = fluid temperature (°C)

A heat balance was performed on the pit fluid:

$$q_{conv,a} - q_{conv,f} = q_{stored} \qquad [3.14]$$

where

$q_{conv,a}$ = convection flux between the fluid and air (W/m²)
$q_{conv,f}$ = convection flux between the slab and fluid (W/m²)
q_{stored} = stored energy (W/m²)

This produced an equation which was iterated along with equation [3.13b], since t_s and t_f were both unknown:

$$t_f(\tau) = \frac{\left\{h_f\, t_s(\tau) + h_a\, t_r(\tau) + \frac{(m\, c_p)}{step}\, t_f(\tau - 1)\right\}}{\left\{h_f + h_a + \frac{(m\, c_p)}{step}\right\}} \qquad [3.15]$$

where

t_f = fluid temperature (°C)
h_f = convection coefficient between the slab and the fluid (W/m²K)
t_s = slab temperature (°C)
τ = time step number
h_a = convection coefficient between the air and the fluid (W/m²K)
t_r = room temperature (°C)
m = mass of pit liquid per m² (kg/m²)

c_p = specific heat of pit liquid (J/kg-K)
step = time step (s)

The convection coefficients, h_f and h_a, were solved using natural convection equations. The h_f term was determined using liquid manure thermal properties while h_a was found using air properties. Liquid thermal properties were assumed as: density, 1010 kg/m^3; specific heat, 4190 J/kg-K; conductivity, 0.658 W/m K; and kinematic viscosity, 2.97E-06 m^2/s [1].

All of the above solutions had a common need for thermal response factors to use the TRFM equations. A program written by Boufadel (1987) was utilized to calculate the response factors. The program was written in FORTRAN and used English units. The input required was the time step, the number of layers, and the conductivity, thermal diffusivity, and thickness for each layer. Program output included the response factors (in English units) and the summation of the X factors, the Y factors, and the Z factors. These summations were used to be sure the program was calculating correct response factors since each summation should equal the overall conductivity of the wall. The program is included in Appendix A.

During model development, it became apparent that using a small time step and a massive conduction unit would result in unacceptable response factors. This made it necessary to divide the conduction unit into two smaller components, each with a unique set of response factors, but all functioning together. Figure 6 illustrates the division. TRFM equations were written for each component using the guidelines in the above equations. It was assumed that the flux, q_{mid}, and the temperature, t_{mid}, at the interface were continuous. This method was tested by comparison to cases in which a single set of response factors worked. Differences between the double and single component methods were small and were assumed to be due a result of rounding errors. This method

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[1] Waste Management course notes, Department of Agricultural Engineering, University of Minnesota, Charles J. Clanton, instructor

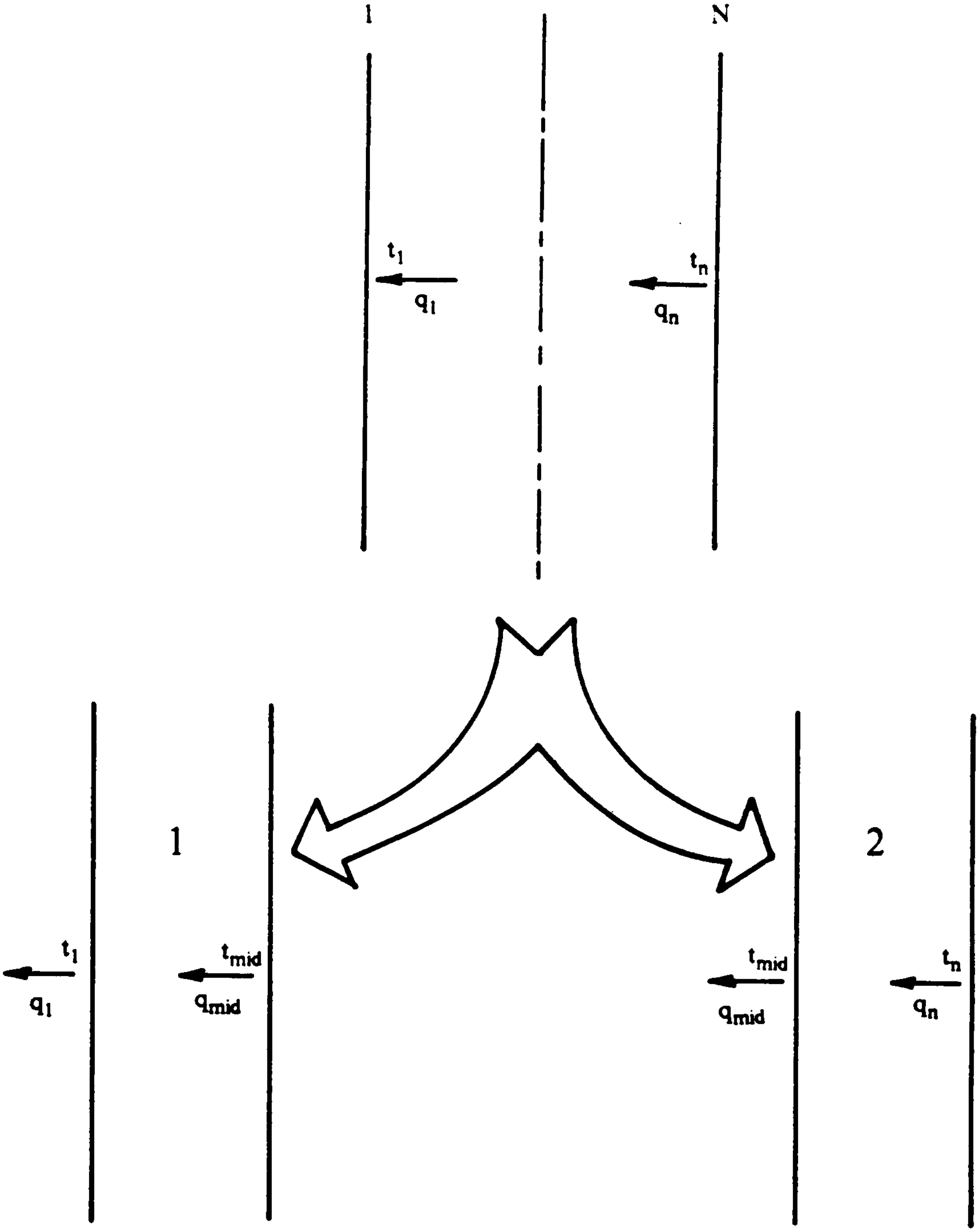

Figure 6. Diagram of single conduction unit divided into two components.

of partitioning a conduction unit allowed for greater flexibility in choosing time steps and wall thicknesses.

3.2.2 Solar Load

A subroutine was written to convert standard solar irradiation data to a quantity suitable for use in solar load calculations. This subroutine followed the method described by Duffie and Beckman (1980) and is explained in detail below.

The first step was to calculate solar time, which refers to the angular motion of the sun across the sky. Solar noon is the time at which the sun crosses the meridian of the observer. Solar time can be calculated from standard time using the following equations:

$$\mathrm{Time}_{sol} = \mathrm{Time}_{st} + 4(L_{st} - L_{loc}) + E \qquad [3.16a]$$

$$E = 9.87 \sin(2B) - 7.53 \cos B - 1.5 \sin B \qquad [3.16b]$$

$$B = 360 \frac{(n - 81)}{364} \qquad [3.16c]$$

where

Time_{sol} = solar time
Time_{st} = standard time
L_{st} = standard meridian for the local time zone (degrees west)
L_{loc} = longitude of the location in question (degrees west)
E = equation of time (minutes)
B = intermediate value
n = day of the year

The locations of the standard meridians for the continental United States are: Eastern time, 75 °W; Central time, 90 °W; Mountain time, 105 °W; and Pacific time, 120 °W.

In order to calculate the solar load, the angle between the beam radiation on a surface and the normal to that surface, called the angle of incidence, must be calculated. This is calculated by using a complex trigonometric equation which relates the building angles to the angle of the radiation:

$$\cos\Theta = \sin\delta\ \sin\Phi\ \cos\beta - \sin\delta\ \cos\Phi\ \sin\beta\ \cos\gamma + \cos\delta\ \cos\Phi\ \cos\beta\ \cos\omega$$
$$+ \cos\delta\ \sin\Phi\ \sin\beta\ \cos\gamma\ \cos\omega + \cos\delta\ \sin\beta\ \sin\gamma\ \sin\omega \qquad [3.17a]$$

$$\delta = 23.45\ \sin\left\{360\,\frac{(284 + n)}{365}\right\} \qquad [3.17b]$$

where

Θ = angle of incidence, angle between the beam radiation on a surface and the normal to that surface
δ = declination; angular position of the sun at solar noon with respect to the plane of the equator (δ between -23.45 ° and 23.45 °)
Φ = latitude, the angular location north or south of the equator (north is positive)
β = slope; angle between the plane surface in question and the horizontal (β between 0 and 180 °)
γ = surface azimuth angle, deviation of the projection on a horizontal plane of the normal to the surface from the local meridian (0 ° equals due south, east negative, west positive)
ω = hour angle, angular displacement of the sun east or west of the local meridian due to rotation of the earth of its axis at 15 ° per hour (morning negative, afternoon positive)
n = day of the year

Solar radiation can be broken into beam and diffuse radiation. Beam radiation occurs as a result of the direct contact of solar rays to some surface. Beam irradiance is generally measured with an instrument that tracks the sun. This irradiance is designated as G_{bn}, and its value may be used to calculated the beam irradiance which falls on any tilted surface, G_{bT}:

$$G_{bT} = G_{bn} \cos \Theta \qquad [3.18]$$

where

G_{bT} = beam irradiance on a tilted surface (W/m^2)
G_{bn} = normal beam irradiance (W/m^2)
Θ = angle of incidence, angle between the beam radiation on a surface and the normal to that surface

The diffuse irradiance is somewhat more elusive than beam irradiance. Three different approaches to calculate diffuse radiation were given by Duffie and Beckman (1980). The first one assumes that most of the diffuse radiation comes from an area immediately surrounding the sun. This method assumes that the ratio of radiation on a tilted surface to radiation on a horizontal surface is the same for diffuse radiation as that calculated for beam radiation. This approximation works best on clear days.

The second method assumes that diffuse radiation is isotropic, meaning uniformly distributed over the entire sky. This is a reasonable approximation when there is uniform cloud cover or when the sky is hazy.

The third method considers radiation to have three components: beam, diffuse, and solar radiation diffusely reflected from the ground. This method is said to be an improvement over the second method but is more complex, requiring assumptions about reflectance properties.

For this research, the second method was chosen. To calculate the diffuse component, the zenith angle of the sun must be used to find the beam irradiance on a horizontal surface:

$$\cos \Theta_z = \cos\delta \cos\Phi \cos\omega + \sin\delta \sin\Phi \qquad [3.19]$$

$$G_b = G_{bn} \cos\Theta_z \qquad [3.20]$$

where

Θ_z = zenith angle, angle between the sun and the zenith
δ = declination; angular position of the sun at solar noon with respect to the plane of the equator (δ between -23.45 ° and 23.45 °)
Φ = latitude, the angular location north or south of the equator (north is positive)
ω = hour angle, angular displacement of the sun east or west of the local meridian due to rotation of the earth of its axis at 15 ° per hour (morning negative, afternoon, positive)
G_b = beam irradiance on a horizontal surface (W/m^2)
G_{bn} = normal beam irradiance (W/m^2)

The total irradiance on a horizontal surface is a measured quantity and can be used to find the diffuse component of irradiance:

$$G_d = G - G_b \qquad [3.21]$$

where

G_d = diffuse irradiance (W/m^2)
G = total irradiance on a horizontal surface (W/m^2)
G_b = beam irradiance on a horizontal surface (W/m^2)

The solar load on a particular surface can then be calculated:

$$q_s(\tau) = \alpha(G_{bT} + G_d) \qquad [3.22]$$

where

q_s = solar load on a surface at time τ (W/m^2)
α = absorptivity of the wall surface
G_{bT} = beam irradiance on a tilted surface (W/m^2)
G_d = diffuse irradiance (W/m^2)

The value for absorptivity in the above equation, and emissivity in previous equations, are generally difficult to find so they are quite often assumed. Table 7 gives values for certain painted surfaces (Esmay and Dixon, 1986).

Once q_s was calculated, it was substituted into equation [3.1] to complete the heat balance on the outer surface.

3.2.3 Psychrometric Subroutine

The pschrometric subroutine was used to convert measured wet and dry bulb temperatures to humidity ratios. This was necessary to check calculated humidity ratios against saturation ratios. This subroutine uses equations described by ASHRAE (1989).

The water vapor partial pressure at saturation was calculated first. Equation [3.23a] was used for dry bulb temperatures between -100 and 0 °C, and equation [3.23b] was used for dry bulb temperatures between 0 and 200 °C.

Table 7. Absorptivity and emissivity of different paints, Esmay and Dixon (1986).

Paint	α	ε
Bright new aluminum	0.20	0.43
White (0.43 mm on aluminum)	0.20	0.91
Black (0.43 mm on aluminum)	0.96	0.88
Gloss white	0.35	0.95
Light blue	0.39	0.94
Red	0.87	0.96

$$\ln(P_{ws}) = \frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \ln(T) \qquad [3.23a]$$

$$\ln(P_{ws}) = \frac{C_8}{T} + C_9 + C_{10} T + C_{11} T^2 + C_{12} T^3 + C_{13} \ln(T) \qquad [3.23b]$$

where

P_{ws} = saturation vapor pressure (Pa)
T = dry bulb temperature (K)
C_1 = -5674.5359
C_2 = 6.3925247
C_3 = -0.9677843E-02
C_4 = 0.62215701E-06
C_5 = 0.20747825E-08
C_6 = -0.9484024E-12
C_7 = 4.1635019
C_8 = -5800.2206
C_9 = 1.3914993
C_{10} = -0.04860239
C_{11} = 0.41764768E-04
C_{12} = -0.14452093E-07
C_{13} = 6.5459673

The saturation humidity ratio and the humidity ratio were then calculated:

$$w_s = 0.62198 \frac{P_{ws}}{(P - P_{ws})} \qquad [3.24]$$

$$w = \frac{\{(2501 - 2.381\, t_{wb})\, w_s - (t - t_{wb})\}}{\{2501 + 1.805\, t - 4.186 t_{wb}\}} \qquad [3.25]$$

where

w_s = saturation humidity ratio (kg H2O/kg dry air)
P_{ws} = saturation vapor pressure (Pa)
P = atmospheric pressure (101325 Pa)
w = humidity ratio (kg H2O/kg dry air)
t_{wb} = wet bulb temperature (°C)
t = dry bulb temperature (°C)

3.3 *Failure Model*

The failure model was developed to calculate indoor temperature and humidity ratio dynamically at various time intervals during a short-term (90 minutes or less) power failure. The TRFM was initialized as discussed in a previous section. An iterative scheme was used by the computer program to calculate these values after a power failure occurred. The following steps were used:

STEP 1: The room temperature (t_r), inside surface temperatures (t_1) for each conduction surface, and the inside humidity ratio (w_i) were set equal to the previous time step values to give the iteration a starting point. Data on the solar incidence, outdoor humidity, and the exterior ambient temperatures at the new time step were input. The solar subroutine was called and returned the effective sky temperature (t_{sky}) and the total solar incidence on each wall surface (q_s).

STEP 2: The mean convection (h_m) and radiant coefficients (h_r) were calculated for the outside surface as illustrated in the previous sections.

STEP 3: The outside surface temperature (t_n) for each conduction surface was calculated using equation [3.9b]. If the absolute difference between the old and new value of t_n for any conductive surface exceeded the set tolerance, then another t_n was calculated which was the average between the old and the new values, and was used as the program returned to step 2 for the wall in question. The tolerance for this iteration was set to calculate temperatures to the nearest one-hundredth of a degree; if tolerances were not small, inaccuracies grew quickly because of the interdependence of iteratively solved variables.

STEP 4: The mean convection coefficients for the interior surfaces were calculated using natural convection equations which were explained in a previous section.

STEP 5: Using the new t_n values calculated in step 3, the new interior surface temperature (t_l) values were calculated by using equation [3.11b]. Tolerance was checked as described earlier to determine the accuracy. If the tolerance was exceeded, then an average of the old and new t_l was used and the program returned to step 3.

STEP 6: Animal latent and sensible heat production were calculated using the NCR swine model as a subroutine. Temperature was an input for this subroutine. It was theorized that swine heat production does not respond instantaneously to temperature fluctuations, so temperature was adjusted using the previous temperatures:

$$t_{NCR} = \frac{\{t_r(\tau) + t_r(\tau - 1) + t_r(\tau - 2)\}}{3} \qquad [3.26]$$

where

t_{NCR} = room temperature input to the NCR swine model (°C)
t_r = room temperature at some time (°C)
τ = the current time step

The swine model returns two different total heat production amounts, one from the environmental subroutine and one from the energy balance subroutine. These two values are generally quite close, but the environmental value was chosen for use here because of its adaptation for small pigs. The sensible heat production was obtained by subtracting latent heat production from total heat production. During model development, it became obvious that latent heat production was being overpredicted for a failure situation. After the sensible heat production was found, the latent heat was adjusted as follows:

$$Q_{ea} = Q_e\left(1.3 - \frac{w_i}{w_s}\right) \qquad [3.27]$$

where

Q_{ea} = evaporative or latent heat production after adjustment (W/pig)
Q_e = evaporative or latent heat production predicted from the NCR model (W/pig)
w_i = indoor humidity ratio (kg H2O/kg dry air)
w_s = saturation humidity ratio for indoor air (kg H2O/kg dry air)

This particular equation was chosen because it was theorized that rising humidity within the room, during a power failure, inhibited the evaporation rates needed to maintain normal levels of latent heat loss. It was theorized originally that as the relative humidity approached 100 percent, latent heat production should approach zero. This was not the case, and the factor 1.3 was used in equation [3.27] rather than 1.0. A trial and error technique was used to arrive at this equation by using a portion of the validation data. It should be noted that no weight gain is added to the body weight by the model during a power failure.

STEP 7: The infiltration rate was determined using equation [2.66]. Enthalpy of the inside and outside air was then calculated using:

$$h = t + w(2501 + 1.805\,t) \qquad [3.28]$$

where

h = enthalpy of the air (KJ/kg dry air)
t = air temperature (°C)

w = humidity ratio (kg H2O/kg dry air)

The difference between the enthalpy of the outdoor and indoor air was multiplied by the mass flow rate to yield the infiltration energy loss:

$$Q_i = \frac{Q_{inf}}{spvol} 1000 (h_o - h_i) \qquad [3.29]$$

where

Q_i = infiltration heat loss (W)
Q_{inf} = infiltration rate (m^3/s)
spvol = specific volume of the room air (m^3/kg)
h_o = enthalpy of the outdoor air (KJ/kg dry air)
h_i = enthalpy of the indoor air (KJ/kg dry air)

STEP 8: The energy content of the room at the previous time step was calculated:

$$Q_{old} = \frac{(h_i(\tau - 1)\, vol)}{spvol} \qquad [3.30]$$

where

Q_{old} = energy at the last time step within the room (m^3/s)
$h_i(\tau - 1)$ = enthalpy of the indoor air at the last time step (KJ/kg dry air)
vol = volume of the room (m^3)
spvol = specific volume of the room air (m^3/kg)

STEP 9: The change in energy content of the room air was calculated by adding the fluxes which occurred during the time step. The fluxes included sensible heat production by the animals, infiltration losses, heat gain from lighting, and conductive losses. Conductive losses include steady state loss through windows and doors and were calculated using the convective equation with the inside surface temperature and the room temperature.

$$\Delta Q = step(Q_{anim} + Q_i + Q_{lights} + Q_{cond}) \qquad [3.31]$$

where

ΔQ = energy change during one time step (J)
step = length of the time step (s)
Q_{anim} = sensible heat production of the animals (W)
Q_i = infiltration heat loss (W)
Q_{lights} = heat produced by the lights (W)
Q_{cond} = heat flux through all conductive surfaces (W)

STEP 10: The new energy level in the room was determined using equation [2.69] and then was converted to a new room temperature:

$$Q_{new} = Q_{old} + \Delta Q \qquad [2.69]$$

$$t_r = \frac{\left\{ \frac{Q_{new}}{m_a} - 2501\, w_i \right\}}{(1 + 1.805\, w_i)} \qquad [3.32]$$

where

Q_{new} = energy content in the building at the present time (W)
Q_{old} = energy content in the building at the previous time step (W)
ΔQ = energy change during one time step (J)
t_r = room temperature (°C)
m_a = total mass of the room air (kg)
w_i = humidity ratio inside the building (kg H2O/kg dry air)

If the new t_r was not within the tolerance, then an average of the old and new t_r was returned to step 3.

STEP 11: Latent heat production was converted from an energy quantity to a moisture quantity by dividing by the latent heat of vaporization. The change in humidity ratio was calculated assuming no moisture storage in the building:

$$\Delta w = \frac{step}{m_a}[dotma(w_o - w_i) + w_{anim}] \qquad [3.33]$$

where

Δw = moisture change during one time step (kg H2O/kg dry air)
step = time step (s)
m_a = total mass of the room air (kg)
dotma = mass flow rate of infiltration air (kg/s)
w_o = outside humidity ratio (kg H2O/kg dry air)
w_i = inside humidity ratio (kg H2O/kg dry air)
w_{anim} = moisture production by the animals (kg/s)

STEP 12: The new humidity ratio was calculated using equation [2.70]. However, if animal moisture was added to the air in one calculation, then the new ratio would be an obviously erroneous result in some cases. To eliminate this problem, equations [3.33] and [2.70] were used together in a loop, taking sixty smaller steps to calculate w_{new}. If the humidity tolerance was not met, the program returned to step 3. The tolerance for humidity was chosen as 0.0005 kg H2O/kg dry air.

$$w_{new} = w_{old} + \Delta w \qquad [2.70]$$

where

w_{new} = inside humidity ratio at the present time step (kg H2O/kg dry air)

w_{old} = inside humidity ratio at the previous time step (kg H2O/kg dry air)
Δw = moisture change during one time step (kg H2O/kg dry air)

STEP 13: Once all parameters were found at the present time step, the next step was initiated at step 1.

An example of the input and output for FAILURE, along with the program code is located in Appendix B.

3.4 Operational Model

The operational model was developed to calculate the amount of supplemental heat required, the feed consumption, and the growth of pigs in a nursery. Applying this tool, the user will have an option of selecting temperature set-points or adopting an optimizing scheme to determine the temperature at which the least cost per unit of gain produced will be incurred.

The first option in the model performs heat and moisture balances for the building using the temperature set-points provided by the user. If no supplemental heat is projected, or if supplemental heat requirements will exceed the heater capacity, then a new room temperature is calculated. The second option examines a variety of temperatures and selects a temperature at each hour which minimizes total cost per unit of gain produced. The program uses the following steps:

STEP 1: Inputs which were constant for the duration of the simulation were read into the program. Ventilation rates were input in four stages, each stage containing the rate (m^3/s) and the day and time that the next ventilation rate was started. Temperature set-points for the furnace were input in a similar, four-stage manner. A sample data file can be found in Appendix C.

STEP 2: The TRFM was initialized by using 100 steps for each conduction surface.

STEP 3: The dynamic environmental conditions were input. These included outdoor humidity and temperatures of areas external to the nursery, as well as solar incidence data. If data was recorded in steps smaller than one hour, then data from one hour were read in and averaged to give hourly readings. The solar subroutine was called and returned the effective sky temperature (t_{sky}) and the solar load (q_s) on each wall surface.

STEP 4: The ventilation rate and room temperature were set by comparing the day and time of the current time step with the day and time of the ventilation and temperature step changes. When the change time was reached, the next ventilation rate or temperature was used. If optimization had been selected, the room temperature was set at 32 °C to begin the iteration to find the optimal room temperature.

STEP 5: The mean convection (h_m) and radiant (h_r) coefficients were calculated for the outside surface as illustrated in previous sections.

STEP 6: The outside surface temperature (t_n) for each conduction surface was calculated using equation [3.9b]. If the absolute difference between the old and new value of t_n was greater than the specified tolerance, then another t_n was calculated which was the average of the old and the new values. The program then returned to step 5 for the wall under consideration.

STEP 7: The mean convection coefficients for the interior surfaces were calculated using natural convection equations which were explained in a previous section.

STEP 8: Using the new t_n values calculated in step 6, the new interior surface temperature (t_1) values were calculated using equation [3.11b]. Again, the tolerance was checked to determine the accuracy. If the tolerance was exceeded, then an average of the old and new t_1 was used and the program returned to step 3.

STEP 9: The NCR swine submodel was called to determine the feed intake, and the latent and sensible heat production. This submodel was adapted to calculate production values on an hourly basis rather than the original daily basis. No consideration was given to variation of production due to diurnal cycles. The gain was added to the body weight until later in the program.

STEP 10: The ventilation subroutine was then used to calculate the heat flux through the ventilation. Moisture was added to the air in 60 steps using equation [3.33] since moisture added in one step created unreasonable results. Moisture added to the room from spillage and animal waste was assumed to be negligible because of the use of a slatted floor. The enthalpy values of indoor and outdoor air were then calculated using equation [3.28]. The ventilation heat flux was then calculated:

$$Q_v = \frac{rate}{spvol} 1000 (h_o - h_i) \qquad [3.34]$$

where

Q_v = ventilation heat flux (W)
rate = ventilation rate (m^3/s)
spvol = specific volume of the room air (m^3/kg)
h_o = enthalpy of the outdoor air (KJ/kg dry air)
h_i = enthalpy of the indoor air (KJ/kg dry air)

STEP 11: The required supplemental heat was calculated using a simple energy balance:

$$Q_{supp} = - Q_{anim} - Q_v - Q_{lights} - Q_{cond} \qquad [3.35]$$

where

Q_{supp} = required supplemental heat (W)
Q_{anim} = heat load from the animals (W)
Q_v = ventilation heat flux (W)
Q_{lights} = heat load from the lighting (W)
Q_{cond} = heat flux due to conduction (W)

STEP 12: The moisture addition from the furnace was considered. It was assumed that propane (C_3H_8) was combusted with an unvented furnace within the room for supplemental heating. The chemical equation illustrates that 4 moles of water are liberated for every 1 mole of C_3H_8 combusted:

$$C_3H_8 + 5\,O_2 + 5(3.76\,N_2) = 3\,CO_2 + 4\,H_2O + 18.8\,N_2 \qquad [3.36]$$

It was assumed that the lower heating value of propane was 89 MJ/m³ (86,000 Btu/gal). The combustion of one cubic meter of propane produces four cubic meters of water vapor or 7.538 kg of water. (This assumes one gallon of propane equals 36 ft³ of vapor and one pound of water vapor equals 8.5 ft³.)

STEP 13: The ventilation subroutine added the moisture produced by combustion. If the calculated humidity ratio was not within the specified tolerance for iterative calculations, then the program returned to step 11 to recalculate Q_{supp}.

STEP 14: The Q_{supp} term was then examined. If Q_{supp} was less than zero, it was assumed that the room temperature would have risen above the set room temperature; therefore, t_r was increased by 0.1 °C and the program returned to step 5. This was repeated until Q_{supp} exceeded zero. At this point, if the optimization option was being pursued, an indicator was set to cause the program to skip the remaining optimization searches for temperatures below this calculated temperature during that time period. This newly found t_r value was equivalent to the lowest temperature at which the building may be kept under these conditions.

If Q_{supp} was greater than the heater capacity (5861 W or 20,000 btu/hr for the facility used for validation), the t_r was reduced by 0.1 °C and the program returned to step 5. This continued until the resulting t_r represented the highest temperature at which the room could be kept under these conditions.

STEP 15: The amount of propane needed was determined and used to find the cumulative fuel cost. The feed cost was also determined. The amount of cumulative gain was calculated at the room temperature being used.

STEP 16: The total cumulative cost (feed and fuel) was divided by the total gain produced to yield cost per unit of gain. If the program was not optimizing, then this was the end of one time step and the program returned to step 3 to begin the next time step.

If the program was optimizing, the cost per unit gain and the room temperature were noted. The room temperature was then decreased by 0.5 °C and the program returned to step 5. The optimization continues changing the room temperature while retaining the minimum cost value and its associated temperature until the room minimum temperature or 10 °C is reached, whichever comes first.

STEP 17: The temperature at which cost was minimal was then used in step 5, proceeding through all calculations. Gain was then added to body weight and the model returned to step 3 to begin the next time step.

Sample input and output, as well as the program code are located in Appendix C.

Chapter 4

Model Validation

4.1 Introduction

Validation of the computer models was performed by comparing model performance to occurrences in an actual building. Using actual measured inputs to the building as inputs to the model yields two sets of values for comparison, one from the actual building and one from the computer model of the simulated building.

Within this chapter, several steps used for validation are discussed. The building used for validation purposes is discussed, as well as the instrumentation used to collect the needed data. Then, for each model, the format of the trials is explained, along with statistical tests performed to evaluate the validity of the simulation models.

4.2 Building Used for Validation

Field data were collected at the Virginia Tech Swine Center. The building used for this study contained three nurseries, one farrowing, one grower-finisher, and assorted utility and feed rooms. Only two of the nursery rooms were used for this study. A schematic of the relevant portion of the building is shown in Figure 7.

The exterior and hallway walls of the building were made of concrete blocks; block cores of the exterior walls were filled with vermiculite. Other walls were wood frame, stud walls with batt insulation. The composition of the walls in Nursery 1 and 2 are in Table 8 and Table 9, respectively. Both tables are reported in English rather than SI units since the TRFM computer program (Appendix A) was written for English units. The building exterior was painted white and the roof was made of brown shingles.

Both nursery rooms were set up as negative pressure, mechanically ventilated systems. Along the hallway side of each nursery was a slotted adjustable inlet which forced air across the ceiling. Bringing inlet air through the hallway provided some air tempering during cold periods. Each nursery also had three exhaust fans: two that vented the plugged shallow pit, and one that was for summer ventilation and was not used during this study. All four pit exhaust fans were "Mini-brute 8" (MB-8) models made by AAA Associates. The summer ventilation fans were winterized by covering them with polyethylene. The operational fans were running at speeds different from the manufacturer's ratings, as seen in Table 10. The rated flow rates were adjusted using one of the fan laws:

$$Q_1 = Q_2 \frac{N_1}{N_2} \qquad [4.1]$$

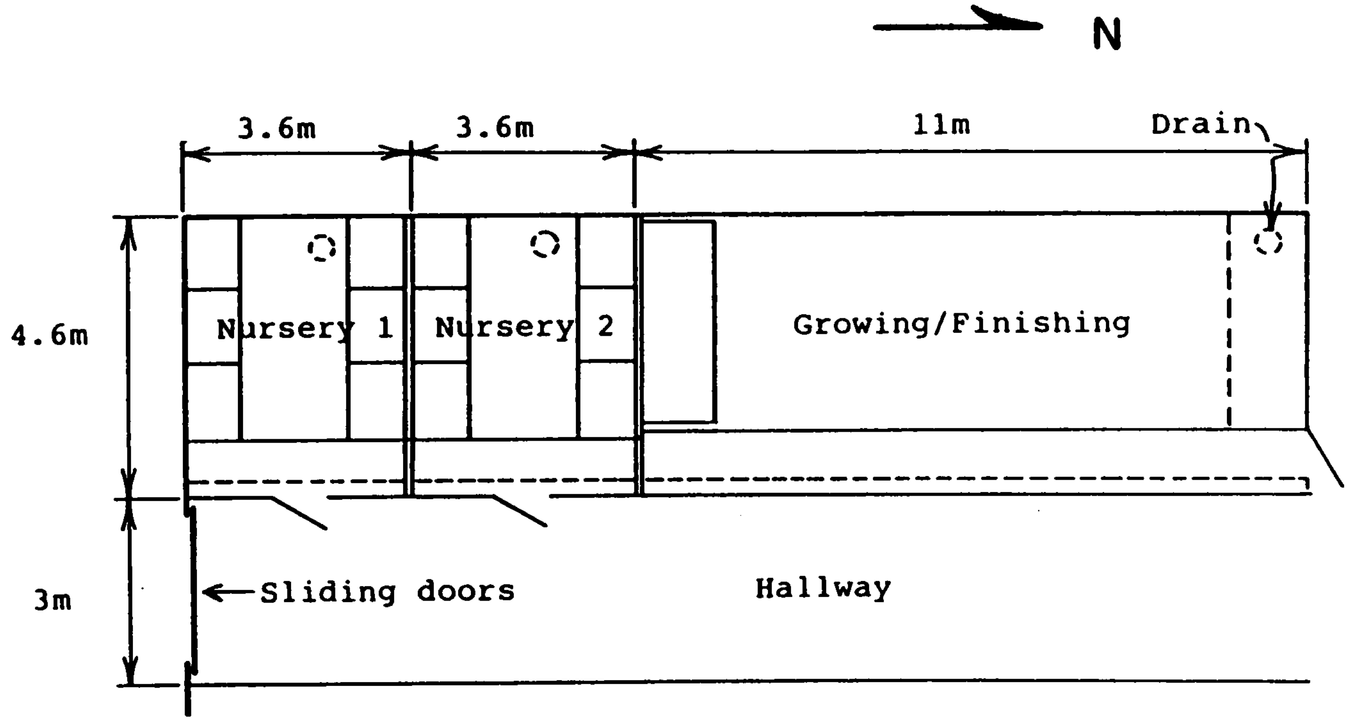

Figure 7. Partial floor plan of the swine facility used for validation.

Table 8. Building material properties for Nursery 1.

Component	α (ft^2/hr)	Δx (ft)	k (Btu/hr-ft-°F)
Wall 1 (North)			
Kemlite	-----	-----	-----
0.5" Plywood	6.765E-03	0.0417	0.0667
3.5" Batt Insulation	6.625E-02	0.2917	0.0265
0.5" Plywood	6.765E-03	0.0417	0.0667
Kemlite	-----	-----	-----
	Area = 13.34 m^2	R = 12.2 (ft^2-°F-hr/Btu)	
Wall 2 (South)			
12" Concrete Block(filled)	0.0348	1.0	0.39
1" Polyurethane	0.0398	0.0833	0.0208
Kemlite	-----	-----	-----
	Area = 13.34 m^2	R = 6.6 (ft^2-°F-hr/Btu)	
Wall 3 (East)			
8" Concrete Block	0.0492	0.667	0.6
Kemlite	-----	-----	-----
	Area = 8.55 m^2	R = 1.1 (ft^2-°F-hr/Btu)	
Wall 4 (West)			
12" Concrete Block (filled)	0.0348	1.0	0.39
Kemlite	-----	-----	-----
	Area = 10.61 m^2	R = 2.6 (ft^2-°F-hr/Btu)	
Wall 5 (Ceiling)			
5" Loose Cellulose	0.0271	0.4167	0.0246
.5" Plywood	0.00676	0.0417	0.0667
Metal Sheathing	1.48	0.01042	37.5
	Area = 16.84 m^2	R = 17.6 (ft^2-°F-hr/Btu)	
Wall 6 (On-Grade Slab)			
12" Soil	0.0208	1.0	0.5
4" Gravel	0.0208	0.33	0.5
4"Concrete	0.0267	0.333	0.8
	Area = 13.29 m^2	R = 2.4 (ft^2-°F-hr/Btu)	
Door			
1.75" Wooden			
	Area = 1.36 m^2	R = 3.0 (ft^2-°F-hr/Btu)	
Window			
Double Pane			
	Area = 0.49 m^2	R = 1.7 (ft^2-°F-hr/Btu)	

Table 9. Building material properties for Nursery 2.

Component	α (ft^2/hr)	Δx (ft)	k (Btu/hr-ft-°F)
Wall 1 (North)			
Kemlite	-----	-----	-----
0.5″ Plywood	6.765E-03	0.0417	0.0667
3.5″ Batt Insulation	6.625E-02	0.2917	0.0265
0.5″ Plywood	6.765E-03	0.0417	0.0667
Kemlite	-----	-----	-----
	Area = 13.34 m^2	R = 12.2 (ft^2-°F-hr/Btu)	
Wall 2 (South)			
Kemlite	-----	-----	-----
0.5″ Plywood	6.765E-03	0.0417	0.0667
3.5″ Batt Insulation	6.625E-02	0.2917	0.0265
0.5″ Plywood	6.765E-03	0.0417	0.0667
Kemlite	-----	-----	-----
	Area = 13.34 m^2	R = 12.2 (ft^2-°F-hr/Btu)	
Wall 3 (East)			
8″ Concrete Block	0.0492	0.667	0.6
Kemlite	-----	-----	-----
	Area = 8.55 m^2	R = 1.1 (ft^2-°F-hr/Btu)	
Wall 4 (West)			
12″ Concrete Block (filled)	0.0348	1.0	0.39
Kemlite	-----	-----	-----
	Area = 10.61 m^2	R = 2.6 (ft^2-°F-hr/Btu)	
Wall 5 (Ceiling)			
5″ Loose Cellulose	0.0271	0.4167	0.0246
.5″ Plywood	0.00676	0.0417	0.0667
Metal Sheathing	1.48	0.01042	37.5
	Area = 16.84 m^2	R = 17.6 (ft^2-°F-hr/Btu)	
Wall 6 (On-Grade Slab)			
12″ Soil	0.0208	1.0	0.5
4″ Gravel	0.0208	0.33	0.5
4″Concrete	0.0267	0.333	0.8
	Area = 13.29 m^2	R = 2.4 (ft^2-°F-hr/Btu)	
Door			
1.75″ Wooden			
	Area = 1.36 m^2	R = 3.0 (ft^2-°F-hr/Btu)	
Window			
Double Pane			
	Area = 0.49 m^2	R = 1.7 (ft^2-°F-hr/Btu)	

Table 10. Fan rpm from the product literature and actual tests.

	Speed (rpm)		
Fan Speed	**Literature**	**Nursery 1**	**Nursery 2**
High	3400	3460	3450
Medium 2	2800	3160	2930
Medium 1	2500	2950	2570
Low	1600	2150	1690

where

Q_1 = flow rate of the fan under consideration
Q_2 = flow rate of the tested fan
N_1 = speed of the fan under consideration (rpm)
N_2 = speed of the tested fan (rpm)

The adjusted fan performance data appears in Table 11.

Because of the unusual configuration of the building, some assumptions and special programming were necessary. The attic temperature was used as an input to the models. This generally would not be a necessary; however, in this case, the entire building shared a common attic, making it difficult to calculate the attic temperature without knowing the heat fluxes from other areas of the building. Also, for this type of building it was necessary to use measured temperatures in the adjoining spaces within the building for inputs. In a normal situation, the outdoor temperature could be used for external temperatures at all surfaces; however, each room had different external temperatures, so separate temperatures were required for each surface.

The rooms were each equipped with an L. B. White, unvented gas heater. The heaters were rated at 5861 W (20,000 btu/hr) and were controlled by a thermostat hung near the center of each room.

The nursery rooms measured 4.6 m by 3.6 m by 2.3 m. Pigs were kept in double deck nursery pens that were approximately 0.9 m by 1.2 m with six pens on each level. Generally 4 pigs were kept in each pen.

Table 11. Total fan flow rate from each nursery compared to product literature ratings.

	Total Flow with Shutter in Place (m^3/s)						
	Static Pressure (Pa)						
	0	12.4	24.9	31.1	37.3	49.8	62.2
High Speed							
Rated	0.270	0.243	0.223	0.223	0.254	0.284	0.191
Nurs 1	0.275	0.247	0.227	0.227	0.259	0.289	0.194
Nurs 2	0.244	0.247	0.226	0.226	0.258	0.288	0.194
Medium 2 Speed							
Rated	0.222	0.192	0.208	0.233	0.229	0.156	0.130
Nurs 1	0.251	0.217	0.235	0.263	0.258	0.176	0.147
Nurs 2	0.232	0.201	0.218	0.244	0.240	0.163	0.136
Medium 1 Speed							
Rated	0.198	0.168	0.212	0.159	0.133	0.118	0.101
Nurs 1	0.234	0.198	0.250	0.188	0.157	0.139	0.119
Nurs 2	0.203	0.173	0.218	0.163	0.137	0.121	0.104
Low Speed							
Rated	0.127	0.133	0.066	0.051	0.040	0.011	-----
Nurs 1	0.171	0.179	0.089	0.069	0.054	0.015	-----
Nurs 2	0.134	0.141	0.070	0.054	0.042	0.012	-----

4.3 Instrumentation

Data were collected using a Campbell Scientific CR10 with a 32 channel multiplexer. Thermocouples were placed in both nurseries in the furnace outlet, near the fan controller, and in the center of the room (which was assumed to measure the average room temperature). Thermocouples were also used to measure temperatures in the attic, hallway, grower-finisher, and outdoors.

An aspirated psychrometer was placed on top of the upper deck to measure wet and dry bulb temperature within each nursery. Another psychrometer was placed in the hallway, near the air inlets to measure the humidity of the incoming air.

A stand for mounting the solar instrumentation was built on the south side of the barn. The stand was built of treated lumber to withstand the elements, and stood 2 m high to avoid shading by surrounding structures. Three instruments were mounted on the stand. The pyranometer, used to measure total shortwave radiation, was mounted horizontally. It produced 9.52E-06 volts m^2/W and performed linearly to within 0.5 percent. The pyrgeometer, used to measure longwave radiation, was also mounted horizontally and used a battery-powered circuit to compensate for instrument temperature effects. It produced 4.67E-06 volts m^2/W. The pyrheliometer was used to measure normal incidence and had an electric, solar-tracking device. This device had to periodically be reaimed at the sun, but otherwise tracked properly for several days before requiring readjustment. It produced 8.31E-06 volts m^2/W.

The CR10 was set to read the solar instruments at 5 second intervals and all other instruments at 30 second intervals. These values were then averaged over a 10 minute period, except during failure tests when averages were over a one minute period. The averages of all readings were then stored in the CR10's memory. Approximately 6 days and 8 hours of data could be stored without risking the loss of data due to overwriting.

Data was uploaded from the CR10 to an IBM portable PC using software provided by Campbell Scientific. Data was then uploaded to the VAX computer system in the Agricultural Engineering Department, and was processed into report form using more software provided by Campbell Scientific.

4.4 Failure Model Validation

4.4.1 Trial Format

Before each failure test, the psychrometric wet bulb wicks were cleaned and the water reservoirs were refilled. Wind velocity was measured using a hot wire anemometer. Each trial was started by turning off the exhaust fans and space heaters in both nurseries. Both nurseries were shut down simultaneously in order to prevent leakage between them due to pressure differences. The lights were left on for all trials (except number 11) so that animals could be observed for signs of stress. Animals were also being used in studies conducted by the Animal Science Department, so failure trial duration was kept short (90 minutes or less) to avoid animal stress. Trial descriptions are detailed in Table 12.

Several input values such as absorptivity (α), emissivity (ε), and the effective leakage area (L) could not be readily measured. Estimates were made using information from various references, and then four trials were used to calibrate these values in the model. The trials used for calibration were chosen in order to isolate different sources of variability in the model. For example, failure

Table 12. Description of the individual failure trials.

No.	Day	Time	Duration minutes	Body Weight kg	Age days	Wind m/s	Pigs No.	Solar Load W
Trials Using Nursery Number 1								
11	362	1120	40	20.8	66	1.5	47	911
12[2]	362	1900	60	20.8	66	1.5	47	0
13	4	1920	70	25.0	74	7.0	47	0
15[2]	42	1140	30	n/a	n/a	0.5	0	985
16[1]	57	1630	60	8.6	42	5.0	48	266
17	63	1300	50	10.3	48	0.5	47	413
18	78	1440	40	16.5	63	1.0	47	1059
19[2]	84	1200	60	19.5	69	0.2	47	939
110	85	1530	60	20.0	70	0.1	47	641
Trials Using Nursery Number 2								
22	362	1900	60	20.8	66	1.5	48	0
23	4	1920	70	25.0	74	7.0	48	0
24	28	940	60	15.0	51	0.5	46	106
25[2]	42	1140	30	n/a	n/a	0.5	0	171
26[1]	57	1630	60	8.6	42	5.0	48	206
27	63	1300	50	10.3	48	0.5	48	207
28	78	1440	40	16.5	63	1.0	48	828
29	84	1200	60	19.5	69	0.2	48	329

1 Fluctuating Solar Load

2 Excluded from analysis because used for calibration.

trial numbers 15 and 25 had no animals present, which allowed elimination of error due to the NCR swine model and allowed calibration of the L value in each nursery. Failure number 19 was run with a large solar load and with large pigs. Failure number 12 was run at night to eliminate solar effects. These four trials used for calibration were excluded from statistical analysis to avoid biasing the results.

From the calibration, it was found that the absorptivity of the concrete-block sidewalls was approximately 0.4, emissivity was 0.9, effective leakage area for Nursery 1 was 75 cm^2, and for Nursery 2 it was 500 cm^2. It was observed that one of the exhaust fans in Nursery 2 spun backwards during trials. This indicated air infiltration through the fan housing, perhaps caused by leakage between the grower/finisher room (which was operating during trials) and Nursery 2.

4.4.2 Results and Statistical Evaluation

The model was run for each of the 17 failure tests. Example input and output from the program, as well as the program code appears in Appendix B. Actual and simulated temperatures, along with corresponding differences are in Table 13 for Nursery 1, and in Table 14 for Nursery 2. Actual and simulated humidity ratios are in Table 15 for Nursery 1, and Table 16 for Nursery 2. Humidity ratios are only given for reference purposes; temperature fit was the parameter used for validation.

Several methods of evaluating model validity were used. One of the easiest methods is that of visual analysis. Plots comparing actual temperatures and humidity ratios to the simulated values were made of each of the 17 failure tests. This was done to visually assess the model fit. Figure 8 is a plot of failure trial number 11, and Figure 9 depicts number 29. Both are examples of typical good fits encountered during visual analysis. Figure 10 is a plot of failure trial number 12 and is an example of a typical bad fit encountered. By visually assessing fit, an experienced eye

Table 13. Temperature results of the failure trials and simulations for Nursery 1.

Trial No.	Temperature (C) at Time (min) from Failure							
	0	10	20	30	40	50	60	70
11	21.7	23.6	24.8	25.3	26.0	----	----	----
actual	21.7	24.3	25.2	25.6	25.8	----	----	----
diff	----	-0.65	-0.43	-0.23	0.17	----	----	----
12	22.6	25.7	26.2	26.6	27.1	27.4	27.7	----
actual	22.6	23.7	24.1	24.6	25.1	25.5	25.9	----
diff	----	2.0	2.0	2.0	1.9	1.9	1.8	----
13	15.7	22.8	24.3	24.5	25.0	25.5	25.9	26.2
actual	15.7	18.3	19.2	19.9	20.8	21.3	21.6	21.9
diff	----	4.5	5.1	4.6	4.2	4.3	4.3	4.4
15	25.7	20.6	18.7	17.9	----	----	----	----
actual	25.7	20.6	19.4	18.3	----	----	----	----
diff	----	-0.05	-0.72	-0.46	----	----	----	----
16	30.3	26.7	26.3	26.9	27.1	27.1	27.1	----
actual	30.3	28.5	28.0	27.6	27.1	26.7	26.1	----
diff	----	-1.8	-1.7	-0.76	-0.05	0.38	0.96	----
17	26.3	25.8	26.2	26.5	26.8	26.9	27.3	----
actual	26.3	26.2	26.3	26.4	26.6	26.7	27.7	----
diff	----	-0.32	-0.07	0.13	0.20	0.29	-0.34	----
18	22.8	24.9	26.0	26.3	26.7	----	----	----
actual	22.8	25.2	25.6	26.1	26.3	----	----	----
diff	----	-0.26	0.37	0.24	0.33	----	----	----
19	24.3	26.1	27.1	27.5	28.2	28.6	28.8	----
actual	24.3	26.4	27.2	27.5	27.9	28.0	28.5	----
diff	----	-0.37	-0.16	0.00	0.31	0.59	0.37	----
110	27.8	28.2	28.8	29.5	29.8	30.1	30.3	----
actual	27.8	30.1	30.4	30.9	31.3	31.6	32.1	----
diff	----	-1.9	-1.6	-1.5	-1.5	-1.5	-1.7	----

Table 14. Temperature results of the failure trials and simulations for Nursery 2.

Trial No.	Temperature (C) at Time (min) from Failure							
	0	10	20	30	40	50	60	70
22	21.2	24.8	25.1	24.6	24.7	24.8	25.1	----
actual	21.2	22.5	23.3	23.7	24.2	24.6	25.2	----
diff	----	2.3	1.7	0.93	0.49	0.25	-0.13	----
23	15.7	20.7	21.4	21.0	21.1	21.3	21.6	21.6
actual	15.7	17.9	18.6	18.9	19.5	20.3	20.6	20.7
diff	----	2.8	2.7	2.1	1.6	1.0	0.94	0.96
24	23.5	23.5	23.8	24.3	24.5	24.6	24.7	----
actual	23.5	24.1	24.5	24.7	25.0	25.2	25.4	----
diff	----	-0.67	-0.67	-0.36	-0.52	-0.60	-0.73	----
25	22.0	18.9	17.5	16.9	----	----	----	----
actual	22.0	19.1	17.7	16.5	----	----	----	----
diff	----	-0.23	-0.20	0.48	----	----	----	----
26	28.6	24.2	23.6	23.8	23.8	23.7	23.5	----
actual	28.6	26.9	26.7	26.2	25.7	25.1	24.5	----
diff	----	-2.7	-3.1	-2.4	-1.9	-1.4	-0.95	----
27	24.1	24.4	25.1	25.2	25.2	25.2	----	----
actual	24.1	25.7	25.9	26.1	26.2	26.3	----	----
diff	----	-1.3	-0.85	-0.87	-1.0	-1.1	----	----
28	23.9	24.3	24.5	24.9	25.3	----	----	----
actual	23.9	24.0	24.7	24.8	25.2	----	----	----
diff	----	0.33	-0.18	0.09	0.17	----	----	----
29	22.2	25.6	26.7	26.8	27.4	27.7	27.9	----
actual	22.2	25.4	26.0	26.5	27.0	27.3	27.5	----
diff	----	0.14	0.67	0.31	0.42	0.46	0.39	----

Table 15. Humidity ratio results of the failure trials and simulations for Nursery 1.

Trial	Humidity Ratio (g/kg) at Time (min) from Failure							
No.	0	10	20	30	40	50	60	70
11	6.0	11.1	15.2	18.4	20.6	----	----	----
actual	6.0	13.4	16.1	16.8	17.1	----	----	----
diff	----	-2.3	-0.9	1.6	3.5	----	----	----
12	11.4	15.4	18.8	21.2	23.1	24.7	26.0	----
actual	11.4	14.7	15.9	16.4	16.7	16.9	17.1	----
diff	----	0.7	2.8	4.8	6.5	7.8	8.9	----
13	5.0	9.9	14.2	17.3	19.7	21.4	22.8	23.8
actual	5.0	10.6	11.7	12.1	12.5	12.7	12.6	12.7
diff	----	-0.7	2.6	5.2	7.2	8.7	10.2	11.0
15	7.2	7.2	7.2	7.2	----	----	----	----
actual	7.2	5.3	5.0	5.0	----	----	----	----
diff	----	2.0	2.2	2.3	----	----	----	----
16	14.2	16.1	17.5	18.3	19.0	19.6	20.2	----
actual	14.2	16.6	16.6	16.1	15.5	15.1	14.7	----
diff	----	-0.5	0.8	2.2	3.4	4.5	5.4	----
17	10.3	13.1	15.4	17.3	19.0	20.4	21.3	----
actual	10.3	14.7	16.1	16.7	17.2	17.3	10.8	----
diff	----	-1.5	-0.7	0.6	1.8	3.1	10.5	----
18	8.1	12.1	15.5	18.3	20.6	----	----	----
actual	8.1	15.3	16.5	17.6	18.0	----	----	----
diff	----	-3.2	-1.1	0.7	2.6	----	----	----
19	10.7	15.3	19.1	22.1	24.3	26.2	27.8	----
actual	10.7	17.8	20.1	20.9	21.2	21.2	21.2	----
diff	----	-2.5	-1.0	1.3	3.2	5.0	6.6	----
110	19.3	22.9	25.8	27.9	29.7	31.2	32.3	----
actual	19.3	27.1	28.7	30.1	31.2	31.4	32.6	----
diff	----	-4.3	-2.9	-2.2	-1.5	-0.3	-0.2	----

Table 16. Humidity ratio results of the failure trials and simulations for Nursery 2.

Trial	Humidity ratio (g/kg) at Time (min) from Failure							
No.	0	10	20	30	40	50	60	70
22	18.9	18.5	18.5	18.5	18.5	18.5	18.5	----
actual	18.9	20.1	20.8	21.4	21.8	22.5	22.8	----
diff	----	-1.6	-2.4	-2.9	-3.3	-4.0	-4.4	----
23	8.0	9.7	10.8	11.6	12.0	12.3	12.3	12.3
actual	8.0	10.9	12.0	12.4	12.6	12.7	13.0	13.1
diff	----	-1.2	-1.2	-0.8	-0.6	-0.4	-0.6	-0.8
24	8.0	10.1	11.6	12.4	13.1	13.8	14.3	----
actual	8.0	13.5	15.0	16.0	16.7	17.1	17.1	----
diff	----	-3.4	-3.4	-3.5	-3.5	-3.3	-2.8	----
25	6.9	6.6	6.6	6.6	----	----	----	----
actual	6.9	5.2	4.7	4.7	----	----	----	----
diff	----	1.4	1.9	1.9	----	----	----	----
26	11.2	11.5	11.5	11.5	11.5	11.5	11.5	----
actual	11.2	14.0	14.6	14.3	13.7	12.9	12.3	----
diff	----	-2.5	-3.1	-2.8	-2.2	-1.5	-0.8	----
27	11.0	12.5	13.3	13.9	14.5	14.9	----	----
actual	11.0	16.0	17.1	17.7	18.4	18.6	----	----
diff	----	-3.5	-3.8	-3.8	-3.9	-3.6	----	----
28	7.4	11.0	13.7	15.5	16.4	----	----	----
actual	7.4	14.4	15.7	16.1	16.6	----	----	----
diff	----	-3.5	-2.0	-0.6	-0.2	----	----	----
29	10.5	14.5	17.7	20.0	21.5	22.8	23.7	----
actual	10.5	16.4	18.2	19.0	19.7	19.3	19.4	----
diff	----	-1.9	-0.5	1.0	1.9	3.5	4.3	----

can evaluate the feasibility of the model. The physical meaning of the simulation may otherwise become lost in a tangle of numbers and calculations.

The plots indicated that values predicted by the model were much closer to actual values in some trials than in others. For instance, predicted and actual results are similar in Figure 8 and Figure 9, but the model appears to overestimate the temperature rise as well as the humidity rise in Figure 10. The most obvious difference between these trials was the difference in solar load. Trials 11 and 29 were performed during the day and trial 12 was performed at night. This could be an indication that either the absorptivity value or other thermal properties of the walls were in error.

It was apparent from the plots that humidity was not predicted with accuracy. It was noted during model development that the model was sensitive to humidity changes; in attempting to predict humidity and temperature, humidity was overpredicted when temperature was adequately predicted. Since the enthalpy equation was used to convert energy to a humidity ratio and temperature, humidity and temperature were strongly related. At times the calculated humidity ratio exceeded the saturation point. In early model development, this condition prompted the indoor humidity ratio to be set equal to the saturation humidity ratio. The remaining moisture (the difference between the calculated and saturation humidity ratios) was assumed to condense and therefore, add energy to the air. Because of this condition, temperatures were inflated to compensate for the reduction of the humidity ratio from the calculated level to the saturation level. The model was then changed to allow the calculated humidity ratio to exceed saturation, which produced better model temperature prediction.

Several factors could have contributed to the erroneous humidity ratios. The balance performed on humidity within the nursery did not account for moisture storage or evaporation from interior surfaces; however, the model still overpredicted humidity in many cases. This could be due, in part, to equation [3.27] used to adjust the latent heat production during a power failure. This equation

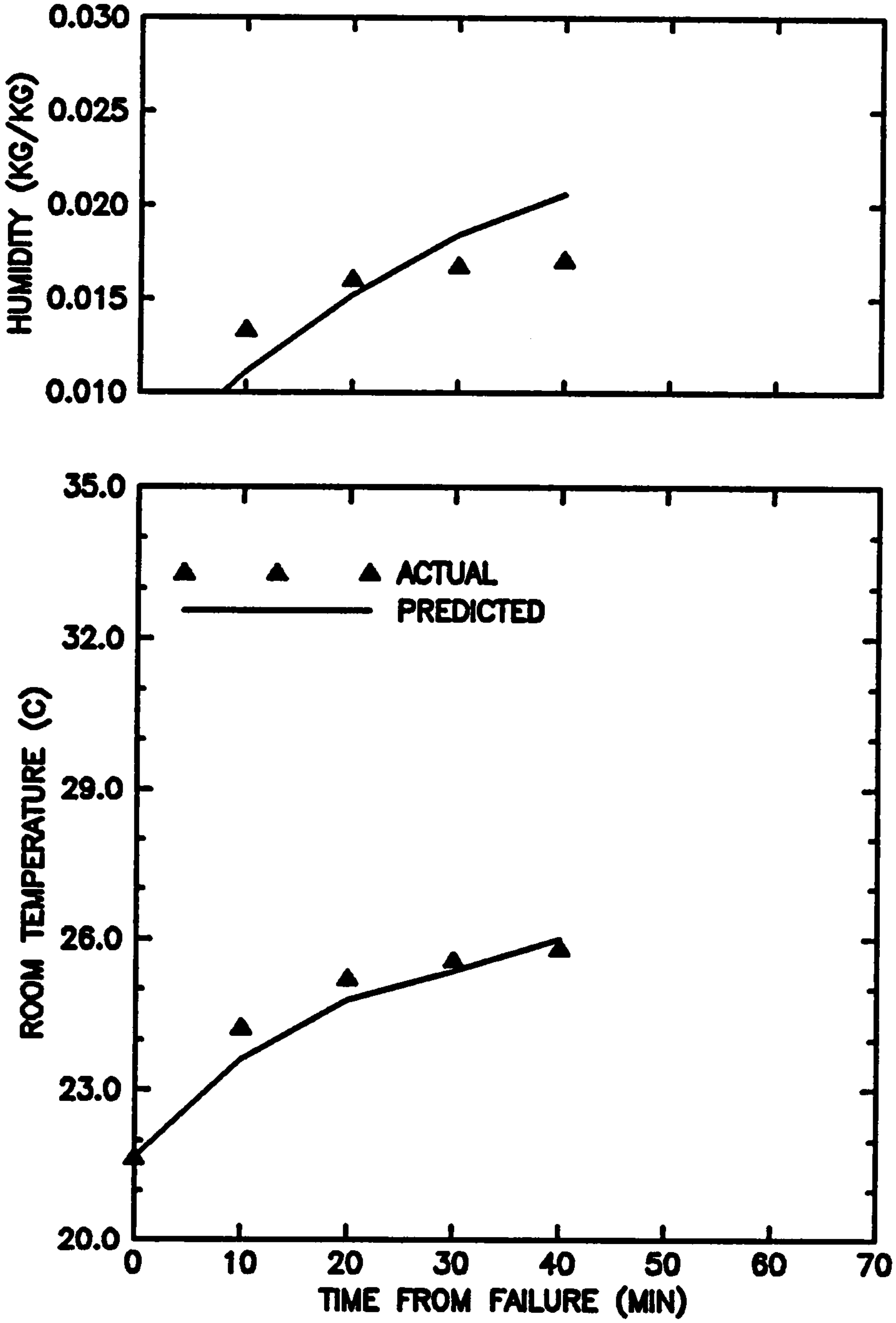

Figure 8. Actual versus simulated values for failure number 11.

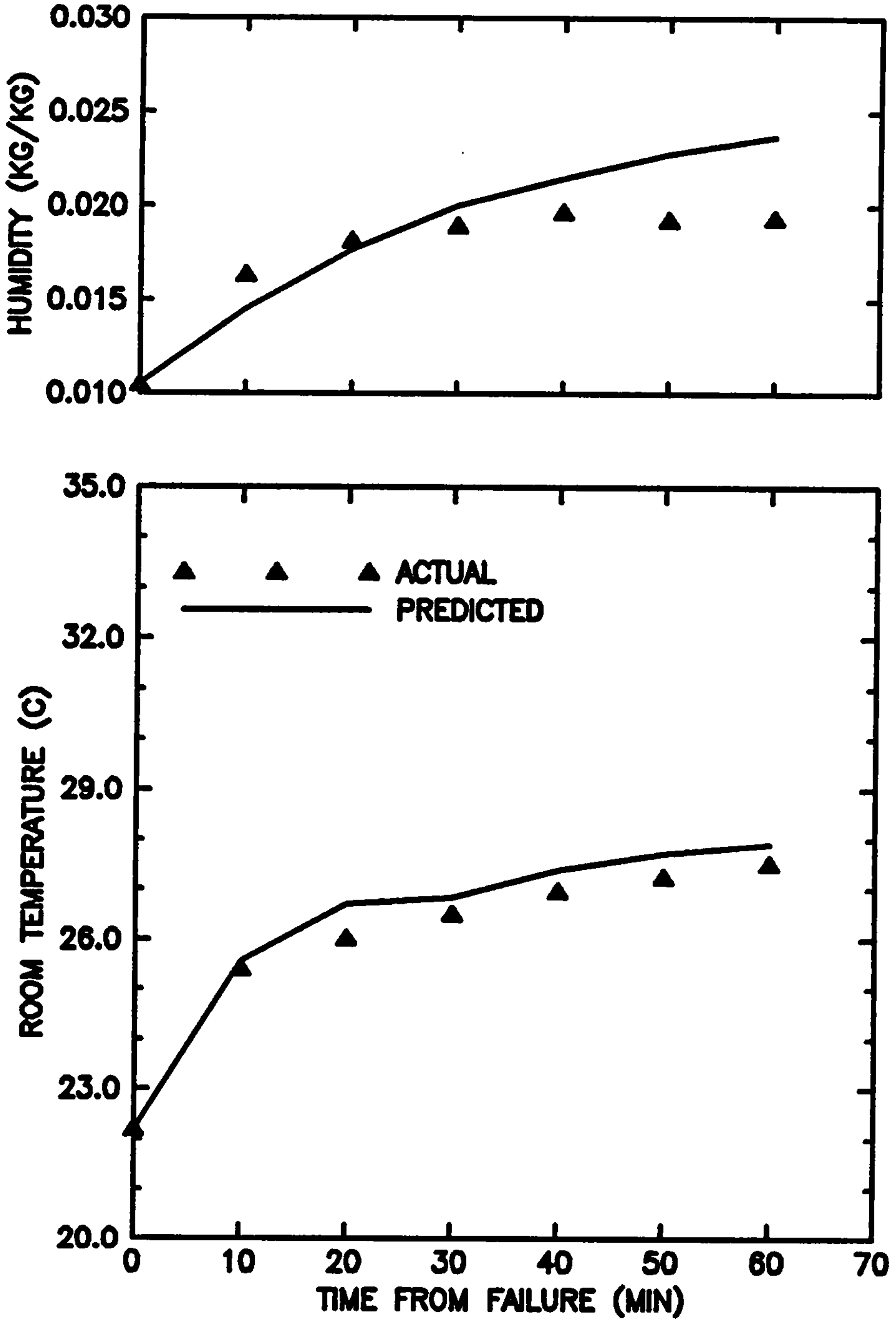

Figure 9. Actual versus simulated values for failure number 29.

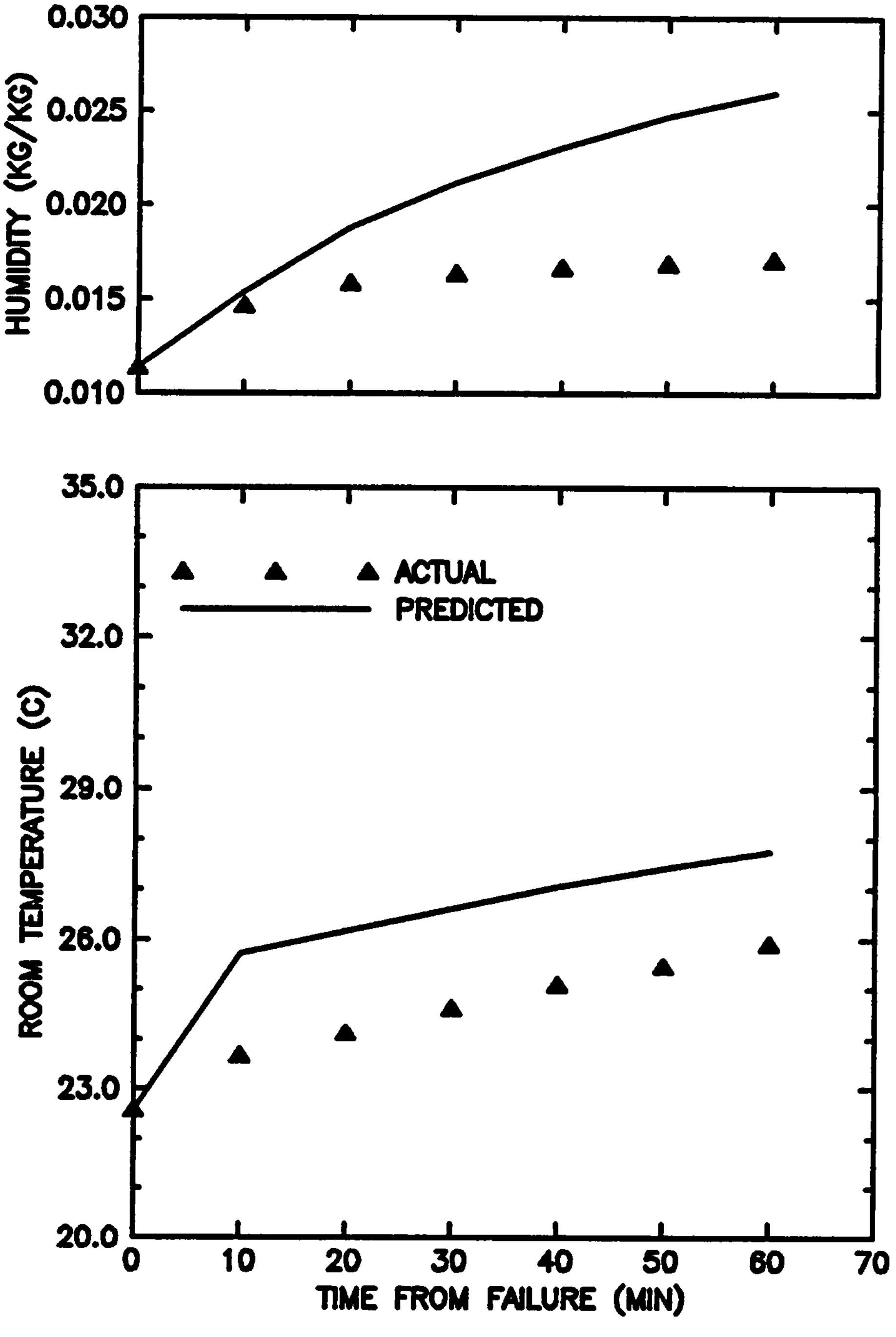

Figure 10. Actual versus simulated values for failure number 12.

includes a factor of 1.3 which was calibrated into the model. The other factor may be the prediction of latent heat production obtained from the NCR swine model. The animals used in the research herein were near the lower size limit for which the swine model was developed.

Standard statistical tests were used to quantify model validity based on 13 failure trials. Model results were difficult to analyze statistically. Simulated and actual data points were serially correlated which violates many assumptions associated with commonly-used statistical procedures. Three different procedures were selected which would help assess the model fit. The first, a Kruskal-Wallis nonparametric one-way layout test, was used to evaluate the variation in model error between individual model runs. This test involved ranking the absolute difference between simulated and actual temperature points and then comparing the sum of the ranks for each trial. This test was supplemented using a protected least significant difference (LSD) test to determine which trials were statistically similar. Nonparametric procedures were used from Hollander and Wolfe (1973).

The Kruskal-Wallis test gave strong evidence ($p < 0.005$) that not all of the simulations were statistically similar. The protected LSD test divided the trials into several groups. Table 17 gives some of the information for these tests including trial number, and the average of the absolute value of the differences (simulated minus actual values) for each trial. The average rank was calculated by ranking all data points in ascending order. Then, for each failure trial, the ranks were added and averaged. The groups are results of the LSD test. The trials were ordered according to their average rank, in ascending order. Adjacent trials were then tested to determine if they were statistically similar at the 0.1 level. The numbers in the Groups column correspond to groups of like trials. It was noted that the groups with larger average ranks, and thus the larger mean absolute differences, generally were trials with either no solar load or a large fluctuation in solar load during the test. This indicates possible errors in assumed wall characteristics, causing errors in the thermal responsiveness of the walls to solar loads.

Table 17. Results of the Kruskal-Wallis and protected LSD tests for the failure trials.

Trial No.	Mean Absolute Difference (°C)	Average Rank	Groups
11	0.37	18.38	1
13	4.50	69.00	---
16	0.94	34.75	2,3
17	0.20	9.70	1
18	0.30	16.38	1
110	1.61	51.58	3,4
22	0.97	32.80	2,3
23	1.74	51.71	4
24	0.59	29.17	2
26	2.09	55.58	4
27	1.01	41.40	3
28	0.19	9.50	1
29	0.40	21.17	2

The second statistical test was the t test. It was assumed that the distribution of the model error was normally distributed at each time step. This allowed the t test to be used at each of the time steps of 10, 20, 30, 40, 50, 60, and 70 minutes to determine if, at each time step, the mean of the errors equaled zero.

The t tests on individual time steps (Table 18) all failed to reject the hypothesis that the population means at each time step equaled zero. P values for these tests ranged from 0.42 to 0.80. The 90 percent confidence intervals were calculated for each step and all included zero. This result indicates that the model has no more of a tendency to overpredict than to underpredict a temperature response to a power failure.

The third statistical test used regression on the mean absolute model error for each trial based on the average inputs for each trial. This method was taken from Reynolds and Chung (1986). The independent variables used were average solar load (Q_s), body weight (bw), outdoor temperature (t_o), wind velocity (V), age of the pigs (age), and the nursery number (N).

Regression helped to define the largest contributors to the errors of the model. Regression was performed using the absolute mean difference (AMD) between the actual and simulated temperatures as the dependent variable, and the independent variables, one at a time. When this was done, V and Q_s individually were significant contributors to the AMD at the 10 percent level. A stepwise regression procedure was then performed using all the independent variables in the model. This method systematically determined the best fit for a one variable model, a two variable model, and so forth. This procedure indicated that a model containing wind velocity, alone, was a significant contributor to model error at the 10 percent level. The other independent variables added little when included in the regression model.

The contribution of wind velocity is understandable since it plays a role in calculation of convective coefficients and infiltration rates. Solar load appeared to be a contributing factor in the

Table 18. Results of the t test at different time steps.

Time	n	Mean Difference (°C)	S.D.	T statistic	p value
10	13	0.0477	2.048	0.084	> 0.80
20	13	0.1577	2.115	0.269	0.79
30	13	0.1838	1.730	0.383	0.71
40	13	0.2031	1.526	0.480	0.65
50	10	0.2010	1.670	0.381	0.72
60	9	0.3070	1.753	0.525	0.62
70	2	2.670	2.418	1.56	0.42

protected LSD test, and the regression test seemed to reconfirm that absorptivity and other exterior wall characteristics may be a significant influence on model error.

Several factors appear to have hampered the power failure model accuracy. Wind velocity and solar load were indicated as significant contributors to model error. Wind velocity affects infiltration and convection calculations. Solar load was affected by thermal characteristics of the wall because thermal storage affects the rate at which solar incidence is transferred to solar load. Walls in this facility were made of concrete block which were supposedly filled with vermiculite. After years of building operation, insulation may have deteriorated, or may even have been installed improperly. This makes assessment of wall characteristics a guess at best. A frame wall type building may be easier to model because insulation values can more accurately be assessed. Also, heat storage, which is less in frame walls than in concrete block walls, may have compounded mistakes made in assigning wall characteristics. Humidity prediction also contributed to error.

It should be noted that during failure tests, temperatures generally rose less than 5 °C. Veit et al. (1985) used a larger stocking density (a triple deck versus a double deck nursery in this study) and therefore obtained a greater temperature increase. They also concluded pit gas concentrations rapidly increase during a short power failure. In this scenario, perhaps more danger exists from toxic gases than from sustained elevated temperatures.

4.5 Operational Model Validation

4.5.1 Trial Format

In order to validate the operational model, data were collected continuously from December 1, 1988, to March 29, 1989, in the two nursery rooms discussed earlier. There were occasional lapses in the data due to miscellaneous errors such as equipment failures, and loss of data due to allowing too much time to lapse between downloading operations. Discrete data points were needed for statistical comparison. In order to create a satisfactory number of data points, each week was considered to be a separate trial. This also made the analysis easier because pig weights and feed consumption were tabulated each week by swine farm personnel.

During the trials two basic feed rations, listed in Table 19, were used. The observed fan speeds are in Table 20. Table 21 contains the observed furnace settings for Nursery 1, and Table 22 contains values for Nursery 2. Trial descriptions are detailed in Table 23.

Two methods of examining fuel usage were used. The first was done by merely recording the gas meter reading during each trip to the farm. This method was approximate because the meter could only be read in 100 cubic feet increments; however, it provided a way of checking model output for fuel consumption. The other method involved using the temperature of the furnace exit air and the room air temperature. These temperatures were recorded and averaged over a ten minute interval by the data acquisition system. The length of time furnaces ran was compared to the temperature rise through the furnace on several occasions in order to develop calibration equations. Regression was performed on this data for both nurseries, resulting in the following regression equations:

Table 19. Description of the nursery feed rations.

Description	Diet No. 1	Diet No. 2	Units
Crude Protein	20.0	17.9	Percent
Digestible Crude Protein	85.0	85.0	Percent
Biological Value	65.0	65.0	Percent
Digestible Energy	14.057	14.2	KJ/g
Net Energy	10.0	10.0	KJ/g
Lysine	1.15	0.95	Percent
Tryptophan	0.27	0.23	Percent
Threonine	0.825	0.706	Percent
Dry Matter	89.6	89.0	Percent
Pelletized	No	No	
Antibiotics	No	No	

Table 20. Fan speed settings during the trials.

Fan Speed	Expected m^3/s	From		To	
		Day	Time	Day	Time
Medium 1	0.168	336	1200	347	800
Low	0.133	347	800	355	1200
Medium 1	0.168	355	1200	359	1200
Medium 2	0.192	359	1200	5	1200
Low	0.133	5	1200	27	1200
Medium 1	0.168	27	1200	40	1200
Low	0.133	40	1200	62	1500
Medium 1	0.168	62	1200	75	1100
Medium 2	0.192	75	1100	88	1200

Table 21. Furnace settings for Nursery 1.

Temperature	From		To	
°C	Day	Time	Day	Time
		Nursery 1 Group 1		
27	336	1200	342	1200
26	342	1200	356	800
25	356	800	357	1200
26	357	1200	359	1200
23	359	1200	362	2000
20	362	2000	363	1800
18	363	1800	3	1200
16	3	1200	5	800
8	5	800	5	1200
		Nursery 1 Group 2		
16	5	1200	5	1800
27	5	1800	6	900
30.5	6	900	10	1500
29.5	10	1500	20	1700
15	20	1700	21	800
27.5	21	800	23	1700
28.5	23	1700	27	1400
25.5	27	1400	35	1200
24	35	1200	37	1200
25.5	37	1200	40	1200
		Nursery 1 Group 3		
31	46	1200	51	1600
21	51	1600	51	2200
30	51	2200	53	1200
29	53	1200	58	1600
28	58	1600	60	1200
26	60	1200	63	1400
27	63	1400	65	1500
29	65	1500	67	1200
28	67	1200	70	1500
26	70	1500	71	1000
25	71	1000	75	1100
24	75	1100	88	1200

Table 22. Furnace settings for Nursery 2.

Temperature °C	From		To	
	Day	Time	Day	Time
		Nursery 2 Group 1		
24	336	1200	338	1100
27	338	1100	342	1200
26	342	1200	356	800
25	356	800	357	1200
26	357	1200	359	1200
21	359	1200	362	2000
18	362	2000	363	1800
15	363	1800	3	1200
16	3	1200	5	800
8	5	800	5	1200
		Nursery 2 Group 2		
12	5	1200	5	1800
26	5	1800	6	900
31	6	900	10	1500
29.5	10	1500	12	1200
26.5	12	1200	14	800
23.5	14	800	18	1000
25.5	18	1000	19	1200
24.5	19	1200	20	1500
29.5	20	1500	22	800
27.5	22	800	23	1600
24	23	1600	26	1200
25	26	1200	29	1000
21.5	29	1000	30	1400
23.5	30	1400	33	1200
25.5	33	1200	35	1200
24	35	1200	37	1200
25.5	37	1200	40	1200
		Nursery 2 Group 3		
29.5	46	1200	51	2200
27.5	51	2200	57	1800
29	57	1800	60	1200
26.5	60	1200	63	1400
25	63	1400	65	1600
27	65	1600	66	1000
24	66	1000	67	1200
24.5	67	1200	71	1400
23	71	1400	74	1200
22	74	1200	83	1800
24	83	1800	86	1300
20	86	1300	88	1200

Table 23. Descriptions of the operational trials.

Trial No.	Starting Day	Starting Time	Initial Weight	No. Pigs	Initial Age	Diet No.
			kg		Days	
N1G1W3	336	1200	10.50	48	39	1
N1G1W4	343	1200	12.65	48	46	2
N1G1W5	350	1200	15.05	48	53	2
N1G1W6	357	1200	18.40	48	60	2
N1G1W7	364	1200	-----	48	67	2
N1G2W1	5	1200	7.50	48	28	1
N1G2W2	12	1200	-----	47	35	1
N1G2W3	19	1200	-----	46	42	1
N1G2W4	26	1200	-----	46	49	1
N1G2W5	33	1200	-----	45	56	1
N1G3W1	46	1200	7.13	48	28	1
N1G3W2	53	1200	7.75	48	35	1
N1G3W3	60	1200	9.25	47	42	1
N1G3W4	67	1200	11.71	47	49	1
N1G3W5	74	1200	15.26	47	56	1
N1G3W6	81	1200	18.24	47	63	1
N2G1W3	336	1200	10.50	48	39	1
N2G1W4	343	1200	12.65	48	46	2
N2G1W5	350	1200	15.05	48	53	2
N2G1W6	357	1200	18.40	48	60	2
N2G1W7	364	1200	-----	48	67	2
N2G2W1	5	1200	7.50	48	28	1
N2G2W2	12	1200	-----	48	35	1
N2G2W3	19	1200	-----	47	42	1
N2G2W4	26	1200	-----	46	49	1
N2G2W5	33	1200	-----	46	56	1
N2G3W1	46	1200	7.20	48	28	1
N2G3W2	53	1200	7.81	48	35	1
N2G3W3	60	1200	9.46	48	42	1
N2G3W4	67	1200	12.02	48	49	1
N2G3W5	74	1200	15.46	48	56	1
N2G3W6	81	1200	18.73	48	63	1

For Nursery 1,

$$\Delta t = -0.415 + 0.1109\,(t_{furn} - t_r) \qquad [4.2]$$

$$r^2 = 0.9671, \quad MSE = 0.406$$

For Nursery 2,

$$\Delta t = -1.371 + 0.1355\,(t_{furn} - t_r) \qquad [4.3]$$

$$r^2 = 0.9457, \quad MSE = 0.721$$

where

Δt = amount of time furnace runs in 10 minutes (minutes)
t_{furn} = exit temperature of furnace air (°C)
t_r = room temperature (°C)
r^2 = correlation coefficient
MSE = mean square error (minutes)

It was further assumed that when the furnaces were operating for a full 10 minute data collection cycle, the output was 5861 W (20,000 btu/hr). From the above equations, the Nursery 1 furnace produced a difference of 93.9 °C and the Nursery 2 furnace produced a difference of 83.9 °C during a ten minute period. The following equations were derived assuming that an idle furnace produces no temperature rise:

For Nursery 1,

$$\text{Heat} = 62.4\,(t_{furn} - t_r) \qquad [4.4]$$

For Nursery 2,

$$\text{Heat} = 69.9\,(t_{furn} - t_r) \qquad [4.5]$$

where

Heat = heat output of the furnace (W)
t_{furn} = exit temperature of furnace air (°C)
t_r = room temperature (°C)

The two equations above allow the average temperature rise through the furnaces to be converted to wattage outputs for comparison with the simulation. Some inaccuracies were present due to the heat-up and cool-down periods during furnace cycling. This error is illustrated by the presence of intercepts in the regression equations ([4.2] and [4.3]); however, the intercepts were not significant at the 1 percent level, indicating that this error was minimal.

Like the failure model, several inputs to the operational model were unknown. Some of the unknown values were equated to a value deemed appropriate by reference materials. These values were adjusted by running the simulation model with one set of data, and then comparing it to actual data. This was continued until acceptable errors were obtained. Values for solar absorptivity (α) and emissivity (ε) were assumed equal to 0.4 and 0.9 as was found with the failure model. Wind velocity was assumed to average 4 m/s. This estimate sufficed since wind was used only in the convection calculations; however, wind does affect the ventilation rate on a continuous basis. To remedy this problem, average ventilation rates were used with the model. Average rates were found by using segments of data that used a common fan speed. The ventilation rates were adjusted until the average of the furnace output errors (from the temperature rise technique) was near zero, and the average absolute difference of error was at a low point. The searches for the average ventilation rates were started from fan data as shown in Table 11, and resulted in rates for Nursery 1 of 0.082, 0.125 and 0.150 m^3/s for low, medium 1, and medium 2 speeds, respectively. For Nursery 2, the rates were 0.130, 0.220 and 0.262 m^3 /s, respectively. Nursery 1 ventilation rates were far below the product literature ratings for the fans. This will be discussed further in the next section.

4.5.2 Results and Statistical Evaluation

The operational model was used to simulate 16 weeks of data for both nurseries. Each week was considered to be a separate trial to produce sets of data for comparison. Comparisons were performed between the actual and simulated values of fuel consumption, daily feed consumption, and daily growth.

Table 24 presents readings of the gas meters and simulated fuel consumption in cubic feet. Readings are given as standard cubic feet since gas meters in the U.S. generally are read in these units. Taking the gas meter reading as the actual gas consumed (in reality it is +/- 100 ft^3), percent error was calculated. For Nursery 1, each comparison yielded a negative error, indicating that the model underpredicted fuel consumption. Total gas consumption was underpredicted by 20.3 percent. Nursery 2 produced a mixture of positive and negative errors, and tended to overpredict the total gas consumption by 11.1 percent.

A t test was used to test the hypothesis that the mean error (simulated minus actual) was not different from zero. For Nursery 1, the test strongly rejected the hypothesis ($p < 0.002$). For Nursery 2, the test rejected the hypothesis, but not nearly as strongly ($p = 0.029$). Wilcoxon's signed ranks test, which is an equivalent nonparametric test, yielded similar results indicating that, for both nurseries, the model did not consistently imitate the nursery building.

The data from both nurseries were combined into one data set and statistically tested using a t test with the hypothesis that the mean of all the differences was not different from zero. The test failed to reject the hypothesis; however, this was not considered a meaningful test. It makes no

Table 24. Comparisons of simulated and actual gas meter readings.

From		To		Gas Consumption (ft^3)		Percent
Day	Time	Day	Time	Simulated	Actual	Error
			Nursery 1			
351	1120	357	900	629	700	-10.1
357	900	362	1200	531	700	-24.1
362	1200	364	1340	92	100	-8.0
364	1340	4	1030	135	200	-32.5
4	1030	9	1520	423	700	-39.6
9	1520	15	1650	685	800	-14.4
15	1650	21	800	583	700	-16.7
28	930	33	1950	422	500	-15.6
33	1950	36	1120	236	300	-21.3
47	1900	51	2050	487	700	-30.5
51	2050	56	1415	545	700	-22.1
63	1350	69	1930	787	900	-12.6
69	1930	71	1430	153	200	-23.5
71	1430	77	1300	411	600	-31.5
84	1045	85	1430	66	100	-34.0
				Overall Average		-20.3
			Nursery 2			
351	1120	357	900	910	700	30.0
357	900	362	1200	755	700	7.9
362	1200	364	1340	206	100	106.0
364	1340	4	1030	150	200	-25.0
4	1030	9	1520	631	600	5.2
9	1520	15	1650	764	500	32.8
15	1650	21	800	535	400	33.8
28	930	33	1950	490	500	-2.0
33	1950	36	1120	42	0	-----
47	1900	51	2050	661	600	10.2
51	2050	56	1415	636	700	-9.1
63	1350	69	1930	901	900	0.1
69	1930	71	1430	181	200	-9.5
71	1430	77	1300	566	500	13.2
84	1045	85	1430	115	100	15.0
				Overall Average		11.1

physical sense to allow errors for different nurseries to compensate for one another, so nurseries were analyzed separately from here on.

Table 25 presents results using the method of calculating the furnace output based on the average temperature of the outlet. Average wattage output is listed, as well as the total accumulated fuel usage in cubic feet. Some of the trials were based on fewer hours due to lapses in collected input data. The averages and totals were calculated using the hours of data available.

Table 25 to indicates a result similar to that given by the gas meter comparison. The results for Nursery 1 indicate that the model underpredicts the fuel usage by 18.3 percent, and Nursery 2 underpredicts by 3.1 percent. The t test for Nursery 1 data strongly ($p < 0.002$) rejects the hypothesis that the mean of the errors was not different from zero. Nursery 2 results indicate that the mean of the error was, in fact, similar to zero ($p = 0.395$). Wilcoxon's signed ranks test was also performed on the two data sets and yielded similar results. This indicated that the model does an acceptable job of predicting fuel usage for Nursery 2 and does not for Nursery 1.

Predicting fuel usage in a building with large amounts of heat loss through the ventilation system is not an easy task, as evidenced here. The errors involved in fuel consumption within this model were most likely due to erroneous estimation of ventilation rates. Ventilation rates calibrated for use in the model greatly differ from rates specified in the product literature. This in itself was not surprising, but model calibration for the two nurseries resulted in vastly different ventilation rates, even though ventilation systems were similar. Several factors may have contributed to this calibration difference. Two possibilities become evident since the ventilation rates were calibrated using the furnace output method. The furnaces may not have performed as 5861 W (20,000 btu/hr) heaters. If the furnace in Nursery 1 had been performing at a lower level due to a clogged gas jet or for some other reason, the ventilation rate for Nursery 1 would have been calibrated at a lower level to compensate for the error. The other possibility is that the rates were actually different.

Table 25. Comparisons of simulated and actual gas usage using the furnace temperature method.

Trial No.	Simulated		Actual		Percent Error
	Average Watts	Total ft^3	Average Watts	Total ft^3	
		Nursery 1			
N1G1W3	3459	687[1]	5137	1020[1]	-32.7
N1G1W4	3442	693[1]	4255	857[1]	-19.1
N1G1W5	3044	730	3546	851	-14.2
N1G1W6	2512	603	3052	732	-17.7
N1G1W7	702	169	907	218	-22.6
Total	13159	2882	16897	3678	-22.1
N1G2W1	2972	713	3390	813	-12.3
N1G2W2	3319	796	4086	980	-18.8
N1G2W3	2689	572[1]	3051	649[1]	-11.9
N1G2W4	2453	589	2812	675	-12.8
N1G2W5	3239	777	3728	894	-13.1
Total	14672	3447	17067	4011	-14.0
N1G3W1	3108	746	4236	1016	-26.6
N1G3W2	3368	678[1]	4246	855[1]	-20.7
N1G3W3	3030	727	3636	872	-16.7
N1G3W4	2915	700	3620	869	-19.5
N1G3W5	2466	500[1]	3101	629[1]	-20.5
N1G3W6	2029	487	2000	480	1.5
Total	16916	3838	20839	4721	-18.8
Overall Total	44747	10167	54803	12410	-18.3
		Nursery 2			
N2G1W3	5147	1022[1]	5761	1144[1]	-10.7
N2G1W4	4820	971[1]	4558	918[1]	5.8
N2G1W5	4415	1059	3604	865	22.5
N2G1W6	3466	832	3894	934	-11.0
N2G1W7	996	239	1464	351	-32.0
Total	18844	4123	19281	4212	-2.3
N2G2W1	4133	992	3853	925	7.3
N2G2W2	2693	646	2332	560	15.5
N2G2W3	3008	640[1]	2050	436[1]	46.7
N2G2W4	2951	708	2874	690	2.7
N2G2W5	821	197	1547	371	-46.9
Total	13606	3183	12656	2982	7.5
N2G3W1	3710	890	4850	1164	-23.5
N2G3W2	4448	896[1]	5079	1023[1]	-12.4
N2G3W3	3973	953	4172	1001	-4.8
N2G3W4	3443	826	4019	965	-14.3
N2G3W5	3970	805[1]	3769	764[1]	5.3
N2G3W6	2788	669	2691	646	3.6
Total	22332	5039	24580	5563	-9.1
Overall Total	54782	12345	56517	12757	-3.1

1 This figure was averaged on a reduced number of hours

This could have been due to some unseen ventilation configuration upstream from the fan which affected fan performance.

Another point that should be made involves the errors which occurred in spite of the calibration. The calibration was done several times for each fan speed, and then the ventilation rates found at each speed were averaged. Therefore, errors were inherent since averages were used.

Several factors could have affected ventilation rate in the nurseries over a given period of time. Dust could have accumulated and interfered with normal ventilation. Wind and human interference also could have affected rates. Wind changes the pressure on the outside of the building and it affects the flow of air due to the normal difference in static pressure between the inside and outside of the building. The validation building had fans exposed to wind effects. Human interference could have influenced actual ventilation rates. Several people worked in and around the nurseries. The adjustable inlet could have been changed several times throughout the study without such information being recorded and considered. It is also possible that the fan speeds were changed for short periods of time to accommodate the workers. All of these factors would have changed the ventilation rate and, thus, the accuracy of the fuel consumption predicted by the model during a particular trial.

Feed consumption was another important output used for validation of this model. Table 26 shows the average daily feed consumption (ADF) per pig. ADF was used rather than the total feed consumption due to incomplete input data sets for certain weeks. Also, on several occasions, pigs died during the tests. The operational model does not allow for loss of pigs, so weekly simulations reduced error due to the dynamic number of pigs.

The percent error for ADF remained small for all of the tests except Nursery 1, Group 2. For this group, only the final ADF was measured and the model appeared to underestimate the feed consumed by 22.1 percent. However, for Nursery 1 the overall error was an underprediction of 1.6

Table 26. Comparisons of simulated and actual average daily feed consumption (ADF).

Trial No.	No. Hours	Simulated ADF (kg/pig)	Actual ADF (kg/pig)	Percent Error
		Nursery 1		
N1G1W3	139	0.596[1]	0.571	4.4
N1G1W4	141	0.719[1]	0.712	1.0
N1G1W5	168	0.857	0.884	-3.0
N1G1W6	168	1.066	-----	-----
N1G1W7	168	1.329	-----	-----
Average		0.724	0.722	0.3
N1G2W1	168	0.297	-----	-----
N1G2W2	168	0.477	-----	-----
N1G2W3	149	0.582[1]	-----	-----
N1G2W4	168	0.768	-----	-----
N1G2W5	168	0.947	-----	-----
Average		0.614	0.750	-22.1
N1G3W1	168	0.296	0.140	111.4
N1G3W2	141	0.423[1]	0.500	-15.4
N1G3W3	168	0.577	0.500	15.4
N1G3W4	168	0.692	0.770	-10.1
N1G3W5	142	0.890[1]	0.930	-4.3
N1G3W6	168	1.071	-----	-----
Average		0.568	0.576	-1.3
Overall Ave		0.630	0.640	-1.6
		Nursery 2		
N2G1W3	139	0.577[1]	0.571	1.1
N2G1W4	141	0.723[1]	0.712	1.5
N2G1W5	168	0.857	0.884	-3.1
N2G1W6	168	1.080	-----	-----
N2G1W7	168	1.352	-----	-----
Average		0.719	0.722	-0.4
N2G3W1	168	0.299	0.130	130.0
N2G3W2	141	0.430[1]	0.540	-20.0
N2G3W3	168	0.570	0.540	5.6
N2G3W4	168	0.726	0.790	-8.1
N2G3W5	142	0.904[1]	0.820	10.2
N2G3W6	168	1.109	-----	-----
Average		0.586	0.564	3.9
Overall Ave		0.636	0.623	2.1

[1] This figure was averaged on a reduced number of hours

percent, and for Nursery 2, an overprediction of 2.1 percent. These errors appear to be very reasonable, but should only be used over a period of one day or longer. The NCR model was changed to predict feed consumption and growth on an hourly basis. It is unreasonable to think that pigs perform uniformly over an entire day. One day of model output can be trusted, but an hour of output is merely the daily performance divided equally into 24 portions.

The statistical tests verified that the model ADF fits the data well. Tests for Nurseries 1 and 2 both failed to reject the hypothesis that the mean of the model error was not different from zero. These tests gave strong evidence that the model predicted valid ADF values for Nursery 1 ($p = 0.772$) and Nursery 2 ($p = 0.705$).

The final output that was validated was growth. This information appears in Table 27. Like feed consumption, growth was validated using average daily growth (ADG) per pig for the same reasons stated above.

The simulated ADG appears to fit the collected data well for all cases. The individual trials varied in accuracy, but the errors of one group tended to compensate for other errors within that same group. Nursery 1 was found to underpredict growth by 1.3, 2.6, and 1.3 percent for the three groups, with an overall error of 1.7 percent underprediction. Nursery 2 had group errors of 0.8 and 3.8 percent underpredictions, with an overall underprediction of 2.8 percent. These appear to be acceptable predictions for ADG.

For both nurseries, statistical tests failed to reject the hypothesis that the mean of the error was not different from zero. This was concluded with strong evidence for Nursery 1 ($p = 0.788$) and Nursery 2 ($p = 0.615$).

From the validation of the operational model, it was concluded that feed consumption and growth were predicted with an average accuracy within 10 percent in most cases. However, fuel

Table 27. Comparisons of simulated and actual average daily growth (ADG).

Trial No.	No. Hours	Simulated ADG (kg/pig)	Actual ADG (kg/pig)	Percent Error
		Nursery 1		
N1G1W3	139	0.311[1]	0.307	1.3
N1G1W4	141	0.355[1]	0.343	3.5
N1G1W5	168	0.446	0.479	-6.9
N1G1W6	168	0.599	-----	-----
N1G1W7	168	0.749	-----	-----
Average		0.371	0.376	-1.3
N1G2W1	168	0.117	-----	-----
N1G2W2	168	0.244	-----	-----
N1G2W3	149	0.317[1]	-----	-----
N1G2W4	168	0.456	-----	-----
N1G2W5	168	0.588	-----	-----
Average				
	at 17 days	0.206	0.265	-22.3
—	17-34 days	0.531	0.494	7.5
Average		0.369	0.379	-2.6
N1G3W1	168	0.124	0.089	39.3
N1G3W2	141	0.203[1]	0.214	-5.1
N1G3W3	168	0.294	0.351	-16.2
N1G3W4	168	0.398	0.507	-21.5
N1G3W5	142	0.551[1]	0.427	29.0
N1G3W6	168	0.662	-----	-----
Average		0.314	0.318	-1.3
Overall Ave		0.342	0.348	-1.7
		Nursery 2		
N2G1W3	139	0.313[1]	0.307	1.9
N2G1W4	141	0.359[1]	0.343	4.7
N2G1W5	168	0.446	0.479	-6.9
N2G1W6	168	0.611	-----	-----
N2G1W7	168	0.762	-----	-----
Average		0.373	0.376	-0.8
N2G3W1	168	0.127	0.130	-2.2
N2G3W2	141	0.209[1]	0.240	-12.9
N2G3W3	168	0.311	0.370	-15.9
N2G3W4	168	0.428	0.490	-12.6
N2G3W5	142	0.561[1]	0.470	19.4
N2G3W6	168	0.685	-----	-----
Average		0.327	0.340	-3.8
Overall Ave		0.344	0.354	-2.8

[1] This figure was averaged on a reduced number of hours

consumption was predicted with an average accuracy near 20 percent in many cases. While fuel cost is substantial in a swine nursery, it is generally far outweighed by feed cost. Perhaps the most important parameters in terms of cost are feed consumption and growth. They are more completely analyzed in the next section.

4.5.3 Optimization

The optimization option of the operational model was run using the six groups of animals involved in this study. Approximate current prices of $0.35 per kg of feed and $1.45[2] per gallon of propane were used as inputs to the model. The results appear in Table 28 in comparison to simulated results using the actual building settings as inputs. Group 1 (N1G1 and N2G1) was simulated for five weeks, beginning when the animals were 39 days old. Group 2 (N1G2 and N2G2) and Group 3 (N1G3 and N2G3) began with animals 28 days old; Group 2 ran for five weeks and Group 3 for six weeks.

In all cases, the optimization simulation appeared to produce more gain, more economically than the conventional temperature regime. This could have two benefits. First, it costs less to produce a kg of gain, and second, production of the gain takes a shorter time. Therefore, pigs occupy the nursery for a shorter period of time and incur less fixed costs as well. However, it should be remembered that validation was performed on the operational model and the extension of its application to optimization was purely theoretical.

The optimized temperatures were compared to the nursery set point used during normal operation, the lower critical temperature of the animals, and the outdoor temperature. Figure 11 and Figure 14 illustrate Group 1; Figure 12 and Figure 15 illustrate Group 2; and Figure 13 and Fig-

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[2] This price was current for small quantity delivery. Current domestic-use price is $0.87 per gallon.

Table 28. Comparisons of optimization and non-optimization runs on six groups of pigs.

Trial	Total Fuel		Total Feed		Total Gain	Cost
No.	Gallons	Dollars	Kg	Dollars	Kg	$/kg gain
N1G1						
Opt	0.46	0.66	1655.97	579.59	907.52	0.64
No Opt	90.38	131.05	1508.62	528.02	805.51	0.82
Diff	-89.92	-130.39	147.35	51.57	102.01	-0.18
N1G2						
Opt	0.99	1.43	1088.50	380.98	637.16	0.60
No Opt	100.24	145.35	962.20	336.77	538.32	0.90
Diff	-99.25	-143.92	46.30	44.21	98.84	-0.30
N1G3						
Opt	1.95	2.83	1471.37	514.98	869.62	0.60
No Opt	83.53	121.11	1339.07	468.67	774.92	0.76
Diff	-81.58	-118.28	132.30	46.31	94.7	-0.16
N2G1						
Opt	1.04	1.50	1703.44	596.20	939.63	0.64
No Opt	124.24	180.14	1531.32	535.96	820.62	0.87
Diff	-123.20	178.64	172.12	60.24	119.01	-0.17
N2G2						
Opt	2.85	4.14	1124.87	393.71	659.25	0.60
No Opt	119.46	173.22	1019.33	356.77	580.52	0.91
Diff	-116.61	-169.08	105.54	36.94	78.73	-0.31
N2G3						
Opt	2.84	4.11	1548.64	542.02	916.03	0.60
No Opt	137.90	199.95	1373.96	480.88	794.80	0.86
Diff	-135.06	-195.84	174.68	61.14	121.23	-0.26

ure 16 illustrate Group 3. In all cases, the optimum temperature was below the set point. In several of the figures, a spike appears at 32°C after which the graph resumes a typical appearance. This spike was caused by instability of the NCR swine submodel when young pigs lost weight when first placed in the nursery. Optimization found the point at which the cost per kg of gain lost was minimized. Pigs losing weight produce a negative cost per unit of gain produced, so the model optimized by finding the least absolute cost. This forced large fluctuations in temperature. This indicated that the model was only appropriate for pigs which are gaining body weight.

It should be noted that the set point is a constant and does not reflect variations which normally occur due to fluctuations of the outdoor temperature. The optimum temperature was often the temperature at which no heat was added; therefore, it fluctuated with the outdoor temperature. It appeared odd that optimization temperatures corresponded closely to the temperature at which no heat was required. To attempt to rationalize this result, the stepwise optimization scheme was analyzed. Table 29 shows a progression of temperature steps calculated by the model while solving for the optimum temperature. N1G3W1 was calculated with pigs weighing 7.13 kg, N1G3W2 at 7.75 kg, and N1G3W3 at 9.25 kg. In all cases, as temperature was decreased the cost of fuel decreased, more than compensating for the increase of feed cost. The animals gained faster and consumed more feed, but the efficiency of growth increased at lower temperatures. Therefore, it was concluded that production was more cost efficient at temperatures near the point of no heat addition than it was at elevated temperatures.

The swine model was idealized at lower temperatures. The current recommendation for temperature control, given by Hinkle et al. (1979), specifies a temperature range of 27 to 29°C for the initial two weeks post-weaning for early-weaned pigs. After that, the temperature should be decreased gradually to a range of 21 to 24°C. These temperature recommendations are based on knowledge of stress in pigs. When animals are too cold, they are stressed and, therefore, more prone to disease. The swine model does not take cold stress into account, and consequently, recommends temperatures lower than those recommended for stress-reduction.

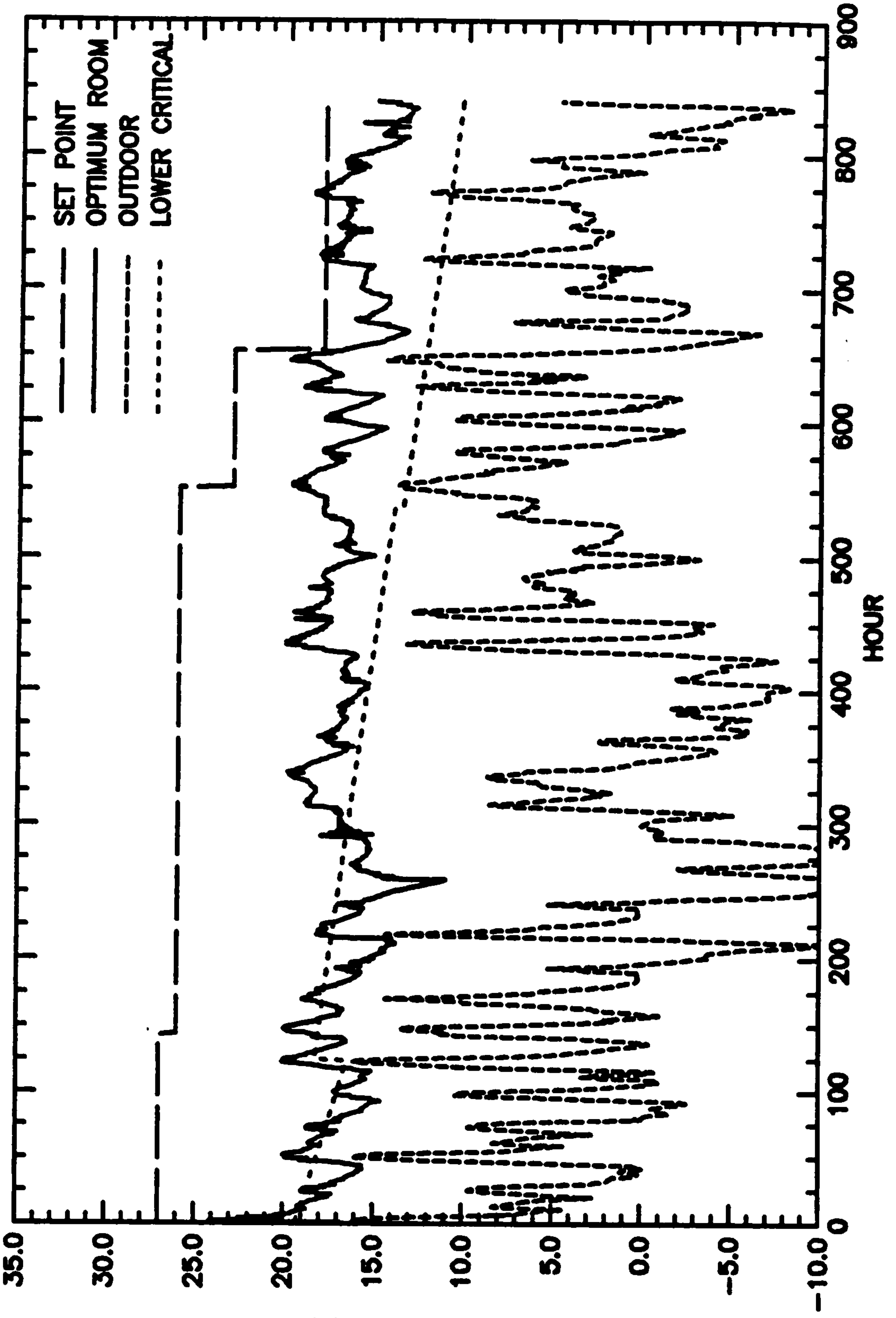

Figure 11. Results of the optimization of Nursery 1 Group 1.

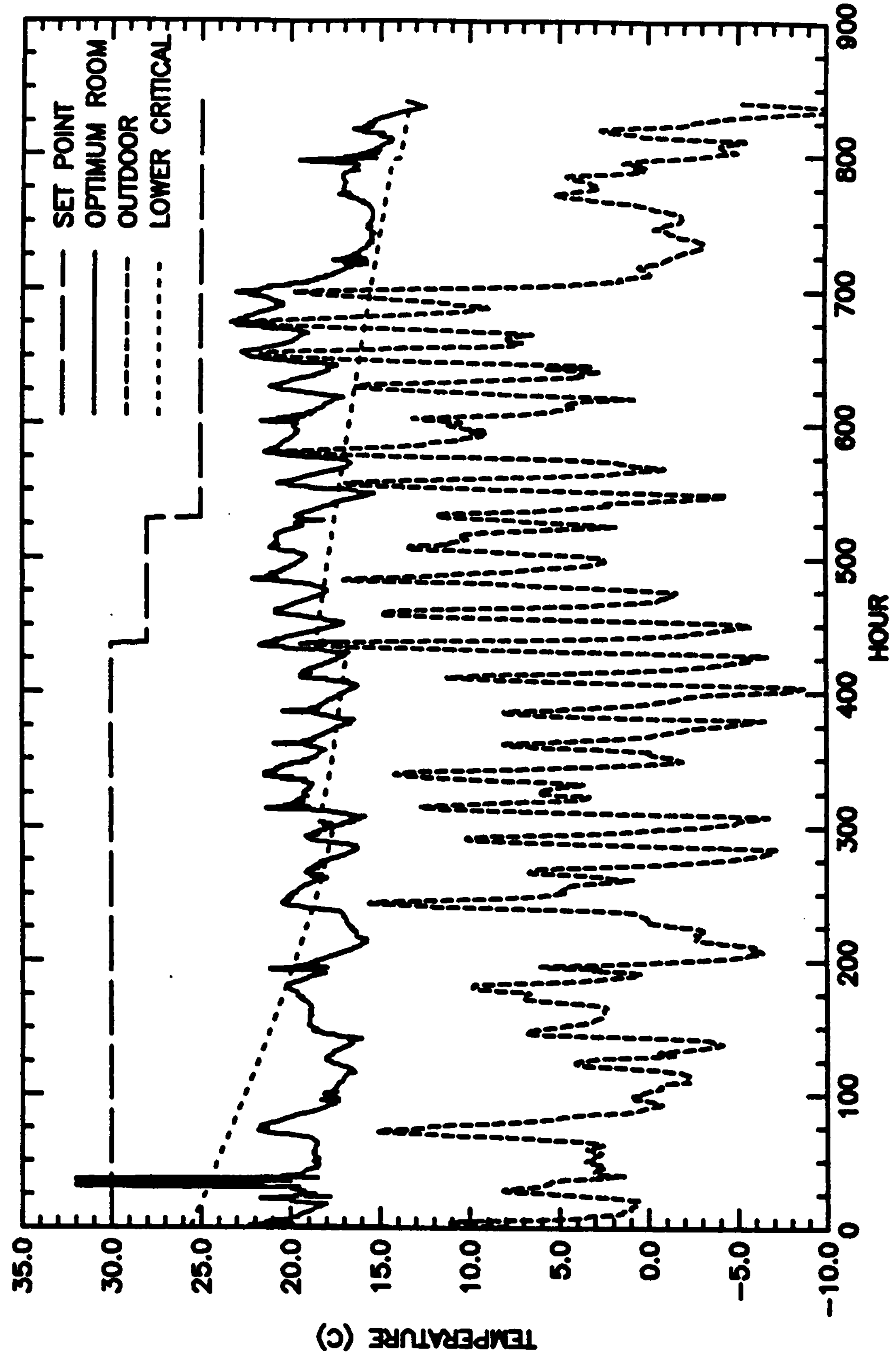

Figure 12. Results of the optimization of Nursery 1 Group 2.

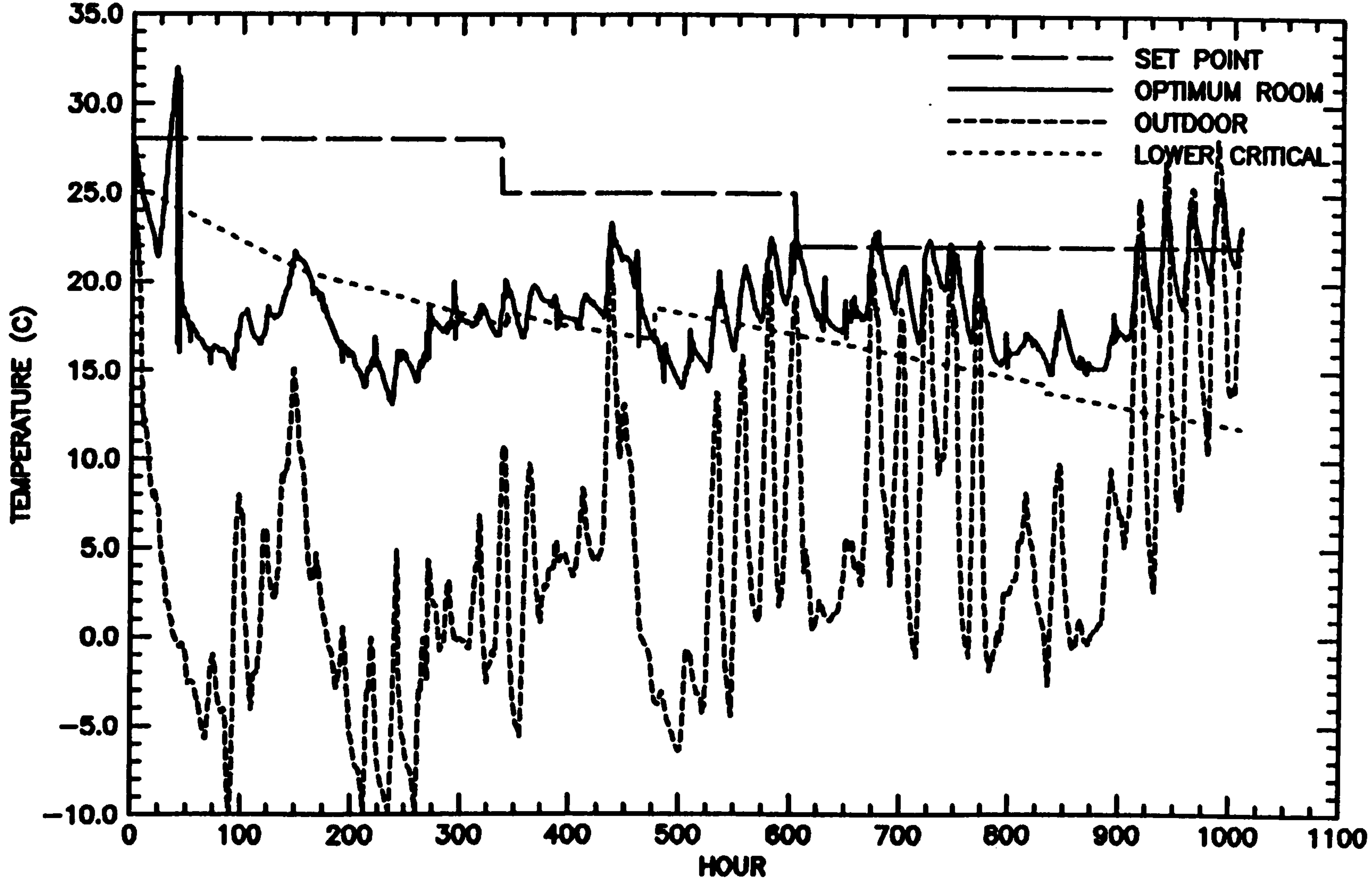

Figure 13. Results of the optimization of Nursery 1 Group 3.

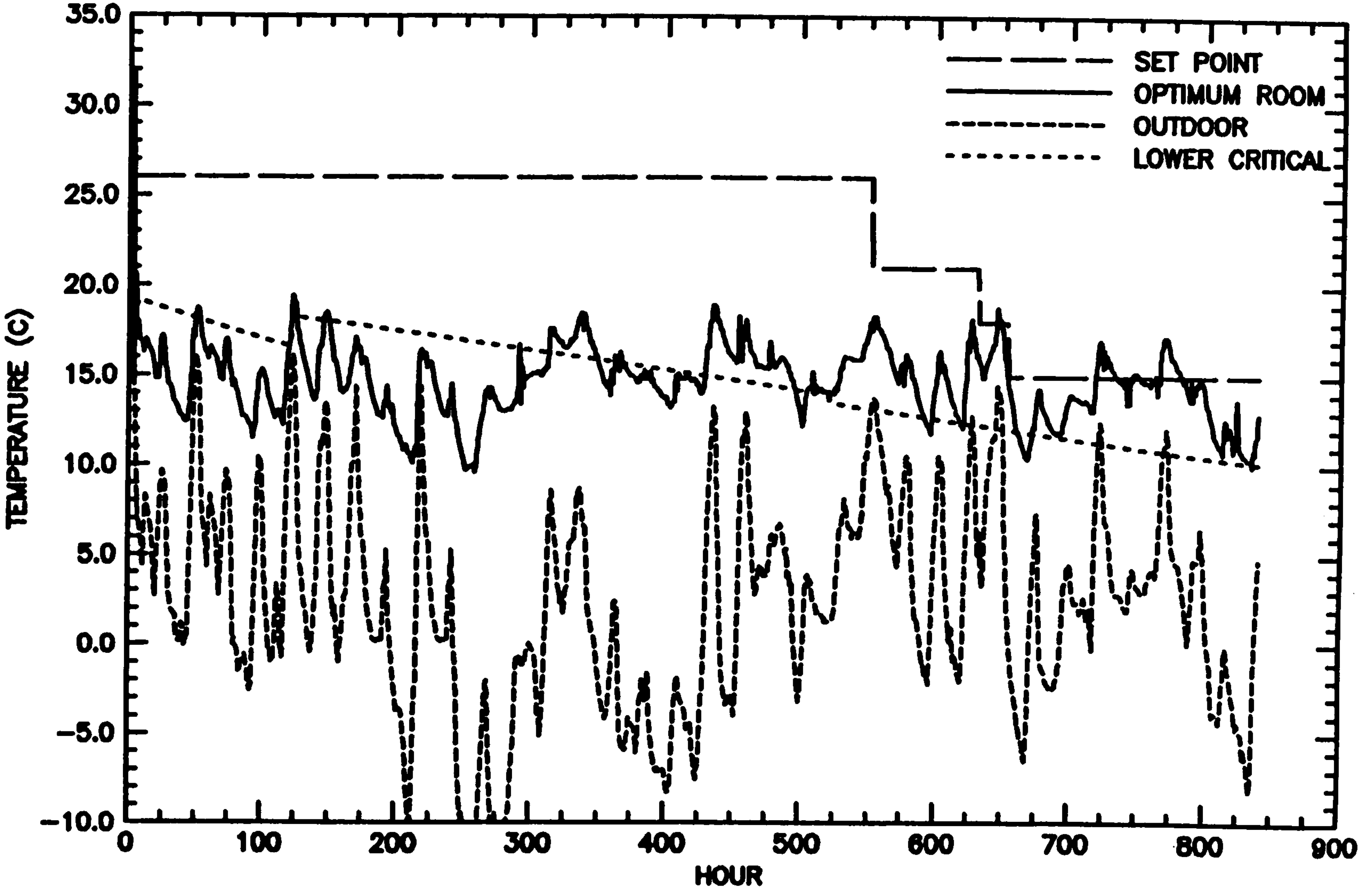

Figure 14. Results of the optimization of Nursery 2 Group 1.

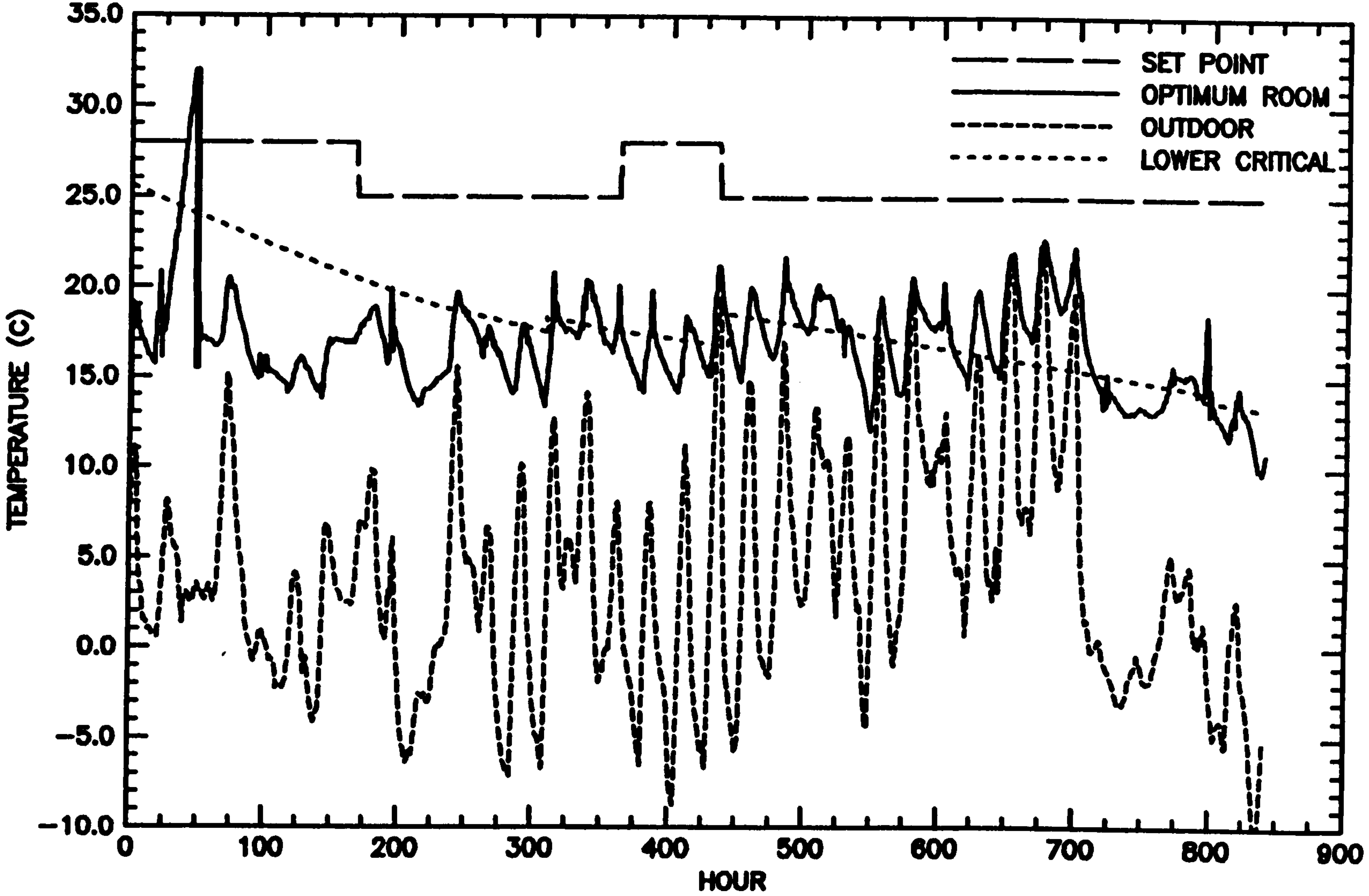

Figure 15. Results of the optimization of Nursery 2 Group 2.

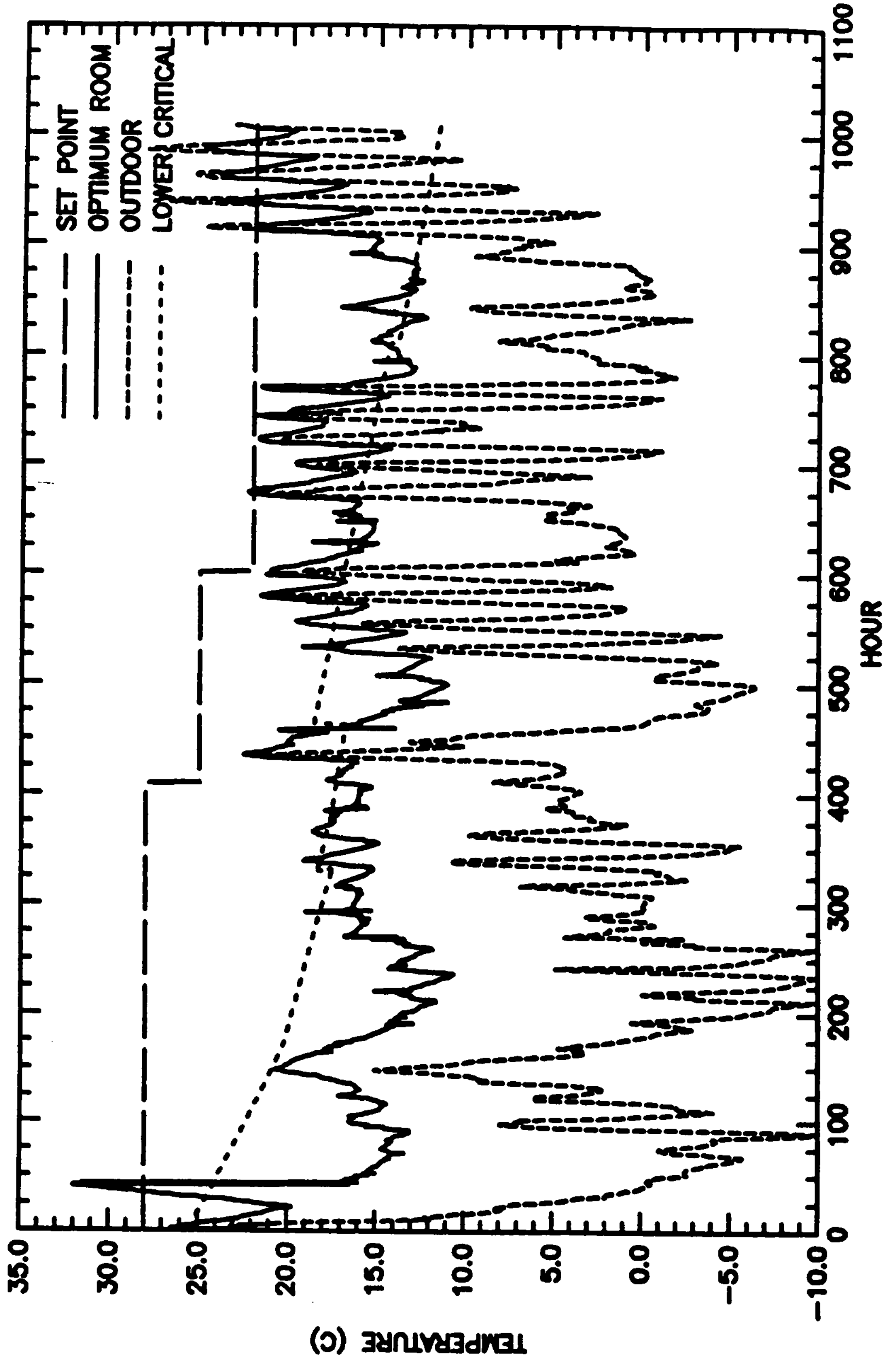

Figure 16. Results of the optimization of Nursery 2 Group 3.

Table 29. Tabulation of production values at different temperature steps.

Room Temp	Fuel	Group Costs Feed	Total	Individual Feed	Gain	Feed/ Gain	Cost/ kg gain
°C	$/hr	$/hr	$/hr	gm/hr	gm/hr		
			N1G3W1				
32	0.12	0.14	0.26	8.12	-2.50	-0.398	-2.09
30	0.09	0.14	0.23	8.26	-2.49	-0.302	-1.92
28	0.07	0.14	0.21	8.39	-2.45	-0.292	-1.76
26	0.04	0.14	0.18	8.51	-2.42	-0.284	-1.59
24	0.02	0.15	0.17	8.63	-2.39	-0.277	-1.44
22.2	0.00	0.15	0.15	8.78	-2.63	-0.299	-1.17
			N1G3W2				
32	0.18	0.26	0.44	15.33	6.59	0.430	1.39
30	0.16	0.26	0.42	15.60	6.82	0.437	1.29
28	0.13	0.27	0.40	15.85	7.04	0.444	1.19
26	0.11	0.27	0.38	16.10	7.25	0.450	1.10
24	0.09	0.27	0.36	16.33	7.45	0.456	1.01
22	0.07	0.28	0.35	16.56	7.66	0.463	0.94
20	0.05	0.28	0.33	16.79	7.85	0.467	0.87
18	0.02	0.29	0.31	17.07	8.01	0.469	0.81
16	0.00	0.29	0.29	17.33	8.00	0.462	0.76
			N1G3W3				
32	0.18	0.33	0.51	20.09	10.04	0.500	1.08
30	0.15	0.34	0.49	20.44	10.38	0.508	1.01
28	0.13	0.34	0.47	20.78	10.71	0.515	0.94
26	0.11	0.35	0.46	21.11	11.03	0.523	0.88
24	0.09	0.35	0.44	21.42	11.34	0.529	0.82
22	0.06	0.36	0.42	21.73	11.64	0.536	0.77
20	0.04	0.36	0.40	22.02	11.94	0.542	0.72
18	0.02	0.37	0.39	22.30	12.23	0.548	0.67
16.3	0.00	0.37	0.37	22.54	12.47	0.553	0.63

This optimization, while unproven by direct comparison to conventional temperature control, shows potential for cost savings. A comparison of feed to fuel cost in the non-optimizing mode of the model shows feed cost generally exceeding fuel cost by 200 to 400 percent; therefore, prediction of fuel consumption is not as critical as feed consumption. This model predicted feed consumption and growth with admirable accuracy, indicating that perhaps the magnitude of realized savings by using optimized temperatures is not accurate, but most certainly, there is potential for savings. The model neglects the effect of cold-stressing young animals, thereby taking an idealistic view of production at cooler than normal operating temperatures.

Chapter 5

Sensitivity Analysis

The sensitivity of the models was analyzed by varying selected inputs, one at a time, to determine the impact of the change on model output. Inputs were varied by a percentage representing reasonable estimates for margins of error.

5.1 Failure Model

Failure number 19 was selected for sensitivity analysis of the failure model because it was representative of typical trials. Several inputs were varied and the output compared to the actual model output, in order to analyze sensitivity. The nominal parameters used as input values for failure number 19 appear in Table 30.

The nominal parameters data were used as inputs to the model to produce an reference output. Then, one at a time, input values were changed by some percentage. This percentage was selected

Table 30. Nominal parameter values for failure model sensitivity analysis.

Input	Symbol	Value	Units
Absorptivity	α	0.4	----
Body Weight	bw	19.5	kg
Conductivity	k	0.39 (12″ block) 0.60 (8″ block)	Btu/hr-ft-°F
Crude Protein	CP	20	percent
Digestible Energy	DE	14.057	percent
Emissivity	ε	0.9	----
Indoor Air Movement	AM	0.15	m/s
Leakage Area	L	0.0075	m^2
Net Energy	NE	10	KJ/g
Specific Heat-Density	$c_p\rho$	11.20 (12″ block) 12.19 (8″ block)	Btu/ft^3 °F

in conjunction with its probable variability. For instance, it would be logical to use 50 and 150 percent of the original absorptivity as input to the sensitivity analysis, because it was an estimated parameter, but it would be unlikely that animal body weight or crude protein would vary by 50 percent from the true value. The outputs for the model with the varied inputs were then compared to the original output. For each input, the percentage the input had been varied when the maximum error occurred was recorded.

Most of the inputs tested made a small difference in the model results with the exception of crude protein which made no difference. An example of the sensitivity analysis comparison may be seen in Table 31.

The maximum error at the 60 minute time step was evaluated for each input (Table 32). The errors were described in terms of degrees C, percent error, percent varied, and percent error per percent input varied (PEPIV). PEPIV was used to analyze the extent to which the output was affected by the input. For instance, for every one percent that body weight input was changed, a change of 0.076 °C in the final predicted temperature resulted.

None of the inputs appear to have dominated the error. Many of the inputs to the swine model appear to have greater influence on error than inputs to the building model. It was surprising that after determining that wind velocity was a major contributor to error during model validation, it produced the smallest PEPIV and was, therefore, the least sensitive input. The actual wind velocity for this trial was 0.2 m/s. The wind velocity may vary by as much as 1000 percent or more during windy conditions. Even though the PEPIV was small, it may produce the largest error because of the large range of variability.

Even though no inputs appear overly sensitive (since all of the PEPIV values were less than 0.1), it should be noted that all inputs related to wall characteristics, when combined, could create a

Table 31. Failure model output variation due to 10 percent changes in body weight input.

Δt (min)	Inside Temperature (°C) at body weight (kg) 17.55	 19.5	 21.45
10	26.07	26.07	26.05
20	26.95	27.06	27.16
30	27.36	27.54	27.93
40	27.79	28.19	28.35
50	28.36	28.56	28.72
60	28.66	28.84	29.06

Table 32. **Maximum error at 60 minutes during failure simulation.**

	Maximum Error at 60 Minutes			
Input	**°C**	**% Error**	**% Input Varied**	**PEPIV[1]**
bw	0.22	0.76	10	0.076
ε	0.83	2.90	-50	-0.058
NE	0.14	0.49	-10	-0.049
DE	0.12	0.42	10	0.042
$c_p\rho$	0.13	0.45	-20	-0.023
k	0.12	0.42	-20	-0.021
α	-0.21	-0.73	-40	0.018
AM	0.22	0.76	50	0.015
L	-0.12	-0.42	50	-0.0083
V	0.05	0.17	-50	-0.0035

[1] Percent Error per Percent Input Varied

larger error. This would explain the results of the regression test which indicate errors based on solar load; solar load would change with changing wall characteristics.

Outputs do not necessarily vary linearly with changes in input. It should be noted that sensitivity analysis is generally done with only one typical trial. Therefore, care should be taken in making broad assumptions based on its results.

5.2 Operational Model

Sensitivity analysis was performed on the operational model in the non-optimizing mode. Trial N1G3W4 was selected as a representative trial for analysis. Parameters selected for testing and their corresponding nominal values appear in Table 33.

Each of the parameters was changed one at a time by a certain percentage, both positive and negative, which appeared to be a reasonable margin of error for the input. At the end of the one week trial, output values were compared to the original values and the maximum error recorded for each input. Such comparisons were done for gain, feed consumption, fuel consumption, and the fuel and feed cost per kg of gain produced. The maximum value of error (varied output minus original output) is presented for each input. The percent error, percent the input value was varied at the point which the maximum error occurred in the output, and the percent error per percent input varied (PEPIV) are also tabulated.

The PEPIV gives a perspective on how much effect the individual input had on output. For instance, Table 34 gives the PEPIV value for crude protein to be 1.7. This means than increasing the value of crude protein by one percent in the model would increase the predicted gain by 1.7 percent.

Table 33. Nominal parameter values for operational model sensitivity analysis.

Input	Symbol	Value	Units
Absorptivity	α	0.4	----
Body Weight	bw	11.71	kg
Conductivity	k	0.39 (12″ block) 0.60 (8″ block)	Btu/hr-ft-°F
Crude Protein	CP	20	percent
Digestible Energy	DE	14.057	percent
Emissivity	ε	0.9	----
Feed Wastage	waste	4.0	percent
Furnace Set Point	setpt	28.0 26.0 25.0	°C
Indoor Air Movement	AM	0.15	m/s
Net Energy	NE	10	KJ/g
Number of Pigs	pigs	47	----
Specific Heat-Density	$c_p\rho$	11.20 (12″ block) 12.19 (8″ block)	Btu/ft^3 °F
Ventilation Rate	vent	0.125	m^3/s

Table 34. **Maximum error in total gain at the end of a one week operational simulation.**

Input	Maximum Error After One Week			
	kg of gain	% Error	% Input Varied	PEPIV[1]
CP	21.91	17.0	10	1.7
DE	-21.42	-16.6	10	-1.66
bw	15.72	12.2	10	1.22
pigs	-5.48	-4.3	-4.4	0.98
setpt	6.79	5.3	-10	-0.53
NE	6.46	5.0	10	0.50
waste	5.92	4.6	-50	-0.092
vent	1.09	0.85	-50	-0.017
AM	0.87	0.68	50	0.014
$c_p\rho$	0.03	0.0	20	0.00
α	0.0	0.0	50	0.00
ε	0.0	0.0	50	0.00
k	0.0	0.0	20	0.00

[1] Percent Error per Percent Input Varied

Table 34 presents the analysis for total group gain for one week. The building thermal characteristics ($c_p\rho$, α, ε, and k) appear to have little effect upon gain. Feed characteristics (CP, DE, and NE), on the whole, seem to be the most sensitive parameters, while the size and number of pigs housed and the furnace set points were sensitive, but to a lesser degree. Any input with a PEPIV value greater than 0.1 was considered as sensitive. These results are believable since the swine submodel reacts to the environment to which the pigs were exposed. The furnace set points establish the environment, so building characteristics should make little difference in the swine submodel calculations. The feed characteristics and the size of the pigs would be expected to influence the rate of gain. The number of pigs creates sensitivity because the total gain for the group was tabulated.

Table 35 illustrates a similar point for total feed consumption. As in the gain analysis, building characteristics have a very small effect on the amount of feed consumed. The same inputs that had a significant effect upon gain also affect feed consumption. In this case, the model was the most sensitive to the number and size of animals. Digestible energy of the feed, furnace set points, and crude protein also were significant with the remaining inputs all adding little to the total sensitivity; i. e., all the remaining PEPIV values were below 0.1. The explanation given for gain holds true for feed consumption.

The most sensitive inputs that affected fuel consumption (Table 36) were furnace set points, digestible energy, ventilation rate, net energy, and animal body weight. The furnace set points and ventilation rate were expected to affect fuel consumption since both were strongly related to the supplemental heat required. Digestible energy, net energy, and body weight are related to the rate of animal heat production, so they affect supplemental heat requirements.

Table 37 presents the sensitivity of the cost per unit of gain produced as it was affected by the inputs. This output is a culmination of the other outputs since it combines feed and fuel usage with growth. The overall evaluation shows feed characteristics (crude protein, digestible energy, and

Table 35. Maximum error in total feed consumed at the end of a one week operational simulation.

	Maximum Error After One Week			
Input	kg of feed	% Error	% Input Varied	PEPIV[1]
pigs	-9.72	-4.3	-4.4	0.97
bw	-21.76	-9.5	-10	0.95
DE	-21.61	-9.5	10	-0.95
setpt	-5.88	-2.6	10	-0.26
CP	3.42	1.5	10	0.15
NE	0.30	0.13	10	0.013
waste	0.9	0.39	-50	-0.0079
AM	0.86	0.38	50	0.0075
vent	0.28	0.12	-50	-0.0025
$c_p\rho$	0.01	0.0	20	0.00
α	0.0	0.0	50	0.00
ε	0.0	0.0	50	0.00
k	0.0	0.0	20	0.00

[1] Percent Error per Percent Input Varied

Table 36. Maximum error in total fuel consumed at the end of a one week operational simulation.

Input	Maximum Error After One Week			
	gal of fuel	% Error	% Input Varied	PEPIV[1]
setpt	6.79	35.0	10	3.50
DE	-2.23	-11.5	-10	1.15
vent	-8.41	-43.4	-50	0.87
NE	-1.23	-6.3	10	-0.63
bw	0.37	1.9	-10	-0.19
k	-0.36	-1.9	-20	0.093
AM	-0.67	-3.5	50	-0.069
ε	-0.45	-2.3	-50	0.046
α	0.31	1.6	-50	-0.032
CP	0.05	0.26	10	0.026
pigs	0.02	0.10	-4.4	-0.023
$c_p\rho$	0.04	0.21	-20	-0.010
waste	-0.02	-0.10	50	-0.002

[1] Percent Error per Percent Input Varied

net energy) to be three of the four most sensitive inputs. Furnace set points also exhibited significant sensitivity. The size and number of pigs housed and the ventilation rate were also significant. Feed wastage, naturally, affects overall costs somewhat. None of the building thermal characteristics showed significant influence upon the output.

From the sensitivity analysis of the operational model several things can be concluded. The building thermal characteristics (α, ε, $c_p\rho$, and k) seemed to have little effect upon model outputs. In an operational model, only a small portion of the total heat loss occurs through the conductive surfaces, supporting the above conclusion. Feed characteristics (DE, NE, and CP) play an important role in the model. The furnace set points and ventilation also play a large role in the model.

Of all of these inputs, only feed characteristics, furnace set points, and ventilation rates are easily changed in a swine production facility. Feed characteristics have been researched by experts and information on feed formulation is generally available to producers. Ventilation reduction has also been researched and practical limits have been determined to maintain air quality within the facility. The furnace set points appear to be the only parameter that is not controlled based on a universal recommendation from experts. Producers tend to follow their own temperature control scheme. Finding the temperature set points at which cost per unit of gain produced is minimized is the objective of the optimizer program.

Table 37. Maximum error in total cost per kg of gain produced at the end of a one week operational simulation.

	Maximum Error After One Week			
Input	$/kg of gain	% Error	% Input Varied	PEPIV[1]
CP	0.13	15.5	-10	-1.55
setpt	0.11	13.1	10	1.31
DE	0.11	13.1	10	1.31
NE	0.05	5.9	-10	-0.59
bw	-0.04	-4.8	10	-0.48
pigs	-0.01	-1.2	4.4	-0.27
vent	0.11	13.1	50	0.26
waste	-0.04	-4.8	50	-0.096
k	-0.01	-1.2	-20	0.060
ε	-0.01	-1.2	-50	0.024
AM	-0.01	-1.2	50	-0.024
α	0.00	0.0	50	0.00
$c_p\rho$	0.00	0.0	20	0.00

[1] Percent Error per Percent Input Varied

Chapter 6

Conclusions

6.1 Failure Model

A model was developed to predict the temperature in a swine nursery during a power failure. Results from this study support the following conclusions:

1. The simulation model worked well for the building used in this study under normal daytime conditions, but becomes less reliable during periods of low or fluctuating solar loads. The model had no more of a tendency to overpredict than to underpredict.

2. The TRFM method of calculating conduction losses was a substantial part of this method of modeling short term power failures. The accuracy of predicted conduction losses using this method is related to characteristics of the wall such as specific heat, conductivity, and density of wall components. Emissivity and absorptivity values also impact on accuracy of the TRFM method.

3. Windy conditions contributed to failure model error. This was expected because wind was a component of the convection, as well as the building infiltration calculations.

4. Humidity plays a major role in determining the nursery room temperature rise during a failure. A standard swine heat production model must be adjusted to compensate for the reduction in evaporative potential during times of high humidity within the barn.

5. In this study, the magnitude of the temperature rise did not appear to present as much possible danger to the animals as the possibility of build-up of high concentrations of pit gases.

6.2 Operational Model

An operational model was developed to predict pig growth, feed consumption, fuel consumption, and, ultimately, feed and fuel cost per unit of gain. A temperature optimization routine was incorporated as an option in the program. Results from this study indicate the following conclusions:

1. The operational model predicts pig growth and feed consumption with acceptable accuracy for the building used in validation. Prediction of the fuel consumption was somewhat less accurate, and depended upon the accuracy of furnace set points, ventilation rate estimates, and feed characteristics.

2. Fuel cost was small in proportion to feed cost. Inaccuracy in prediction of fuel usage did not substantially affect the calculation of cost per unit of gain.

3. The optimization program shows a potential for reduced fuel and feed cost per unit of gain produced, thereby improving profit for the producer. This approach was idealized and did not account for the effects of cold induced stress.

4. The operational model should be used over a period of one day or longer. Hourly readings represent daily averages converted to an hourly basis and, therefore, normal production fluctuations during the day are neglected.

5. The optimizing program mode was somewhat unstable for small pigs which were losing weight due to early weaning and should by limited to pigs which are predicted to gain weight.

6.3 Recommendations for Future Work

1. The failure and operational models should be tested using a building which is more typical of commercial swine production.

2. Pit gas concentrations should be measured during power failures to determine their importance and impact on production. Modeling of such gas build-up would provide a more complete failure model.

3. Pressure transducers should be incorporated into the environmental control system to better understand fluctuations in ventilation rates, and thereby compensate for them within the operational model.

4. The use of more accurate instrumentation of gas consumption and ventilation air flow would allow for better accuracy of the operational model.

5. Comparisons should be made between a "typical" nursery and one instrumented and controlled by the computer optimizing program.

6. The swine model should incorporate the effects of cold stressing early-weaned pigs.

7. Diurnal variations in swine production should be incorporated into the swine model for use on an hourly basis.

8. The operational and failure models should be assessed using a variety of buildings, weather situations, and sizes of pigs, in order to build more confidence in the validity of both models.

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Appendix A. Thermal Response Factor Program

The following program was developed by George Boufadel, graduate student, and William Thomas, Professor, of the Mechanical Engineering Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

A.1 Example Input

```
1.00d0                                          time step (hours)
1   1   1   1                                   output decisions
3           1.00d0                         no. of layers, time step
0.00676d0   0.0417d0    0.0667d0           diffusivity, thickness, conductivity
0.06625d0   0.2917d0    0.0265d0           ft²/s, ft, Btu/ft-hr-°F
0.00676d0   0.0417d0    0.0667d0
```

A.2 Program Code

```
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION RFX(5,200),RFY(5,200),RFZ(5,200),XJ(5)
      DIMENSION RX(200),RY(200),RZ(200),SJ(5,5)
      DIMENSION RFAX(5,5,200),RFAY(5,5,200),RFAZ(5,5,200)
      DIMENSION SSX(5),SSY(5),SSZ(5)
      DIMENSION UW(5),DJ(5,5),UD(5)
C***********************************************************************
C
C    THIS PROGRAM CALCULATES THE THERMAL RESPONSE FACTORS
C    ------------------------------------------------
C
C     THIS PROGRAM IS EXECUTED FROM VM1  (NOT VMBATCH)
C     ----------------------------------------
C
C    INPUT:
C    -----
```

```
C       KW  = THE NUMBER OF WALLS IN THE CALCULATIONS
C       KW  = 1
C
C    2. WALL INFORMATION : NPB, NPXYZ, NPHORF, NGRAPH
C                     N, DLT
C                     NCL(1)
C                      :
C                     NCL(N)
C                     IF(NCL(1).EQ.1)READ(5,*)A(1),B(1),C(1),D(1)
C                     IF(NCL(1).EQ.0)READ(5,*)AL(1),XL(1),XK(1)
C                      :   :   :   :   :   :   :
C                     IF(NCL(N).EQ.1)READ(5,*)A(N),B(N),C(N),D(N)
C                     IF(NCL(N).EQ.0)READ(5,*)AL(N),XL(N),XK(N)
C          NPB    = DO NOT PRINT THE ROOTS IF NPB = 1
C          NPXYZ  = DO NOT PRINT X, Y OR Z IF NPXYZ = 1
C          NPHORF = DO NOT PRINT THE HIGHER ORDER RESPONSE
C               FACTORS IF NPHORF = 1
C          NGRAPH = DO NOT CALCULATE AND PRINT THE FUNCTIONS A
C               AND B  VERSUS THE ROOTS IF NGRAPH = 1
C
C
C    N = NUMBER LAYERS IN THE SLAB  ; DLT = TIME INCREMENTS ( HOURS )
C    AL(I) = DIFFUSIVITY OF LAYER 'I' ; XL(I) = THICKNESS LAYER 'I' ;
C    XK(I) = THERMAL CONDUCTIVITY OF LAYER 'I' ;
C    R(I) = RESISTANCE OF LAYER 'I' ;
C    U = OVERALL HEAT TRANSFER COEFFICIENT ;
C
C
C
C        KRFO = THE ORDER OF RESPONSE FACTORS THAT WILL
C             BE USED IN THE FORMULATIONS.
C
C        IF KNPP = 0 DO NOT CALCULATE THE J'S
C        IF KNPP = 1 CALCULATE THE J'S
C
C
C        UW(K)   = OVERALL HEAT TRANSFER COEFFICIENT OF WALL K
C
C*********************************************************************
C
C
C*********************************************************************
C   OUTPUT:
C   -------
C      FOR THE WALL :
C
C      A. WRITE NN ;
C            NN = THE ORDER OF RESPONSE FACTORS CALCULATED
C      B. WRITE RFAX(K,NN,J), RFAY(K,NN,J), RFAZ(K,NN,J) = THE
C            RESPONSE FACTORS OF EACH WALL
C         K= 1,2,..,KW ; KW = NUMBER OF WALLS CONSIDERED
C      C. WRITE XJ(K,J) = THE J'S ARE THE COEFFICIENTS OF THE
C                  PREVIOUS FLUXES
C                  K = 1,2,..,KW
C                  J = 1,2,..,5
C
C*********************************************************************
C
C
      KW=1
C
C **************   RESPONSE FACTORS OF THE WALL    ***************
C
      NRPT=0
      READ(5,*)DLT
      DO 31 K=1,KW
      CALL RESFAC (3,1,DLT,U,RX,RY,RZ,RFX,RFY,RFZ,XJ)
      NN=3
C      UW(K)=U
      DO 32 J=1,15
C      RFAX(K,NN,J)=RX(J)
C      RFAY(K,NN,J)=RY(J)
```

```
C     RFAZ(K,NN,J)=RZ(J)
C     RFAX(K,NN,J)=5.678264*RFX(NN,J)
C     RFAY(K,NN,J)=5.678264*RFY(NN,J)
C     RFAZ(K,NN,J)=5.678264*RFZ(NN,J)
      RFAX(K,NN,J)=RFX(NN,J)
      RFAY(K,NN,J)=RFY(NN,J)
      RFAZ(K,NN,J)=RFZ(NN,J)
   32 CONTINUE
      DO 60 I=1,5
      SJ(K,I)=XJ(I)
C     SJ(K,I)=0.D0
   60 CONTINUE
   31 CONTINUE
      WRITE(25,7)NN
      DO 40 K=1,KW
      SSX(K)=0.0
      SSY(K)=0.0
      SSZ(K)=0.0
      DO 40 J=1,15
      WRITE(25,4)RFAX(K,NN,J),RFAY(K,NN,J),RFAZ(K,NN,J)
      SSX(K)=SSX(K)+RFAX(K,NN,J)
      SSY(K)=SSY(K)+RFAY(K,NN,J)
      SSZ(K)=SSZ(K)+RFAZ(K,NN,J)
   40 CONTINUE
      DO 55 K=1,KW
      DO 55 I=1,5
      WRITE(25,4)SJ(K,I)
   55 CONTINUE
      DO 902 K=1,KW
      DO 902 IJ=1,30
C     IF((DABS(RFAY(K,NN,IJ))).GE.1.D0)NRPT=1
      NRPT=0
  902 CONTINUE
      IF(NRPT.EQ.0)WRITE(25,7)NRPT
      IF(NRPT.EQ.1)WRITE(25,7)NRPT
      IF(NRPT.EQ.0)GO TO 901
C     DLT=0.20D0
      DO 831 K=1,KW
      CALL RESFAC (3,1,DLT,U,RX,RY,RZ,RFX,RFY,RFZ,XJ)
      NN=3
C     UW(K)=U
      DO 832 J=1,30
C     RFAX(K,NN,J)=RX(J)
C     RFAY(K,NN,J)=RY(J)
C     RFAZ(K,NN,J)=RZ(J)
      RFAX(K,NN,J)=RFX(NN,J)
      RFAY(K,NN,J)=RFY(NN,J)
      RFAZ(K,NN,J)=RFZ(NN,J)
  832 CONTINUE
      DO 860 I=1,5
      SJ(K,I)=XJ(I)
C     SJ(K,I)=0.D0
  860 CONTINUE
  831 CONTINUE
      WRITE(25,7)NN
      DO 840 K=1,KW
      SSX(K)=0.0
      SSY(K)=0.0
      SSZ(K)=0.0
      DO 840 J=1,30
      WRITE(25,4)RFAX(K,NN,J),RFAY(K,NN,J),RFAZ(K,NN,J)
      SSX(K)=SSX(K)+RFAX(K,NN,J)
      SSY(K)=SSY(K)+RFAY(K,NN,J)
      SSZ(K)=SSZ(K)+RFAZ(K,NN,J)
  840 CONTINUE
      DO 855 K=1,KW
      DO 855 I=1,5
      WRITE(25,4)SJ(K,I)
  855 CONTINUE
  901 CONTINUE
C
    4 FORMAT(3F20.11)
```

```
    7 FORMAT(I6)
C
      STOP
      END
      SUBROUTINE RESFAC (KRFO,KNPP,DLT,U,RX,RY,RZ,RFX,RFY,RFZ,XJ)
C             CALCULATION OF RESPONSE FACTORS FOR
C                   MULTI-LAYER WALL
C              ****** Xi, Yi AND Zi ******
C              ALSO WE ARE CALCULATING FIRST, SECOND
C            THIRD, FOURTH AND FIFTH ORDER RESPONE  FACTORS
C        WHERE : RFX(1,J), RFY(1,J), RFZ(1,J)  FIRST ORDER R.F.
C              RFX(2,J), RFY(2,J), RFZ(2,J)  SECOND ORDER R.F.
C                 :        :        :
C                 :        :        :
C              RFX(5,J), RFY(5,J), RFZ(5,J)  FIFTH ORDER R.F.
C
C          KRFO = THE ORDER OF RESPONSE FACTORS THAT WILL
C               BE USED IN THE FORMULATIONS.
C
C          IF KNPP = 0 DO NOT CALCULATE THE J'S
C          IF KNPP = 1 CALCULATE THE J'S
C
C          US     = OVERALL HEAT REANFER COEFFICIENT OF THE
C                 SLAB  ( BASEMENT )
C
C          UW(K)   = OVERALL HEAT TRANSFER COEFFICIENT OF WALL K
C
C
C
C         FIRST THE ROOTS ARE DETERMINED USING "1/2 INTERVAL METHOD"
C
C
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION E(7),A(7),B(7),C(7),D(7),AL(7),XL(7),R(7)
      DIMENSION RB(200),XK(7),NCL(7),AA(7),AB(7),AC(7),AD(7)
      DIMENSION XG(7),SA(7),SB(7),RX(200),RY(200),RZ(200)
      DIMENSION RFX(5,200),RFY(5,200),RFZ(5,200)
      DIMENSION RR(5),XJ(5)
C           **************************************
C      N = NUMBER LAYERS IN THE SLAB  ; DLT = TIME INCREMENTS ( HOURS )
C      AL(I) = DIFFUSIVITY OF LAYER 'I' ; XL(I) = THICKNESS LAYER 'I' ;
C      XK(I) = THERMAL CONDUCTIVITY OF LAYER 'I' ;
C      R(I) = RESISTANCE OF LAYER 'I' ;
C      U = OVERALL HEAT TRANSFER COEFFICIENT ;
C
C
C           NPB    = DO NOT PRINT THE ROOTS IF NPB = 1
C           NPXYZ  = DO NOT PRINT X, Y OR Z IF NPXYZ = 1
C           NPHORF = DO NOT PRINT THE HIGHER ORDER RESPONSE
C                 FACTORS IF NPHORF = 1
C           NGRAPH = DO NOT CALCULATE AND PRINT THE FUNCTIONS A
C                 AND B  VERSUS THE ROOTS IF NGRAPH = 1
C
C
C
      READ(5,*)NPB,NPXYZ,NPHORF,NGRAPH
      READ(5,*)N
      NM=N+1
      DO 14 I=1,N
      READ(5,*)NCL(I)
   14 CONTINUE
      CHKU=0.0D0
      DO 11 I=1,N
      IF(NCL(I).EQ.1)READ(5,*)A(I),B(I),C(I),D(I)
      IF(NCL(I).EQ.0)READ(5,*)AL(I),XL(I),XK(I)
      IF(NCL(I).EQ.1)CHK=B(I)
      IF(NCL(I).EQ.0)CHK=(XL(I)/XK(I))
      CHKU=CHKU+CHK
   11 CONTINUE
      CHKU=1.D0/CHKU
      WRITE(21,2)CHKU
C  2 FORMAT(4X,' THE OVERALL HEAT TRANSFER COEFFICIENT IS = ',F30.25)
```

```
C                   *************************
C     IF NCL(I)=1   LAYER 'I' IS A CONVECTIVE LAYER ( READ THE
C          MATRIX ELEMENTS OF LAYER 'I' : A(I)=1 , B(I)=1/(H) WHERE
C          'H' IS THE CONVECTIVE HEAT TRANSFER COEFFICIENT ,
C          C(I)=0  ,  D(I)=1  )
C     IF NCL(I)=0   LAYER 'I' IS NOT CONVECTIVE ( READ : AL , XL , XK )
C                   *************************
      RT=0.D0
      DO 16 I=1,N
      IF(NCL(I).EQ.1)GO TO 10
      R(I)=XL(I)/XK(I)
      GO TO 12
   10 R(I)=B(I)
   12 CONTINUE
      RT=RT+R(I)
   16 CONTINUE
      U=1.D0/RT
      WRITE(20,*)U
      CC=0.D0
      CC1=0.D0
      CC2=0.D0
C
C                 IF THE NUMBER OF LAYERS ARE < 6
C            DECREASE THE FORMULATED EQUATIONS TO THE NUMBER OF
C                      LAYERS SPECIFIED
      IF(N.EQ.6)GO TO 15
      DO 17 I=NM,6
      A(I)=1.D0
      D(I)=1.D0
      B(I)=0.D0
      C(I)=0.D0
   17 CONTINUE
   15 CONTINUE
C
C        CALCULATION OF THE FUNCTION B FOR PLOTTING REASONS
C                IF NGRAPH IS NOT EQUAL TO 1
C
      IF(NGRAPH.EQ.1)GO TO 36
      X=20.0
      SDX=2.0
      DO 35 K=1,100
      RB(K)=X
      DO 33 I=1,N
      IF(NCL(I).EQ.1)GO TO 33
      E(I)=DSQRT((RB(K)*(XL(I)**2))/AL(I))
      A(I)=DCOS(E(I))
      B(I)=(R(I)*(DSIN(E(I))))/E(I)
      C(I)=-(E(I)*DSIN(E(I)))/R(I)
      D(I)=A(I)
   33 CONTINUE
      CALL SUBB (A,B,C,D,B6)
      CALL SUBA (A,B,C,D,A6)
C     WRITE(20,555)RB(K),B6,A6
C 555 FORMAT(3F15.7)
      X=X+SDX
   35 CONTINUE
   36 CONTINUE
C
C              THE CALCULATIONS OF THE ROOTS BK(I)
C
C     DX=0.01
      DX=0.05
      X2=0.01
      DO 22 K=1,45
C     DO 22 K=1,65
      IF(K.GE.20)DX=0.1
C     IF(K.GE.20)DX=0.8
      IF(K.GE.40)DX=0.5
C     IF(K.GE.40)DX=1.2
   21 X1=X2
      X2=X1+DX
      RB(K)=X1
```

```
      DO 23 I = 1,N
      IF(NCL(I).EQ.1)GO TO 23
      E(I) = DSQRT((RB(K)*(XL(I)**2))/AL(I))
      A(I) = DCOS(E(I))
      B(I) = (R(I)*(DSIN(E(I))))/E(I)
      C(I) = -(E(I)*DSIN(E(I)))/R(I)
      D(I) = A(I)
   23 CONTINUE
      CALL SUBB (A,B,C,D,B10)
      RB(K) = X2
      DO 25 I = 1,N
      IF(NCL(I).EQ.1)GO TO 25
      E(I) = DSQRT((RB(K)*(XL(I)**2))/AL(I))
      A(I) = DCOS(E(I))
      B(I) = (R(I)*(DSIN(E(I))))/E(I)
      C(I) = -(E(I)*DSIN(E(I)))/R(I)
      D(I) = A(I)
   25 CONTINUE
      CALL SUBB (A,B,C,D,B11)
      IF((B10*B11).GT.0.D0)GO TO 21
   24 X = (X1 + X2)/2.0
      RB(K) = X
      DO 26 I = 1,N
      IF(NCL(I).EQ.1)GO TO 26
      E(I) = DSQRT((RB(K)*(XL(I)**2))/AL(I))
      A(I) = DCOS(E(I))
      B(I) = (R(I)*(DSIN(E(I))))/E(I)
      C(I) = -(E(I)*DSIN(E(I)))/R(I)
      D(I) = A(I)
   26 CONTINUE
      CALL SUBB (A,B,C,D,B1)
      IF((B1*B10).LT.0.0)X2 = X
      IF((B1*B10).GT.0.0)X1 = X
      IF((B1*B10).GT.0.0)B10 = B1
      IF(DABS(X2-X1).GT.1.0 E-9)GO TO 24
      X = (X2 + X1)/2.0
      RB(K) = X
      IF(NPB.EQ.1)GO TO 22
      WRITE(20,240)K,RB(K)
  240 FORMAT(I5,F20.9)
   22 CONTINUE
C
C
C
C
C      **********************************************************
C
C                CALCULATIONS OF  X , Y AND Z
C
C      **********************************************************
C
C       CALCULATIONS OF  DA/DP , DB/DP AND DD/DP AT P = 0.0
C
      DRA = 0.D0
      DRB = 0.D0
      DRD = 0.D0
      DO 50 I = 1,N
      IF(NCL(I).EQ.1)GO TO 50
      DO 52 J = 1,N
      AA(J) = 1.D0
      AB(J) = R(J)
      AC(J) = 0.D0
      AD(J) = 1.D0
   52 CONTINUE
      NK = I
      AA(NK) = (XL(NK)**2)/(2.D0*AL(NK))
      AB(NK) = (R(NK)*(XL(NK)**2))/(6.D0*AL(NK))
      AC(NK) = (XL(NK)**2)/(R(NK)*AL(NK))
      AD(NK) = AA(NK)
      IF(N.EQ.6)GO TO 44
      DO 42 II = NM,6
      AA(II) = 1.D0
```

```
      AD(II) = 1.D0
      AB(II) = 0.D0
      AC(II) = 0.D0
   42 CONTINUE
   44 CONTINUE
      CALL SUBA (AA,AB,AC,AD,DA)
      CALL SUBB (AA,AB,AC,AD,DB)
      CALL SUBD (AA,AB,AC,AD,DD)
      DRA = DRA + DA
      DRB = DRB + DB
      DRD = DRD + DD
   50 CONTINUE
C
C     ************************************************
C
C
      DO 110 I = 1,45
      RX(I) = 0.D0
      RY(I) = 0.D0
      RZ(I) = 0.D0
  110 CONTINUE
      KN = 1
  132 CONTINUE
      XSUM = 0.D0
      YSUM = 0.D0
      ZSUM = 0.D0
      X1SUM = 0.D0
      Y1SUM = 0.D0
      Z1SUM = 0.D0
      DO 60 K = 1,45
      B5 = 0.D0
      DRBP = 0.0
      IF((RB(K)*DLT).GT.75.D0)GO TO 66
      RA = ((DEXP(-RB(K)*DLT))/(DLT*(RB(K)**2)))
      IF((RB(K)*2.D0*DLT).GT.75.D0)GO TO 82
      RA1 = ((DEXP(-2.D0*RB(K)*DLT))*(1-2.D0*(DEXP(RB(K)*DLT))))/
     + (DLT*(RB(K)**2))
   82 CONTINUE
      DO 61 I = 1,N
      IF(NCL(I).EQ.1)GO TO 63
      E(I) = DSQRT((RB(K)*(XL(I)**2))/AL(I))
      A(I) = DCOS(E(I))
      B(I) = R(I)*(DSIN(E(I))/E(I))
      C(I) = -(E(I)/R(I))*DSIN(E(I))
      D(I) = A(I)
   63 CONTINUE
   61 CONTINUE
      CALL SUBD (A,B,C,D,D5)
      CALL SUBA (A,B,C,D,A5)
      DO 70 I = 1,N
      IF(NCL(I).EQ.1)GO TO 73
      DO 72 J = 1,N
      IF(NCL(J).EQ.1)GO TO 74
      E(J) = DSQRT((RB(K)*(XL(J)**2))/AL(J))
      XG(J) = (XL(J)**2)/(2.D0*AL(J))
      SA(J) = ((DSIN(E(J)))/E(J))
      SB(J) = (SA(J)-DCOS(E(J)))/(E(J)**2)
      AA(J) = DCOS(E(J))
      AB(J) = R(J)*SA(J)
      AC(J) = -(E(J)*DSIN(E(J)))/R(J)
      AD(J) = AA(J)
      GO TO 71
   74 CONTINUE
      AA(J) = A(J)
      AB(J) = B(J)
      AC(J) = C(J)
      AD(J) = D(J)
   71 CONTINUE
   72 CONTINUE
      NO = I
      AA(NO) = XG(NO)*SA(NO)
      AB(NO) = XG(NO)*R(NO)*SB(NO)
```

```
      AC(NO) = (XG(NO)*(SA(NO) + DCOS(E(NO))))/R(NO)
      AD(NO) = AA(NO)
      CALL SUBB (AA,AB,AC,AD,B5)
      DRBP = DRBP + B5
   73 CONTINUE
   70 CONTINUE
      XSUM = XSUM + ((RA*D5)/DRBP)
      YSUM = YSUM + (RA/DRBP)
      ZSUM = ZSUM + (RA*(A5/DRBP))
      X1SUM = X1SUM + ((RA1*D5)/DRBP)
      Y1SUM = Y1SUM + (RA1/DRBP)
      Z1SUM = Z1SUM + ((RA1*A5)/DRBP)
      IF(((KN + 1)*RB(K)*DLT).GT.75.0)GO TO 66
      RA2 = ((1.D0-DEXP(RB(K)*DLT))**2)/(DLT*(RB(K)**2))
      RA3 = RA2*(DEXP(-(KN + 1)*DLT*RB(K)))
C      IF(RX(KN).LT.DABS(1.D-18))GO TO 86
      RX(KN + 1) = RX(KN + 1) + ((RA3*D5)/DRBP)
      RY(KN + 1) = RY(KN + 1) + (RA3/DRBP)
      RZ(KN + 1) = RZ(KN + 1) + ((RA3*A5)/DRBP)
C      WRITE(21,*)RX(KN + 1),RY(KN + 1),RZ(KN + 1)
C
      IF((DABS(RY(KN + 1))).LT.0.000001)GO TO 86
C
   60 CONTINUE
   66 CONTINUE
   86 CONTINUE
      IF(KN.GE.3)GO TO 134
      RX(1) = XSUM + U + ((DRD*U)/DLT)-((DRB*(U**2))/DLT)
      RY(1) = YSUM + U-((DRB*(U**2))/DLT)
      RZ(1) = ZSUM + U + ((DRA*U)/DLT)-((DRB*(U**2))/DLT)
      RX(2) = X1SUM-((DRD*U)/DLT) + ((DRB*(U**2))/DLT)
      RY(2) = Y1SUM + ((DRB*(U**2))/DLT)
      RZ(2) = Z1SUM-((DRA*U)/DLT) + ((DRB*(U**2))/DLT)
  134 CONTINUE
      KN = KN + 1
      IF(KN.LT.45)GO TO 132
      DO 112 I = 1,45
      IF(NPXYZ.EQ.1)GO TO 109
      WRITE(20,200)I,RX(I),RY(I),RZ(I)
  109 CC = CC + RX(I)
      CC1 = CC1 + RY(I)
      CC2 = CC2 + RZ(I)
  112 CONTINUE
      DIFFU = CC-CHKU
      DIFFU1 = CC1-CHKU
      DIFFU2 = CC2-CHKU
      JJO = 0
      IF(DABS(DIFFU).GT.0.0001)JJO = 1
      IF(DABS(DIFFU1).GT.0.0001)JJO = 1
      IF(DABS(DIFFU2).GT.0.0001)JJO = 1
C      IF(JJO.NE.1)GO TO 827
      WRITE(21,2)CHKU
    2 FORMAT(4X,' THE OVERALL HEAT TRANSFER COEFFICIENT IS = ',F15.10)
      WRITE(21,3)CC,CC1,CC2
    3 FORMAT(2X,' SUM X = ',F12.8,2X,' SUM Y = ',
     + F12.8,2X,' SUM Z = ',F12.8)
  827 CONTINUE
C     COX = RX(19)/RX(18)
C     COY = RY(19)/RY(18)
C     COZ = RZ(19)/RZ(18)
C     WRITE(21,*)COX,COY,COZ
      RFX(1,1) = RX(1)
      RFY(1,1) = RY(1)
      RFZ(1,1) = RZ(1)
C
      AC1 = DEXP(-(DLT*RB(1)))
      AC2 = DEXP(-(DLT*RB(2)))
      AC3 = DEXP(-(DLT*RB(3)))
      AC4 = DEXP(-(DLT*RB(4)))
      IF(DABS(RB(5)).GT.50.0)AC5 = 0.0
      IF(DABS(RB(5)).GT.50.0)GO TO 499
      AC5 = DEXP(-(DLT*RB(5)))
```

```
  499 CONTINUE
C
      IF(DABS(AC2).LT.0.0000001)AC2=0.0
      IF(DABS(AC3).LT.0.0000001)AC3=0.0
      IF(DABS(AC4).LT.0.0000001)AC4=0.0
      IF(DABS(AC5).LT.0.0000001)AC5=0.0
C      WRITE(20,*)AC1,AC2,AC3,AC4,AC5
      DO 300 I=2,45
      RFX(1,I)=RX(I)-(AC1*RX(I-1))
      RFY(1,I)=RY(I)-(AC1*RY(I-1))
      RFZ(1,I)=RZ(I)-(AC1*RZ(I-1))
  300 CONTINUE
C     COR1=RFX(1,10)/RFX(1,9)
      RFX(2,1)=RFX(1,1)
      RFY(2,1)=RFY(1,1)
      RFZ(2,1)=RFZ(1,1)
      DO 302 I=2,45
      RFX(2,I)=RFX(1,I)-(AC2*RFX(1,I-1))
      RFY(2,I)=RFY(1,I)-(AC2*RFY(1,I-1))
      RFZ(2,I)=RFZ(1,I)-(AC2*RFZ(1,I-1))
  302 CONTINUE
C     COR2=RFX(2,19)/RFX(2,18)
      RFX(3,1)=RFX(2,1)
      RFY(3,1)=RFY(2,1)
      RFZ(3,1)=RFZ(2,1)
      DO 304 I=2,45
      RFX(3,I)=RFX(2,I)-(AC3*RFX(2,I-1))
      RFY(3,I)=RFY(2,I)-(AC3*RFY(2,I-1))
      RFZ(3,I)=RFZ(2,I)-(AC3*RFZ(2,I-1))
  304 CONTINUE
C     COR3=RFX(3,19)/RFX(3,18)
      RFX(4,1)=RFX(3,1)
      RFY(4,1)=RFY(3,1)
      RFZ(4,1)=RFZ(3,1)
      DO 306 I=2,45
      RFX(4,I)=RFX(3,I)-(AC4*RFX(3,I-1))
      RFY(4,I)=RFY(3,I)-(AC4*RFY(3,I-1))
      RFZ(4,I)=RFZ(3,I)-(AC4*RFZ(3,I-1))
  306 CONTINUE
C     COR4=RFX(4,19)/RFX(4,18)
      RFX(5,1)=RFX(4,1)
      RFY(5,1)=RFY(4,1)
      RFZ(5,1)=RFZ(4,1)
      DO 308 I=2,45
      RFX(5,I)=RFX(4,I)-(AC5*RFX(4,I-1))
      RFY(5,I)=RFY(4,I)-(AC5*RFY(4,I-1))
      RFZ(5,I)=RFZ(4,I)-(AC5*RFZ(4,I-1))
  308 CONTINUE
C     COR5=RFX(5,19)/RFX(5,18)
C     WRITE(21,*)COR1,COR2,COR3,COR4,COR5
      IF(NPHORF.EQ.1)GO TO 330
      ST1=0.0
      ST2=0.0
      ST3=0.0
      ST4=0.0
      ST5=0.0
      DO 310 I=1,45
      WRITE(20,210)I,RX(I),RFX(1,I),RFX(2,I),RFX(3,I),RFX(4,I),RFX(5,I)
      ST1=ST1+RFX(1,I)
      ST2=ST2+RFX(2,I)
      ST3=ST3+RFX(3,I)
      ST4=ST4+RFX(4,I)
      ST5=ST5+RFX(5,I)
  310 CONTINUE
      WRITE(20,*)ST1,ST2,ST3,ST4,ST5
      ST1=0.0
      ST2=0.0
      ST3=0.0
      ST4=0.0
      ST5=0.0
      DO 312 I=1,45
      WRITE(20,210)I,RY(I),RFY(1,I),RFY(2,I),RFY(3,I),RFY(4,I),RFY(5,I)
```

```
      ST1 = ST1 + RFX(1,I)
      ST2 = ST2 + RFX(2,I)
      ST3 = ST3 + RFX(3,I)
      ST4 = ST4 + RFX(4,I)
      ST5 = ST5 + RFX(5,I)
  312 CONTINUE
      WRITE(20,*)ST1,ST2,ST3,ST4,ST5
      ST1 = 0.0
      ST2 = 0.0
      ST3 = 0.0
      ST4 = 0.0
      ST5 = 0.0
      DO 314 I = 1,45
      WRITE(20,210)I,RZ(I),RFZ(1,I),RFZ(2,I),RFZ(3,I),RFZ(4,I),RFZ(5,I)
      ST1 = ST1 + RFX(1,I)
      ST2 = ST2 + RFX(2,I)
      ST3 = ST3 + RFX(3,I)
      ST4 = ST4 + RFX(4,I)
      ST5 = ST5 + RFX(5,I)
  314 CONTINUE
      WRITE(20,*)ST1,ST2,ST3,ST4,ST5
  210 FORMAT(I3,6F12.9)
  330 CONTINUE
      IF(NPXYZ.EQ.1)GO TO 332
  200 FORMAT(1I3,3F20.11)
  332 CONTINUE
C     WRITE(21,*)DEXP(-(RB(1)**2)*DLT) !!!! THIS IS NOT CORRECT FOR 'CR'
C     WRITE(21,*)DEXP(-RB(1)*DLT) !!!!!   THIS IS THE CORREST ONE
C     WRITE(21,*)RX(88)/RX(87)
C     WRITE(21,*)RY(88)/RY(87)
C     WRITE(21,*)RZ(88)/RZ(87)
C
C
C             CALCULATIONS OF THE J'S
C
C
CCC   IF(KNPP.EQ.0)GO TO 430
      K = KRFO
      KK = K + 1
      RR(1) = AC1
      RR(2) = AC2
      RR(3) = AC3
      RR(4) = AC4
      RR(5) = AC5
      IF(K.EQ.5)GO TO 420
      DO 410 J = KK,5
      RR(J) = 0.0
  410 CONTINUE
  420 CONTINUE
      XJ(1) = RR(1) + RR(2) + RR(3) + RR(4) + RR(5)
      XJ(2) = RR(1)*(RR(2) + RR(3) + RR(4) + RR(5)) + RR(2)*(RR(3) + RR(4) + RR(5))
     X + RR(3)*(RR(4) + RR(5)) + RR(4)*RR(5)
      XJ(3) = RR(1)*RR(2)*(RR(3) + RR(4) + RR(5)) + RR(1)*RR(3)*(RR(4) + RR(5))
     X + RR(1)*RR(4)*RR(5) + RR(2)*RR(3)*(RR(4) + RR(5))
     X + RR(4)*RR(5)*(RR(2) + RR(3))
      XJ(4) = RR(1)*RR(2)*(RR(3)*RR(4) + RR(3)*RR(5) + RR(4)*RR(5))
     X + RR(3)*RR(4)*RR(5)*(RR(1) + RR(2))
      XJ(5) = RR(1)*RR(2)*RR(3)*RR(4)*RR(5)
C     WRITE(20,5)RR(1),RR(2),RR(3),RR(4),RR(5)
C     WRITE(20,5)XJ(1),XJ(2),XJ(3),XJ(4),XJ(5)
C 5   FORMAT(5F13.10)
  430 CONTINUE
      RETURN
      END
C     ***************************************************************
C        SUBROUTINE SUBA  :  CALCULATES 'A' FOR N UP TO 6 LAYERS
C     ***************************************************************
      SUBROUTINE SUBA (A,B,C,D,XA)
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION A(6),B(6),C(6),D(6)
      XA = A(1)*A(2)*A(3)*A(4)*A(5)*A(6) + B(1)*C(2)*A(3)*A(4)*A(5)*A(6)
      XA = XA + A(1)*B(2)*C(3)*A(4)*A(5)*A(6) + B(1)*D(2)*C(3)*A(4)*A(5)*A(6)
```

```
      XA = XA + A(1)*A(2)*B(3)*C(4)*A(5)*A(6) + B(1)*C(2)*B(3)*C(4)*A(5)*A(6)
      XA = XA + A(1)*B(2)*D(3)*C(4)*A(5)*A(6) + B(1)*D(2)*D(3)*C(4)*A(5)*A(6)
      XA = XA + A(1)*A(2)*A(3)*B(4)*C(5)*A(6) + B(1)*C(2)*A(3)*B(4)*C(5)*A(6)
      XA = XA + A(1)*B(2)*C(3)*B(4)*C(5)*A(6) + B(1)*D(2)*C(3)*B(4)*C(5)*A(6)
      XA = XA + A(1)*A(2)*B(3)*D(4)*C(5)*A(6) + B(1)*C(2)*B(3)*D(4)*C(5)*A(6)
      XA = XA + A(1)*B(2)*D(3)*D(4)*C(5)*A(6) + B(1)*D(2)*D(3)*D(4)*C(5)*A(6)
      XA = XA + A(1)*A(2)*A(3)*A(4)*B(5)*C(6) + B(1)*C(2)*A(3)*A(4)*B(5)*C(6)
      XA = XA + A(1)*B(2)*C(3)*A(4)*B(5)*C(6) + B(1)*D(2)*C(3)*A(4)*B(5)*C(6)
      XA = XA + A(1)*A(2)*B(3)*C(4)*B(5)*C(6) + B(1)*C(2)*B(3)*C(4)*B(5)*C(6)
      XA = XA + A(1)*B(2)*D(3)*C(4)*B(5)*C(6) + B(1)*D(2)*D(3)*C(4)*B(5)*C(6)
      XA = XA + A(1)*A(2)*A(3)*B(4)*D(5)*C(6) + B(1)*C(2)*A(3)*B(4)*D(5)*C(6)
      XA = XA + A(1)*B(2)*C(3)*B(4)*D(5)*C(6) + B(1)*D(2)*C(3)*B(4)*D(5)*C(6)
      XA = XA + A(1)*A(2)*B(3)*D(4)*D(5)*C(6) + B(1)*C(2)*B(3)*D(4)*D(5)*C(6)
      XA = XA + A(1)*B(2)*D(3)*D(4)*D(5)*C(6) + B(1)*D(2)*D(3)*D(4)*D(5)*C(6)
      RETURN
      END
C     ****************************************************************
C       SUBROUTINE SUBB  :  CALCULATES 'B' FOR N UP TO 6 LAYERS
C     ****************************************************************
      SUBROUTINE SUBB (A,B,C,D,XB)
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION A(6),B(6),C(6),D(6)
      XB = A(1)*A(2)*A(3)*A(4)*A(5)*B(6) + B(1)*C(2)*A(3)*A(4)*A(5)*B(6)
      XB = XB + A(1)*B(2)*C(3)*A(4)*A(5)*B(6) + B(1)*D(2)*C(3)*A(4)*A(5)*B(6)
      XB = XB + A(1)*A(2)*B(3)*C(4)*A(5)*B(6) + B(1)*C(2)*B(3)*C(4)*A(5)*B(6)
      XB = XB + A(1)*B(2)*D(3)*C(4)*A(5)*B(6) + B(1)*D(2)*D(3)*C(4)*A(5)*B(6)
      XB = XB + A(1)*A(2)*A(3)*B(4)*C(5)*B(6) + B(1)*C(2)*A(3)*B(4)*C(5)*B(6)
      XB = XB + A(1)*B(2)*C(3)*B(4)*C(5)*B(6) + B(1)*D(2)*C(3)*B(4)*C(5)*B(6)
      XB = XB + A(1)*A(2)*B(3)*D(4)*C(5)*B(6) + B(1)*C(2)*B(3)*D(4)*C(5)*B(6)
      XB = XB + A(1)*B(2)*D(3)*D(4)*C(5)*B(6) + B(1)*D(2)*D(3)*D(4)*C(5)*B(6)
      XB = XB + A(1)*A(2)*A(3)*A(4)*B(5)*D(6) + B(1)*C(2)*A(3)*A(4)*B(5)*D(6)
      XB = XB + A(1)*B(2)*C(3)*A(4)*B(5)*D(6) + B(1)*D(2)*C(3)*A(4)*B(5)*D(6)
      XB = XB + A(1)*A(2)*B(3)*C(4)*B(5)*D(6) + B(1)*C(2)*B(3)*C(4)*B(5)*D(6)
      XB = XB + A(1)*B(2)*D(3)*C(4)*B(5)*D(6) + B(1)*D(2)*D(3)*C(4)*B(5)*D(6)
      XB = XB + A(1)*A(2)*A(3)*B(4)*D(5)*D(6) + B(1)*C(2)*A(3)*B(4)*D(5)*D(6)
      XB = XB + A(1)*B(2)*C(3)*B(4)*D(5)*D(6) + B(1)*D(2)*C(3)*B(4)*D(5)*D(6)
      XB = XB + A(1)*A(2)*B(3)*D(4)*D(5)*D(6) + B(1)*C(2)*B(3)*D(4)*D(5)*D(6)
      XB = XB + A(1)*B(2)*D(3)*D(4)*D(5)*D(6) + B(1)*D(2)*D(3)*D(4)*D(5)*D(6)
      RETURN
      END
C     ****************************************************************
C       SUBROUTINE SUBC  :  CALCULATES 'C' FOR N UP TO 6 LAYERS
C     ****************************************************************
      SUBROUTINE SUBC (A,B,C,D,XC)
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION A(6),B(6),C(6),D(6)
      XC = C(1)*A(2)*A(3)*A(4)*A(5)*A(6) + D(1)*C(2)*A(3)*A(4)*A(5)*A(6)
      XC = XC + C(1)*B(2)*C(3)*A(4)*A(5)*A(6) + D(1)*D(2)*C(3)*A(4)*A(5)*A(6)
      XC = XC + C(1)*A(2)*B(3)*C(4)*A(5)*A(6) + D(1)*C(2)*B(3)*C(4)*A(5)*A(6)
      XC = XC + C(1)*B(2)*D(3)*C(4)*A(5)*A(6) + D(1)*D(2)*D(3)*C(4)*A(5)*A(6)
      XC = XC + C(1)*A(2)*A(3)*B(4)*C(5)*A(6) + D(1)*C(2)*A(3)*B(4)*C(5)*A(6)
      XC = XC + C(1)*B(2)*C(3)*B(4)*C(5)*A(6) + D(1)*D(2)*C(3)*B(4)*C(5)*A(6)
      XC = XC + C(1)*A(2)*B(3)*D(4)*C(5)*A(6) + D(1)*C(2)*B(3)*D(4)*C(5)*A(6)
      XC = XC + C(1)*B(2)*D(3)*D(4)*C(5)*A(6) + D(1)*D(2)*D(3)*D(4)*C(5)*A(6)
      XC = XC + C(1)*A(2)*A(3)*A(4)*B(5)*C(6) + D(1)*C(2)*A(3)*A(4)*B(5)*C(6)
      XC = XC + C(1)*B(2)*C(3)*A(4)*B(5)*C(6) + D(1)*D(2)*C(3)*A(4)*B(5)*C(6)
      XC = XC + C(1)*A(2)*B(3)*C(4)*B(5)*C(6) + D(1)*C(2)*B(3)*C(4)*B(5)*C(6)
      XC = XC + C(1)*B(2)*D(3)*C(4)*B(5)*C(6) + D(1)*D(2)*D(3)*C(4)*B(5)*C(6)
      XC = XC + C(1)*A(2)*A(3)*B(4)*D(5)*C(6) + D(1)*C(2)*A(3)*B(4)*D(5)*C(6)
      XC = XC + C(1)*B(2)*C(3)*B(4)*D(5)*C(6) + D(1)*D(2)*C(3)*B(4)*D(5)*C(6)
      XC = XC + C(1)*A(2)*B(3)*D(4)*D(5)*C(6) + D(1)*C(2)*B(3)*D(4)*D(5)*C(6)
      XC = XC + C(1)*B(2)*D(3)*D(4)*D(5)*C(6) + D(1)*D(2)*D(3)*D(4)*D(5)*C(6)
      RETURN
      END
C     ****************************************************************
C       SUBROUTINE SUBD  :  CALCULATES 'D' FOR N UP TO 6 LAYERS
C     ****************************************************************
      SUBROUTINE SUBD (A,B,C,D,XD)
      IMPLICIT REAL*8 (A-G,O-Z)
      DIMENSION A(6),B(6),C(6),D(6)
      XD = C(1)*A(2)*A(3)*A(4)*A(5)*B(6) + D(1)*C(2)*A(3)*A(4)*A(5)*B(6)
      XD = XD + C(1)*B(2)*C(3)*A(4)*A(5)*B(6) + D(1)*D(2)*C(3)*A(4)*A(5)*B(6)
```

```
XD=XD+C(1)*A(2)*B(3)*C(4)*A(5)*B(6)+D(1)*C(2)*B(3)*C(4)*A(5)*B(6)
XD=XD+C(1)*B(2)*D(3)*C(4)*A(5)*B(6)+D(1)*D(2)*D(3)*C(4)*A(5)*B(6)
XD=XD+C(1)*A(2)*A(3)*B(4)*C(5)*B(6)+D(1)*C(2)*A(3)*B(4)*C(5)*B(6)
XD=XD+C(1)*B(2)*C(3)*B(4)*C(5)*B(6)+D(1)*D(2)*C(3)*B(4)*C(5)*B(6)
XD=XD+C(1)*A(2)*B(3)*D(4)*C(5)*B(6)+D(1)*C(2)*B(3)*D(4)*C(5)*B(6)
XD=XD+C(1)*B(2)*D(3)*D(4)*C(5)*B(6)+D(1)*D(2)*D(3)*D(4)*C(5)*B(6)
XD=XD+C(1)*A(2)*A(3)*A(4)*B(5)*D(6)+D(1)*C(2)*A(3)*A(4)*B(5)*D(6)
XD=XD+C(1)*B(2)*C(3)*A(4)*B(5)*D(6)+D(1)*D(2)*C(3)*A(4)*B(5)*D(6)
XD=XD+C(1)*A(2)*B(3)*C(4)*B(5)*D(6)+D(1)*C(2)*B(3)*C(4)*B(5)*D(6)
XD=XD+C(1)*B(2)*D(3)*C(4)*B(5)*D(6)+D(1)*D(2)*D(3)*C(4)*B(5)*D(6)
XD=XD+C(1)*A(2)*A(3)*B(4)*D(5)*D(6)+D(1)*C(2)*A(3)*B(4)*D(5)*D(6)
XD=XD+C(1)*B(2)*C(3)*B(4)*D(5)*D(6)+D(1)*D(2)*C(3)*B(4)*D(5)*D(6)
XD=XD+C(1)*A(2)*B(3)*D(4)*D(5)*D(6)+D(1)*C(2)*B(3)*D(4)*D(5)*D(6)
XD=XD+C(1)*B(2)*D(3)*D(4)*D(5)*D(6)+D(1)*D(2)*D(3)*D(4)*D(5)*D(6)
RETURN
END
```

A.3 Example Output

```
  THE OVERALL HEAT TRANSFER COEFFICIENT IS =    0.0815798960
SUM X =   0.08157990   SUM Y =   0.08157990   SUM Z =   0.08157990


         X                  Y                  Z
  ----------------   ----------------   ----------------
   0.50879273577      0.04065388416      0.50879273577
  -0.42941305239      0.04003985229     -0.42941305239
   0.00173821448      0.00042404932      0.00173821448
  -0.00000008007      0.00000003202     -0.00000008007
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000
   0.00000000000      0.00000000000      0.00000000000

         J
  ----------------
   0.00566461836
   0.00000050026
   0.00000000000
   0.00000000000
   0.00000000000
```

Appendix B. FAILURE Model

B.1 Example Input Files

The failure model requires five input files. These were set to accommodate the data collection system used for validation. The files include: the general input file, the transfer function file, the ambient input file, the solar input file, and the nursery input file. The data files are shortened samples of the actual data files.

B.1.1 General Input File

```
362.   1120.      DAY AND TIME OF FAILURE
17.9              CRUDE PROTEIN (%)
85.0              DIGESTIBLE C P (%)
65.0              C P BIOLOGICAL VALUE (%)
14.2              DIGESTIBLE ENERGY (KJ/G)
10.0              NET ENERGY (KJ/G)
0.95              LYSINE (%)
0.23              TRYPTOPHAN (%)
0.706             THREONINE (%)
0.10              COST ($/KG)
4.0               FEED WASTAGE (%)
2                 PELLETED (1=YES)
2                 ANTIBIOTICS (1=YES)
2                 GILTS/PEN
115.0             MAXIMUM PROTEIN DEPOSITION (G/DAY)
2                 BARROWS/PEN
105.0             MAXIMUM PROTEIN DEPOSITION (G/DAY)
0                 BOARS/PEN
130.0             MAXIMUM PROTEIN DEPOSTION (G/DAY)
20.0              INSIDE TEMPERATURE (C)
0.15              AIR MOVEMENT (M/S)
2.                FLOOR TYPE
0.28              FLOOR SPACE/PIG
20.8              INITIAL WEIGHT (KG)
66.               INITIAL AGE (DAYS)
```

```
47.                NUMBER OF PIGS
0.0075   1.5       EFFECTIVE LEAKAGE (M2) AND WIND VELOCITY (M/S)
```

B.1.2 Transfer Function File

```
6  3  15                   NURSERY 1
 1             WALL 1 SINGLE COMPONENT
   2.10290231394     0.00010764004     2.10290231394
  -3.22334727288     0.00804191882    -3.22334727288
   1.31538927813     0.01899940047     1.31538927813
  -0.16715894679     0.00556243444    -0.16715894679
   0.00515001186     0.00022400671     0.00515001186
   0.00000166754     0.00000165133     0.00000166754
   0.00000000869     0.00000000869     0.00000000869
   0.00000000005     0.00000000005     0.00000000005
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
  -0.00000000000     0.00000000000    -0.00000000000
   0.00000000000    -0.00000000000     0.00000000000
   0.00000000000    -0.00000000000     0.00000000000
   0.74826790768
   0.16235496355
   0.01034713733
13.34   15.0   20.0  0.9  0.4
 2                     WALL 2 DOUBLE COMPONENTS
   0.33205883958     0.00002221871     5.77779653965
  -0.51842488510     0.00285403000   -10.73313754696
   0.23913272417     0.00937042673     5.86783541686
  -0.03809098343     0.00365627867    -0.92168473073
   0.00141600943     0.00018752061     0.02526188344
   0.00000019475     0.00000141982     0.00002026839
   0.00000000041     0.00000000526     0.00000006892
   0.00000000000     0.00000000002     0.00000000024
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   1.27186317124
   0.36707377684
   0.01632419290
   5.77779653898     0.00000000409     5.77779653898
 -13.49657765803     0.00008670935   -13.49657765803
  10.78337335629     0.00280100145    10.78337335629
  -3.35332018875     0.00957521412    -3.35332018875
   0.30585819936     0.00751903728     0.30585819936
   0.00483114935     0.00207346512     0.00483114935
   0.00041176219     0.00032090152     0.00041176219
   0.00004321954     0.00004015322     0.00004321954
   0.00000481818     0.00000471461     0.00000481818
   0.00000054691     0.00000054341     0.00000054691
   0.00000006241     0.00000006230     0.00000006241
   0.00000000713     0.00000000713     0.00000000713
   0.00000000082     0.00000000082     0.00000000082
   0.00000000009     0.00000000009     0.00000000009
   0.00000000001     0.00000000001     0.00000000001
   1.75015211044
   0.93750796781
   0.14998616653
13.34   5.  0.9   0.4
 1                   WALL 3 SINGLE COMPONENT
   7.47577046421     0.00000065348     7.47577046421
 -15.67013169956     0.00148511985   -15.67013169956
  10.81159580842     0.01911847335    10.81159580842
  -2.74964621700     0.03029088966    -2.74964621700
```

```
    0.19306957589     0.01035520222     0.19306957589
    0.00172351787     0.00113731008     0.00172351787
    0.00007910116     0.00007296766     0.00007910116
    0.00000415638     0.00000409176     0.00000415638
    0.00000022415     0.00000022347     0.00000022415
    0.00000001215     0.00000001214     0.00000001215
    0.00000000066     0.00000000066     0.00000000066
    0.00000000004     0.00000000004     0.00000000004
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    1.51033619949
    0.65786012149
    0.07811495800
8.55  5.0  0.9  0.4
2                 WALL 4 DOUBLE COMPONENT
    5.77779653919     0.00000994645     5.77779653919
  -11.02683712647     0.00554144006   -11.02683712647
    6.63759635391     0.03828668124     6.63759635391
   -1.37771657069     0.03375028311    -1.37771657069
    0.07240017231     0.00572023593     0.07240017231
    0.00034000080     0.00027100756     0.00034000080
    0.00000788879     0.00000766424     0.00000788879
    0.00000019960     0.00000019887     0.00000019960
    0.00000000511     0.00000000510     0.00000000511
    0.00000000013     0.00000000013     0.00000000013
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    1.32269840638
    0.47036848960
    0.04050666952
    5.77779653919     0.00000994645     5.77779653919
  -11.02683712647     0.00554144006   -11.02683712647
    6.63759635391     0.03828668124     6.63759635391
   -1.37771657069     0.03375028311    -1.37771657069
    0.07240017231     0.00572023593     0.07240017231
    0.00034000080     0.00027100756     0.00034000080
    0.00000788879     0.00000766424     0.00000788879
    0.00000019960     0.00000019887     0.00000019960
    0.00000000511     0.00000000510     0.00000000511
    0.00000000013     0.00000000013     0.00000000013
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    1.32269840638
    0.47036848960
    0.04050666952
10.61  5.0  0.9    0.4
1                 WALL 6 SINGLE COMPONENT
    3.70175538010     0.00000004413     0.41298827416
   -8.37737119808     0.00011684875    -0.81988163365
    6.30005879426     0.00159798232     0.53166198468
   -1.76088098602     0.00271987007    -0.12818195554
    0.14161726083     0.00106305865     0.00897090427
    0.00044734949     0.00015056509     0.00009890776
    0.00003384683     0.00001377643     0.00000636830
    0.00000270051     0.00000113867     0.00000049176
    0.00000021755     0.00000009234     0.00000003937
    0.00000001756     0.00000000746     0.00000000317
    0.00000000142     0.00000000060     0.00000000026
    0.00000000011     0.00000000005     0.00000000002
    0.00000000001     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    0.00000000000     0.00000000000     0.00000000000
    1.39945548093
    0.56394775236
    0.06501781179
```

```
16.84  5.0  0.9   0.4
 2                    WALL 7 (SLAB) DOUBLE COMPONENT
    13.53074208212     -0.00000000105     9.58132554151
   -36.00679031903      0.00000071843   -25.49695860420
    33.83417223672      0.00013891366    23.95857048381
   -12.87316876733      0.00165573542    -9.11502997910
     1.48424843553      0.00423563664     1.05234246878
     0.03694126970      0.00383960425     0.02715568793
     0.00510346121      0.00180582806     0.00403107676
     0.00097682439      0.00060253652     0.00082304143
     0.00021832617      0.00017227904     0.00019119357
     0.00005250614      0.00004611519     0.00004686735
     0.00001305100      0.00001200347     0.00001175112
     0.00000329118      0.00000308748     0.00000297471
     0.00000083516      0.00000079013     0.00000075610
     0.00000021250      0.00000020177     0.00000019252
     0.00000005413      0.00000005148     0.00000004906
     2.07532329176
     1.38122814227
     0.29236209553
     9.58132553338      0.00000000614     9.58132553338
   -26.32299794356      0.00000006493   -26.32299794356
    25.69525333871      0.00003087242    25.69525333871
   -10.23205533168      0.00054267590   -10.23205533168
     1.24348877146      0.00193557903     1.24348877146
     0.03513399323      0.00239461962     0.03513399323
     0.00556618537      0.00149008056     0.00556618537
     0.00121017665      0.00062976013     0.00121017665
     0.00030409417      0.00021961130     0.00030409417
     0.00008222206      0.00006988194     0.00008222206
     0.00002308780      0.00002128432     0.00002308780
     0.00000661012      0.00000634653     0.00000661012
     0.00000191132      0.00000187279     0.00000191132
     0.00000055543      0.00000054980     0.00000055543
     0.00000016182      0.00000016099     0.00000016182
     2.16153676463
     1.51198308727
     0.34065018311
13.29  22.  0.0  0.4
1  1   0
```

B.1.3 Ambient Input File

```
DAY  TIME    NUR1    NUR2    HALL    ATTIC     G/F     OUT    TOWB    TODB
            DEG C   DEG C   DEG C   DEG C   DEG C   DEG C   DEG C   DEG C
--------------------------------------------------------------------------
361  1000   23.48   20.49   5.538   2.231   10.59   3.891    .554   1.618
361  1010   22.41   20.23    5.81   2.722   11.38   4.035    .956   2.083
361  1020   22.94   21.19   6.391   3.293   12.17   4.498   1.419   2.623
361  1030    23.7   19.95   6.738   3.776   10.55   4.884   1.871   3.133
361  1040   22.52   20.92   6.807   4.404   12.52   5.672   2.393    3.75
361  1050   22.23   21.15    7.17   5.167   10.84   6.432   2.861   4.389
361  1100   23.33   19.93    7.49   5.546   12.53   6.656   3.374   4.986
361  1110   22.96   21.24    7.05   6.047   11.91   6.959   3.883    5.39
361  1120   22.97    19.9    8.02   6.757   11.53   6.582   4.364   6.118
361  1130   22.73   21.05    8.19    7.43   11.95    5.96   4.853   6.864
361  1140   23.14   20.26    7.54    8.08   10.98    7.49   5.327    7.34
361  1150   23.57   21.31   6.897     8.4   12.45       8   5.616    7.53
361  1200   23.11    19.8    7.49    9.11   12.89    7.96   6.149    8.19
```

B.1.4 Solar Input File

DAY	TIME	SKY RAD KW/M2	TOTAL RAD KW/M2	NORMAL RAD KW/M2
361	1000	.229	.366	.803
361	1010	.228	.382	.831
361	1020	.231	.411	.843
361	1030	.232	.429	.851
361	1040	.237	.445	.861
361	1050	.24	.459	.867
361	1100	.242	.472	.873
361	1110	.241	.484	.877
361	1120	.245	.495	.886
361	1130	.246	.502	.884
361	1140	.25	.517	.897
361	1150	.25	.522	.893
361	1200	.245	.466	.763

B.1.5 Nursery Input File

DAY	TIME	TBGI DEG C	TBGE DEG C	FURN DEG C	FAN T DEG C	INLET DEG C	TWB DEG C	TDB DEG C
361	1000	23.04	23.48	106.1	27.36	5.719	9.2	12.62
361	1010	22.65	22.41	80.7	24.99	5.946	9.26	12.67
361	1020	23.05	22.94	83.7	25.38	6.312	9.35	12.89
361	1030	23.29	23.7	98.3	27.23	6.565	9.39	12.99
361	1040	22.62	22.52	86.3	25.55	6.672	9.34	12.93
361	1050	22.69	22.23	70.9	24.24	6.931	9.8	13.56
361	1100	23.06	23.33	84.5	26.26	7.23	10	13.74
361	1110	22.73	22.96	98.8	26.58	6.859	9.61	13.34
361	1120	22.97	22.97	73.7	24.58	7.87	10.15	14.16
361	1130	23	22.73	68.69	24.27	8.18	10.64	14.71
361	1140	23.18	23.14	77.8	24.91	7.55	10.6	14.46
361	1150	23.16	23.57	96	26.63	6.967	10.01	13.91
361	1200	23.06	23.11	86.3	24.89	7.72	10.48	14.69

TBGI = INTERNAL TEMPERATURE OF THE BLACK GLOBE (NOT USED)
TBGE = EXTERNAL TEMPERATURE OF THE BLACK GLOBE
FURN = FURNACE EXIT TEMPERATURE
FAN T = TEMPERATURE NEAR THE FAN CONTROLLER
INLET = TEMPERATURE OF THE INLET AIR
TWB = WET BULB TEMPERATURE OF THE NURSERY
TDB = DRY BULB TEMPERATURE OF THE NURSERY

B.2 Program Code

```
C ****************************************************
C
C      THIS PROGRAM SIMULATES A POWER FAILURE
C            IN A SWINE NURSERY
C
C
C           IT WAS DEVELOPED
C               BY
C           JAY DAVID HARMON
C
C          UNDER THE DIRECTION
C               OF
C         ELDRIDGE R. COLLINS, JR.
C
C             JUNE, 1989
C
C ****************************************************
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      COMMON /INFILT/ DAILY(18),WO(1000),WI(1000),PIGS,QI,QCNDSD
     $ ,QANIM,QINF
      COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(1000),TOLER,NURSNO
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/ONE/IFI,IDAY,IAGE,ICOMP
C
C ****************************************************
C
C             INPUT FILES
C
C ****************************************************
C
C     INPUT FILE NO. 1
C       CONTAINS RESPONSE FACTORS AND WALL
C       CHARACTERISTICS
C
C        NMWALL, K, NRF
C           NMWALL: NUMBER OF CONDUCTION UNITS
C           K: NUMBER OF FLUX FACTORS
C           NRF: NUMBER OF TEMPERATURE RESPONSE FACTORS
C R     II  NUMBER OF CALCULATION COMPONENTS (1 OR 2)  II
C E      I  X(1),Y(1),Z(1)     IN BTU/HR-FT2-F         I
C P      I  X(2),Y(2),Z(2)                       I
C E      I    .,.,.                         I
C A  T   I     .,.,.                         I
C T  I   I  X(NRF),Y(NRF),Z(NRF)                     I
C S  M   I   J(1)                             I
C    E   I  J(2)                             I
C N  S   I   .                               I
C M      I   J(K)                             I
C W      I  AREA,TA,TR,EMISS,ABSORP (FOR FIRST TIME)    I
C A     II  AREA,EMISS,ABSORP (OTHER TIMES)            II
C L          AREA: WALL AREA (M2)
C L          TA: OUTSIDE TEMPERATURE FOR INITIALIZATION (C)
C           TR: ROOM TEMPERATURE FOR INITIALIZATION (C)
C           EMISS: WALL EMISSIVITY
C           ABSORP: WALL ABSORPTIVITY
C
C      FOR THE LAST WALL:
C      NURSERY NO., DIRN, DIRE
C        DIRN: WIND DIRECTION (1=NORTH, O=SOUTH)
C        DIRE: WIND DIRECTION (1=EAST, 0=WEST)
C
C ****************************************************
C
C     INPUT FILE NO. 2
```

```
C       CONTAINS AMBIENT DATA
C
C      DAY, TIME, RNURS1, RNURS2, AHALL, ATTIC
C       FINISH, AMBT, ATWB, ATDB
C
C       DAY: JULIAN DAY
C       TIME: MILITARY TIME
C       RNURS1: TEMPERATURE OF NURSERY 1 (C)
C       RNURS2: TEMPERATURE OF NURSERY 2 (C)
C       AHALL: HALLWAY TEMPERATURE (C)
C       ATTIC: ATTIC TEMPERATURE (C)
C       FINISH: GROWER/FINISHER TEMPERATURE (C)
C       AMBT: AMBIENT OUTDOOR TEMPERATURE (C)
C       ATWB: AMBIENT WET BULB (C)
C       ATDB: AMBIENT DRY BULB (C)
C
C
C **************************************************
C
C      INPUT FILE NO. 3
C       CONTAINS SOLAR INPUT
C
C      DAY, TIME, GSKY, G, GBN
C       DAY: JULIAN DAY
C       TIME: MILITARY TIME
C       GSKY: RADIATION FROM A PYHRGEOMETER (W/M2)
C       G: RADIATION FROM A HORIZONTAL PYRANOMETER (W/M2)
C       GBN: RADIATION FROM A PYRHELIOMETER (W/M2)
C
C
C **************************************************
C
C      INPUT FILE NO. 4
C       CONTAINS GENERAL INFORMATION FOR THE MODEL
C
C      FAILDAY, FAILTIME
C         FAILDAY: DAY OF FAILURE (JULIAN DAY)
C         FAILTIME: TIME OF FAILURE (MILITARY)
C      CRUDE PROTEIN OF THE DIET (%)
C      DIGESTIBLE CRUDE PROTEIN (%)
C      CRUDE PROTEIN BIOLOGICAL VALUE (%)
C      DIGESTIBLE ENERGY (KJ/G)
C      NET ENERGY (KJ/G)
C      LYSINE (%)
C      TRYPTOPHAN (%)
C      THREONINE (%)
C      FEED COST ($/KG)
C      FEED WASTAGE (%)
C      PELLETED (1=YES)
C      ANTIBIOTICS (1=YES)
C      GILTS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      BARROWS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      BOARS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      INSIDE TEMPERATURE (C)
C      INTERIOR AIR MOVEMENT (M/S)
C      FLOOR TYPE (1=CONCRETE, 2=SLATS)
C      FLOOR SPACE/PIG (M2)
C      INITIAL WEIGHT (KG)
C      INITIAL AGE (DAYS)
C      NUMBER OF PIGS
C      LEAKAGE AREA (M2) AND WIND VELOCITY (M/S)
C
C **************************************************
C
C      INPUT FILE NO. 10
C       CONTAINS ACTUAL NURSERY CONDITIONS
C
C      DAY, TIME, X3, X4, X5, X6, X7, RNTWB, RNTDB
C       DAY: JULIAN DAY
```

```
C       TIME: MILITARY TIME
C       X3..X7: UNNEEDED INPUTS
C       RNTWB: NURSERY WET BULB (C)
C       RNTDB: NURSERY DRY BULB (C)
C
C **************************************************
C
C
C  SET THE TOLERANCE FOR THE TEMPERATURE ITERATION AND THE
C   TIME STEP LENGTH (IN SECONDS)
C
      TOLER=0.01
      STEP=600.
      FAILSTEP=-999.
      IAGE=0
C
C  READ IN THE DAY AND TIME OF THE POWER FAILURE
C
      READ(4,*) FAILDAY,FAILTIME
C
C  READ IN THE INFORMATION THAT PERTAINS TO THE FEED, PHYSIOLOGICAL
C   AND HOUSE CHARACTERISTICS AT THE TIME OF THE FAILURE
C
      DO 22 I=1,12
        READ(4,*) FEED(I)
   22 CONTINUE
      DO 23 I=1,6
        READ(4,*) PHYS(I)
   23 CONTINUE
      READ(4,*) HOUSE(2)
      READ(4,*) HOUSE(3)
      READ(4,*) HOUSE(4)
      READ(4,*) HOUSE(11)
C
C  READ IN THE AGE AND BODY WEIGHT (KG) AT THE TIME OF FAILURE
C
      READ(4,*) BW
      READ(4,*) AGE
C
C  READ IN THE NUMBER OF PIGS, EFFECTIVE LEAKAGE (M2) AND WIND VELOCITY (M/S)
C
      READ(4,*) PIGS
      READ(4,*) EL,V
      PHYS(7)=PHYS(1)+PHYS(3)+PHYS(5)
      PHYS(8)=(PHYS(1)*PHYS(2)+PHYS(3)*PHYS(4)+PHYS(5)*PHYS(6))/PHYS(7)
      PHYS(9)=660.*(PHYS(8)*0.001)-35.
C
C  INITIALIZE THE TRANSFER FUNCTION METHOD
C
      CALL INITL(V)
C
C  SET THE HEADERS FOR THE OUTPUT FILES
C
      WRITE(5,13)
   13 FORMAT(25X,'   TIME      AMBIENT            ROOM')
      WRITE(5,14)
   14 FORMAT(25X,'   STEP    TEMP   HUMIDITY    TEMP   HUMIDITY')
      WRITE(5,15)
   15 FORMAT(25X,'    NO.      C    KG/KG       C    KG/KG')
      WRITE(5,16)
   16 FORMAT(25X,' ----------------------------------------')
      WRITE(9,26)
   26 FORMAT(5X,'      TEMPERATURE (DEGREE C)        ',
     $ '       HUMIDITY RATIO (KG/KG)')
      WRITE(9,24)
   24 FORMAT(5X,'    ACTUAL   SIMULATED DIFFERENCE  TIME',
     $ '    ACTUAL  SIMULATED DIFFERENCE')
      WRITE(8,27)
   27 FORMAT('    S-A TEMP   TIME     TO        V      BW      ',
     $ 'AGE    QSOLAR      QE   ')
C
C  THIS SECTION IS PARTICULAR TO THE BUILDINGS USED FOR VALIDATION
```

```
C ****************************************************************
C
C SET QLIGHTS,ARDOOR,ARWIND
C
    QLIGHTS = 1.2*240.
    ARDOOR = 1.36/17.2
    ARWIND = .49/9.6
C
C ****************************************************************
C
C START THE MAIN PORTION OF THE PROGRAM
C
    DO 10 ITIME = 1,200
C
C ITAU  = BEGINS WITH THE PROGRAM INITIALIZATION
C ITIME = BEGINS WITH THE ACTUAL CALCULATION PHASE
C
      ITAU = 100 + ITIME
      WI(ITAU) = WI(ITAU-1)
C
C READ THE AMBIENT INPUT
C
      READ(2,*) DAY,TIME,RNURS1,RNURS2,AHALL,
     $  ATTIC,FINISH,AMBT,ATWB,ATDB
      CALL PSYCHRO(ATWB,ATDB,WO(ITAU))
      READ(10,*) X1,X2,X3,X4,X5,X6,X7,RNTWB,RNTDB
      CALL PSYCHRO(RNTWB,RNTDB,REALWI)
C
C BEFORE THE FAILURE, THE ACTUAL HUMIDITY IS USED
C
      IF(FAILSTEP.EQ.-999.)WI(ITAU) = REALWI
C       REALWI = WI(ITAU)
C
C THIS SECTION IS PARTICULAR TO THE BUILDING USED FOR VALIDATION
C ************************************************************
C
C SET THE SURROUNDING ENVIRONMENTAL TEMPERATURES
C
      IF(NURSNO.EQ.1)THEN
        TA(1,ITAU) = RNURS2
        TA(2,ITAU) = AMBT
        IF(DAY.GT.FAILDAY.OR.DAY.EQ.FAILDAY.AND.TIME.GT.FAILTIME)THEN
          TR(ITAU) = TR(ITAU-1)
        ELSE
          TR(ITAU) = RNURS1
        ENDIF
      ENDIF
      IF(NURSNO.EQ.2)THEN
        TA(1,ITAU) = FINISH
        TA(2,ITAU) = RNURS1
        IF(DAY.GT.FAILDAY.OR.DAY.EQ.FAILDAY.AND.TIME.GT.FAILTIME)THEN
          TR(ITAU) = TR(ITAU-1)
        ELSE
          TR(ITAU) = RNURS2
        ENDIF
      ENDIF
      TA(3,ITAU) = AHALL
      TA(4,ITAU) = AMBT
      TA(5,ITAU) = ATTIC
C ************************************************************
C
C READ THE SOLAR INPUT
C
      CALL SOLAR(NURSNO,SKYTEM,ITAU)
C
C
C THIS SECTION IS PARTICULAR TO THE BUILDING USED FOR VALIDATION
C ************************************************************
C
C SET THE SURROUNDING "SKY" TEMPERATURES TO CALCULATE LONG
C   WAVE RADIATION (DEGREES K)
C
```

```
      IF(NURSNO.EQ.1)THEN
        TSKY(1,ITAU)=RNURS2+273.15
        TSKY(2,ITAU)=(((SKYTEM+273.15)**4.+(AMBT+273.15)**4.)/2)**.25
      ENDIF
      IF(NURSNO.EQ.2)THEN
        TSKY(1,ITAU)=FINISH+273.15
        TSKY(2,ITAU)=RNURS1+273.15
      ENDIF
      TSKY(3,ITAU)=AHALL+273.15
      TSKY(4,ITAU)=(((SKYTEM+273.15)**4.+(AMBT+273.15)**4.)/2)**.25
      TSKY(5,ITAU)=ATTIC+273.15
C
C **************************************************************
C
      IF(DAY.EQ.FAILDAY.AND.TIME.EQ.FAILTIME+10.)THEN
        WRITE(5,19)
        WRITE(7,19)
C         WRITE(8,19)
   19   FORMAT('     THIS IS THE POINT OF FAILURE')
      ENDIF
   12 CALL WALLS
      CALL SLAB
C
C SET UP STEP-WISE CALCULATION OF TR
C
     IF(DAY.EQ.FAILDAY.AND.TIME.EQ.FAILTIME)THEN
C
C    CALCULATE THE ENERGY AT THE PREVIOUS STEP
C
        VOL=48.8
        FAILSTEP=ITAU
        HO=TR(ITAU)+WI(ITAU)*(2501.+1.805*TR(ITAU))
        SPVOL=(8.315/28.97)*(TR(ITAU)+273.15)/101.325*
     $   (1.+1.6078*WI(ITAU))
        QOLD=HO/(SPVOL/VOL)
      ENDIF
C
C SIMULATE THE FAILURE
C
      IF(DAY.GE.FAILDAY)THEN
       IF(DAY.GT.FAILDAY.OR.DAY.EQ.FAILDAY.AND.TIME.GT.FAILTIME)THEN
        E=0.0
        F=0.0
        DO 11 I=1,4
          E=E+H1C(I)*AREA(I)*T1(I,ITAU)
          F=F+H1C(I)*AREA(I)
   11    CONTINUE
        E=E+H1C(6)*AREA(6)*TF(ITAU)+H1C(5)*AREA(5)*T1(5,ITAU)
        F=F+H1C(6)*AREA(6)+H1C(5)*AREA(5)
        HOUSE(2)=(TR(ITAU)+TR(ITAU-1)+TR(ITAU-2))/3.
        IF(PIGS.GT.0.0)THEN
          CALL PIGINTL
          CALL INTAKE
C
C   CALCULATE THE FACTOR FOR MOISTURE EVAPORATION POTENTIAL
C
          CALL PSYCHRO(TR(ITAU),TR(ITAU),WS)
          FACTOR=1.3-(WI(ITAU)/WS)
          DAILY(13)=D(13)*FACTOR
          WMOISD=D(13)-DAILY(13)
          D(13)=DAILY(13)
          DAILY(8)=D(8)*4.184*11.57E-03
C
C   CALCULATE THE SENSIBLE HEAT PRODUCTION
C
          QANIM=(D(12)-D(13)-WMOISD)*PIGS
          DAILY(12)=D(12)
        ELSE
          DAILY(8)=0.0
          DAILY(13)=0.0
          DAILY(12)=0.00
          QANIM=0.0
```

```
        ENDIF
C
C   CALCULATE THE INFILTRATION HEAT LOSS
C
        CALL INFIL(EL,V)
C
C   CALCULATE THE CHANGE IN ENERGY
C
        DELQ=STEP/1000.*(QANIM+QI+QCNDSD+QLIGHTS+(ARDOOR+ARWIND)*
     $       (TA(3,ITAU)-TR(ITAU))+E-F*TR(ITAU))
       QNEW=QOLD+DELQ
C
C   CALCULATE THE NEW TEMPERATURE
C
        TRNEW=(QNEW*SPVOL/VOL-2501.*WI(ITAU))/(1.+1.805*WI(ITAU))
        DELTA=(TRNEW-TR(ITAU))
        IF(ABS(DELTA).GE.TOLER)THEN
         TR(ITAU)=TRNEW-DELTA/2.
         GOTO 12
        ENDIF
C
C    ADD THE MOISTURE COMPONENT AND RETURN TO TEMPERATURE ITERATIION
C
        CALL MOIST
        IF(WI(ITAU+1).NE.-6999.)GOTO 12
        QOLD=QNEW
       ENDIF
      ENDIF
      IF(FAILSTEP.NE.-999.)THEN
C
C  OUTPUT THE RESULTS AT EACH STEP
C
       WRITE(5,17) ITIME,TA(4,ITAU),WO(ITAU),TR(ITAU),WI(ITAU)
       WRITE(7,18) ITIME,(Q1(I,ITAU),I=1,6),QI
       SAWDIFF=WI(ITAU)-REALWI
       SATIME=(ITAU-FAILSTEP)*10.
       IF(NURSNO.EQ.1)THEN
        SATDIFF=TR(ITAU)-RNURS1
        WRITE(9,25) RNURS1,TR(ITAU),SATDIFF,SATIME,REALWI,WI(ITAU)
     $     ,SAWDIFF
       ELSE
        SATDIFF=TR(ITAU)-RNURS2
        WRITE(9,25) RNURS2,TR(ITAU),SATDIFF,SATIME,REALWI,WI(ITAU)
     $     ,SAWDIFF
       ENDIF
       QSOLAR=0.0
       DO 31 I=1,4
        QSOLAR=QS(I,ITAU)+QSOLAR
  31   CONTINUE
C       WRITE(8,30) SATDIFF,SATIME,TA(4,ITAU),V,BW,AGE,QSOLAR,D(13)
      ENDIF
  25  FORMAT(5X,4(F10.2),3(F10.4))
  30  FORMAT(8F10.2)
  17  FORMAT(25X,I6,2(F10.2,F10.5))
  18  FORMAT(5X,I5,7F10.1)
  21  FORMAT(5X,3F10.1)
      IF(SATIME.GE.90.)GOTO 999
  10 CONTINUE
 999 STOP
     END
C
C   ******************************************************
C
     SUBROUTINE INITL(VELOCITY)
C
C  THIS SUBROUTINE INITIALIZES THE TRANSFER FUNCTION COMPUTATIONS
C    FOR EACH CONDUCTION LOSS SURFACE
C
     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
     COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
     COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
     COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
```

```
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(1000),TOLER,NURSNO
      COMMON /MIDTEMP/NMCOMP(8),TMID(8,1000),QMID1(8,1000),QMID2(8,1000)
C
C READ:
C   NMWALL: NUMBER OF CONDUCTION LOSS UNITS
C   K : THE NUMBER OF FLUX FACTORS USED (ORDER +1)
C   NRF: THE NUMBER OF TEMPERATURE RESPONSE FACTORS
C
      READ(1,*) NMWALL,K,NRF
      DO 12 NW = 1,NMWALL
c
c READ:
c   NMCOMP: NUMBER OF CALCULATION COMPONENTS INTO WHICH THE WALL
c        WILL BE DIVIDED
c
       READ(1,*) NMCOMP(NW)
       DO 13 NC=1,NMCOMP(NW)
        DO 10 I=1,NRF
C
C READ THE RESPONSE FACTORS
C
         READ(1,*) X(NW,NC,I),Y(NW,NC,I),Z(NW,NC,I)
C
C CHANGE THE RESPONSE FACTORS FROM ENGLISH TO SI UNITS  (W/M2 K)
C
         X(NW,NC,I)=X(NW,NC,I)*5.678
         Y(NW,NC,I)=Y(NW,NC,I)*5.678
         Z(NW,NC,I)=Z(NW,NC,I)*5.678
  10    CONTINUE
        DO 11 I=1,K
C
C READ THE FLUX FACTORS
C
         READ(1,*) XJ(NW,NC,I)
  11    CONTINUE
  13   CONTINUE
C
C READ THE WALL AREA, THE AMBIENT TEMPERATURES, AND THE
C   INITIAL ROOM TEMPERATURE
C
C    H1C: THE CONVECTION COEFFICIENT AT THE INSIDE SURFACE (W/M2 K)
C    HNC: THE CONVECTION COEFFICIENT AT THE OUTSIDE SURFACE (W/M2 K)
C    AREA: AREA OF THE CONDUCTION UNITS (M2)
C    EMISS: EMISSIVITY OF THE OUTER WALL SURFACE
C    ABSORP: ABSORPTIVITY OF THE OUTER WALL SURFACE
C    TA: AMBIENT TEMPERATURE (C)
C    TR: INITIAL GUESS AT THE ROOM TEMPERATURE  (C)
C    TSKY: EFFECTIVE SKY TEMPERATURE FOR LONGWAVE EMMISION (K)
C    QS: THE SOLAR RADIATION ON THE SURFACE  (W/M2)
C
       IF(NW.EQ.1)THEN
        READ(1,*) AREA(NW),TA(NW,1),TR(1),EMISS(1),ABSORP(1)
       ELSE
        READ(1,*) AREA(NW),TA(NW,1),EMISS(NW),ABSORP(NW)
       ENDIF
C
C READ IN:
C   NURSNO: NURSERY NUMBER
C   DIRN: NORTH - SOUTH DIRECTION (1 = FROM NORTH, 0 = FROM SOUTH)
C   DIRE: EAST - WEST DIRECTION (1 = FROM EAST, 0 = FROM WEST)
C
      IF(NW.EQ.6)THEN
       READ(1,*) NURSNO,DIRN,DIRE
       SPEEDN=ABS(VELOCITY)
       SPEEDE=ABS(VELOCITY)
C
C CALCULATE THE EXTERIOR SURFACE CONVECTION COEFFICIENTS
C
C
C THESE CALCULATIONS ARE PARTICULAR TO THE BUILDING USED FOR
C  VALIDATION
```

```
C **********************************************************
C
      IF(NURSNO.EQ.1)THEN
       IF(DIRN.EQ.1.)THEN
        HNC(4)= 2.438*SPEEDN**.8
       ELSE
        HNC(4)=(16.57*SPEEDN**.8-20.6)/3.6
       ENDIF
       IF(DIRE.EQ.1.)THEN
        HNC(2)=2.929*SPEEDE**.8
       ELSE
        HNC(2)=(20.16*SPEEDE**.8-20.6)/4.6
       ENDIF
      ELSE
       IF(DIRN.EQ.1.)THEN
        HNC(4)=2.506*SPEEDN**.8
       ELSE
        HNC(4)=3.411*SPEEDN**.8
       ENDIF
      ENDIF
     ENDIF
C **********************************************************
C
C
C
C INITIALIZE THE TRANSFER FUNCTION EQUATIONS
C
      IF(NMCOMP(NW).EQ.1)THEN
c
c INITIALIZE FOR A WALL MADE OF A SINGLE CALCULATION COMPONENT
c
       DO 14 L=1,100
        T1(NW,L)=TR(1)-1.
        TN(NW,L)=TA(NW,1)+1.
        W=0.0
        U=0.0
        V=0.0
        S=0.0
        IF(L.GT.1)THEN
C
C CALCULATE THE FLUX FACTOR
C
         IF(L.LE.K)THEN
          DO 15 M=1,L-1
           V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
           U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
 15        CONTINUE
         ELSE
          DO 16 M=1,K
           V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
           U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
 16        CONTINUE
         ENDIF
        ENDIF
C
C CALCULATE THE TEMPERATURE FACTORS
C
        IF(L.LT.NRF)THEN
         DO 17 N=1,L
          S=S+Y(NW,1,N)*T1(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
          W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
 17      CONTINUE
        ELSE
         DO 18 N=1,NRF
          S=S+Y(NW,1,N)*T1(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
          W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
 18      CONTINUE
        ENDIF
        Q1(NW,L)=U+W
        QN(NW,L)=V+S
 14    CONTINUE
```

```
     ELSE
C
C INITIALIZE FOR DOUBLE CALCULATION COMPONENTS
C
      DO 19 L = 1,100
       T1(NW,L) = TR(1)-1.
       TN(NW,L) = TA(NW,1) + 1.
       TMID(NW,L) = (TN(NW,L) + T1(NW,L))/2.
       W = 0.0
       U = 0.0
       V = 0.0
       S = 0.0
       W1 = 0.0
       U1 = 0.0
       U2 = 0.0
       W2 = 0.0
       IF(L.GT.1)THEN
C
C CALCULATE THE FLUX FACTOR
C
        IF(L.LE.K)THEN
         DO 20 M = 1,L-1
          V = V + (-1.)**(M + 1)*XJ(NW,1,M)*QN(NW,L-M)
          U = U + (-1.)**(M + 1)*XJ(NW,1,M)*QMID1(NW,L-M)
          U1 = U1 + (-1.)**(M + 1)*XJ(NW,2,M)*Q1(NW,L-M)
          U2 = U2 + (-1.)**(M + 1)*XJ(NW,2,M)*QMID2(NW,L-M)
  20     CONTINUE
        ELSE
         DO 21 M = 1,K
          V = V + (-1.)**(M + 1)*XJ(NW,1,M)*QN(NW,L-M)
          U = U + (-1.)**(M + 1)*XJ(NW,1,M)*QMID1(NW,L-M)
          U1 = U1 + (-1.)**(M + 1)*XJ(NW,2,M)*Q1(NW,L-M)
          U2 = U2 + (-1.)**(M + 1)*XJ(NW,2,M)*QMID2(NW,L-M)
  21     CONTINUE
        ENDIF
       ENDIF
C
C CALCULATE THE TEMPERATURE FACTORS
C
       IF(L.LT.NRF)THEN
        DO 22 N = 1,L
         W = W + X(NW,1,N)*TMID(NW,L-N + 1)-Y(NW,1,N)*TN(NW,L-N + 1)
         S = S + Y(NW,1,N)*TMID(NW,L-N + 1)-Z(NW,1,N)*TN(NW,L-N + 1)
         W1 = W1 + X(NW,2,N)*T1(NW,L-N + 1)-Y(NW,2,N)*TMID(NW,L-N + 1)
         W2 = W2 + Y(NW,2,N)*T1(NW,L-N + 1)-Z(NW,2,N)*TMID(NW,L-N + 1)
  22    CONTINUE
       ELSE
        DO 23 N = 1,NRF
         W = W + X(NW,1,N)*TMID(NW,L-N + 1)-Y(NW,1,N)*TN(NW,L-N + 1)
         S = S + Y(NW,1,N)*TMID(NW,L-N + 1)-Z(NW,1,N)*TN(NW,L-N + 1)
         W1 = W1 + X(NW,2,N)*T1(NW,L-N + 1)-Y(NW,2,N)*TMID(NW,L-N + 1)
         W2 = W2 + Y(NW,2,N)*T1(NW,L-N + 1)-Z(NW,2,N)*TMID(NW,L-N + 1)
  23    CONTINUE
       ENDIF
       Q1(NW,L) = U1 + W1
       QMID1(NW,L) = U + W
       QMID2(NW,L) = U2 + W2
       QN(NW,L) = V + S
C    WRITE(5,99) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
  99 FORMAT(4F10.3)
  19   CONTINUE
     ENDIF
     TA(NW,100) = TA(NW,1)
  12 CONTINUE
    TR(101) = TR(1)
    TF(100) = 15.
    RETURN
    END
C
C  *****************************************************
C
C
```

```
      SUBROUTINE WALLS
C
C THIS SUBROUTINE CALCULATES THE SURFACE TEMPERATURES AND HEAT
C   LOSSES THROUGH THE WALLS AND CEILING
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
      COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(1000),TOLER,NURSNO
      COMMON /MIDTEMP/NMCOMP(8),TMID(8,1000),QMID1(8,1000),QMID2(8,1000)
C
C KEY TO WALL NUMBERS:
C    1 = NORTH
C    2 = SOUTH
C    3 = EAST
C    4 = WEST
C    5 = CEILING
C    6 = SLAB
C
C
C INITIALIZE THE VARIABLES
C
      L=ITIME+100
      IF(NMWALL.EQ.1)THEN
       NMW=1
      ELSE
       NMW=NMWALL-1
      ENDIF
      DO 51 NW=1,NMW
       T1(NW,L)=T1(NW,L-1)
       TN(NW,L)=TN(NW,L-1)
       IF(NMCOMP(NW).EQ.2)TMID(NW,L)=TMID(NW,L-1)
C
C CALCULATE A AND B USING THE TRANSFER FUNCTION EQUATIONS
C
       W=0.0
       U=0.0
       V=0.0
       S=0.0
       R=0.0
       R1=0.0
       P=0.0
       P1=0.0
       A=0.0
       B=0.0
       C=0.0
       C1=0.0
C
C CALCULATE THE FLUX FACTOR
C
       DO 19 M=1,K
        V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
        IF(NMCOMP(NW).EQ.1)THEN
         U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
        ELSE
         U=U+(-1.)**(M+1)*XJ(NW,2,M)*Q1(NW,L-M)
         R=R+(-1.)**(M+1)*XJ(NW,2,M)*QMID2(NW,L-M)
         R1=R1+(-1.)**(M+1)*XJ(NW,1,M)*QMID1(NW,L-M)
        ENDIF
   19  CONTINUE
C
C CALCULATE THE TEMPERATURE FACTORS
C
       DO 20 N=2,NRF
        IF(NMCOMP(NW).EQ.1)THEN
         S=S+Y(NW,1,N)*T1(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
         W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
        ELSE
         S=S+Y(NW,1,N)*TMID(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
         W=W+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
```

```
         P1 = P1 + X(NW,1,N)*TMID(NW,L-N + 1)-Y(NW,1,N)*TN(NW,L-N + 1)
         P = P + Y(NW,2,N)*T1(NW,L-N + 1)-Z(NW,2,N)*TMID(NW,L-N + 1)
        ENDIF
   20  CONTINUE
       A = V + S
       B = U + W
       C = R + P
       C1 = R1 + P1
C
C  SET THE LENGTH OF THE WALL CURRENTLY BEING CALCULATED
C
       IF(NW.GE.1.AND.NW.LE.4)XLENG = 2.6
       IF(NW.EQ.5)XLENG = 1.02
C
C  DETERMINE THE RAYLEIGH NUMBER
C
   50  RA1 = ABS((2.644D10*(T1(NW,L)-TR(L))*XLENG**3.)/
    $  (273.15 + (T1(NW,L) + TR(L))/2.))
C
C  CALCULATE THE SURFACE FREE CONVECTION COEFFICIENTS FOR THE
C    INNER SURFACES
C
       IF(NW.GE.1.AND.NW.LE.4)THEN
        H1C(NW) = 0.0265/XLENG*(0.825 + 0.3244*RA1**.1667)**2
       ELSE
        H1C(NW) = 0.0265/XLENG*0.27*RA1**.25
       ENDIF
C
C  ITERATIVELY SOLVE FOR THE RADIANT COEFFICIENT AND THE OUTSIDE
C    SURFACE TEMPERATURE
C
C  CALCULATE THE OUTSIDE RAYLEIGH NUMBER
C
   52  RAN = ABS((2.644D10*(TN(NW,L)-TA(NW,L))*XLENG**3.)/
    $  (273.15 + (TN(NW,L) + TA(NW,L))/2.))
C
C  CALCULATE THE SURFACE FREE CONVECTION COEFFICIENTS FOR THE
C    OUTER SURFACES WHICH ARE NOT EXPOSED TO WIND
C
       IF(NURSNO.EQ.1)THEN
        IF(NW.EQ.1.OR.NW.EQ.3.)THEN
         HNC(NW) = 0.0265/XLENG*(0.825 + 0.3244*RAN**.1667)**2.
        ENDIF
       ELSE
        IF(NW.GE.1.OR.NW.LE.3)THEN
         HNC(NW) = 0.0265/XLENG*(0.825 + 0.3244*RAN**.1667)**2.
        ENDIF
       ENDIF
       IF(NW.EQ.5)THEN
        HNC(NW) = 3.975D-03/XLENG*RAN**0.333
       ENDIF
C
C  CALCULATE THE RADIANT COEFFICIENT

       HR = EMISS(NW)*5.669E-08*(TSKY(NW,L)**2. +
    $   (TN(NW,L) + 273.15)**2.)*(TSKY(NW,L) + TN(NW,L) + 273.15)
C
C  CALCULATE THE NEW OUTER SURFACE WALL TEMPERATURE
C
       IF(NMCOMP(NW).EQ.1)THEN
        TNNEW = (A + Y(NW,1,1)*T1(NW,L) + HR*TSKY(NW,L)-HR*273.15 +
    $   HNC(NW)*TA(NW,L) + ABSORP(NW)*QS(NW,L))/(Z(NW,1,1) + HR + HNC(NW))
       ELSE
        TNNEW = (A + Y(NW,1,1)*TMID(NW,L) + HR*TSKY(NW,L)-HR*273.15 +
    $   HNC(NW)*TA(NW,L) + ABSORP(NW)*QS(NW,L))/(Z(NW,1,1) + HR + HNC(NW))
       ENDIF
C
C  DETERMINE THE CHANGE FROM THE PREVIOUS TEMPERATURE TO THE NEWLY
C    CALCULATED ONE
C
       DELTA = (TNNEW-TN(NW,L))
       IF(ABS(DELTA).GT.TOLER)THEN
```

```
         TN(NW,L)=TNNEW-DELTA/2.
         GOTO 52
        ENDIF
C
C   SOLVE ITERATIVELY FOR THE INSIDE SURFACE TEMPERATURE
C
        IF(NMCOMP(NW).EQ.1)THEN
         T1NEW=(Y(NW,1,1)*TN(NW,L)+H1C(NW)*TR(L)-B)/(X(NW,1,1)+H1C(NW))
        ELSE
         T1NEW=(Y(NW,2,1)*TMID(NW,L)+H1C(NW)*TR(L)-B)/
     $     (X(NW,2,1)+H1C(NW))
        ENDIF
C
C DETERMINE THE DIFFERENCE BETWEEN THE NEWLY CALCULATED INTERIOR
C   SURFACE TEMPERATURE AND THE OLD ONE
C
        DELTA=(T1NEW-T1(NW,L))
        IF(ABS(DELTA).GT.TOLER*10.)THEN
         T1(NW,L)=T1NEW-DELTA/2.
         GOTO 50
        ENDIF
C
C ITERATIVELY SOLVE FOR THE MIDPOINT TEMPERATURE IF A MIDPOINT IS
C   BEING USED
C
        IF(NMCOMP(NW).EQ.2)THEN
         TMIDNE=(C-C1+Y(NW,2,1)*T1(NW,L)+Y(NW,1,1)*TN(NW,L))/
     $     (X(NW,1,1)+Z(NW,2,1))
         DELTA=(TMIDNE-TMID(NW,L))
         IF(ABS(DELTA).GT.TOLER)THEN
          TMID(NW,L)=TMIDNE-DELTA/2.
          GOTO 52
         ENDIF
        ENDIF
C
C CALCULATE THE HEAT LOSS THROUGH THE EXTERIOR WALL SURFACE, THE
C   INTERIOR WALL SURFACE AND THE MIDDLE OF THE WALL
C
        IF(NMCOMP(NW).EQ.1)THEN
         QN(NW,L)=A+Y(NW,1,1)*T1(NW,L)-Z(NW,1,1)*TN(NW,L)
         Q1(NW,L)=B+X(NW,1,1)*T1(NW,L)-Y(NW,1,1)*TN(NW,L)
        ELSE
         QN(NW,L)=A+Y(NW,1,1)*TMID(NW,L)-Z(NW,1,1)*TN(NW,L)
         Q1(NW,L)=B+X(NW,2,1)*T1(NW,L)-Y(NW,2,1)*TMID(NW,L)
         QMID1(NW,L)=C1+X(NW,1,1)*TMID(NW,L)-Y(NW,1,1)*TN(NW,L)
         QMID2(NW,L)=C+Y(NW,2,1)*T1(NW,L)-Z(NW,2,1)*TMID(NW,L)
        ENDIF
C        WRITE(5,98) NW,T1(NW,L),TN(NW,L),TA(NW,L),H1C(NW),HNC(NW)
C        WRITE(5,*) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
  98  FORMAT(I5,5F10.3)
  51 CONTINUE
      RETURN
      END
C
C
C   ********************************************************
C
C
      SUBROUTINE SLAB
C
C THIS SUBROUTINE CALCULATES THE SLAB TEMPERATURE, THE PIT FLUID
C   TEMPERATURE AND THE HEAT FLOW THROUGH THE SLAB
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
      COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(1000),TOLER,NURSNO
      COMMON /MIDTEMP/NMCOMP(8),TMID(8,1000),QMID1(8,1000),QMID2(8,1000)
C
C IN THIS SUBROUTINE:
```

```
C     TN:   THE DEEP GROUND TEMPERATURE BELOW THE SLAB (C)
C     T1:   THE SLAB TEMPERATURE (C)
C     TF:   THE PIT FLUID TEMPERATURE   (C)
C     HFC:  CONVECTION COEFFICIENT BETWEEN THE SLAB AND FLUID (W/M2 K)
C     H1C:  CONVECTION COEFFICIENT BETWEEN THE FLUID AND THE AIR (W/M2 K)
C     DENS: THE MASS OF PIT LIQUID (KG/M2)
C     SPHT: SPECIFIC HEAT OF THE PIT LIQUID (J/KG K)
C     STEP: THE TIME STEP (S)
C
C
C  CALCULATE C USING THE TRANSFER FUNCTION EQUATIONS
C
      NW=NMWALL
      L=ITIME+100
      T1(NW,L)=T1(NW,L-1)
      TN(NW,L)=22.
      TF(L)=TF(L-1)
      DENS=202.
      SPHT=4190.
      STEP=600.
      W=0.0
      U=0.0
      C=0.0
      D=0.0
      E=0.0
C
C  CALCULATE THE FLUX FACTOR
C
      DO 19 M=1,K
C
C     FOR A SINGLE LAYER
C
       IF(NMCOMP(NW).EQ.1)THEN
        U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
C
C     FOR A DOUBLE LAYER
C
       ELSE
        U=U+(-1.)**(M+1)*XJ(NM,2,M)*Q1(NM,L-M)
        R=R+(-1.)**(M+1)*XJ(NM,1,M)*QMID1(NM,L-M)
        R1=R1+(-1.)**(M+1)*XJ(NM,2,M)*QMID2(NM,L-M)
       ENDIF
   19 CONTINUE
C
C  CALCULATE THE TEMPERATURE FACTORS
C
      DO 20 N=2,NRF
C
C     FOR A SINGLE LAYER
C
       IF(NMCOMP(NW).EQ.1)THEN
        W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
C
C     FOR A DOUBLE LAYER
C
       ELSE
        W=W+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
        S=S+X(NW,1,N)*TMID(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
        S1=S1+Y(NW,2,N)*T1(NW,L-N+1)-Z(NW,2,N)*TMID(NW,L-N+1)
       ENDIF
   20 CONTINUE
      C=U+W
      D=R+S
      E=R1+S1
C
C  ITERATIVELY SOLVE FOR THE SLAB TEMPERATURE AND THE FLUID TEMPERATURE
C
   50 H1C(NW)=ABS((TR(L)-TF(L))/(273.15+(TF(L)+TR(L))/2.))
      H1C(NW)=2.95*H1C(NW)**.25
      HFC=ABS((TF(L)-T1(NW,L))/(273.15+(TF(L)+T1(NW,L))/2.))
      HFC=390.3*HFC**.25
C
```

```
C   CALCULATE THE UPPER SLAB SURFACE TEMPERATURE
C
      IF(NMCOMP(NW).EQ.1)THEN
       T1(NW,L)=(Y(NW,1,1)*TN(NW,L)-C+HFC*TF(L))/(HFC+X(NW,1,1))
      ELSE
       T1(NW,L)=(Y(NW,2,1)*TMID(NW,L)-C+HFC*TF(L))/(HFC+X(NW,2,1))
      ENDIF
C
C   CALCULATE THE MIDPOINT TEMPERATURE FOR A DOUBLE LAYER APPLICATION
C
      IF(NMCOMP(NW).EQ.1)THEN
       TMIDNE=(E+Y(NW,2,1)*T1(NW,L)-D+Y(NW,1,1)*TN(NW,L))/
     $  (X(NW,1,1)+Z(NW,2,1))
       DELTA=(TMIDNE-TMID(NW,L))
       IF(ABS(DELTA).GE.TOLER)THEN
        TMID(NW,L)=TMIDNE-DELTA/2.
        GOTO 50
       ENDIF
      ENDIF
C
C   CALCULATE THE FLUID TEMPERATURE
C
      TFNEW=(HFC*T1(NW,L)+H1C(NW)*TR(L)+DENS*SPHT*TF(L-1)/STEP)/
     $ (HFC+H1C(NW)+DENS*SPHT/STEP)
      DELTA=(TFNEW-TF(L))
      IF(ABS(DELTA).GE.TOLER)THEN
       TF(L)=TFNEW-DELTA/2.
C       WRITE(5,*) TF(L),T1(NW,L),H1C(NW),HFC
       GOTO 50
      ENDIF
      IF(NMCOMP(NW).EQ.1)THEN
       Q1(NW,L)=X(NW,1,1)*T1(NW,L)-Y(NW,1,1)*TN(NW,L)+C
      ELSE
       Q1(NW,L)=X(NW,2,1)*T1(NW,L)-Y(NW,2,1)*TMID(NW,L)+C
       QMID1(NW,L)=X(NW,1,1)*TMID(NW,L)-Y(NW,1,1)*TN(NW,L)+D
       QMID2(NW,L)=Y(NW,2,1)*T1(NW,L)-Z(NW,2,1)*TMID(NW,L)+E
      ENDIF
C      WRITE(5,*) Q1(NW,L),TF(L),T1(NW,L)
C      WRITE(5,*) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
      QN(NW,L)=0.0
      RETURN
      END
C
C
C
C   *******************************************************
C
      SUBROUTINE INFIL(EL,V)
C
C
C THIS SUBROUTINE CALCULATES THE INFILTRATION OF AMBIENT AIR
C   INTO THE BUILDING
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
      COMMON /INFILT/ DAILY(18),WO(1000),WI(1000),PIGS,QI,QCNDSD
     $ ,QANIM,QINF
C
C SET THE PARAMETERS
C  WHERE:
C   EL=EFFECTIVE LEAKAGE AREA (M2)
C   V=WIND SPEED (M/S)
C   CP=GENERALIZED SHIELDING COEFFICIENT
C   R=FRACTION OF LEAKAGE ON HORIZONTAL SURFACES
C   DEL=TERRAIN PARAMETER
C   GAMMA=TERRAIN PARAMETER
C   H=HEIGHT OF STRUCTURE
C   X=CEILING LEAKAGE-FLOOR LEAKAGE DIVIDED BY TOTAL LEAKAGE
C
      L=ITIME+100
      CP=0.1
```

```
      DEL=0.2
      GAMMA=0.85
      R=0.0
      X=0.0
      H=2.9
C
C
C THESE CALCULATIONS ASSUME THAT THE MEASUREMENT IS TAKEN AT
C   THE BUILDING AT THE BUILDING HEIGHT
C
C CALCULATE THE WIND PARAMETER
C
      FW=CP*(1-R)**.333
C
C CALCULATE THE STACK PARAMETER
C
      FS=(1+R/2.)/3.*(1.-X**2./(2.-R)**2.)**1.5*
     $  (9.8*H/(TR(L)+273.15))**.5
C
C CALCULATE THE AIR INFILTRATION
C
      QINF=EL*SQRT(FS**2.*ABS(TR(L)-TA(4,L))+FW**2.*V**2.)
C
C CALCULATE THE NEW HUMIDITY RATIO INDOORS (WINEW)
C
      VOL=48.8
      STEP=600.
      SPVOL=8.315/28.97*(TR(L)+273.15)*(1.+1.6078*WI(L))/101.325
      DOTMA=QINF/SPVOL
C
C CALCULATE THE INDOOR AND OUTDOOR ENTHALPY VALUES
C
      HI=TR(L)+WI(L)*(2501.+1.805*TR(L))
      HO=TA(4,L)+WO(L)*(2501.+1.805*TA(4,L))
C
C CALCULATE THE HEAT LOST DUE TO INFILTRATION
C
      QI=DOTMA*1000.*(HO-HI)
      RETURN
      END
C
C
C
C ******************************************************
C
      SUBROUTINE MOIST
C
C
C THIS SUBROUTINE CALCULATES THE NEW HUMIDITY RATIO OF THE
C   BUILDING
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      COMMON /LOSS/ T1(8,1000),TN(8,1000),Q1(8,1000),QN(8,1000),ITIME
      COMMON /INFILT/ DAILY(18),WO(1000),WI(1000),PIGS,QI,QCNDSD
     $ ,QANIM,QINF
      L=ITIME+100
      QCNDSD=0.0
      VOL=48.8
      STEP=600.
C
C  CALCULATE THE MOISTURE PRODUCTION
C
      SPVOL=8.315/28.97*(TR(L)+273.15)*(1.+1.6078*WI(L))/101.325
      WDOTAN=DAILY(13)*PIGS/2430.E03
      DOTMA=QINF/SPVOL
      WOLD=WI(L-1)
      DO 10 I=1,60
        DELW=STEP/60.*(((DOTMA*WO(L)+WDOTAN)-DOTMA*WOLD)/(VOL/SPVOL))
        WOLD=WOLD+DELW
   10 CONTINUE
```

```
      WINEW=WOLD
C
C CHECK THE INTERNAL HUMIDITY RATIO FOR SATURATION
C
      TWTEMP=TR(L)
      CALL PSYCHRO(TWTEMP,TR(L),WTEST)
      IF(WTEST.LT.WINEW)THEN
C         WRITE(6,*) L,WTEST,TR(L)
C         WCH=WINEW-WTEST
        IF(ABS(WCH).GT.0.001)THEN
C           WINEW=WTEST
C           WDOTAN=60./STEP*DELW*VOL/SPVOL+DOTMA *WINEW-DOTMA*WO(L)
C           QE=WDOTAN*2430.E03/PIGS
C           DELQE=DAILY(13)-QE
C           DAILY(13)=QE
C           RATIO=DAILY(13)/DAILY(12)
C           IF(RATIO.GT.0.20)THEN
C             DAILY(12)=DAILY(12)-DELQE
C            QANIM=(DAILY(12)-DAILY(13))*PIGS
C           ELSE
C             WINEW=WTEST+WCH
C
C  CALCULATE THE AMOUNT OF CONDENSATE
C
C             CONDEN=WCH*VOL/SPVOL
C
C  CALCULATE THE HEAT GAIN DUE TO CONDENSATION
C
C             HFG=2430.
C             QCNDSD=HFG*1000.*CONDEN/STEP
C           ENDIF
        ENDIF
      ENDIF
      DELTA=WINEW-WI(L)
      IF(ABS(DELTA).GE.0.0005)THEN
        WI(L)=WINEW-DELTA/2.
C       WRITE(6,*) L,QCNDSD,DAILY(12),QE,TR(L),WTEST,WI(L)
      ELSE
        WI(L+1)=-6999.
        ENDIF
      RETURN
      END
C
C
C
C ******************************************************
C
      SUBROUTINE SOLAR(NURSNO,SKYTEM,L)
C
C THIS SUBROUTINE PROCESSES THE SOLAR DATA FILE TO DETERMINE
C   THE SOLAR LOAD ON THE WEST AND SOUTH WALLS OF THE SWINE
C   NURSERY AND THE EFFECTIVE SKY TEMPERATURE
C
C
C   THE DATA READ IN IS THE DAY, TIME, AND THE READINGS FROM
C     A PYRGEOMETER, PYRANOMETER (HORIZONTAL), AND A PYRHELIOMETER
C     (NORMAL BEAM)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,1000),TA(8,1000),QS(8,1000),TR(1000)
      PI=3.14159
      READ(3,*) DAY,TIME,GSKY,G,GBN
      DO 14 M=1,8
        QS(M,L)=0.0
   14 CONTINUE
C
C CALCULATE THE EFFECTIVE SKY TEMPERATURE (DEGREES K)
C
      SKYTEM=(GSKY/5.67E-11)**.25-273.15
C
C CALCULATE THE SOLAR TIME
C
```

```
      B=360.*(DAY-81.)/364.*PI/180.
      E=9.87*SIN(2.*B)-7.53*COS(B)-1.5*SIN(B)
C
C     CHANGE THE TIME TO A DECIMAL
C
      ATIME=TIME/100.
      DO 10 I=1,24
        AHOUR=I
        DECTIME=AHOUR-ATIME
        IF(DECTIME.GT.0.0)THEN
          AHOUR=AHOUR-1.
          DMIN=  (ATIME-AHOUR)*100./60.
          DECTIME=AHOUR+DMIN
          GOTO 11
        ENDIF
   10 CONTINUE
   11 SOLTIME=DECTIME+(4.*(75.-80.5)+E)/60.
      IF(SOLTIME.LT.0.0)SOLTIME=SOLTIME+24.
C
C   CALCULATE THE DECLINATION AND HOUR ANGLES
C
      D=23.45*SIN(360.*(284.+DAY)/365.*PI/180.)
      W=(SOLTIME - 12.)*15.*PI/180.
C
C   CALCULATE THE INCIDENCE ANGLES FOR THE WEST WALL AND HORIZONTAL
C
      BETA=90.*PI/180.
      GAMMA=60.*PI/180.
      RLAT=37.5*PI/180.
      COSTH=-SIN(D*PI/180.)*COS(RLAT)*COS(GAMMA)
     $  +COS(D*PI/180.)*SIN(RLAT)*COS(GAMMA)*COS(W)
     $ +COS(D*PI/180.)*SIN(GAMMA)*SIN(W)
      COSTHZ=COS(D*PI/180.)*COS(RLAT)*COS(W)+SIN(D*PI/180.)*SIN(RLAT)
C
C   CALCULATE THE INCIDENCE
C
      GBT=GBN*COSTH
      GB=GBN*COSTHZ
      GD=G-GB
      IF(W.GE.0.0.AND.GBN.GE.0.0)THEN
        QS(4,L)=(GBT+GD)*1000.
      ELSE
        QS(4,L)=GD*1000.
      ENDIF
      IF(QS(4,L).LT.0.0)QS(4,L)=0.0
C
C   CALCULATE THE INCIDENCE ANGLE FOR THE SOUTH WALL OF NURS 1
C
      IF(NURSNO.EQ.1)THEN
        GAMMA=-30.*PI/180.
        COSTH=-SIN(D*PI/180.)*COS(RLAT)*COS(GAMMA)
     $    +COS(D*PI/180.)*SIN(RLAT)*COS(GAMMA)*COS(W)
     $    +COS(D*PI/180.)*SIN(GAMMA)*SIN(W)
C
C   CALCULATE THE INCIDENCE
C
        GBT=GBN*COSTH
        GB=GBN*COSTHZ
        GD=G-GB
        QS(2,L)=(GBT+GD)*1000.
        IF(QS(2,L).LT.0.0)QS(2,L)=0.0
      ENDIF
C     WRITE(7,13) DAY,TIME,SOLTIME,G,GBN,QS(2,L),QS(4,L),SKYTEM
   13 FORMAT(2F10.1,F10.2,2F10.3,3F10.1)
      RETURN
      END
C
C
C ******************************************************
C
      SUBROUTINE PSYCHRO(TWB,TDB,W)
C
```

```
C  THIS SUBROUTINE CALCULATES THE HUMIDITY RATIO GIVEN THE
C    WET AND DRY BULB TEMPERATURE
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL TW
C
C  TWB : WET BULB TEMPERATURE (C)
C  TDB : DRY BULB TEMPERATURE (C)
C   W  : HUMIDITY RATIO (KG H20/KG DA)
C
C  SET THE NEEDED CONSTANTS (FROM ASHRAE FUNDAMENTALS)
C
      C1 = -5674.5359
      C2 = 6.3925247
      C3 = -0.9677843E-02
      C4 = 0.62215701E-06
      C5 = 0.20747825E-08
      C6 = -0.9484024E-12
      C7 = 4.1635019
      C8 = -5800.2206
      C9 = 1.3914993
      C10 = -0.04860239
      C11 = 0.41764768E-04
      C12 = -0.14452093E-07
      C13 = 6.5459673
C
C  SET THE ATMOSPHERIC PRESSURE (Pa)
C
      P = 101325.
C
C  CONVERT THE WET BULB TEMPERATURE FROM DEGREES C TO DEGREES K
C
      TW=TWB+273.15
C
C  CALCULATE THE SATURATED VAPOR PRESSURE FOR AIR OVER ICE
C
      IF(TWB.GE.-100..AND.TWB.LE.0.)THEN
        ALNPWS = C1/TW + C2 + C3*TW + C4*TW**2. + C5*TW**3. + C6*TW**4.
     $   + C7*ALOG(TW)
      ENDIF
C
C  CALCULATE THE SATURATED VAPOR PRESSURE FOR AIR OVER WATER
C
      IF(TWB.GT.0..AND.TWB.LE.200.)THEN
        ALNPWS = C8/TW + C9 + C10*TW + C11*TW**2. + C12*TW**3. + C13*ALOG(TW)
      ENDIF
      PWS = EXP(ALNPWS)
      WS = 0.62198*PWS/(P-PWS)
      W = ((2501.-2.381*TWB)*WS-(TDB-TWB))/(2501. + 1.805*TDB-4.186*TWB)
   11 FORMAT(2F10.1,F10.5)
      RETURN
      END
C
C
C  ****************************************************
C
C        THIS IS THE SECTION CONVERTED FROM THE PROGRAM
C          WRITTEN BY DR. RICHARD EWAN OF THE IOWA STATE
C          ANIMAL SCIENCE DEPARTMENT
C
C  ****************************************************
C **************************************************
C
C  THIS SUBROUTINE INITIALIZES THE ELEMENTS FOR THE PIG MODEL
C
      SUBROUTINE PIGINTL
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION RF45V(4)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/ONE/IFI,IDAY,IAGE,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
```

```
      RF45V(1)=0.04
      RF45V(2)=0.12
      RF45V(3)=0.5
      RF45V(4)=0.0
      IFI=0
      IDAY=0
      IAGE=AGE
      ICOMP=0
      DO 16 I=1,18
        C(I)=0.0
   16 CONTINUE
      CALL COMPO
      PTM=PHYS(9)
      PRM=PHYS(8)
      ADE=FEED(4)/4.184
      ANE=FEED(5)/4.184
      AK=FEED(5)/FEED(4)
      RATCON=FEED(4)*.96
      ANOP=PHYS(7)
      PENSZ=PHYS(8)*PHYS(9)
      DCP=FEED(1)*FEED(2)*0.01
      IFTYPE=HOUSE(4)
      RF45=RF45V(IFTYPE)
      RETURN
      END
C ************************************************
C
C  THIS SUBROUTINE CALCULATES FEED ADJUSTMENTS
C
      SUBROUTINE INTAKE
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/ONE/IFI,IDAY,IAGE,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT
      DIMENSION AAL(4)
      IF(IDAY.EQ.0)THEN
        DO 11 I=1,7
          ADJ(I)=0.0
   11   CONTINUE
      ENDIF
      IDAY=IDAY+1
      H1=0.
      WTM=  BW**.75
C
C  FOR PIGS IN EXCESS OF 18 KG
C
      FI1=13162.*(1.-EXP(-0.0176*BW))
C
C  FOR PIGS LESS THAN 18 KG
C
      IF(IFI.LE.0.AND.IAGE.LE.49)THEN
        FI2=108.*(IAGE-20)-101.
        FI3=456.*BW-9.46*BW**2-1531.
        IF(FI2.GT.FI3)FI2=FI3
        IF(FI2.LT.FI1)FI1=FI2
      ENDIF
C
C  SEX ADJUSTMENT
C
      SEX=(PHYS(3)-PHYS(5)-PHYS(1))/PHYS(7)
      IF(BW.GT.18.)IFI=1
      IF(BW.LT.10.)GOTO 12
      IF(BW.GE.25.)THEN
        CHG=0.214*BW-0.00133*BW**2-4.42
        ADJ(1)=FI1*SEX*CHG*0.01
      ENDIF
C
```

```
C  SPACE AND PIGS/PEN ADJUSTMENT
C
      IF(BW.LE.20.)THEN
        ADJ(2)=1.324*HOUSE(11)-1.5954*HOUSE(11)**2+0.7227
        ADJ(3)=PHYS(7)*(-29.44)
      ENDIF
      IF(BW.GT.20..AND.BW.LE.50.)THEN
        ADJ(2)=0.4293*HOUSE(11)-0.2025*HOUSE(11)**2+0.7725
        ADJ(3)=PHYS(7)*(-8.0)
      ENDIF
      IF(BW.GT.50.)THEN
        ADJ(2)=0.7*HOUSE(11)-0.32*HOUSE(11)**2+0.6165
        ADJ(3)=PHYS(7)*10.24
        ADJ(2)=ADJ(2)*FI1-FI1
      ENDIF
C
C  PELLETIZED ADJUSTMENT
C
      IPELL=FEED(11)
      IF(IPELL.LT.2)THEN
        IF(BW.LT.20.)THEN
          ADJ(4)=FI1*(-9.000001E-02)
        ELSE
          ADJ(4)=FI1*(-0.031)
        ENDIF
      ENDIF
C
C  ANTIBIOTIC ADJUSTMENT
C
      IANTI=FEED(12)
      IF(IANTI.LT.2)THEN
        IF(BW.LE.16.)ADJ(5)=FI1*0.08
        IF(BW.LE.57..AND.BW.GT.16.)ADJ(5)=FI1*0.06
        IF(BW.GT.57.)ADJ(5)=FI1*0.02
      ENDIF
C
C  ENERGY DENSITY ADJUSTMENT
C
      IF(BW.LE.30.)THEN
        IF(ADE.LT.3.3)ADJ(6)=(ADE-3.3)*1388.
        IF(ADE.GT.3.6)ADJ(6)=(ADE-3.6)*183.
      ELSE
        IF(ADE.LT.3.3)ADJ(6)=(ADE-3.3)*2773.
      ENDIF
C
C  ADJUST FEED INTAKE
C
      DO 10 I=1,7
        FI1=FI1+ADJ(I)
        ADJ(I)=0.0
   10 CONTINUE
   12 CALL HAM
C
C  DETERMINE AVAILABLE NUTRIENTS
C
      Q1=QS+QE
      FI1=FMJ*1000./4.184
      FIA=FI1/ADE
      FI1=FI1-(FI1*FEED(10)*0.01)
      FI=FI1/ADE
      H1=QS+QE-Q
      H1=H1*1000./(11.57*4.184)
      ADJ(7)=H1
      Q=FI*FEED(5)/4.184
      EI=FI1
      PI=FI*DCP*0.01
C
C  MAINTENANCE REQUIREMENT
C
      EM=WTM*85
C
```

```
C CHECK ENERGY LIMITS
C
      DD=EM*1.5
      IF(Q.LE.DD)THEN
        PX=0.05*PT*1000.
        PR=0.08*PT-(2.1977*6.25)
        PR=PR*.79-(0.3999*6.25)
        PM=PI-PR
        EU=PM*1.72
        AME=EI-EU
        EPR=5.64*PR
        ALR=Q-EM-H1-EPR
        E=ALR+EPR
        ALR=ALR/9.399999
        IF(E.LT.0.0)ADJ(6)=ABS(E)
        H=AME-E
      ELSE
C
C DETERMINE PROTEIN UTILIZATION
C
        PRTPX=(0.23*(PTM-PT))/PTM
        PR=(PI*FEED(3)*0.01)/(0.94+(0.06/PRTPX))
C
C COMPARE PR TO MAX RATE OF PROTEIN SYNTHESIS
C
        IF(PR.GT.PRM)PR=PRM
        CLYS=FI*FEED(6)*0.01
        RLYS=1.985*BW**0.487
        AAL(1)=CLYS/RLYS
        CTRY=FI*FEED(7)*0.01
        RTRY=0.3017*BW**0.524
        AAL(2)=CTRY/RTRY
        CTHR=FI*FEED(8)*0.01
        RTHR=1.136*BW**0.518
        AAL(3)=CTHR/RTHR
        RPRO=40.5*BW**0.5170001
        AAL(4)=(FI*FEED(1)*0.01)/RPRO
        J=1
        DO 15 I=1,4
          IF(AAL(J).LT.AAL(I))GOTO 15
          J=I
   15   CONTINUE
        IF(AAL(J).LT.1.)THEN
          PR=PR*AAL(J)
          ADJ(J)=PR*(1.-AAL(J))*5.64
        ENDIF
   16   PX=PR/PRTPX
        DD=0.05*PT*1000.
        IF(PX.LT.DD)PX=DD
C
C ENDOGENOUS LOSS OF PROTEIN
C
        EPL=0.06*(PX-PR)
        PM=PI-PR
        EU=PM*1.72
        AME=EI-EU
        EPR=5.64*PR
        ELR=Q-(EM+EPR+H1)
        ALR=ELR/9.399999
C
C FAT SYNTHESIS = PROTEIN RETENTION/3
C
        DD=PR/3.
        IF(ALR.LE.DD)THEN
          PR=PR-10.
          ADJ(5)=ADJ(5)+(10.*5.64)
          GOTO 16
        ENDIF
        E=EPR+ELR
        H=AME-E
      ENDIF
```

```
      CALL LIMIT
c
c  SET THE HEAT PRODUCTION INTO THE DAILY ARRAY
C
C  D(8) = HEAT PRODUCTION CALCULATED IN THE GROWTH SEGEMENT, KCAL/DAY
C  D(12) = HEAT PRODUCTION CALCULATED IN THE ENVIRONMENAL SEGMENT, W
C  D(13) = EVAPORATIVE HEAT LOSS, W
C
      D(8)=H
      D(12)=Q1
      D(13)=QE
      RETURN
      END
C *************************************************
C
C  THIS SUBROUTINE CALCULATES ENVIRONMENTAL TEMPERATURE EFFECTS
C
      SUBROUTINE HAM
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
      COMMON/ONE/IFI,IDAY,IAGE,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT
C
C  INITIALIZE VARIABLES TO PIG VARIABLES
C
      FMJ=FI1*4.184/1000.
      W=BW
      IF(W.LE.12.)THEN
        AM=7.419*W**0.66
      ELSE
        AM=5.091*W**0.75
      ENDIF
      A=9.000001E-02*W**0.67
      F=FMJ*11.57
      Q=AM+(1.-AK)*(F-AM)
      RMJ=AM*0.0864
      CAR=2.0*(ANOP-1)/ANOP*0.075
C
C  CALCULATE NET HEAT EXCHANGE
C
C  SET DEFAULT
C
      RV=0.15
C
C  SET FMAX TO EWAN'S FEED INTAKE
C
      FMAX=FMJ
      TA=HOUSE(2)
C
C  CALCULATE THE LOWER CRITICAL EFFECTIVE AND AIR TEMPERATURES
C
      V=HOUSE(3)
      IF(V.LT.0.15)V=0.15
      RC=W**0.13/(15.7*V**0.6)
      RR=1./5.3
      RA=1./(5.3+1/RC)
      RT=0.02*W**0.33
      FSR=0.21*0.8
      IF(IFTYPE.EQ.4)FSR=0.0
      RF=(FSR/0.2)*RF45*(W/45.)**0.33*ANOP**0.5
      AMINQE=2.*9.000001E-02*(8.+0.07*W)*W**0.67
      IDUM=1
      IF(ICOMP.GT.0)THEN
        QN=Q
        ANUM=QN*(RA+RT)-AMINQE*RA
        DEN=A*(1.+FSR*(RT-RF)/(RT+RF)-CAR)
        ELT=39.-ANUM/DEN
        TA=ELT
```

```
          CALL EFFECT
          ALCET = EFT
        ELSE
  101     CALL EFFECT
          FLCMJ = FMAX + (FMAX*(0.00825*(15.-EFT)))
          FLCWAT = FLCMJ*11.57
          QN = AM + (1.-AK)*(FLCWAT-AM)
          ANUM = QN*(RA + RT)-AMINQE*RA
          DEN = A*(1. + FSR*(RT-RF)/(RT + RF)-CAR)
          ELT = 39.-ANUM/DEN
          ALCET = EFT
          IF(ABS(TA-ELT).GT..01)THEN
            TA = ELT
            GOTO 101
          ENDIF
        ENDIF
        IDUM = 0
        TA = HOUSE(2)
C
C CALCULATE EFFECTIVE TEMPERATURE FOR FEED INTAKE
C
        CALL EFFECT
        AEFT = EFT
        IF(ICOMP.LE.0)THEN
          IF(AEFT.LE.ALCET)THEN
            IDUM = -1
            CALL EFFECT
          ENDIF
          FMJ = FMJ + (FMJ*(0.008255*(15.-EFT)))
          F = FMJ*11.57
          Q = AM + (1.-AK)*(F-AM)
        ENDIF
C
C CALCULATE SENSIBLE HEAT LOSS BASED ON EFFECTIVE TEMPERATURE
C
        QS = A*(39.-AEFT)/(RRA + RRT)
C
C DETERMINE EVAPORATIVE HEAT LOSS
C
        IF(AEFT.GT.ALCET)THEN
          QE = Q-QS
        ELSE
          QE = AMINQE
        ENDIF
        RETURN
        END
C ************************************************
C
C DETERMINE EFFECTIVE TEMPERATURE
C
        SUBROUTINE EFFECT
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
        COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
        COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
        COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
        POLD = 0.0
C
C
C   SET REFERENCE THERMAL RESISTANCES
C
C  REFERENCE CONVECTIVE RESISTANCE
C
        IF(IDUM.GE.1)THEN
          RRCV = W**0.13/(15.5*RV**0.6)
C
C  REFERENCE AIR THERMAL RESISTANCE
C
          RRA = 1/(5.3 + 1/RRCV)
C
C  REFERENCE TISSUE THERMAL RESISTANCE
C
          RRT = 0.03*W**0.33
```

```
          RCV = W**0.13/(15.5*V**0.6)
          RA = 1./(5.3 + 1/RCV)
          RT = 0.02*W**0.33
        ELSE
          RRCV = W**0.13/(12.5*RV**0.6)
          RRCT = 1./(24.55*V**0.46)
          RRT = 0.03*W**0.33
          RRA = 1./(5.2 + 1./(RRCT + RRCV))
C
C   SET ACTUAL THERMAL REFERENCES
C
          RCV = W**0.13/(12.5*V**0.6)
          RCT = 1./(24.55*V**0.46)
          RA = 1./(5.2 + 1./(RCV + RCT))
          IF(IDUM.EQ.-1)RT = 0.03*W**0.33
        ENDIF
C
C  PIG IS ASSUMED TO STANDE 20% OF TIME, I.E. 80% LYING
C
      FSR = .21*.8
      IF(IDUM.EQ.0)FSR = 0.244*0.8
      IF(IFTYPE.EQ.4)FSR = 0.0
      RF = (FSR/0.2)*RF45*(W/45.)**0.33*ANOP**0.5
C
C  INCREMENTAL ROOT SEARCHING STARTS
C
      EFT = -30.
      H = 2.0
C
C  CALCULATE THE FUNCTION VALUE
C
      PNEW = 0.0
      DO 10 I = 1,100
        IF(IDUM.EQ.0)RT = 0.03*W**0.33-0.0024*(EFT-ALCET)
        P1 = (1.0 + FSR*(RA-RF)/(RT + RF)-CAR)*(39.-TA)
        P2 = RA + RT
        P3 = (39.-EFT)/(RRA + RRT)
        PNEW = P1/P2-P3
        UEFT = EFT
        PNO = PNEW*POLD
        IF(PNO.GE.0.0)THEN
          POLD = PNEW
          ALEFT = UEFT
          EFT = EFT + H
        ELSE
          GOTO 12
        ENDIF
   10 CONTINUE
C
C  ASSIGN NEGATIVE TO T1 AND POSITIVE TO T2
C
   12 IF(PNEW.LT.0.0)THEN
        T1 = UEFT
        T2 = ALEFT
      ELSE
        T1 = ALEFT
        T2 = UEFT
      ENDIF
C
C  MIDPOINT SEARCHING
C
      DO 11 I = 1,100
        IF(ABS(PNEW).GE.0.0001)THEN
          EFT = (T1 + T2)/2.
          IF(IDUM.EQ.0)RT = 0.03*W**0.33-0.0024*(EFT-ALCET)
          P1 = (1.0 + FSR*(RA-RF)/(RT + RF)-CAR)*(39.-TA)
          P2 = RA + RT
          P3 = (39.-EFT)/(RRA + RRT)
          PNEW = P1/P2-P3
          IF(PNEW.LT.0.0)THEN
            T1 = EFT
          ELSE
```

```
         T2 = EFT
        ENDIF
       ELSE
        GOTO 13
       ENDIF
   11 CONTINUE
   13 RETURN
      END
C ************************************************
C
C  THIS SUBROUTINE CALCULATES INITIAL COMPOSITION
C
      SUBROUTINE COMPO
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      IF(BW.LT.7.5)THEN
        PT = 0.155*BW + 0.004
        FAT = 0.092*BW-0.16
        AT = 0.029*BW-0.016
        EBW = 0.928*BW + 0.123
        ET = 1700.*BW-1364.
      ENDIF
      IF(BW.GE.7.5.AND.BW.LT.15.)THEN
        PT = 0.149*BW + 0.089
        FAT = 0.0764*BW + 0.0013*BW**2.-0.371
        AT = 0.021*BW + 0.096
        EBW = 0.926*BW + 0.176
        ET = 1.777*BW-3946.
      ENDIF
      IF(BW.GE.15.)THEN
        PT = 0.154*BW-0.212
        FAT = 0.192*BW-0.288
        AT = 0.032*BW-0.073
        EBW = 0.952*BW
        ET = 5640.*PT + 9400.*FAT
      ENDIF
      ALT = PT*(5.5-(0.0116*(BW-5.)))
      FT = FAT*1.1
      RETURN
      END
C ************************************************
C
C  LIMITS AND COMPENSATORY RESPONSE
C
      SUBROUTINE LIMIT
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/ONE/IFI,IDAY,IAGE,ICOMP
      COMP = 0.0
      IF(ICOMP.GT.0)THEN
        ICOMP = 0
        RETURN
      ENDIF
      J = 1
      SUM = 0
      DO 10 I = 1,7
        SUM = SUM + ADJ(I)
        IF(ABS(ADJ(I)).GT.ABS(ADJ(J)))J = I
   10 CONTINUE
      IF(SUM.EQ.0.0)THEN
        LAA = 8
      ELSE
        LAA = J
      ENDIF
      COMP = COMP + ADJ(J)
      DO 11 I = 1,7
        ADJ(I) = 0.0
   11 CONTINUE
      IF(LAA.LT.8)RETURN
      IF(COMP.LE.0.0)RETURN
```

```
COMPDE=FI1*0.05
IF(COMP.GE.COMPDE)THEN
 FI1=FI1+COMPDE
 COMP=COMP-COMPDE
ELSE
 FI1=FI1+COMP
 COMP=0.0
 ICOMP=1
ENDIF
RETURN
END
```

B.3 Example Output File

```
   TIME        AMBIENT                ROOM
   STEP     TEMP   HUMIDITY      TEMP   HUMIDITY
    NO.       C     KG/KG          C     KG/KG
---------------------------------------------
   153      8.83  0.00479      21.66  0.00597
 THIS IS THE POINT OF FAILURE
   154      9.07  0.00500      23.60  0.01113
   155     10.31  0.00520      24.79  0.01520
   156      9.22  0.00531      25.35  0.01839
   157      9.09  0.00549      25.99  0.02063
   158      9.63  0.00566      26.35  0.02246
   159     10.23  0.00584      26.65  0.02392
   160      9.95  0.00603      26.89  0.02509
   161     10.73  0.00621      27.12  0.02603
   162     11.25  0.00626      27.32  0.02680
```

Appendix C. OPERATIONAL Model

C.1 Example Input Files

The operational model requires five input files. These were set to accommodate the data collection system used for validation. The files include: the transfer function file, the general input file, the ambient input file, the solar input file, and the nursery input file. The temperature files are shortened samples of the data files.

C.1.1 General Input File

```
20.0        CRUDE PROTEIN  (%)
85.0        DIGESTIBLE C P (%)
65.0        C P BIOLOGICAL VALUE (%)
14.057      DIGESTIBLE ENERGY (KJ/G)
10.0        NET ENERGY (KJ/G)
1.15        LYSINE (%)
0.27        TRYPTOPHAN (%)
0.825       THREONINE (%)
0.35        COST ($/KG)
4.0         FEED WASTAGE (%)
2           PELLETED (1=YES)
2           ANTIBIOTICS (1=YES)
2           GILTS/PEN
115.0       MAXIMUM PROTEIN DEPOSITION (G/DAY)
2           BARROWS/PEN
105.0       MAXIMUM PROTEIN DEPOSTION (G/DAY)
0           BOARS/PEN
130.0       MAXIMUM PROTEIN DEPOSITION (G/DAY)
20.0        INSIDE TEMPERATURE (C)
0.15        AIR MOVEMENT (M/S)
2.          FLOOR TYPE
0.28        FLOOR SPACE/PIG
11.71       INITIAL WEIGHT (KG)
49.         INITIAL AGE (DAYS)
47.         NUMBER OF PIGS
```

```
1.45                    LP GAS COST ($/GALLON)
4.0                     WIND VELOCITY (M/S)
0.082  62.    1500.     VENTILATION RATE M3/S, DAY, TIME TO CHANGE
0.125  900.   1200.
0.150  900.   1200.
0.500  900.   1200.
28.0   70.    1500.     FURNACE SET POINTS, DAY AND TIME TO CHANGE
26.0   71.    1000.
25.0   900.   1200.
29.5   900.   1200.
168                     NUMBER OF HOURS TO PROCESS
0                       OPTIMIZE, 1= YES
```

C.1.2 Transfer Function File

```
6  3   15          NURSERY 1
 1                NORTH WALL
   0.50879273577     0.04065388416     0.50879273577
  -0.42941305239     0.04003985229    -0.42941305239
   0.00173821448     0.00042404932     0.00173821448
  -0.00000008007     0.00000003202    -0.00000008007
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00566461836
   0.00000050026
   0.00000000000
13.34   25.0   25.0  0.9  0.4
 1                SOUTH WALL
   0.24533635860     0.00000577256     2.35901143484
  -0.38383690873     0.00108790383    -4.77396014858
   0.16780917953     0.00477276227     3.03339101348
  -0.02117325382     0.00270903032    -0.64087806591
   0.00070250100     0.00025685556     0.03117486262
   0.00000041746     0.00000588602     0.00009783664
   0.00000000582     0.00000008808     0.00000134722
   0.00000000008     0.00000000127     0.00000001935
   0.00000000000     0.00000000002     0.00000000028
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   1.43792568437
   0.53994206389
   0.04395838043
 13.34   15.0   0.9   0.4
  1               EAST WALL
   3.05231065378     0.09225683644     3.05231065378
  -2.84245329433     0.41346710948    -2.84245329433
   0.38343856242     0.08429489685     0.38343856242
  -0.00277850382     0.00049866734    -0.00277850382
   0.00000010656     0.00000001450     0.00000010656
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
   0.00000000000     0.00000000000     0.00000000000
```

```
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.34809894215
  0.00426255948
  0.00000022789
8.55  15.0  0.9  0.4
  1                WEST WALL
  2.35901142693      0.00020962911      2.35901142693
 -3.75950143327      0.01827755430     -3.75950143327
  1.69219759542      0.04725108545      1.69219759542
 -0.21600792863      0.01449721513     -0.21600792863
  0.00511953106      0.00058398274      0.00511953106
  0.00000433610      0.00000406093      0.00000433610
  0.00000001725      0.00000001720      0.00000001725
  0.00000000007      0.00000000007      0.00000000007
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  1.00789026590
  0.22329044985
  0.00816032514
 10.61  15.0  0.9  0.4
  1                CEILING
  0.80690684532      0.00749364200      0.16864414331
 -0.92750804104      0.03032071394     -0.13874637461
  0.16419083251      0.00511508590      0.01309233969
 -0.00063827260      0.00002195078     -0.00003871699
  0.00000002932      0.00000000088      0.00000000211
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.00000000000      0.00000000000      0.00000000000
  0.24672131605
  0.00114069907
  0.00000007579
16.84  20.0  0.9  0.4
  1              FLOOR SLAB
  5.52172814177      0.00000000405      3.91195090577
-13.35626399472      0.00002414821     -9.42883213685
 11.13317851105      0.00111088629      7.87134999362
 -3.64901938116      0.00496898234     -2.60401698847
  0.35784786961      0.00511544458      0.25763361019
  0.00546195765      0.00187674902      0.00488208021
  0.00053675886      0.00038206102      0.00050626267
  0.00006937392      0.00006151232      0.00006603134
  0.00000968500      0.00000918425      0.00000923732
  0.00000138411      0.00000133993      0.00000132089
  0.00000019924      0.00000019411      0.00000019017
  0.00000002874      0.00000002806      0.00000002744
  0.00000000415      0.00000000405      0.00000000396
  0.00000000060      0.00000000059      0.00000000057
  0.00000000009      0.00000000008      0.00000000008
  1.82447697439
  1.03975148156
  0.18253301746
13.29  22.0  0.9  0.4
1   1   0
```

C.1.3 Ambient Input File

DAY	TIME	NUR1 DEG C	NUR2 DEG C	HALL DEG C	ATTIC DEG C	G/F DEG C	OUT DEG C	TOWB DEG C	TODB DEG C
67	1210	25.21	22.91	3.949	4.899	13.18	-1.87	2.744	4.015
67	1220	25.47	23.13	3.862	5.421	13.29	-1.769	3.154	4.484
67	1230	25.74	23.21	3.983	5.957	13.25	-1.615	3.449	4.732
67	1240	25.97	23.24	4.119	6.457	13.29	-1.772	3.733	5.157
67	1250	26.23	23.39	4.119	6.86	13.56	-1.041	4.158	5.569
67	1300	26.4	23.63	4.165	7.24	13.53	-.975	4.416	5.83
67	1310	26.56	23.81	4.153	7.62	13.74	-.321	4.801	6.296
67	1320	26.73	23.85	4.312	8.16	13.83	-.727	5.059	6.592
67	1330	26.95	23.89	4.727	8.62	13.83	-.671	5.266	6.846
67	1340	27.02	23.84	2.521	8.85	13.59	-1.11	5.523	7.09
67	1350	26.79	23.71	2.525	8.7	13.34	-.93	5.446	7.18
67	1400	26.96	24.17	4.508	9.22	13.86	-.93	5.822	7.58
67	1410	27.18	24.31	4.567	9.38	14.01	-1.133	6.01	7.79

C.1.4 Solar Input File

DAY	TIME	SKY RAD KW/M2	TOTAL RAD KW/M2	NORMAL RAD KW/M2
67	1210	.271	.624	.051
67	1220	.284	.486	.008
67	1230	.285	.463	.004
67	1240	.285	.445	.002
67	1250	.288	.534	.014
67	1300	.286	.515	.012
67	1310	.292	.522	.01
67	1320	.289	.47	.008
67	1330	.285	.495	.008
67	1340	.285	.428	.002
67	1350	.286	.425	.003
67	1400	.285	.385	.001
67	1410	.285	.324	0

C.1.5 Nursery Input File

DAY	TIME	TBGI DEG C	TBGE DEG C	FURN DEG C	FAN T DEG C	INLET DEG C	TWB DEG C	TDB DEG C
67	1210	25.03	25.21	114.1	3.949	4.943	13.52	17.95
67	1220	25.22	25.47	114	3.862	4.912	13.85	18.62
67	1230	25.42	25.74	114.5	3.983	4.991	13.77	18.31
67	1240	25.63	25.97	114.7	4.119	5.169	13.93	18.51
67	1250	25.88	26.23	114.8	4.119	5.232	14.34	19.11

67	1300	26.11	26.4	115.5	4.165	5.295	14.5	19.34
67	1310	26.26	26.56	115.7	4.153	5.223	14.86	19.82
67	1320	26.41	26.73	116	4.312	5.439	15.05	20.15
67	1330	26.63	26.95	116.4	4.727	5.837	15.06	20.03
67	1340	26.79	27.02	116.3	2.521	4.218	14.85	19.34
67	1350	26.7	26.79	115.8	2.525	4	14.94	19.86
67	1400	26.76	26.96	116.3	4.508	5.764	15.5	20.67
67	1410	26.9	27.18	116.8	4.567	5.738	15.55	20.66

TBGI = INTERNAL TEMPERATURE OF THE BLACK GLOBE (NOT USED)
TBGE = EXTERNAL TEMPERATURE OF THE BLACK GLOBE
FURN = FURNACE EXIT TEMPERATURE
FAN T = TEMPERATURE NEAR THE FAN CONTROLLER
INLET = TEMPERATURE OF THE INLET AIR
TWB = WET BULB TEMPERATURE OF THE NURSERY
TDB = DRY BULB TEMPERATURE OF THE NURSERY

C.2 Program Code

```
C ****************************************************
C
C          OPERATIONAL MODEL
C
C ****************************************************
C
C      THIS PROGRAM SIMULATES A FUEL CONSUMPTION,
C         FEED CONSUMPTION, GROWTH, AND COST
C          PER UNIT OF MEAT GAINED.  IT WILL
C         ALSO CALCULATE OPTIMUM TEMPERATURES
C            IN A SWINE NURSERY
C
C
C             IT WAS DEVELOPED
C                   BY
C             JAY DAVID HARMON
C
C             UNDER THE DIRECTION
C                   OF
C           ELDRIDGE R. COLLINS, JR.
C
C              JULY, 1989
C
C ****************************************************
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL RATE(4),DAYSTEP(4),TIMESTE(4),SETPT(4),DAYPT(4),TIMEPT(4)
      COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
      COMMON /INFILT/ DAILY(18),WO(2000),WI(2000),PIGS,VENTRATE,QV,WDOTSUP
      COMMON /LOSS/ T1(8,2000),TN(8,2000),Q1(8,2000),QN(8,2000),ITIME
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(2000),TOLER,NURSNO
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
C
C ****************************************************
C
C            INPUT FILES
C
C ****************************************************
C
C     INPUT FILE NO. 1
C       CONTAINS RESPONSE FACTORS AND WALL
C       CHARACTERISTICS
C
C        NMWALL, K, NRF
```

```
C          NMWALL: NUMBER OF CONDUCTION UNITS
C          K: NUMBER OF FLUX FACTORS
C          NRF: NUMBER OF TEMPERATURE RESPONSE FACTORS
C R    II  NUMBER OF CALCULATION COMPONENTS (1 OR 2)  II
C E    I   X(1),Y(1),Z(1)    IN BTU/HR-FT2-F          I
C P    I   X(2),Y(2),Z(2)                           I
C E    I    .,.,.                                 I
C A T  I     .,.,.                                I
C T I  I   X(NRF),Y(NRF),Z(NRF)                     I
C S M  I    J(1)                                   I
C   E  I   J(2)                                   I
C N S  I    .                                     I
C M    I   J(K)                                    I
C W    I   AREA,TA,TR,EMISS,ABSORP (FOR FIRST TIME)   I
C A    II  AREA,EMISS,ABSORP (OTHER TIMES)          II
C L         AREA: WALL AREA (M2)
C L         TA: OUTSIDE TEMPERATURE FOR INITIALIZATION (C)
C          TR: ROOM TEMPERATURE FOR INITIALIZATION (C)
C          EMISS: WALL EMISSIVITY
C          ABSORP: WALL ABSORPTIVITY
C
C       FOR THE LAST WALL:
C       NURSERY NO., DIRN, DIRE
C         DIRN: WIND DIRECTION (1=NORTH, O=SOUTH)
C         DIRE: WIND DIRECTION (1=EAST, 0=WEST)
C
C **************************************************
C
C     INPUT FILE NO. 2
C       CONTAINS AMBIENT DATA
C
C     DAY, TIME, RNURS1, RNURS2, AHALL, ATTIC
C       FINISH, AMBT, ATWB, ATDB
C
C       DAY: JULIAN DAY
C       TIME: MILITARY TIME
C       RNURS1: TEMPERATURE OF NURSERY 1 (C)
C       RNURS2: TEMPERATURE OF NURSERY 2 (C)
C       AHALL: HALLWAY TEMPERATURE (C)
C       ATTIC: ATTIC TEMPERATURE (C)
C       FINISH: GROWER/FINISHER TEMPERATURE (C)
C       AMBT: AMBIENT OUTDOOR TEMPERATURE (C)
C       ATWB: AMBIENT WET BULB (C)
C       ATDB: AMBIENT DRY BULB (C)
C
C
C **************************************************
C
C     INPUT FILE NO. 3
C       CONTAINS SOLAR INPUT
C
C     DAY, TIME, GSKY, G, GBN
C       DAY: JULIAN DAY
C       TIME: MILITARY TIME
C       GSKY: RADIATION FROM A PYHRGEOMETER (W/M2)
C       G: RADIATION FROM A HORIZONTAL PYRANOMETER (W/M2)
C       GBN: RADIATION FROM A PYRHELIOMETER (W/M2)
C
C
C **************************************************
C
C     INPUT FILE NO. 4
C       CONTAINS GENERAL INFORMATION FOR THE MODEL
C
C     CRUDE PROTEIN OF THE DIET (%)
C     DIGESTIBLE CRUDE PROTEIN (%)
C     CRUDE PROTEIN BIOLOGICAL VALUE (%)
C     DIGESTIBLE ENERGY (KJ/G)
C     NET ENERGY (KJ/G)
C     LYSINE (%)
C     TRYPTOPHAN (%)
C     THREONINE (%)
```

```
C      FEED COST ($/KG)
C      FEED WASTAGE (%)
C      PELLETED (1=YES)
C      ANTIBIOTICS (1=YES)
C      GILTS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      BARROWS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      BOARS/PEN
C      MAXIMUM PROTEIN DEPOSITION (G/DAY)
C      INSIDE TEMPERATURE (C)
C      INTERIOR AIR MOVEMENT (M/S)
C      FLOOR TYPE (1=CONCRETE, 2=SLATS)
C      FLOOR SPACE/PIG (M2)
C      INITIAL WEIGHT (KG)
C      INITIAL AGE (DAYS)
C      NUMBER OF PIGS
C      LP GAS COST ($/GALLON)
C      VENTILATION RATE 1 (M3/S), DAY AND TIME TO CHANGE
C      VENTILATION RATE 2 (M3/S), DAY AND TIME TO CHANGE
C      VENTILATION RATE 3 (M3/S), DAY AND TIME TO CHANGE
C      VENTILATION RATE 4 (M3/S), DAY AND TIME TO CHANGE
C      FURNACE SET POINT 1 (C), DAY AND TIME TO CHANGE
C      FURNACE SET POINT 2 (C), DAY AND TIME TO CHANGE
C      FURNACE SET POINT 3 (C), DAY AND TIME TO CHANGE
C      FURNACE SET POINT 4 (C), DAY AND TIME TO CHANGE
C      NUMBER OF HOURS TO PROCESS
C      OPTIMIZE, 1=YES
C
C
C ****************************************************
C
C      INPUT FILE NO. 10
C        CONTAINS ACTUAL NURSERY CONDITIONS
C
C      DAY, TIME, X3, X4, X5, X6, X7, RNTWB, RNTDB
C        DAY: JULIAN DAY
C        TIME: MILITARY TIME
C        X3..X7: UNNEEDED INPUTS
C        RNTWB: NURSERY WET BULB (C)
C        RNTDB: NURSERY DRY BULB (C)
C
C ****************************************************
C
C SET THE TOLERANCE FOR THE TEMPERATURE ITERATION AND THE
C   TIME STEP LENGTH (IN SECONDS)
C
C
      CALL HEADERS
      TOLER=0.01
      STEP=3600.
      AGEHR=0.
      DAYHR=0.0
C
C VOL=VOLUME OF THE NURSERY
C
      VOL=48.8
C
C READ IN THE INFORMATION THAT PERTAINS TO THE FEED, PHYSIOLOGICAL
C   AND HOUSE CHARACTERISTICS AT THE INITIAL TIME
C
      DO 22 I=1,12
        READ(4,*) FEED(I)
   22 CONTINUE
      DO 23 I=1,6
        READ(4,*) PHYS(I)
   23 CONTINUE
      READ(4,*) HOUSE(2)
      READ(4,*) HOUSE(3)
      READ(4,*) HOUSE(4)
      READ(4,*) HOUSE(11)
C
```

```
C  READ IN THE AGE AND BODY WEIGHT (KG) AT THE TIME OF FAILURE
C
      READ(4,*) BW
      READ(4,*) AGE
C
C  READ IN THE NUMBER OF PIGS
C
      READ(4,*) PIGS
C
C  READ IN THE FUEL COST
C
      READ(4,*) PFUEL
C
C  READ IN THE WIND VELOCITY
C
      READ(4,*) V
      PHYS(7)=PHYS(1)+PHYS(3)+PHYS(5)
      PHYS(8)=(PHYS(1)*PHYS(2)+PHYS(3)*PHYS(4)+PHYS(5)*PHYS(6))/PHYS(7)
      PHYS(9)=660.*(PHYS(8)*0.001)-35.
C
C  READ IN THE VENTILATION RATE (M3/S) FOR EACH OF FOUR STAGES
C    AND THE DAY AND TIME AT WHICH THE RATE CHANGES SHOULD BE MADE
C
      DO 24 I=1,4
        READ(4,*) RATE(I),DAYSTEP(I),TIMESTE(I)
 24   CONTINUE
C
C  READ IN THE TEMPERATURE SET POINT FOR THE FURNACE (C)
C    AND THE DAY AND TIME AT WHICH IT CHANGES
C
      DO 25 I=1,4
        READ(4,*) SETPT(I),DAYPT(I),TIMEPT(I)
 25   CONTINUE
      CALL INITL(V)
C
C  SET QLIGHTS,ARDOOR,ARWIND *************************************
C
C  THIS SECTION IS PARTICULAR TO THE BUILDING USED FOR VALIDATION
C  **********************************
      QLIGHTS=1.2*240.
      ARDOOR=1.36/17.2
      ARWIND=.49/9.6
C  **********************************
C
C  READ IN THE NUMBER OF HOURS AND THE OPTIMIZATION OPTION TRIGGER
C
      READ(4,*) NUMSTEP
      READ(4,*) IOPT
C
C  START THE MAIN PROGRAM LOOP
C
      DO 10 ITIME=1,NUMSTEP
        ITAU=100+ITIME
        WI(ITAU)=WI(ITAU-1)
C
C  READ THE AMBIENT INPUT AND THE ACTUAL DATA
C
         X1=0.0
         X2=0.0
         X3=0.0
         X4=0.0
         X5=0.0
         X6=0.0
         X7=0.0
         X8=0.0
         X9=0.0
         X10=0.0
         X11=0.0
         AVG=0.0
C
 13   READ(2,*) DAY,TIME,RNURS1,RNURS2,AHALL,
     $  ATTIC,FINISH,AMBT,ATWB,ATDB
```

```
      READ(10,*) Z1,Z2,Z3,Z4,FURN,Z6,Z7,RNTWB,RNTDB
C
C     IF THE READINGS ARE PER MINUTE EXCLUDE THEM
C
      IF(DMOD(TIME,10.D0).EQ.0.0)THEN
C
C     SUM THE READINGS FOR A SINGLE HOUR
C
        X1=X1+RNURS1
        X2=X2+RNURS2
        X3=X3+AHALL
        X4=X4+ATTIC
        X5=X5+FINISH
        X6=X6+AMBT
        X7=X7+ATWB
        X8=X8+ATDB
        X9=X9+RNTWB
        X10=X10+TNTDB
        X11=X11+FURN
        AVG=AVG+1
C
C     IF THE READING IS ON THE HOUR, AVERAGE THE READINGS TO
C       PRODUCE HOURLY AVERAGE READINGS
C
        IF(DMOD(TIME,100.D0).NE.0.0)THEN
          GOTO 13
        ELSE
          RNURS1=X1/AVG
          RNURS2=X2/AVG
          AHALL=X3/AVG
          ATTIC=X4/AVG
          FINISH=X5/AVG
          AMBT=X6/AVG
          ATWB=X7/AVG
          ATDB=X8/AVG
          RNTWB=X9/AVG
          RNTDB=X10/AVG
          FURN=X11/AVG
          CALL PSYCHRO(ATWB,ATDB,WO(ITAU))
          CALL PSYCHRO(RNTWB,RNTDB,REALWI)
          IF(ITAU.EQ.1)WI(ITAU-1)=REALWI
        ENDIF
      ELSE
        GOTO 13
      ENDIF
C
C THIS SECTION WAS USED FOR VALIDATION
C *******************************************
C
C CALCULATE THE ACTUAL TIME THAT THE FURNACE RUNS PER HOUR
C
      IF(NURSNO.EQ.1)THEN
        AVGFT=-0.415+0.1109*(FURN-RNURS1)
        FURNIN=62.4*(FURN-RNURS1)
      ENDIF
      IF(NURSNO.EQ.2)THEN
        AVGFT=-1.3709+0.1355*(FURN-RNURS2)
        FURNIN=69.9*(FURN-RNURS2)
      ENDIF
      IF(FURNIN.LT.0.0)FURNIN=0.0
      IF(FURNIN.GT.5861.)FURNIN=5861.
C
C  *****************************************
C
C SET THE SURROUNDING ENVIRONMENTAL TEMPERATURES
C
C THIS SECTION IS PARTICULAR TO THE VALIDATION BUILDING
C *****************************************
      IF(NURSNO.EQ.1)THEN
        TA(1,ITAU)=RNURS2
        TA(2,ITAU)=AMBT
      ENDIF
```

```
       IF(NURSNO.EQ.2)THEN
         TA(1,ITAU)=FINISH
         TA(2,ITAU)=RNURS1
       ENDIF
       TA(3,ITAU)=AHALL
       TA(4,ITAU)=AMBT
       TA(5,ITAU)=ATTIC
C
C ******************************************
C
C  READ THE SOLAR INPUT
C
       CALL SOLAR(NURSNO,SKYTEM,ITAU)
C
C  SET THE SURROUNDING "SKY" TEMPERATURES TO CALCULATE LONG
C    WAVE RADIATION (DEGREES K)
C
C THIS SECTION IS PARTICULAR TO THE VALIDATION BUILDING
C ******************************************
       IF(NURSNO.EQ.1)THEN
         TSKY(1,ITAU)=RNURS2+273.15
         TSKY(2,ITAU)=(((SKYTEM+273.15)**4.+(AMBT+273.15)**4.)/2)**.25
       ENDIF
       IF(NURSNO.EQ.2)THEN
         TSKY(1,ITAU)=FINISH+273.15
         TSKY(2,ITAU)=RNURS1+273.15
       ENDIF
       TSKY(3,ITAU)=AHALL+273.15
       TSKY(4,ITAU)=(((SKYTEM+273.15)**4.+(AMBT+273.15)**4.)/2)**.25
       TSKY(5,ITAU)=ATTIC+273.15
C
C ******************************************
C
C  SET THE VENTILATION RATE
C
       VENTRATE=RATE(1)
       IF(DAY.GT.DAYSTEP(1).OR.DAY.EQ.DAYSTEP(1)
     $ .AND.TIME.GE.TIMESTE(1))VENTRATE=RATE(2)
       IF(DAY.GT.DAYSTEP(2).OR.DAY.EQ.DAYSTEP(2)
     $  .AND.TIME.GE.TIMESTE(2))VENTRATE=RATE(3)
       IF(DAY.GT.DAYSTEP(3).OR.DAY.EQ.DAYSTEP(3)
     $  .AND.TIME.GE.TIMESTE(3))VENTRATE=RATE(4)
C
C  SET THE FURNACE SET POINT
C
       TR(ITAU)=SETPT(1)
       IF(DAY.GT.DAYPT(1).OR.DAY.EQ.DAYPT(1)
     $ .AND.TIME.GE.TIMEPT(1))TR(ITAU)=SETPT(2)
       IF(DAY.GT.DAYPT(2).OR.DAY.EQ.DAYPT(2)
     $  .AND.TIME.GE.TIMEPT(2))TR(ITAU)=SETPT(3)
       IF(DAY.GT.DAYPT(3).OR.DAY.EQ.DAYPT(3)
     $  .AND.TIME.GE.TIMEPT(3))TR(ITAU)=SETPT(4)
        STPT=TR(ITAU)
C
C  SET THE OPTIMIZATION VARIABLES
C
       IF(IOPT.EQ.1)THEN
         ISKIP=0
         COSTMN=100.
         TMIN=100.
         TR(ITAU)=32.
       ENDIF
  12   CALL WALLS
       CALL SLAB
C
C  CALCULATE THE CONDUCTION HEAT FLUXES
C
       E=0.0
       F=0.0
       DO 11 I=1,4
         E=E+H1C(I)*AREA(I)*T1(I,ITAU)
         F=F+H1C(I)*AREA(I)
```

```
   11 CONTINUE
      E=E+H1C(6)*AREA(6)*TF(ITAU)+H1C(5)*AREA(5)*T1(5,ITAU)
      F=F+H1C(6)*AREA(6)+H1C(5)*AREA(5)
C
C CALL THE PIG SUBPROGRAM
C
      HOUSE(2)=TR(ITAU)
      IF(PIGS.GT.0.0)THEN
       IF(AGEHR.EQ.0.0)CALL PIGINTL
       CALL INTAKE
       DAILY(8)=D(8)*4.184*11.57E-03
       QANIM=(D(12)-D(13))*PIGS
       DAILY(13)=D(13)
      ELSE
       DAILY(8)=0.0
       DAILY(13)=0.0
       QANIM=0.0
      ENDIF
      CALL VENTIL
C
C CALCULATE THE REQUIRED SUPPLEMENTAL HEAT
C
   14 QSUPP=-(QANIM+QV+QLIGHTS+(ARDOOR+ARWIND)*(TA(3,ITAU)-
     $ TR(ITAU))+E-F*TR(ITAU))
C
C ADD THE MOISTURE ADDED BY PROPANE USAGE
C
      WDOTSUP=QSUPP*8.47E-08
      CALL VENTIL
      IF(WI(ITAU+1).NE.-6999.)GOTO 14
C
C IF THE SUPPLEMENTAL HEAT IS LESS THAN ZERO OR GREATER THAN
C  THE HEATER CAPACITY, CALCULATE THE NEW INDOOR TEMPERATURE
C
      IF(QSUPP.LT.0.0)THEN
       QSUPP=0.0
       TR(ITAU)=TR(ITAU)+0.1
       IF(ISKIP.NE.2)ISKIP=1
       GOTO 12
      ENDIF
      IF(QSUPP.GT.5861.)THEN
       QSUPP=5861.
       TR(ITAU)=TR(ITAU)-0.1
       GOTO 12
      ENDIF
C
C DETERMINE THE GROWTH AND FEED INTAKE AT THE PRESENT TEMPERATURE
C
      IF(PIGS.GT.0.0)THEN
       IF(IOPT.EQ.1.AND.ISKIP.NE.2)THEN
        CALL OPTGAIN(WG,FC)
       ELSE
        CALL GAIN
        WG=0.0
        FC=0.0
       ENDIF
      ENDIF
      DIFF=FURNIN-QSUPP
      IF(ITAU.EQ.1)THEN
       GASUM=0.0
      ENDIF
C
C CALCULATE ENERGY USAGE
C
      OPTGAS=GASUM+QSUPP*3600./1000./90735.
      CUFTSUM=OPTGAS*36.
      FUELCOS=OPTGAS*PFUEL
      IF(IOPT.EQ.1.AND.ISKIP.EQ.2.OR.IOPT.EQ.0)GASUM=OPTGAS
C
C CALCULATE THE FEED USAGE
C
      TFEED=(C(11)+FC)/1000.*PIGS
```

```
      FEEDCOS=TFEED*FEED(9)
C
C CALCULATE THE TOTAL GAIN AND COST PER KG OF MEAT
      TMEAT=(C(10)+WG)/1000.*PIGS
      IF(TMEAT.NE.0.)THEN
        TOTAL=(FEEDCOS+FUELCOS)/TMEAT
      ELSE
        TOTAL=100.
      ENDIF
C
C COMPARE FOR THE OPTIMIZATION
C
      IF(ISKIP.EQ.2)GOTO 103
      IF(IOPT.EQ.1)THEN
       IF(TOTAL.GT.0.0.AND.TOTAL.LT.COSTMN.OR.
     $    TOTAL.LT.0.0.AND.ABS(TOTAL).LT.ABS(COSTMN))THEN
        COSTMN=TOTAL
        TMIN=TR(ITAU)
       ENDIF
       WRITE(6,*) COSTMN, TMIN, TR(ITAU)
       WRITE(6,*) FUELCOS, FEEDCOS, TOTAL
       WRITE(6,*) FC,WG
       IF(TR(ITAU).GT.10..AND.ISKIP.EQ.0)THEN
        TR(ITAU)=TR(ITAU)-0.5
        GOTO 12
       ENDIF
      ENDIF
  102 ISKIP=2
      TR(ITAU)=TMIN
      GOTO 12
  103 WRITE(5,17) DAY,TIME,TA(4,ITAU),WO(ITAU),TR(ITAU),WI(ITAU),
     $ QSUPP
C     WRITE(6,99) itime,STPT,TR(ITAU),TA(4,ITAU),D(16)
C 99  FORMAT(2X,I8,4F10.2)
   17 FORMAT(8X,F4.0,2X,F5.0,2X,2(F6.1,2X,F8.5),F10.0)
      WRITE(7,18)DAY,TIME,TR(ITAU),GASUM,CUFTSUM,C(10)/1000.,
     $ C(11)/1000.
   18 FORMAT(2X,2F10.0,F10.1,2F10.2,2F10.3)
      WRITE(8,101) DAY,TIME,GASUM,FUELCOS,TFEED,FEEDCOS,TMEAT,TOTAL
  101 FORMAT(2F10.0,6F10.2)
      TR(ITAU+1)=TR(ITAU)
   10 CONTINUE
C     AVGSUM=SUM/COUNT
C     WRITE(6,*) AVGSUM, FSUM, QSUM
     STOP
     END
C
C ******************************************************
C
     SUBROUTINE INITL(VELOCITY)
C
C THIS SUBROUTINE INITIALIZES THE TRANSFER FUNCTION COMPUTATIONS
C   FOR EACH CONDUCTION LOSS SURFACE
C
     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
     COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
     COMMON /LOSS/ T1(8,2000),TN(8,2000),Q1(8,2000),QN(8,2000),ITIME
     COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
     COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
     COMMON /MISC/ TF(2000),TOLER,NURSNO
     COMMON /MIDTEMP/NMCOMP(8),TMID(8,2000),QMID1(8,2000),QMID2(8,2000)
C
C READ:
C   NMWALL: NUMBER OF CONDUCTION LOSS UNITS
C   K : THE NUMBER OF FLUX FACTORS USED (ORDER +1)
C   NRF: THE NUMBER OF TEMPERATURE RESPONSE FACTORS
C
     READ(1,*) NMWALL,K,NRF
     DO 12 NW = 1,NMWALL
c
c READ:
c  NMCOMP: NUMBER OF CALCULATION COMPONENTS INTO WHICH THE WALL
```

```
c         WILL BE DIVIDED
c
      READ(1,*) NMCOMP(NW)
      DO 13 NC = 1,NMCOMP(NW)
        DO 10 I = 1,NRF
C
C  READ THE RESPONSE FACTORS
C
          READ(1,*) X(NW,NC,I),Y(NW,NC,I),Z(NW,NC,I)
C
C  CHANGE THE RESPONSE FACTORS FROM ENGLISH TO SI UNITS  (W/M2 K)
C
          X(NW,NC,I) = X(NW,NC,I)*5.678
          Y(NW,NC,I) = Y(NW,NC,I)*5.678
          Z(NW,NC,I) = Z(NW,NC,I)*5.678
  10    CONTINUE
        DO 11 I = 1,K
C
C  READ THE FLUX FACTORS
C
          READ(1,*) XJ(NW,NC,I)
  11    CONTINUE
  13  CONTINUE
C
C  READ THE WALL AREA, THE AMBIENT TEMPERATURES, AND THE
C    INITIAL ROOM TEMPERATURE
C
C     H1C: THE CONVECTION COEFFICIENT AT THE INSIDE SURFACE (W/M2 K)
C     HNC: THE CONVECTION COEFFICIENT AT THE OUTSIDE SURFACE (W/M2 K)
C     AREA: AREA OF THE CONDUCTION UNITS (M2)
C     EMISS: EMISSIVITY OF THE OUTER WALL SURFACE
C     ABSORP: ABSORPTIVITY OF THE OUTER WALL SURFACE
C     TA: AMBIENT TEMPERATURE (C)
C     TR: INITIAL GUESS AT THE ROOM TEMPERATURE  (C)
C     TSKY: EFFECTIVE SKY TEMPERATURE FOR LONGWAVE EMMISION (K)
C     QS: THE SOLAR RADIATION ON THE SURFACE  (W/M2)
C
      IF(NW.EQ.1)THEN
        READ(1,*) AREA(NW),TA(NW,1),TR(1),EMISS(1),ABSORP(1)
      ELSE
        READ(1,*) AREA(NW),TA(NW,1),EMISS(NW),ABSORP(NW)
      ENDIF
C
C  READ IN:
C    NURSNO: NURSERY NUMBER
C    DIRN: NORTH - SOUTH DIRECTION (1 = FROM NORTH, 0 = FROM SOUTH)
C    DIRE: EAST - WEST DIRECTION (1 = FROM EAST, 0 = FROM WEST)
C    SPEEDN: NORTH - SOUTH SPEED (M/S)
C    SPEEDE: EAST -WEST SPEED   (M/S)
C
     IF(NW.EQ.6)THEN
       READ(1,*) NURSNO,DIRN,DIRE
       SPEEDN = ABS(VELOCITY)
       SPEEDE = ABS(VELOCITY)
C
C  CALCULATE THE EXTERIOR SURFACE CONVECTION COEFFICIENTS
C
       IF(NURSNO.EQ.1)THEN
         IF(DIRN.EQ.1.)THEN
           HNC(4)=  2.438*SPEEDN**.8
         ELSE
           HNC(4) = (16.57*SPEEDN**.8-20.6)/3.6
         ENDIF
         IF(DIRE.EQ.1.)THEN
           HNC(2) = 2.929*SPEEDE**.8
         ELSE
           HNC(2) = (20.16*SPEEDE**.8-20.6)/4.6
         ENDIF
       ELSE
         IF(DIRN.EQ.1.)THEN
           HNC(4) = 2.506*SPEEDN**.8
         ELSE
```

```
        HNC(4) = 3.411*SPEEDN**.8
       ENDIF
      ENDIF
     ENDIF
C
C
C  INITIALIZE THE TRANSFER FUNCTION EQUATIONS
C
      IF(NMCOMP(NW).EQ.1)THEN
c
c  INITIALIZE FOR A WALL MADE OF A SINGLE CALCULATION COMPONENT
c
       DO 14 L = 1,100
        T1(NW,L) = TR(1)-1.
        TN(NW,L) = TA(NW,1) + 1.
        W = 0.0
        U = 0.0
        V = 0.0
        S = 0.0
        IF(L.GT.1)THEN
C
C  CALCULATE THE FLUX FACTOR
C
         IF(L.LE.K)THEN
          DO 15 M = 1,L-1
           V = V + (-1.)**(M + 1)*XJ(NW,1,M)*QN(NW,L-M)
           U = U + (-1.)**(M + 1)*XJ(NW,1,M)*Q1(NW,L-M)
 15       CONTINUE
         ELSE
          DO 16 M = 1,K
           V = V + (-1.)**(M + 1)*XJ(NW,1,M)*QN(NW,L-M)
           U = U + (-1.)**(M + 1)*XJ(NW,1,M)*Q1(NW,L-M)
 16       CONTINUE
         ENDIF
        ENDIF
C
C  CALCULATE THE TEMPERATURE FACTORS
C
        IF(L.LT.NRF)THEN
         DO 17 N = 1,L
          S = S + Y(NW,1,N)*T1(NW,L-N + 1)-Z(NW,1,N)*TN(NW,L-N + 1)
          W = W + X(NW,1,N)*T1(NW,L-N + 1)-Y(NW,1,N)*TN(NW,L-N + 1)
 17      CONTINUE
        ELSE
         DO 18 N = 1,NRF
          S = S + Y(NW,1,N)*T1(NW,L-N + 1)-Z(NW,1,N)*TN(NW,L-N + 1)
          W = W + X(NW,1,N)*T1(NW,L-N + 1)-Y(NW,1,N)*TN(NW,L-N + 1)
 18      CONTINUE
        ENDIF
        Q1(NW,L) = U + W
        QN(NW,L) = V + S
C     WRITE(5,99) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
 14    CONTINUE
      ELSE
C
C  INITIALIZE FOR DOUBLE CALCULATION COMPONENTS
C
       DO 19 L = 1,100
        T1(NW,L) = TR(1)-1.
        TN(NW,L) = TA(NW,1) + 1.
        TMID(NW,L) = (TN(NW,L) + T1(NW,L))/2.
        W = 0.0
        U = 0.0
        V = 0.0
        S = 0.0
        W1 = 0.0
        U1 = 0.0
        U2 = 0.0
        W2 = 0.0
        IF(L.GT.1)THEN
C
```

```
C  CALCULATE THE FLUX FACTOR
C
          IF(L.LE.K)THEN
           DO 20 M=1,L-1
            V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
            U=U+(-1.)**(M+1)*XJ(NW,1,M)*QMID1(NW,L-M)
            U1=U1+(-1.)**(M+1)*XJ(NW,2,M)*Q1(NW,L-M)
            U2=U2+(-1.)**(M+1)*XJ(NW,2,M)*QMID2(NW,L-M)
 20         CONTINUE
          ELSE
           DO 21 M=1,K
            V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
            U=U+(-1.)**(M+1)*XJ(NW,1,M)*QMID1(NW,L-M)
            U1=U1+(-1.)**(M+1)*XJ(NW,2,M)*Q1(NW,L-M)
            U2=U2+(-1.)**(M+1)*XJ(NW,2,M)*QMID2(NW,L-M)
 21         CONTINUE
          ENDIF
         ENDIF
C
C  CALCULATE THE TEMPERATURE FACTORS
C
         IF(L.LT.NRF)THEN
          DO 22 N=1,L
           W=W+X(NW,1,N)*TMID(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
           S=S+Y(NW,1,N)*TMID(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
           W1=W1+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
           W2=W2+Y(NW,2,N)*T1(NW,L-N+1)-Z(NW,2,N)*TMID(NW,L-N+1)
 22        CONTINUE
         ELSE
          DO 23 N=1,NRF
           W=W+X(NW,1,N)*TMID(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
           S=S+Y(NW,1,N)*TMID(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
           W1=W1+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
           W2=W2+Y(NW,2,N)*T1(NW,L-N+1)-Z(NW,2,N)*TMID(NW,L-N+1)
 23        CONTINUE
         ENDIF
         Q1(NW,L)=U1+W1
         QMID1(NW,L)=U+W
         QMID2(NW,L)=U2+W2
         QN(NW,L)=V+S
C      WRITE(5,99) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
 99 FORMAT(4F10.3)
 19    CONTINUE
      ENDIF
      TA(NW,100)=TA(NW,1)
 12 CONTINUE
    TR(101)=TR(1)
    TF(100)=15.
    RETURN
    END
C
C  *******************************************************
C
C
    SUBROUTINE WALLS
C
C  THIS SUBROUTINE CALCULATES THE SURFACE TEMPERATURES AND HEAT
C   LOSSES THROUGH THE WALLS AND CEILING
C
    IMPLICIT DOUBLE PRECISION (A-H,O-Z)
    COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
    COMMON /LOSS/ T1(8,2000),TN(8,2000),Q1(8,2000),QN(8,2000),ITIME
    COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
    COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
    COMMON /MISC/ TF(2000),TOLER,NURSNO
    COMMON /MIDTEMP/NMCOMP(8),TMID(8,2000),QMID1(8,2000),QMID2(8,2000)
C
C  KEY TO WALL NUMBERS:
C   1 = NORTH
C   2 = SOUTH
C   3 = EAST
C   4 = WEST
```

```
C    5 = CEILING
C    6 = SLAB
C
C
C  INITIALIZE THE VARIABLES
C
      L=ITIME+100
      IF(NMWALL.EQ.1)THEN
       NMW=1
      ELSE
       NMW=NMWALL-1
      ENDIF
      DO 51 NW=1,NMW
       T1(NW,L)=T1(NW,L-1)
       TN(NW,L)=TN(NW,L-1)
       IF(NMCOMP(NW).EQ.2)TMID(NW,L)=TMID(NW,L-1)
C
C  CALCULATE A AND B USING THE TRANSFER FUNCTION EQUATIONS
C
       W=0.0
       U=0.0
       V=0.0
       S=0.0
       R=0.0
       R1=0.0
       P=0.0
       P1=0.0
       A=0.0
       B=0.0
       C=0.0
       C1=0.0
C
C  CALCULATE THE FLUX FACTOR
C
       DO 19 M=1,K
        V=V+(-1.)**(M+1)*XJ(NW,1,M)*QN(NW,L-M)
        IF(NMCOMP(NW).EQ.1)THEN
         U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
        ELSE
         U=U+(-1.)**(M+1)*XJ(NW,2,M)*Q1(NW,L-M)
         R=R+(-1.)**(M+1)*XJ(NW,2,M)*QMID2(NW,L-M)
         R1=R1+(-1.)**(M+1)*XJ(NW,1,M)*QMID1(NW,L-M)
        ENDIF
   19  CONTINUE
C
C  CALCULATE THE TEMPERATURE FACTORS
C
       DO 20 N=2,NRF
        IF(NMCOMP(NW).EQ.1)THEN
         S=S+Y(NW,1,N)*T1(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
         W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
        ELSE
         S=S+Y(NW,1,N)*TMID(NW,L-N+1)-Z(NW,1,N)*TN(NW,L-N+1)
         W=W+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
         P1=P1+X(NW,1,N)*TMID(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
         P=P+Y(NW,2,N)*T1(NW,L-N+1)-Z(NW,2,N)*TMID(NW,L-N+1)
        ENDIF
   20  CONTINUE
       A=V+S
       B=U+W
       C=R+P
       C1=R1+P1
C
C  SET THE LENGTH OF THE WALL CURRENTLY BEING CALCULATED
C
       IF(NW.GE.1.AND.NW.LE.4)XLENG=2.6
       IF(NW.EQ.5)XLENG=1.02
C
C  DETERMINE THE RAYLEIGH NUMBER
C
   50  RA1=ABS((2.644D10*(T1(NW,L)-TR(L))*XLENG**3.)/
```

```
     $  (273.15+(T1(NW,L)+TR(L))/2.))
C
C  CALCULATE THE SURFACE FREE CONVECTION COEFFICIENTS FOR THE
C     INNER SURFACES
C
        IF(NW.GE.1.AND.NW.LE.4)THEN
          H1C(NW)=0.0265/XLENG*(0.825+0.3244*RA1**.1667)**2
        ELSE
          H1C(NW)=0.0265/XLENG*0.27*RA1**.25
        ENDIF
C
C  ITERATIVELY SOLVE FOR THE RADIANT COEFFICIENT AND THE OUTSIDE
C    SURFACE TEMPERATURE
C
C  CALCULATE THE OUTSIDE RAYLEIGH NUMBER
C
   52  RAN=ABS((2.644D10*(TN(NW,L)-TA(NW,L))*XLENG**3.)/
     $   (273.15+(TN(NW,L)+TA(NW,L))/2.))
C
C  CALCULATE THE SURFACE FREE CONVECTION COEFFICIENTS FOR THE
C    OUTER SURFACES WHICH ARE NOT EXPOSED TO WIND
C
        IF(NURSNO.EQ.1)THEN
          IF(NW.EQ.1.OR.NW.EQ.3.)THEN
            HNC(NW)=0.0265/XLENG*(0.825+0.3244*RAN**.1667)**2.
          ENDIF
        ELSE
          IF(NW.GE.1.OR.NW.LE.3)THEN
            HNC(NW)=0.0265/XLENG*(0.825+0.3244*RAN**.1667)**2.
          ENDIF
        ENDIF
        IF(NW.EQ.5)THEN
          HNC(NW)=3.975D-03/XLENG*RAN**0.333
        ENDIF
C
C  CALCULATE THE RADIANT COEFFICIENT

        HR=EMISS(NW)*5.669E-08*(TSKY(NW,L)**2.+
     $   (TN(NW,L)+273.15)**2.)*(TSKY(NW,L)+TN(NW,L)+273.15)
C
C  CALCULATE THE NEW OUTER SURFACE WALL TEMPERATURE
C
        IF(NMCOMP(NW).EQ.1)THEN
          TNNEW=(A+Y(NW,1,1)*T1(NW,L)+HR*TSKY(NW,L)-HR*273.15+
     $     HNC(NW)*TA(NW,L)+ABSORP(NW)*QS(NW,L))/(Z(NW,1,1)+HR+HNC(NW))
        ELSE
          TNNEW=(A+Y(NW,1,1)*TMID(NW,L)+HR*TSKY(NW,L)-HR*273.15+
     $     HNC(NW)*TA(NW,L)+ABSORP(NW)*QS(NW,L))/(Z(NW,1,1)+HR+HNC(NW))
        ENDIF
C
C  DETERMINE THE CHANGE FROM THE PREVIOUS TEMPERATURE TO THE NEWLY
C    CALCULATED ONE
C
        DELTA=(TNNEW-TN(NW,L))
        IF(ABS(DELTA).GT.TOLER)THEN
          TN(NW,L)=TNNEW-DELTA/2.
          GOTO 52
        ENDIF
C
C     SOLVE ITERATIVELY FOR THE INSIDE SURFACE TEMPERATURE
C
        IF(NMCOMP(NW).EQ.1)THEN
          T1NEW=(Y(NW,1,1)*TN(NW,L)+H1C(NW)*TR(L)-B)/(X(NW,1,1)+H1C(NW))
        ELSE
          T1NEW=(Y(NW,2,1)*TMID(NW,L)+H1C(NW)*TR(L)-B)/
     $      (X(NW,2,1)+H1C(NW))
        ENDIF
C
C  DETERMINE THE DIFFERENCE BETWEEN THE NEWLY CALCULATED INTERIOR
C    SURFACE TEMPERATURE AND THE OLD ONE
C
        DELTA=(T1NEW-T1(NW,L))
```

```
      IF(ABS(DELTA).GT.TOLER*10.)THEN
       T1(NW,L)=T1NEW-DELTA/2.
       GOTO 50
      ENDIF
C
C ITERATIVELY SOLVE FOR THE MIDPOINT TEMPERATURE IF A MIDPOINT IS
C   BEING USED
C
      IF(NMCOMP(NW).EQ.2)THEN
       TMIDNE=(C-C1+Y(NW,2,1)*T1(NW,L)+Y(NW,1,1)*TN(NW,L))/
     $       (X(NW,1,1)+Z(NW,2,1))
       DELTA=(TMIDNE-TMID(NW,L))
       IF(ABS(DELTA).GT.TOLER)THEN
        TMID(NW,L)=TMIDNE-DELTA/2.
        GOTO 52
       ENDIF
      ENDIF
C
C CALCULATE THE HEAT LOSS THROUGH THE EXTERIOR WALL SURFACE, THE
C   INTERIOR WALL SURFACE AND THE MIDDLE OF THE WALL
C
      IF(NMCOMP(NW).EQ.1)THEN
       QN(NW,L)=A+Y(NW,1,1)*T1(NW,L)-Z(NW,1,1)*TN(NW,L)
       Q1(NW,L)=B+X(NW,1,1)*T1(NW,L)-Y(NW,1,1)*TN(NW,L)
      ELSE
       QN(NW,L)=A+Y(NW,1,1)*TMID(NW,L)-Z(NW,1,1)*TN(NW,L)
       Q1(NW,L)=B+X(NW,2,1)*T1(NW,L)-Y(NW,2,1)*TMID(NW,L)
       QMID1(NW,L)=C1+X(NW,1,1)*TMID(NW,L)-Y(NW,1,1)*TN(NW,L)
       QMID2(NW,L)=C+Y(NW,2,1)*T1(NW,L)-Z(NW,2,1)*TMID(NW,L)
      ENDIF
C      WRITE(5,98) NW,T1(NW,L),TN(NW,L),TA(NW,L),H1C(NW),HNC(NW)
C      WRITE(5,*) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
   98 FORMAT(I5,5F10.3)
   51 CONTINUE
      RETURN
      END
C
C
C  *******************************************************
C
C
      SUBROUTINE SLAB
C
C THIS SUBROUTINE CALCULATES THE SLAB TEMPERATURE, THE PIT FLUID
C   TEMPERATURE AND THE HEAT FLOW THROUGH THE SLAB
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
      COMMON /LOSS/ T1(8,2000),TN(8,2000),Q1(8,2000),QN(8,2000),ITIME
      COMMON /TRFM/ X(8,2,33),Y(8,2,33),Z(8,2,33),XJ(8,2,5),NMWALL,K,NRF
      COMMON /WALLCH/ H1C(8),HNC(8),AREA(8),EMISS(8),ABSORP(8)
      COMMON /MISC/ TF(2000),TOLER,NURSNO
      COMMON /MIDTEMP/NMCOMP(8),TMID(8,2000),QMID1(8,2000),QMID2(8,2000)
C
C IN THIS SUBROUTINE:
C   TN:  THE DEEP GROUND TEMPERATURE BELOW THE SLAB (C)
C   T1:  THE SLAB TEMPERATURE (C)
C   TF:  THE PIT FLUID TEMPERATURE  (C)
C   HFC:  CONVECTION COEFFICIENT BETWEEN THE SLAB AND FLUID (W/M2 K)
C   H1C:  CONVECTION COEFFICIENT BETWEEN THE FLUID AND THE AIR (W/M2 K)
C   DENS: THE MASS OF PIT LIQUID (KG/M2)
C   SPHT: SPECIFIC HEAT OF THE PIT LIQUID (J/KG K)
C   STEP: THE TIME STEP (S)
C
C
C CALCULATE C USING THE TRANSFER FUNCTION EQUATIONS
C
      NW=NMWALL
      L=ITIME+100
      T1(NW,L)=T1(NW,L-1)
      TN(NW,L)=22.
      TF(L)=TF(L-1)
```

```
      DENS=202.
      SPHT=4190.
      STEP=3600
      W=0.0
      U=0.0
      C=0.0
      D=0.0
      E=0.0
C
C  CALCULATE THE FLUX FACTOR
C
      DO 19 M=1,K
C
C   FOR A SINGLE LAYER
C
       IF(NMCOMP(NW).EQ.1)THEN
        U=U+(-1.)**(M+1)*XJ(NW,1,M)*Q1(NW,L-M)
C
C   FOR A DOUBLE LAYER
C
       ELSE
        U=U+(-1.)**(M+1)*XJ(NM,2,M)*Q1(NM,L-M)
        R=R+(-1.)**(M+1)*XJ(NM,1,M)*QMID1(NM,L-M)
        R1=R1+(-1.)**(M+1)*XJ(NM,2,M)*QMID2(NM,L-M)
       ENDIF
   19 CONTINUE
C
C  CALCULATE THE TEMPERATURE FACTORS
C
      DO 20 N=2,NRF
C
C   FOR A SINGLE LAYER
C
       IF(NMCOMP(NW).EQ.1)THEN
        W=W+X(NW,1,N)*T1(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
C
C   FOR A DOUBLE LAYER
C
       ELSE
        W=W+X(NW,2,N)*T1(NW,L-N+1)-Y(NW,2,N)*TMID(NW,L-N+1)
        S=S+X(NW,1,N)*TMID(NW,L-N+1)-Y(NW,1,N)*TN(NW,L-N+1)
        S1=S1+Y(NW,2,N)*T1(NW,L-N+1)-Z(NW,2,N)*TMID(NW,L-N+1)
       ENDIF
   20 CONTINUE
      C=U+W
      D=R+S
      E=R1+S1
C
C  ITERATIVELY SOLVE FOR THE SLAB TEMPERATURE AND THE FLUID TEMPERATURE
C
   50 H1C(NW)=ABS((TR(L)-TF(L))/(273.15+(TF(L)+TR(L))/2.))
      H1C(NW)=2.95*H1C(NW)**.25
      HFC=ABS((TF(L)-T1(NW,L))/(273.15+(TF(L)+T1(NW,L))/2.))
      HFC=390.3*HFC**.25
C
C   CALCULATE THE UPPER SLAB SURFACE TEMPERATURE
C
      IF(NMCOMP(NW).EQ.1)THEN
       T1(NW,L)=(Y(NW,1,1)*TN(NW,L)-C+HFC*TF(L))/(HFC+X(NW,1,1))
      ELSE
       T1(NW,L)=(Y(NW,2,1)*TMID(NW,L)-C+HFC*TF(L))/(HFC+X(NW,2,1))
      ENDIF
C
C   CALCULATE THE MIDPOINT TEMPERATURE FOR A DOUBLE LAYER APPLICATION
C
      IF(NMCOMP(NW).EQ.1)THEN
       TMIDNE=(E+Y(NW,2,1)*T1(NW,L)-D+Y(NW,1,1)*TN(NW,L))/
     $   (X(NW,1,1)+Z(NW,2,1))
       DELTA=(TMIDNE-TMID(NW,L))
       IF(ABS(DELTA).GE.TOLER)THEN
        TMID(NW,L)=TMIDNE-DELTA/2.
        GOTO 50
```

```
        ENDIF
       ENDIF
C
C      CALCULATE THE FLUID TEMPERATURE
C
       TFNEW=(HFC*T1(NW,L)+H1C(NW)*TR(L)+DENS*SPHT*TF(L-1)/STEP)/
     $ (HFC+H1C(NW)+DENS*SPHT/STEP)
       DELTA=(TFNEW-TF(L))
       IF(ABS(DELTA).GE.TOLER)THEN
        TF(L)=TFNEW-DELTA/2.
C        WRITE(5,*) TF(L),T1(NW,L),H1C(NW),HFC
        GOTO 50
       ENDIF
       IF(NMCOMP(NW).EQ.1)THEN
        Q1(NW,L)=X(NW,1,1)*T1(NW,L)-Y(NW,1,1)*TN(NW,L)+C
       ELSE
        Q1(NW,L)=X(NW,2,1)*T1(NW,L)-Y(NW,2,1)*TMID(NW,L)+C
        QMID1(NW,L)=X(NW,1,1)*TMID(NW,L)-Y(NW,1,1)*TN(NW,L)+D
        QMID2(NW,L)=Y(NW,2,1)*T1(NW,L)-Z(NW,2,1)*TMID(NW,L)+E
       ENDIF
C       WRITE(5,*) Q1(NW,L),TF(L),T1(NW,L)
C       WRITE(5,*) Q1(NW,L),QMID2(NW,L),QMID1(NW,L),QN(NW,L)
       QN(NW,L)=0.0
       RETURN
       END
C
C
C
C *******************************************************
C
C
      SUBROUTINE VENTIL
C
C
C THIS SUBROUTINE CALCULATES THE VENTILATION HEAT LOSS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
      COMMON /LOSS/ T1(8,2000),TN(8,2000),Q1(8,2000),QN(8,2000),ITIME
      COMMON /INFILT/ DAILY(18),WO(2000),WI(2000),PIGS,VENTRATE,QV,WDOTSUP
      L=ITIME+100
C
C CALCULATE THE MOISTURE CHANGE IN THE BUILDING DUE TO AIR EXCHANGE
C
      VOL=48.8
      STEP=3600.
      SPVOL=8.315/28.97*(TR(L)+273.15)*(1.+1.6078*WI(L-1))/101.325
      DOTMA=VENTRATE/SPVOL
      WDOTAN=DAILY(13)*PIGS/2430.E03
      WOLD=WI(L-1)
      DO 10 I=1,60
        DELW=(STEP/60.)*(((DOTMA*WO(L)+WDOTAN)-DOTMA*WOLD)/(VOL/SPVOL))
        WOLD=WOLD+DELW
   10 CONTINUE
      WINEW=WOLD
      CALL PSYCHRO(TR(L),TR(L),WSAT)
      IF(WINEW.GT.WSAT.OR.WINEW.LE.0.0)WINEW=WSAT
c       WRITE(6,*) SPVOL,DOTMA,WDOTAN
c       WRITE(6,*) DELW,WI(L-1),WO(L),WINEW
C
C CALCULATE THE INDOOR AND OUTDOOR ENTHALPY VALUES
C
      HI=TR(L)+WINEW*(2501.+1.805*TR(L))
      HO=TA(3,L)+WO(L)*(2501.+1.805*TA(3,L))
C
C CALCULATE THE HEAT LOST DUE TO VENTILATION
C
      QV=DOTMA*1000.*(HO-HI)
C
C CHECK THE NEW VALUE FOR THE HUMIDITY RATIO
C
      DELTA=WINEW-WI(L)
```

```
      IF(ABS(DELTA).GE.0.0005)THEN
        WI(L) = WINEW-DELTA/2.
      ELSE
        WI(L+1) = -6999.
      ENDIF
      RETURN
      END
C
C
C *******************************************************
C
      SUBROUTINE SOLAR(NURSNO,SKYTEM,L)
C
C THIS SUBROUTINE PROCESSES THE SOLAR DATA FILE TO DETERMINE
C   THE SOLAR LOAD ON THE WEST AND SOUTH WALLS OF THE SWINE
C   NURSERY AND THE EFFECTIVE SKY TEMPERATURE
C
C
C   THE DATA READ IN IS THE DAY, TIME, AND THE READINGS FROM
C     A PYRGEOMETER, PYRANOMETER (HORIZONTAL), AND A PYRHELIOMETER
C     (NORMAL BEAM)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON /AMBIE/ TSKY(8,2000),TA(8,2000),QS(8,2000),TR(2000)
      PI = 3.14159
C
C READ THE SOLAR DATA FILE AND FIND THE HOURLY AVERAGES
C
      X1 = 0.0
      X2 = 0.0
      X3 = 0.0
      AVG = 0.0
C
   12 READ(3,*) DAY,TIME,GSKY,G,GBN
      IF(GSKY.LT.0.0)GSKY = 0.0
      IF(G.LT.0.0)G = 0.0
      IF(GBN.LT.0.0)GBN = 0.0
C
C    IF THE READINGS ARE PER MINUTE EXCLUDE THEM
C
      IF(DMOD(TIME,10.D0).EQ.0.0)THEN
C
C    SUM THE READINGS FOR A SINGLE HOUR
C
C        WRITE(6,*) TIME
        X1 = X1 + GSKY
        X2 = X2 + G
        X3 = X3 + GBN
        AVG = AVG + 1
C
C    IF THE READING IS ON THE HOUR, AVERAGE THE READINGS TO
C      PRODUCE HOURLY AVERAGE READINGS
C
        IF(DMOD(TIME,100.D0).NE.0.0)THEN
          GOTO 12
        ELSE
          GSKY = X1/AVG
          G = X2/AVG
          GBN = X3/AVG
        ENDIF
      ELSE
        GOTO 12
      ENDIF
      DO 14 M = 1,8
        QS(M,L) = 0.0
   14 CONTINUE
C
C CALCULATE THE EFFECTIVE SKY TEMPERATURE (DEGREES K)
C
      SKYTEM = (GSKY/5.67E-11)**.25-273.15
C
```

```
C CALCULATE THE SOLAR TIME
C
      B=360.*(DAY-81.)/364.*PI/180.
      E=9.87*SIN(2.*B)-7.53*COS(B)-1.5*SIN(B)
C
C     CHANGE THE TIME TO A DECIMAL
C
      ATIME=TIME/100.
      DO 10 I=1,24
        AHOUR=I
        DECTIME=AHOUR-ATIME
        IF(DECTIME.GT.0.0)THEN
          AHOUR=AHOUR-1.
          DMIN=  (ATIME-AHOUR)*100./60.
          DECTIME=AHOUR+DMIN
          GOTO 11
        ENDIF
   10 CONTINUE
   11 SOLTIME=DECTIME+(4.*(75.-80.5)+E)/60.
      IF(SOLTIME.LT.0.0)SOLTIME=SOLTIME+24.
C
C CALCULATE THE DECLINATION AND HOUR ANGLES
C
      D=23.45*SIN(360.*(284.+DAY)/365.*PI/180.)
      W=(SOLTIME - 12.)*15.*PI/180.
C
C CALCULATE THE INCIDENCE ANGLES FOR THE WEST WALL AND HORIZONTAL
C
      BETA=90.*PI/180.
      GAMMA=60.*PI/180.
      RLAT=37.5*PI/180.
      COSTH=-SIN(D*PI/180.)*COS(RLAT)*COS(GAMMA)
     $  +COS(D*PI/180.)*SIN(RLAT)*COS(GAMMA)*COS(W)
     $ +COS(D*PI/180.)*SIN(GAMMA)*SIN(W)
      COSTHZ=COS(D*PI/180.)*COS(RLAT)*COS(W)+SIN(D*PI/180.)*SIN(RLAT)
C
C CALCULATE THE INCIDENCE
C
      GBT=GBN*COSTH
      GB=GBN*COSTHZ
      GD=G-GB
      IF(W.GE.0.0.AND.GBN.GE.0.0)THEN
        QS(4,L)=(GBT+GD)*1000.
      ELSE
        QS(4,L)=GD*1000.
      ENDIF
      IF(QS(4,L).LT.0.0)QS(4,L)=0.0
C
C CALCULATE THE INCIDENCE ANGLE FOR THE SOUTH WALL OF NURS 1
C
      IF(NURSNO.EQ.1)THEN
        GAMMA=-30.*PI/180.
        COSTH=-SIN(D*PI/180.)*COS(RLAT)*COS(GAMMA)
     $   +COS(D*PI/180.)*SIN(RLAT)*COS(GAMMA)*COS(W)
     $   +COS(D*PI/180.)*SIN(GAMMA)*SIN(W)
C
C CALCULATE THE INCIDENCE
C
        GBT=GBN*COSTH
        GB=GBN*COSTHZ
        GD=G-GB
        QS(2,L)=(GBT+GD)*1000.
        IF(QS(2,L).LT.0.0)QS(2,L)=0.0
      ENDIF
C      WRITE(7,13) DAY,TIME,SOLTIME,G,GBN,QS(2,L),QS(4,L),SKYTEM
   13 FORMAT(2F10.1,F10.2,2F10.3,3F10.1)
      RETURN
      END
C
C
C **********************************************
C
```

```
      SUBROUTINE PSYCHRO(TWB,TDB,W)
C
C  THIS SUBROUTINE CALCULATES THE HUMIDITY RATIO GIVEN THE
C    WET AND DRY BULB TEMPERATURE
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL TW
C
C  TWB : WET BULB TEMPERATURE (C)
C  TDB : DRY BULB TEMPERATURE (C)
C   W  : HUMIDITY RATIO (KG H20/KG DA)
C
C  SET THE NEEDED CONSTANTS (FROM ASHRAE FUNDAMENTALS)
C
      C1 = -5674.5359
      C2 = 6.3925247
      C3 = -0.9677843E-02
      C4 = 0.62215701E-06
      C5 = 0.20747825E-08
      C6 = -0.9484024E-12
      C7 = 4.1635019
      C8 = -5800.2206
      C9 = 1.3914993
      C10 = -0.04860239
      C11 = 0.41764768E-04
      C12 = -0.14452093E-07
      C13 = 6.5459673
C
C  SET THE ATMOSPHERIC PRESSURE (Pa)
C
      P = 101325.
C
C  CONVERT THE WET BULB TEMPERATURE FROM DEGREES C TO DEGREES K
C
      TW=TWB+273.15
C
C  CALCULATE THE SATURATED VAPOR PRESSURE FOR AIR OVER ICE
C
      IF(TWB.GE.-100..AND.TWB.LE.0.)THEN
        ALNPWS = C1/TW + C2 + C3*TW + C4*TW**2. + C5*TW**3. + C6*TW**4.
     $    + C7*ALOG(TW)
      ENDIF
C
C  CALCULATE THE SATURATED VAPOR PRESSURE FOR AIR OVER WATER
C
      IF(TWB.GT.0..AND.TWB.LE.200.)THEN
        ALNPWS = C8/TW + C9 + C10*TW + C11*TW**2. + C12*TW**3. + C13*ALOG(TW)
      ENDIF
      PWS = EXP(ALNPWS)
      WS = 0.62198*PWS/(P-PWS)
      W = ((2501.-2.381*TWB)*WS-(TDB-TWB))/(2501. + 1.805*TDB-4.186*TWB)
   11 FORMAT(2F10.1,F10.5)
      RETURN
      END
C ***************************************************
C
C  THIS SUBROUTINE CALCULATES WEIGHT GAIN FOR THE
C    OPTIMIZATION WITHOUT AFFECTING THE GLOBAL VARIABLES
C
      SUBROUTINE OPTGAIN(WG,FC)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT,PASTGL
      PTNEW = (PT*1000. + PR)*(5.5-0.0116*(BW-5.))/24.
      GL = (PTNEW-(ALT*1000.))
      IF(DAYHR.GT.0.045)THEN
```

```
        GL=GL*24.
C       IF(PASTGL.GT.0.0)PERCHG=(GL-PASTGL)/PASTGL
C       IF(ABS(PERCHG).GT.0.15)GL=(PASTGL+GL)/2.
      ENDIF
      PASTGL=GL
      GF=1.1*ALR/24.
      GA=0.215*PR/24.
      EBG=GL+GF+GA
      WG=EBG+0.05*EBG
      FC=FIA/24.
      RETURN
      END
C
C
C ****************************************************
C
C     THIS IS THE SECTION CONVERTED FROM THE PROGRAM
C       WRITTEN BY DR. RICHARD EWAN OF THE IOWA STATE
C       ANIMAL SCIENCE DEPARTMENT
C
C ****************************************************
C
C THIS SUBROUTINE INITIALIZES THE ELEMENTS FOR THE PIG MODEL
C
      SUBROUTINE PIGINTL
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION RF45V(4)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      RF45V(1)=0.04
      RF45V(2)=0.12
      RF45V(3)=0.5
      RF45V(4)=0.0
      IFI=0
      DAYHR=0
      AGEHR=AGE
      ICOMP=0
      DO 16 I=1,18
       C(I)=0.0
   16 CONTINUE
      CALL COMPO
      PTM=PHYS(9)
      PRM=PHYS(8)
      ADE=FEED(4)/4.184
      ANE=FEED(5)/4.184
      AK=FEED(5)/FEED(4)
      RATCON=FEED(4)*.96
      ANOP=PHYS(7)
      PENSZ=PHYS(8)*PHYS(9)
      DCP=FEED(1)*FEED(2)*0.01
      IFTYPE=HOUSE(4)
      RF45=RF45V(IFTYPE)
      RETURN
      END
C ***********************************************
C
C THIS SUBROUTINE CALCULATES FEED ADJUSTMENTS
C
      SUBROUTINE INTAKE
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT,PASTGL
      DIMENSION AAL(4)
      IF(DAYHR.EQ.0)THEN
       DO 11 I=1,7
```

```
        ADJ(I)=0.0
   11   CONTINUE
      ENDIF
      H1=0.
      WTM= BW**.75
C
C  FOR PIGS IN EXCESS OF 18 KG
C
      FI1=13162.*(1.-EXP(-0.0176*BW))
C
C  FOR PIGS LESS THAN 18 KG
C
      IF(IFI.LE.0.AND.AGEHR.LE.49)THEN
       FI2=108.*(AGEHR-20)-101.
       FI3=456.*BW-9.46*BW**2-1531.
       IF(FI2.GT.FI3)FI2=FI3
       IF(FI2.LT.FI1)FI1=FI2
      ENDIF
C
C  SEX ADJUSTMENT
C
      SEX=(PHYS(3)-PHYS(5)-PHYS(1))/PHYS(7)
      IF(BW.GT.18.)IFI=1
      IF(BW.LT.10.)GOTO 12
      IF(BW.GE.25.)THEN
       CHG=0.214*BW-0.00133*BW**2-4.42
       ADJ(1)=FI1*SEX*CHG*0.01
      ENDIF
C
C  SPACE AND PIGS/PEN ADJUSTMENT
C
      IF(BW.LE.20.)THEN
       ADJ(2)=1.324*HOUSE(11)-1.5954*HOUSE(11)**2+0.7227
       ADJ(3)=PHYS(7)*(-29.44)
      ENDIF
      IF(BW.GT.20..AND.BW.LE.50.)THEN
       ADJ(2)=0.4293*HOUSE(11)-0.2025*HOUSE(11)**2+0.7725
       ADJ(3)=PHYS(7)*(-8.0)
      ENDIF
      IF(BW.GT.50.)THEN
       ADJ(2)=0.7*HOUSE(11)-0.32*HOUSE(11)**2+0.6165
       ADJ(3)=PHYS(7)*10.24
       ADJ(2)=ADJ(2)*FI1-FI1
      ENDIF
C
C  PELLETIZED ADJUSTMENT
C
      IPELL=FEED(11)
      IF(IPELL.LT.2)THEN
       IF(BW.LT.20.)THEN
        ADJ(4)=FI1*(-9.000001E-02)
       ELSE
        ADJ(4)=FI1*(-0.031)
       ENDIF
      ENDIF
C
C  ANTIBIOTIC ADJUSTMENT
C
      IANTI=FEED(12)
      IF(IANTI.LT.2)THEN
       IF(BW.LE.16.)ADJ(5)=FI1*0.08
       IF(BW.LE.57..AND.BW.GT.16.)ADJ(5)=FI1*0.06
       IF(BW.GT.57.)ADJ(5)=FI1*0.02
      ENDIF
C
C  ENERGY DENSITY ADJUSTMENT
C
      IF(BW.LE.30.)THEN
       IF(ADE.LT.3.3)ADJ(6)=(ADE-3.3)*1388.
       IF(ADE.GT.3.6)ADJ(6)=(ADE-3.6)*183.
      ELSE
       IF(ADE.LT.3.3)ADJ(6)=(ADE-3.3)*2773.
```

```
      ENDIF
C
C  ADJUST FEED INTAKE
C
      DO 10 I = 1,7
       FI1 = FI1 + ADJ(I)
       ADJ(I) = 0.0
   10 CONTINUE
   12 CALL HAM
C
C  DETERMINE AVAILABLE NUTRIENTS
C
      Q1 = QS + QE
      FI1 = FMJ*1000./4.184
      FIA = FI1/ADE
      FI1 = FI1-(FI1*FEED(10)*0.01)
      FI = FI1/ADE
      H1 = QS + QE-Q
      H1 = H1*1000./(11.57*4.184)
      ADJ(7) = H1
      Q = FI*FEED(5)/4.184
      EI = FI1
      PI = FI*DCP*0.01
C
C  MAINTENANCE REQUIREMENT
C
      EM = WTM*85
C
C  CHECK ENERGY LIMITS
C
      DD = EM*1.5
      IF(Q.LE.DD)THEN
        PX = 0.05*PT*1000.
        PR = 0.08*PT-(2.1977*6.25)
        PR = PR*.79-(0.3999*6.25)
        PM = PI-PR
        EU = PM*1.72
        AME = EI-EU
        EPR = 5.64*PR
        ALR = Q-EM-H1-EPR
        E = ALR + EPR
        ALR = ALR/9.399999
        IF(E.LT.0.0)ADJ(6) = ABS(E)
        H = AME-E
      ELSE
C
C  DETERMINE PROTEIN UTILIZATION
C
        PRTPX = (0.23*(PTM-PT))/PTM
        PR = (PI*FEED(3)*0.01)/(0.94 + (0.06/PRTPX))
C
C  COMPARE PR TO MAX RATE OF PROTEIN SYNTHESIS
C
        IF(PR.GT.PRM)PR = PRM
        CLYS = FI*FEED(6)*0.01
        RLYS = 1.985*BW**0.487
        AAL(1) = CLYS/RLYS
        CTRY = FI*FEED(7)*0.01
        RTRY = 0.3017*BW**0.524
        AAL(2) = CTRY/RTRY
        CTHR = FI*FEED(8)*0.01
        RTHR = 1.136*BW**0.518
        AAL(3) = CTHR/RTHR
        RPRO = 40.5*BW**0.5170001
        AAL(4) = (FI*FEED(1)*0.01)/RPRO
        J = 1
        DO 15 I = 1,4
         IF(AAL(J).LT.AAL(I))GOTO 15
         J = I
   15   CONTINUE
        IF(AAL(J).LT.1.)THEN
         PR = PR*AAL(J)
```

```
          ADJ(J)=PR*(1.-AAL(J))*5.64
        ENDIF
  16    PX=PR/PRTPX
        DD=0.05*PT*1000.
        IF(PX.LT.DD)PX=DD
C
C  ENDOGENOUS LOSS OF PROTEIN
C
        EPL=0.06*(PX-PR)
        PM=PI-PR
        EU=PM*1.72
        AME=EI-EU
        EPR=5.64*PR
        ELR=Q-(EM+EPR+H1)
        ALR=ELR/9.399999
C
C  FAT SYNTHESIS = PROTEIN RETENTION/3
C
        DD=PR/3.
        IF(ALR.LE.DD)THEN
          PR=PR-10.
          ADJ(5)=ADJ(5)+(10.*5.64)
          GOTO 16
        ENDIF
        E=EPR+ELR
        H=AME-E
      ENDIF
      CALL LIMIT
C       CALL GAIN
      RETURN
      END
C ************************************************
C
C  THIS SUBROUTINE CALCULATES ENVIRONMENTAL TEMPERATURE EFFECTS
C
      SUBROUTINE HAM
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT,PASTGL
C
C  INITIALIZE VARIABLES TO PIG VARIABLES
C
      FMJ=FI1*4.184/1000.
      W=BW
      IF(W.LE.12.)THEN
        AM=7.419*W**0.66
      ELSE
        AM=5.091*W**0.75
      ENDIF
      A=9.000001E-02*W**0.67
      F=FMJ*11.57
      Q=AM+(1.-AK)*(F-AM)
      RMJ=AM*0.0864
      CAR=2.0*(ANOP-1)/ANOP*0.075
C
C  CALCULATE NET HEAT EXCHANGE
C
C  SET DEFAULT
C
      RV=0.15
C
C  SET FMAX TO EWAN'S FEED INTAKE
C
      FMAX=FMJ
      TA=HOUSE(2)
C
```

```
C  CALCULATE THE LOWER CRITICAL EFFECTIVE AND AIR TEMPERATURES
C
      V = HOUSE(3)
      IF(V.LT.0.15)V = 0.15
      RC = W**0.13/(15.7*V**0.6)
      RR = 1./5.3
      RA = 1./(5.3 + 1/RC)
      RT = 0.02*W**0.33
      FSR = 0.21*0.8
      IF(IFTYPE.EQ.4)FSR = 0.0
      RF = (FSR/0.2)*RF45*(W/45.)**0.33*ANOP**0.5
      AMINQE = 2.*9.000001E-02*(8. + 0.07*W)*W**0.67
      IDUM = 1
      IF(ICOMP.GT.0)THEN
        QN = Q
        ANUM = QN*(RA + RT)-AMINQE*RA
        DEN = A*(1. + FSR*(RT-RF)/(RT + RF)-CAR)
        ELT = 39.-ANUM/DEN
        TA = ELT
        CALL EFFECT
        ALCET = EFT
      ELSE
  101   CALL EFFECT
        FLCMJ = FMAX + (FMAX*(0.00825*(15.-EFT)))
        FLCWAT = FLCMJ*11.57
        QN = AM + (1.-AK)*(FLCWAT-AM)
        ANUM = QN*(RA + RT)-AMINQE*RA
        DEN = A*(1. + FSR*(RT-RF)/(RT + RF)-CAR)
        ELT = 39.-ANUM/DEN
        ALCET = EFT
        IF(ABS(TA-ELT).GT..01)THEN
          TA = ELT
          GOTO 101
        ENDIF
      ENDIF
      IDUM = 0
      TA = HOUSE(2)
C
C  CALCULATE EFFECTIVE TEMPERATURE FOR FEED INTAKE
C
      CALL EFFECT
      AEFT = EFT
      IF(ICOMP.LE.0)THEN
        IF(AEFT.LE.ALCET)THEN
          IDUM = -1
          CALL EFFECT
        ENDIF
        FMJ = FMJ + (FMJ*(0.008255*(15.-EFT)))
        F = FMJ*11.57
        Q = AM + (1.-AK)*(F-AM)
      ENDIF
C
C  CALCULATE SENSIBLE HEAT LOSS BASED ON EFFECTIVE TEMPERATURE
C
      QS = A*(39.-AEFT)/(RRA + RRT)
C
C  DETERMINE EVAPORATIVE HEAT LOSS
C
      IF(AEFT.GT.ALCET)THEN
        QE = Q-QS
      ELSE
        QE = AMINQE
      ENDIF
      RETURN
      END
C ************************************************
C
C  DETERMINE EFFECTIVE TEMPERATURE
C
      SUBROUTINE EFFECT
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
```

```
      COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      POLD = 0.0
C
C
C   SET REFERENCE THERMAL RESISTANCES
C
C   REFERENCE CONVECTIVE RESISTANCE
C
      IF(IDUM.GE.1)THEN
        RRCV = W**0.13/(15.5*RV**0.6)
C
C   REFERENCE AIR THERMAL RESISTANCE
C
        RRA = 1/(5.3 + 1/RRCV)
C
C   REFERENCE TISSUE THERMAL RESISTANCE
C
        RRT = 0.03*W**0.33
        RCV = W**0.13/(15.5*V**0.6)
        RA = 1./(5.3 + 1/RCV)
        RT = 0.02*W**0.33
      ELSE
        RRCV = W**0.13/(12.5*RV**0.6)
        RRCT = 1./(24.55*V**0.46)
        RRT = 0.03*W**0.33
        RRA = 1./(5.2 + 1./(RRCT + RRCV))
C
C   SET ACTUAL THERMAL REFERENCES
C
        RCV = W**0.13/(12.5*V**0.6)
        RCT = 1./(24.55*V**0.46)
        RA = 1./(5.2 + 1./(RCV + RCT))
        IF(IDUM.EQ.-1)RT = 0.03*W**0.33
      ENDIF
C
C   PIG IS ASSUMED TO STANDE 20% OF TIME, I.E. 80% LYING
C
      FSR = .21*.8
      IF(IDUM.EQ.0)FSR = 0.244*0.8
      IF(IFTYPE.EQ.4)FSR = 0.0
      RF = (FSR/0.2)*RF45*(W/45.)**0.33*ANOP**0.5
C
C   INCREMENTAL ROOT SEARCHING STARTS
C
      EFT = -30.
      H = 2.0
C
C   CALCULATE THE FUNCTION VALUE
C
      PNEW = 0.0
      DO 10 I = 1,100
        IF(IDUM.EQ.0)RT = 0.03*W**0.33-0.0024*(EFT-ALCET)
        P1 = (1.0 + FSR*(RA-RF)/(RT + RF)-CAR)*(39.-TA)
        P2 = RA + RT
        P3 = (39.-EFT)/(RRA + RRT)
        IF(P2.NE.0.0)PNEW = P1/P2-P3
        UEFT = EFT
        PNO = PNEW*POLD
        IF(PNO.GE.0.0)THEN
          POLD = PNEW
          ALEFT = UEFT
          EFT = EFT + H
        ELSE
          GOTO 12
        ENDIF
   10 CONTINUE
C
C   ASSIGN NEGATIVE TO T1 AND POSITIVE TO T2
C
   12 IF(PNEW.LT.0.0)THEN
        T1 = UEFT
```

```
        T2 = ALEFT
       ELSE
        T1 = ALEFT
        T2 = UEFT
       ENDIF
C
C  MIDPOINT SEARCHING
C
       DO 11 I = 1,100
        IF(ABS(PNEW).GE.0.0001)THEN
          EFT = (T1 + T2)/2.
          IF(IDUM.EQ.0)RT = 0.03*W**0.33-0.0024*(EFT-ALCET)
          P1 = (1.0 + FSR*(RA-RF)/(RT + RF)-CAR)*(39.-TA)
          P2 = RA + RT
          P3 = (39.-EFT)/(RRA + RRT)
          IF(P2.NE.0.0)PNEW = P1/P2-P3
          IF(PNEW.LT.0.0)THEN
            T1 = EFT
          ELSE
            T2 = EFT
          ENDIF
        ELSE
          GOTO 13
        ENDIF
   11 CONTINUE
   13 RETURN
      END
C ************************************************
C
C  THIS SUBROUTINE CALCULATES INITIAL COMPOSITION
C
      SUBROUTINE COMPO
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      IF(BW.LT.7.5)THEN
        PT = 0.155*BW + 0.004
        FAT = 0.092*BW-0.16
        AT = 0.029*BW-0.016
        EBW = 0.928*BW + 0.123
        ET = 1700.*BW-1364.
      ENDIF
      IF(BW.GE.7.5.AND.BW.LT.15.)THEN
        PT = 0.149*BW + 0.089
        FAT = 0.0764*BW + 0.0013*BW**2.-0.371
        AT = 0.021*BW + 0.096
        EBW = 0.926*BW + 0.176
        ET = 1.777*BW-3946.
      ENDIF
      IF(BW.GE.15.)THEN
        PT = 0.154*BW-0.212
        FAT = 0.192*BW-0.288
        AT = 0.032*BW-0.073
        EBW = 0.952*BW
        ET = 5640.*PT + 9400.*FAT
      ENDIF
      ALT = PT*(5.5-(0.0116*(BW-5.)))/24.
      FT = FAT*1.1
      RETURN
      END
C ************************************************
C
C  LIMITS AND COMPENSATORY RESPONSE
C
      SUBROUTINE LIMIT
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMP = 0.0
      IF(ICOMP.GT.0)THEN
        ICOMP = 0
```

```
        RETURN
      ENDIF
      J=1
      SUM=0
      DO 10 I=1,7
        SUM=SUM+ADJ(I)
        IF(ABS(ADJ(I)).GT.ABS(ADJ(J)))J=I
   10 CONTINUE
      IF(SUM.EQ.0.0)THEN
        LAA=8
      ELSE
        LAA=J
      ENDIF
      COMP=COMP+ADJ(J)
      DO 11 I=1,7
        ADJ(I)=0.0
   11 CONTINUE
      IF(LAA.LT.8)RETURN
      IF(COMP.LE.0.0)RETURN
      COMPDE=FI1*0.05
      IF(COMP.GE.COMPDE)THEN
        FI1=FI1+COMPDE
        COMP=COMP-COMPDE
      ELSE
        FI1=FI1+COMP
        COMP=0.0
        ICOMP=1
      ENDIF
      RETURN
      END
C *************************************************
C
C THIS SUBROUTINE CALCULATES WEIGHT GAIN
C
      SUBROUTINE GAIN
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/INTAK/FI1,FI2,FI3,WTM,ADJ(7),PR,ALR,E,PM
      COMMON/HAMP/FMJ,QS,QE,Q,LAA
      COMMON/EFF/TA,RV,IDUM,V,W,CAR,EFT,RA,RT,RF,ALCET,RRA,RRT
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      COMMON/FOUR/H,AME,FIA,Q1,H1,AEFT,ELT,PASTGL
      PTNEW=(PT*1000.+PR)*(5.5-0.0116*(BW-5.))/24.
      GL=(PTNEW-(ALT*1000.))
      IF(DAYHR.GT.0.045)THEN
        GL=GL*24.
C         IF(PASTGL.GT.0.0)PERCHG=(GL-PASTGL)/PASTGL
C         IF(ABS(PERCHG).GT.0.15)GL=(PASTGL+GL)/2.
      ENDIF
      PASTGL=GL
      GF=1.1*ALR/24.
      GA=0.215*PR/24.
      EBG=GL+GF+GA
      ALWG=EBG+0.05*EBG
      BW=BW+(ALWG*0.001)
      EBW=EBW+EBG*0.001
      PT=PT+(PR*0.001)/24.
      ALT=PTNEW*0.001
      FAT=FAT+(ALR*0.001)/24.
      AT=AT+(GA*0.001)
      ET=ET+E/24.
      FT=FT+(GF*0.001)
      D(1)=BW
      D(2)=PR/6.25/24.
      D(3)=E/24.
      D(4)=GL
      D(5)=GF
      D(6)=GA
      D(7)=PM
      D(8)=H
```

```
      D(9)=AME/24.
      D(10)=ALWG
      D(11)=FIA/24.
      D(12)=Q1
      D(13)=QE
      D(14)=H1
      D(15)=AEFT
      D(16)=ELT
      D(17)=ALCET
      D(18)=FIA*FEED(9)/1000./24.
      DO 102 I=1,18
        C(I)=C(I)+D(I)
  102 CONTINUE
      DAYHR=DAYHR+1/24.
      AGEHR=AGEHR+1/24.
      WRITE(12,100) DAYHR,AGEHR,LAA,D(3),D(4),D(5),D(6),D(10),D(1),D(8),
     $ D(9),D(11),(D(10)/D(11))
  100 FORMAT(1X,F4.1,1X,F4.1,3X,I1,3X,F5.0,2X,F5.1,3X,F6.1,1X,F4.1,
     $ 1X,F6.0,1X,F5.1,1X,F5.0,1X,F6.0,1X,F5.0,1X,F5.3)
      WRITE(13,101) DAYHR,AGEHR,LAA,D(1),D(10),D(11),(D(10)/D(11)),
     $  D(12),(D(13)/D(12)),D(15),D(16),D(17),
     $  (D(8)*11.57*4.184*0.001)
  101 FORMAT(1X,F4.1,2X,F4.1,3X,I1,4X,F5.1,2X,F5.0,2X,F5.0,2X,F5.3,
     $ 1X,F5.1,1X,F5.3,2X,F4.1,1X,F4.1,1X,F5.1,1X,F5.1)
      RETURN
      END
C ************************************************
C
C  THIS SUBROUTINE PRINTS CARCASS AND ENVIRONMENTAL SUMMARIES
C
      SUBROUTINE SUMRY
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      COMMON/INIT/FEED(12),PHYS(9),HOUSE(12),AGE,BW,D(18),B(18),C(18)
      COMMON/ONE/IFI,DAYHR,AGEHR,ICOMP
      COMMON/TWO/PTM,PRM,ADE,ANE,AK,RATCON,ANOP,PENSZ,DCP,RF45,IFTYPE
      COMMON/THREE/PT,FAT,AT,EBW,ET,ALT,FT
      DO 400 I=1,18
        B(I)=C(I)/DAYHR
  400 CONTINUE
      WRITE(14,401)
  401 FORMAT(19X,'************ CARCASS COMPOSITION SUMMARY ',
     $ '***************')
      WRITE(14,*)
      WRITE(14,402) BW
  402 FORMAT(14X,'  FINAL BODY WEIGHT ....... ',F6.1,' KG')
      WRITE(14,403) EBW,(100.*EBW/BW)
  403 FORMAT(14X,'  EMPTY BODY WEIGHT ....... ',F6.1,' KG .. ',
     $ F6.2,' % BODY WEIGHT')
      WRITE(14,404) (PT+AT+FAT),(100.*(PT+AT+FAT)/EBW)
  404 FORMAT(14X,'  DRY MATTER CONTENT....... ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WATER=EBW-PT-FAT-AT
      PWATER=100.*WATER/EBW
      WRITE(14,405) WATER,PWATER
  405 FORMAT(14X,'  WATER CONTENT  ........ ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WRITE(14,406) (PT/6.25),(100.*(PT/6.25)/EBW)
  406 FORMAT(14X,'  NITROGEN CONTENT  ....... ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WRITE(14,407) PT,(100.*PT/EBW)
  407 FORMAT(14X,'  PROTEIN CONTENT ........ ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WRITE(14,408) FAT,(100.*FAT/EBW)
  408 FORMAT(14X,'  FAT CONTENT .......... ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WRITE(14,409) AT,(100.*AT/EBW)
  409 FORMAT(14X,'  ASH CONTENT .......... ',F6.1,' KG .. ',
     $ F6.2,' % EMPTY BODY WEIGHT')
      WRITE(14,410)  ET,(ET/EBW)
  410 FORMAT(14X,'  ENERGY CONTENT........ ',F8.0,' KCAL .',F7.1,
     $ ' KCAL/KG EBW ')
      WRITE(14,411) ALT,(100.*ALT/EBW)
```

```
 411 FORMAT(14X,'  LEAN TISSUE CONTENT . . . . . .  ',F6.1,' KG . . ',
   $  F6.2,' % EMPTY BODY WEIGHT')
    WRITE(14,412) FT,(100.*FT/EBW)
 412 FORMAT(14X,'  FAT TISSUE CONTENT. . . . . . .  ',F6.1,' KG . . ',
   $  F6.2,'% EMPTY BODY WEIGHT')
    BFAT=0.91*FAT+0.5
    WRITE(14,413) BFAT
 413 FORMAT(14X,'  BACKFAT . . . . . . . . . . . .  ',F6.1,' MM ')
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,414)
 414 FORMAT(17X,'**************  ENVIRONMENTAL SUMMARY  ***************')
    WRITE(14,*)
    WRITE(14,415) B(12)
 415 FORMAT(14X,'  AVG TOTAL HEAT PRODUCTION . . . . . . . . . . .',
   $  F5.1,' WATTS')
    WRITE(14,416) B(13)
 416 FORMAT(14X,'  AVG LATENT HEAT PRODUCTION. . . . . . . . . . .',
   $  F5.1,' WATTS')
    WRITE(14,417) (B(13)/B(12))
 417 FORMAT(14X,'  LATENT TO TOTAL HEAT RATIO. . . . . . . . . . .',
   $  F5.3)
    WRITE(14,418) B(15)
 418 FORMAT(14X,'  AVG EFFECTIVE TEMPERATURE . . . . . . . . . . .',
   $  F5.1,' C')
    WRITE(14,419) B(16)
 419 FORMAT(14X,'  AVG LOWER CRITICAL AIR TEMPERATURE. . . . . . .',
   $  F5.1,' C')
    WRITE(14,420) B(17)
 420 FORMAT(14X,'  AVG LOWER CRITICAL EFFECTIVE TEMPERATURE. . . .',
   $  F5.1,' C')
    WRITE(14,421) B(14)
 421 FORMAT(14X,'  AVG COLD THERMOGENSIS . . . . . . . . . . . . .',
   $  F5.0,' KCAL')
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,*)
    WRITE(14,422)
 422 FORMAT(17X,'**************  FINANCIAL SUMMARY  ***************')
    WRITE(14,*)
    WRITE(14,423) B(18)
 423 FORMAT(14X,'  AVG DAILY FEED COST . . . . . . . . . . . $ ',F5.2)
    WRITE(14,424) C(18)
 424 FORMAT(14X,'  TOTAL FEED COST . . . . . . . . . . . . . $ ',F6.2)
    RETURN
    END
C
C
C
    SUBROUTINE HEADERS
    IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
    WRITE(12,15)
    WRITE(12,12)
    WRITE(12,13)
    WRITE(12,14)
 15 FORMAT(1X,'    **************************    NUTRITION REPORT',
   $ '    ***************************')
 12 FORMAT(1X,'                    ---------- GAIN ----------',
   $ '  BODY')
 13 FORMAT(1X,'  DAY AGE LIMIT ENERGY  LEAN    FAT  ASH  WEIGHT',
   $ ' WEIGHT  HP    ME   FEED  GAIN')
 14 FORMAT(1X,'                    KCAL   G      G   G    G  ',
   $ '  KG   KCAL  KCAL   G    FEED')
    WRITE(13,16)
    WRITE(13,17)
    WRITE(13,18)
    WRITE(13,19)
 16 FORMAT(1X,' ****************************   ENVIRONMENT REPORT',
```

```
 $ '  **************************')
17 FORMAT(1X,'              BODY                  ',
 $ 'LATENT:')
18 FORMAT(1X,' DAY AGE LIMIT  WEIGHT  ADG    ADF    GAIN   HP  ',
 $ 'TOTAL  AEFT  ELT ALCET  HP2')
19 FORMAT(1X,'                 KG     G      G     FEED   W  ',
 $ '      C   C   C     W')
  WRITE(7,20)
20 FORMAT(1X,'    DAY     TIME    ROOM TEMP    CUM. FUEL USAGE',
 $ '  MEAT GAIN   FEED ')
  WRITE(7,22)
22 FORMAT(1X,'                   DEG C     GAL LP     CU FT ',
 $ '    KG        KG')
  WRITE(7,21)
21 FORMAT(1X,'     ***********************************************',
 $ '********************')
  WRITE(5,23)
23 FORMAT(1X,'     DAY   TIME        OUTDOOR        ROOM',
 $ '       SUPP. HEAT')
  WRITE(5,27)
27 FORMAT(1X,'                DEG C    KG/KG  DEG C  KG/KG',
 $    '     WATTS')
  WRITE(5,28)
28 FORMAT(1X,'     ****************************************',
 $ '******************')
  WRITE(8,24)
24 FORMAT(1X,'   DAY     TIME          FUEL          ',
 $ '    FEED          MEAT      TOTAL')
  WRITE(8,25)
25 FORMAT(1X,'                    GALLONS     $       ',
 $ ' KG        $        KG    $ PER KG MEAT')
  WRITE(8,26)
26 FORMAT(1X,'  ********************************************',
 $ '****************************************')
  RETURN
  END
```

C.3 Example Output Files

C.3.1 Environmental Conditions File

```
DAY   TIME        OUTDOOR          ROOM          SUPP. HEAT
               DEG C    KG/KG  DEG C  KG/KG         WATTS
***********************************************************
 67.  1300.     -1.5  0.00440  28.0   0.00412        3917.
 67.  1400.     -0.8  0.00493  28.0   0.00866        4231.
 67.  1500.     -1.2  0.00506  28.0   0.00866        4150.
 67.  1600.     -1.1  0.00533  28.0   0.00902        3727.
 67.  1700.     -0.7  0.00533  28.0   0.00902        4022.
 67.  1800.     -1.2  0.00516  28.0   0.00902        4058.
 67.  1900.     -1.6  0.00485  28.0   0.00902        4110.
 67.  2000.     -2.1  0.00458  28.0   0.00902        4182.
 67.  2100.     -2.4  0.00435  28.0   0.00873        4234.
 67.  2200.     -2.6  0.00416  28.0   0.00873        4295.
 67.  2300.     -3.0  0.00402  28.0   0.00842        4383.
 68.     0.     -3.2  0.00392  28.0   0.00842        4444.
```

C.3.2 Usage and Cost File

```
DAY        TIME             FUEL                        FEED               MEAT      TOTAL
                    GALLONS          $           KG            $           KG        $ PER
                                                                                   KG MEAT
*************************************************************************************************
67.        1300.       0.16         0.23         1.21         0.12         0.67       0.52
67.        1400.       0.32         0.47         2.43         0.24         0.86       0.82
67.        1500.       0.49         0.71         3.65         0.36         1.30       0.83
67.        1600.       0.64         0.92         4.87         0.49         1.85       0.76
67.        1700.       0.80         1.15         6.08         0.61         2.47       0.71
67.        1800.       0.96         1.39         7.30         0.73         3.14       0.67
67.        1900.       1.12         1.62         8.53         0.85         3.82       0.65
67.        2000.       1.29         1.86         9.75         0.97         4.50       0.63
67.        2100.       1.45         2.11        10.97         1.10         5.18       0.62
67.        2200.       1.62         2.35        12.20         1.22         5.86       0.61
67.        2300.       1.80         2.61        13.43         1.34         6.55       0.60
68.           0.       1.97         2.86        14.66         1.47         7.23       0.60
```

C.3.3 Swine Submodel Environmental Report

```
*************************** ENVIRONMENT REPORT *************************
DAY  AGE   LIMIT   BW    AHG  AHF   GAIN    HP    L/T    AEFT   ELT   LCET  HP2
                   KG     G    G    FEED    W             C      C     C     W
0.0  49.0    4    11.7   14.  26.   0.552  55.9  0.542   28.0   16.9  17.0  49.3
0.1  49.1    4    11.7    4.  26.   0.159  56.0  0.542   28.0   16.9  17.0  49.3
0.1  49.1    4    11.7    9.  26.   0.356  56.0  0.542   28.0   16.9  17.0  49.4
0.2  49.2    4    11.7   12.  26.   0.455  56.0  0.542   28.0   16.9  17.0  49.4
0.2  49.2    4    11.8   13.  26.   0.505  56.0  0.543   28.0   16.9  17.0  49.4
0.3  49.3    4    11.8   14.  26.   0.555  56.1  0.543   28.0   16.9  17.0  49.5
0.3  49.3    4    11.8   14.  26.   0.556  56.2  0.543   28.0   16.9  17.0  49.5
0.3  49.3    4    11.8   14.  26.   0.556  56.2  0.543   28.0   16.9  17.0  49.6
0.4  49.4    4    11.8   14.  26.   0.556  56.3  0.543   28.0   16.9  17.0  49.6
0.4  49.4    4    11.8   15.  26.   0.556  56.3  0.543   28.0   16.8  16.9  49.7
0.5  49.5    4    11.8   15.  26.   0.557  56.4  0.543   28.0   16.8  16.9  49.8
0.5  49.5    4    11.9   15.  26.   0.557  56.4  0.544   28.0   16.8  16.9  49.8
```

DAY = Day of the simulation
AGE = Age of the pig
LIMIT = Factor limiting growth
  1 = Lysine
  2 = Thrptophan
  3 = Threonine
  4 = Protein
  5 = Fat
  6 = Energy
  7 = Temperature
  8 = None
BW = Body weight
AHG = Average hourly gain
AHF = Average hourly feed
GAIN/FEED = Gain to feed ratio

HP = Heat production (from environmental subroutine)
L/T = Ration fo latent to total heat production
AEFT = Effective temperature
ELT = Lower critical air temperature
LCET = Lower critical effective temperature
HP2 = Heat production (from growth segment)

C.3.4 Swine Submodel Nutrition Report

```
*************************  NUTRITION REPORT  *************************
                           ------------- GAIN -------------
DAY  AGE   LIMIT ENER  LEAN FAT    ASH    W    BW    HP    ME    FEED  G/
                 KCAL   G    G      G     G    KG   KCAL  KCAL    G    F
0.0  49.0    4    37.  10.1  3.1   0.4   14.  11.7  1018.  79.   26.  0.552
0.1  49.1    4    37.   0.4  3.1   0.4    4.  11.7  1019.  79.   26.  0.159
0.1  49.1    4    37.   5.3  3.1   0.4    9.  11.7  1020.  79.   26.  0.356
0.2  49.2    4    37.   7.7  3.1   0.4   12.  11.7  1020.  80.   26.  0.455
0.2  49.2    4    37.   9.0  3.1   0.4   13.  11.8  1021.  80.   26.  0.505
0.3  49.3    4    37.  10.2  3.1   0.4   14.  11.8  1022.  80.   26.  0.555
0.3  49.3    4    37.  10.2  3.1   0.4   14.  11.8  1023.  80.   26.  0.556
0.3  49.3    4    37.  10.3  3.1   0.4   14.  11.8  1024.  80.   26.  0.556
0.4  49.4    4    37.  10.3  3.1   0.4   14.  11.8  1026.  80.   26.  0.556
0.4  49.4    4    37.  10.3  3.1   0.4   15.  11.8  1027.  80.   26.  0.556
0.5  49.5    4    37.  10.3  3.1   0.4   15.  11.8  1028.  80.   26.  0.557
0.5  49.5    4    37.  10.3  3.1   0.4   15.  11.9  1029.  80.   26.  0.557
```

DAY = Day of the simulation
AGE = Age of the pig
LIMIT = Factor limiting growth
- 1 = Lysine
- 2 = Thrptophan
- 3 = Threonine
- 4 = Protein
- 5 = Fat
- 6 = Energy
- 7 = Temperature
- 8 = None

ENER = Energy gain
LEAN = Lean gain
FAT = Fat gain
ASH = Ash gain
W = Hourly weight gain
BW = Body weight
HP = Heat production (from the growth segment)
ME = Metabolizable energy intake
FEED = Hourly feed intake
G/F = Gain to feed ratio