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HEAT AND MOISTURE LOADS IN DAIRY BARNS

by

RICHARD ANDREW SMITH

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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Abstract

The most critical parameters in the design of environmental control systems for confinement livestock facilities are the heat and moisture production of the animals. Since existing design values are based on experiments involving few animals, rigidly controlled conditions, and often only physiological variables, the application of these figures to commercial facilities may result in unsatisfactory environmental control. The problems associated with measuring heat and moisture production in large livestock buildings were surmounted by the development, at the University of Alberta, of a data acquisition and recording system with the capacity for this scale of monitoring. This system was used to examine the environmental conditions in two tie-stall and two free-stall barns under commercial production conditions.

For each barn, dry-bulb temperatures and dewpoints of incoming, outgoing, and ambient air, together with exhaust air flows, were monitored continuously over a 48-hour period. The heat losses, through conduction and ventilation, and the supplemental heat gains were calculated using these variables. The heat and moisture loads, in turn, were derived from the heat gains and losses from the buildings. The relationships between the heat and moisture production of the livestock and various environmental variables were explored and the effect of the housing system assessed. Finally, the measured heat and moisture production data were

compared to the values contained in current design codes and manuals.

The weather varied tremendously during the monitoring period, causing a 10°C range of average inside temperatures in the four barns. The water vapour removal rates varied from 0.34 kg/h cow, in the coldest tie-stall barn, to 1.05 kg/h cow in the warmest free-stall unit. These two barns also had the extreme rates of sensible heat removal, with the tie-stall facility being highest at 2963 kJ/h cow, compared to 2650 kJ/h cow in the free-stall barn. The heat and moisture loads were related closely, but not exclusively, to the inside temperature. The housing arrangement was a factor in both sensible and latent heat production, but had the most pronounced effect on the latter, with moisture loads in the free-stall barns being significantly higher at comparable temperatures.

There was considerably more variation in the measured data than in the existing design values; the design equations appeared to produce acceptable median values, but did not predict the range of production rates noted in this study. Moreover, these design values seemed to underestimate not only the actual moisture production levels, but also the influence of this variable on total heat production. There were no statistically significant differences, at the five percent level, between the measured and design values for tie-stall heat production and for all average sensible heat removal rates, but the measured moisture and total heat production of the free-stall barns were not in agreement with the design values. In a comparison of the relationships between heat and moisture production and inside temperature, only in the moisture production data was there a similarity between the measured and design figures.

Acknowledgements

As is the case with almost any human endeavour, this thesis represents the culmination of the work of many people. The author would like to recognize and express his gratitude to some of these people.

The financial assistance provided to this project by Agriculture Canada is gratefully acknowledged. Professor Brian McQuitty, whose contagious interest in livestock buildings provided the inspiration for this study, freely contributed his advice and experience. His patience and assistance are greatly appreciated. John Feddes and Dale Travis were invaluable during the collection and sorting of the data, both for their knowledge of the data acquisition system and for their enthusiasm for the monitoring process. The cooperation of the four farmers involved, Harry Pederson, Henry West, Peter Kopp, and Marvin Molzan, and the use of their facilities are gratefully acknowledged.

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Table of Contents

List of Tables

List of Figures

1. Introduction

Man's desire to live and raise livestock in areas where the climate is not conducive to such endeavours has made modification of natural environments essential. With the advent of confinement housing of livestock and poultry came the need for environmental control in these buildings. As economic conditions have forced production to become more intensive, the importance and required capabilities of environmental control systems have increased dramatically.

Young (1979) estimated that two-thirds of the livestock in North America were raised in areas where the average January temperature is below freezing, and this proportion would undoubtedly be much higher in Canada. Canadian dairy herds, therefore, are dominated by Holstein cows, a European breed that is particularly well adapted to cold weather. Despite this fact, the decline in milk production, increased feed requirements, and, most importantly, management problems associated with low temperatures have precipitated a trend toward "warm" confinement dairy facilities. In these sealed and well-insulated barns, mechanical ventilation systems and, in some instances, supplemental heating are employed to achieve a balance between heat and moisture production and dissipation at some optimum environmental conditions. Indeed, the possibility of providing such conditions is the fundamental justification for the expense incurred in constructing and operating these buildings.

Winter ventilation rates usually are determined by the moisture production of the animals, and supplemental heating is used to overcome any deficit between the building heat losses, by ventilation and conduction, and the sensible heat production of the animals. Therefore, accurate estimates of the animals' heat production are critical to the design of functional environmental control systems. Measurements of these heat production parameters have been undertaken, but most experiments have involved small numbers of animals housed in controlled environmental chambers. Furthermore, many of these studies have considered only the physiological heat and moisture production of the animals, while ignoring the significant moisture contribution of wet surfaces in the barns. The use of these data in calculating the heat and moisture balance of a large commercial dairy barn, and the subsequent development of an environmental control system based on this balance, must be questioned. The sophisticated computer models and numerical techniques now being employed in the design process are of little value if they are founded upon unreliable production data.

Establishing the need for the measurement of heat and moisture production under commercial conditions is relatively simple. At the very least, this research is necessary to establish the validity of existing design values under modern commercial conditions. In the event that these values are not accurate, the research becomes even more important as a basis for the determination of valid design parameters. Unfortunately, the collection of these data is a difficult and complex proposition. The size of most dairy barns has precluded, until recently, the rigorous monitoring of these structures, while the cost of erecting a research facility of this magnitude is prohibitive. Only the development of a system of instrumentation and data recording and processing capable of collecting and compiling the vast quantity of information required to derive an accurate energy balance for a typical livestock building made intensive studies of commercial dairy barns possible. The objective of this project was to utilize this system, along with the cooperation of four dairy producers, to monitor the heat and moisture loads of two tie-stall and two free-stall barns under normal operating conditions. These loads then could be compared to existing design values and analysed with respect to their potential application to future design problems. A further assessment of the effects of the housing system on heat and moisture loads also could be undertaken.

2. Literature Review

2.1 Environmental Design in Livestock Buildings

The definition of the environment within a livestock building and the specifications used to describe this environment are sources of considerable disagreement. Esmay (1979) defined environment as the total of all conditions that affect animals' development, response and growth, and divided this total into three sections, entitled physical, social, and thermal environment. Thompson (1974) separated the environment into a contact segment, consisting of the housing and machinery with which the animal interacts, and a non-contact segment, consisting of the temperature, relative humidity, lighting, and air-borne pollutants. Smith (1972) introduced the additional concept of environmental quality, meaning the degree of freedom from contaminants and pollution. Although these factors can all have an effect on the productive efficiency of livestock, the area of principal concern, for agricultural engineers and for this thesis, is the thermal environment.

The pertinent variables determining the thermal environment are the dry-bulb temperature, relative humidity, and movement of the surrounding air, as well as the distribution of radiant energy within the structure. The traditional method of specifying thermal environments has been to state the temperature and relative humidity of the ambient air. These parameters are measured and understood easily, and provide an acceptable description of the physical environment. However, they do not adequately describe the environment from a physiological point of view. Monteith (1973) outlined three principles that should be followed by environmental specifications, that is, they should apply to all homeothermic species, they should be based on standard climatological measurements and be valid both indoors and outdoors, and they should be, as far as possible, independent of the physical nature or state of the interface between the homeotherm and its environment. Monteith (1973) further stated the desirability of separating the physical state of an organism's environment from its physiological response to that environment. These ideas have been embodied in the concept, described by Smith (1972), of specifying environmental demand rather than environmental temperature. Environmental demand may be defined as the rate at which total heat is transferred from a source to the environment and can be applied to livestock buildings as well as animals.

2.1.1 Energy Balance

The thermal environment in a livestock building was described by Esmay (1979) as a steady flow system of an incompressible fluid: moist air. The environment, therefore, may be analyzed on the basis of energy conservation within the system. Environmental conditions will be de[illegible]ed by the climatic state at which a balance occurs be[illegible] the gains and losses of energy within the building . This concept of an energy balance is dependent upon the assumption of steady-state conditions, an assumption that Sparks and Young (1979) did not consider to be valid, particularly at high rates of ventilation and heat production. In developing computer models for the design and simulation of ventilation in livestock buildings, these authors replaced the steady-state heat and moisture equations with differential equations, which indicated change over time. Nevertheless, the vast majority of design work is based on a steady-state energy balance. The errors introduced by the use of this procedure are likely much less significant than those associated with the measurement of the actual design values.

Under steady-state conditions, livestock buildings follow the First Law of Thermodynamics; that is, the total energy within the system is conserved. Thermal energy is produced by the animals, by lighting and mechanical equipment, by supplemental heating systems, and, to a small extent, by people working in the barn. This energy is in the form of sensible and latent heat, the latter being the heat involved in the vaporization of moisture. The energy is dissipated by the ventilation system, the building itself, and supplementary cooling systems. Smith (1972) included a factor for heat storage in a barn energy balance, but, under normal conditions, the magnitude of this variable would be insignificant. The majority of the sensible heat generated by the animals, equipment and heating system is removed by the ventilating air, with smaller percentages lost through the structure, by conduction, and through evaporation of moisture from wet surfaces. Animals produce moisture both as water vapour in respired air and water in wastes, sweat, and spillage from drinking bowls. Evaporation of this liquid component contributes to a sizeable increase in the latent heat production. Some of this moisture may be lost through condensation on building surfaces, but environmental control systems are designed to prevent condensation and this loss has been neglected by Sparks and Young (1979) and nearly all others deriving energy balances. Similarly, ASHRAE (1978) suggested that moisture transfer through the structural components also could be ignored. Thus, latent heat dissipation is considered to take place almost entirely through the ventilation system.

2.1.2 Environmental Control

Although environmental control is often not a fundamental consideration in the decision to house livestock, there is still a need, as stated by Esmay (1979), to modify the environment for the benefit of the animals. The degree to which the environment is modified can vary from open shelters, which simply act as a barrier to sun, wind, and precipitation, to sealed, insulated buildings with complete air-conditioning systems. Ultimately, an economic assessment of the cost of environmental modification compared to the associated production gains will dictate the design of the barn. All livestock buildings are affected by the local climate, an environment over which no control can be exerted. Smith (1973) recommended that the natural environment be exploited, as far as possible, instead of being excluded by expensive measures. Compensating for the limitations of the natural climate is the essential purpose of environmental control systems.

The heat gains and losses from a structure are determined by its location, orientation, and construction. Upon completion of the building, these factors are fixed and very little change in heat transmission can be induced. Only the internal environment is susceptible to management influences on a continuing basis. Smith (1972) identified two basic variables through which the microclimate of livestock buildings could be altered: heat input and air movement. Heat input is dependent upon species and liveweight of the animals, stocking densities, ration composition, animal feed intake, and supplementary heating or cooling. Air movement through the building is governed by the ventilation system. Indeed, Scott et al (1983) called the ventilation systems the vehicle by which the indoor environment is determined.

The critical features of the ventilation system in controlling the thermal environment are the volume of air moved and the distribution of the incoming air. The quantity of air is a function of the amount of heat and moisture to be removed; the required distribution is governed by the location of the animals and equipment in the barn. After the desired climatic conditions for the livestock being housed have been identified, the ventilation and air-conditioning systems are designed to produce, as nearly as possible, this environment.

2.2 Animal Physiology

A principle too often overlooked by designers is that livestock buildings are constructed for the purpose of housing animals. Sainsbury and Sainsbury (1979) considered the physiological and health requirements of the animals to be the first priority in designing livestock buildings. The extent to which these requirements are met will determine the productive efficiency of the animals and, therefore, the profitability of the enterprise. Furthermore, Hahn (1974) suggested that as production levels increased, environmental factors gained in importance relative to nutrition and genetics. The importance of the animals to a livestock operation is very obvious; the contribution of the animals to the thermal environment in barns merits equal consideration. ASHRAE (1978) estimated that 80 percent of the total heat produced in a confinement building, housing mature animals at high densities, was a result of animal heat losses. Scott et al (1983) stressed the consideration of the physiological requirements of the animal in terms of the environment. Esmay (1979) recognized the need for an understanding of the physiological base for the animals' response to the environment, and the physical aspects of the environment and their effect on animals' heat loss to the environment.

2.2.1 Thermoregulation

Dairy cows and other mammals are homeothermic, that is, they are able to maintain a relatively constant deep body temperature over a wide range of environmental conditions. Thermoregulation refers to the process by which the state of homeothermy is maintained. Wiersma (1976) stated that homeothermy depends on a dynamic equilibrium between heat production and heat loss and this idea describes thermoregulation very accurately.

The animal uses physical and physiological mechanisms to maintain the balance between heat production and dissipation. The mechanisms listed by Wiersma (1976) included altering behavior, controlling internal heat production, and controlling heat transfer from the central core of the body to the environment. ASHRAE (1981) divided heat transfer control into physical and chemical reactions. The behavioral responses to thermal stress include altered feed intake, changes in level of exercise, shivering, and huddling together. Intensive livestock production in confinement buildings can interfere with some of these natural mechanisms, including the basic response of seeking more favourable conditions. A chemical adjustment to the metabolic rate can modify the heat production, while changes in respiration, production of surface moisture (sweating), blood circulation to the skin (vasomotion), and hair covering (piloerection) will affect the dissipation of heat.

2.2.2 Animal Energy Balance

The energy balance at the animal level is a fundamental consideration, because this balance will determine the amount of energy available for production, reproduction, or work. Smith (1973) proposed an energy model where production was a function of the difference between the energy intake from feed and the energy lost through basal metabolism, thermoregulation, and physical work. The total metabolizable energy, according to Scott et al (1983), is equal to the gross energy intake minus the losses of energy in fecal, urinary, and gaseous wastes. This metabolizable energy is available as metabolic heat or as the energy for milk, egg, and tissue production, depending on the environmental conditions.

When production is expressed as a variable in an energy balance equation, the effects of the various thermoregulatory responses discussed previously become clear. The energy balance can be examined in more detail through the derivation of a heat balance equation. In this expression, the metabolic heat production is related to the rate of mechanical work and the rates of heat transfer by radiation, convection, conduction, and evaporation. Monteith (1973) used a simplified equation in which the difference between metabolic heat production and mechanical work was derived from the product of a single coefficient and the equivalent temperature difference between the environment and the interface between the animal and the environment. The coefficient and the equivalent air temperature represented the dry-bulb temperature, humidity, wind speed, and radiation of the environment, while the equivalent temperature of the interface described the conditions at this location.

Scott et al (1983) equated the sum of all inputs to a factor obtained by multiplying body weight by the specific heat of the body mass and multiplying this product by the derivative of the change in body temperature with respect to time. In the zone of homeothermy, the body temperature remains constant, so this factor equals zero. Thus, the rate of metabolic heat production is equal to the rate at which heat is lost. Since the rate of mechanical work will be negligible under confinement conditions, the heat transfer may be divided into sensible losses, from conduction, convection and radiation, and evaporative or latent losses. ASHRAE (1981) identified the ingestion of cold material as a minor source of heat transfer. Hamada (1971), however, felt that this loss may be compensated for by the heat arising from fermentation in the rumen, a factor that is not included in metabolic rates determined by the calculation method of indirect calorimetry.

2.2.2.1 Metabolic Heat Production

Metabolic heat production is the result of the chemical energy contained in food being converted into heat energy. Esmay (1979) considered it a key measurable index in environmental research, even though the researcher is concerned ultimately with animal growth or product yield. The amount of metabolizable energy available is governed by the feed intake, while the metabolic heat produced from this energy will be determined by the physiological state of the animal and by the surrounding environment. The levels of production and activity will affect the basic metabolic rate, while the environmental demand can cause an increase in the heat production from this basal point. The fact that metabolic heat production responds readily and consistently to temperatures outside the "comfort" zone has made this parameter a popular indicator of animal response to environments.

Although the body weight of an animal influences the metabolic rate, this relationship has been difficult to define mathematically. Human metabolic rates usually are expressed as a function of body surface area. Brody and Elting (1926) derived a formula relating the surface area of a dairy cow to its weight raised to the power of 0.56. Subsequent research has shown, however, that the metabolic heat production of animals is related more closely to another power of body weight than to the surface area.

Blaxter and Wainman (1961) presented heat production as a function of surface area, but used the product of 0.09 and the weight raised to the power of 0.667 in their formula for surface area. Brody (1945) calculated the basic metabolic rate as a function of the body weight raised to the power of 0.734, while Kleiber (1975) concluded that the metabolic rate was more proportional to the weight raised to the power of 0.75. The phrases, metabolic body size or metabolic weight, have been used to describe this latter expression, which seems to have gained general acceptance. Esmay (1979) defined the basal metabolic rate as the minimal rate of heat production while the animal is fasting and resting, and subjected to effective environmental temperatures in the thermoneutral zone.

2.2.2.2 Evaporative Heat Loss

Evaporative heat loss in cattle takes place in the respiratory tract and at the skin surface. The cutaneous evaporation can be divided further into losses by diffusion of water vapour through the skin and by sweating. Evaporative losses can be adjusted by biological reactions within the animal, but are also subject to physical laws. The physical regulation of evaporation from a surface is related to the conditions at the surface and of the surrounding air. The respective water vapour concentrations and the air-flow rate are the critical factors in the exchange.

Biological responses include variations in respiratory volume and secretion of sweat. McLean (1973) identified evaporation as the principal means by which homeotherms avoid becoming overheated in warm environments. Evaporative heat losses tend to decrease with a reduction in temperature, but a minimum level of evaporation is established by respiratory needs and passive diffusion.

The exchange of moisture by diffusion is thought to be a mechanism by which non-sweating animals can dissipate heat at their outer surfaces. In theory, the evaporation takes place below the skin and the water vapour diffuses through the skin. This is a passive process that is not subject to thermoregulatory control. According to Scott et al (1983), this diffusion exchange may be a significant portion of the evaporative heat loss at low ambient temperatures, but becomes a rapidly decreasing fraction at high environmental temperatures.

Although most domestic animals are considered to be non-sweating, evaporative losses from the body surface of cattle have been found by Kibler and Brody (1950) to form the majority of the total latent heat loss. Cattle have sweat glands located near the hair follicles and Scott et al (1983) noted the correlation between evaporation and the number of sweat glands. These glands are not developed particularly well and are not capable of producing large quantities of sweat. This is a result of the slow secretion, described by Esmay (1979), and the periodic rather than continuous increases in production found by Wiersma (1976). The sweat secreted by the glands is moved to the skin surface where the physical laws affecting evaporation gain control. Under conditions of high temperature and humidity, the vapour pressure at the skin surface reaches the saturation point and the sweat builds up on the hair surfaces, where it either evaporates or falls off (McLean, 1973).

The evaporation of moisture from the respiratory tract is the major source of latent heat loss in most domestic animals and is a significant component of the latent loss of cattle. The inspired air is heated to the deep body temperature and may become nearly saturated with moisture. The temperature and humidity of the inspired air will dictate the amount of evaporation that takes place on a unit volume basis. The respiratory rate, which is physiologically controlled, determines the total volume of air respired. Cattle are able to respond to heat stress by increasing their respiration rate, thus raising the rate of evaporative heat loss. Scott et al (1983) described the response of animals to severe heat stress as a phase of rapid, shallow breaths followed by slower, deeper breaths. This procedure is designed to meet the demands of high evaporative heat loss and gas exchange while avoiding alkalosis.

Wiersma (1976) recognized that although cattle were capable of panting and sweating, they were limited in both. ASHRAE (1981) considered the reduced evaporative efficiency of panting that resulted from less inspired air reaching a saturated state at the deep body temperature. Furthermore, the heat produced by the additional work needed for panting nullifies, to some extent, the gains in evaporative heat loss.

2.2.2.3 Sensible Heat Loss

Heat transfer by conduction, convection, and radiation obeys certain fundamental relationships and these control the sensible heat losses of animals. The animal has an influence on the amount of heat produced, the heat transfer to the body surface, and the insulative effect of the hair covering, but environmental conditions will determine finally, on the basis of physical laws, the actual heat loss. Heat is transferred from the body core to the surface by conduction through the tissues and convection through the blood stream. The overall level of thermal insulation achieved by steers, under conditions of vasoconstriction and piloerection, was measured by Blaxter and Wainman (1961) and found to be 0.42°C m^2/W.

The transfer of heat by convection occurs when portions of a fluid move from one area to another area that is at a different temperature. Convective transfer between a solid surface and a fluid is the result of a fluid layer coming into contact with the solid, being heated or cooled by conduction, then following convection currents to a new location within the fluid.

Mitchell (1973) described two different kinds of convective heat transfer. Free or natural convective heat transfer is caused by the density difference between warm and cold sections of a fluid and occurs continuously in thermally non-homogeneous fluids. Forced convective heat transfer is the result of pressure differences created by winds or currents in the fluid. Since the surface temperature of animals is usually different than the temperature of the surrounding fluid (air), free convective transfer is nearly always happening. Forced convective transfer takes place in the respiratory tract and when the body is in the presence of draughts or wind. Mitchell (1973) concluded that the forced convective transfer from the respiratory tract was rarely significant, while the free convective heat transfer was highly significant. The presence of forced convective heat transfer, according to Mitchell (1973), does not eliminate the effects of free convection. The convective heat transfer of animals is a function of the area, temperature, and configuration of the body surface; the temperature of the surrounding air; and the movement of air over the body.

Thermal radiation refers to the transfer of heat energy, by electromagnetic waves, between two surfaces at different temperatures. The waves used in this transmission occupy two distinct wavebands at opposite ends of the thermal radiation spectrum. All surfaces absorb and emit long-wave radiation, while short-wave radiation is generated by the sun. Short-wave radiation is absorbed and reflected, in varying degrees, by surfaces on earth. Short-wave radiation affects animals exposed to sunlight and located near windows in barns, but has only an indirect effect on the energy balance of animals in a confinement livestock building. Radiation from the sun can alter significantly the heat gains or losses of the building itself and, in this way, contributes to the total energy balance of the structure.

The loss of heat through long-wave radiation is an important component of the animal's sensible heat loss. Cena (1973) defined the net radiation exchange as the difference between the total radiation absorbed by a surface and the total radiation emitted and reflected. Monteith (1973) considered the heat exchange by radiation to be composed of two factors: the long-wave radiation loss from the animals if they were surrounded by walls at the air temperature and the radiative gain that would occur if the animal body surface was equal in temperature to the air. Long-wave radiation exchange between two surfaces is governed by the Stefan-Boltzmann Law, which states that the energy loss is equal to the product of a constant and the difference between the fourth powers of the respective absolute temperatures. The absorptivity, emissivity and area of the body surface will determine the magnitude of the radiative heat loss under particular temperature conditions.

Cena (1973) discussed the difficulty in calculating a radiative balance caused by the lack of uniformity in the surface of animals and suggested that the exchange may be considered to take place at a layer close to the surface of the hair coat. The fact that other forms of sensible heat loss are more dependent on a temperature difference than the values of the temperatures themselves, while radiation heat transfer changes rapidly with an adjustment in temperature was noted by Esmay (1979). Long-wave radiation heat loss was described by Cena (1973) as accounting for 50 percent of the sensible heat loss of sheep and as the most important single factor affecting the comfort and thermoregulatory response of man.

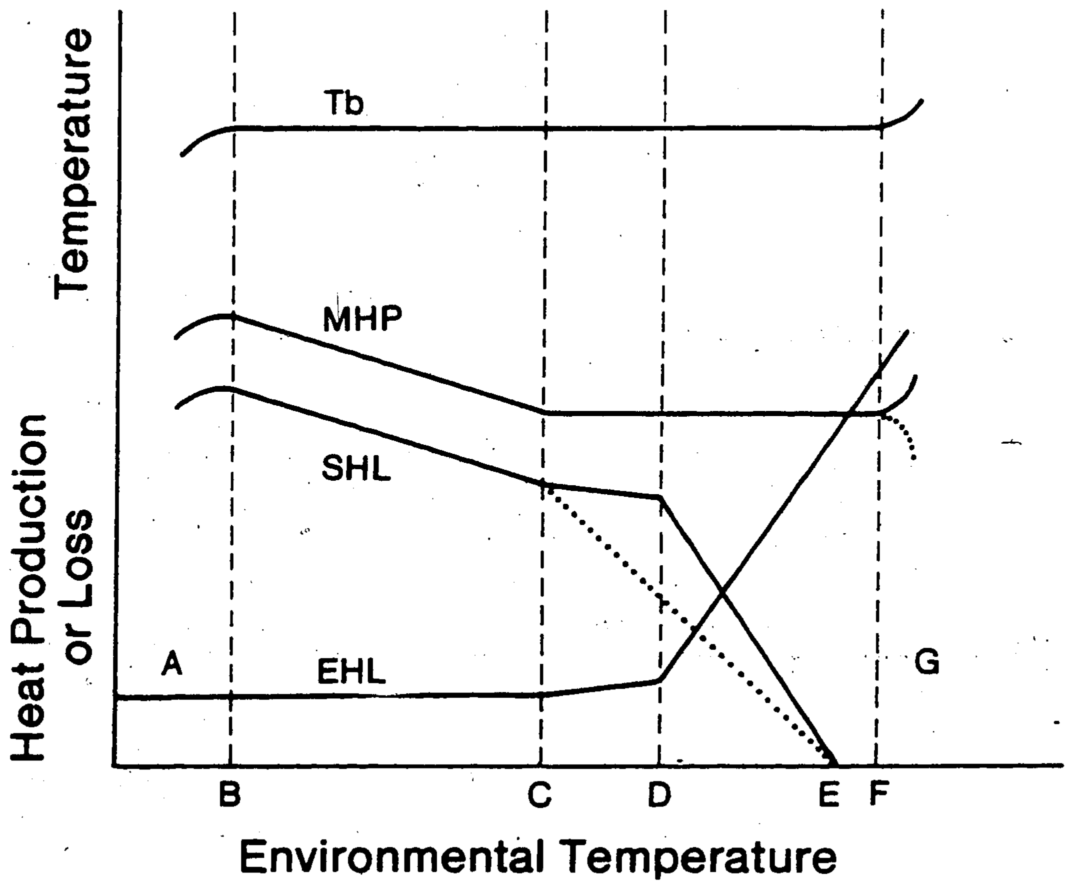
Heat loss by conduction occurs when energy is exchanged by solid particles in contact with one another. Wiersma (1976) considered conductive heat loss in livestock to be significant only when the animals were lying down and, therefore, a function of behavior. When the animals are in contact with a colder surface, the magnitude of the heat loss depends on the area of contact, the temperature of the surface, and the thermal conductivity of the material. Heat losses by conduction would be quite significant in hog barns, where animals with a sparse hair coat spend a good deal of time lying on concrete floors, but much less so in dairy barns, where animals with a thick coat of hair lie on beds of straw.

2.2.3 Thermal Zones

The consideration of animal environments almost inevitably leads to an examination of thermal zones. These zones may be defined as ranges of environmental conditions over which the animal's thermal responses will follow a consistent pattern. The physiological functions considered in the definition of thermal zones are the deep body temperature, the metabolic heat production, the sensible heat losses, and the evaporative heat losses. For lack of a more complete environmental description, these functions usually are related to the air temperature alone. Such a comparison is not completely accurate, but is probably valid, since heat production and dissipation are most closely associated with temperature. Although the effect of environmental temperature on the pertinent physiological parameters has been well documented and, in fact, is generally agreed upon, the definition of thermal zones and the terminology used to describe these ranges remain unclear.

Since livestock operators are concerned ultimately with the production of meat, milk, or eggs, the efficiency of the animals in producing these commodities likely would be the most useful indicator of thermal response. Unfortunately, most research has dealt with physiological indices, and productive efficiencies have had to be extrapolated from this information. The issue is further complicated by the problem, identified by Scott et al (1983), that the optimum thermal environment, based on economics, disease control, and labour factors, may not coincide necessarily with the optimum environment for thermoregulation. Kleiber (1975) considered the temperature range where sensible heat loss is fairly constant to be the thermal zone where the most efficient feed conversion will occur. Sainsbury and Sainsbury (1979) defined a thermocomfort zone as the range over which the animal will give optimal performance and considered this zone to be contained in a broader thermoneutral zone which was specified as a range of temperature where no metabolic demands are imposed.

The thermal zones of mammals often are illustrated graphically. The chart in Figure 2.1 was developed by Mount (1973), but is very similar to a figure that Esmay (1979) adapted from Kleiber (1961). On this chart, zone BF is the thermoregulatory range or zone of homeothermy, while zones A and G are areas of hypothermia and hyperthermia, respectively. Temperature C is the point at which metabolic heat production begins to rise with decreasing ambient temperature, while temperature D is the level where evaporative heat losses begin to rise sharply as ambient temperature increases. Temperature E, where the sensible heat loss reaches zero, is the surface temperature of the animal. Mount (1973) specified environmental temperature as a state where the air and mean radiant temperature were equal and located in a regime of free convection, with a relative humidity of 50 percent. The branched line for



Tb = Deep-body Temperature
MHP = Metabolic Heat Production
SHL = Sensible Heat Loss
EHL = Evaporative Heat Loss

Figure 2.1. Thermal zones of mammals (Mount, 1973).

metabolic heat production in zone G signifies both the increased energy used in the panting and exertion of thermoregulation and the decreased production resulting from a reduction in feed intake. Using this illustration, a reasonable and precise assessment of the defined thermal zones is possible.

The most common definition of the thermoneutral zone, as noted previously, would correspond to zone CF in Figure 2.1. A similar area was described by Webster (1973) when he stated that within the thermoneutral zone, heat loss and energy intake are independent of environmental temperature. Esmay (1979) also used a comparable zone of thermoneutrality and described it as a range where physical, rather than physiological, regulation of homeothermy is possible. Mount (1973) suggested that an animal at minimum metabolic rate, but maintaining homeothermy only by greatly increased evaporative heat loss, should not be considered to be in a neutral condition. Mount (1973) proposed an alternative zone of least thermoregulatory effort, defined as a range of environmental temperatures in which, for a given level of feeding, the metabolic rate is at a minimum and evaporative heat loss is not increased as a result of panting or sweating. This is zone CD in Figure 2.1, which corresponds to Kleiber's (1975) range of most efficient feed conversion. This zone is often very narrow, sometimes covering a range of only 1°C.

The lower limit of thermal neutrality, referred to as the lower critical temperature, generally is recognized as the temperature below which metabolic heat production increases (temperature C in Figure 2.1). Esmay (1979), however, considered the upper and lower critical temperatures to be at the boundaries of homeothermy (temperatures B and F). The upper critical temperature has proven to be more difficult to define, but Webster's (1973) statement that it is the temperature above which performance is depressed by heat is apt, if not precise. This would place the upper limit of the thermoneutral zone somewhere between D and E in Figure 2.1, which is a realistic location. The use of either D or F as an upper critical temperature creates a thermoneutral zone that deviates excessively from the range of optimum production.

2.3 Heat and Moisture Production Research

The design of an environmental control system for a livestock building involves a determination of the size and operation of the ventilation and heating or cooling systems required to achieve an energy balance at some optimum environmental conditions. Several of the factors in the building energy balance can be measured or calculated with a considerable degree of accuracy. The heat produced by mechanical equipment and supplemental heating systems can be assessed with reasonable precision. Similarly, the energy dissipated by conductive losses through the building, by ventilation, and by supplemental cooling is relatively easy to derive from basic equations. The heat produced by people working in the building is of such small magnitude that even large errors in calculation would not significantly affect the efficiency of the design.

Unfortunately, the variable that can be determined with the least certainty is also the most important factor in the energy balance, that is, the heat and moisture production of the animals. Buffington et al (1972) considered estimates of the heat and moisture lost by animals inside a building to be the least reliable of all the factors contributing to the temperature and humidity conditions. Barlott and McQuitty (1976) encountered similar difficulties while developing a model of the thermal environment in confinement livestock buildings. Accurate heat and moisture production data were considered necessary for the validation and improvement of the model.

2.3.1 Historical Perspective

The measurement of the heat and moisture production of animals has been accomplished traditionally by either direct or indirect calorimetry. Indirect calorimetry is capable of providing valid data on the animal's production, but does not account for the evaporation of moisture from surfaces in the room. Direct calorimetry produces figures from situations more closely related to field conditions, but the problems of instrumenting calorimeters have restricted the size of these chambers.

Agricultural engineers became involved with thermoregulation research, according to Stewart (1976), as a result of their work on the ventilation of livestock structures. Brody (1945) credits Lavoisier with originating the methods of direct and indirect calorimetry in 1777. Bond (1976) attributed the first measurements of animal heat production to Crawford (1779), who determined heat loss by measuring the temperature of a jacket of water surrounding a calorimeter. The effects of environment on dairy cow production were considered by Henry and Morrison (1917), who reported on a 1907 test which found that cows produced more butterfat as temperatures fell and produced less milk when exposed to cold rains. King (1908) set a standard of purity for livestock buildings by specifying that not more than 3 percent of air in a stable could be respired air. Kelly (1928) stated that optimum air conditions for dairy cows could not be specified and suggested the development of a comfort zone for environmental design. Kelly (1940) summarized the available data on the heat production of livestock and presented a graph based on information gathered by Armsby and Kriss (1921). These researchers had conducted some of the earliest experiments using direct calorimetry at Pennsylvania State University. They kept a few cows under ordinary barn conditions, with average feed intake and milk production, and close to a state of thermoneutrality. From these tests, a critical temperature was identified and a figure of 3165 kJ/h cow(454 kg) was calculated for the total heat production of dairy cattle.

A major limitation of early research, identified by Buffington et al (1972), was the measurement of heat and moisture production from animals on the basis of the standard metabolic rate, a theoretical physiological state that rarely occurs under natural conditions. Furthermore, Stewart (1976) considered that research, up to 1959, was intended primarily to increase knowledge of basic thermoregulation, with applications to animal housing being a secondary benefit.

One of the most important milestones in the development of information on the heat and moisture production of dairy cattle was the completion, in February, 1948, of the Psychroenergetic Laboratory at The University of Missouri. The laboratory consisted of an 18.3-m x 12.2-m rigid frame building which contained two 5.5-m x 7.9-m test rooms. Each of these rooms had sufficient capacity for six mature cows in stanchions or nine calves in pens. Ventilation was provided by a combination of recirculated and fresh air, with the fresh air being preconditioned in adjoining rooms. The temperature and volume of the ventilation air was measured, along with the surface temperatures, air temperatures, and humidity in the chamber. Conductive heat loss, heat production of lights, and heat storage in the structure were all calculated or estimated.

Thompson and Stewart (1952) described the laboratory as a controlled-climate barn rather than a calorimeter. Over the period from 1948 to 1959, sixteen environmental tests were carried out at the University. Yeck and Stewart (1959) reported that twelve of these tests measured the effects of temperature, humidity, wind, and heat radiation on mature cattle, while four considered the effects of temperature on calves. The goal of the work at the Psychroenergetic Laboratory, as elucidated by Brody (1946), was to furnish the basic physiological data for building shelters designed to achieve maximal production and profit. The results obtained from research undertaken at this facility have since formed the basis for nearly all dairy cattle environmental designs in North America.

Originally, many designers felt that the results of controlled thermoregulatory research could be applied to commercial livestock buildings. Stewart (1976), however, noted a division of research, in the early 1960's, into work on thermoregulation as an end in itself, and on searches for optimum environments in an economic framework. He further observed a pattern whereby physiologists obtained basic thermoregulatory data from small groups of animals, while engineers gathered information on thermal behavior under field conditions. A good deal of the work on thermoregulation has not proven to be practical, but Stewart (1970) recognized that the effect of many environmental parameters is of more interest to physiologists than engineers. Part of the difficulty was explained by Monteith (1973), who proposed the paradox that micrometeorologists need to know what parameters the physiologist requires, but the physiologist may be unsure of the value of measurements until they have been completed.

These conflicts demonstrate the necessity for a multi-disciplinary approach to environmental research. Smith (1972) stated that real problems seldom are confined to one discipline and Stewart (1970) suggested that there was not enough knowledge in any single discipline to deal with environmental problems in animal housing. Stewart (1970) also considered that the value of all environmental research is [illegible]ined by the degree to which it can be related to production of the most protein at the least cost. Stewart (1973) noted the need to compare physiological indices to performance, but realized the difficulty in accurately assessing the effects of the thermal environment, due to the interference of other environmental factors.

The current status and future requirements of environmental research have been examined by several authors. Not surprisingly, there has been some difference of opinion, both on the adequacy of existing knowledge and the direction research should take. Housing and environmental design, in Smith's (1972) estimation, had been sufficiently well treated to enable engineers to deal with the thermal environment properly. Smith (1972) felt, however, that health and hygiene would eventually impose the limits on production, and hence the need for an examination of environmental quality rather than thermal engineering.

Webster (1973) found that most research involved taking animals from a standard environment and exposing them, for a short time, to thermal stress. This provides insights into temperature regulation, but little information on the effect of an environment on animals living under production conditions. Stewart (1970) considered the available heat and moisture production data to be adequate, but later (Stewart, 1973) cautioned against the careless extrapolation of results obtained in psychrometric chambers to natural environments. He also noted that controlled temperature work, unfortunately, was more popular than field investigations.

With particular reference to dairy housing, Bates (1974) stated that, despite the proliferation of free-stall barns, all environmental control systems were being designed on an empirical basis from information gathered in stanchion barns. He emphasized consideration of the constraints under which research was conducted when applying the results to field problems. Strom and Feenstra (1980) found a general lack of research, on dairy cows, meeting their criteria for valid heat and moisture production information.

While the effects of steady state temperatures on dairy cattle had been well documented, Stewart (1970) felt that information on cyclical temperature regimes and air velocities was deficient. Bond (1976) also described the need for knowledge on the effects of dynamic air temperatures and air velocities, as well as relative humidity, radiant energy, and acclimation. Stewart (1970) suggested economic evaluations of environmental systems, especially the derivation of the costs associated with deviations of the environment from optimal conditions.

Both Stewart (1970) and Bates (1974) considered the probable differences in the behavior and requirements of dairy cows housed in the comparatively large groups found in most barns. Bates (1974) was concerned especially about the lack of information on certain aspects of free-stall housing, particularly the evaporation of moisture from the large, wet alley surfaces and the shift in animal population at milking time.

The resolution of the difficulties posed by these areas of insufficient knowledge seems, on the basis of the preceeding observations, to be contingent upon the collection of more field data. Although acknowledging the need to deal with commercially-sized facilities, Stewart (1970) stated that the cost of these facilities was the prime deterrent to research conducted under what Bates (1974) called real conditions. As a viable alternative to the construction of large research facilities, Stewart (1970) proposed the development of research projects relying on the use of farmer-owned facilities. The data acquisition system, developed at the University of Alberta by Feddes and McQuitty (1977), was designed for the exact purpose of overcoming the problems of instrumentation, data recording, and information processing associated with investigations of this nature. This system made it feasible for researchers to collect and compile environmental data from livestock buildings under actual operating conditions, thereby substantially increasing the practicality of undertaking field studies.

2.3.2 Physiological Research

Most of the physiological research into the energy balance of dairy cows may be divided, following a concept advanced in the previous section, into research dealing strictly with the physiological reactions of the animal, particularly thermoregulation, and that involving the effects of the environment on the production of the animals. Some studies have considered both subjects and a few have even tried to relate the two, but these are in the minority.

2.3.2.1 Metabolic Heat Production

Since the amount of energy available for dissipation and, more importantly, the energy available for milk production are dependent, at a given level of feed intake, on the metabolic heat production, this parameter has received a considerable amount of research attention. The metabolic heat production, or metabolic rate, of dairy cows has been studied under a wide variety of conditions involving fluctuations in environment, production, feeding, and stages of gestation and lactation.

Many of these experiments, as Strom and Feenstra (1980) pointed out, have yielded heat production data as by-products of feed trials. With careful interpretation, however, these results may provide valid information, both for assessing absolute values and for comparing with other figures. There is also a lack of uniformity in the methods of expressing heat production and the physical units. For this reason, the metabolic heat production values have been converted, when sufficient information was available, into kilojoules per hour kilogram raised to the power of 0.75 (kJ/h $Kg^{0.75}$), as specified by Kleiber (1975). The basic metabolic rate of a fasting, resting animal, in the zone of thermoneutrality, was determined by Brody (1945) to be 11.2 kJ/h $Kg^{0.75}$. Webster (1973) estimated the heat production of fasting cattle to be 13.7 - 17.3 kJ/h $Kg^{0.75}$. Obviously, the demands imposed on the animals by growth, production, and pregnancy will tend to increase this metabolic rate.

Keener and Conrad (1976) developed a dynamic simulation model of energy flow in bovines. The model was designed principally to calculate growth rates under different feeding programs, but also was used to determine, on the basis of inputs from Ragsdale et al (1949), the heat production of a dry Holstein cow at different temperatures. The model estimated the metabolic heat production of the cow to be 35.3, 30.6, and 27.7 kJ/h $Kg^{0.75}$ at temperatures of 0°C, 12°C, and 24 °C, respectively.

Flatt et al (1965) used open-circuit indirect calorimetry to measure the heat production of six mature Holstein cows, on three different rations, during a lactation period. In the early stages of the period, the cows generated an average of 4176 kJ/h and produced an average of 15.4 kg of milk per day. The average heat and milk production of the late lactation segment were 3456 kJ/h and 8.5 kg/day, respectively. Flatt et al (1969a) used a similar procedure to measure the effect of ration composition and energy utilization on eight Holstein cows. The cows were fed three maintenance rations and confined in a chamber where the average temperature was 20.7°C with the relative humidity around 71 percent. The non-pregnant animals converted 57 percent of the gross energy intake into metabolic heat, while the pregnant animals utilized 66 percent for heat production. The non-pregnant cows had an overall heat production of 18.0 kJ/h $kg^{0.75}$, whereas the pregnant cows generated 22.0 kJ/h $kg^{0.75}$.

Flatt et al (1969b) conducted further experiments on fourteen high yielding Holstein cows, again using three rations, although these were fed ad libitum. The trials were carried out at various stages of lactation. The average temperature and relative humidity in the respiration chamber were 21.4°C and 75.2 percent, respectively. The metabolic heat production was found to be the largest single source of energy loss, regardless of the ration or stage of lactation, averaging 44.1 percent of the gross energy losses. There were no statistically significant differences (at the 5 percent level) in heat production as a result of either ration composition or stage of lactation. During the tests, the daily milk production ranged from 0.92 to 45.8 kg, with the average being 16.5 kg. The metabolic rate varied from 23.4 to 44.3 kJ/h $kg^{0.75}$, with an average heat production of 33.5 kJ/h $kg^{0.75}$.

Tests of energy metabolism on two different feeds were undertaken by Demchenko (1969). The trials took place over a period of four years and involved two groups of heifers raised through their first lactation. Indirect calorimetry and balance tests were used to determine the energy gains and losses. Demchenko (1969) found a strong relationship between heat production and live weight and reported an overall range of 584.3 to 819.7 kJ/h 100 kg. The figures from one test group of five heifers were tabulated, with average values of 34.2 kJ/h $kg^{0.75}$ and 16.8 kg/day listed for the heat and milk production, respectively.

A table of metabolic heat generation at various levels of milk production was presented by Webster (1973), based on data from Flatt et al (1969b). The metabolic rate of dry, pregnant cows was estimated at 20.5 kJ/h $kg^{0.75}$, while the heat production of lactating cows ranged from 25.6 kJ/h $kg^{0.75}$ at 2 gallons/day (9.1 kg/day) to 35.3 kJ/h $kg^{0.75}$ at 8 gallons/day (36.4 kg/day).

The most comprehensive studies of the relationship between environmental temperature and metabolic heat production were carried out at the University of Missouri Psychroenergetic Laboratory and were summarized by Yeck and Stewart (1959). The results of 308 observations were examined and the effects of the temperature fluctuations calculated. The change in metabolic heat production was found to be 0.16 kJ/h $kg^{0.75}$ per degree Celsius temperature difference. The overall equation for the metabolic heat production of Holsteins was:

$$Q=30.35-0.16t,$$

where Q is heat production, kJ/h $kg^{0.75}$, and t is the ambient temperature, °C. On the basis of a statistical correlation, milk production was found to increase the metabolic rate by 0.38 kJ/h $kg^{0.75}$ per kilogram of milk produced daily.

2.3.2.2 Partition of Heat Losses

While the total heat dissipated by livestock is physiologically important, the partition of this value into sensible and latent heat losses has particular significance in the design of environmental control systems for animal houses. This is especially true in cold climates where the sensible and latent heat production of the animals have opposite effects on the environmental conditions within the building. The sensible heat is beneficial and tends to reduce the heat deficit in the barn, while the latent heat is the critical factor contributing to the ventilation requirements that create this heat deficit. Physiologically, the partition of animal total heat loss is related most directly to the environmental temperature, but various studies also have examined the effects of air velocity and relative humidity on this division.

There is general agreement that latent or evaporative heat losses increase with rising temperatures, while sensible heat losses decline. However, unlike sensible heat losses, which effectively are reduced to zero when the air temperature reaches the body temperature, evaporative losses have a minimum level established by respiratory requirements and passive diffusion through the skin . Kibler and Brody (1952) determined that the minimum loss of heat by evaporation was 10 percent of the total heat loss. ASHRAE (1978) documented, in graphical form, the percentage of total heat lost by evaporation. The values ranged from a 10 percent minimum to values of 12 percent at 0°C, 18 percent at 10°C, 38 percent at 20°C, and 70 percent at 30°C. Yeck and Stewart (1959) and Kibler and Brody (1950) found the latent proportion of the total heat to be 25 percent at 10°C.

Kibler and Brody (1950) further divided the latent heat losses into surface and respiratory vaporization. The respiratory component was found to be about 20 percent of the total evaporative losses. DeShazer (1981) produced an equation linking the percentage of the heat loss attributed to evaporation and the ambient air temperature. The equation,

$$y = 20 + \exp 0.19t^{0.9},$$

where y equals the percentage of the total heat lost by evaporation and t is the ambient temperature, °C, was meant to be a general expression for all livestock.

Absolute values for evaporative heat losses from cattle range upward from the minimum of 2.81 kJ/h $kg^{0.75}$ liveweight, as determined by Blaxter (1962). Esmay (1979) estimated the respiratory losses as 1.55 1.94 kJ/h $kg^{0.75}$ at -10°C and 5.80 kJ/h $kg^{0.75}$ at 35°C. He also predicted a maximum sustained rate of surface vaporization of 15.41 kJ/h $kg^{0.75}$.

Sensible heat losses usually are determined from the difference between latent and total heat dissipation. Kibler and Brody (1952) measured the sensible losses of lactating Holstein cows over temperatures varying from 17°C to -14°C and derived a formula,

$$Qs=27.0-0.32t,$$

where Qs is the sensible heat loss, kJ/h $kg^{0.75}$, and t is the ambient air temperature, °C. Keener and Conrad (1976), in their simulation model, calculated the sensible heat losses of a dry Holstein cow to be 28.4 kJ/h $kg^{0.75}$ at 0°C and 12.0 kJ/h $kg^{0.75}$ at 24°C.

In addition to the obvious impact of ambient temperature on heat losses, air velocity over the animal can have a significant effect, both on the total heat dissipation and the partition of the heat losses. Blaxter and Wainman (1964) found that an increase in air velocity from 0.18 m/s to 0.72 m/s reduced the evaporative losses of steers slightly, while raising sensible losses. All of the changes were statistically insignificant, except for the 7 percent increase in sensible losses caused by the wind at temperatures in the 0°C range. Thompson et al (1954) also measured the greatest evaporative losses at low air speeds, with dissipation rates being consistently lower at medium (1.8 - 2.7 m/s) and high (3.6 - 4.0 m/s) velocities. Surprisingly, the evaporation was lowest in the medium range of wind speed. The reduction in latent heat loss in the pr ence of wind is likely a result of the increase in sensible losses which lessens the demand for evaporative dissipation of heat. This physiological adjustment counteracts the physical effect of increased a movement, which would be a corresponding rise in evapora n from the animal surface. Thompson (1957) measured additions to the total heat load of up to 25 percent when air velocity, at -7°C, was increased from 0.2 m/s to 4.5 m/s, but at temperatures of 18°C, very little difference was found.

The consequences of increased relative humidity can be predicted theoretically from basic physical relationships. The reduced vapour pressure gradient between the animal's skin and the air will cause the evaporative heat losses to decline. This occurrence has serious implications at high environmental temperatures, where latent heat losses are critical to the maintenance of homeothermy. At low temperatures, the relative magnitude of evaporative losses makes fluctuations in these values insignificant. McLean and Calvert (1972) exposed four Jersey steers to a wide range of humidities at temperatures of 15°C and 35°C. At 15°C, increasing the relative humidity resulted in a decline in both respiratory and surface vapourization rates, as well as the total heat loss. At 35°C, the rising relative humidity caused the body temperature, respiratory frequency, and sensible heat loss to increase. The animals maintained a constant total heat loss only at the expense of higher body temperatures and respiration frequencies. Shanklin and Stewart (1966) tested the effects of three relative humidities at each of two temperatures, 27°C and 32°C, and found that increasing the relative humidity caused the surface temperature of cows to rise.

An overall assessment of the effects of air velocity and relative humidity leads to the conclusion that they produce their most significant heat loss fluctuations at opposite ends of the environmental temperature scale. Relative humidity seems to have little influence on heat dissipation at low temperatures, but increases the environmental demand and exacerbates the effects of heat stress at high ambient temperatures. Conversely, while increased air velocity can relieve heat stress slightly, the greatest impact of air speeds is on the sensible heat losses of animals at low temperatures. In the design of confinement livestock buildings, air velocity is usually relatively low at the animal level and this parameter seldom has a direct influence on the animal energy balance. Relative humidities, however, tend to be high in these buildings and are considered an extremely important factor in the thermal environment.

2.3.2.3 Thermal Zones

The dissension among animal scientists regarding the definition of thermal zones for dairy cattle has created a similar disparity in the identification of the boundaries of these zones. Logically, the thermal parameter about which agreement is most common, the lower critical temperature, has been measured and reported upon with the greatest frequency. The limits of a relatively broad zone of thermoneutrality have been roughly established, although few researchers have been willing to specify an exact upper critical temperature. The uncertainty affecting the physiological definition of a thermoneutral zone has been responsible for the use of milk production tests in determining a zone of optimal production. Such a zone has greater relevance for the operator and, therefore, the designer of livestock buildings.

The lower critical temperature, being the point below which the metabolic heat production increases from the basal level, is dependent upon several factors. The most obvious variable influencing this temperature is feed intake, but milk production, thermal insulation, and the basal metabolic rate itself also can alter its magnitude. Webster (1973) considered thermal stress to be less governed by absolute values than by the extent to which the environment deviated from the conditions to which the animals were accustomed.

Since the majority of the heat loss at low temperatures is sensible, most equations for the lower critical temperature have included an assessment of the resistance to heat flow of the animal's body and hair covering. Blaxter (1962) utilized a cooling constant to describe this insulative effect and entered this in an equation for critical temperature based on thermoneutral metabolic rate, minimum evaporative heat loss, and the heat used to warm feeds and water to body temperature. Using this equation, Blaxter and Wainman (1961) calculated the critical temperatures of steers to be 18°C, while fasting, and 6 to 7°C on maintenance feed. When applied to dairy cattle, the equation yielded temperatures of -6°C for cows producing 9 kg of milk daily and -18°C for those producing 18 kg.

Webster (1973) assigned values to the tissue and external insulation of dairy cows and derived critical temperatures of -14°C for dry pregnant cows and -32°C for cows producing 20 kg of milk daily. In contrast to this, Thompson (1976) suggested -1°C as a lower critical temperature for high yielding cows. A comprehensive formula for determining the critical temperature was developed by Hamada (1971), who used an optimum temperature of 17°C for dairy cows, rather than the body temperature, as a baseline. The formula related the critical temperature to latent heat losses as a function of metabolic rate and the increase in sensible heat loss associated with decreasing temperatures. Using this expression, Hamada (1971) calculated critical temperatures of 2°C for cows on maintenance feed; -4°C for cows producing 10 kg of fat-corrected milk daily, and -10 °C for cows producing 20 kg of milk.

The upper limit of the zone of thermoneutrality, depending on the definition of this limit, would appear to be somewhere between 20 and 30°C. This boundary is affected, to a much larger extent than the lower critical temperature, by environmental conditions other than temperature. The influence of the relative humidity on evaporative heat losses will alter significantly the ability of the animal to remain comfortable. The zone of optimal production also seems to end in the range noted above, so there is a difficulty in separating the two values. Webster (1973) estimated the limit of thermoneutrality at 30°C, but suggested 20 to 25°C as the highest temperature for maximum production. Hahn (1976) considered 24°C to be the maximum acceptable temperature for dairy cows. Webster (1973) also noted that high producing cows, with comparable increases in metabolic rate, would exhibit a lower tolerance to heat than animals on maintenance rations.

2.3.2.4 Environmental Effects and Recommendations

Although physiological knowledge is essential for a complete understanding of the relationship between livestock and their environment, the viability of any operation is determined by the productive efficiency of the animals. Johnson (1965) noted that under optimum environmental conditions, the production of milk will vary only with the genetic capabilities of the cow. Hence, the effect of the thermal environment on production is of utmost importance in the design and operation of livestock buildings. The productivity of dairy cows is relatively easy to measure and the volume of milk yielded under various environmental conditions has been examined closely. Although the desire to provide an ideal environment often must be tempered by economic considerations, a practical range of acceptable conditions, over which milk production remains close to a maximum level, has been established.

Virtually all of the dairy animals in Canada are European breeds, of which the Holstein is easily the most popular. These animals are well suited to the climate in Western Canada, having a low heat tolerance, but being very hardy. The Holsteins, in particular, are able to maintain a high level of milk production at low temperatures, albeit at the expense of reduced feed efficiency. Since feed usually has been less expensive than sophisticated shelters, confinement housing of cows has been difficult to justify on the basis of milk production alone. On the other hand, the susceptability of these breeds to heat stress has generated considerable interest, throughout the southern regions of North America, in measures designed to protect the cows from conditions of high temperature, humidity, and radiation.

Low temperatures stimulate the appetite of dairy cows, but cause some reduction in milk yield. The milk fat content tends to increase, and Young (1979) suggested that the higher level of feed intake may offset the influence of temperature on milk yield. The overall effect, however, is a loss of feed efficiency. Young and Christopherson (1974) also noted that prolonged exposure to cold resulted in an increase in the thermoneutral heat production, a condition that would reduce the energy available for milk production. Johnson (1965) reported that, according to all literature, cows could lactate successfully at low temperatures, but with reduced production and increased feed intake.

The effects of low fluctuating temperatures on Holstein cows were studied comprehensively by MacDonald and Bell (1958). Low temperatures caused the heart rate and rectal temperatures to increase, while reducing the respiratory rate. As temperatures declined, the requirement for more metabolic heat caused the feed intake to increase. This effect was accompanied by a corresponding increase in water consumption. The daily milk yield was found to decrease significantly at temperatures below -4°C, with the rate of decline becoming sharper when temperatures fell below -12 °C. Williams and Bell (1964) conducted similar experiments, but held the relative humidity in the barn to 72 - 79 percent rather than the 90 - 100 percent allowed in the previous studies by MacDonald and Bell (1958). Under these conditions, no decline in milk yield was noted at temperatures as low as -16°C.

Other work on the effects of temperature on milk yield was conducted at the University of Missouri. Ragsdale et al

(1950) measured the milk production of cattle at various temperatures, with relative humidities in the 40 - 60 percent range. The maximum production occurred at 10°C, but no significant reduction in yield resulted from temperatures as low as -13°C. In a direct comparison of these two temperatures, production was down less than 7 percent, although the feed to milk ratio was raised by almost 15 percent. Yeck and Stewart (1959) summarized the results from several experiments and concluded that Holstein production was essentially unchanged to a temperature of -12°C.

As would be expected from animals well adapted to low temperatures, the reaction of Holstein dairy cows to high temperatures is much more dramatic. The inability of the animals to maintain homeothermy and their diminished appetite contribute to a sizeable decline in production. High relative humidity and solar radiation can accelerate this decline, which is more pronounced in high yielding cows. Ragsdale et al (1950) found that milk production of Holsteins was reduced by temperatures over 21°C. Between 21°C and 27°C, the decline was gradual, but after 27°C, production dropped quickly. In the Yeck and Stewart (1959) summary, milk production was determined to be 90 percent of normal at 27°C, but only 65 percent of normal at 32°C.

The effects of relative humidity have been incorporated into various Temperature-Humidity or Discomfort Indices. These equations derive a figure based on dry-bulb temperatures and wet-bulb temperatures or dewpoints, and are applicable at environmental temperatures over 18°C. One such index, developed by Bianca (1962), used a weighting of 65 percent for wet-bulb temperatures and 35 percent for dry-bulb readings. Environmental recommendations then can be made on the basis of Discomfort Index values and, in this way, are more meaningful than a simple temperature range. Berry et al (1964) developed a formula for calculating the actual decline in milk production from a factored sum of wet-bulb and dry-bulb temperatures.

One characteristic of all natural and most modified environments that is not included in many controlled temperature experiments is the diurnal cycling of temperatures. Yeck and Stewart (1959) concluded that the effect of the diurnal cycle on production was roughly comparable to constant exposure of the animals to the average temperature of the cycle. Data from Kibler and Brody (1956) support this statement, provided that the range of temperatures is 10°C or less. A wider diurnal cycle resulted in significant stress on the animals, although Yeck and Stewart (1959) found no production decline over a 40°C cycle. Brody et al (1955) determined that diurnal conditions, as contrasted to constant temperatures, would extend the upper and lower ranges of the thermal zones. On the basis of these studies, ASHRAE (1981) considered design loads calculated from average daily environmental temperatures to be sufficiently accurate. In any case, the control of the environment by the ventilation system would be affected by the two to four-hour lag in the response of the animals' moisture production to maximum and minimum temperatures, a characteristic that was reported by Esmay (1979).

The recommended environmental conditions for dairy cows are linked closely to the milk production experiments cited previously, with all the specified ranges falling in the zone of optimal production. The parameters most often identified are dry-bulb temperature and relative humidity, although some reference is made to Discomfort Index limits. Ventilation rates and heating or cooling requirements, then, have been calculated in accordance with the environmental limits. An important factor in environmental design, as reported by McDowell (1974), is that milk yield is most highly correlated with conditions on the preceeding two to five days. Johnson (1965) identified a "comfort zone", based on research by Ragsdale et al (1950), as the optimal zone for milk production. This zone was located between -15°C and 27°C, but Johnson (1965) suggested that the use of a narrower range of temperatures, from -1°C to 16°C, would account for differences due to species and other influences. Both the upper and lower limits of the comfort zone would be constricted by increased relative humidity. Wind would extend the boundaries at high temperatures and reduce the limit at low temperatures; solar radiation would have the opposite effect. The highest milk production, according to Stewart (1960), occurs in the 7 to 18°C range, where relative humidity has no significant influence on animal performance.

There is a high degree of uniformity in the design specifications available, particularly in the middle and upper segments of the zones. Hahn (1976) suggested the acceptable temperature range for lactating cows was 4°C - 24°C. ASHRAE (1978) and ASAE (1981) extended the lower limit to 2°C and ASAE (1981) suggested the use of a Discomfort Index at temperatures above 21°C. Stewart (1960) stated that the Discomfort Index should have a value of 75 or less for optimum production. Albright and Alliston (1971) further lowered the boundary for Holstein cattle to -12°C. Stevens et al (1974) proposed a maximum acceptable temperature of 30°C, for a duration of less than one hour and with relative humidities under 50 percent. A range of relative humidities from 40 to 80 percent was considered acceptable by ASAE (1981) and Sainsbury (1974), although ASHRAE (1978) recommended a 55 - 75 percent zone. Winter ventilation rates are calculated on the basis of moisture production and, therefore, are peculiar to the inside and outside design conditions. Summer ventilation rates are applicable over wider geographical areas, since the use of untempered outside air often results in barn temperatures exceeding the specified limit for maximum production. Bates (1976) and ASAE (1981) suggested a summer ventilation rate of 30 or more air changes per hour, while ASHRAE (1978) and Guss and Grout (1973) considered 100 l/s cow(454 kg) to be adequate.

2.3.3 Design Values for Heat and Moisture Production

The most severe limitation to the validity of environmental system designs is imposed by the accuracy of the heat and moisture production information. Nearly all values for dairy cattle have been derived from experiments involving a small number of animals housed in calorimeters. The effects of commercial housing conditions have to be estimated, since, as Esmay (1979) stated, the heat and moisture production for the building system, rather than the animals themselves, is necessary for design purposes. Hellickson et al (1974) noted that ventilation rates could be calculated from thermodynamic relationships, but had to be based on data representative of the climatic conditions and production system.

A popular dairy housing system that has not been examined adequately is the use of free-stalls. Turnbull (1973) identified the fact that the free-stall barn very likely would produce more water vapour than tie-stall barns of a similar size. Even in tie-stall barns, the evaporation of mosture from wet surfaces adds significantly to the latent heat production developed from calorimetric trials. Furthermore, a certain portion of the sensible heat produced, approximately 20 percent according to Bruce (1982), is utilized in this vapourization and dissipated as latent heat. These deficiencies in experimental results have caused the environmental design of most dairy facilities to be based on either the indiscriminate application of existing data to a variety of situations or attempts to modify these data by the introduction of unsubstantiated factors.

The most extensive testing of the heat and moisture production of dairy cows, under conditions most closely approximating commercial housing, has taken place at the University of Missouri Psychroenergetic Laboratory. The testing apparatus and procedures were described in detail in a preceeding section. Data obtained from these experiments form the basis for the production values and ventilation rates prescribed in nearly all North American design manuals, including the Canadian Farm Building Code (1977), the ASAE Yearbook (1981), Midwest Plan Service (1980), ASHRAE (1978 and 1981), Esmay (1979), and Scott et al (1983).

The measurements performed at the Psychroenergetic Laboratory provide better design information than physiological studies because the evaporation of moisture from wet surfaces in the room was incorporated into the moisture production. However, the small capacity of the rooms (6 cows), the exclusive employment of stanchions, and the unknown effects of confining animals in environmental chambers have made the universal application of the results to commercial barns somewhat questionable.

Early testing of heat and moisture production at the University of Missouri was reported by Thompson and Stewart (1952). The effects of air temperature on the heat dissipation of lactating Holstein cows were measured during both a winter and summer period. These trials established the trend toward an increase in total heat production and a reduction in the ratio of latent to total heat with decreasing temperatures. A 20 percent rise in total heat production occurred as the temperature was lowered from 27°C to -12°C. Thompson and Stewart (1952) also found that the percentage of latent heat produced by the test room was higher than that for the animals alone. An equation was derived that related air temperature to the ratio of total heat removed per pound of moisture exchanged. This equation could be used to determine the ventilation requirements when only one of the total heat or latent heat production was available. The energy transfer associated with personnel, equipment, feed, bedding, and water was excluded from the heat exchange calculations. An increase in total heat loss for higher producing cows was noted, but, all secondary factors being equal, the moisture production in a stall varied directly with the animal size.

A summary of the research undertaken at the University of Missouri was compiled by Yeck and Stewart (1959). This paper included a graph of stable heat and moisture production at various temperatures, with the relative humidity ranging from 55 to 70 percent. The information provided in this graph has formed the basis of the values given in the design manuals listed previously. Yeck and Stewart (1959) estimated that the metabolic heat production of the animals accounted for 75 percent of the heat produced in the room, with the remainder attributed to anaerobic production inside the animals and bacterial action in the gutters. At temperatures up to 10°C, 55 to 60 percent of the moisture dissipated was vapourized directly from the animals. As temperatures rose above 10°C, the proportion of evaporation directly attributable to the animals increased rapidly. Due to the extensive application of these production figures, the values determined by Yeck and Stewart (1959) at comparable temperatures have been tabulated, in Chapters 4.2 and 4.3, with the results of the research undertaken for this thesis.

A further examination of the influence of humidity on heat and vapour dissipation was described by Cargill and Stewart (1966). These studies assessed the effects of high relative humidities on the heat production at 27°C and 32°C. Cows were alternated between a room at test conditions and a room under reference conditions of 18°C and 50 percent relative humidity. Data for both rooms were pooled and equations for the heat and moisture production derived. Equations also were developed for the relationship of the relative humidity and Discomfort Index to the total heat and vapour production. Increases in humidity were found to reduce both the total heat and total vapour dissipation. As in other tests at the Psychroenergetic Laboratory, the heat produced by equipment and personnel was estimated and subtracted from the energy exchanges.

Design values for the heat and moisture output of dairy cattle were published by Sainsbury and Sainsbury (1979). Upon examination, these production figures show very little deviation from the data of Yeck and Stewart (1959). Sainsbury and Sainsbury (1979) sought to expand the range of housing conditions over which the figures would be acceptable by proposing that moisture production be increased by varying percentages, depending on the housing system. Additions of 25 percent, for evaporation from manure and free water in swine barns, and 200 percent, for cattle bedded in deep straw, were suggested. The daily removal of manure was considered to reduce the mosture load by 25 to 50 percent. The application of these factors to dairy barns involves a great deal of uncertainty, since most dairy housing systems in Alberta have some bedding, but also daily manure removal.

The natural progression of heat and moisture production experiments, from studies of individual animals, through trials with small groups in controlled environment chambers, to examinations of livestock under actual production conditions, was described by Hellickson et al (1972), who undertook the measurement of the energy dissipation of beef cattle under commercial conditions. The study involved 47 Angus-Hereford heifers, weighing 320 to 450 kg, confined in a fully-slatted, closed confinement beef building. The heat and moisture loads were calculated from measurements of the dry-bulb temperatures and dewpoints of the ventilation air, together with the volume of air flowing through the barn. Adjustments to the data were made for equipment, personnel and conductive heat transfer. The authors found no significant relationship between total heat production and any environmental parameter. The latent heat production was related to the dry-bulb temperature, but with only 18 percent of the variation accounted for. The dry-bulb temperature was responsible for 73 percent of the fluctuations in sensible heat production, and the dry-bulb temperature and animal density together accounted for 78 percent of these changes. The sensible heat production was usually negative at temperatures above 27°C.

A more comprehensive experiment involving the same building was reported by Remmele et al (1973). This study included an examination of the heat and mosture production of the manure tank under the slatted floor. Forty-seven Hereford steers, weighing between 241 and 291 kilograms, were confined in the barn for a period of three months in the late summer and early fall. Measurements of the environmental conditions and the properties of the ventilating air were made every three hours. The most significant parameters in determining the latent heat production were the inlet relative humidity and the animal density, which accounted for 34 percent of the variation. These same factors were responsible for 35 percent of the fluctuation in sensible heat production. The same percentage of the sensible heat production was attributable to the inlet dry-bulb temperature, while the inlet temperature and relative humidity combined to account for 39 percent. The manure tank added an average of 216 KJ/h per animal to the latent heat and removed an average of 180 KJ/h per animal of sensible heat. The latent heat production decreased as the relative humidity and animal density increased, while the sensible heat production was enhanced by rising humidity. The total and latent heat production were higher than the results obtained at the University of Missouri, whereas the sensible heat dissipation was lower.

When considered in the context of dairy barns, the heat and moisture loads measured by Hellickson et al. (1974) and Remmele et al. (1973) are more valuable for their relationships to environmental variables than for their absolute production figures. Presumably, the animals did experience some weight gain through the trials, but the heat production induced by this would not be comparable to the increased metabolic rate of a high-yielding cow. The considerable weight difference between the young animals and lactating Holsteins further reduces the practicality of extrapolating the data. Another factor that Strom and Feenstra (1980) considered significant is heat production due to pregnancy in the cows. Although the authors corrected for the latent heat production of the manure tank, the high levels of moisture dissipation recorded in the barn would indicate that the calculated values were not completely representative of the effects of the manure storage cell.

A very detailed examination of available heat and moisture production literature was conducted in Denmark by Strom and Feenstra (1980), who derived rigorous heat loss equations from this information. The authors developed criteria by which the sources of energy exchange information could be evaluated, then compiled lists of primary literature, which essentially met all requirements, and secondary literature, which was deficient in one or more of the selection parameters. The experiments were evaluated on the basis of acclimatization period, duration of measurement, level of production, and the inclusion of feeding and housing information. Strom and Feenstra (1980) considered two weeks to be an acceptable acclimatization period, but waived this rule for animals within the thermoneutral range. The minimum duration of the experiments was set at 24 hours, so that diurnal variations could be included in the data. The authors also searched for trials involving breeds and feeding levels that were compatible with intensive livestock production. The basic energy model involved the calculation of the total heat loss from the product of the uncorrected heat loss and a temperature correction factor. The uncorrected total heat loss was equal to the sum of the heat dissipation resulting from maintenance, growth, pregnancy and milk production. The sensible heat loss was determined by multiplying the total heat loss by a factor derived from the ambient air temperature, while the latent heat loss was the difference between the two. All data were plotted on graphs and curves drawn to fit the information, with consideration given to the comparative importance of the values. A final curve, based on a general expression equating some power of the independent variable to the dependent variable, was developed for each diagram.

For dairy cows specifically, Strom and Feenstra (1980) discovered very little data on maintenance heat production and the additional heat produced by pregnancy, but better treatment of the heat loss added by milk production. Both the primary and secondary lists contained references cited in the physiological research section of this paper. The temperature correction factor is the ratio of the total heat loss at a given temperature to the total heat loss at a base temperature of 20°C. A general curve for cattle, swine, and poultry yielded satisfactory values for dairy cows at temperatures down to 10°C, below which a special curve was necessary. The uncertainty of the data describing the proportion of heat lost as sensible and latent energy at various temperatures led the authors to conclude that a general curve for the sensible heat loss factor was accurate enough for practical designs. Strom and Feenstra (1980) also considered the existing information on dairy floor systems to be insufficient for the determination of mathematical factors.

As a design tool for calculating heating and ventilation requirements, Strom and Feenstra (1980) introduced the concept of a heat producing unit (hpu), which is defined as having a total heat loss of 1000 W at 20°C. The heat and moisture loads of any livestock building then could be expressed as heat producing units, based on the number of animals of each type per heat producing unit. Only one set of curves for total, sensible, and latent heat production would be needed for the design of any livestock building. A table of typical animal densities, in hpu per unit area, would facilitate the rapid calculation of generalized building heat loads. Strom and Feenstra (1980) suggested that a 500 kilogram dairy cow comprised 1.16 heat producing units and that the average density of dairy barns was 0.2 hpu/m² of floor area.

A comparison of the heat and moisture production figures yielded by their equations and ASAE (1981) was compiled as a summary by Strom and Feenstra (1980). The authors first evaluated the sources of the ASAE (1981) information according to the criteria specified earlier. The results published by Yeck and Stewart (1959) were criticized for having no acclimatization period, a lack of information on feeding levels, and production not considered to be intensive. The dairy cow heat loss figures of Strom and Feenstra (1980) tended to be a little higher than the ASAE (1981) values, but since the former were highly correlated with milk production, these differences could be attributed to slight variations in this parameter. Heat and moisture loads calculated from the Strom and Feenstra (1980) equations also are included, in Chapters 4.2 and 4.3, with the results of this research.

While the mathematical integrity of the Danish work is undeniable, the validity of the data upon which the equations are founded certainly is open to question. Most of the heat loss information was gleaned from physiological studies involving very few animals. Therefore, these values provide a much better representation of the physiological factors influencing heat production than the contribution of the environmental conditions. As in the case of the research of Yeck and Stewart (1959), the accuracy of these equations in predicting the heat and moisture production in dairy barns under typical commercial conditions remains to be proven.

3. Experimental Procedures

The objective of this experiment was to monitor the heat and moisture production of dairy cows, in commercial confinement facilities, under practical operating conditions. This necessitated the selection of barns already in production, which then were instrumented and examined with as little disruption to the normal routine as possible. The implementation of such studies was contingent upon the cooperation of producers and the availability of a system capable of measuring environmental parameters in these structures. The testing was conducted on four dairy barns in central Alberta during the period from January to March of 1979.

3.1 Experimental Facilities

After consideration of the necessary design and management features, the barns were selected from information provided by Alberta Agriculture staff and some of the farmers involved in the experiment. Two tie-stall and two free-stall operations were monitored, both to facilitate a comparison of the heat and moisture produced under the two systems and to reduce the serious deficiency in design data relating to the latter. Tie-stall barns are those in which the cows are confined in their stalls by devices such as stanchions or neck-chains. The animals are fed, watered, and, in most cases, milked while in the stalls. In free-stall barns, the cows are able to enter and leave the stalls at will, while utilizing central feeding, watering, and milking areas. The most critical factor in the evaluation of potential barns was the feasibility of instrumenting them. This condition precluded the use of very large or poorly sealed buildings in which accurate measurement of temperatures and air flows would not be practical.

While the design of the barns differed and there was some variation in herd management, the operations had many features in common. The barns were all constructed of wood-frames, on concrete foundations, and had concrete floors. The structures were insulated with glass fibre and mechanically ventilated. The two long walls of each barn also included plastic sections, of varying heights, for the admission of natural light. All the cows were bedded in straw and had unlimited access to water. The manure usually was removed from the barns on a daily basis. The cows were milked twice daily, in the early morning and evening, and had relatively good production, ranging from 17 to 21 kg/day during the experiment. With few exceptions, the animals were of the Holstein breed in each of the four barns, with the average liveweight per cow, in the producers' estimation, being approximately 550 kg. All four operations were characterized by a high level of management expertise and the practice of sound animal husbandry.

The calculation of heat and moisture losses was complicated by the presence in the barns of animals other than milking cows. Varying numbers of pregnant cows, newly-freshened cows, and calves were housed with the main herd. The vastly different size and metabolic activity of these animals, when compared to the milking cows, resulted in corresponding disparities in heat production. The tie-stall barns contained, in addition to the stalls, a series of maternity and calf pens. One of these barns also had a row of raised calf stalls. In the older free-stall barn, calves were housed in the storage area of the feed alley. Economic considerations, such as the cost of separate calving facilities, cause these management practices to be relatively common, if not highly recommended. A description of the animal population in each barn is included in Table 3.1, the age and liveweight of the calves and dry cows having been estimated by the author.

A brief description of the barns that were tested follows, with the order reflecting the chronology of the monitoring. Figures 3.1 through 3.4 illustrate some of the design details of these barns.

3.1.1 Barn TS-1. Tie-Stall

This was a relatively new barn of wood-frame construction with a large, arched loft area (Figure 3.1). The livestock area was 47.7 m by 12.2 m, with 2.1-m high side walls. The walls and ceiling were sheathed, on both sides, with plywood and insulated with RSI-2.1 glass fibre. The two side walls included continuous, 375-mm high sections

Table 3.1 ANIMAL POPULATIONS.

Barn	Stall System	Animal Area (m^2)	Number of Animals	Average Liveweight (Kg)
TS-1	Tie-stall	582	46 milking cows	550
			19 calves	55
FS-1	Free-stall	404	45 milking cows	550
			3 dry cows	550
			7 calves	80
TS-2	Tie-stall	576	49 milking cows	550
			8 dry cows	550
			22 large calves	80
			12 small calves	60
FS-2	Free-stall	571	82 milking cows	550
			2 dry cows	550

of tinted plastic. Additional insulation was provided to approximately one third of the ceiling by bales of hay stacked in the loft. The barn contained two rows of 25 tie-stalls ("comfort stalls"), facing outward, with a gutter and chain-cleaner running behind them. The pens were located on both sides of the central alley at one end of the barn. During the monitoring period, the barn housed 46 milking cows and 19 calves, the latter having an estimated average liveweight of 55 kg. The cows were fed baled hay and grain from the side alleys, and milked in their stalls. Manure was removed daily from the barn onto a spreader. Ventilation air entered the room through baffled inlets located along the side walls, adjoining the ceiling. Stale air was exhausted by one two-speed and two variable-speed fans, 410 mm in

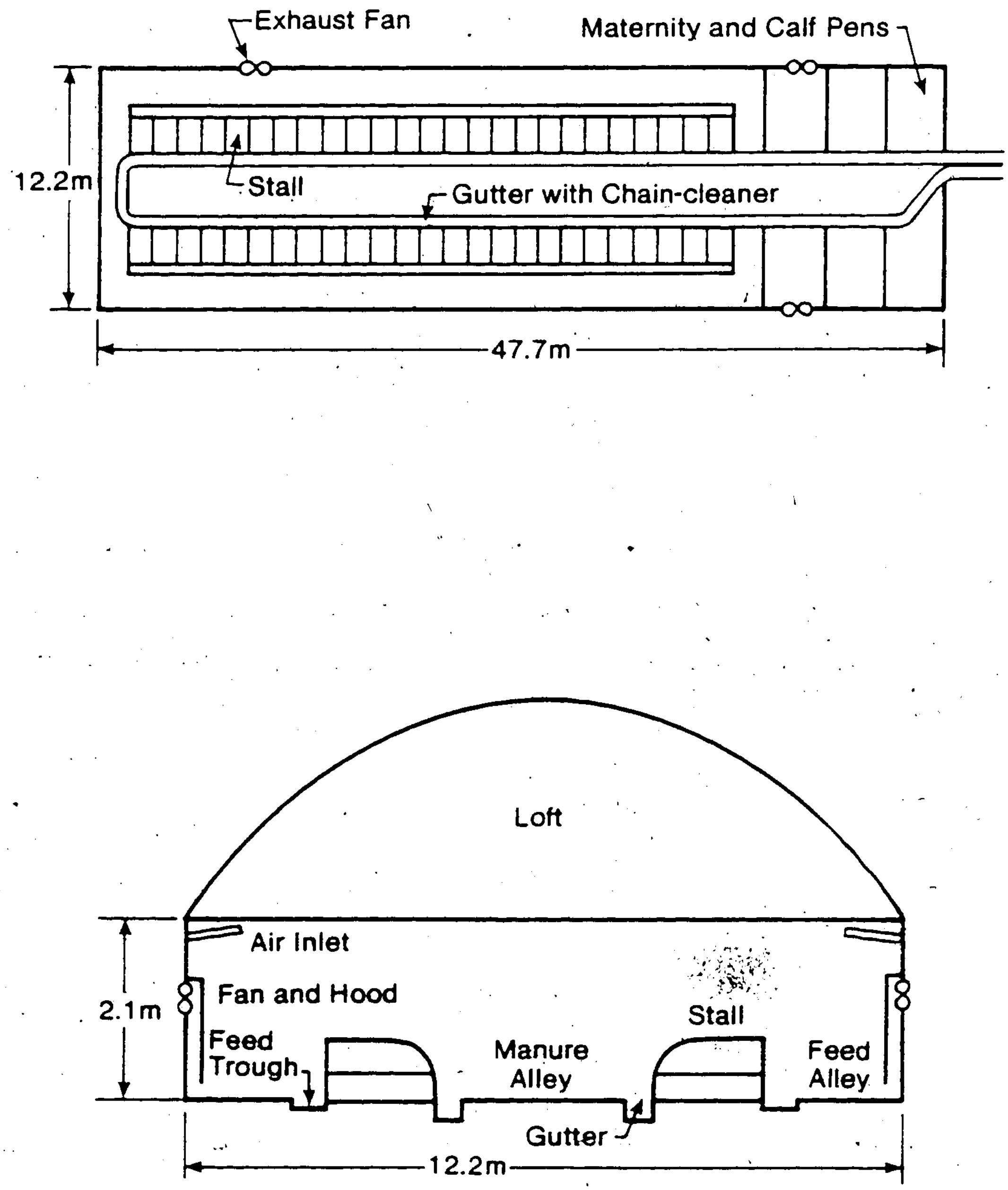


Figure 3.1. Barn TS-1 – floor plan and cross-section.

diameter, located in the side walls. These fans were thermostatically controlled and covered, on the inside, by a hood that formed a 150-mm by 450-mm passage extending from the fan to just above the floor. The front of the hood could be opened, to admit air directly to the fan, or closed, thereby forcing the exhaust air to enter the passage through the bottom of the hood. Closing the front of the hood thus had the effect of reducing the air flow through the fan.

3.1.2 Barn FS-1. Free-Stall

This was an older building, with stud-frame walls and truss rafters. The overall animal area was 32.9 m by 13.7 m, but the milking parlour occupied 46.5 m^2 in one corner (Figure 3.2). The walls of the barn consisted of a 550-mm concrete portion under a 2.1-m stud section, for a total height of 2.65 m. The walls were sheathed, on both sides, with plywood,except for continuous, 375-mm high plastic sections on the side walls. The sheathing on the ceiling was also plywood. The walls were insulated with RSI-2.1 glass fibre batts, while the ceiling contained RSI-3.5 glass fibre. The stalls were arranged in two rows along the side walls and two short rows adjacent to the end of the central feed area. This area was used for feed storage and consumption, as well as confinement of calves. Forty-five milking cows, three pregnant or newly-freshened cows, and seven calves were housed in the barn during the testing period. The average liveweight of the calves was estimated

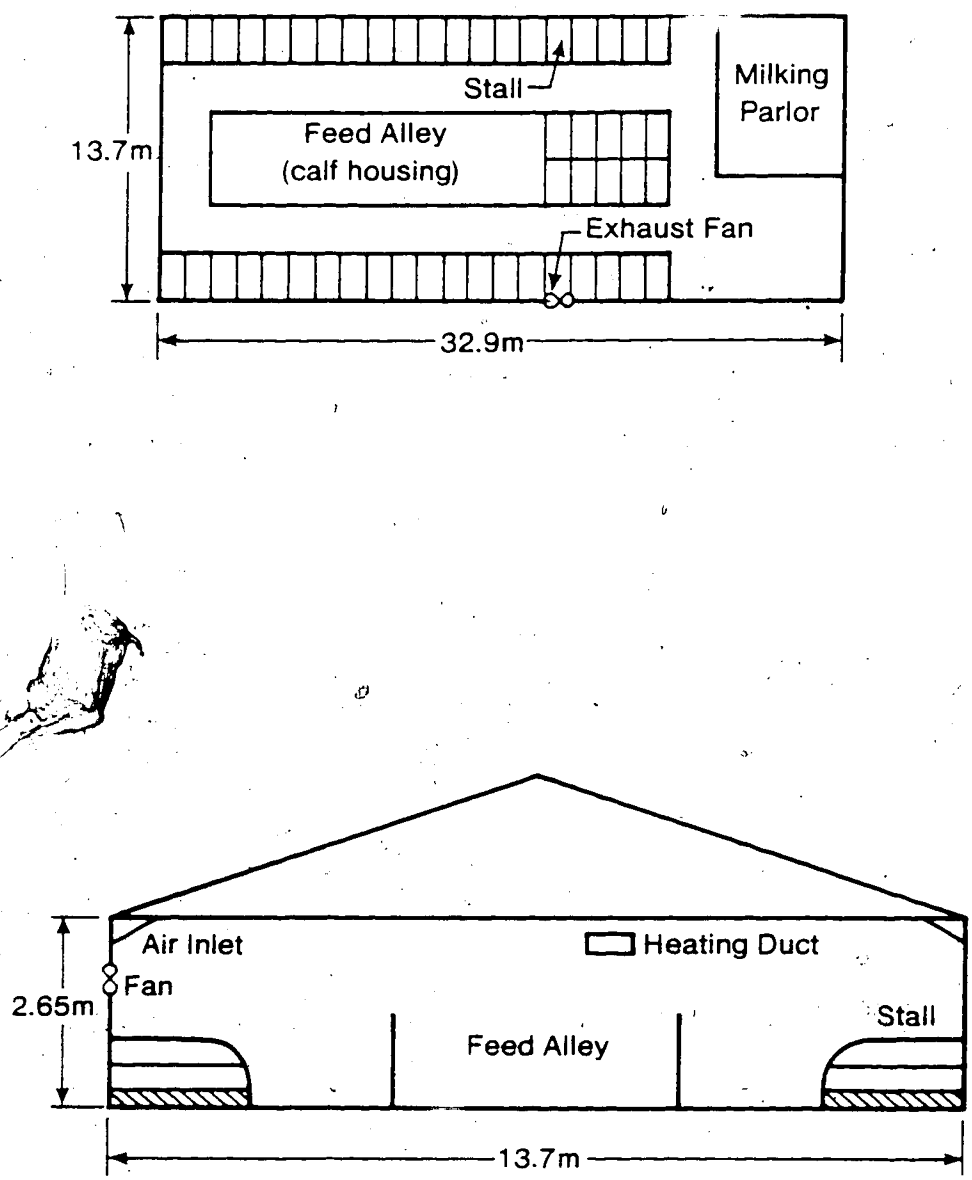
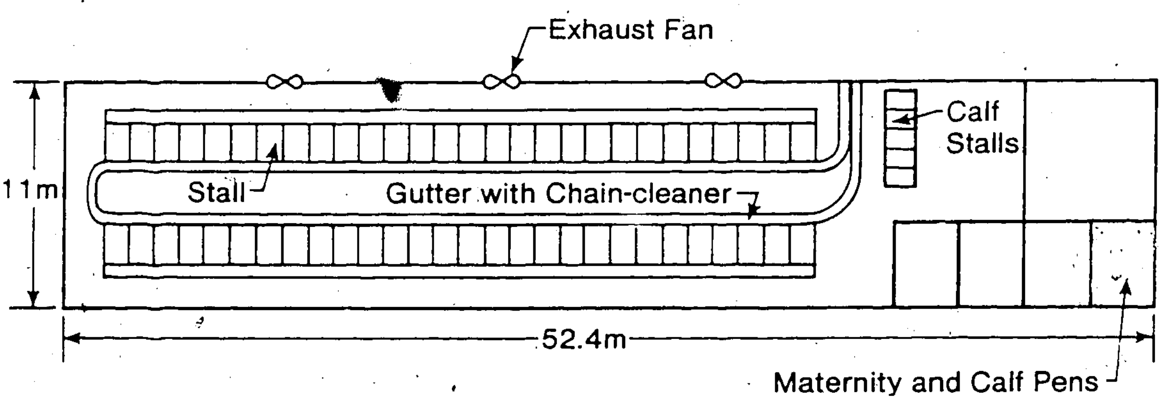


Figure 3.2. Barn FS-2 – floor plan and cross-section

at 80 kg. The cows consumed baled hay in the barn and grain in the parlour during milking. The manure was scraped, by tractor, from the alleys to a chain cleaner, and loaded onto a spreader daily. The ventilation system was powered by a thermostatically-controlled, variable-speed exhaust fan, 610 mm in diameter, located in a side wall. Incoming air was distributed by baffled air inlets cut into the ceiling along the side walls. Supplemental heat was supplied t this barn by a forced-air furnace located in a room adjacent to the cattle housing area. This furnace also was controlled by a thermostat. The heated air entered the barn from a 200-mm by 450-mm duct mounted just below the ceiling, near the centre of the barn.

3.1.3 Barn TS-2. Tie-Stall

This two-year-old barn was constructed with stud-frame walls and truss rafters, and contained a 52.4-m by 11-m herd area (Figure 3.3). The 2.4-m stud sections were set on a 100-mm concrete curb and included continuous, 375-mm high plastic panels on the side walls. The ceiling and interior walls were sheathed with metal and insulated with RSI-3.5 glass fibre. The exterior wall sheathing consisted of plywood and metal. Fifty-six stalls were arranged in two rows, facing outward, with a gutter and chain-cleaner behind them. Pens and calf stalls were located adjacent to the central alley at one end of the barn. The barn was occupied by 49 milking cows, eight dry cows, and 34 calves during the



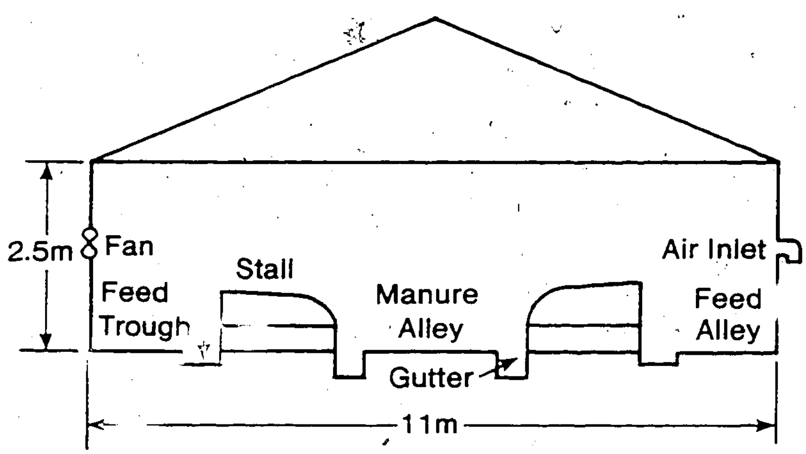


Figure 3.3. Barn TS-2 — floor plan and cross-section

monitoring. The 12 smaller calves had an estimated average liveweight of 60 kg, while the 2[illegible] larger calves were judged to have an average liveweight of [illegible] kg. The cows were confined in the stalls by stanchions and subjected to feeding and milking regimes similar to those employed in Barn TS-1. The gutter was cleaned daily, with the manure pumped to storage using a 'molehill' system. The cows were released from the barn during this cleaning period. Ventilation was provided by a series of air inlets in one side wall and three thermostatically-controlled fans in the opposite wall. The inlets measured 12 cm by 36 cm and were equipped with sliding covers for manual adjustment of the opening size, while the variable-speed fans were 4[illegible]0 mm in diameter.

3.1.4 Barn FS-2. Free-Stall

This was essentially a conventional barn with stud frame walls and truss rafters, but had a 610-mm foundation wall, resulting in a 3.0-m high ceiling. The livestock area was 49.7 m by 12.5 m with 50.5 m² removed from one corner by the milking parlour (Figure 3.4). Sheathing consisted of plywood on the inside of the walls, plywood and metal on the outside of the walls, and metal on the ceiling. The side walls also included continuous, 300-mm high plastic sections. The barn was insulated with RSI-2.1 glass fibre in the walls and RSI-3.5 glass fibre in the ceiling. Two rows of free-stalls were located adjacent to the side walls,

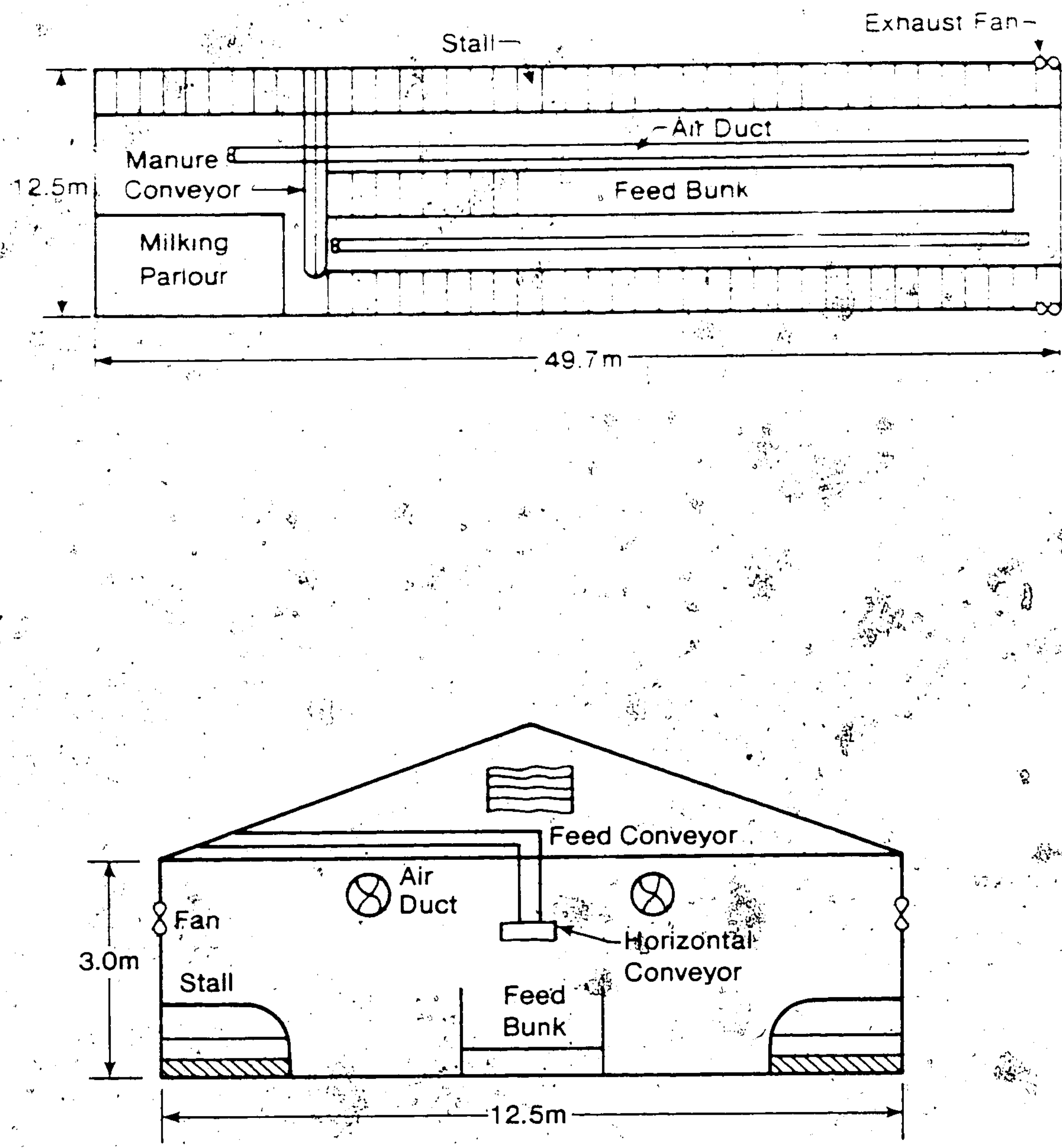


Figure 3.4. Barn FS-2 — floor plan and cross-section.

while a feed bunk and a small number of stalls occupied the centre of the barn. Eighty-two milking cows and two dry cows were housed in the barn at the time of testing. The cows were fed silage and a small amount of baled hay in the barn and grain in the parlour. Manure was scraped daily by tractor into a chain-cleaner which conveyed it to a slurry pump. This barn was ventilated by a pressurized-inlet system, using two fans, 610 mm in diameter, to force the incoming air through two circular plastic ducts suspended over the alleys and running the length of the barn. Air from the attic was supplied to these fans by four ceiling vents, having an average area of [illegible] m^2. Air escaped from the plastic ducts through a series of holes cut into both sides. Stale air was exhausted by a pair of thermostatically-controlled, two-speed fans, 610 mm in diameter, located in the side walls at the opposite end of the barn from the intakes.

3.2 Data Acquisition System

The essential equipment used in this experiment was a data acquisition system developed at the University of Alberta (Feddes and McQuitty, 1977). The electronic sensing and recording equipment had been installed in an air-conditioned trailer, which could be transported to the site of the facility to be monitored. There, remote sensors were located in and around the building and connected by extension wire to the instruments in the trailer. Signals from the various sensing devices were conditioned to a 0 to 10-volt range, converted into a digital format, then recorded on punched tape. For this experiment, the paper tape was processed through the Amdahl 470 V7 computer located on the University of Alberta campus. A portable computer terminal also was used to transmit data to the computer via telephone. This arrangement facilitated the processing of data during the monitoring period and permitted rapid detection of faulty equipment or sensors.

The basic temperature sensing device in this system was the thermistor (Fenwal Electronics, Framingham, Mass.), a semi-conductor whose electrical resistance is very sensitive to changes in temperature. The calibration of the thermistors and subsequent development of a logarithmic regression equation relating ambient temperature to the resistance exhibited by the devices had been performed by the manufacturer. For this monitoring process, the thermistors were incorporated into a voltage divider circuit and were used to measure dry-bulb temperatures. The circuit included an input voltage of 10 volts and an input resistance of 10K ohms. This resulted in a very low current passing through the thermistor, a condition that was desirable for the prevention of heating in the sensor. The output voltage was monitored by the data acquisition system. The equations used to derive the resistance of the thermistor from the output voltage, as well as the regression equation provided by Fenwal Electronics, have been listed in Appendix 4.

Because of the relative magnitude of ventilation heat losses and the inherent difficulty in monitoring ventilation systems, the units of perhaps the greatest importance were the air-speed sensors developed by the University of Alberta Department of Agricultural Engineering (Feddes and McQuitty, 1980). These sensors, used in the determination of the velocity of the air leaving the exhaust fans, consisted of an exposed thermistor which was heated by the passage of a current through it. When these thermistor anemometers were placed in a air stream, the heat loss and subsequent temperature decrease were proportional to the velocity of the air. The air-speed sensors were calibrated in an air velocity calibrator which was constructed by the Department of Mechanical Engineering, University of Alberta. Variations in the fabrication of the sensors necessitated the development of individual calibration curves describing the reaction of each thermistor anemometer to different air speeds. The circuitry for the air-speed sensors was similar to that used for the thermistors, except that the input resistance was greatly reduced to facilitate heating of the sensor, and a bias voltage was imposed on the output to bring it within the range of the data acquisition system. Each group of air-speed sensors was accompanied by a thermistor which provided a base temperature to which the temperature of the air-speed sensors could be compared. The equation of the calibration curves and the expressions used to derive the air speeds from the output voltages also are shown in Appendix A.

A small pump and plastic tubing were used to draw air samples from the facility into the trailer, where the dewpoints were measured by a dewpoint hygrometer (model 880, Cambridge Systems, Mass.). In the hygrometer, the air samples were passed over a reflecting surface which was cooled to the dewpoint of the air. At this temperature, the moisture from the air would condense on the surface, thereby interfering with the reflection of light and causing the temperature to be recorded. Unfortunately, the hygrometer could not provide accurate measurements of dewpoints when the dry-bulb temperatures were below -10°C. With the relative dryness of the air and the low temperatures, the hygrometer consistently would measure dewpoints that were higher than the dry-bulb temperatures.

The data acquisition system was used to monitor many parameters that were not pertinent to this study. Some of these included the concentrations of various gases (carbon dioxide, ammonia, and hydrogen sulfide) in the air, the wind direction and speed, the magnitude of direct and indirect solar radiation, and the static pressure differentials between the inside and outside environments. A second concurrent study also featured some preliminary work with plates designed to measure the heat fluxes across the structural components of a building.

3.3 Building Instrumentation

Because all of the factors involved in the heat and moisture balance could be derived from dry-bulb temperatures, dewpoints, and exhaust-fan air flows, these were the critical parameters to be monitored. The heat and moisture produced by the animals were dissipated through the conductive heat losses of the structure and the ventilation system. Measurement of this production was, therefore, dependent upon a knowledge of the climatic conditions inside and outside of the barn and the volume and characteristics of the exhausted air. With the exception of any variations caused by structural or management systems, the instrumentation used in the experiment was common to all four barns.

In an attempt to determine the conductive heat losses from the buildings, thermistors were taped onto the inner and outer surfaces of the various components. The readings of these thermistors, however, were found to be affected significantly by radiation and ambient temperatures, and did not reflect accurately the actual surface temperatures. Therefore, the conductive heat losses were derived from the ambient air temperatures on the warm and cold sides of the sections involved.

Conditions inside each barn were monitored by six thermistors (Fenwal Electronics, Framingham, Mass.) and three air-sampling tubes suspended about 60 cm below the ceiling. These sensors were installed at locations designed to provide a representative measurement of the internal environment. The thermistors were placed at the intersection of lines dividing the building into quarters longitudinally and thirds laterally. The tubes were located at the quarter points of the building's longitudinal centre line, except in Barn FS-2, where two of the tubes were mounted upstream from the fan. Three thermistors were placed in the loft or attic areas for an assessment of the heat lost through the ceiling and the heat gained through heating of this space by solar radiation. A thermistor also was mounted immediately upstream from each fan to measure the exhaust air temperature. Additional thermistors were placed in holes drilled in the concrete foundation walls (where applicable) and floors for the purpose of measuring surface temperatures. Floor temperatures were measured by two thermistors, one located immediately adjacent to an outside wall and the other located approximately 300 mm from this wall. One thermistor, placed about halfway up the wall, was deemed sufficient for determining the temperature of the foundations. The location of these sensors within each barn was dictated by convenience and the protection of the wires from people and animals.

Conditions outside the structures typically were measured by three thermistors located in the foundation walls, the ground, and the outside air. The placement of the thermistors in the foundation wall and ground corresponded to the location of the sensors measuring temperatures in the floor and interior wall surface. The thermistor measuring the outside dry-bulb temperature was sheltered from the wind, sun, and precipitation by straw bales. Due to the cold weather experienced during the study, the outside dewpoints were beyond the range of temperatures over which the hygrometer was accurate. Consequently, these temperatures were extracted from Environment Canada weather records compiled at a station less than 24 km from the experimental sites.

Exhaust air volumes were measured by suspending air-speed sensors (Feddes and McQuitty, 1980) in wooden ducts attached to the outside of the fan housing. These ducts, including straighteners designed to reduce the turbulence of the air flow, were constructed according to specifications outlined by Jorgenson (1961), who also prescribed locations for the sensors. Two of the thermistor anemometers were used to measure velocities in the ducts affixed to the 410-mm diameter fans, while four sensors were used to monitor the 610-mm diameter fans. Since the air speeds were derived from temperature fluctuations, a thermistor was also suspended in each duct to provide a reference temperature. Despite the presence of fans powering the inlets in Barn FS-2, the exhaust fans still created a negative pressure in the building, so special monitoring procedures for this system were unnecessary. A hot-wire anemometer (Sierra Instruments, Redlands, Cal.) was used to compile an air-velocity profile for each duct. This instrument had been calibrated, previously, using the air velocity calibrator belonging to the Department of Mechanical Engineering, University of Alberta. The number of points in the velocity profiles ranged from nine to 25, depending on the size of the exhaust ducts. The ratio between the overall mean velocity obtained from the profile and the mean of the velocities at the positions occupied by the air-speed sensors then was calculated. The result of this calculation was a factor by which the mean value of the readings from the sensors in each duct could be multiplied to obtain the air velocity in that duct. The exhaust air volume of each fan, then, was the product of the air velocity and the area of the duct.

A similar process, involving an air-speed sensor and velocity profile, was used to determine the volume of heated air introduced into Barn FS-1 by the furnace. A thermistor in each of the hot-air, and cold-air return, ducts measured the dry-bulb temperatures, from which the sensible heat output of the system was calculated.

Although the presence of people and the operation of lights in the barns contributed heat to the environment, no precise records of these factors were collected. A photocell, however, was placed in each barn for the purpose of establishing a pattern of light usage. The effect of lighting and personnel on the energy balance were not considered to be of significance in structures of the size involved nor in relation to the number of animals in each barn. Moreover, the operation of the barns was, in this respect, typical of commercial dairy enterprises, so that incorporation of any additional heat production from these sources into that arising from the animals could be justified.

Several production parameters, in addition to those pertinent to the energy balance and monitored by the data acquisition system, were of interest and, therefore, recorded manually. A mechanical water meter was inserted into the lines supplying the watering bowls or tanks. Daily readings of the flow through this meter were used to determine the water consumption of the animals. Total milk production was obtained from the milk truck receipts, while information on the feed consumption of the animals was provided by the producers. Since the manure was removed from Barns TS-1 and FS-1 by means of a spreader, measurement of the weight of manure and straw hauled on a typical day was possible. Portable scales were used to measure, while the manure spreaders were empty and with each load, the weight on the wheels and hitch of the implement. The moisture content of the manure from the tie-stall barn was determined by oven drying of the samples, and the moisture content of the manure from the free-stall barn was estimated, based on data given by the Midwest Plan Service (1980).

The final stage in the instrumentation of the barns was the calibration of the monitoring equipment and the selection of a scanning rate. The sensing and measuring devices had been calibrated prior to the start of the experiment, but further verification of their accuracy was required at each site. Manual measurements of dry-bulb temperatures and relative humidities were conducted with a battery-powered psychrometer. The hot-wire anemometer (Sierra Instruments, Redlands, Cal.) was used to measure air speeds in the ducts attached to the exhaust fans. These readings then were compared to the initial output from the data acquisition system, at which time, any problems with the system could be identified and rectified. The flexibility of the data logger necessitated a decision regarding the frequency with which the sensors were scanned. Air samples were drawn from each location, in sequence, for a four-minute period. The air sampling duration and sequence were controlled by the data logger through the use of solenoid valves in the sampling lines. Four sampling points were required at each site, three inside the barn and one for the outside air, but a fifth tube was placed in the trailer so the warm and relatively dry air could serve to clear the hygrometer. Another benefit was that the number of sampling periods in an hour (15) would be a multiple of the number of sampling locations. Thus, the dewpoints and pressure differentials were measured exactly three times each hour. This frequency also was considered satisfactory for measuring dry-bulb temperatures and, accordingly, the thermistor output was monitored at 20-minute intervals. Readings from the air-speed sensors were recorded at four-minute intervals, but only those values corresponding to the time of the thermistor measurements were used in the subsequent data analysis.

3.4 Data Collection

After instrumentation was complete, the barns were monitored for several days, as continuously as equipment failures, power interruptions, and other unforeseen circumstances allowed. Continuity was considered to be critical to the identification of the effects that climatic changes and management operations had on subsequent heat and moisture production. The monitoring period, itself, usually lasted five days, but six days were required for preparing the equipment and instrumenting the barns. Removal of the sensors took an additional three days, so the total time spent at each site was approximately two weeks.

An experimental period of 48 consecutive hours had been decided upon earlier. This period would include two full diurnal cycles and would provide, when the variables had been calculated on an hourly basis, a sufficient number of values for further mathematical analysis. While monitoring a single barn throughout an entire winter or, ideally, several winters would have yielded precise and detailed information about the animals in that particular environment, this procedure would have ignored the significant influence of management practices on heat and moisture production. The benefits to be gained by studying several barns seemed to be greater than the disadvantages of the relatively short experimental period. Forty-eight hours appeared to best satisfy the concurrent constraints of compiling enough information and covering all four barns during one winter.

During the monitoring period in a barn, the most important task was maintenance of the instrumentation and the data acquisition system. Frequent observation of the livestock area was necessary to ensure that any abnormal occurrences affecting the heat and moisture balance would be recorded. All sensing devices located near the cows were susceptible to mechanical damage, while the air-speed sensors collected a considerable quantity of dust that had to be removed at least once daily. Using the battery-powered psychrometer, manual measurements of the dry-bulb temperature and relative humidity in the barns were conducted twice daily, with the results compared to the information from the data acquisition system. The reading on the water meter was recorded daily, while the milk production, the feed consumption, and the manure production (from Barns TS-1 and FS-1) were recorded once during the testing period. The voltages being punched on the paper tape could be transcribed and examined for irregularities, but the most valuable information was obtained by using the terminal to run the data through the processing program on the Amdahl 470/V7 computer at the University of Alberta campus. Using this program, which is described in the following section, the output at the terminal comprised actual values of the environmental variables being monitored.

3.5 Data Processing and Analysis

At the conclusion of the monitoring period, the punched tapes were transported to the University of Alberta and read into the Amdahl 470/V7 computer. A Fortran computer program then was used to read the raw voltages and process these readings into the actual units of the parameters being measured. The equations used in the processing have been compiled in Appendix A. The results of the processing were tabulated and a representative 48-hour interval was selected from within the monitoring period. In the selection of the interval, consideration was given to successful functioning of the data acquisition system and normal operation of the barn itself, but no attempt was made to choose a period of uniform temperatures or ventilation. Once the testing interval had been determined, all readings from this period were converted, manually, into hourly means. This involved the calculation of the mean value of the dry-bulb temperatures, air speeds, and dewpoints that had been monitored at 20-minute intervals. For certain parameters, such as the inside temperature, where several sensors had been used in the monitoring procedure, the mean value of the output from these sensors was derived. The result of this secondary processing was a series of 48 values, for each parameter, corresponding to the hours selected as the t... ... period. These values, along with the hourly means of the manual measurements, were stored in a computer file for use in the calculation of heat and moisture production. The most pertinent of these data have been tabulated in Appendix E.

3.5.1 Calculation of Heat and Moisture Production

The calculation of conductive heat losses was based on descriptions of the building materials provided by the farmers involved. The composite thermal resistances of the various building components then were computed from values provided by several sources: Canadian Farm Building Code (1977); Tobey and Turnbull (1976); and ASHRAE (1981). The conductive heat loss of each component was a product of the area, temperature differential across the component, and thermal resistance. The equations used in these calculations are listed in Appendix B.

The energy lost through ventilation was dependent upon the volume of air exhausted and the condition of the air entering and leaving the barn. Standard psychrometric equations (ASHRAE, 1981; Carpenter, 1962) were used to derive the enthalpy, specific humidity, relative humidity, and specific volume from the dry-bulb temperatures and dewpoints of the inside and outside air. The product of the duct area and average air speed yielded the ventilation volume, which was converted into the hourly mass of air exhausted. The hourly heat and moisture loss, then, was the product of this mass and the difference between inside and outside enthalpies and specific humidities, respectively. The sensible heat component of the ventilation heat loss was determined in a separate calculation using the psychrometric principles of heat gain. All equations used in this process have been included in Appendix B.

The final step in the processing was to determine the heat and moisture production of each animal unit, using the 550-kg cows as the basic unit. Information from several sources (Strom and Feenstra, 1980; Yeck and Stewart, 1959; Canadian Farm Building Code, 1977; Midwest Plan Service, 1980; ASAE Yearbook, 1981) was used to determine the relationship between the total heat production of the milking cows and that of the calves and dry cows. On the basis of this information, the heat production caused by the rapid growth of young calves appeared to be comparable to the heat arising from milk production in the mature cows. For this reason, the heat production of these animals per unit of metabolic weight (liveweight raised to the power of 0.75) could be considered equal. Using this relationship, together with a subjective evaluation of the heat and moisture contributed by the dry cows, the animal population of each barn was expressed in terms of 550-kg cows. The moisture or latent heat production was simply the quotient of the ventilation moisture loss and the number of cows. The sensible heat production was equal to the sum of the conductive losses and the sensible heat component of the ventilation losses, with, in the case of Barn FS-2, the supplemental heat subtracted. The total heat production of the animals was determined by adding the ventilation heat loss to the conductive heat loss, again with adjustments for the energy output of the furnace in Barn FS-1.

3.5.2 Analysis of the Data

The computer program used in processing the raw data into total heat and moisture production figures computed the mean value of each parameter. The heat and moisture losses predicted by the equations of Yeck and Stewart (1959) and Strom and Feenstra (1980) at comparable temperatures also were calculated and averaged, the latter computations being done on a programmable calculator. For the purpose of comparison, the range and standard deviations of all three sets of values were determined. Statistical comparisons, using "t" and "F" distribution tests described by Johnson (1973), were undertaken as well.

The question of a suitable size for the animal units arose during the analysis of the data. Dairy cattle heat and moisture production traditionally had been expressed on a per 1000-lb liveweight basis. When converted to the SI system, this animal unit became an arithmetically cumbersome 454-kg. The 550-kg cows used in this experiment proved to be similarly unwieldy. Rather than using units that merely represented conversions of convenient Imperial standards, the heat and moisture production values were calculated on a

500-kg liveweight basis, this being an SI unit of comparable mathematical simplicity to 1000-lb liveweight. Conversion of the cows' heat and moisture production to the 500-kg basis was based on the metabolic weight of the animals. Thus, the factor applied to the production values was the ratio of 500-kg to 550-kg, raised to the power of 0.75.

Since Yeck and Stewart (1959) related heat production directly to the inside temperature and Strom and Feenstra (1980) included temperature in their calculations of heat production, an essential aspect of the analysis process was an examination of the influence of environmental parameters on heat and moisture output. The statistics module (Hewlett-Packard, Corvallis, Ore.) for a programmable calculator and procedures specified by Johnson (1973) were used in this analysis. First, the strength of the relationship, as reflected by the linear correlation coefficient, was established. Where there was significant correlation, regression analysis was employed to quantify the relationship. In the cases of insignificant correlation, other environmental variables or combinations of these variables then were examined. The inside temperature was an obvious variable to be studied, but the effects of relative humidity, ventilation rate, housing system, and herd management also were considered.

Upon examination of the heat and moisture output data, a trend toward higher production, particularly of sensible heat, at certain times of the day was identified. The increased activity of the animals at milking time and the low level of activity during the night caused noticeable variations in heat production. This effect was especially pronounced in the free-stall barns where the animals could move about freely. As a result, a numerical evaluation of the animals' activity levels was developed by tabulating the sensible heat production values from each barn in order of magnitude and comparing these production levels to the time of day. On the basis of this comparison, each hour of the day was assigned an activity level value, from one to twenty-four, depending on the mean ranking of the sensible heat production during this hour. The highest level was assigned to five P.M., during the afternoon milking, while the lowest level occurred at ten in the morning, when the cows were resting after the morning milking. The concept of activity levels then was introduced into the regression analyses for total and sensible heat production, where their use as independent variables contributed to the statistical significance of the relationships.

4. Experimental Results and Discussion

4.1 Test Conditions

There were wide fluctuations in the weather during the monitoring period. The first two barns (TS-1 and FS-1) were studied under cold conditions, when the average temperature was around -20°C, while the latter two barns (TS-2 and FS-2) were examined during milder weather. Even within the 48 hours that each barn was tested, temperature ranges of up to 16°C were noted. The broad range of conditions expanded the scope of the experiment, but prevented the direct comparison of systems that would have been possible if there had been more uniformity in the outside environment. A temperature regime, from Barn TS-1, typical of those recorded during the study is illustrated in Figure 4.1. The relatively constant inside temperature, with a range of only 5°C, is a result of a responsive ventilation system and little change in the outside temperature. The average outside temperature was -23.9°C and the magnitude of the diurnal variations was small.

Environmental conditions inside all four barns were very satisfactory, as the temperatures and relative humidities were well within the ranges prescribed in design specifications. Reasonable control of these parameters was achieved through the ventilation systems and, in the case of Barn FS-1, the supplemental heating unit. In all cases, the variation in the barn temperature was less than that in

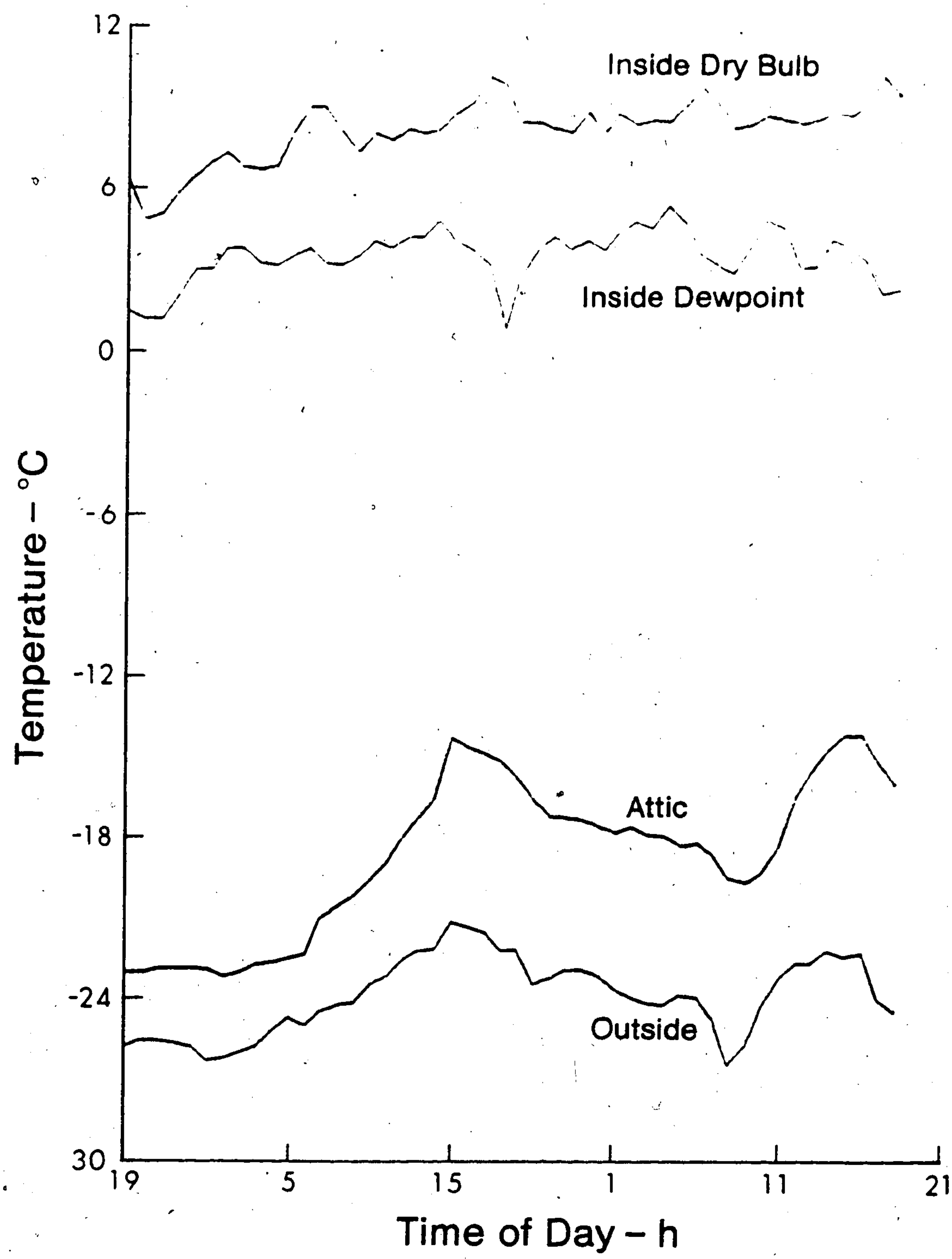


Figure 4.1. Typical temperature regime – Barn TS-1

the outside temperature. Although the maximum relative humidity in each barn was over 80 percent, the average values were all under 75 percent. These conditions were created by average ventilation rates ranging from 17.1 L/s cow in the coldest tie-stall barn (TS-1) to 46.3 L/s cow in the warmest free-stall facility (FS-2). Air distribution within the barns appeared to be acceptable, despite static pressure differentials generally below the 1.6 mm water gauge that is recommended, by Munroe et al (1981), for negative pressure systems. A summary of the critical environmental variables, together with some management features of the barns, is contained in Table 4.1. In this table, the exposure factor is a measurement of the total conductive heat transfer of the barns for every degree temperature difference and animal unit. The exposure factor reflects the size of the structure, the animal density within the barn, and the level of insulation in the various building components.

4.2 Heat and Moisture Production

The heat and moisture production of the cows was derived from the heat losses of the barns. Figure 4.2 illustrates typical conductive heat losses, for Barn TS-1, divided into the portions attributed to each building component. The relatively low energy loss through the ceiling was a result of the hay bales stacked in the loft. The magnitude of floor perimeter losses for foundations with

Table 4.1 ENVIRONMENTAL VARIABLES AND MANAGEMENT FEATURES.

Variable	Mean Values Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Equivalent Number of 550 Kg Cows	48.26	49	61	84
Exposure Factor (kJ/h °C cow)	29.9	34.2	39.6	36.7
Outside Temperature (°C)	-23.9	-18.6	-0.4	3.4
Range	(-26--21)	(-26--13)	(-9-8)	(-5-8)
Inside Temperature (°C)	8.1	6.4	13.1	16.3
Range	(5-10)	(4-10)	(9-17)	(12-21)
Ventilation Rate (l/s cow)	17.1	28.3	44.0	46.3
Range	(10-27)	(20-58)	(36-60)	(36-55)
Supplemental Heat (kJ/h cow)		793		
Range		(708-889)		
Inside Relative Humidity (%)	72	73	69	72
Range	(54-81)	(64-82)	(59-85)	(59-81)
Static Pressure Differential (mm W.G.)	0.31	1.43	1.68	1.21
Water Consumption (kg/cow day)	76.8	76.8	86.4	74.4
Milk Production (Kg/cow day)	18.4	20.2	20.9	16.7
Moisture Production in Manure (kg/cow day)	52.4	46.9	52.4	46.9

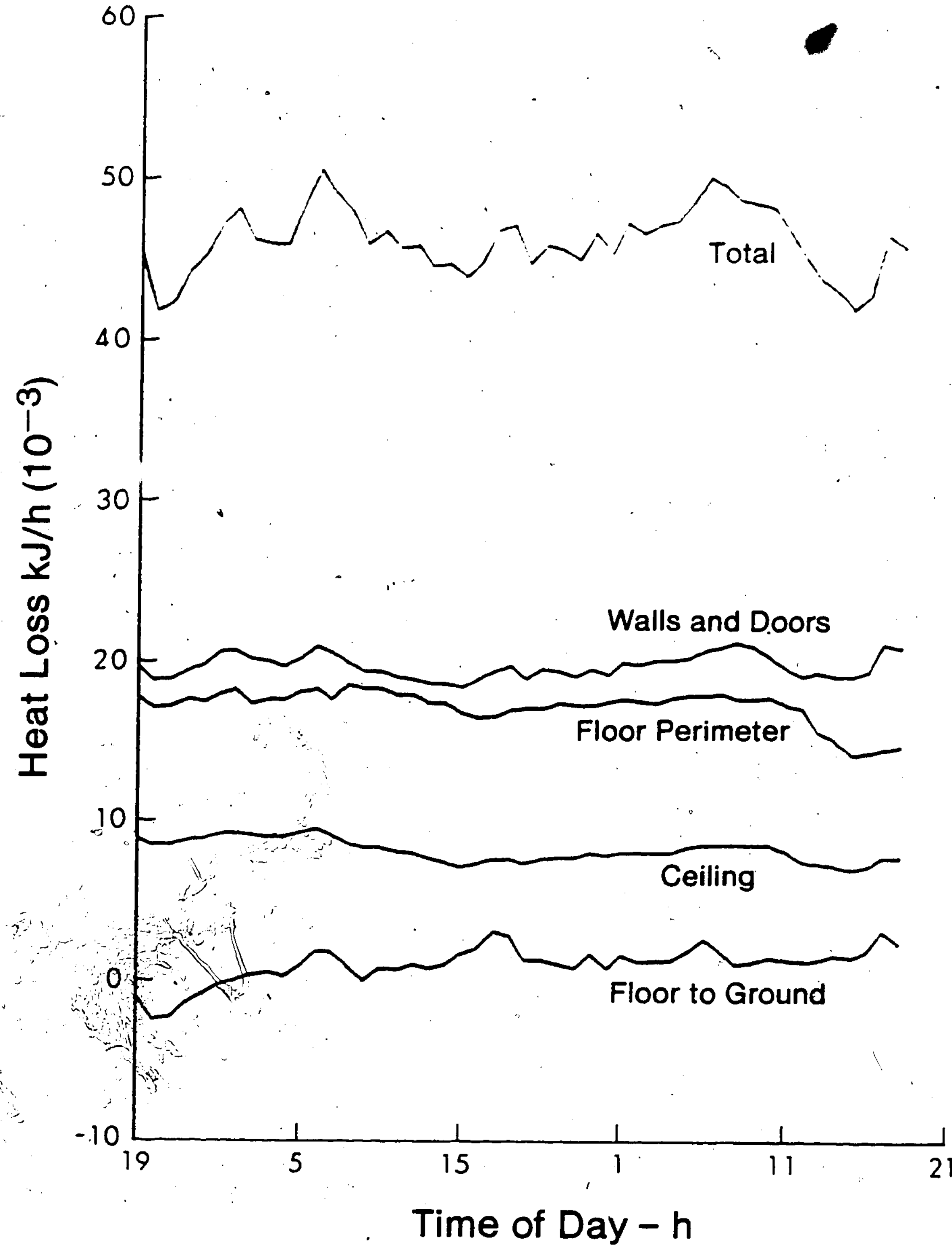


Figure 4.2. Typical conductive heat losses – Barn TS-1

no insulation, in this instance almost 40 percent, is demonstrated clearly.

A detailed examination of the conductive heat losses of a building would have to include the sensible heat gained from solar radiation. The thermistors in the attic spaces sensed the energy transferred through the roof, but there was no attempt to calculate the gain through the walls. The thermistors located on the exterior walls facing the sun were warmed considerably, and undoubtedly some heat transfer and storage did occur. On the corresponding interior surfaces, however, the thermistors did not seem to be affected greatly. The high level of insulation in the structures dampened the effects, not only of solar radiation, but of the entire external environment. The interior temperatures responded to the outside temperature, the ventilation rate, and movement of the animals, but did not react noticeably to the influence of the sun. Also, Barn TS-1 was monitored during cloudy weather, while the sun was shining for only one of the days Barn FS-2 was monitored. For these reasons, the magnitude of solar heat gains during the experiment was considered small enough that failure to include these would introduce no more error than ignoring long-wave radiation losses at night. Furthermore, the overwhelming heat loss through ventilation meant that minor alterations to the conductive heat transfer would have a negligible impact on the total energy losses of the buildings.

The total heat dissipation from Barn TS-1, as illustrated in Figure 4.3, was typical of all four barns studied. The relative significance of conductive losses is reflected by the almost perfect correlation of ventilation heat losses with the total dissipation. The losses by conductance were not particularly sensitive to the minor temperature variations found in this experiment and as the temperatures rose, an ever increasing proportion of the heat was lost through the ventilation process. The partition of the heat losses for all barns is given in Table 4.2, together with the ratios of conductive heat loss to total and sensible heat losses included.

Table 4._ BUILDING HEAT LOSS BY SOURCE.

Variable	Mean Values Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Conductive Heat Loss (kJ/h cow)	954	853	533	475
Ventilation Heat Loss (kJ/h cow)	3118	4115	4262	5227
Total Heat Loss (kJ/h cow)	4072	4968	4795	5702
Conductive/Total	0.23	0.17	0.11	0.08
Conductive/Sensible	0.30	0.23	0.18	0.17

Summaries of the total, latent, and sensible heat loads are presented in Tables 4.3 to 4.5, with the latent heat expressed in terms of moisture production. The range and

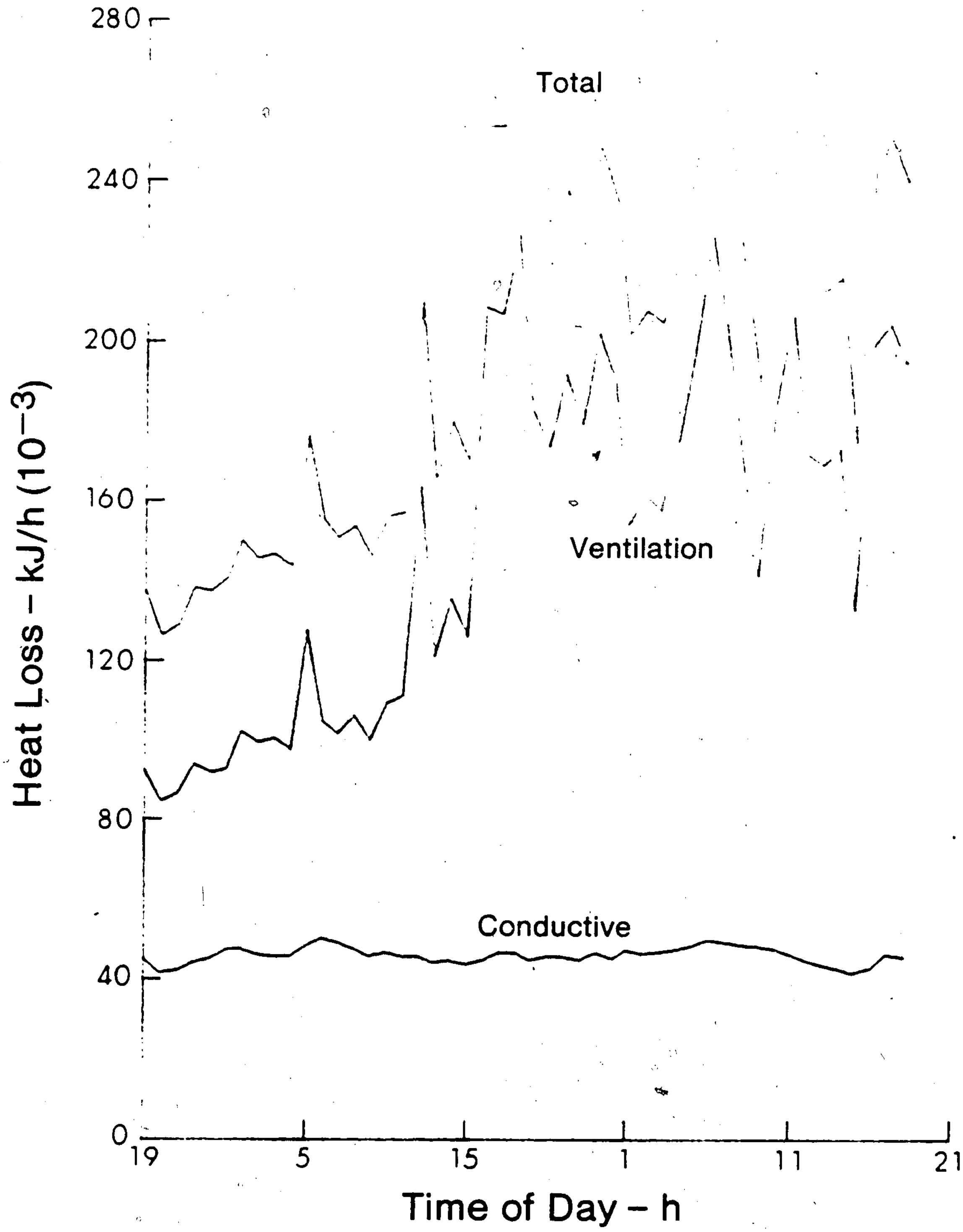


Figure 4.3. Typical total heat losses - Barn TS-1

standard deviation of each parameter have been included to show the variability that existed during the monitoring. These characteristics became important during analysis of the data because production figures that were significantly different appeared equal when only the means were compared.

Since uncertainty about the validity of existing heat production figures was a fundamental reason for this research, the values calculated from the equations of Yeck and Stewart (1959) and Strom and Feenstra (1980) have been included in these tables. The Yeck and Stewart (1959) equations were dependent only on the dry-bulb temperature, while the Strom and Feenstra (1980) equations also included factors for the milk production and stage of pregnancy of the cows. These equations were used to calculate heat and moisture production values for each of the 48 hours that the barns were monitored. From this compilation, the means, ranges, and standard deviations of these predicted values were derived. The design equations used in these calculations have been listed in Appendix C.

The total heat production is an important animal characteristic, but is not as meaningful a parameter in the design of environmental control systems as its latent and sensible components. Temperature fluctuations cause opposite reactions in sensible and latent heat production; these tend to diminish the cumulative change in total energy dissipation, but have a tremendous impact on environmental conditions. Most researchers, including Esmay (1979),

Table 4.3 TOTAL HEAT PRODUCTION - kJ/h cow (500 kg).

Source	Mean Values Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Measured	3791	3884	4464	5310
Range	(2437-5317)	(2765-7358)	(3726-5551)	(4068-7132)
Std.Dev.	860	1238	439	580
Predicted				
Yeck and Stewart(1959)	4061	4115	3906	3805
Range	(4000-4162)	(4003-4190)	(3784-4039)	(3665-3942)
Std.Dev.	36	169	238	191
Strom and Feenstra(1980)	3805	4000	3978	3589
Range	(3776-3866)	(3938-4057)	(3964-4018)	(3589-3607)
Std.Dev.	22	32	14	4

Table 4.4 MOISTURE PRODUCTION - kg/h cow (500 kg).

Source	Mean Values Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Measured	0.34	0.47	0.72	1.05
Range	(0.17-0.47)	(0.30-0.97)	(0.50-0.93)	(0.72-1.60)
Std.Dev.	0.09	0.19	0.10	0.16
Predicted				
Yeck and Stewart(1959)	0.50	0.50	0.59	0.62
Range	(0.50-0.54)	(0.46-0.54)	(0.54-0.62)	(0.59-0.67)
Std.Dev.	0.01	0.02	0.03	0.02
Strom and Feenstra(1980)	0.34	0.35	0.42	0.44
Range	(0.34-0.36)	(0.34-0.38)	(0.37-0.49)	(0.36-0.55)
Std.Dev.	0.01	0.01	0.03	0.04

Table 4.5 SENSIBLE HEAT PRODUCTION - kJ/h cow (500 kg).

Source	Mean Values Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Measured	2963	2707	2689	2650
Range	(2009-4309)	(1897-5008)	(2023-3524)	(1890-3067)
Std.Dev.	623	796	331	284
Predicted				
Yeck and Stewart(1959)	2804	2905	2520	2333
Range	(2693-2992)	(2700-3042)	(2297-2765)	(2074-2585)
Std.Dev.	65	90	130	101
Strom and Feenstra(1980)	2966	3143	2963	2545
Range	(2905-3060)	(3035-3218)	(2783-3121)	(2264-2729)
Std.Dev.	32	47	90	97

Monteith (1973), Strom and Feenstra (1980), and Yeck and Stewart (1959) have concluded that is very little variation in the total heat output when animals are in a thermoneutral state, although the data indicate an inverse relationship between temperature and total heat production. The results of this experiment, however, exhibited a high degree of variability, with a range of 1519 kJ/h in the mean values for the barns, as is illustrated in Table 4.3. Furthermore, there was an increase in total heat losses with rising mean temperatures, while free-stall barns had greater losses at comparable temperatures than tie-stall barns. These trends appeared to be the result of the expanded influence of moisture production on total heat production under the conditions noted.

The moisture loads followed predictable trends, with production increasing in the warmer barns and comparatively higher levels in the free-stall facilities. The overall range in the measurements of latent heat output, in the order of 1.5 kg/h cow, was surprising and, indeed, this range itself far exceeded the maximum values determined from previous research. The inside temperature regime appeared to have a profound effect on the moisture production, but the relative humidity and ventilation rate also seemed to be influential. The movement of air through the barn and the relative humidity of this air are obviously important factors in the evaporative heat transfer from barn surfaces, a parameter which Yeck and Stewart (1959) found to account for 40 percent of moisture production at low temperatures. The response of the moisture loads to variations in the relative humidity and ventilation rate was difficult to ascertain because of the experimental procedure. Since these loads were derived directly from the ventilation rate, there was no certain way of establishing whether the increased moisture was caused by higher ventilation rates or the ventilation rates merely were reflecting an increase in moisture production resulting from other causes.

Typical moisture dissipation by ventilation is illustrated in Figure 4.4, for Barn FS-2 ··th design figures included for comparative purpos ·is was a free-stall barn and had the highest mean inside temperature

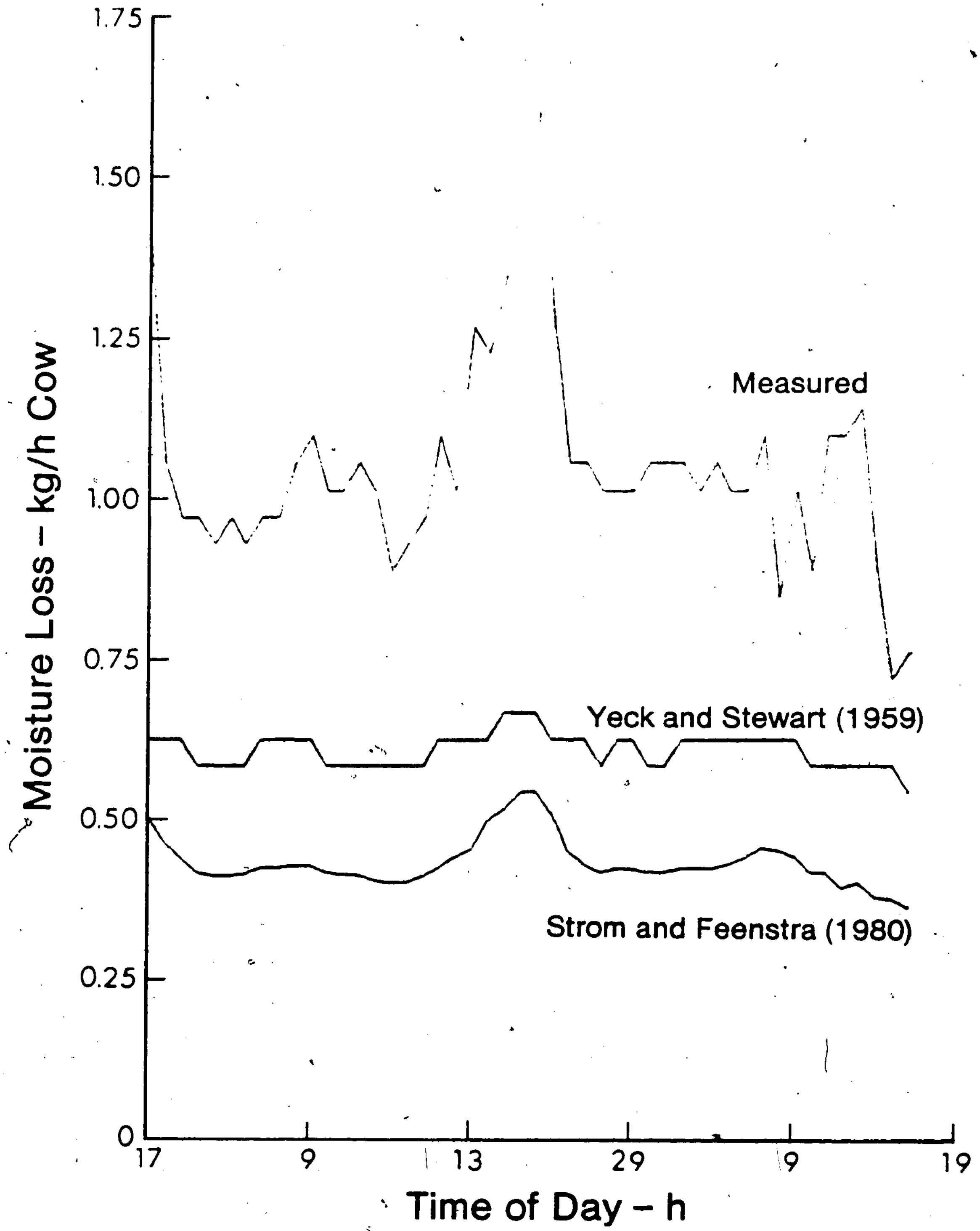


Figure 4.4. Typical moisture losses – Barn TS-2

of the four barns in the experiment, so the production levels were not unexpected. Another contributing factor could have been the high moisture content of the silage that was fed on a continuous basis. The extreme peak in the centre of the graph was caused by a combination of warm conditions and the increased activity of the cattle prior to milking.

The measured sensible heat production was more difficult to assess. There was considerably less variation among the barns than was noted in the other parameters. As Table 4.5 illustrates, less than a 12 percent separation (313 kJ/h) existed between the highest and lowest of the mean sensible heat loads. Sensible heat was the variable which most closely agreed with the design values, although the variability of the loads measured in each barn was higher than expected. The inside temperature regime seemed to have an influence on the sensible heat production, but not the same strong influence it exerted on moisture production. On the other hand, the activities of the animals appeared to be a significant factor, even in the tie-stall barns where movement of the animals was restricted. Once the pattern of eating, sleeping, and milking had been identified, the dependence of sensible heat loads on the time of day became apparent. Within each barn, the sensible heat production increased as the ventilation rate rose, possibly demonstrating enhanced convective heat transfer. Unfortunately, the comparison of sensible heat production to ventilation rates involved the same predicament faced in the assessment of moisture production: the air movement could have been either the cause or the effect of greater sensible heat loads.

The typical variation in sensible heat production in each barn is shown in Figure 4.5, for Barn TS-2. The values followed an easily recognized diurnal pattern, with highest energy output when the cows were aroused for the morning milking and lowest dissipation during the warmth of the late afternoon. The sharper peaks are indicative of major alterations to the ventilation rate and, therefore, are associated with the response of the environmental control system rather than the heat output of the animals. Although the ranges of the values were different, a reasonable similarity existed between the measured heat loads and those predicted by the equations of Yeck and Stewart (1959) and Strom and Feenstra (1980). This agreement between measured and predicted sensible heat production was greater for the tie-stall barns than for the free-stall facilities.

The importance of the division of total heat into sensible and latent components warranted an examination of the proportions measured in this experiment. As is illustrated in Table 4.6, the portion of total heat lost as moisture was lowest in Barn TS-1, at 22 percent. From there, the latent heat contribution rose, in increments of approximately 10 percent, through the succeeding barns to a high of 48 percent in Barn FS-2. These latent heat

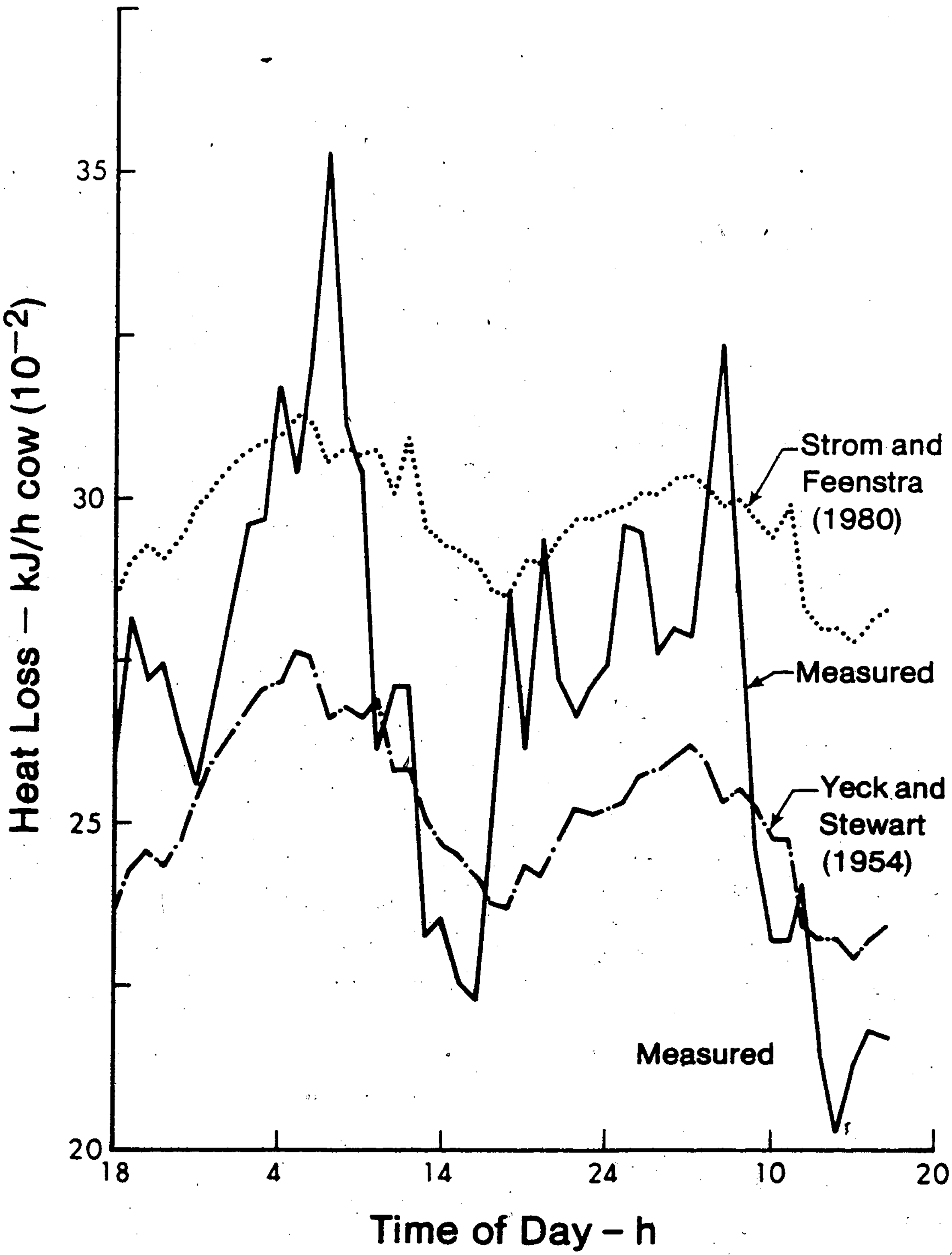


Figure 4.5. Typical sensible heat losses – Barn TS-2

components greatly exceeded the values cited in the literature review for comparable temperatures, but much of this earlier research involved studies of metabolic heat production only. The work of Yeck and Stewart (1959), in which six cows were monitored by direct calorimetry, was in much closer agreement with the figures compiled here, although the effect of free-stall housing was not adequately treated. Strom and Feenstra (1980) calculated a sensible heat loss factor based on a general equation for all livestock. When applied to dairy cattle, this equation appeared, even in these authors' own estimation, to attribute an excessive proportion of the total animal heat losses to the sensible component.

The variations between the measured and design values in the division of total heat loss were very likely related to the fundamental difference between measuring the heat dissipated by a livestock building and by the animals themselves. Bruce (1982) emphasized the process in which a certain percentage of the sensible heat produced by the animals is converted to latent heat through the evaporation of moisture from wet surfaces. This could explain the apparent underestimation of moisture production by Strom and Feenstra (1980) and others who examined metabolic heat production or utilized indirect calorimetry. The conversion from sensible to latent heat would be enhanced by the conditions in large commercial facilities and be particularly active in free-stall barns. The moisture production data collected during this experiment included any sensible heat that had been converted, so the extent of this conversion could not be calculated directly. Yeck and Stewart (1959), however, had reported the total vapourization rates from lactating cows at various temperatures. These data were used to determine the latent heat production from the wet surfaces in each barn and thus, the percentage of sensible heat that had been converted to latent heat. The results of these calculations are summarized in Table 4.6. Not surprisingly, the conversion of sensible heat increased as the temperature rose, with the large alleys in Barn FS-1 more than compensating for the fact that the inside temperature in this barn was slightly lower than in Barn TS-1. Ultimately though, the sources of heat and moisture within a particular barn are of less consequence than the actual levels of production, since the latter are used in the design of environmental control systems. Thus, the value of having realistic design information was sufficient justification for an experimental procedure that precluded the direct measurement of sensible heat conversion.

4.3 Analysis of Results

The data presented in the previous section, though interesting, had little value as only a collection of heat and moisture loads. The development of relationships between heat and moisture production and environmental parameters

Table 4.6 CONVERSION OF SENSIBLE HEAT TO LATENT HEAT.

Source	Mean Values - kJ/h cow (500 kg)			
	Barn TS-1	Barn FS-1	Barn TS-2	Barn FS-2
Temperature (°C)	8.1	6.4	13.1	16.3
Total Heat Production	3791	3884	4464	5310
Sensible Heat Production	2963	2707	2689	2650
Latent Heat Production	821	1135	1738	2535
Animal Latent Heat Production (Yeck&Stewart, 1959)	680	644	824	1022
Latent Heat/ Total Heat	0.22	0.29	0.39	0.48
Percentage of Sensible Heat Converted	5	15	25	36
Percentage of Total Heat Converted	4	13	20	28

was essential if the results were to be used for comparisons with existing values or for application to design problems. This analysis was hindered by the lack of replication in the monitoring process, an effect that made isolation of environmental parameters from other variables impossible. The genetic characteristics of the herd, the nutritional value of the feed, and the management system of the operator were factors that influenced the heat and moisture production of the cows in each barn. These features were an intrinsic part of the measured heat production and did not affect the analysis within a particular barn. However, comparisons amoung barns or the combination of values from several barns could be undertaken only on the assumption that the genetic quality and herd management in the facilities were either similar or did not affect the heat and moisture production. A final purpose of the analysis was the establishment, where possible, of equations expressing heat and moisture production in terms of one or more environmental parameters. Validation of the equations would be, of course, a prerequisite to their widespread acceptance, but the existence of the expressions provides a basis for future research.

4.3.1 Relation of Energy Production to Environmental Parameters

Since the physiological relationships between temperature and heat production have been established clearly, the logical place to begin relating heat loads to environmental variables was with inside temperatures. This is the parameter that traditionally has been associated most closely with heat and moisture generation and design specifications nearly always tabulate these loads as a function of ambient temperature. The influences of relative humidity, air movement, and animal management have been studied, but are not well documented and have not been related mathematically to heat and moisture production.

Coefficients of linear correlation were calculated for the relationships between the total, sensible and latent heat production of each barn and the respective inside temperatures. A summary of these calculations is presented in Table 4.7. Only the sensible heat in barn 4 was not significantly dependent, at the 5 percent level, on the inside temperature. With the exception of the moisture and total heat production in Barn TS-2, close to 50 percent of the variation, as measured by r^2, in all other heat and moisture loads was attributable to the ambient temperature in the barns. The weakness of some relationships in Barns TS-2 and FS-2 could have been a result of the high ventilation rates in the structures. At these ventilation levels, the heat and moisture production derived from air volume was less likely to be an accurate indication of the animals' response to temperature fluctuations. The almost insignificant correlation of the total heat in Barn TS-2 with the temperature is a predictable effect of the conflicting reactions of the sensible and latent heat production to temperature changes. What would be described intuitively as the dominant component of the respective heat losses in Barns TS-2 and FS-2, sensible heat in the tie-stall barn and latent heat in the warm, free-stall barn, exhibited a strong correlation with temperature in each case.

In the instances of poor or insignificant correlation, the possible dependence of the heat and moisture production

Table 4.7 HEAT PRODUCTION AND INSIDE TEMPERATURE.

Values of the Correlation Coefficient, r, between inside temperature and heat production			
Barn	Total Heat Production	Sensible Heat Production	Latent Heat Production
Barn TS-1	0.78	0.77	0.74
Barn FS-1	0.71	0.71	0.68
Barn TS-2	-0.30	-0.71	0.39
Barn FS-2	0.69	0.23	0.82

Critical value of r = + or - 0.285- Johnson (1973)
(significance level of 5%, 46 degrees of freedom)

on other parameters was explored. The inclusion of activity levels with the inside temperature resulted in a coefficient of correlation of 0.44 when compared to the sensible heat production in Barn FS-2. The link between the relative humidity and sensible heat in this building had similar strength (r=-0.42), but a combination of all three factors produced no more improvement in the correlation. In Barn TS-2, the addition of activity levels doubled the proportion of the variation in total heat accounted for by environmental variables, although the two parameters had opposite effects on the heat production. The moisture production in this facility had a greater correlation with relative humidity (r=0.50) than temperature. Together, the two factors were responsible for two-thirds of the variation in moisture loads. The positive correlation between relative humidity and moisture levels seems, at first, to contradict physical laws, since increases in relative humidity should tend to suppress evaporation, thereby reducing the moisture losses. In this monitoring process, however, the measured relative humidities were most likely a result of the evaporation that had taken place already, rather than an indication of the imminent vapourization.

4.3.2 Secondary Comparison of Energy Production to Temperature

The preliminary relationships between heat and moisture production and environmental parameters were based on consideration of the barns individually, and included all 48 measurements from each barn. The separate analysis of the barns provided insight into the environmental parameters that influenced heat and moisture production and the comparative strength of this influence. When the data from a barn was being examined, knowledge of the specific conditions during the monitoring period could be used to explain anomalies in the results. The absence of variation due to the management, production, or genetic quality of the herd expedited the search for significant relationships. All of these factors, however, while assisting the development of primary relationships, imposed severe limitations on the application of this information. As long as the relationships between environmental variables and heat production were linked with specific barns, their use in comparisons with design values or predicting production in other barns was highly questionable. The passive monitoring procedure, where temperatures were allowed to fluctuate freely and measurements were taken at timed intervals, did not necessarily produce readings that reflected stable conditions. This effect reduced the validity of relating single heat and moisture production values to the environmental parameters from which they had been derived. Comparison of this measured production with design values calculated from the inside temperature also could not be considered a reasonable technique. Since the fundamental purposes of this research were to evaluate the existing design values and to establish the effects of the two management systems, sorting of the data into realistic units and combining measurements from two barns were essential.

The design heat and moisture loads were derived from equations in which inside temperature was the independent variable. A similar arrangement of the experimental results was natural, particularly in view of the statistically significant correlation between inside temperatures and nearly all heat loads. A further division, into the production in free-stall and tie-stall barns, followed the design of the experiment and facilitated a comparison of these housing systems. Temperature increments of 1°C were selected as the basic unit; this range was small enough to provide sufficient separation of the data, yet large enough, in most cases, to reduce adequately the effect of a single reading. The experimental procedure caused wide variations in the number of values for each temperature increment, with this number ranging from one to twenty-seven. This irregularity, however, was considered an acceptable consequence of studying barns under commercial conditions.

The refinement of the relationships between energy production and inside temperature involved the compilation of the various heat loads at each temperature and the calculation of the mean value of these loads. The activity levels were included in the consideration of total and sensible heat production. The figures for the barns with common housing systems then were combined and tabulated, together with the comparable Yeck and Stewart (1959) and Strøm and Feenstra (1980) values. Grouping of the measured values in this way facilitated a more realistic comparison of these results with the design values. Furthermore, an evaluation of the improved relationships between the combined values and inside temperatures, and the subsequent development of regression equations not dependent on individual barns, were possible. Ideally, the final result of this process would have been a series of valid equations relating the total, latent, and sensible heat production of tie-stall and free-stall barns to specific environmental parameters.

Since the lack of replication in this experiment precluded a quantitative assessment of the effects of the genetic and management features within each barn, the combination of data from two barns was predicated on the assumption that the influence of these features could be ignored. This assumption was tested by plotting the heat production values from each housing system against the inside temperatures. On the basis of these plots and the linear correlation between inside temperature and heat production, the significance of individual barn management was evaluated. Only for moisture production, where the coefficients of linear correlation with the inside temperature were 0.85 for the tie-stall barns and 0.94 for the free-stall barns, was the influence of barn management considered weak enough to be neglected. Thus, the total and sensible heat production values were separated by barn, as well as by housing system. The combination or separation of the free-stall heat loads was very simple, since the inside temperatures measured in the two barns were discrete. In the tie-stall facilities, an overlapping of the inside temperatures at three increments made these processes more difficult.

The total heat production from the barns is listed in Table 4.8, with the activity levels noted in parentheses. The extreme difference in the measured values compared to the design figures is apparent, even when the measured data have been condensed and represented by a mean value. The increase in the Strom and Feenstra (1980) levels at the transition from Barn TS-1 to Barn TS-2, which contradicts the normal effect of increasing temperature on total heat production, is a result of their high degree of dependence on milk production. The overall linear correlation of the tie-stall measured values with inside temperature had a coefficient of 0.75, which is significant at the 5 percent level. This relationship, however, was composed of the positive correlation between the heat production and temperature in Barn TS-1 and the negative correlation between the parameters in Barn TS-2. In the lower temperatures of Barn TS-1, there was a very strong relationship between the temperature and total heat production, but this dependence was considerably weakened in the warmer environment of Barn TS-2.

In the values from the free-stall barns, the disadvantages of the experimental procedure are well illustrated by the lack of continuity in the temperatures, not only between the barns, but within the readings for Barn FS-2. The total heat production and inside temperature had a similar coefficient of linear correlation to that determined for the tie-stall operations, but, in this instance, both barns were characterized by a positive correlation between heat loads and temperature. There was also a tremendous difference between the production levels measured in Barn FS-2 and the design values. These effects would appear to be a result of the high moisture loads in this facility.

The relationship between moisture production and temperature for the tie-stall and free-stall facilities are illustrated in Table 4.9. Once divided on the basis of

Table 4.8 TOTAL HEAT PRODUCTION BY TEMPERATURE INCREMENT

Temperature (°C)	Mean Values - kJ/h cow (500 kg) Measured (activity levels)	Predicted Yeck and Stewart(1959)	Predicted Strom and Feenstra(1980)
TIE-STALL BARNS			
Barn TS-1			
4.5	2437 (18)	4176	3881
5.5	2574 (15)	4144	3856
6.5	2736 (9)	4111	3830
7.5	3395 (7)	4082	3812
8.5	3982 (11)	4050	3812
9.5	4999 (22)	4021	3866
10.5	4992 (24)	3985	3931
Barn TS-2			
8.5	4630 (16)	4050	4026
9.5	4510 (4)	4021	4010
10.5	4560 (9)	3985	3996
11.5	4781 (11)	3956	3985
12.5	4680 (10)	3924	3978
13.5	4313 (10)	3895	3971
14.5	4266 (24)	3863	3967
15.5	4615 (23)	3830	3964
16.5	4115 (14)	3798	3960
FREE-STALL BARNS			
Barn FS-1			
4.5	3136 (11)	4176	4043
5.5	3341 (10)	4144	4014
6.5	3780 (11)	4111	3996
7.5	3953 (15)	4082	3974
8.5	3528 (22)	4050	3960
9.5	7247 (17)	4021	3942
Barn FS-2			
11.5	4763 (22)	3956	3611
13.5	4806 (12)	3895	3604
14.5	5155 (8)	3863	3593
15.5	5195 (11)	3830	3589
16.5	5119 (10)	3798	3589
17.5	5173 (18)	3769	3589
19.5	6296 (18)	3704	3586
20.5	6844 (23)	3704	3586

housing systems, this parameter exhibited the strongest dependence of any energy variable on the inside temperature and, consequently, the weakest link with individual barn management. This was likely a result of the contribution made to the moisture production by evaporation from wet surfaces in the barn. The genetic qualities of the cows and the nutritional value of the feed would have little or no influence on the evaporation process. The effect of animal activity on this process was considered to be similarly insignificant, hence the exclusion of the activity levels from the examination of moisture production. The range of the measured values again far exceeded that of the design values, particularly in the free-stall barns. The minute response of the Strom and Feenstra (1980) data to environmental changes at low temperatures necessitated the use of three digits in tabulating these moisture loads. The measured moisture production behaved as expected, increasing with rising temperatures and being generally higher in the free-stall buildings. The data were characterized by a series of plateaus, where the production essentially was unchanged over a temperature range of several degrees, connected by segments where the temperature increments were associated with sharp increases in moisture loads. Despite this feature, the moisture production in both systems had a high degree of correlation with the inside temperature.

In order to compare the effect of the two stall configurations, a two-way analysis of variance was

Table 4.9 MOISTURE PRODUCTION BY TEMPERATURE INCREMENT

Temperature (°C)	Mean Values - kg/h cow (500 kg) Measured	Predicted Yeck and Stewart (1959)	Strom and Feenstra (1980)
TIE-STALL BARNS			
4.5	0.17	0.49	0.334
5.5	0.17	0.50	0.336
6.5	0.20	0.50	0.340
7.5	0.30	0.51	0.344
8.5	0.37	0.52	0.349
9.5	0.50	0.54	0.363
10.5	0.56	0.55	0.379
11.5	0.76	0.56	0.396
12.5	0.75	0.57	0.408
13.5	0.71	0.58	0.422
14.5	0.66	0.59	0.439
15.5	0.77	0.60	0.457
16.5	0.77	0.61	0.479
FREE-STALL BARNS			
4.5	0.36	0.49	0.349
5.5	0.40	0.50	0.351
6.5	0.46	0.50	0.354
7.5	0.47	0.51	0.358
8.5	0.42	0.52	0.363
9.5	0.95	0.54	0.371
11.5	0.76	0.56	0.358
13.5	0.80	0.58	0.383
14.5	1.01	0.59	0.398
15.5	1.01	0.60	0.414
16.5	1.03	0.61	0.443
17.5	1.07	0.62	0.454
19.5	1.31	0.64	0.506
20.5	1.50	0.65	0.535

undertaken, using a GPSS program on the Amdahl computer at the University of Alberta. The purpose of this analysis, in which temperature and stall type were the independent variables, was to determine whether housing was a statistically significant factor in moisture production. The eleven temperatures common to the tie-stall and free-stall monitoring and the 165 readings associated with these temperatures were included in the study. The validity of the analysis was dependent on the assumption that the management characteristics of the individual barns were not a factor in moisture production. This conclusion seemed to be justified by the relationships between temperature and moisture production in the two housing systems, but the lack of replication made verification of this impossible. The analysis of variance is summarized in Table 4.10, with the F values, calculated for the variation due to housing and temperature, also shown. On the basis of these figures, both of the independent variables appear to have, at the 1 percent level, a significant effect on moisture loads.

The sensible heat production values from the barns are shown in Table 4.11. While the sensible heat levels in the tie-stall barns were not statistically different and were both strongly correlated with temperature, the reactions of this parameter to temperature changes in the two barns were of an opposite nature. As a result, the coefficient of correlation between the combined values and the inside temperature was only 0.16, which is far from significant at the five percent level. With increasing temperatures, the sensible heat production appeared to rise fairly rapidly until 9 or 10°C, then decrease at a similar rate.

Table 4.10 ANALYSIS OF VARIANCE - MOISTURE PRODUCTION.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F Values
Stall System	1	4.48	4.48	104.75
Temperature	10	36.00	3.60	84.08
Stall System by Temperature	10	1.62	0.16	3.79
Measurements within Temperature	143	6.12	0.04	
Total	164	73.12		

Presumably, a minimum level of sensible heat production existed somewhere above the temperature range monitored in this experiment.

The positive correlation between temperature and sensible heat in Barn TS-1 is an apparent contradiction of physiological principles, but the inside temperature range was well within the thermoneutral zone for dairy cattle, so that metabolic heat production could be expected to remain relatively constant. The increasing sensible heat loads were most likely a result of greater ventilation rates and increased heat transfer from the surface of the animals, but also could have been caused by variations in animal activity. The additional air movement would tend to cause more convective heat loss and reduce the insulative effect of the hair covering. Since 9 to 10°C could be considered an optimum temperature for the cows, this could also be a point

Table 4.11 SENSIBLE HEAT PRODUCTION BY TEMPERATURE INCREMENT

Temperature	Mean Values - kJ/h cow (500 kg)		
	Measured	Predicted	
		Yeck and	Strom and
(°C)	(activity levels)	Stewart(1959)	Feenstra(1980)
TIE-STALL BARNS			
Barn TS-1			
4.5	2009 (18)	3013	3074
5.5	2113 (15)	2956	3042
6.5	2225 (9)	2898	3013
7.5	2657 (7)	2840	2984
8.5	3078 (11)	2786	2969
9.5	3902 (22)	2725	2992
10.5	3803 (24)	2671	3018
Barn TS-2			
8.5	3120 (16)	2786	3131
9.5	2950 (4)	2725	3099
10.5	3053 (9)	2671	3067
11.5	2822 (11)	2610	3031
12.5	2783 (10)	2556	2992
13.5	2549 (10)	2498	2952
14.5	2585 (18)	2437	2909
15.5	2650 (23)	2383	2862
16.5	2178 (14)	2322	2808
FREE-STALL BARNS			
Barn FS-1			
4.5	2236 (11)	3013	3200
5.5	2333 (10)	2956	3172
6.5	2635 (11)	2898	3139
7.5	2754 (15)	2840	3110
8.5	2484 (22)	2786	3082
9.5	4874 (17)	2725	3049
Barn FS-2			
11.5	2797 (22)	2610	2743
13.5	2783 (12)	2498	2675
14.5	2599 (8)	2437	2635
15.5	2650 (11)	2383	2592
16.5	2502 (10)	2322	2545
17.5	2484 (18)	2268	2491
19.5	2981 (18)	2153	2365
20.5	3031 (23)	2095	2297

where physiological control of heat losses is at a minimum. At temperatures approaching this point, the animals would be reducing the restrictions on heat transfer, thereby increasing the sensible heat losses. While the rising temperatures would, at the same time, be causing an increase in latent heat production, this variable is not extremely responsive to climatic changes at low temperatures. Therefore, the expanded volume of incoming air would be capable of evaporating a large percentage of the moisture from wet surfaces, thus reducing the magnitude of the conversion of sensible to latent heat. When the temperatures exceeded 10°C, however, the capacity for further physiological adjustments would be limited and the rapid increase in moisture production would contribute to a decline in sensible heat loads.

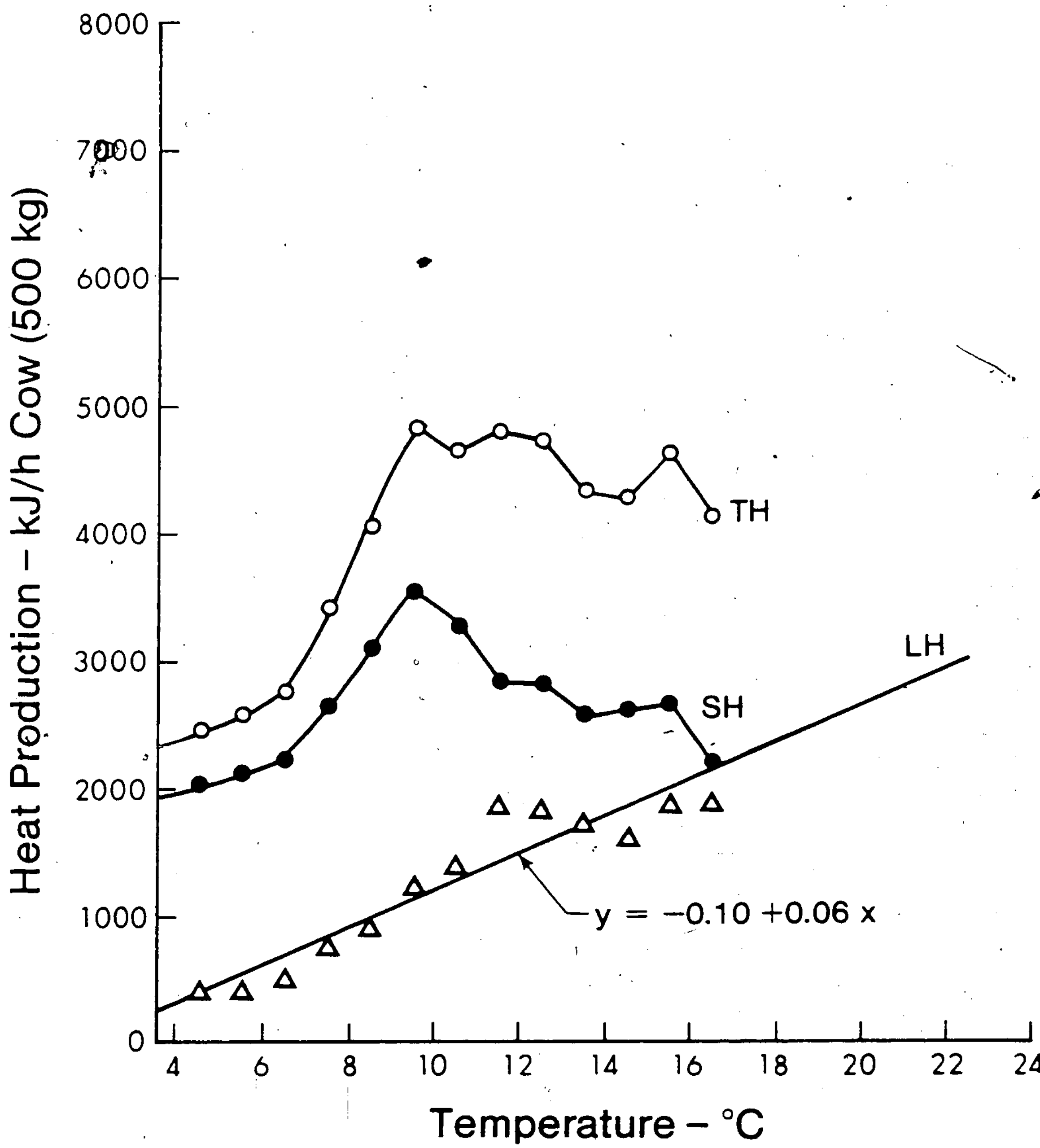
In the free-stall sensible heat production, the value at 9.5°C was derived from four measurements at the end of the monitoring period, when a rapid increase in temperature caused wide fluctuations in the environmental conditions. Since the monitoring period ended before an equilibrium could be established and the extreme production levels were likely a result of the data acquisition system measuring the environmental change rather than the altered heat production, this value was not included in correlation analysis. Although the coefficient of correlation between the combined production data and the inside temperature was, at 0.62, statistically significant, this probably did not accurately reflect the relationship of the two parameters. The heat production seemed to follow the same pattern as the tie-stall loads, despite the lack of measurements at 10.5°C and the exaggerated production at 9.5°C.

The varying and often contradictory nature of the relationships between heat production and inside temperature hindered the development of meaningful regression equations. In the case of both total and sensible heat production, the data from the four barns had to be separated before a significant expression could be calculated. This condition was the result of the strong dependence of sensible heat production on management and the dominating effect, in most cases, of this component on total heat production. The effect of individual barn management was the reason why an analysis of variance could not be used to assess the impact of the stall system on total and sensible heat production. The influence of management was reflected further by the significance of the activity levels in the regression equations for these parameters. Only the moisture production results could be combined, successfully, by housing system. The regression equations developed for the tie-stall and free-stall barns accounted for 88 and 90 percent, respectively, of the variation in moisture loads. The regression equations calculated for all heat production variables have been tabulated in Appendix D.

To summarize the analysis of heat production and inside temperatues, the relationships between the parameters have been depicted graphically in Figures 4.6 and 4.7, with the former presenting the tie-stall values and the latter, the free-stall data. The results of the analysis of variance justify the separation of the heat loads on the basis of the housing system, particularly when moisture production is such a critical factor in environmental design. The regression equations relating moisture production to the inside temperature have been included. An interesting feature of these figures is that the slopes of the two lines representing moisture production are equal, meaning that the response of this parameter to inside temperature in each housing system was similar. There was a constant difference between tie-stall and free-stall moisture production that was independent of temperature. While the curves and equations in these figures would obviously need validation and refinement before being used as design tools, they nevertheless provide the best insight into the heat and moisture loads measured in this experiment.

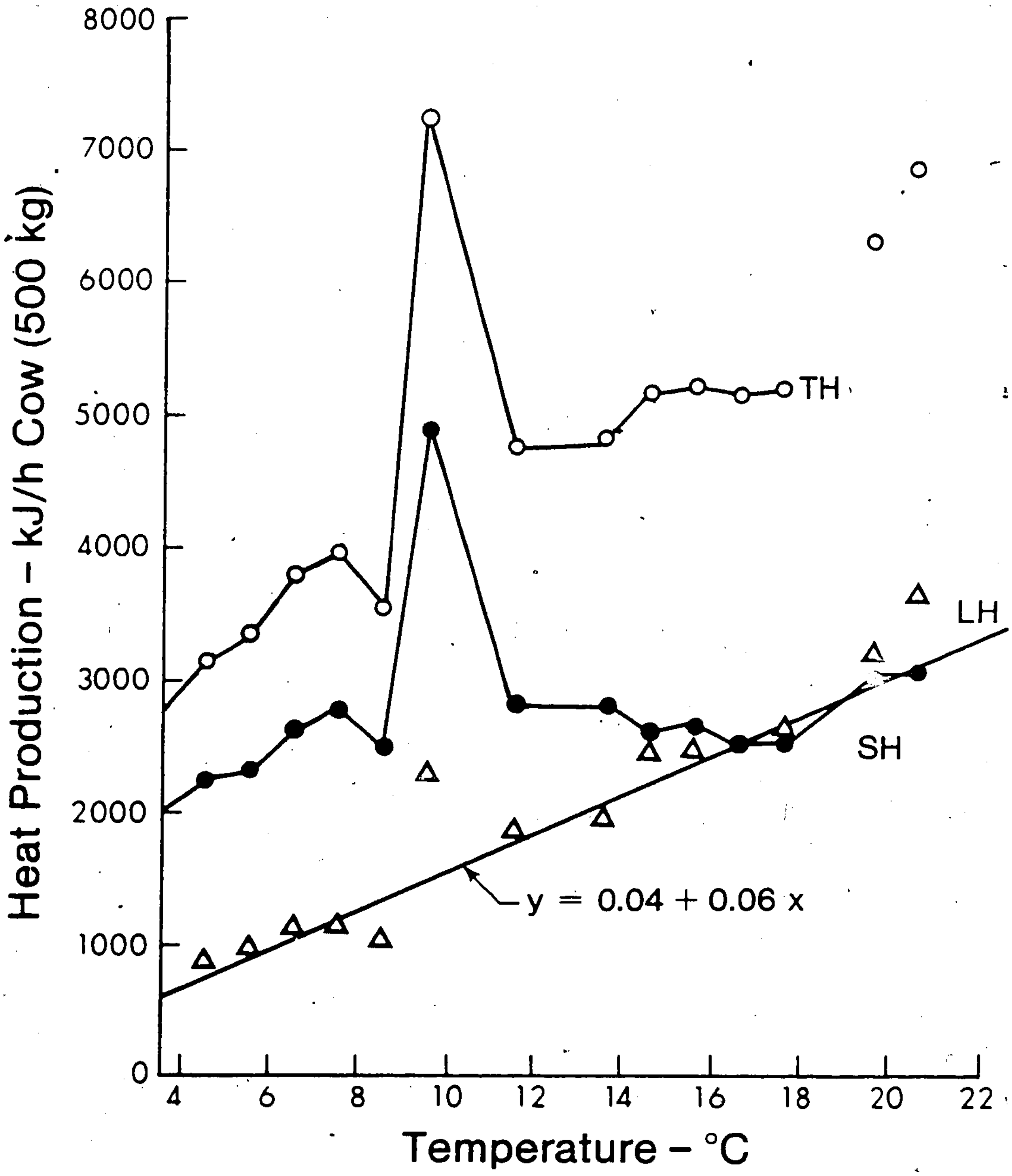
4.3.3 Comparison of Measured with Design Values

The danger in comparing the results of separate studies is that experimental conditions may obscure differences that exist or create apparent differences where none exist. The Strom and Feenstra (1980) work relies heavily on physiological research and Yeck and Stewart (1959) monitored a controlled environment, while in this experiment, the heat and moisture loads of commercial dairy facilities were



TH(○) = Total Heat Production
LH(Δ) = Latent Heat Production
SH(●) = Sensible Heat Production

Figure 4.6. Tie-stall heat production and temperature relationships.



TH(○) = Total Heat Production
LH(△) = Latent Heat Production
SH(●) = Sensible Heat Production

Figure 4.7. Free-stall heat production and temperature relationships.

measured under normal operating conditions. These disparities normally would make direct comparisons amoung the data treacherous. The previous research, however, is being applied to the design of environmental control systems for large dairy barns, so such a comparison is indeed warranted.

The examination of the measured and design values comprised both subjective and statistical comparisons. The statistical comparisons provided a quantitative assessment, while the subjective analysis was responsible for the identification of important trends. Many features of the relationship between measured and design values were illustrated in the tables summarizing the heat and moisture production in the four barns (Tables 4.3 to 4.5). Not surprisingly, the range and standard deviation of the measured data exceeded that of the design values by a wide margin. This was a predictable occurrence, since the latter were calculated from equations that represented a composite description of more widely varying data. Even when the measured production was condensed for the secondary evaluations of environmental effects, the variation was generally much greater than the design information exhibited. The design values seemed to occupy a middle ground between the production extremes and were often in agreement with the measured data in the 8 to 12°C range. At higher or lower temperatures, however, the differences between measured and design information were increased considerably.

Moisture production was the area of greatest disagreement, although the relationship between temperature and latent heat was common to all the studies. The Strom and Feenstra (1980) equations consistently predicted production far below the levels that were measured. The Yeck and Stewart (1959) figures agreed with the tie-stall production at 10°C and with the free-stall moisture at 7.5°C, but were considerably lower than the values measured at higher temperatures. Because of the narrow range of moisture loads, the Yeck and Stewart (1959) values also exceeded the measured production at low temperatures. The increased moisture production in the free-stall facilities further enhanced the disparity between measured and design values, but the researchers had not considered this housing arrangement. This difference, therefore, was to be expected.

In contrast to the moisture loads, sensible heat production was the parameter about which agreement was most general. There were no large differences amoung the average values computed for each barn, and less than 10 percent separated the means when the measured data were grouped by temperature increments. The positive correlation between temperature and sensible heat, in Barns TS-1 and FS-1, contradicted the relationships established by the design information, while the design values again appeared to be too high at low temperatures and too low at high temperatures. Furthermore, the reduced sensible heat production in the free-stall barns was not reflected by these figures. The Strom and Feenstra (1980) data, being closely related to milk production and the result of a generous evaluation of sensible heat production, differed considerably from the measured levels in barns where the milk production or moisture loads varied from the norm.

Total heat production exhibited the cumulative effects of the trends noted in the sensible and latent heat comparisons. In the tie-stall barns, at moderate temperatures, there was little variation between the measured and design values. In the free-stall barns and at the boundaries of the temperature ranges, a great deal of disparity was evident. The design equations predicted very little variation in the total heat loads at the temperatures considered in this experiment, with the highest standard deviation, 238 kJ/h, occurring in the Yeck and Stewart (1959) figures for Barn TS-2. On the other hand, the lowest standard deviation of the measured values was the 439 kJ/h found in the data for the same barn. The relatively constant total heat production in the design values was predicated upon the balancing effect of the opposite reactions of sensible and latent heat to increasing temperatures. The balance did not materialize in the measured results, as rapidly increasing moisture loads and more stable sensible heat loads contributed to wide changes in total heat production. Also, the design total heat loads declined with rising temperatures, while the total heat production measured in both housing systems increased with the temperature, and only Barn TS-2 had a negative correlation between this variable and total heat.

The statistical comparisons between the measured and design data involved a "t" distribution test, described by Johnson (1973), on the hypothesis that there was no difference between the values. The first operation in the testing procedure was a comparison of the respective standard deviations of the measured and design values, using an "F" distribution test also described by Johnson (1973). The equation used for the derivation of "t" depended on the statistical equality or inequality of the standard deviations. As would be expected, some of the observed relationships between the measured and design heat loads could not be validated statistically. The equations used in this analysis have been summarized in Appendix D.

A summary of the statistical comparisons is presented in Table 4.12, with the calculated value of t listed for each of the paramters. The heat and moisture loads were tested at the 5 percent level of significance and the + symbol denotes rejection of the hypothesis. This rejection would indicate that the data being compared were, in fact, statistically different. On the basis of the statistical information, there was little disagreement between the measured and design values for the tie-stall facilities, with the only significant difference occuring between the measured sensible heat and the Strom and Feenstra (1980)

Table 4.12 STATISTICAL COMPARISON OF MEASURED WITH DESIGN VALUES.

	Values of t	
	Yeck and Stewart(1959)	Strom and Feenstra(1980)
Tie-Stall Barns		
Moisture Production	-1.71 (-)	1.84 (-)
Sensible Heat Production- Barn TS-1	-0.20 (-)	-0.53 (-)
Barn TS-2	-1.35 (-)	-2.33 (+)
Total Heat Production	-0.39 (-)	-0.18 (-)
Free-Stall Barns		
Moisture Production	2.56 (+)	4.31 (+)
Sensible Heat Production	0.34 (-)	-1.24 (-)
Total Heat Production	2.58 (+)	3.24 (+)

Using "t" tests on the hypothesis that the mean values are equal

- level of significance = 5%
- (+) denotes rejection of the hypothesis (significant difference)
- (-) denotes failure to reject the hypothesis

values for Barn TS-2. There also seemed to be agreement on the sensible heat production of the free-stall barns, despite the differences that were apparent when the data were reviewed. Statistically significant differences did exist between the measured free-stall moisture production and both sets of design values. This variation was most likely responsible for the rejection of the hypothesis for the free-stall total heat as well. While the statistical analysis weakened the validity of some relationships, it did confirm the supposition that free-stall moisture loads and, hence, total heat production were not accurately predicted by existing design values.

5. Conclusions

This experiment could have been divided logically into two sections: the compilation of the heat and moisture production figures and the comparisons between these data and existing design values. The conclusions derived from this information can be partitioned similarly, although the separation is not always absolute. After careful consideration of the experimental procedure and data analysis methods, the following conclusions were drawn:

1. Animal sensible heat and moisture production were most closely related to the inside temperature, but other environmental conditions, such as animal activity, relative humidity, and ventilation rates, had a definite effect on these loads. Sensible heat production was highly susceptible to the influence of management actions.

2. The housing system was a significant factor in both sensible heat and moisture production, although there was no statistical difference between the mean values of sensible heat production in the tie-stall and free-stall barns. The moisture production in the free-stall barns was significantly higher, at comparable ambient temperatures, than in the tie-stall facilities.

3. All heat production parameters exhibited more variation than is predicted by the existing design values. These values seem to provide acceptable median values, in most cases, but tended to be too high at low inside temperatures and too low at higher temperatures.

4. Moisture loads, with average values ranging from 0.34 to 1.05 Kg/h cow (500 kg), had a greater effect on total heat production than was anticipated on the basis of the design equations. This influence was more pronounced in the free-stall barns and at higher temperatures, but moisture production generally was underestimated, except at low inside temperatures.

5. There was overall statistical agreement between the design values and the tie-stall heat loads; this was also true of all barn sensible heat production rates, which ranged from 2650 to 2963 kJ/h cow (500 kg). There were, however, statistically significant differences between the design values and the measured moisture and total heat production of the free-stall barns.

6. The relationships between the heat production variables and inside temperatures varied considerably from those defined by the design equations. The nature of the relationships for moisture production were similar, although the absolute values were different. The effect of inside temperatures on measured total heat production was in direct contrast to that noted in the design information and the response of the measured sensible heat to temperature agreed with the design graphs for only Barns TS-2 and FS-2.

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7. Appendix A - Processing Equations

The data acquisition system provided readings in the form of voltages. The equations used to derive the actual values of the parameters being studied are summarized below. Calibration equations have been included, where appropriate.

1. Dry-Bulb Temperature- thermistors

Calculate resistance from voltages

$$R=E/(.10-E/10000)$$

calculate temperature from resistance

$$1/T=AX^3 + BX + C$$

where R = resistance of sensor, ohms

E = output of data acquisition system, volts

T = temperature, °K

X = ln R

A = regression constant, $.2091/10^6$

B = regression constant, $.2759/10^3$

C = regression constant, $.1380/10^2$

2. Air Speeds- air-speed sensors

Calculate resistance from voltages for air-speed sensor

$$E=(5EB/3.1 + EO)/2.5$$

$$I=(15 - E)/316 - E/2000$$

$$R=E/I$$

Resistance of accompanying thermistor, as well as the temperatures of the thermistor and air-speed sensors, were derived from the equation listed in the dry-bulb temperature section.

Calculate air speed from temperatures

AS=A(EI/(TA - TT))**B

where E = voltage across sensor, volts

EB = bias voltage, volts

EO = output from data acquisition system, volts

R = resistance of sensor, ohms

I = current across sensor, amperes

AS = air speed, m/s

A = sensor coefficient

TA = temperature of sensor, °K

TT = ambient air temperature, °K

** = raised to the power of

B = sensor power coefficient

3. Dewpoints- dewpoint hygrometer

DP=8.54E - 30.06

where DP = dewpoint, °C

E = output from data acquisition system, volts

8. Appendix B - Heat and Moisture Balance Equations

The heat and moisture production of the cows was derived from the heat losses, through conduction and ventilation, from the barns.

1. Conductive Heat Loss

The conductive heat loss of each building component was calculated using the equation

$$Q=A(TI - TO)/R$$

where Q = heat loss, kJ/h

A = area of the component, m^2

TI = temperature on the inside of the component, °C

TO = temperature on the outside of the component, °C

R = thermal resistance of the component, m^2 °C h/kJ

2. Ventilation Volume

The volume of air exhausted from each barn was calculated using the equation

$$Vol=A(AS)C$$

where Vol = volume of air exhausted, m^3/s

A = duct area, m^2

AS = air speed, m/s

C = factor derived from duct calibration

3. Psychrometric Equations

The heat and moisture lost through ventilation depended on the volume of air exhausted and the psychrometric characteristics of the incoming and exhaust air, with the total heat loss based on the enthalpy difference and the moisture loss based on the humidity ratios. The equations in the processing program used Imperial units; the heat and moisture loss parameters, themselves, were converted to SI units.

```
P=10**(10.80(1 - TT) + 5.03LOG(TT) +
1.50**-4(1 - 10**(-8.30((1/TT) - 1))) +
0.43**-3(10**(4.77(1 - TT)) - 1) - 2.22)
PP=29.92P
W=.622PP/(B - PP)
H=.24T + W(1061 + .45T)
V=(((.754(T + 459.7))/B)(1 + (W/.622)))
WS=.622PPD/(B - PPD)
RH=(100W/WS)/(1 - ((1 - W/WS)(PPD/B)))
```

where P = pressure, in Hg

** = raised to the power of

TT = temperature ratio of 273.16°K to dewpoint, °K

PP = vapour pressure of the air, in Hg

W = humidity ratio, lb moisture/lb dry air

B = barometric pressure, in Hg

H = enthalpy, BTU/lb dry air

T = dry-bulb temperature, °F

V = specific volume of the inside air, ft³/lb dry air

WS = saturation humidity ratio of the air, lb moisture/lb dry air

PPD = vapour pressure of the saturated air.

calculated using the dry-bulb temperature, in Hg

RH = relative humidity, %

4. Heat and Moisture Losses

After the units had been coordinated, the heat and moisture losses from the barns could be calculated using the following equations

$$THL = Vol(HI - HO)/V + sum(Q)$$

$$ML = Vol(WI - WO)/V$$

$$SHL = Vol(.24)(TI - TO)/V + sum(Q)$$

where THL = total heat loss, kJ/h

ML = moisture loss, kg/h

SHL = sensible heat loss, kJ/h

HI, HO = inside and outside enthalpies, respectively, kJ/kg dry air

WI, WO = inside and outside humidity ratios, respectively, kg/kg dry air

9. Appendix C - Design Equations

The design equations proposed by Yeck and Stewart (1959) and Strom and Feenstra (1980) were used to calculate the predicted heat and moisture production under the conditions encountered in this experiment. The equations are listed below, with the definition of the variables preceding them. The use of metabolic weights, as described in section 3.5.2, allowed conversion of the equations to a 500-kg liveweight basis.

THL = total heat loss, kJ/h cow

SHL = sensible heat loss, kJ/h cow

ML = moisture loss, kg/h cow

T = inside temperature, °C

1. Yeck and Stewart (1959) Equations

$$THL = 4317.06 - 31.33T$$

$$SHL = 3269.79 - 57.40T$$

$$ML = 0.4308 + 0.0107T$$

2. Strom and Feenstra (1980) Equations

QM = 18.[illegible]5

$$QP = 5.76(10^{-5})(D^3)$$

$$QMK = 108.03M$$

$$FT = 10^{-5}(-T + 20)^3$$

$$THL = (QM + QP + QMK)FT$$

$$SHL = THL(-1.85(10^{-7})(T + 10)^4 + 0.80)$$

$$ML = (TKL - SHL)/2413.98$$

where QM = maintenance heat loss, kJ/h cow

QP = pregnancy heat loss, kJ/h cow

** = raised to the power of

D = days since service

QMK = heat loss due to milk production, kJ/h cow

M = daily milk yield, kg at 4%

FT = temperature correction factor

10. Appendix D - Regression Analysis and Statistical Equations

1. Regression Analysis

- Following is a summary of the coefficients of linear correlation and the regression equations calculated for the relationships between all heat production parameters and inside temperatures.

y = heat or moisture production, kJ/h cow or kg/h cow

t = inside temperature, °C

a = activity level

TOTAL HEAT PRODUCTION

Tie-Stall Barns
Correlation with temperature, r=0.75
Regression equations
Barn TS-1

$y=-98.13 + 496.46$	$r^2=0.93$
-include activity levels	
$y=-308.11 + 449.22t + 34.79a$	$r^2=0.97$

Barn TS-2

$y=5080.21 - 46.68t$	$r^2=0.34$
-include activity levels	
$y=5095.72 - 53.87t + 5.53a$	$r^2=0.36$

Free-Stall Barns
Correlation with temperature, r=0.73
Regression equations
Barn FS-1

$y=-93.63 + 608.26t$	$r^2=0.55$
-include activity levels	
$y=-6.03 + 1133.86t - 262.80a$	$r^2=0.76$

Barn FS-2

$y=1895.69 + 218.48t$	$r^2=0.79$
-include activity levels	
$y=1702.19 + 199.87t + 32.40a$	$r^2=0.84$

MOISTURE PRODUCTION

Tie-Stall Barns
Correlation with temperature, r=0.94
Regression equation

$y=-0.10 + 0.06t$ $r^2=0.88$

Free-Stall Barns

Correlation with temperature, $r=0.95$

Regression equation

$y=0.04 + 0.06t$ $r^2=0.90$

SENSIBLE HEAT PRODUCTION

Tie-Stall Barns

Barn TS-1

Correlation with temperature, $r=0.96$

Regression equation

$y=198.83 + 350.35t$ $r^2=0.92$

-include activity levels

$y=32.00 + 316.80t + 27.65a$ $r^2=0.96$

Barn TS-2

Correlation with temperature, $r=-0.92$

Regression equation

$y=3967.96 - 97.99t$ $r^2=0.85$

-include activity levels

$y=3981.53 - 113.36t + 13.97a$ $r^2=0.90$

Free-Stall Barns

Correlation with temperature, eliminate value at 9.5°, $r=0.62$

Regression equations

Barn FS-1

$y=133.60 + 393.20t$ $r^2=0.55$

-include activity levels

$y=189.23 + 727t - 166.90a$ $r^2=0.76$

Barn FS-2

$y=2497.99 + 15.49t$ $r^2=0.15$

-include activity levels

$y=2215.10 + 12.68t + 20.25a$ $r^2=0.42$

2. Statistical Equations

The statistical comparisons between the measured and design values involved a "t" distribution test on the assumption that the means were equal. The first step was to perform an "F" distribution test on the variances.

$$F=S1^2/S2^2$$

where $S1, S2$ = standard deviations of the measured and design values

If the value of F was significant at the 5 percent level, the variances were considered unequal.

When the variances were considered equal,

$$t=(X1 - X2)/SP(1/n1 + 1/n2)^{0.5}$$

$$SP=(((n1 - 1)S1^{2} + (n2 - 1)S2^{2})/(n1 + n2 - 2))^{0.5}$$

$$df=n1 + n2 - 2$$

When the variances were not considered equal,

$$t=(X1 - X2)/(S1^{2}/n1 + S2^{2}/n2)^{0.5}$$

$$df=((S1^{2}/n1 + S2^{2}/n2)^{2}/((S1^{2}/n1)^{2}/(n1 + 1) + (S2^{2}/n2)^{2}/(n2 + 1))) - 2$$

where $X1, X2$ = means of the measured and design values

$n1, n2$ = number of measured and design values

df = degrees of freedom

11. Appendix E - Data Summary

The most pertinent data in the calculation of heat and moisture production are summarized on the following pages. The variables have been defined below:

TIME = hour number during the monitoring period

TPIN = mean inside temperature, °C

TPOT = mean outside temperature, °C

TPAT = mean attic temperature, °C

DPIN = mean inside dewpoint, °C

DPOT = mean outside dewpoint, °C

RLHM = mean inside relative humidity, %

VENT = ventilation rate, cfm

COND = conductive heat loss, thousands of BTU/h

SUPP = supplemental heat gain, thousands of BTU/h

VHEAT = ventilation heat loss, thousands of BTU/h

THEAT = total heat loss, thousands of BTU/h

MOIS = moisture loss, lb/h cow

SENS = sensible heat loss, BTU/h cow

Barn TS-1

TIME	TPIN	TPOT	TPAT	DPIN	DPOT	RLHM	VENT
1	6.3	-25.7	-23.0	1.5	-31.9	71.3	1101
2	4.9	-25.5	-23.0	1.2	-31.5	76.9	1051
3	5.1	-25.5	-22.8	1.2	-31.3	75.9	1072
4	5.9	-25.6	-22.8	2.0	-31.1	76.0	1126
5	6.5	-25.7	-22.8	3.0	-31.2	78.3	1064
6	7.0	-26.3	-22.9	3.0	-32.2	75.7	1052
7	7.3	-26.2	-23.1	3.8	-31.8	78.4	1131
8	6.8	-26.0	-23.0	3.8	-31.9	81.2	1116
9	6.7	-25.7	-22.7	3.3	-31.2	78.9	1154
10	6.9	-25.1	-22.6	3.2	-30.6	77.3	1133
11	8.1	-24.7	-22.4	3.5	-30.3	72.7	1453
12	9.0	-25.0	-22.3	3.8	-30.3	69.9	1159
13	9.0	-24.4	-21.0	3.3	-29.9	67.4	1150
14	8.1	-24.2	-20.5	3.2	-29.7	71.2	1229
15	7.3	-24.1	-20.1	3.5	-29.1	76.8	1171
16	8.0	-23.4	-19.5	4.0	-29.1	75.8	1268
17	7.8	-23.1	-18.9	3.8	-29.2	75.8	1312
18	8.2	-22.5	-17.9	4.2	-28.4	75.9	1928
19	8.0	-22.2	-17.3	4.2	-28.8	76.9	1440
20	8.2	-22.1	-16.5	4.8	-27.4	79.1	1590
21	8.8	-21.1	-14.3	4.0	-28.0	71.8	1521
22	9.2	-21.3	-14.7	3.7	-28.1	68.4	2507
23	10.1	-21.5	-14.9	3.2	-28.4	62.2	2450
24	9.8	-22.2	-15.2	0.8	-28.8	53.5	2788
25	8.4	-22.1	-15.8	2.7	-28.9	67.3	2229
26	8.4	-23.4	-16.6	3.7	-29.5	72.2	2010
27	8.2	-23.2	-17.2	4.2	-29.5	75.9	2223
28	8.0	-22.9	-17.3	3.7	-29.3	74.2	2119
29	8.8	-22.9	-17.4	4.0	-29.5	71.8	2340
30	8.0	-23.1	-17.6	3.7	-29.5	74.2	2235
31	8.7	-23.6	-17.8	4.3	-29.8	73.8	1746
32	8.3	-23.9	-17.6	4.7	-29.7	78.0	1811
33	8.5	-24.1	-17.9	4.5	-29.7	75.9	1768
34	8.4	-24.2	-18.0	5.3	-29.2	80.8	1921
35	9.0	-23.8	-18.3	4.7	-28.5	74.4	2202
36	9.7	-23.9	-18.2	3.5	-29.0	65.2	2543
37	9.1	-24.7	-18.7	3.2	-30.8	66.5	2291
38	8.2	-26.4	-19.5	2.8	-30.6	68.7	1900
39	8.3	-25.7	-19.7	3.8	-30.5	73.3	1556
40	8.6	-24.3	-19.3	4.8	-30.0	77.0	2036
41	8.5	-23.2	-18.3	4.5	-30.1	75.9	2356
42	8.3	-22.7	-16.5	3.0	-30.3	69.2	2051
43	8.5	-22.7	-15.6	3.0	-30.0	63.3	2011
44	8.7	-22.2	-14.8	4.0	-29.7	72.3	2036
45	8.6	-22.4	-14.2	3.8	-30.1	71.8	1561
46	9.0	-22.3	-14.2	3.3	-30.8	67.4	2357
47	10.1	-24.0	-15.2	2.0	-30.1	57.1	2341
48	9.4	-24.4	-16.1	2.2	-31.1	60.7	2224

Barn TS-1 - Page 2

COND	SUPP	VHEAT	THEAT	MOIS	SENS
42.9		87.3	130.2	0.4	2232
39.6		80.1	119.7	0.4	2045
40.1		82.0	122.1	0.4	2086
42.0		89.1	131.1	0.5	2223
43.1		87.1	130.2	0.5	2196
44.9		88.2	133.1	0.5	2261
45.6		96.7	142.3	0.5	2382
43.8		94.1	137.9	0.5	2298
43.6		95.4	139.0	0.5	2325
43.5		92.5	136.0	0.5	2278
46.0		121.0	167.0	0.7	2756
47.9		99.3	147.3	0.5	2479
46.6		96.2	142.9	0.5	2414
45.5		100.5	145.9	0.5	2444
43.6		94.6	138.2	0.5	2298
44.3		103.3	147.6	0.6	2424
43.2		105.3	148.5	0.6	2431
43.4		154.9	198.3	0.9	3135
42.2		114.6	156.8	0.7	2519
42.3		128.1	170.4	0.8	2696
41.6		119.1	160.7	0.7	2577
42.4		197.6	240.1	1.1	3760
44.4		195.5	240.0	1.1	3830
44.6		214.5	259.1	1.0	4284
42.3		172.7	215.0	0.9	3447
43.4		164.0	207.4	0.9	3314
43.2		181.8	225.0	1.0	3534
42.6		169.6	212.2	1.0	3360
44.2		191.4	235.6	1.1	3713
43.0		179.8	222.8	1.0	3522
44.8		145.8	190.6	0.8	3056
44.1		152.4	196.5	0.9	3117
44.6		149.3	193.9	0.8	3100
44.9		165.0	210.0	1.0	3295
46.0		186.9	233.0	1.1	3676
47.4		213.9	261.3	1.1	4196
46.9		193.3	240.2	1.0	3891
46.1		162.3	208.3	0.8	3442
45.9		133.7	179.6	0.7	2950
45.6		174.2	219.9	1.0	3473
44.1		195.2	239.3	1.1	3732
42.6		162.2	204.7	0.9	3286
41.4		159.6	201.0	0.9	3228
40.7		163.7	204.4	0.9	3216
39.7		125.4	165.0	0.7	2649
40.5		188.5	229.0	1.0	3620
44.0		193.4	237.4	0.9	3913
43.3		183.9	227.3	0.9	3730

Barn FS-1

TIME	TPIN	TPOT	TPAT	DPIN	DPOT	RLHM	VENT
1	6.9	-16.6	-12.8	1.0	-22.4	66.0	2711
2	7.4	-16.8	-13.3	1.7	-22.2	67.1	2850
3	7.4	-17.1	-13.5	2.5	-22.1	71.0	2877
4	7.7	-17.5	-13.7	2.7	-22.4	70.6	2940
5	6.6	-17.7	-14.0	1.8	-22.9	71.4	2812
6	6.4	-18.0	-14.0	1.8	-23.1	72.4	2773
7	6.3	-17.9	-14.2	1.7	-22.9	72.4	2809
8	6.8	-17.6	-14.3	1.5	-22.5	68.9	2869
9	6.5	-17.4	-14.6	2.3	-22.5	74.5	2711
10	6.2	-17.5	-14.4	1.8	-22.4	73.4	2724
11	5.9	-18.1	-14.7	2.3	-23.4	77.7	2661
12	5.6	-18.1	-14.8	2.5	-23.6	80.4	2733
13	5.8	-17.8	-14.7	2.2	-23.9	77.6	2846
14	6.2	-18.4	-14.9	2.5	-24.3	77.1	2726
15	6.6	-19.1	-15.0	2.3	-25.2	74.0	2781
16	6.7	-19.3	-15.1	2.8	-25.4	76.1	2743
17	7.3	-18.2	-14.8	2.7	-24.7	72.6	2822
18	6.6	-17.9	-13.9	3.7	-25.4	81.7	2748
19	6.3	-17.2	-13.0	1.0	-25.1	68.8	2602
20	7.8	-16.9	-11.5	2.3	-24.4	68.1	2583
21	7.7	-17.0	-10.8	2.2	-24.6	68.1	2583
22	7.7	-17.7	-10.1	1.8	-24.6	66.2	2509
23	8.2	-18.0	-10.1	2.2	-25.0	65.8	2555
24	8.0	-18.4	-10.7	2.5	-25.8	68.2	2496
25	7.1	-18.9	-11.8	1.7	-27.5	68.5	2492
26	7.5	-20.2	-13.1	2.7	-29.5	71.6	2473
27	6.6	-22.6	-14.6	2.0	-29.1	72.4	2304
28	5.1	-24.2	-16.0	0.8	-32.7	73.7	2234
29	4.4	-25.3	-17.1	0.7	-31.7	76.9	2176
30	4.2	-26.2	-18.1	0.3	-32.0	75.7	2114
31	4.0	-24.6	-18.5	0.5	-28.0	77.9	2144
32	4.0	-22.6	-18.5	0.5	-25.9	77.9	2092
33	4.2	-21.0	-18.1	1.2	-25.6	80.8	2210
34	4.5	-20.9	-17.8	1.0	-25.3	78.0	2217
35	4.5	-21.0	-17.8	1.2	-25.9	79.1	2122
36	4.1	-21.3	-17.9	1.2	-27.1	81.4	2112
37	4.5	-20.4	-17.7	0.8	-25.7	76.9	2340
38	4.6	-20.0	-17.7	1.0	-25.6	77.4	2195
39	5.0	-19.2	-17.4	1.7	-25.1	79.2	2225
40	5.1	-18.8	-17.1	1.7	-24.6	78.6	2356
41	5.6	-17.7	-16.2	1.7	-24.1	76.0	2217
42	6.3	-16.0	-14.7	1.7	-23.3	72.4	4805
43	4.7	-14.2	-12.5	1.5	-22.2	79.7	4542
44	7.6	-13.5	-10.0	1.3	-22.0	64.3	6077
45	9.5	-12.9	-8.6	.5	-21.6	66.1	5664
46	9.7	-13.8	-7.9	3.2	-21.3	63.9	5481
47	10.0	-14.3	-7.7	3.7	-21.8	64.9	5415
48	9.3	-15.5	-8.4	3.3	-22.3	66.1	5345

Barn FS-1 - Page 2

COND	SUPP	VHEAT	THEAT	MOIS	SENS
39.8	35.1	165.9	170.7	0.9	2485
43.7	34.3	180.7	190.1	1.0	2772
45.7	32.9	187.5	200.3	1.1	2897
45.1	33.7	196.3	207.7	1.1	2999
42.5	35.6	180.2	187.1	1.0	2705
42.3	37.2	178.4	183.5	1.0	2644
41.8	37.4	179.2	183.6	1.0	2643
42.1	36.3	182.6	188.4	1.0	2742
41.1	35.5	173.6	179.2	1.0	2544
39.6	35.7	171.4	175.3	1.0	2505
39.4	35.7	171.8	175.4	1.0	2476
39.2	35.8	176.1	179.5	1.0	2506
40.0	36.0	181.5	185.6	1.1	2608
40.3	35.6	180.2	184.8	1.1	2612
42.1	34.2	188.8	196.7	1.1	2839
41.8	34.3	190.0	197.4	1.1	2823
38.2	36.1	191.7	193.8	1.1	2733
31.4	36.5	187.0	181.9	1.1	2418
26.1	36.8	161.1	150.5	0.9	2079
31.7	35.6	169.6	165.7	1.0	2302
33.9	36.0	169.3	167.2	1.0	2339
35.0	36.4	166.1	164.7	0.9	2352
37.4	35.7	174.4	176.1	1.0	2530
39.1	36.3	173.0	175.8	1.0	2515
42.4	35.0	168.9	176.3	0.9	2576
43.7	37.1	179.7	186.3	1.0	2694
44.2	36.4	171.6	179.4	0.9	2680
42.4	37.8	164.5	169.1	0.8	2561
42.5	38.8	161.7	165.5	0.8	2520
43.0	39.4	158.8	162.4	0.8	2506
41.5	39.6	153.6	155.5	0.8	2362
40.3	39.3	141.4	142.3	0.7	2127
40.0	38.9	145.7	146.7	0.8	2128
40.3	38.9	146.0	147.4	0.8	2157
40.6	41.1	141.0	140.5	0.8	2035
40.3	41.3	140.6	139.6	0.8	2011
41.9	41.1	151.4	152.2	0.8	2219
44.2	39.0	141.3	146.5	0.8	2144
41.6	38.2	143.6	147.0	0.8	2101
40.6	37.9	150.4	153.1	0.9	2177
38.6	39.2	138.6	138.0	0.8	1932
30.2	39.2	290.1	281.2	1.8	3841
26.2	38.5	244.6	232.3	1.6	2992
31.3	37.6	340.4	340.2	2.1	4667
39.3	35.2	353.5	357.6	2.3	4789
41.0	34.6	349.6	356.0	2.2	4905
43.4	34.4	358.2	367.2	2.3	5055
43.6	[illegible]	356.3	365.0	2.2	5098

Barn TS-2

TIME	TPIN	TPOT	TPAT	DPIN	DPOT	RLHM	VENT
1	15.9	3.8	11.1	8.7	-5.5	62.3	6052
2	14.7	1.5	6.8	7.3	-5.7	61.1	6077
3	14.2	1.0	4.9	6.3	-5.3	59.0	5799
4	14.6	0.5	3.8	8.0	-5.1	64.6	5437
5	13.9	0.2	2.9	8.3	-6.7	68.9	5345
6	12.7	-1.3	1.5	6.8	-6.3	67.3	5062
7	11.9	-2.6	0.1	6.3	-7.9	68.5	5179
8	11.1	-3.8	-1.4	5.8	-9.0	69.8	5347
9	10.5	-5.2	-2.8	5.7	-10.3	72.1	5340
10	9.9	-5.8	-3.8	4.7	-10.5	70.0	5370
11	9.6	-7.3	-5.0	4.8	-11.6	72.0	5367
12	8.8	-8.3	-6.2	3.8	-12.3	70.8	5037
13	9.0	-8.8	-6.9	3.7	-12.6	69.4	5118
14	10.7	-8.8	-7.0	4.7	-12.2	66.4	5157
15	10.3	-8.3	-6.2	4.2	-11.5	65.8	4711
16	10.6	-7.0	-4.2	4.8	-9.8	67.3	4882
17	10.1	-5.3	-1.2	4.3	-8.0	67.2	4750
18	12.1	-2.7	2.3	5.3	-5.9	63.1	5147
19	9.5	0.7	6.9	5.2	-4.7	63.1	5147
20	13.4	2.2	10.9	6.2	-3.6	61.7	5927
21	14.1	2.9	13.2	6.8	-3.1	61.4	6022
22	14.4	3.4	14.4	7.0	-2.8	61.1	5816
23	14.8	3.7	14.[illegible]	7.7	-2.1	62.4	5626
24	15.5	3.8	13.0	8.3	-1.9	62.2	6049
25	15.8	3.0	10.2	8.8	-2.1	63.1	6400
26	14.5	2.0	6.7	8.0	-2.9	65.0	5844
27	14.8	1.3	4.6	8.0	-2.9	63.7	6173
28	13.9	0.9	3.2	8.5	-3.5	69.9	5866
29	13.1	0.4	2.5	8.2	-4.0	72.1	5873
30	13.2	0.0	1.9	8.2	-4.4	71.7	5751
31	13.0	-0.5	1.2	8.8	-5.1	75.6	5684
32	12.8	-1.6	0.7	9.0	-5.0	77.7	5827
33	12.2	-2.5	-0.5	9.0	-5.1	80.8	5681
34	12.1	1.8	-0.6	9.0	-5.7	81.3	5568
35	11.7	-2.4	-1.0	9.2	-5.5	84.6	5581
36	11.4	[illegible].0	-2.1	8.5	-6.5	82.3	5435
37	11.9	-3.6	-2.8	8.5	-6.2	79.7	5491
38	[illegible]	-3.4	-3.0	9.2	-6.9	78.7	5661
39	12.5	-2.1	-1.5	8.0	-3.9	74.0	5393
40	13.1	0.6	2.1	8.2	-2.2	72.1	5438
41	13.8	2.4	8.2	8.3	-2.1	69.4	5656
42	12.7	5.6	15.4	8.7	-0.5	69.4	5656
43	16.2	7.2	17.8	9.3	-0.4	63.6	7734
44	16.6	7.6	20.4	-40.0	1.8	63.3	6836
45	16.6	8.0	20.5	-40.0	0.5	64.6	6603
46	17.0	7.9	18.5	10.2	1.0	64.2	6512
47	16.5	7.3	15.8	10.8	1.6	69.0	6581
48	16.2	6.6	13.5	10.7	1.1	69.9	6200

Barn TS-2 - Page 2

COND	SUPP	VHEAT	THEAT	MOIS	SENS
31.1		267.6	298.7	2.1	2644
31.9		263.9	295.8	1.8	2873
31.8		237.8	269.6	1.5	2769
33.7		249.9	283.6	1.7	2798
32.8		254.3	287.1	1.9	2686
31.7		226.1	257.8	1.5	26[illegible]
31.5		238.6	276.1	1.6	2738
31.2		250.2	281.4	1.6	2874
31.7		262.1	293.7	1.7	3010
31.2		254.6	285.8	1.5	3023
32.1		271.2	303.3	1.6	3230
31.5		250.1	281.6	1.4	3093
32.8		260.5	293.3	1.4	3261
36.7		284.8	321.6	1.6	3588
34.6		246.6	281.3	1.3	3174
33.5		246.2	279.7	1.4	3102
29.6		210.0	239.6	1.2	2664
30.7		220.4	251.0	1.3	2758
30.7		220.4	251.0	1.3	2758
25.4		210.0	235.4	1.4	2371
25.6		216.9	242.5	1.4	2402
26.5		207.5	233.0	1.4	2297
26.5		204.9	231.5	1.4	2266
28.9		232.9	261.8	1.6	2544
31.9		267.7	299.7	1.8	2915
31.4		237.5	268.9	1.6	2758
33.3		261.7	295.1	1.7	2988
32.4		255.0	287.4	1.8	2771
31.2		252.2	283.4	1.8	2708
32.1		254.5	286.7	1.8	2761
32.4		266.9	299.4	1.9	2790
33.1		285.4	318.5	2.0	3014
32.9		282.4	315.4	2.0	3004
32.0		272.2	304.2	2.0	2808
31.8		276.8	308.6	2.0	2847
32.2		269.0	301.2	1.9	2843
33.9		280.7	314.6	1.9	3070
36.2		308.7	344.9	2.2	3291
32.5		247.4	279.9	1.6	2857
30.8		219.7	250.5	1.5	2509
28.1		217.3	245.4	1.5	2356
28.1		217.3	245.4	1.5	235[illegible]
25.5		261.8	287.3	2.1	24[illegible]
24.9		214.4	239.3	1.6	2202
24.9		219.8	244.6	1.8	2062
27.3		222.6	249.9	1.8	2172
27.9		230.9	258.8	1.9	2222
29.1		225.1	254.2	1.8	2213

Barn FS-2

TIME	TPIN	TPOT	TPAT	DPIN	DPOT	RLHM	VENT
1	19.5	5.9	12.9	13.8	-4.0	69.6	8817
2	17.9	4.7	10.1	11.7	-2.4	67.0	8566
3	16.8	3.9	7.6	10.2	-3.[illegible]	65.0	9003
4	15.8	3.3	5.9	10.3	-3.2	69.8	8545
5	15.4	3.2	4.9	10.0	-3.9	70.2	8357
6	15.4	2.9	4.6	10.3	-4.0	71.6	8416
7	15.6	2.5	4.2	10.5	-3.5	71.6	8195
8	16.0	2.4	4.0	11.0	-3.4	72.2	7939
9	16.0	3.5	4.5	11.0	-3.4	72.2	8105
10	16.2	3.9	4.9	11.5	-3.7	73.7	8286
11	16.2	3.3	4.7	11.0	-5.3	7[illegible].3	8278
12	15.7	2.5	4.0	10.[illegible]	-5.2	72.[illegible]	8112
13	15.6	2.0	3.8	10.5	-5.4	71.6	8110
14	15.6	1.4	3.2	11.3	-5.9	75.6	7774
15	15.1	0.6	2.6	10.6	-6.1	75.5	7684
16	14.8	0.6	3.0	9.7	-5.6	7[illegible].5	7459
17	14.7	2.5	5.0	10.0	-5.5	73.4	7712
18	15.2	2.6	7.4	10.3	-5.5	72.5	7926
19	16.0	3.[illegible]	9.[illegible]	11.3	-5.[illegible]	73.6	8230
20	16.8	3.7	12.0	10.7	-4.3	67.2	8452
21	17.5	4.8	15.7	11.2	-4.3	66.5	9786
22	19.3	5.6	18.8	11.2	-4.1	5[illegible].4	9600
23	19.9	6.4	17.9	12.5	-3.7	62.4	9601
24	20.7	7.2	18.2	12.8	-3.5	60.5	9648
25	20.9	7.1	16.0	15.0	-3.1	69.0	9444
26	19.7	5.6	13.3	13.3	-1.8	66.5	9032
27	17.5	4.4	9.2	11.3	-2.3	67.0	8960
28	16.4	3.3	6.8	11.3	-2.5	71.8	8777
29	15.8	2.5	5.5	11.3	-2.1	74.6	8584
30	16.0	2.3	4.5	11.5	-2.5	74.6	8403
31	16.0	2.1	4.1	11.3	-3.0	73.6	8173
32	15.7	2.5	4.1	11.5	-3.2	76.1	8232
33	15.7	2.5	4.0	12.0	-2.7	78.6	8156
34	15.9	2.7	4.0	12.3	-2.5	79.2	8084
35	16.0	4.0	4.9	12.0	-2.5	77.1	7775
36	16.1	4.2	5.2	12.2	-2.8	77.7	7949
37	16.4	4.8	5.7	12.0	-2.8	75.2	7936
38	16.8	7.1	7.0	11.8	-2.5	72.3	8004
39	17.6	7.9	8.3	13.0	-1.3	74.4	8099
40	17.4	8.1	9.2	12.0	0.7	70.6	8003
41	17.0	6.0	7.9	12.3	-1.2	73.8	8065
42	15.8	4.7	6.3	11.8	-0.1	77.1	7986
43	15.8	4.9	7.0	12.0	-4.1	78.1	7983
44	14.4	2.9	6.2	10.5	-6.7	77.4	8272
45	14.9	-0.6	4.1	11.7	-9.3	81.2	7411
46	13.4	-2.0	2.4	8.2	-10.4	70.7	7260
47	13.1	-3.1	0.9	7.7	-11.1	69.7	6322
48	12.0	-4.7	-1.0	7.7	-13.2	74.9	6336

Barn FS-2 - Page 2

COND	SUPP	VHEAT	THEAT	MOIS	SENS
36.5		515.4	551.9	3.3	2929
37.9		428.3	466.[illegible]	2.5	2824
39.5		418.9	458.4	2.3	2919
39.3		395.9	435.2	2.3	2728
39.0		383.6	422.6	2.2	2624
39.6		398.2	437.6	2.3	2700
40.2		395.8	436.0	2.2	2751
40.4		399.4	439.9	2.3	2762
38.2		392.0	430.2	2.3	2596
38.0		411.7	449.7	2.5	2603
38.6		423.1	461.9	2.6	2714
40.3		412.3	452.7	2.4	2744
41.7		415.5	457.2	2.4	2828
43.6		426.9	470.5	2.5	2852
44.3		417.9	462.2	2.4	2886
42.0		377.5	419.6	2.1	2748
36.6		367.[illegible]	404.5	2.2	2432
33.7		389.[illegible]	423.0	2.3	2517
29.3		425.8	455.1	2.6	2589
28.3		418.7	447.0	2.4	2670
25.4		489.7	515.1	3.0	2913
26.5		492.5	519.0	2.9	3061
28.0		518.6	546.6	3.2	3031
29.4		526.0	555.4	3.3	3053
35.7		579.5	615.2	3.8	3121
39.4		497.9	537.3	3.0	3122
39.8		436.0	475.8	2.5	2942
41.6		430.8	472.4	2.5	2922
43.2		420.8	463.9	2.4	2928
44.0		426.4	470.4	2.4	2956
44.1		418.2	462.4	2.4	2925
42.3		417.9	460.2	2.5	2801
41.7		420.4	462.2	2.5	2772
41.0		421.3	462.3	2.5	2741
36.8		381.9	418.8	2.4	2409
37.2		396.4	433.6	2.5	2438
36.3		386.7	423.0	2.4	2373
31.8		355.2	386.9	2.4	2013
32.5		373.8	406.2	2.6	2035
29.9		318.0	347.9	2.0	1923
33.8		373.8	407.6	2.4	2270
36.4		348.8	385.2	2.1	2309
34.6		391.9	426.5	2.6	2249
34.4		404.7	439.1	2.6	2428
45.4		454.3	499.7	2.7	2969
45.2		387.6	432.9	2.1	2921
46.9		342.8	389.7	1.7	2744
49.1		358.3	407.4	1.8	2850