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THE UNIVERSITY OF ALBERTA

HEAT AND MOISTURE LOADS AND AIR QUALITY IN COMMERCIAL BROILER BREEDER BARNS

by

© JEREMIAH MARTIN O'CONNOR

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

EDMONTON, ALBERTA

FALL, 1986

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SUMMER, 1986

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and, recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled HEAT AND MOISTURE LOADS AND AIR QUALITY IN COMMERCIAL BROILER ~~BREEDER~~ BARNS submitted by JEREMIAH MARTIN O'CONNOR in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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[illegible]

Date 1986-07-18

Abstract

The maintenance of optimum environmental conditions in close confinement poultry facilities is contingent upon the provision of effective, energy-efficient, environmental control systems. With broiler breeder housing, the design of such systems is based on poultry heat and moisture production data estimated from poultry metabolic size or extrapolated from calorimeteric data for other types of poultry. In addition, little data are available on the production rates of air contaminants such as ammonia, carbon dioxide, hydrogen sulphide, and dust, and on the concentrations of these contaminants as they occur in commercial breeder housing.

Accordingly, a study was initiated whose objectives were to establish breeder heat and moisture loads and their variability under commercial conditions, to establish production rates and concentrations of air contaminants and to determine the possible effects of manure storage systems and management practices on these air quality parameters.

Three commercial broiler breeder barns, one utilising deep-pit manure storage and two utilising shallow-pit systems, were monitored for 24-hour periods at intervals of approximately three to four weeks during their production cycles. A data acquisition system developed by the Department of Agricultural Engineering, University of Alberta, for the monitoring of commercial livestock housing, was used for this purpose.

The major components of a building energy balance, including the heat losses due to ventilation and conduction and the supplemental heat gains, were calculated, allowing po[redacted]t and moisture production to be determined as the unknown terms in the [redacted].

The bird total heat production ranged from a mean of 67.7 kJ/(h.bird) to 75.4 kJ/(h.bird), while the means of the latent heat production ranged from 25.7 to 36.2 kJ/(h.bird). The two shallow-pit barns had the maximum and minimum values of 37 and 24%, respectively, for the proportion of sensible to latent heat converted in the evaporation of litter moisture. The ratio of latent heat to total heat in the ventilated air ranged from 0.34 to 0.42, with more latent heat being exhausted in the deep-pit barn.

Poultry RQ values were estimated using the calculated total heat production and carbon dioxide production data. The overall means of the predicted RQ's ranged from 1.1 to 1.2, consistent with a high energy diet composition. The metabolizable energy efficiency of production also was estimated and a value of 0.24 was obtained for the birds in this study.

The quality of the broiler breeder environment was evaluated by establishing ranges of background concentrations for the primary air contaminants. Mean daily ambient ammonia concentrations ranging from 17 to 123 ppm were considered to be potentially hazardous to both operators and birds. Although the respirable dust

concentrations found in the three barns (range of 1 to 49 particles/mL) were not considered to pose a potential health hazard by themselves, excessive ammonia concentrations in combination with the substantial dust concentrations were considered to result in an uncomfortable and unhealthy environment.

Acknowledgements

Funding for the project was provided by the Agricultural Research Council of Alberta under the Farming for the Future program. The guidance of the project supervisor, Professor Brian McQuitty, and the assistance of Peter Clark and Dale Travis are gratefully appreciated. The cooperation of the two producers, Mr. A. Balson and Mr. H. Klaasen, also is acknowledged.

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of a consumer society have necessitated the subst highly efficient intensive livestock systems for extensive ones. The requirement for a steady supp agricultural products, regardless of season or cl forced producers to provide livestock environment to optimum productivity.

The theoretical objective of livestock housi create an environment which will benefit the anir therein. The provision of a "comfortable" enviror conjunction with an appropriate feeding regime, s result in maximum productivity, whether in terms milk, or egg production. However, the regulation animal environment is a function of the capital a operating costs of the system and the return fron expected levels of productivity. Therefore, the c considerations in the control of livestock envirc not the desire for maximum productivity or a conc animal welfare but purely economic ones. Intensiv management systems are already quite advanced and relatively sophisticated refinements remain to be out to increase their efficiencies. However, futu in world economics could dictate that even small in the efficiency of production will be of benefi producer. According to Curtis (1981), the area wi

scope for improvement lies in our understanding of the relationships between the animal and its environment.

In any total confinement livestock system, ventilation is the single most critical element in determining both the quality of the environment and the overall system efficiency. To maintain the desired environmental conditions a balance must be achieved between heat and moisture production and dissipation. Minimum ventilation rates are determined by the need to control the moisture level within the building to protect the building structure and avoid indirect effects on animal hygiene (Smith, 1973). However, doubts have been expressed (McQuitty, 1985) as to the validity of moisture control as the sole criterion for minimum ventilation rates under severe winter conditions. The build-up of gaesous and particulate contaminants under low ventilation conditions may be sufficient to cause concern for animal and operator health. Therefore, there is a need to identify the existence of such a problem by measuring the concentrations of these contaminants in close-confinement systems. Production rates of these contaminants, as well as the rates of moisture production, can then be established to determine minimum ventilation requirements at any time during a production cycle. If the corresponding heat production values are known, a heat balance can be carried out to accurately determine the supplementary heat requirement for a particular ventilation regime.

Many of the heat and moisture production data currently available to the agricultural engineer were obtained through calorimetry studies. The volume of thermoregulation data for poultry is small compared to that for other animals (Scott, 1976) but the situation has improved in recent years. Bottcher and Timmons (1982) have advised the need for caution in applying calorimetric data to field conditions. Feddes et al. (1984a) reported a larger proportion of sensible to latent heat conversion for evaporation of litter moisture than for bird latent heat production. Consequently, lower values for sensible heat production might be expected in the field, especially where management systems require the in-house storage of litter over long periods of time.

There is a definite requirement for, and absence of, livestock housing standards, especially in relation to ventilation rates. Stewart (1976) poses the problem that, in the past, many recommendations were ignored by producers, partly because they were too complicated to carry out. The introduction of standards covering the complete range of confinement livestock operations would simplify the day-to-day management of such systems and eliminate mistakes due to the invalid extrapolation of data between different systems. Also, modern technological advancements allow for the automatic implementation of complicated control mechanisms, resulting in closer interlocking of the control variables, which, for the purposes of environmental control, are the supplementary heating and ventilation systems.

Future economic trends could result in producers having to take a more stringent scientific approach to feed regulation, coupled with highly-tuned environmental control systems. Mechanisms could be introduced for acclimating livestock so as to regulate the temperature range for optimum production and hence reduce the energy inputs into the system. Temperature regimes could be implemented to take advantage of animals' compensatory growth capabilities. Ventilation systems could be designed to maintain in-house temperatures closer to either the upper or lower critical temperatures, depending on climatic conditions. *In vito* monitoring of contaminant concentrations could be carried out in "high risk" houses to determine minimum ventilation requirements on the appropriate basis.

However far into the future these developments might be, the least complex of them cannot be achieved without accurate thermoregulatory data, which takes into account the adaptability and behavioural responses of large numbers of animals under commercial conditions. With respect to poultry breeders, little thermoregulatory data are available, either calorimetric or otherwise. Bearing in mind these long term goals and the present day need for standards, a study was undertaken during Winter-Spring conditions, the objectives of which were to measure in the field the heat and moisture production rates of broiler breeders during an entire production cycle and to establish background concentrations and production rates of the important contaminants, as

influenced by various housing and management practices.

2. The Poultry Environment - A Literature Review

2.1 Introduction

Armstrong (1973) described the animal's external environment as consisting of all the external influences affecting the life of the animal. Siegel (1974) considered the animal environment to consist of all combinations of conditions in which an animal lives, except those imposed by heredity and, therefore includes the internal environment (including the effects of infections and physical malfunctions) as well as the external environment. Curtis (1981) considered the external environment to consist of the many physical, chemical and biological factors that surround the animal. Esmay (1977) divided these factors into physical, social and thermal. Monteith (1973) considered the thermal factors to be the most important as far as heat loss from the animal is concerned. These thermal factors include the wet-bulb and dry-bulb temperatures of the ambient air, the movement of the air surrounding the animal and the radiant energy exchange between the animal and the environment.

Poultry, like other domestic animals, are homeothermic, that is, they can maintain deep-body temperatures within narrow limits despite wide fluctuations in ambient temperatures (Scott et al., 1983). Indeed, the maintenance of body homeothermy is essential for the continued well-being of an animal (Mount, 1979).

2.2 Animal Physiology

2.2.1 Animal Energy Balance and Metabolizable Energy

Wood (1974) attributes the life sustaining qualities of living organisms to their ability to operate as open thermodynamic systems, as a result of which energy is obtained from the environment and used to support the vital and non-vital processes. The maintenance of thermal equilibrium between the animal and the environment requires a balance between the energy gains to the animal and its rate of heat dissipation. These energy gains are a function of the available energy for metabolism and the energy produced through doing work.

Under optimal thermal conditions, the utilizable proportion of the dietary energy intake is divided between the animal's maintenance energy requirements and the energy required for production. Figure 2.1 illustrates the conventional model, as given in NRC (1981), for the partitioning of dietary energy. The Apparent Digestible Energy is the Gross Energy intake minus the energy lost in the feces. The digestibility of dietary energy depends on the feed composition and the level of feed intake. The Metabolizable Energy is that proportion of the Gross Energy that becomes available for metabolism. It is defined as the Digestable Energy minus the energy losses in the digestion processees and the energy associated with waste products in the urine. For poultry, depending on the composition of the

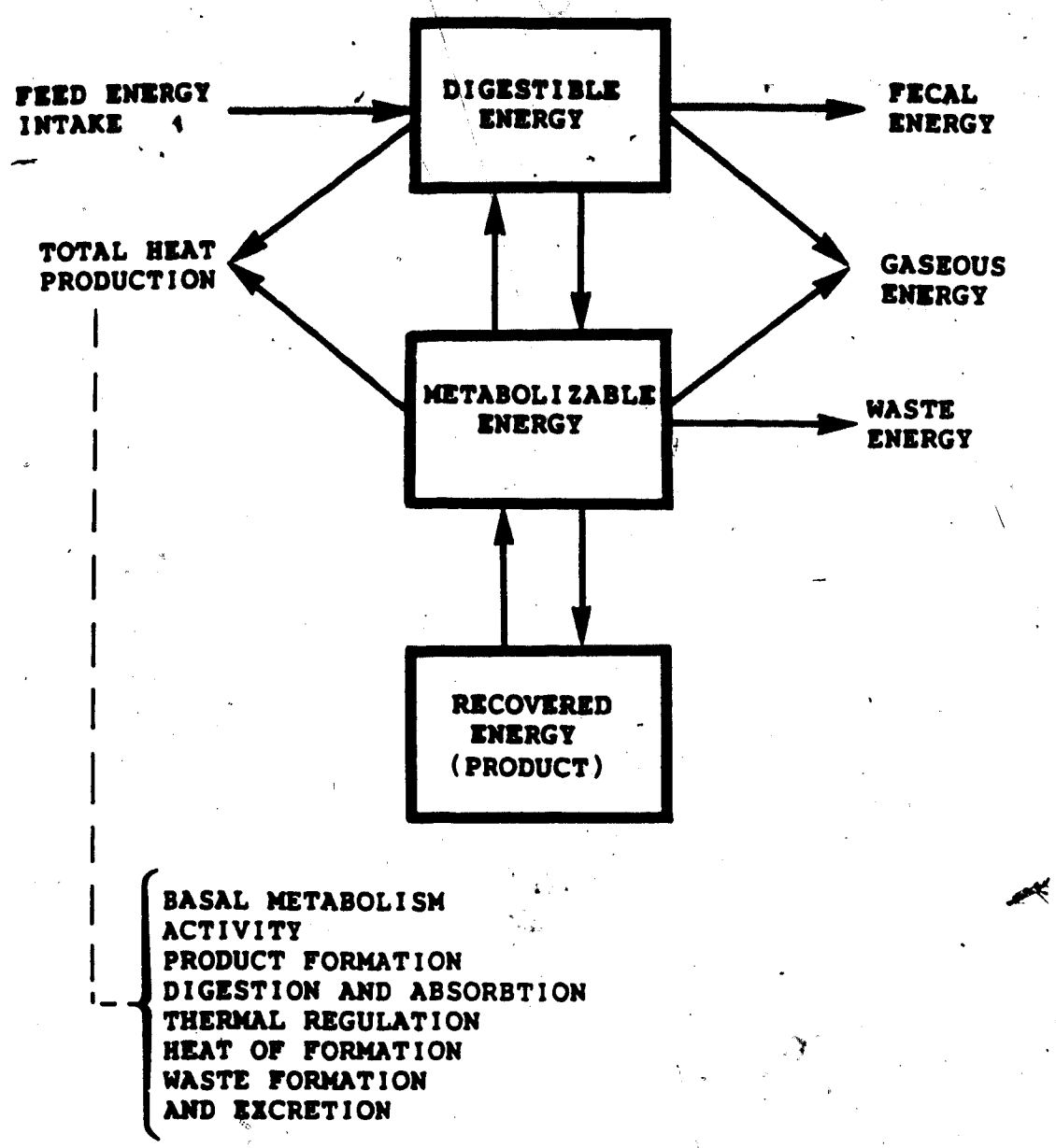


Figure 2.1 The idealised flow of energy through a mammal (NRC, 1981).

diet, environment, temperature and species, between 70 and 90% of the Gross Energy intake can be made available for metabolism (Esmay, 1977).

2.2.2 Metabolic Heat Production

From the energy balance of Figure 2.1, metabolizable energy is partitioned into heat production and energy for product formation. The Metabolic Heat Production (MHP) is a function of the net maintenance requirement and the heat increments of maintenance and production. For a given animal, MHP is proportional to body size, age, activity and diet (Monteith, 1973). Kleiber (1975) postulated that MHP was proportional to body weight raised to the power of 0.75. McLean (1973), on the other hand, stated that the influence of the environment on an animals' sensible heat exchange is best described by Newton's Law of Cooling, expressed in terms of surface area. However, a relationship between body weight and surface area has been shown to exist for the entire spectrum of animal species. As stated by Monteith (1973), the relationship is "that surface area is proportional to body weight raised to the power of 0.66, for any set of objects with different sizes but similar geometry." DeShazer et al. (1970) stated that MHP is also dependent on the level of acclimation to environmental conditions.

When the animal is unstressed, approximately one quarter of its maintenance requirements goes to support

vital body functions (Curtis, 1981). The remainder is used to maintain homeothermic conditions. Because an animal's MHP is a function of several factors, the concept of the Standard Metabolic Rate (SMR) was introduced as an estimate of an animals' basic maintenance requirements. The SMR defines the rate of metabolic heat production when the animal is in a fasting and resting state and not subjected to thermal stress. Curtis (1981) estimated the average SMR for food mammals and birds to be 3.4 $W/kg^{.75}$, in terms of body weight, while Monteith (1973) gave a value of 50 W/m^2, in terms of surface area.

2.2.3 Effective Environmental Temperature

The influence of thermal stresses on the MHP, which in turn affects the energy available for production, requires an understanding of the animal's physiological responses to effective environmental temperature. Rohles (1974) stated that environmental temperature can be divided into air temperature and mean radiant temperature but the effects of either could not be studied independently of relative humidity. Esmay (1977) defined environmental temperature as the effective temperature which includes all the variable climatic factors, such as wetand dry-bulb temperatures, air movement, radiation and temperature of the surroundings. Curtis (1981) considered the effective environmental temperature to be that of an isothermal, still environment that results in the same heat exchange as the subject

environment.

Gagge (1981) determined standard indices to describe the total heat exchange of man in any environment in terms of the heat exchange that would occur in any familiar environment. However, in practice, the most commonly used indicator of environmental conditions is the dry-bulb temperature of the ambient air, meaning that an animals' physiological response to a particular environment rarely is based on the combined effects of several climatic factors.

2.2.4 Thermal Zones

Animal physiologists have long since accepted the concept of thermal zones but have failed to agree on precise definitions or locations of the critical points. Kleiber (1975) considered the thermal zone for the most efficient feed conversion as the temperature range where the animal's sensible heat losses remain fairly constant. Esmay (1977) defined thermoneutrality as the range of effective environmental temperatures in which the animal is able to maintain homeothermic conditions using only physical compensatory mechanisms. In general terms, Mount (1973) considered the thermoneutral zone to be that temperature range in which the metabolic rate is minimal and constant. More specifically, he recommended the definition of several environmental zones, including the "zone of least thermoregulatory effort", defined as that range of environmental temperatures in which, for a given level of

feeding, the metabolic rate of a resting animal is at a minimum and evaporative heat loss due to panting and sweating, is constant. Smith (1973) stated that the thermal comfort of an animal can be associated with that range of temperatures in which a balance is readily achieved between the MHP and the environmental demand, while the animal is not subjected to thermal stress.

Mount (1973) developed a diagram to illustrate the relationship between the animal's heat regulation strategies and environmental temperature. In Figure 2.2, zone BD represents the thermoneutral zone, where, at a fixed level of feed intake and activity, the MHP is minimal and independent of environmental temperature (Clark et al., 1981). Zone BC is Mount's "zone of least thermoregulatory effort", in which homeothermy is maintained by regulating the blood flow to the peripheral tissues. Smith (1973) defines a temperature, measured when air movement is zero and radiation negligible, below which an animal has to increase its MHP to maintain a constant deep-body temperature, as the lower critical temperature (LCT), point B in the diagram. Between the points A and B, evaporative heat losses are at a minimum and the sensible heat losses are proportional to the difference in deep-body and environmental temperatures. Point A represents the point of incipient hypothermia, beyond which an animal can no longer maintain homeothermic conditions and deep-body temperature falls.

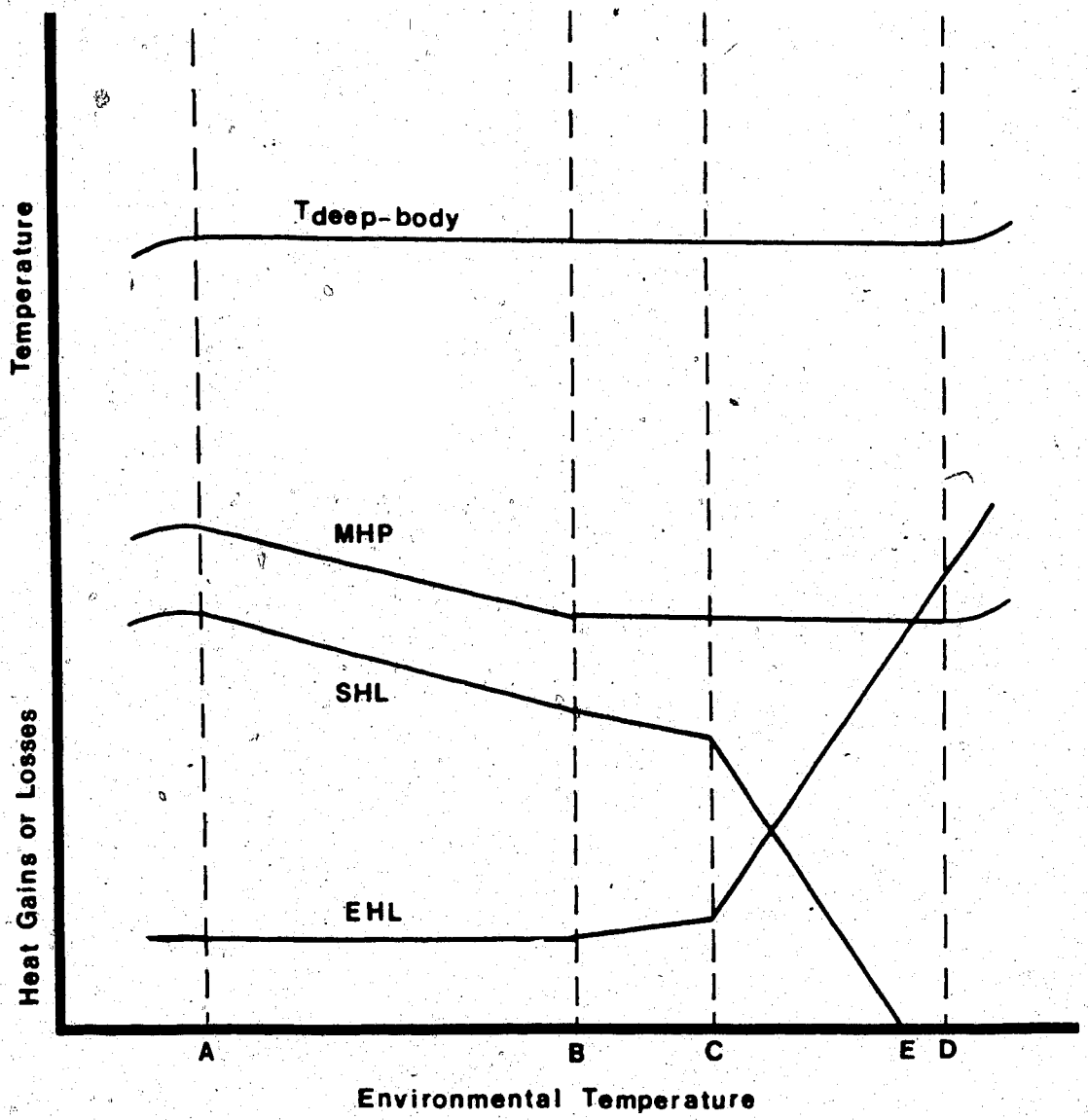


Figure 2.2 Thermal zones of mammals (Mount, 1973).

After point C, the importance of evaporative heat loss as a heat loss mechanism steadily increases. Sensible heat losses gradually decrease as environmental temperature approaches core temperature, until at a point E, sensible heat losses are zero. Point D represents the point of incipient hyperthermia, usually termed the Upper Critical Temperature (UCT), with MHP starting to increase as active heat loss mechanisms come into play.

The location of the UCT and LCT are determined by the animals MHP at thermoneutrality (Curtis, 1981). According to Clark et al. (1981), the higher the MHP at thermoneutrality, the wider the thermoneutral zone and the lower the UCT and LCT. Because of this dependence on MHP, locations of the UCT and LCT are influenced by body size, age, feed type and level. Factors which affect the rate of heat dissipation, such as the animal's thermal insulation, level of acclimation and behavioural responses to thermal stresses, will also affect the locations of these points.

Esmay (1977) quoted thermoneutral temperature ranges of 32-35°C and 18-24°C for Rhode Island Red layers at 5 and 52 weeks old, respectively. Romijn and Lokhorst (1966) reported values of 20°C and 30°C for the LCT and UCT respectively of mature North Holland Blue hens, weighing approximately 3 kg. Curtis (1981) gave values of 32°C and 18°C for the LCT for young and mature broilers, respectively. In his comprehensive review of poultry research, Bond (1974) stated that most breeds of poultry begin to show signs of low

temperature stress at 7°C by increasing feed consumption. Payne (1967), as cited by Bond (1974), stated that above 30°C, layers will decrease their feed intake about 1.6% for each 1°C rise in temperature. However, Romijn and Vreugdenhil (1969) concluded that there is no indication of the existence of a zone of thermoneutrality for fowl.

2.2.5 Thermoregulation

As homeothermic animals, poultry attempt to maintain constant deep-body temperatures via adaptive responses to environmental stimuli. Curtis (1981) used the word stress to describe any environmental factor which produces an adaptive response, and strain to describe any functional, structural, or behavioural reaction to an environmental stress. Wilson (1971) stated that the animal's performance is the integral effect of all the stressful environmental influences. Under conditions of cold stress, if metabolic rate is increased to maintain deep-body temperature, a higher proportion of food intake is employed in thermoregulation and body mass declines unless feed intake is increased (McArthur, 1975). From an animal health point of view, Hyslop (1974) stated that stress and fatigue increase significantly the persistence of bacteria in the alimentary tract. The continuous use of the physiological thermoregulatory mechanisms also can result in the initiation of pathogenic conditions, due to changes in blood chemistry and ulceration of the gastro-intestinal tract (Selye, 1951, as cited by

Siegel, 1974).

Thermoregulatory mechanisms have been described as either behavioural or physiological. Scott (1976) stated behavioral mechanisms to include postural adjustments, huddling or the selection of a more favourable environment. DeShazer et al. (1970) reported an increase in sensible heat loss of between 20 and 40% for a hen in a standing, rather than a sitting position. Esmay (1977) reported a 12% decrease in heat loss for chicks with their heads under their wings. Wathes and Clark (1981a) estimated the sensible heat loss of broilers in a cluster to be between 30 and 60% of that of individual birds, depending on age. The heat production of poultry associated with activity levels also has been reported. However, the ability of poultry to alter or choose their environment is limited in close confinement poultry housing.

Physiological thermoregulatory mechanisms involve the regulation of MHP and heat dissipation, by varying the metabolic rate and adjusting or inducing respiratory heat loss, sweating, vasomotion and piloerection (Scott et al., 1983). Scott (1976) used the concept of negative feedback control to describe the mechanism which stimulates these physiological responses. Any change in the thermal environment can cause an imbalance in the animal's rates of heat production and dissipation, which in turn, cause a change in body temperature. A reference temperature is compared with a controlled temperature and the difference,

if any, is corrected by adjusting the heat production or heat loss mechanisms. The control of body temperature is integrated through the hypothalamus, using sensory information from the skin, spine, body core, and hypothalamus. Temperature sensors, located in peripheral tissue and body core, transduce the temperature information into neural signals. The hypothalamus then processes the impulses and initiates a coordinated neural discharge to the sites of hormone production (Esmay, 1977). This, in turn, stimulates the release of steroid hormones, causing the synthesis of new cellular protein in the target tissue. The required "functional response" is produced, therefore, from that tissue to return deep-body temperature to the reference value (O'Malley and Means, 1974, as cited by Siegel, 1974). Behavioural thermoregulatory mechanisms are activated in the same way and are, therefore, dependent on the same physiological control system.

2.2.6 Heat Production

Poultry produce heat due to the exothermic reactions associated with the metabolism of absorbed food, as well as through maintenance processes and physical activity. Various tissues produce different amounts of heat. According to Webster (1981), the most metabolically active tissues are those which contain protein, heat production being closely related to protein deposition. The most important sites of heat production include the liver, the gastrointestinal

tract, the kidneys, and skeletal muscle (Kelly, 1984). Skeletal muscle plays an important role in heat production outside the thermoneutral zone in that it is the major site for both shivering and non-shivering thermogenisis. As a result of cold stress, shivering thermogensis is induced to increase heat production by physical motion and associated chemical transformations. Christopherson (1980) stated that the extra heat produced is directly proportional to the number of degrees below the LCT and inversely proportional to the animals' insulation. In poultry, shivering thermogenisis is the main mechanism for increasing heat production below the thermoneutral zone (Scott, 1976). In response to cold stress, poultry can increase their heat production to between 3 and 4 times the rate at thermoneutrality (Esmay, 1977).

The association of poultry heat production with activity levels also has been recognised. Ota and McNally (1961) reported that layer heat production was lower during darkness than during the light hours. A recent study on the rates of heat production in commercial laying barns confirmed this finding, with layer heat production being reduced by as much as 25% during darkness (Feddes et al., 1985). The influence of lighting period on poultry heat production has been attributed to the variations in activity levels associated with light and darkness.

When organic compounds are oxidized, animal heat production is correlated closely with the oxygen (O_2)

consumption and the carbon dioxide (CO_2) production plus the nitrogen (N_2) excreted (Flatt, 1969). This principle forms the basis of indirect calorimetric methods and assumes that heat production results from the breakdown of carbohydrates, lipids and proteins, only. Romijn and Lokhorst (1961) developed an equation, similar to one given by Esmay (1977) and Scott (1976), based on this principle, to calculate the heat production of chickens. The equation, as given by Scott (1976), is:

$$Q = 16200\ O_2 + 5000\ CO_2 \qquad (2.1)$$

where Q = rate of heat prodution, W

O_2 = oxygen consumption, m^3/s, and,

CO_2 = carbon dioxide production, m^3/s.

According to Lundy et al. (1978), a correction term for excreted nitrogen can be omitted, the resulting error being typically in the region

Esmay (1977) defined the respiratory quotient (RQ) as being the ratio of the volume of CO_2 produced to the volume of O_2 consumed. Because different amounts of O_2 are associated with the oxidation of various carbohydrates, lipids and proteins, an animal's RQ at any time is dependent on the composition of its diet. Brouwer (1965), as cited by Flatt (1969), recommended RQ's of 0.81, 0.71 and 1.00 for the oxidation of protein, lipid and carbohydrate in the

animal body. The RQ's of normally fed poultry are not constant over a 24-hour period. Values are at a minium before the lighting is switched on and rise rapidly as metabolism increases with level of activity. RQ's reach a maximum just after feeding, due to the greater activity of the digestive tract and the specific dynamic action of the food (Romijn and Lockhorst, 1966). The same authors noted the close agreement in data obtained from North Holland Blue layers and Cape ducks and reported the RQ of a fully fed North Holland Blue to fluctuate between 0.69 and 0.83. Lundy et al. (1978) reported mean RQ's of 0.96 for two different layer strains, fed *ad libitum* on standard diets (Metabolizable Energy = 11.17 MJ/kg) and kept in a ventilated room at 20.5°C.

Several researchers, including Deighton and Hutchinson (1940), Ota and McNally (1961) and Jordan and Dale (1963), have employed laboratory-based direct calorimetry methods to estimate poultry heat production rates. Such methods involve the measurement of either the air temperature increase across a calorimeter or the heat transferred across the walls (Bottcher and Timmons, 1982). Indeed, heat and moisture production data for engineering design purposes (Midwest Plan Service, 1976; American Society of Agricultural Engineers, 1979) are still based on the findings reported by Ota and McNally (1961).

The first data on the heat production of broilers were reported by Reece et al. (1969) and Deaton et al. (1969),

who used whole-house, direct calorimetry on birds under commercial conditions. Similarly, Bottcher and Timmons (1982), Feddes et al. (1984a), Feddes et al. (1985) and Glennon (1985) reported poultry heat and moisture production in commercial houses. However, little or no research has been carried out on the heat and moisture production of broiler breeders, with design data usually being calculated on the basis of metabolic weight.

2.2.7 Heat Losses

According to Richards (1973), with ambient temperatures up to 20°C, the major proportion of poultry heat loss is subject to the influence of physiological thermoregulatory mechanisms which alter the conductance of the superficial tissues by changing the amount of blood flowing through them. With ambient temperatures greater than 25°C, evaporative heat loss mechanisms are augmented by panting until, at temperatures approaching the bird's deep-body temperature, all of the heat dissipated is by evaporative modes.

Both sensible and evaporative heat loss mechanisms rely on the transmission of heat through the circulatory system from the more metabolically-active core to the cooler skin tissues. This occurs mainly by convection, although some heat is transmitted through the body mass by conduction. Evaporation occurs at the skin surface and the remainder of the heat energy is transfered through the feathers or cover

insulation by conduction, from where it can be dissipated to the environment. Heat loss to the environment is accomplished by a combination of sensible and evaporative modes, depending on the effective environmental temperature.

2.2.8 Sensible Heat Losses

The Sensible Heat Loss (SHL) of poultry can be partitioned into conductive, convective and radiant heat transfer. The largest resistance to thermal exchange between the fowl and the environment is in the feather coat (Wathes and Clark, 1981b), the insulative value of which depends largely on the thermal conductance of the trapped air within the feathers (Curtis, 1981). Wathes and Clark (1981b) reported that the SHL's of poorly feathered birds were twice that of normally-feathered birds in the temperature range of 0 to 30°C. Poultry can increase the thermal resistance of their cover insulation by fluffing out their feathers, thereby increasing the cover thickness.

The evidence suggests that control of poultry SHL is by vasomotor control of the unfeathered regions (Scott, 1976). Large differences in temperature have been measured in unfeathered skin areas while feathered skin temperatures remained relatively constant and close to deep-body temperature. Richards (1973) attributed these differences to changes in local blood flow. Vasodilation and vasoconstriction are the mechanisms by which relaxation or contraction of muscles in the blood cell walls regulate the

flow of blood to the peripheral tissues. Temperature variations of between 10 to 15°C have been reported between areas of the comb, wattle and feet, at constant temperatures at or below thermoneutrality (Scott, 1976).

2.2.8.1 Convective Heat Loss

Convection is heat transfer brought about by the interchange of warm and cold fluids. Two types of convective heat transfer can occur, depending on the method by which motion is induced in the fluid. "Free convection" relies on density differences associated with temperature gradients, while "forced convection" is brought about by the action of external forces to cause relative motion within the fluid. According to Wathes and Clark (1981a), air velocities encountered in controlled-environment livestock housing are such that convective heat transfer in such houses is brought about by a combination of both mechanisms.

Clark et al. (1981) gave an equation to describe the rate of heat transfer due to convection as:

$$Q_v = Nu\ k\ \Delta T/d \qquad (2.2)$$

where Q_v = rate of convective heat transfer, W

Nu = dimensionless Nusselt number

k = fluid thermal conductivity, W/(m.°K)

ΔT = temperature difference between air and surface, °K, and

d = characteristic dimension, m.

For forced convection, with air as the fluid, the Nusselt Number (Nu) is related to the Reynolds Number (Re) according to:

$$Nu = 0.23\ Re^{0.60} \qquad (2.3)$$

when $10^3 \leq Nu \leq 5 \times 10^4$.

The Reynolds number can be calculated, knowing the air velocity, the kinematic viscosity and the characteristic dimension of the animal. Randall (1981) developed a model, based on a similar model for growing pigs by Bruce and Clark (1979), to predict the heat production of laying hens. In estimating convective heat loss, Randall (1981) used a characteristic dimension, d, in terms of body weight:

$$d = b\ M^{0.33} \qquad (2.4)$$

where b = 0.052, and

M = liveweight, kg.

Wathes and Clark (1981a) used a similar equation for the characteristic dimension of broilers, also as a function of liveweight, with b = 0.131.

Combining Eqns. 2.2, 2.3 and 2.4 and assuming a value of 0.026 W/(m.°K) for the thermal conductivity of air, yields an equation for the convective heat loss of broilers and broiler breeders, as follows:

$$C = 10.79\ V^{0.60}\ A\ \Delta T / M^{0.13} \qquad (2.5)$$

where C = rate of convective heat loss, W

V = air velocity, m/s, and

A = area of exposed skin, m^2.

The rate of convective heat transfer is heavily dependent on the thermal insulation of the boundary layer of air surrounding the bird, which, in turn, depends on such properties as shape, orientation to air, aerodynamic profile and roughness, and air velocity (Curtis, 1981). Van Kampen (1981) reported that the initiation of an air flow of 1.4 m/s, incident on either the head or the body of a sitting White Leghorn hen at 20°C was sufficient to cause an immediate 15% increase in heat production.

Convective heat exchange also occurs in poultry respiratory tracts. As well as the latent component of heat loss due to saturating the inspired air, heat is also lost by convection in raising the temperature of the inspired air to body temperature. Scott (1976) expressed the respiratory sensible heat loss as:

$$R = M\,c\,(T_1 - T) \qquad (2.6)$$

where R = respiratory sensible heat loss, W

M = ventilation rate of inspired air, kg/s

c = specific heat of air at constant pressure, kJ/(kg.°K), and

T_1 = temperature of the expired air, °K, and,

T = ambient temperature, °K.

However, Canton et al. (1983) determined that the sensible heat transfer from the respiratory tract accounted for only 7 to 12% of the total respiratory heat loss in mature, male broiler breeders under various conditions of thermal stress.

2.2.8.2 Radiative Heat Loss

Radiative heat transfer in an animal environment involves both the absorption and emission of energy. Depending on the wavelength of the electromagnetic radiation, animals can be exposed to short-wave solar radiation (0.3 to 3μm) or long-wave thermal radiation (3 to 100μm). For poultry in close-confinement housing, the solar radiation load is zero but the heat transfer due to long-wave radiation usually accounts for approximately half of the fowls total SHL (Cena, 1973).

The net radiant heat transfer between any object and its surroundings depends on the emissivities of the object's

surface and the surfaces of the surroundings. Cena (1973) gave an equation for the net radiant heat transfer between an object and its surroundings as:

$$Q_r = \sigma\ (T_{bs}^4 - T_s^4)\ A_{bs}/A \qquad (2.7)$$

where Q_r = net radiant heat transfer, W

σ = Stefan-Boltzman constant, 56.7×10^{-9} $W/(m^2.°K^4)$

T_{bs}, T_s = absolute temperature of bird surface and enclosure surfaces, °K, and

A_{bs}, A = area of bird and enclosure surfaces, m^2.

Equation 2.7 is a simplified version of an equation given by Scott (1976) and assumes the emissivity of the bird's surface and that of its surroundings to be unity. Randall (1981) assumed the emissisivity of skin, comb and wattle to be 0.99 and that of the building material to be 0.90. In practice, this quantity will depend on the level of thermal insulation which, for adequately designed buildings, should be sufficient to ensure surface temperatures close to that of the ambient air temperature.

The effective surface area of the radiating object is posture dependent and, as such, can be difficult to determine. The radiated flux through the animal coat or feathers also depends on the temperature gradient within the fibre of the coat. However, Randall (1981) assumed the

radiant heat transfer from the feathered area to be negligible, due to its property as an insulator.

2.2.8.3 Conductive Heat Loss

Conduction is the transfer of heat through a medium as a result of a temperature gradient without material movement (Curtis, 1981). The conductive heat transfer depends on the contact area between the two surfaces and their thermal conductivities. However, contact areas between poultry and solid surfaces tend to be small and materials such as wood in slatted floors and straw in nest boxes and littered floors have low thermal conductivities. In caged or on-floor poultry systems, contact occurs between large numbers of birds but conductive heat transfer is negligible due to the similar temperatures of the contact areas. For these reasons, conductive heat loss is not considered to be an important avenue of heat transfer for poultry.

2.2.9 Evaporative Heat Loss

As environmental temperatures increase the proportion of heat lost by sensible modes decreases and evaporative heat exchange becomes the major avenue for heat dissipation. The cooling effect of evaporation is due to the endothermic nature of the reaction in which water in the liquid form is converted to water vapour. Scott (1976) stated that two pathways exist for evaporative heat transfer in poultry, namely, the diffusion of water vapour through the skin and

evaporation of water from the respiratory tract. At lower temperatures, when evaporative heat losses are at a minimum, cutaneous evaporative heat losses predominate while at higher environmental temperatures, under conditions of thermal stress, evaporation from the respiratory tract supersedes all other heat dissipation mechanisms.

2.2.9.1 Latent Respiratory Heat Loss

Respiratory heat exchange involves a combination of latent and convective heat transfer in that the inspired air is warmed and humidified in the upper respiratory tract, so that it reaches body temperature and saturation before entering the lung (Canton et al., 1983). Scott (1976) calculated the latent respiratory heat loss of a fowl as:

$$L = I\ (W_1 - W_2)\ h \qquad (2.8)$$

where L = latent respiratory heat loss, W

I = ventilation rate of inspired air, kg/s

W_1, W_2 = humidity ratios of expired and inspired air, kg H_2O/kg dry air, and

h = latent heat of vapourization, kJ/kg.

At temperatures greater than 25°C, blood flow is directed more to the head appendages and respiratory system (Van Kampen, 1971, as cited by Scott (1976)), resulting in the predominance of evaporative heat loss mechanisms and

associated convective heat exchange processes. Evaporative heat loss is affected by the relative humidity of the inspired air and controlled by regulating the respiratory frequency (McLean, 1973). Van Kampen (1981), stated that evaporative water loss decreased with increasing ambient vapour pressure. Poultry can increase their respiration rates by as much as 20 times that of the basal level (Curtis, 1981). Although this has the effect of decreasing the tidal volume (volume of air per inspiration), the total rate of volume flow increases because of the increase in respiration rate (Scott, 1976). Under conditions of severe heat stress, normal evaporative heat loss mechanisms are augmented by gullar flutter and open-mouthed panting, at environmental temperatures greater than 41°C (Esmay, 1977).

2.2.9.2 Heat Loss by Diffusion

All animals lose heat by passive diffusion of water vapour through the skin. Birds differ from most other animals in that they do not possess sweat glands, thereby lacking the means to control cutaneous evaporation (Scott, 1976). The same author gave an equation to calculate the rate of cutaneous heat transfer through passive diffusion as:

$$Q_d = h_{fg} D A_s (P_s - P_a) \qquad (2.9)$$

where Q_d = rate of cutaneous heat transfer, W

D = permeance coefficient of skin to water vapour, m^2/s

A_s = area of skin surface, m^2,

P_s = saturated vapour pressure at skin temperature, kPa, and

P_s = vapour pressure of the ambient air, kPa.

The rate of cutaneous heat transfer is independent of environmental temperature but depends on a vapour pressure gradient for its driving force. Therefore, at high ambient temperatures, high relative humidities inhibit both passive diffusion and respiratory evaporative heat losses. Van Kampen (1971), as cited by Scott (1976), estimated that passive diffusion accounted for 15% and 60% of the total evaporative heat loss at 40°C and 10°C, respectively. However, at low environmental temperatures, evaporative heat losses tend to be constant and relatively insignificant compared to sensible heat losses and so the contribution of cutaneous evaporation to total heat losses is relatively small.

2.3 Air Quality

If the animal environment is considered to consist of all the factors that affect the animal, then the quality of the air which the animal breathes is an important component of the environment in that it can have a direct or indirect

effect on the animal's performance (Curtis, 1981). For economic reasons close confinement management systems are now utilized almost universally in large-scale poultry operations, subjecting the world's poultry population to environments in which the composition of the air differs from that of atmospheric conditions. The practice of using low levels of ventilation, especially under cold weather conditions, has given rise to speculation as to the validity of the criteria for determining minimum ventilation rates (Charles and Payne, 1966; Brannigan and McQuitty, 1971). Ryan et al. (1983) stated that reduced levels of ventilation hold the potential for creating an environment hazardous to bird health due to the buildup of high concentrations of air contaminants.

Curtis (1981) pointed out the problem that faces the agricultural engineer in relation to air quality in animal environments. He noted the lack of quantitive data on air pollutants in animal environments and also pointed out that little is known of the effects of such contaminants on the animal's health or productivity. McQuitty (1985) argued the necessity for the utilization of data from both areas in order to establish "upper limits of acceptibility" for each contaminant and to establish adequate minimum ventilation rates to prevent the occurrence of these "upper limits". McQuitty and Feddes (1982) questioned the validity of applying human threshold limit values (TLV's) to livestock, especially as human TLV's are not calculated on the basis of

a continuous exposure time.

Clark and McQuitty (1985) stated the importance of knowledge of production rates of the major contaminants for the purposes of designing effective environmental control systems. Until recently, the expected levels of air contaminants were difficult to estimate for the various close confinement livestock operations because the effects of different housing systems and management practices on the production rates of these contaminants were not known. Recent work on this subject (Leonard et al., 1984; McQuitty et al., 1985; Clark and McQuitty, 1985; and Glennon, 1985) has sought to remedy this situation but, at the same time, it also has emphasised the magnitude of the problems to be addressed in doing so.

Changes in ambient air conditions in close confinement poultry houses are being affected continuously by the poultry housed therein. As a result of the fowls' metabolic processes, the concentration of O_2 in the air is reduced while CO_2 concentrations are increased. Water vapour is added to the environment due to the fowls' evaporative heat loss mechanisms and the evaporation of water from the stored manure. Ammonia (NH_3) is produced as a result of the decomposition of nitrogenous compounds in the animal manure. The generation of methane (CH_4) and hydrogen sulphide (H_2S) is also associated with the in-house storage of animal manures. Skin debris and broken feather barbules have been identified as being some of the major constituents of the

particulate contaminants found in poultry houses (Koon et al., 1963).

2.3.1 Ammonia

Ammonia has been described as the most prominent of the non-particulate contaminants as far as close confinement poultry housing is concerned (Scott et al. 1983; Al-Mashadani et al., 1984; McQuitty et al., 1985). According to Elliot and Collins (1982), NH_3 is the product of the decomposition of uric acid within the poultry litter.

Wolfe et al. (1968) stated that NH_3 production is determined primarily by litter conditions. Litter moisture content, temperature, pH, aeration, porosity, and the amount of NH_3-producing fecal matter all influence the various processes involved in the conversion of the nitrogen containing compounds in the poultry manure to atmospheric NH_3. As well as the effect of litter conditions on NH_3 production, Lillie (1970), as cited by Carr and Nicholson (1980), pointed out the influence of ventilation, bird density and season.

Figure 2.3, developed by Elliot and Collins (1982), illustrates the various stages of the conversion process. The first stage involves the aerobic degradation of uric acid to aqueous NH_3 and NH_4^+ ions. This step is strongly dependent on the temperature and pH of the litter, with increased rates of bacterial ammonification occurring at higher temperatures (up to 35°C) and under alkaline

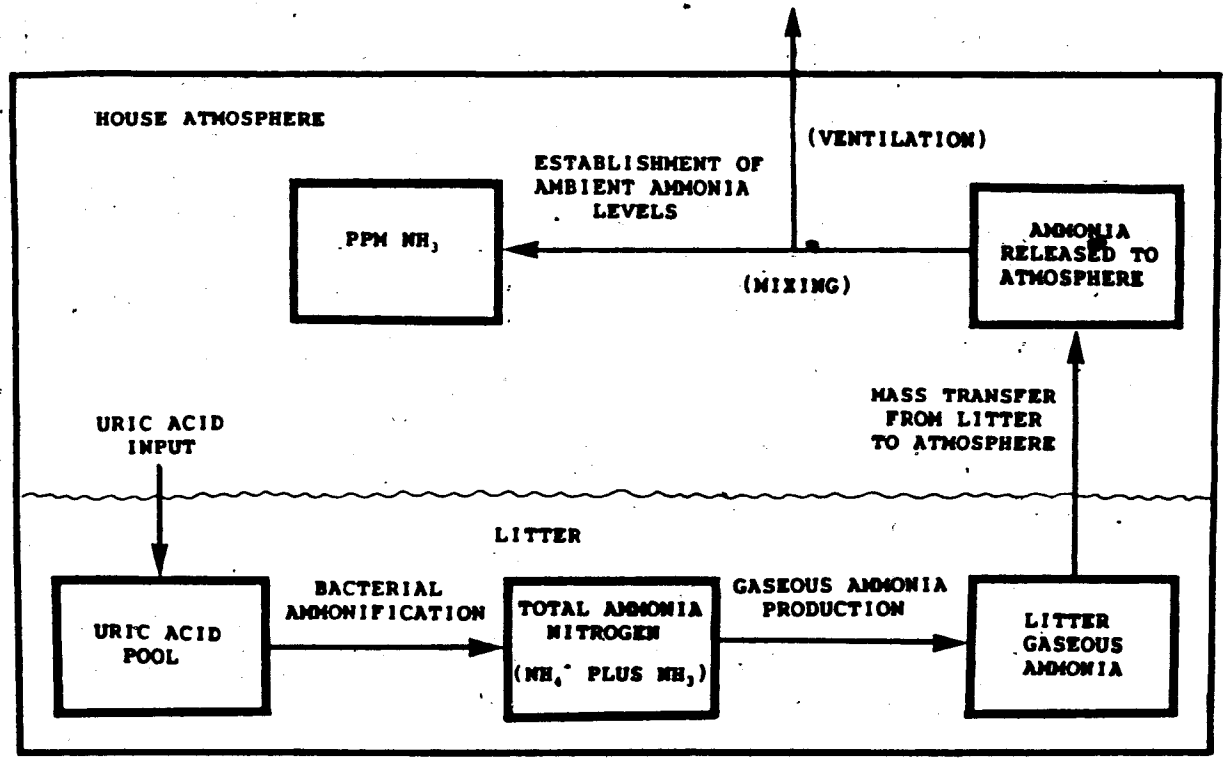


Figure 2.3 Ammonia volatilization in poultry house litter (Elliot and Collins, 1982).

conditions (pH not greater than 9.0) (Elliot and Collins, 1982). The production of gaseous NH_3 within the litter depends on the establishment of equilibrium conditions between the soluble and gaseous fractions, which, in turn, depends on litter temperature and pH. Ammonia then is transferred from the litter to the environment due to the difference in NH_3 partial pressures. The rate of accumulation of NH_3 in the poultry environment is dependent on its rate of removal by the ventilation system.

Leonard et al. (1984) reported that NH_3 production rates in broiler barns increased exponentially with time over the production cycle when fresh litter was used at the beginning of the cycle. Increases in the dietary protein intake of the broilers during the course of the production cycle probably resulted in an increased uric acid content of the feces. McQuitty et al. (1985) noted large differences in NH_3 production rates for layer barns due to different manure storage times. The barn with the most frequent manure removal practices had significantly lower NH_3 production rates. Turnbull and Snoeyenbos (1973), as cited by Elliot and Collins (1982), stated that the pH of poultry litter increases with age up to maximum of about 8.5 due to the production of NH_3 from the degradation of uric acid. Reece et al. (1979) reported that, for an on-floor system for broilers, NH_3 release was negligible at pH's below 7.0 and increased up to a maximum of 8.3.

McQuitty (1985) described NH_3 as being an irritant gas "to exposed moist surface tissues, causing inflammation of the mucous membranes of the eye and respiratory passages". Indeed, the adverse effects of exposure to NH_3 to poultry health were first reported by Bullis et al. (1950) and Faddout and Ringrose (1950), both as cited by Carr and Nicholson (1980). These authors noted the increased incidence of keraconjuctivitis in chickens when exposed to NH_3. Anderson et al. (1964) reported that short exposures to between 20 and 50 ppm of NH_3 significantly increased the susceptibility of chickens to the Newcastle disease virus. Al-Mashadani et al. (1984) reported that chickens continuously exposed for 20 days to NH_3 at various concentrations up to 90 ppm all showed signs of pulmonary lesions, with consequent effects on their ability to lose heat by evaporative modes. Deaton and Reece (1980) reported that, from day 1, a four week exposure to NH_3 concentrations as high as 100 ppm significantly increased broiler mortality.

Several authors also have studied the effects of NH_3 on poultry performance and production. Charles et al. (1966a) found that exposure to 100 ppm of NH_3 during brooding reduced broiler growth rates. Reece et al. (1980) reported that broilers exposed to 50 ppm during brooding had reduced body weights, with feed conversion becoming progressively worse with higher exposure concentrations. Curtis (1981) stated that NH_3 concentrations of between 75 and 100 ppm

depressed the growth performance of broilers and replacement pullets by 15%. Both Charles and Payne (1966b) and Curtis (1981) reported effects of exposure to concentrations up to 100 ppm on egg production. The first study found that exposure to NH_3 during the growing period depressed hen-day egg production, while Curtis (1981) reported a decrease of up to 15% in egg production for laying hens due to a 10-week exposure. McQuitty (1985) suggested the possibility of adverse effects on the hatchability of eggs from breeder facilities with high ambient NH_3 concentrations.

As far as product quality in broilers is concerned, Froning and Sackett (1984) found that 7-day, preslaughter exposures of greater than 75 ppm significantly influenced breast muscle characteristics, with consequent effects on the quality of the meat. Curtis (1981) postulated that in layer houses, eggs exposed to high concentrations of NH_3 before collection suffered a deterioration in quality.

In livestock housing, the only standards which exist for permissible levels of contaminant gases are based on the calculated "safe" levels for the operators (Nordstrom and McQuitty, 1976). The TLV for NH_3 for time-limited exposures, recommended by the ACGIH (1984), is 25 ppm, while the SFBIU (1984) recommended maximum allowable NH_3 concentrations in farm buildings of 20 ppm. In practice, NH_3 concentrations in close confinement poultry housing often can exceed this value. Anderson et al. (1964) observed that minimum ventilation rates were sufficient to cause NH_3

concentrations of between 50 and 100 ppm in commercial layer barns. McQuitty et al. (1984) monitored contaminant concentrations in layer facilities during the winter months. They reported that, for two of three barns involved in the study, mean daily NH_3 concentrations of 33 ppm and 53 ppm were measured over the monitoring period. Such high concentrations of NH_3 not only have consequences as far as effects on poultry health, production and product quality are concerned but concern also must be expressed for operator health. As far as the distribution of NH_3 concentrations are concerned, Brannigan and McQuitty (1972) found that the diffusion of both NH_3 and CO_2 gases within an enclosed ventilated space was independent of relative densities but was strongly influenced by the distribution of sensible heat.

The most effective means of NH_3 control in poultry housing is through good management practices, ensuring frequent manure disposal. However, deep-pit systems of housing tend to allow for prolonged storage of the droppings over an entire production cycle, which, in the case of layers and breeders can be anything up to 40 weeks. In such cases, the conventional method of NH_3 control has been by means of the ventilation system. Rising energy costs and the decline of profits have created a renewed interest in energy conservation. Since the 1970's, researchers have applied themselves, with only limited success, to ways of reducing NH_3 production from the litter as a means of controlling

atmospheric NH_3 concentrations. Seltzer et al. (1969), as cited by Ryan et al. (1983), and Reece et al. (1979) tried chemial methods to inhibit the rate of NH_3 production from the litter. However, the large quantities of chemicals required for adequate control of NH_3 release in commercial volumes of poultry litter make chemical methods economically unviable. Ryan et al. (1983) developed a combination "NH_3 scrubber" and dehumidification unit to reduce both moisture and NH_3 concentrations in poultry houses, allowing lower minimum ventilation rates to be utilized. However, the high energy demand of the air modification unit make the system economically unfeasible at present day energy costs.

2.3.2 Carbon Dioxide

Carbon dioxide is produced as a result of the metabolic activity of the birds and is expired via air exchange in the lungs (Nordstom and McQuitty, 1976). The relationship between CO_2 production and metabolic rate, used in conjunction with RQ values, is the basis for the determination of animal heat production using indirect calorimetry methods.

In terms of pollutant effects, Nordstrom and McQuitty (1976) classified CO_2 as a simple asphyxiant, "inducing asphyxia entirely by excluding O_2 from the lungs". It is an odorless gas, normally occurring in the atmosphere at concentrations of between 300 and 350 ppm, depending on geographical location and time of year (Reece and Lott,

1980).

Wilson and Edwards (1950), as cited by Reece and Lott (1980), exposed chicks to various concentrations of CO_2 and "found no noticable effects at 4000 ppm, gasping and distress at 118,000 ppm, and death at 174,000 ppm". Reece and Lott (1980) noted the lack of information on the effects of high CO_2 concentrations on poultry production. Helbacka et al. (1963), as cited by Deaton and Reece (1980), found that short exposures of laying hens (12 to 54 hours) to levels up to 50,000 ppm was sufficient to decrease egg production and reduce shell thickness. Curtis (1981), however, reported increased shell thicknesses when laying hens were exposed to high CO_2 environments.

Although CO_2 concentrations within close confinement poultry houses are far higher than atmospheric concentrations, the levels attained are not considered significant in terms of contaminant load (McQuitty and Feddes, 1982). While the ACGIH (1984) recommended a human TLV for CO_2 of 5,000 ppm, the SFBIU (1984) suggested a maximum concentration of 3000 ppm as an upper safe limit in farm buildings. Leonard et al. (1984), McQuitty et al. (1985) and Glennon (1985) all reported mean daily CO_2 concentrations in broiler, layer and replacement pullet operations to be less than 5,000 ppm.

2.3.3 Hydrogen Sulphide

Hydrogen sulphide is produced during the anaerobic degradation of the constituents of animal manures (Curtis, 1981). It is a colourless gas with the charcteristic odour of rotten eggs. Nordstrom and McQuitty (1976) classified H_2S as an irritant gas in sublethal concentrations. However, the dangers associated with exposures to high concentrations of H_2S have long been recognised, with acute H_2S poisoning being directly responsible for more human and livestock fatalities than any other gas (Curtis, 1981). Such fatalities have been associated almost exclusively with the agitation of stored slurries, resulting in the release of gas concentrations of up to 1000 ppm (McQuitty and Rhodes, 1982). However, Nordstrom and McQuitty (1976) state that no poultry fatalities have been reported which can be attributable to the toxic effects of high concentrations of H_2S.

Little data are available on the effects of low concentrations of H_2S on poultry production. Petrov (1966), as cited by Nordstrom and McQuitty (1976), found that exposure to levels of up to 100 ppm of H_2S, in combination with high levels of NH_3 and CO_2, decreased egg production by 9%.

The SFBIU (1984) gave a TLV of 0.5 ppm for a continuous time-limited exposure, with a short-term TLV of 5 ppm. The TLV suggested by the ACGIH (1984) was higher, at 10 ppm. In practice, concentrations of H_2S in close confinement poultry houses have not been found to exceed this level. Glennon

(1985) observed maximum H_2S concentrations of 142 ppb in a caged replacement layer facility over the course of a five month-period. The maximum measured value coincided with removal of the stored droppings. McQuitty et al. (1985) reported a maximum ambient concentration of 30 ppb in a deep-pit type laying barn.

2.3.4 Other Gaesous Contaminants

Although NH_3, and, to a lesser extent, CO_2 and H_2S, are considered the main gaseous contaminants associated with poultry housing, many other gases are produced from the degradation of the organic and inorganic material in the litter. These include CH_4 and other short-chain hydrocarbons, organic acids, amines, amides, sulphides and disulphides (Nordstrom and McQuitty, 1976). Although CH_4 is produced directly by ruminants in the fermentation process as well as in the manure, non-ruminant methane production is not considered significant in terms of pollutant load.

As far as effects on air quality are concerned, most of the other byproducts of the manure decomposition process are associated with odour problems, considered to have "nuisance" effects rather than effects on the health of poultry or operators (Nordstom and McQuitty, 1976).

2.3.5 Dust

Particulate contaminants are another component of the pollutant load in close confinement poultry facilities.

Extrememly high concentrations of atmospheric dust are found in poultry houses in northern climates, particularly under minimum ventilation conditions (Wolfe et al., 1968). Because of its role as a transport system for micro-organisms, dust has long been considered a significant contaminant in relation to livestock and operator health (Dutkiewicz, 1978).

Curtis (1981) described dust as consisting of small solid particles that have become dispersed in the air. In livestock buildings, dust is produced by the disintegration of solid matter (Cermak and Ross, 1978), leading to particle sizes as small as 0.1 μm. The ability of particles to remain in suspension is dependent on their settling velocity - a function of particle shape and density. Honey and McQuitty (1976) defined an aerosol as "any two-phase system in which a finely divided solid or liquid is dispersed in a gas." Silverman et al. (1971), as cited by Honey and McQuitty (1976), listed those properties which control the physical and chemical behaviour of particles in an aerosol. They included size, size distribution, shape, specific gravity and surface characteristics. Curtis (1981) used the term aerodynamic size to refer to the diameter of a unit-density sphere having the same terminal settling velocity as the particle in question regardless of the above mentioned properties.

Cermak and Ross (1978) noted the lack of any standard dust classification system and divided dust into respirable

and non-respirable fractions. Size determines how far into the respiratory tract a particle may travel. In general, particles greater than 5 μm are not considered hazardous, as they are usually removed at various sites in the larger air passages (Honey amd McQuitty, 1976). Particles smaller than 5 μm are potentially the most hazardous because of their ability to penetrate as far as the bronchioles and alveoli and, therefore, are classified as the respirable fraction. Anderson et al. (1966) observed that up to 55% of poultry house dust particles had diameters less than 10 μm when the birds were least active. Leonard et al. (1984), however, in an investigation of dust concentrations in commercial broiler housing, reported that the mean maximum daily respirable dust concentration was five times higher than the corresponding maximum value for the non-respirable fraction, indicating the relatively higher levels of potentially dangerous material.

The penetrative ability of dust particles is an important property as far as respiratory diseases are concerned, either as a direct result of irritation of respiratory tissue by the dust particles themselves or by the sensitizing action of micro-organisms in the dust (Dutkiewicz, 1978). According to Wolfe et al. (1968), large counts of viable micro-organisms have been obtained from poultry house dust. Indeed, it is the ability of dust to act as a pathogen disseminator which makes it almost as important as direct contact in the spread of disease in

close confinement housing (Curtis, 1981). Dutkiewicz (1978) concluded that high exposure to agricultural dust, especially dust from poultry facilities, created a hazard to agricultural workers because of the high levels of dust-borne bacteria associated with such dust. Curtis (1981) noted the importance of poultry house dust in the transmission of Marek's disease. Prince et al. (1971), as cited by Honey and McQuitty (1976), reported that the number of cases of Marek's disease and their severity was directly related to the length of exposure to infectious dust-laden air. Wolfe et al. (1968) found that the incidence of airsacculitis among turkeys at slaughter was significantly affected by ambient dust concentrations.

As well as those consequences associated with poultry and operator health, high levels of dust also have been blamed for the impaired operation and control of electrical and mechanical equipment (Wolfe et al., 1968). In addition, the importance of dust in poultry house odour problems has also been noted. Cermak and Ross (1978) stated that dust particles with aerodynamic diameters of between 5 and 20 μm are primarily responsible for the transportation of obnoxious odours. As large quantities of dust are expelled by poultry house ventilation systems, dust produced within these houses makes a significant contribution to odour problems from poultry houses (Burnett, 1969).

According to Koon et al. (1963), dust from caged layers was shown to consist of two types of particulate matter. The

majority of the particles were flat, flaky and cellular in structure, ranging in diameter from 1 to 450 µm and identified as skin debris and feed particles. The other particles were long and cylindrical, with an average diameter of 4 µm and were identified as broken feather barbules. Curtis (1981) also indicated poultry litter and soil particles as sources of dust production, while McQuitty (1985) mentioned dust from bedding and building materials as other possible sources.

Grub et al. (1965) determined that dust production for caged layers and broilers on litter was a function of temperature, relative humidity, bird activity and litter age. Birds tended to produce more dust at lower temperatures due to increased activity levels. Dust production also increased with decreasing relative humidities, probably associated with increased moisture in the litter. Honey and McQuitty (1976) observed no difference in dust concentrations produced at lower humidities but noted a significant increase in the number of settled particles. Curtis (1981) stated that the rate of dust generation in poultry houses also depended on bird type, breed and age, as well as on housing system. Younger birds can be expected to produce more dust during shedding of their down feathers while moulting in older birds has the same effect. Koon et al. (1963) reported that floor-raised broilers produced 50% more dust than broilers raised on wire under similar thermal conditions.

While Cermak and Ross (1978) noted the lack of TLV's in relation to concentration and duration of exposure to dust, Honey and McQuitty (1976) related the difficulty in comparing available data because of the difference in solids-loading units, the lack of standard measurement techniques and the different sampling devices used. In this respect, O'Blenis et al. (1984), as cited by McQuitty (1985), suggested an upper limit for dust of 4 mg/m^3, while the ACGIH (1984) recommended a TLV of 420 particles/ml for respirable dust.

Several authors reported dust concentrations in terms of respirable and non-respirable fractions. Leonard et al. (1984), in a study on commercial broiler facilities, reported a maximum respirable dust concentrations of 6788 particles/L, while the maximum concentration of particles greater than 5 μm was 1300 particles/L. McQuitty et al. (1985), using the same sampling device and measurement techniques, reported that mean daily respirable concentrations for three caged layer facilities ranged from 8300 to 12700 particles/L and 4100 to 4400 particles/L, for the light and dark periods, respectively.

Having accepted the significance of dust in relation to operator and poultry health, research has been initiated to determine methods to control the levels of dust within poultry facilities. The most obvious means of dust reduction is by increasing the ventilation rate, although if the ventilation rate is too high, this may have the effect of

increasing the amount of dust in suspension, by disturbing settled dust. Deaton and Reece (1980) suggested the maintenance of litter moisture contents between 25 and 30% as a compromise between dust generation and NH_3 production. Filtration techniques also have been applied as a means of reducing dust concentrations and odour problems in livestock buildings. Licht and Miner (1979) described a packed bed, wet gas scrubber capable of removing 90% of the non-respirable dust fraction from a swine unit, with a corresponding reduction in odour intensity. Sprinkler systems have been utilized by turkey growers to prevent dust generation but this has the disadvantage of increasing litter moisture content, causing increased NH_3 production.

2.4 Environmental Control

According to Curtis (1981), the purpose of close confinement livestock housing is to modify the macroenvironment, so as to result in a microenvironment conducive to unimpaired animal health, production and performance. Hellickson et al. (1983) stated that the ability to maintain the desired environmental conditions within confinement housing depends on the design and operation of the ventilation system. Optimum environmental conditions depend on the removal of the products of animal metabolism and their replacment with fresh air, while at the same time maintaining the required thermal conditions. With this object in mind, Curtis (1981) recommended a threshold

ventilation rate of 750 times the respiratory minute volume of the livestock housed in the structure. The provision of positive air movement and uniform conditions across the entire floor area is especially important in poultry housing (Randall, 1979). Hellickson et al (1983) stated other objectives of the ventilation system to include the prevention of rapid changes and wide fluctuations in house temperatures and to prevent draughts at animal level. The design of ventilation systems requires the consideration of such factors as the type, age and number of animals being housed, the management practices associated with the system of housing, the construction and location of the house and expected weather conditions.

2.4.1 House Energy Balance

Assuming steady-state conditions, the design of environmental control systems can be based on the Conservation of Energy Principle (Hinkle and Stombaugh, 1983), with the heat gains to the environment equalling the heat losses. The non-climatic dependent components of the heat gains include the animals' sensible heat production and the heat produced by lights, feeders, fan motors etc. Heat is brought in through the ventilation system when outside temperatures exceed those of the animal environment. In winter conditions the situation is reversed, with heat being lost to the outside. Supplemental heating also may have to be added in order to maintain thermoneutral conditions. The

major heat losses from the environment consist of the conductive heat loss through the building fabric, the heat used in the evaporation of water from the litter and waterers, and the above mentioned ventilation heat losses under cold external conditions. Ventilation heat losses are the most significant as far as energy losses from the house are concerned. Feddes et al. (1984a) reported, for example, that ventilation heat losses accounted for as much as 93% of the total heat loss from commercial broiler housing under cold temperature conditions.

In the design of confinement housing ventilation rates, external design temperatures are based on statistically-determined weather data. The ventilation rate required to maintain the desired environmental conditions is calculated by assuming values for animal sensible heat and moisture production. Under cold weather conditions, the amount of supplemental heating required can be determined by assuming a value for the ventilation rate.

Charles and Payne (1966a) suggested the inclusion of an additional factor in the house energy balance to account for the removal of high levels of air contaminants. However, ventilation rates based on the control of air contaminant levels are difficult to determine without accurate knowledge of the production rates of such contaminants (Clark and McQuitty, 1985).

The assumption of steady-state conditions in the design of livestock housing ventilation rates is based on the

assumption of complete mixing or, in other words, that air entering through the inlet is assumed to be "instantaneously and uniformly dispersed throughout the airspace" (Barber and Ogilvie, 1984). The same authors, in a scale-model study of a slot-ventilated airspace, demonstrated the occurrence of incomplete mixing but could not account for the under-ventilation and over-ventilation of certain areas solely by the theories of short-circuiting and by the existence of stagnant zones within the airspace. They concluded that effective ventilation rates varied from 80 to 110% of the calculated value and that rates designed on the basis of complete mixing could be in error by the same amount.

2.4.2 Theory of Ventilation

Ventilation systems for livestock housing employ either natural or mechanical means to introduce air flow into the animal environment. Natural ventilation relies on thermal buoyancy forces and wind to create the desired effects. Such systems are inherently variable in nature and are more suited to temperate climates or to livestock operations where temperature control is not critical.

Mechanical ventilation utilizes fans and inlets, along with thermally-activated controls, to cause air flow within the structure. Evaporative coolers, filtration devices and recirculation mechanisms also can be included for special purposes. Negative pressure or exhaust systems are by far

the most commonly used for poultry house ventilation applications, with the principle of operation of such systems being that air is introduced into the structure due to the pressure difference across the inlet openings, induced by the operation of the exhaust fans.

2.4.2.1 Air-Flow Patterns

The major factors that determine the performance characteristics of any ventilation system are the quantity and distribution of the incoming air. The type of air-flow pattern which is set up is influenced by several factors, the most important of which are the velocity of the incoming air, the design and location of the inlets and the positioning of obstructions within the house.

Any ventilating air jet entering a structure is subjected to strong localised thermal and inertial forces. Such forces are produced by convective heat currents set up by the sensible heat production of the animals and, in the case of jets entering close to walls and ceilings, the Coanda effect. As the jet projects further into the airspace, it expands and slows down due to the continuous exchange of momentum with ambient air. This exchange results in the entrainment of ambient air into the ventilation stream, inducing secondary air movement. These flow paths and their subsequent deflection by internal obstructions form the distinctive air-flow pattern for that particular design of ventilation system. The design of the internal

layout of a specific livestock house is based on the determination of such air-flow patterns to ensure uniform distribution of the ventilating air.

Another requisite of the ventilation system, especially in cold weather climates, is to prevent the cold ventilating air from dropping to stock level on entry. Temperature differences between the jet and the entrained air cause buoyancy forces to be created, causing a free jet to fall if colder than the ambient air. Randall (1979), Curtis (1981) and Winchell (1982) recommended inlet velocities of 5 m/s to ensure adequate penetration and the creation of turbulence for the entrainment of ambient air. High inlet velocities are also necessary to negate possible wind-pressure effects.

Randall (1975) found that the design and location of the inlet greatly affected air distribution, while outlet design had little effect. In any negative pressure ventilation system the air flow through the fans equals the air flow through the inlets. Because the inlet velocity is a function of static pressure, which in turn is dependent on fan capacity, any change in the ventilation rate will cause a corresponding change in inlet velocity. Therefore, in order to maintain adequate velocities, inlet areas should be adjusted in line with the ventilation rate. This is particularly relevant when minimum ventilation rates are employed so that stable air-flow patterns are maintained and the build up of stagnant zones is minimised. Turnbull and Bird (1981) recommended a design static pressure

differential of 1.3 mm of H_2O to ensure an inlet velocity of 4 m/s.

The penetration distance of cold ventilation jets is an important characteristic under minimum ventilation conditions in cold winter climates. Walker (1977) noted that temperature differences of 18°C between ambient and ventilating air were not sufficient to overcome the Coanda effect. However, with extremely low outside temperatures, the buoyancy forces created would cause the incoming jet to drop to animal level upon entry, irrespective of inlet velocity. Because of the influence of buoyancy forces, especially at low ventilation rates, Randall and Battams (1979) investigated the possibility of using the Archimedes Number (Ar) rather than jet velocity as the criteria for the control of ventilating jets. They concluded that this dimensionless number, a ratio of buoyancy to momentum forces, could predict sucessfully jet trajectories and air flow patterns. Leonard and McQuitty (1985) used cold ventilation jets and varying inlet designs and orifice locations to determine values of Ar for use in the design and control of ventilation systems. They recommended a value of Ar of less than 50 for continuous slots adjacent to the ceiling. Barber et al. (1982) proposed a method of improving ventilation system performance by preheating the ventilating air, thereby decreasing the buoyancy forces acting on the jet and decreasing Ar.

As well as the presence of obstructions within the ventilated air space, other factors which influence the distribution of ventilating air include inlet location, infiltration, significant in negative pressure systems, and the use of slatted floors (Wilson et al., 1983). Circulation fans are often used in conjunction with low ventilation regimes to minimise temperature stratification.

2.4.2.2 Fans and Ventilation System Control

While the air inlets are primarily responsible for the distribution of ventilating air within the structure, the fans and the fan controls are responsible for regulating the volume of incoming air. However, both components of the ventilation system are connected intimately in that varying any characteristic of either component invariably affects the characteristics of the other.

With ambient dry-bulb temperature being the most commonly-used index of the condition of the environment, most regulation of ventilation systems is achieved through temperature control. Minimum ventilation requirements are provided by continuously operating single, dual or variable-speed fans. Larger flow rates are provided by additional fans which, ideally, are thermostatically controlled in increments, 1 to 2°C apart, to engage until thermostat set points are reached.

In order to maintain the required static-pressure differential and, hence, inlet velocities, ventilation

control systems incorporate a means of controlling inlet area in response to changes in the ventilation rate, with most confinement housing systems relying on operator judgement to manually adjust inlet areas. Although vital in minimising energy losses through the ventilation system, integration of the ventilation and supplemental heating control systems by means of an interlock relay is seldom carried out in practice.

2.4.3 Heating System

In order to maintain thermoneutral temperature conditions in cold weather climates, close confinement poultry houses usually require the addition of some form of supplemental heat. Depending on the type of operation, the requirements of the heating system can be for both space and localized heating. Gas-fired, hooded brooders are usually employed in growing operations, while the most commonly used system for the space heating of poultry houses utilizes a combination hot-water boiler and exposed black-iron pipe system (Winchell, 1982). The rate of heat transfer to the poultry environment across the total length of piping is proportional to the temperature difference between the average water temperature and the temperature of the environment, as well as the mass flow rate of water within the pipe.

3. Objectives

Although large-scale confinement housing systems have become the norm for most poultry operations, little or no data exist on the levels or production rates of the thermal and non-thermal parameters as they occur in such houses. Consequently, using the data acquisition system developed in the Department of Agricultural Engineering, University of Alberta, for the in-house monitoring of commercial livestock housing, three broiler breeder facilities were monitored with the following objectives:

1. To determine the total, sensible and latent heat production of confined broiler breeders in three typical commercial houses.
2. To determine the influence of management practices and manure storage systems on the thermal characteristics of broiler breeder facilities and on the air quality within them.
3. To quantify the rates of production of atmospheric contaminants such as NH_3, CO_2, H_2S, and dust and to establish base line data for these contaminants in broiler breeder facilities.
4. To evaluate the effectiveness of heating and ventilation systems in broiler breeder facilities, based on the findings of this study.

4. Experimental Facilities and Procedures

4.1 Facilities

This study was conducted during the period from September, 1984 to May, 1985. As the objectives of the study required the determination of heat and moisture production and air quality in broiler breeder barns under cold winter conditions, the selection of barns for monitoring was limited to those whose production cycles coincided with the desired weather conditions. Consequently, three broiler breeder barns were selected for monitoring on this basis as well as on the basis of feasibility of instrumenting the barns and co-operation of the producer. Although accessibility was a major factor in barn selection, the shortage of barns fulfilling the other requirements neccessitated considerable travelling and, hence, limited the length and frequency of data collection cycles.

The first barn, hereafter designated Barn BA, was situated east of Edmonton near Ardrossen, Alberta. The second barn, Barn BB, was situated near Edberg, while the third, Barn BC, was close to the town of New Norway, Alberta. Barns BB and BC were operated by the same producer. The broiler breeders were grown separately from older birds and moved in each case to the laying house at about 19 weeks of age. The production cycle lasted from approximately 22 to 60 weeks of age, with peak production occurring between 31 and 33 weeks of age. Barns BA and BB were monitored for a

total of eight days, while Barn BC was monitored for six days. This corresponded to one 24-hour data collection period approximately every four weeks of the production cycle. The production cycles in Barns BA and BB coincided with the cooler weather experienced in Alberta in fall-winter-spring, while that for Barn BC extended into warm, late-spring weather.

All three barns employed a 1/3 litter, 2/3 slatted floor system, with the raised slatted area being situated on either side of a central passage-way/scratch area. The poultry droppings were allowed to accumulate throughout the production cycle. A tractor and a front-end loader were used to remove the droppings when the barns were emptied of birds.

Barns BA and BB were single-storey structures measuring 10 by 38 m and 12 by 52 m, respectively. Each barn had a ceiling height of approximately 2.7 m. Barn BC was a deep-pit type poultry unit, with the lower half of the structure for manure storage situated below ground level. This barn measured 9 by 68 m, with a ceiling height of approximately 2.7 m. The concrete floor of the deep-pit was 2.2 m below slat level. All three barns were of windowless design and similar wood-frame construction, with interior walls and ceilings sheathed with wood and insulated with glass fibre batts. Exterior walls utilised corrugated metal cladding, in all cases. Figures 4.1 and 4.2 show schematics of Barns BA and BC, respectively, with the layout and

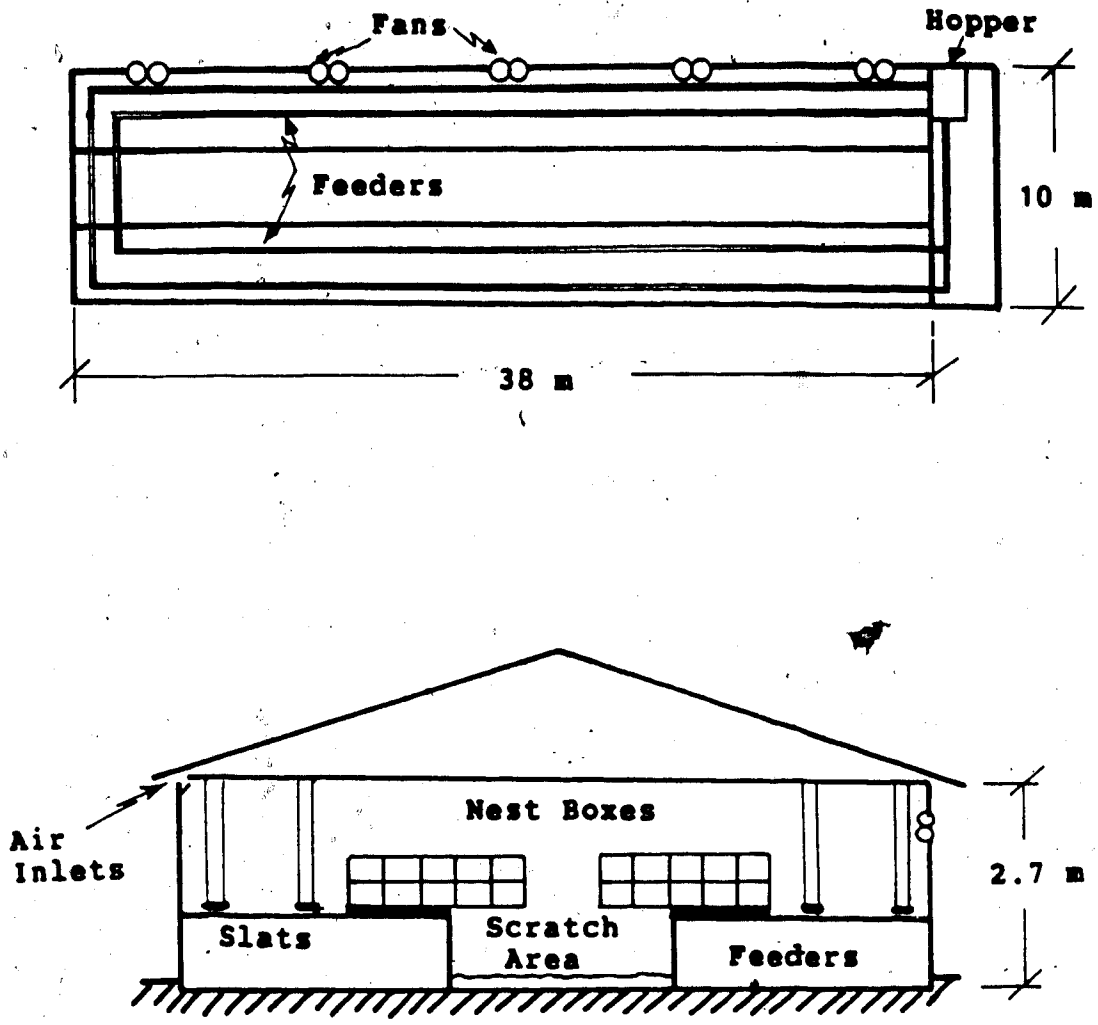
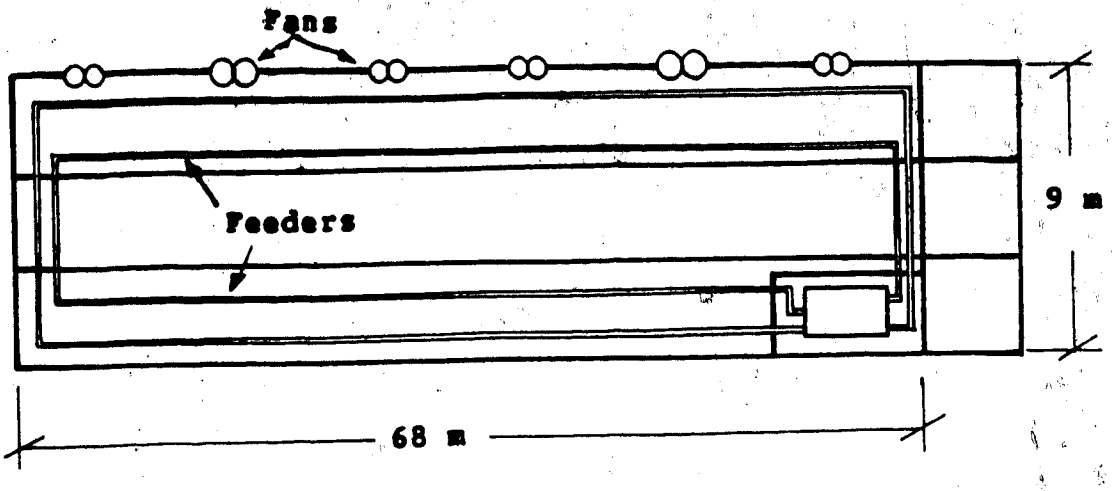


Figure 4.1 Schematic of Barns BA and BB.



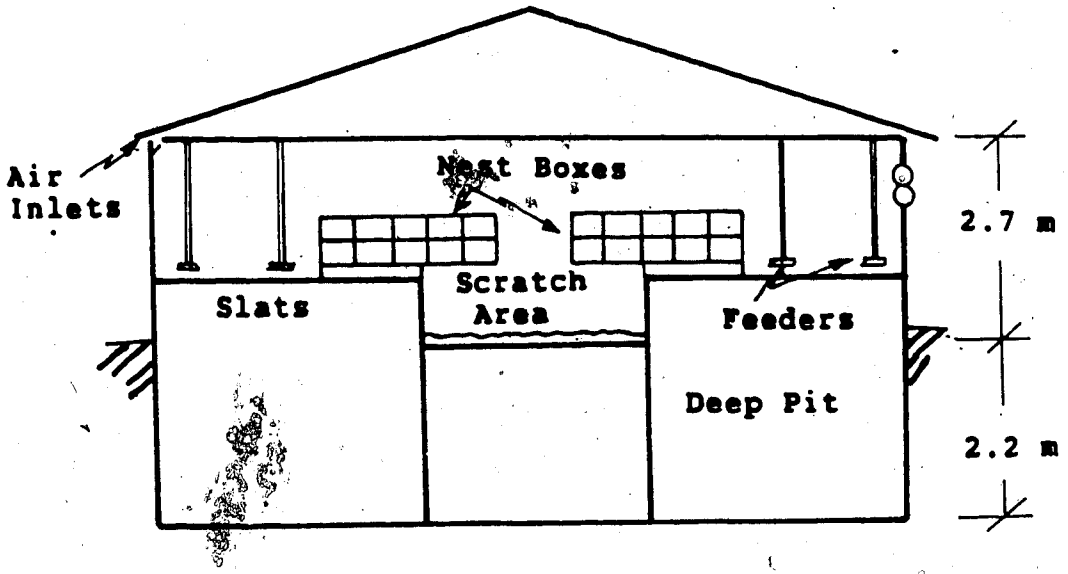


Figure 4.2 Schematic of Barn BC.

construction of Barn BB being similar in all respects to that of Barn BA.

The total building thermal resistance was calculated by summing the thermal resistances of the seperate building components, namely, walls, ceilings, floors, floor perimeters, and foundation walls. These thermal resistances were, in turn, calculated using the individual material thermal resistances as well as the thermal resistance of the surface air film and were found to be similar in all three barns due to the similar barn constructions. The total thermal resistances were estimated to be 3.80, 3.95 and 1.75 $(m^2.°C)/W$, for the ceilings, walls and floors, respectively. Perimeter insulation was not used in any of the three barns studied.

All three barns had similar feeding and watering systems. Feeding was carried out automatically, either twice or three times daily, depending on the barn, using time-activated, chain-and-trough type feeders. Feeding rates in Barn BA were regulated by means of a weigh-hopper, while the producer in Barns BB and BC used feeder operation times calibrated to provide the appropriate feeding rates in these barns. Standard dome-type waterers, situated over the centre of each slatted area, were provided at a rate of approximately one waterer for every 100 birds to give a constant supply of fresh water.

The lighting requirements were provided by rows of incandescent lights, time-clock controlled and spaced

equally apart, with the number of lights used varying from barn to barn. The lighting programs in all three barns provided 14 hours of light during the production period, as recommended by the relevant management guides, with normal working hours occurring within the light period.

Each house provided two-tier individual nest boxes, approximately one for every four female birds, positioned perpendicular to the slats and extending over the litter space to facilitate egg collection. In all three barns, egg collection was carried out by hand, three times daily, with the operators checking the nest boxes and removing the gathered eggs on suspended trolleys.

Poultry breeds were different for all three barns but were all of the heavy broiler breeder variety. Table 4.1 details the relevant management data for each of the barns, including numbers of birds housed and stocking densities.

Ventilation in the barns was provided by cross-flow, negative pressure systems. Barns BA and BB had variable width, continuous-slot inlets for the introduction of fresh air, while Barn BC employed 15 intermittent slot inlets, 1.0 m in length and spaced approximately 3.0 m apart, for the same purpose. Insulated hinged baffles were employed by all three systems to direct the flow of air along the ceiling, with inlets located beneath the eaves on the opposite side of the building from the fans. Inlet area control relied on operator judgement to manually adjust inlet openings.

TABLE 4.1 MANAGEMENT DATA FOR THE THREE BROILER BREEDER BARNS DURING THE STUDY PERIOD.

Barn	BA	BB	BC
Number of birds			
- at start:	2600	4831	4908
- at end:	2338	4442	4766
Mortality, %	10	8	3
Bird age, weeks			
- at start:	31	27	33
- at end:	57	55	49
Floor area, m^2/bird	0.155	0.134	0.118
Egg collection	manual	manual	manual
- time, hrs	7:00	7:00	7:00
(approximate)	11:00	11:00	11:00
	15:00	15:00	15:00
Feeder operation		chain-in-trough	
- time, hrs	5:00	8:00	6:30
(15 minutes)	6:15	8:30	7:15
			8:00
Time lights on, hrs	4:00	4:30	4:00
Time lights off, hrs	18:00	18:30	18:00

Barn BA had five, 56-cm diameter, fans, equally spaced on the leeward side of the building. Of the four fans in operation during the course of the data collection, two were of the two-speed type and two were variable-speed. The centres of the fans were located 1.35 m above slat level. All four fans had separate thermostatic controllers.

In Barn BB, four, 46-cm diameter, variable-speed and two, 61-cm diameter, constant-speed fans were mounted in the leeward side of the barn. The constant-speed fans were not used throughout the monitoring period and the fan openings were sealed to prevent the influx of air. The fan centres were located 1.35 m above slat level.

Barn BC had six fans, four, 56-cm diameter, constant-speed fans and two, 61-cm diameter, variable-speed fans, located in the windward side of the building. Initially, only the variable-speed fans were used but, as outside temperatures increased towards the end of the monitoring period, the constant-speed fans came into operation. All six fans were controlled individually using separate thermostats.

In order to achieve the required air-flow rates, the ventilation fans utilised in the three barns were all of the axial-flow, propeller variety. Shrouds were provided for all fans to reduce the effects of wind on fan performances. In addition to the ventilation fans, all three barns utilised two ceiling-mounted fans to aid in air-mixing. These fans were located on the fan side of the buildings, approximately

one quarter of a barn's length from either end.

Hot-water heating was the source of supplemental space heating in all three barns, with the natural-gas-fueled boiler in Barn BA and the solid-fuel boilers in Barns BB and BC being housed outside the confines of the barns. Hot water was circulated from the boiler room through loops of horizontally-mounted, black-iron piping. In addition to variations in pipe diameters and spacings, all three barns utilised different pipe lengths and pipe configurations to ensure the uniform distribution of heat across the barns. Barn BA utilised five loops of nominal 46-mm piping, with a total pipe length of 350 m, three loops being mounted on the air inlet side of the barn and the remaining two loops mounted on the fan side of the barn. Barns BB and BC both used nominal 51-mm piping, with Barn BB utilising wall- and ceiling-mounted pipe arrangements of 400 m total length and located on the inlet side of the barn. Barn BC utilised 500 m of wall-mounted piping in two loops, located on both sides of the building, in addition to a short length of vertical piping at the south end of the barn. The flow of hot water was controlled thermostatically in each barn, with Barn BA utilising a proportional bypass controller, and Barns BB and BC using discrete on/off control of the circulating pump.

4.2 Experimental Procedures and Equipment

In order to conduct a continuous evaluation of both the thermal and the air quality conditions of the poultry

environment, a data acquisition system, developed by Feddes and McQuitty (1977, 1981) and housed in a mobile laboratory, was employed to measure and record the relevant environmental parameters. Parameters were either measured *in situ* or air samples were drawn from the required location within the poultry house and the analysis conducted in the laboratory itself. All the wiring and sample lines were installed in each barn before the commencement of commercial operations and were fed through either an inlet opening or a fan opening not normally in use. While the internal wiring and sensing elements arrangements were permanent in nature, their connection with the instrumentation in the mobile laboratory was designed to facilitate easy hook-up and disconnection with the minimum of disruption to the poultry housed within the building. In this regard, all sensors were connected to two multi-conductor extension cables, with the laboratory side having permanent connections to the appropriate instrumentation. The plastic tubing used for air sampling at the various locations were fed through a 100-mm diameter, metal conduit, protecting them from exposure to harsh external temperatures. The temperature in the conduit was maintained at room temperature using a thermostatically-controlled electric heating cable and glass fibre insulation taped to the outside surface. In this way, air samples taken from the bird environment maintained their thermal properties as they travelled from the sampling locations to the analysers situated in the trailer.

4.2.1 Energy Data Acquisition

Because of the importance of the ventilation system in relation to heat losses from the poultry environment, accurate measurement of the ventilation rates was considered critical in the determination of accurate house heat and moisture balances. The procedure used to determine air flow rates, as prescribed by Jorgensen (1983), necessitated the use of insulated discharge ducts, incorporating air straighteners, downstream from each exhaust fan. Air-flow measurements were taken at the locations in the duct, as prescribed by Jorgensen (1983), and used to determine the overall air-flow rate from each of the exhaust fans. Ducts were constructed according to fan sizes, with duct areas of 0.31 and 0.21 m^2 corresponding to the 56 and 46-cm diameter fans in Barns BA and BB, respectively. The duct areas for the small fans in Barn BC were 0.31 m^2, while those for the large ducts were 1.1 m^2. All ducts were less than the length of 11.5 times the duct diameter recommended by Jorgensen (1983), with all the small ducts being 3.66 m in length. As the ducts were fabricated away from the poultry barns, this was considered the maximum feasible duct length for transportation reasons. The large ducts were constructed on site but duct length was limited for reasons of practicality. In Barns BB and BC, the plywood shrouds were removed and the ducts were permanently placed over the fan openings except in the case of the constant-speed fans in

Barn BC. For these fans, as well as for the fans in Barn BA, transition pieces were constructed to facilitate the easy coupling of the ducts to the shrouds as the duct assemblies had to be dismantled after each data collection run.

A hot-wire anemometer (Sierra Instruments, Redlands, Ca.) or a thermistor anemometer (Model TA300, Airflow Developments, Buckinghamshire, England) was used to establish velocity profiles by measuring a traverse of 25 locations close to the end of each duct. Fan air-flow rates were calculated as the product of the mean duct air velocities and duct areas, with the overall ventilation rate calculated as the sum of the flow rates from each fan. Because of the effect of strong winds on the accuracy of the calibration measurements, extra air-flow calibrations were carried out when windy conditions were in effect. Both instruments were calibrated periodically in a small scale air-velocity calibrator located in the Department of Mechanical Engineering, University of Alberta. The design of the calibration device ensured the delivery of an air jet of known velocity, with jet velocity a function of pressure differential between the calibration chamber and the room. The required velocity range was achieved by selecting the appropriate orifice size. The instrument to be calibrated was subjected to varying jet velocities, with the pressure drop accross the orifice plate being measured by a Validyne pressure transducer (Sierra Instruments, Ca.). The anemometer calibration relationships are given in Appendix

A.

In order to match fan performances with air-flow rates, fan speeds were monitored using magnetically-activated electronic switches mounted on the fan housing. The switches were activated using the Hall Effect principle, by magnets mounted on the rotating fan shafts, causing pulses to be emitted. These pulses were integrated using a frequency-to-voltage converter, with the output voltage being proportional to fan speed. Manual air-flow measurements were calibrated with fan speeds over the entire fan performance range to establish a relationship between the two parameters.

The greatest influence on fan capacities in exhaust ventilation systems is the static pressure differential between the inside and the outside of the barn. Changes in this static pressure differential due to adjustments in inlet area, variations in wind speed and direction and changes in operating fan configurations due to variations in outside conditions, were expected to cause variations in fan capacities over short periods of time. This affect was considered negligible, however, when determining air-flow rates from the large constant-speed fans in Barn BC, with a constant fan capacity, based on the mean calculated air-flow from the manual air-velocity measurements, being assumed over the course of the data collection period. For this reason, as many air-flow calibrations were carried out during a data collection period as was practical in order to

obtain a more accurate "average" of the varying air-flow rates due to changing fan capacities. However, the number of such calibrations actually conducted was limited due to restrictions on time and labour. The operating status of the constant-speed fans was determined by placing a thermistor (Model, UUB 31J1, Fenwal Electronics, Framingham, Mass.) at the fan end of the ducts. The status was checked every four minutes, with a measured duct temperature of within 5°C of ambient house temperature designating a fan in operation.

The static pressure differential between inside and outside the barn was measured every four minutes using a low-range differential pressure transducer (Validyne, Model DP45, Sierra Instruments, Ca.), together with a carrier demodulator (CD15 Universal Transducer Indicator, Validyne Engineering Corp.) to convert the output to a voltage proportional to the differential pressure. This pressure transducer was calibrated before each data collection run using an inclined manometer, with the output from the demodulator being a linear relationship of 0.39 V/mm H_2O.

The heat and moisture contents of the air entering and leaving each barn were calculated from the dewpoints and dry-bulb temperatures of the outside and exhaust air, respectively. Incoming air temperatures were measured at the air inlets to ensure that any prewarming of the air was accounted for, while thermistors located at each fan indicated the dry-bulb temperature of the exhausted air. Dewpoints were measured twice hourly at each fan location as

well as outside by drawing air samples via plastic tubing to an optical-condensation dewpoint hygrometer (Model 880, Cambridge Systems, Waterdown, Mass.), the principle of operation being that the commencement of condensation of water vapour out of the air sample was detected by an optical [illegible] mechanism. The rated accuracy of this instrument [illegible] °C. However, when outside temperatures were below approximately -8°C, the dewpoint hygrometer failed to measure outside dewpoints accurately and, in such cases, dewpoint data were estimated using data from the weather station at the Edmonton International Airport. The resultant error from such a procedure was not considered significant due to the relatively small water vapour concentration of air at such low temperatures.

Dewpoints and dry-bulb temperatures also were recorded at various locations within each barn to provide data representitive of the poultry environment. Each barn was divided into six sections, thirds by length and halves by width, with dry-bulb temperatures being measured at the centre of each section, approximately 1.5 m from the ceiling. In addition, a high and low level thermistor was placed in the two centre sections to provide an indication of any temperature stratification that might occur. High level thermistors were located about 0.5 m below the ceiling, while the low level thermistors were located approximately 0.4 m above the floor, corresponding to just above bird level in the scratch area. An additional

thermistor was placed beneath slat level in Barn BC to provide an indication of pit temperature. Ambient dry-bulb temperatures as well as those measured at the inlet and outside locations were monitored every 20 minutes, while dry-bulb temperatures recorded at the exhaust fans were monitored every four minutes. Thermistors were factory calibrated, with the regression equation relating thermistor electrical resistance to temperature given in Appendix A. The manufacturers claimed that these curve-matched thermistors were accurate to within 0.2°C over a temperature range of 0 to [illegible]°C. Thermistors were multiplexed by a data logger into a constant-current circuit to give a voltage output, ranging from appromixately 0 to 10 volts, as a function of thermistor electrical resistance. Appendix A details the resistance relationship for the [illegible]t-current circuit.

Ambient dewpoint measurements were made in the centre of each barn as well as in the centre of the corner sections opposite the fans at either end of the barn. Measurements were taken twice hourly at the centre location and once hourly at the end sections. Dry-bulb temperatures also were measured at the centre of each barn for use in conjunction with dewpoints to determine ambient relative humidities. The maintenance of conduit temperatures close to barn temperatures ensured that no condensation occurred in the air sampling lines en route to the laboratory. In addition, checks were made on ambient dewpoints using a hand-held

digital psychrometer (90023-C, Atkins Technical Inc., Gainsville, Florida), measuring wet-bulb depression with a rated accuracy of 0.1°C and a temperature and humidity sensor (MIK-2000, Novasina AG, Zurich, Switzerland), specified as being accurate to 0.7°C and two percent relative humidity over the temperature range encountered in this study. Wet-bulb temperatures were recorded manually using a sling psychrometer as a further check. All instruments showed good agreement with each other, with not more than a difference of five percent in relative humidities measured by the various instruments close to air sampling points.

Two methods were used to measure the supplemental heat input into each barn from the hot-water heating systems. Water-flow rate measurements were made in Barn BB and BC using an ultrasonic Doppler flow-meter (Polysonics Flowmeter, Houston, Tx.), utilising the Doppler Principle as its basis of operation. This instrument was calibrated against a magnetohydrodynamic flow-meter (Type 1803 Sans-CA, Foxborough CO. Ltd., Le Salle, Quebec) in the Civil Engineering Hydraulics Laboratory, University of Alberta. The regression equation relating the Doppler reading to flow is given in Appendix A. Barn BA utilised a thermistor-controlled proportional bypass valve to regulate the flow of hot water into the barn. A bridge-rectifying circuit was built to convert the AC output from the thermistor to a DC voltage which was calibrated for

water-flow rate. The equation relating water-flow rate and voltage is given in Appendix A. Water temperature was estimated by placing two thermally-insulated thermistors, one on the inlet and one on the outlet pipe to the boiler. The supplemental heat was calculated as a function of the temperature differential and hot-water flow rate. However, variable flow measurements could not be made because a continouus voltage output from the Doppler flowmeter could not be achieved. Because variable flow situations were in effect during certain data collection runs in Barns BB and BC, the second method of supplemental heat determination was based on the heat transferred per unit length of pipe, as a function of the difference between average pipe temperature and ambient temperature. Average pipe temperature was calculated as the mean of the inlet and outlet pipe temperature.

The conductive heat losses from each of the breeder barns were measured using heat-flux plates described by DeShazer et al. (1982). These plates were attached to the inside surfaces where significant heat transfer was assumed to occur. Walls that were heated on both sides as well as floors subjected to litter build up, were not instrumented. The locations of the heat-flux plates were chosen on the basis of representative surface temperatures as measured by an infrared pyrometer (Omega Engineering, Stamford, Conn.) and inside wall and ceiling surfaces were used to exclude any solar radiation heat gains to the plate surfaces.

The measured conductive heat losses were checked against corresponding values calculated using temperature data and the known thermal characteristics of the building components. An additional check was carried out using a commercially-available heat flow-meter (Concept Engineering, Old Saybrook, Conn.), having a claimed accuracy of one percent over the temperature range of -30 to 110.0°C, and which also was used as a standard in the calibration of the individual heat-flux plates. The calibration procedure involved the comparison of temperature differentials across the standard and a heat-flux plate, both placed on a heated copper plate. Equations were developed to relate the temperature differential across each heat-flux plate to heat flow.

4.2.2 Air Quality Measurements

Monitoring of the concentrations of the atmospheric contaminants such as NH_3, CO_2 and H_2S was effected at the same locations and at the same time as the dewpoints. Contaminant concentrations were measured at the exhaust fans to determine their production rates, while ambient concentrations were measured just above bird height. Background data for the calculation of NH_3 and CO_2 production rates were provided by measuring outside concentrations of these contaminants.

The gas sample lines were connected to an automatic-sequencing sampler (Feddes and McQuitty, 1977) which drew an air sample from a new location every four minutes and distributed it to the relevant instruments for dewpoint and gas concentration analysis. The sampler had a built-in vacuum pump and utilised solenoid-activated valves on each sample line to control sample sequencing.

The NH_3 and CO_2 conentrations were measured using non-disp[redacted] infrared gas analysers (Model 315A, Beckman, Fullerton, Ca.), with the zeros and spans being set with certified calibration gases (Matheson Gas Products, Edmonton, Canada) at the start of, as well as during, each data collection run. Accuracies of within two percent of the readings were claimed by the manufacturers for these instruments. Periodic checks were carried out on ambient NH_3 and CO_2 concentrations using hand-held Draeger tubes. Concentrations of H_2S were measured using a sulphur analyser (Melroy Laboratories, Springfield, Virginia) which utilised a flame-photometric, detection process. The voltage outputs from these analysers were calibrated by the manufacturer and the equations relating gas concentrations to voltages are given in Appendix A.

Atmospheric dust concentrations were measured at one location in the centre of each barn. A separate sample line and vacuum pump drew sample air through an iso-kinetic probe to maintain turbulent flow and prevent particle aggregation, and, from thence, to a photometric particle counter (Climet

Instrumentation, Redlands, Ca.). Sampling was carried out for 15 minutes of each hour of each run, with particle counts of five different size ranges being conducted every three minutes. The five size ranges consisted of particles greater than 0.5, 1.0, 2.0, 5.0, and 10 μm, with particle concentrations being expressed in counts per one hundreth of a cubic foot of air sampled. These particle counts were further allocated to two overall groups, namely, particles less than 5 μm and particles greater than 5 μm.

Table 4.2 gives a summary of the primary sensors and their locations in the three breeder barns monitored. In addition to those parameters already mentioned, comprehensive field notes were made during each monitoring run, recording observations or making periodic measurements of any variables that might affect indirectly the barn heat and moisture parameters.

4.3 Data Recording and Processing

The heart of the data collection system was a microprocessor-controlled data logger (Feddes and McQuitty, 1981), which received and processed [illegible] from the various sensors. The data logger (Technical Services, University of Alberta) had a 144-input channel capability, 32 of which were reserved for general analog inputs and the remainder for thermistor inputs. Scanning of the input signals was controlled by a manually-adjusted time clock, with the recording of rapidly-changing signals, such as

TABLE 4.2 SUMMARY OF THE PRIMARY SENSORS, THEIR LOCATIONS AND SCANNING RATES, FOR THE THREE BARNS MONITORED.

Sensor type, sampling rate, and location	Number of locations Barn BA	Barn BB	Barn BC
Thermistors: 3 readings per hour:			
outside	1	1	1
inlet	3	3	3
high level	2	2	2
mid-height	6	6	6
low level	2	2	2
below slats	0	0	1
barn centre	1	1	1
Total:	15	15	16
Heat flux plates: 3 readings per hour:			
ceiling	1	1	1
walls	3	3	3
Total:	4	4	4
Thermistors: 15 readings per hour:			
exhaust	4	4	4
downstream from fan	4	4	2
hot water	2	2	2
Total:	10	10	8
Sequential sampling: 2 readings per hour: dewpoint, ammonia, carbon dioxide, hydrogen sulphide[1]			
exhaust	4	4	4
ambient	1	1	1
outside	1	1	1
Pressure differential: 4-minute readings:	1	1	1
Dust: sequential particle size counts: 1 reading per hour:	1	1	1
Fan rpm: 4-minute readings:	4	4	4

[1] Daily readings of hydrogen sulphide.

differential pressure, fan speeds and fan temperatures, being carried out every four minutes. A 20-minute monitoring rate was used for other signals with longer time constants. Table 4.2 details the scanning rates for the various sensors.

The environmental data collected over the 24-hour monitoring run were recorded on paper tape, a portable terminal or a chart recorder. The latter was used to graph the output of any two output channels from the data logger, while the portable terminal gave printouts of the outputs when desired. The output from the dust sampler was recorded on a separate paper tape.

The digitilized paper-tape data were read by a paper-tape reader at the Computing Services Centre, University of Alberta, and transformed into raw voltages. These raw voltages were further processed into the relevant engineering units on a mainframe system, utilising computer programs developed in the Department of Agricultural Engineering, University of Alberta. Appendix A lists the equations used in the Fortran program to convert the raw voltages to engineering units, while Appendix B provides an error analysis of the data measurement system. The error analysis was based on a worst-case scenario, with the real errors associated with the measurement of the various parameters being expected to be somewhat less than these calculated values. Backup copies of all data were stored on magnetic tape as duplication of data could not be

accomplished.

4.4 Energy Balance

A separate Fortran program was developed to perform the mathematical operations on the raw data to calculate the relevant heat and moisture balance parameters in terms of hourly and daily averages, and averages based on lighting period. Because of their unique wiring configurations, however, separate programs were developed for each of the barns. Standard psychrometric equations (ASHRAE, 1981) were used to calculate the enthalpies, specific volumes and specific humidities of the incoming and exhaust air for the three broiler breeder barns. Using the calculated ventilation rates, the gains in total heat and moisture to the incoming air were determined. Conductive heat losses and supplemental heat gains were measured directly, allowing poultry total heat production as well as the latent heat production in the breeder house to be determined. Net poultry sensible heat production was determined by subtracting the calculated latent heat component from total heat production, while the proportion of bird sensible heat converted in the evaporation of litter moisture was determined by a procedure described later (Section 5.2.4). Appendix C details those equations used in the above energy balance, while Appendix D gives an example of the output from the energy balance program. All production data derived from the energy balance were expressed on a per bird basis

to facilitate comparisons between barns with different bird densities.

The same program was used to calculate hourly and daily averages of air contaminant concentrations as well as combining ventilation rates with contaminant concentrations to give mean hourly and daily contaminant production rates.

5. Results and Discussion

5.1 Environmental Control

5.1.1 Temperature and Relative Humidity

Variations in the weather conditions encountered during the monitoring period influenced the environmental conditions within the barns. Mean recorded outside temperatures over the course of each production cycle were similar, -3.1°C, -2.2°C and 1.7°C for Barns BA, BB and BC, respectively, but significant variations occurred in mean daily outside temperatures, with the minimum of -23.5°C and the maximum of 14.5°C both occurring during monitoring of Barn BA.

Environmental control systems were required to respond to rapid fluctuations in outside temperature, the largest being a drop of 25°C occurring during monitoring of Barn BB over a 20-hour period. The response to such changes by the supplemental heating and ventilation systems was reflected in their ability to maintain relatively constant ambient temperatures, with ambient temperature representing the mean of all temperatures measured at various locations within the barns. The maximum diurnal fluctuations in mean ambient temperatures were 5.3, 11.0 and 6.1°C for Barns BA, BB and BC, respectively, with the uncharacteristically large value occurring in Barn BB due to the large drop in outside temperature noted above. With minimum ventilation rates in effect, the establishment of ambient temperatures in the

range 11 to 12°C would seem to indicate the failure of the supplemental heating system to cope with very low outside temperatures. However, with the above-mentioned exception, the range of observed ambient temperatures in all three barns indicate the satisfactory performance of the environmental control systems as far as temperature control was concerned. Table 5.1 details the overall mean ambient temperatures and their ranges for each of the barns.

In all cases barn relative humidities were well below the maximum of 80% recommended for breeder barns by Winchell (1982), with the maximum mean daily RH of 75.3% occurring in Barn BB. Table 5.1 gives the overall mean relative humidities for each of the barns over the course of the monitoring period. These values indicate the overestimation of winter ventilation rates, with possible subsequent energy losses if rates had been based soley on humidity control.

Temperature profiles were used as an indication of the degree of air mixing within each barn. The establishment of vertical temperature gradients was confirmed in all barns by the outputs of the high, low and medium level thermistors. Figure 5.1 illustrates the variation in temperatures at different heights during a 24-hour monitoring cycle in Barn BC. The hourly fluctuations in house temperatures were mainly due to the thermostatic control of the exhaust fans.

Mean temperature gradients of 1.8, 1.2 and 0.6°C were measured between the low and higher level sensor locations for Barns BA, BB and BC, respectively, with little

TABLE 5.1 SUMMARY OF OPERATIONAL PARAMETERS - OVERALL MEAN MEASURED VALUES

Parameter	Barn BA	Barn BB	Barn BC
Outside Temperature, °C	-3.1	-2.2	1.7
Range	-24/15	-17/4	0/4
Ambient Temperature, °C	17.5	18.9	18.8
Range	15/20	15/22	18/20
Exhaust Temperature, °C	18.1	18.0	18.2
Range	15/20	13/22	17/20
Ambient Relative Humidity, %	55	58	60
Range	50/70	51/75	52/71
Static Pressure Differential, mm H_2O	0.6	10.4	7.4
Range	0/1	4/14	6/10
Ventilation rate, L/(s.bird)	0.85	0.65	0.82
Range	0.5/1.8	0.5/0.9	0.7/1.0

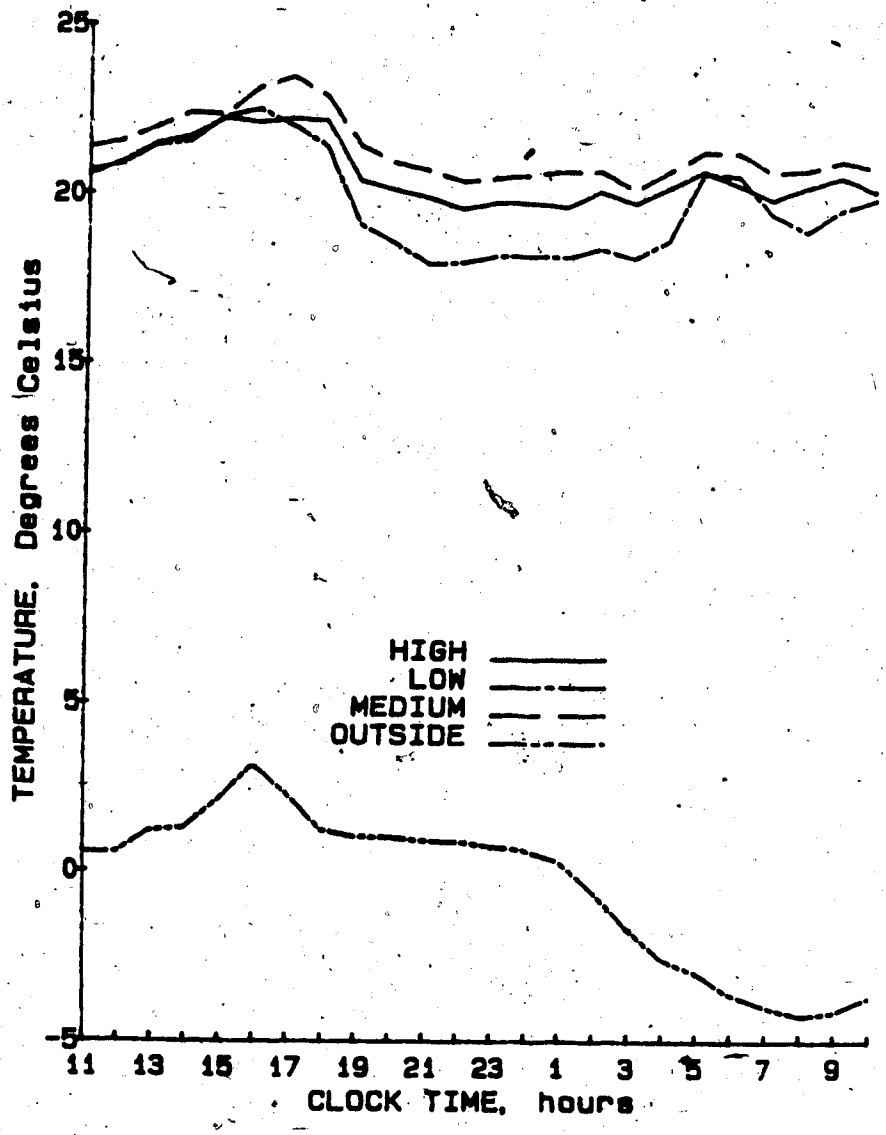


Figure 5.1 High, low, medium, and outside dry-bulb temperatures in Barn BC with 39-week old birds.

difference between the high and medium thermistors in all cases. As was to be expected, low level thermistors measured the lowest temperature, regardless of ventilation rate, due to their positioning in the scratch area just below the level of the slats. High level thermistors registered higher temperatures in Barn BA and initially in Barn BC, while Barn BB exhibited higher temperatures at the medium level. With the utilization of higher ventilation rates in Barn BC during the latter half of the production cycle, higher temperatures were recorded at mid-height, indicating a change in air distribution pattern resulting from the operation of the large fans. In general, variations among low, medium and high temperatures were small in each of the barns, suggesting that a high degree of air mixing was achieved in all three barns.

The thermistor beneath slat level in Barn BC gave an indication of the air temperature within the deep pit area. When an output was recorded, pit temperatures were at least 3°C cooler than ambient, with higher ventilation rates resulting in pit temperatures closer to ambient levels.

Exhaust temperatures were compared with the corresponding mean ambient temperatures and found to be warmer in Barn BA but colder in Barns BB and BC but temperature differences were not considered significant, being less than 1°C in most cases. With minimum ventilation rates in effect in Barn BA, large temperature variations occurred between the north and the south ends of the barn.

Minimum ventilation requirements were provided by a constant speed fan, located at one end of the barn, resulting in the probable underventilation of some areas. No such variations [illegible] in Barns BB and BC indicating a uniformity of [illegible]mental conditions in these barns.

Variations in [illegible] and outside temperatures were found to have occurred during the periods of light and darkness. The mean ambient temperature difference between light and dark periods was 1.0, 3.5 and 1.1°C for Barns BA, BB and BC, respectively, with higher temperatures being observed during the light hours.

5.1.2 Ventilation

Inlet air velocities depend primarily on the static pressure differentials between the inside and the outside of the barn. Measured static pressure differences were used, therefore, as an indication of the potential for mixing of the ventilating and the ambient air. Barns BB and BC had mean daily static pressures differences ranging from 4.2 to 13.7 mm of H_2O, respectively, with overall means (Table 5.1) of 10.4 and 7.4 mm of H_2O, respectively. These values exceeded the 1.3 mm of H_2O prescribed by Turnbull and Bird (1981). The mean static pressure difference in Barn BA was 0.63 mm of H_2O (Table 5.1), with little variation in the daily means about this figure. Noticeable infiltration through a large door at one end of the barn undoubtedly affected static pressure differences. These low pressure

differences, in combination with the location of the fan providing the minimum rate, ensured the underventilation of certain areas of the barn. However, even when all four fans were in operation, the ventilation system demonstrated an inability to achieve the recommended static pressure difference.

Table 5.1 shows the overall mean of the daily ventilation rates employed in the barns during the course of the monitoring period. These figures tend to be misleading in that Barn BA is shown to have the highest overall mean ventilation rate. This is due mainly to a very high daily mean ventilation rate of 1.78 L/(s.bird) measured during unusually warm weather at the start of the production cycle. Other means for Barn BA were much lower, ranging from 0.45 to 0.79 L/(s.bird). In general, Barn BC tended to employ higher ventilation rates with less variation on a daily basis (range of 0.74 to 0.98 L/(s.bird)) because of the higher outside temperatures experienced during the production cycle. These values compare favourably with the recommended spring rate of 0.95 L/(s.bird) (Winchell, 1982). However, the mean measured ventilation rates for Barns BA and BB were shown to be far in excess of the value of 0.29 L/(s.bird) prescribed for minimum ventilation rates (Winchell, 1982). While acknowledging the possible influence of poor fan location on the air distribution within the barn, the low static pressure differences in Barn BA and the existence of underventilated areas seem to question the

validity of such a rate for the initiation of satisfactory air-flow patterns. On the other hand, the maintenance of low relative humidities at the relatively high ventilation rates observed in Barns BB and BC suggests that the recommended minimum ventilation rate based on moisture control should lie somewhere between these rates and the value given by Winchell (1982).

Table 5.2 shows the mean daily ventilation rates expressed as separate means for the light and dark periods. Barn BA had the highest means for both light and dark periods as well as the largest variation (0.29 L/(s.bird)) between means for light and dark. Satisfactory performance of the supplemental heating and ventilation systems should ensure the maintenance of the required ambient temperatures, irrespective of outside temperatures or internal heat loads. The fact that variations in ambient temperatures occurred suggests that environmental conditions were dictated by the ventilation system due to inadequate thermostatic control or the lack of interlocking control of the fans with the supplemental heating system.

In general, satisfactory control of environmental conditions and adequate air distribution were achieved in all three barns, except when minimum ventilation rates were employed in Barns BA and BB in combination with extremely low outside temperatures.

5.2 House Energy Balance

TABLE 5.2 MEAN VENTILATION RATES AND AMBIENT TEMPERATURES DURING THE LIGHT AND DARK HOURS FOR THE BROILER BREEDER PRODUCTION CYCLE.

Bird Age weeks	Ventilation Rate L/(s.bird)		Ambient Temperature °C	
	Light	Dark	Light	Dark
		Barn BA		
31	0.72	0.58	18.5	17.9
34	1.74	1.83	20.2	19.1
37	0.69	0.85	18.4	18.3
45	0.77	0.63	16.8	14.8
48	0.91	0.62	17.5	15.9
52	0.46	0.43	16.0	14.3
57	0.84*	0.71*	18.6	16.9
Mean	0.88	0.81	18.0	16.9
		Barn BB		
27	0.89	0.90	18.1	15.0
31	0.72	0.70	20.7	19.0
36	0.58*	0.57*	23.2	21.2
40	0.60	0.46	16.3	12.6
43	0.60*	0.59*	21.5	20.5
48	0.54	0.51	21.4	19.8
51	0.65	0.54	19.6	18.4
55	0.78	0.74	16.0	16.0
Mean	0.67	0.63	19.6	16.1
		Barn BC		
33	0.75	0.71	20.4	20.4
36	0.75	0.77	18.3	18.5
39	0.78	0.72	19.0	17.6
43	0.96*	0.78*	19.4	17.9
46	1.04*	0.83*	18.8	16.7
Mean	0.86	0.76	19.2	18.2

* Denotes corrected ventilation rates.

The design of the experimental procedure was such that all non-physiological heat sources and losses were measured directly and used to determine the heat production of the broiler breeder flock. The measured heat gains included the heat from lights and mechanical equipment as well as the gains from supplemental heating. The losses from the system were considered to be those due to air exchange or ventilation, and the conductive heat losses through the building fabric. Heat sources or losses too insignificant to measure, along with any experimental error, were considered negligible and incorporated into the calculated term.

5.2.1 Ventilation Correction Term

In general, the application of a heat and moisture balance to the data from each of the barns showed close agreement between calculated parameters over most of the production cycle. However, certain data pertaining to either one or two of the 24-hour monitoring cycles for each barn, were deemed to be erroneous due to a discrepancy in calculated parameters for these monitoring cycles in relation to the others. In all cases, the monitoring procedures were similar and no significant departures were observed from "normal" barn conditions that might have accounted for the inconsistency in measurements. This led the author to believe that the error in the measurements was due to an instrument malfunction.

Further analysis of these data showed significant differences to exist between CO_2 production rates for these monitoring cycles and all other cycles. As feed levels were being maintained at similar levels for these as for adjacent monitoring cycles, large differences in CO_2 production rates between 24-hour periods were not expected to occur. The zero and span of the infrared gas analyser used for the measurement of CO_2 concentrations was checked with certified calibration gases both before and during each monitoring cycle. Being confident, therefore, of the accuracy of the measured CO_2 concentrations, the only other factor which could contribute to the error in the CO_2 production rates was an error in the measurement of the ventilation rate. This postulation was confirmed later when calibration of the thermistor anemometer (Model TA3000, Airflow Developements, Bucks., England), which was used for a short time while the hot-wire anemometer (Sierra Instruments, Cal.) was being serviced, showed it to be out of calibration. In fact, subsequent calibrations of the same instrument showed it to go out of calibration in a relatively short time when utilized for air flow measurements in dusty environments.

Assuming the inconsistencies in the heat and moisture balance parameters for the monitoring cycles in question to be accounted for by the error in the ventilation rate measurements, a procedure was initiated to check the validity of the measured data using a corrected ventilation rate.

The rate of production of CO_2 is a function of animal metabolic rate. As discussed earlier, an animal's metabolic rate is influenced by many factors, the most important of which include environmental temperature, activity and the rate of feed intake. For poultry housed in close confinement facilities under thermoneutral conditions, feed intake is the single most important influence on the rate of metabolism, with a direct relationship existing between CO_2 production and feed intake. Knowing the rate of feed intake at any time during the production cycle and the composition of the diet, the rate of CO_2 production may be determined using its calorific value. Carbon dioxide production rates determined in this way may be used as a check against measured values, assuming that poultry metabolism is the only source of CO_2 production in the poultry environment.

Although no direct measurements were made during the study of the rate of feed intake, the assumption was made that the operators followed the guidelines laid down in their management manuals. In both cases, feed was delivered premixed, with feed composition being as prescribed. The operator of Barn BA used a scale to determine the appropriate feed quantities, while the operator of Barns BB and BC utilized feeder operating times calibrated to ensure correct feeding rates. Evidence of good management practices on the part of the operators were the high levels of productivity which were attained in all three barns. In all three barns, egg production, in terms of egg numbers per

day, exceeded the projected production levels specified by the relevant management guides (Hubbard Farms Management Guide, 1985; Arbor Acres Management Guide, 1985).

Arbor Acres (1985) recommends a low fat, low fibre feed composition for producing breeders, with a 16% crude protein content and an M.E. of 12 MJ/kg. After peak production has been reached, feed intake is restricted to increase feed efficiency by reducing the rate of body-weight increase. Indeed body-weights are expected to change little during the 30 or more weeks following peak production. Based on this fact, the birds may be assumed to be at maintenance. Taking into account the energy cost of egg production as well as the composition of the feed, an RQ of one was assumed for birds in the latter part of the production cycle. The metabolisable energy intake before peak production is assumed to be diverted to growth rather than egg production, also resulting in an RQ close to one.

Using the calorific values of CO_2 and O_2, Brody (1945) determined the expected CO_2 production and O_2 consumption rates for a given RQ. For an RQ of one, 21.1 L of CO_2 will be produced per MJ of energy metabolized. Using the ME content of the feed, together with the rate of feed intake over the breeder production cycle, an equation was developed to relate CO_2 production to bird age. This equation represents a second degree polynomial with an R^2 of 0.96 and is:

$$Y = 5.247 - 5.081 \times 10^{-2} X + 3.105 \times 10^{-4} X^2 \qquad (5.1)$$

where Y = rate of CO_2 production, L/(h.bird), and

X = bird age, weeks

This equation was used to predict the CO_2 production rates for those 24-hour monitoring cycles which were considered in error.

Comparisons between the predicted and erroneous values yielded a correction factor which was applied to the ventilation rates in question. Heat and moisture balances then were carried out based on the new ventilation rates, with the corrected values of the heat and moisture parameters being used in the calculation of overall means. Such corrected values are denoted by an asterisk when they appear in the tabulations of results. The major components of a heat and moisture balance for the data collection cycles in question are listed in uncorrected form in Appendix E, together with the correction factors applied.

An equation also was developed to relate the measured CO_2 production rates after peak production with bird age but excluding those values considered to be in error. The equation, which represented a second degree polynomial with an R^2 of 0.65185, is:

$$Y = 4.919 - 2.988 \times 10^{-2} X + 3.006 \times 10^{-5} X^2 \qquad (5.2)$$

where Y = rate of production of CO_2, L/(h.bird), and,

X = bird age, weeks

Because of the relatively weak degree of correlation between measured CO_2 production and bird age, this relationship was not used as a means to predict CO_2 production but rather to justify the use of Eqn. 5.1 for the same purpose.

Consequently, a statistical analysis was performed on the theoretical and measured (uncorrected) CO_2 production rates, using an unpaired *t* test, available in an APL statistical package. The hypothesis tested was that there was no difference between the measured and theoretical values, assuming that the population variances were equal. Values of *t* at 5, 10 and 20% confidence levels were 2.064, 1.711 and 1.316, respectively, for 24 degrees of freedom. The calculated t value was 0.309, indicating that the hypothesis could not be rejected at any of the three confidence levels tested. Therefore, the applicability of Eqn. 5.1 to predict CO_2 production rates and hence, correct measured ventilation rates, was considered to be verified statistically.

5.2.2 Building Components

Figure 5.2 illustrates the hourly variation of the heat balance components during the course of a typical monitoring run in Barn BB. This figure illustrates the importance of

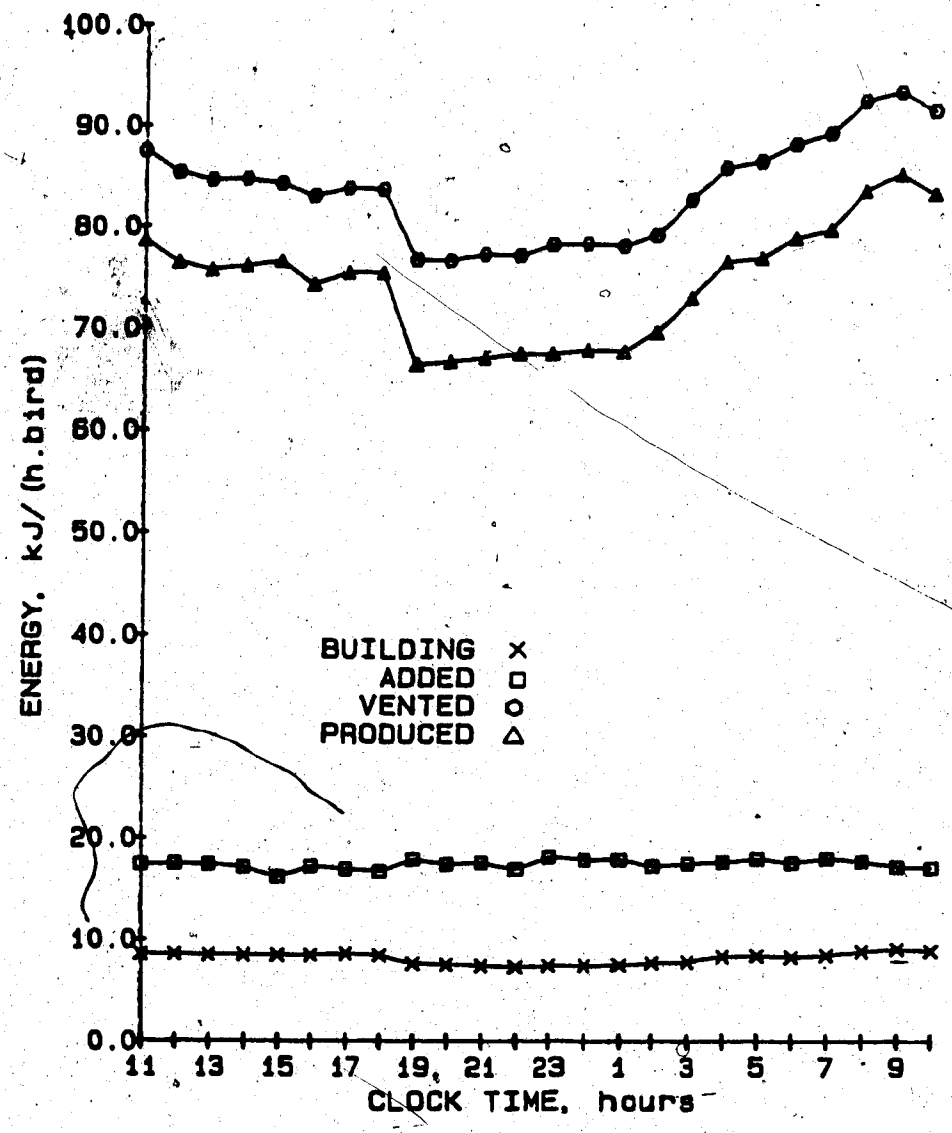


Figure 5.2 Mean hourly ventilation, building, supplemental, and poultry components of the heat balance with 31-week old birds in Barn BB.

the ventilation heat loss component in the building heat balance. While the conductive heat losses remained relatively constant during the 24-hour cycle, ventilation heat losses fluctuated along with variations in the ventilation rate. Bird total heat production rates also exhibited diurnal fluctuations due to changes in bird activity levels. Peaks in heat production corresponded to times of maximum bird activity.

The mean daily values for the heat gains and losses for the full production cycles are given in Table 5.3. The amount of supplemental heating used varied according to barn, with Barn BA having the maximum requirement of 67.8 kJ/(h.bird) when outside temperatures were extremely low. Barn BA also exhibited large variations in daily supplemental heating requirements, while Barns BB and BC showed relatively constant demands.

The ratios of the ventilation heat losses to the total building heat losses (Table 5.3) were high in all three barns and relatively constant, especially in Barns BB and BC, despite variations in the ventilation rates. Mean ratios over the full production cycle were 0.88 for Barns BB and BC, while Barn BA had a ratio of 0.89, demonstrating the predominance of the ventilation system as the major source of building heat losses.

In determining the structural heat-flow component of the building energy balnce, the heat gains due to solar radiation were assumed to be negligible because of the high

TABLE 5.3 DAILY MEAN HEAT BALANCE DATA FOR EACH RUN DURING THE BREEDER PRODUCTION CYCLE.

Bird age (weeks)	Conductive heat loss	Added heat	Vented heat	Bird heat	Vent. heat/ Total heat loss
	kJ/(h.bird)				
			Barn BA		
31	7.4	0.0	61.1	68.5	0.88
34	6.2	0.0	73.5	79.7	0.92
37	10.7	6.3	108.4	112.9	0.90
45	13.6	49.7	127.6	91.4	0.89
48	9.2	27.6	81.7	63.3	0.89
52	15.8	67.8	96.4	44.3	0.84
57	10.4	52.0	106.7*	65.1*	0.92
Mean		29.1	93.6	75.0	0.89
			Barn BB		
27	6.7	18.0	86.3	75.1	0.92
31	8.2	17.4	83.7	74.5	0.90
36	9.3	16.9	71.3*	64.1*	0.87
40	9.6	20.2	61.4	51.5	0.84
43	9.7	18.0	86.0*	78.1*	0.89
48	10.2	18.3	78.0	69.9	0.87
51	9.2	17.6	77.6	69.2	0.88
55	6.9	6.8	58.8	58.9	0.88
Mean		16.7	75.4	67.7	0.88
			Barn BC		
33	12.1	27.6	96.3	80.8	0.87
36	10.3	21.8	86.0	74.4	0.88
39	10.7	21.5	84.4	73.6	0.87
43	10.1	17.8	84.7*	76.9*	0.88
46	9.0	8.8	71.0*	71.1*	0.87
Mean		19.5	84.5	75.4	0.88

*Denotes corrected environmental parameters

levels of insulation used in each of the barns. Although attic temperatures were not measured, the assumption of a negligible solar heat gain through the ceiling was supported by the fact that previous studies on livestock barns (Smith, 1983; Quille, 1985) with similar levels of insulation and carried out under similar climatic conditions indicated little difference existed between attic and outside temperatures. The building structural heat loss was found to vary little over a 24-hour monitoring cycle. The greatest range in mean daily values (6.2 to 15.8 kJ/(h.bird)) occurred for Barn BA due to the greater variability in outside temperatures during the production cycle.

5.2.3 Animal Heat Production

Table 5.3 details the daily means of the bird total heat production rate for each of the barns studied. The mean total heat production rate over the full production cycle was 75.0, 67.7 and 75.4 kJ/(h.bird) for Barns BA, BB and BC, respectively. Barn BA showed the largest variation in mean daily heat production rate, with values ranging from 44.3 to 112.9 kJ/(h.bird). Barns BB and BC exhibited much less variation. In all cases, house temperatures were similar and considered to be within the birds' zone of thermoneutrality, so variations in bird total heat production had to be explained by factors other than ambient temperature.

With total heat production being expected to follow the rate of feed intake, the highest overall total heat

production rate was expected to occur in Barn BC due to the lower mean bird age over the course of the monitoring cycle, resulting from the higher rates of feed intake. The relatively high total heat production rate for Barn BA could be explained in terms of bird activity, with the birds in Barn BA being observed to be flightier and more aggressive than birds in the other two barns. The lower stocking densities employed in Barn BA also could have influenced bird activity and affected huddling behaviour.

Table 5.4 details total heat production rates, based on the overall means for the light and dark periods. Barn BA had the highest overall mean for the light hours and also exhibited the greatest difference between means for light and dark periods. All three barns showed an overall reduction in total heat production from light hours to darkness, the mean reductions being 18, 12 and 2% for Barns BA, BB and BC, respectively. The diurnal variation in heat production can be attributed to a decrease in bird activity levels during darkness, resulting in a corresponding decrease in metabolic rate. The variations in the magnitude of this reduction may be, in part, due to the differing heat production rates and bird densities. Indeed, Barn BC, with the highest mean bird density, had the smallest overall reduction, while Barn BA had the lowest mean bird density and the greatest reduction.

The overall means of the latent heat removed by the ventilation system were 36.2, 25.7 and 35.5 kJ/(h.bird) from

TABLE 5.4 OVERALL MEAN HEAT PRODUCTION DATA FOR THE LIGHT AND DARK HOURS.

	Barn BA		Barn BB		Barn BC	
	Light	Dark	Light	Dark	Light	Dark
Ventilation heat loss, kJ/(h.bird)	97.9	87.7	78.0	71.7	83.9	85.3
Building heat loss, kJ/(h.bird)	10.5		8.7		10.4	
Bird total heat production, kJ/(h.bird)	82.3	67.7	71.5	62.6	76.1	74.4
Percentage reduction, light to dark, %	18		12		2	
Supplemental heat gain, kJ/(h.bird)	26.3	33.0	15.8	17.9	18.4	21.4
Latent heat production, kJ/(h.bird)	37.7	34.2	26.3	25.0	36.9	33.7
Moisture production, g/(h.bird)	13.1	10.3	11.2	8.4	12.7	9.6
Latent heat removed/total heat removed	0.39	0.39	0.33	0.34	0.44	0.40

Table 5.5, corresponding to overall mean moisture production rates of 11.9, 10.0 and 11.4 g/(h.bird) for Barns BA, BB and BC, respectively. Although a quantative analysis of litter moisture content was not carried out, the higher moisture production rates in Barn BA are substantiated by the fact that the litter in Barn BA was observed to be drier than the litter in Barm BB. The trends were similar to those for total heat production, with Barns BA and BC having similar latent loads and Barn BB having the lowest. The latent heat production rate in Barn BA was highest due, in part, to the high total heat production rates and the low relative humidities found in this barn. This barn had the lowest overall mean ambient temperature by about 1°C and, while temperature was expected to influence latent heat production, the difference in temperatures between Barn BA and Barns BB and BC was not sufficient to depress the latent heat production below the levels of the other two. Barn BC showed the least variation in latent heat production, with daily means ranging from 26.0 to 38.6 kJ/(h.bird) due, most probably, to the maintenance of very similar environmental conditions throughout the production cycle. Barn BB had the minimum daily latent heat production of 7.9 kJ/(h.bird) which occurred when ambient temperatures fell to 11°C during severe cold weather.

Barn BC, utilizing deep-pit manure storage, had the highest ratio of latent to total heat production, even though the same barn had the highest mean relative

TABLE 5.5 SUMMARY OF THE SENSIBLE AND LATENT HEAT COMPONENTS DURING THE BREEDER PRODUCTION CYCLE.

	Barn BA	Barn BB	Barn BC
Bird total heat production, kJ/(h.bird)	75.0	67.7	75.4
Sensible heat production, kJ/(h.bird)	38.8	41.8	39.8
Total latent heat production, kJ/(h.bird)	36.2	25.7	35.5
Moisture production g /(h.bird)	11.9	10.0	11.4
Building latent heat production, kJ/(h.bird)	25.1	17.1	26.8
Building latent heat/total latent heat	0.74	0.59	0.75
Percentage Sensible heat converted, %	37	24	36

humidities during the production cycle, due to wet litter conditions, and pit temperatures lower than ambient levels. This could be due to a more efficient evaporation process because of air patterns set up within the pit area. The evaporation of moisture from poultry litter relies on the transfer of water vapour from the manure into the ambient air due to vapour pressure gradients set up by the air circulation patterns within the breeder house. However, due to the progressively deeper manure levels as the production cycle progresses, the initiation of air patterns below the slats of shallow pit systems is prohibited. On the other hand, the air patterns set up in the deep-pit area increase the rate of evaporation by increasing the vapour pressure gradient.

Table 5.4 gives the overall daily means of latent heat production for the light and dark hours. All three barns showed a decrease in latent heat production during darkness, the reductions being 9, 5 and 9% for Barns BA, BB and BC, respectively. However, the ratio of latent heat removed to total heat removed for the light and dark periods remained unchanged in Barns BA and BB due to corresponding reductions in total heat production, indicating that evaporation of moisture from the litter was unaffected by lighting period. While total heat production remained relatively unchanged in Barn BC, a higher proportion of this total heat production during the light hours was in the latent form due to the lower night time temperatures below slat level. As

ventilation rates tended to be reduced during the dark hours, the ratio of latent heat to total heat production was reduced due to the decreasing pit temperature. This was substantiated by the fact that during one particular monitoring period the ventilation rate actually increased during the dark hours, resulting in a higher mean pit temperature and greater latent heat production than during the light hours.

The results of this study demonstrate the influence of temperature and manure storage system on the production of latent heat in broiler breeder houses, with deep-pit systems producing more latent heat but the rate of latent heat production being ultimately dependent on temperature.

5.2.4 Sensible to Latent Heat Conversion

Bird total heat production included both a sensible and a latent heat component. Because the birds' sensible heat output is used in the evaporation of moisture from the litter and, to a lesser extent, from waterers and spillages, the calculated value for the bird sensible heat production only accounts for that portion which remains in the sensible form. The proportion of sensible heat used for the evaporation of building moisture was determined by estimating bird latent heat production and subtracting it from the total latent heat production, as calculated from the house energy balance.

The bird sensible heat production was calculated as the total heat production minus the latent heat fraction. Because the birds were considered to be in a thermoneutral state and maintaining constant metabolic weights over most of their production cycles, bird sensible heat production also was expected to remain relatively constant over the production cycle. However, as the calculated sensible output represented only the fraction of bird sensible heat production that remained after conversion to latent heat, the calculated value was expected to vary along with the magnitude of the conversion. Table 5.6 shows the daily means of the bird sensible heat production, with the overall means of 38.8, 41.8 and [illegible]8 kJ/(h.bird) for Barns BA, BB and BC, respectively, showing close agreement with each other. Barn BB had the highest mean despite having the lowest overall bird total heat production rate. All three barns showed only small variations from these mean values, indicating a relatively constant proportion of sensible to latent heat conversion throughout the production cycle.

Because no data exist on the latent heat production of broiler breeders, values were estimated using calorimetrically determined moisture production data for broilers, as cited by Scott et al. (1983), and corrected for metabolic body size. The final value for breeder latent heat production was based on the assumption that bird weight was constant throughout the production cycle, with a mean value of 3.6 kg (Arbor Acres Management Guide, 1985), implying

TABLE 5.6 TOTAL, LATENT AND SENSIBLE HEAT PRODUCTION OF THE BROILER BREEDERS IN BARNS BA, BB AND BC.

Bird total heat	Sensible heat	Total latent heat	Building latent heat[1]	Total latent /bird total heat	Building latent/total latent heat	Sensible heat converted
kJ/(h.bird)						
Barn BA						
68.5	[illegible]	27.3	18.6	0.40	0.68	0.27
79.7	[illegible]	38.1	29.4	0.48	0.77	0.37
112.9	[illegible]	42.5	38.8	0.38	0.80	0.30
91.4	[illegible]	43.8	35.1	0.46	0.80	0.38
63.3	[illegible]	28.6	19.9	0.45	0.70	0.32
44.3	[illegible]	24.1	15.4	0.54	0.64	0.35
65.1*	16.0*	49.1*	40.4*	0.75*	0.82*	0.62*
Barn BB						
75.1	48.5	26.6	17.9	0.35	0.67	0.24
74.5	44.4	30.1	21.4	0.40	0.71	0.29
64.1*	32.6*	31.5*	22.8*	0.49*	0.73*	0.36*
51.5	43.6	7.9	0.0	0.15	0.0	0.0
78.1*	41.1*	37.0*	28.3*	0.47*	0.77*	0.36*
69.1	41.0	28.1	19.4	0.41	0.69	0.28
69.2	40.3	28.9	20.2	0.42	0.70	0.29
58.9	43.2	15.7	7.0	0.27	0.45	0.12
Barn BC						
80.8	42.6	38.2	29.5	0.47	0.77	0.37
74.4	37.4	37.0	28.3	0.50	0.77	0.38
73.6	35.7	37.9	29.2	0.51	0.77	0.40
76.9*	38.3*	38.6*	29.9*	0.50*	0.78*	0.39*
71.1*	45.1*	26.0*	17.3*	0.37*	0.67*	0.24*

[1] Based on a constant bird latent heat production of 8.66kJ/(h.bird).
* Denotes corrected values.

that breeder latent heat production was also constant throughout the cycle. An initial moisture production of 2.44 g H_2O/(h.kg) was used for broilers (average liveweight of 1.1 kg) based on the mean of the data presented by Scott et al. (1983). The estimated value for breeder moisture production, including the correction for metabolic weight, was 0.993 g/(h.kg), corresponding to 8.66 kJ/(h.bird).

Table 5.6 details the proportion of poultry sensible heat production which was used for evaporation of moisture within the house. The conversion ratios in all three barns was relatively constant and showed good agreement with each other. Barn BC had the highest conversion rate as well as the lowest sensible heat production, with an average of 37% of the birds' sensible heat production being converted to the latent form. Barn BB had the lowest overall mean conversion, 24%, due, in part, to the fact that, during one of the monitoring cycles, no moisture apparently was produced apart from the birds' own moisture production because of the low ambient temperatures experienced within the barn.

The evaporation of moisture from the stored manure accounted for 74, 59 and 75% of the total latent heat in Barns BA, BB and BC, respectively (Table 5.5), over their entire production cycles. Values were similar in all three barns, indicating that similar amounts of moisture were removed from each barn. Indeed, variations in the means of the ratios of building latent to total latent heat

production were similar to the variations in the means for moisture production. The relatively low overall mean for Barn BB was as a result of the zero value obtained for the daily mean building latent heat production during one monitoring cycle. Disregarding this value would have resulted in an overall mean of 0.67 for the ratio of building latent to total latent heat production, bringing it closer into line with the means for Barns BA and BC.

Equations relating poultry heat production to bird age are detailed in Appendix F. Regression analyses were carried out on the basis of 24-hour daily means.

5.3 Predicted RQ Values and Metabolizable Energy Efficiency

Equation 2.1, developed from an equation by Romijn and Lokhorst (1961), was used to predict poultry RQ's during the course of the production cycle. The predicted RQ's, based on the daily means of bird total heat and carbon dioxide production rates, are presented in Table 5.7. The overall means for the predicted values were 1.1, 1.2 and 1.1 for the birds in Barns BA, BB and BC, respectively. These values are in agreement with the value of 0.96 reported by Lundy et al. (1978) for fully fed North Holland Blue hens. The predicted RQ's also are consistent with the high carbohydrate content of the breeder ration. This would seem to verify the accuracy of the measured bird total heat production rates.

The metabolizable energy intake was then partitioned into the energy for maintenance and the energy required for

TABLE 5.7 DAILY MEANS OF THE MEASURED AND PREDICTED BIRD RQ VALUES AND CARBON DIOXIDE PRODUCTION RATES FOR EACH RUN IN THE THREE BARNS.

Bird age (weeks)	Measured total heat production kJ/(h.bird)	Predicted RQ's	Carbon dioxide production L/(h.bird)
	Barn BA		
31	68.5	1.4	4.09
34	79.7	1.1	4.04
37	112.9	0.6	3.64
45	91.4	0.8	3.54
48	63.3	1.3	3.55
52	44.3	1.7	3.07
57	65.1*	1.1*	3.36*
Mean	75.0	1.1	3.61
	Barn BB		
27	75.1	1.1	3.74
31	74.5	1.1	3.83
36	64.1*	1.4*	3.82*
40	51.5	1.4	3.10
43	78.1*	1.0*	3.64*
48	69.1	1.2	3.77
51	69.2	1.1	3.55
55	58.9	1.4	3.52
Mean	67.7	1.2	3.62
	Barn BC		
33	80.8	1.1	4.09
36	74.4	1.2	3.96
39	73.6	1.1	3.76
43	79.6*	1.0*	3.64*
46	71.1*	1.1*	3.50*
Mean	75.4	1.1	3.77

* Denotes corrected environmental parameters.

egg production, assuming that growth was negligible during the breeder production cycle. The maintenance energy of the birds was estimated using an equation developed by Greniger et al. (1975) for the maintenance energy requirement of poultry as a function of environmental temperature. The equation is as follows:

$$H = 458\, W^{0.75}\, (e^{(0.014(22-T))}) \qquad (5.3)$$

where H = maintenance energy, kJ

W = body weight, kg, and

T = environmental temperature, °C.

Assuming a body weight of 3.6 kg and an environmental temperature of 19°C, the maintenance energy requirement of the broiler breeders was calculated as 1242 kJ. If the birds are assumed to be at peak production, each bird could be expected to consume 0.165 kg of feed per day, with an ME content of 12 MJ/kg, or 1980 kJ/day. Using 75.0 kJ/(h.bird) or 1800 kJ/(d.bird) as a representative value for bird total heat production, the energy remaining for egg production is 180 kJ/(d.bird). According to Greniger et al. (1975), the energy cost of egg production is approximately 6.5 kJ/g. Assuming egg weight to be 60g, the energy required to produce one egg is 390 kJ/egg. Based on this value, the breeders in this study could be expected to produce an egg every two days. The actual production figures ranged from

approximately five eggs per week during peak production to two eggs per week at the end of the breeder production cycle.

The metabolizable energy efficiency or the proportion of the metabolizable energy over and above the maintenance requirement that was utilized for production also was estimated. Using the same assumptions as above, a value of 0.24 was obtained, comparing favourably with the values reported by Greniger et al. (1975) for laying hens.

5.4 Carbon Dioxide Production

Carbon dioxide concentrations were measured at each exhaust fan as well as at three locations within each barn. Little difference was found between ambient concentrations and those measured at the fans for Barns BA and BB. Barn BC, however, had slightly higher ambient concentrations, exhibiting trends similar to ambient and exhaust temperatures but, again, the difference was not considered significant.

Table 5.9 shows the daily means of CO_2 concentrations for each of the monitoring periods. The daily means based on averages for the light and dark hours also are presented in Table 5.10. The overall means for ambient CO_2 concentrations over the entire monitoring cycle were 1953, 2241 and 2013 ppm, for Barns BA, BB and BC, respectively. The maximum daily ambient concentration of 2727 ppm, recorded in Barn BB, was lower than the human TLV of 5000 ppm recommended by

TABLE 5.8 MEAN CARBON DIOXIDE PRODUCTION AND CONCENTRATION DATA AND VENTILATION RATES FOR EACH OF THE BARNS MONITORED.

Bird age, weeks	CO_2 Production L/(h.bird)	CO_2 Exhaust ppm	CO_2 Ambient ppm	Ventilation Rate L/(s.bird)
		Barn BA		
31	4.09	2381	2108	0.66
34	4.04	1293	1294	1.78
37	3.64	2080	1886	0.76
45	3.54	2116	2087	0.72
48	3.55	1942	1872	0.79
52	3.07	1562	1868	0.76
57	3.36*	1562	1868	0.76*
Mean	3.61	1968	1953	0.85
		Barn BB		
27	3.74	1547	1717	0.90
31	3.83	1908	2035	0.71
36	3.82*	2715	2727	0.52*
40	3.10	2496	2453	0.45
43	3.64*	2485	2473	0.57*
48	3.77	2706	2477	0.53
51	3.55	2285	2268	0.61
55	3.52	1774	1778	0.76
Mean	3	2202	2241	0.63
		Barn BC		
33	4.09	2105	2370	0.74
36	3.96	2040	2246	0.76
39	3.76	1702	1780	0.76
43	3.64*	1639	1785	0.90*
46	3.50*	1743	1885	0.98*
Mean	3.77	1846	2013	0.83

* Denotes corrected values.

the ACGIH (1984) and the 3000 ppm recommended by the SFBIU (1984). Hence, the CO_2 concentrations were not considered to be hazardous in terms of operator or poultry health.

All three barns showed diurnal variations in ambient CO_2 concentrations and similar variations in concentrations measured at the exhaust fans. Ambient concentrations averaged 11, 22 and 16% lower during the dark hours, for Barns BA, BB and BC, respectively, with the lower night-time concentrations being due to the decreased levels of CO_2 production associated with inactivity.

Production rates of CO_2 were calculated as the product of the ventilation rate and the difference between CO_2 concentrations outside the house and those measured at the exhaust fans. The mean measured CO_2 production rates for each of the 24-hour monitoring cycles, including those corrected for ventilation rates, are given in Table 5.9. All three barns showed close agreement in CO_2 production rates, the overall means being 3.61, 3.62 and 3.77 L/(h.bird) for Barns BA, BB and BC, respectively. This indicates that similar feed compositions were used and that feed conversion efficiencies were similar in all three barns, despite differences in breed. In general, CO_2 production followed expected trends, with the maximum values occurring at the beginning of the study, corresponding to maximum rates of feed intake, and decreasing gradually as the production cycle progressed.

Although Barn BC did have the highest overall mean CO_2 production rate, this value was expected to be higher relative to the production rates from the other barns. Because the birds in Barn BC were younger than the birds in Barns BA and BB, their metabolic rate should be higher and, hence, CO_2 production rates should be greater. However, differences in breed and feathering, together with greater observed levels of activity in other barns, could have contributed to lessening the difference between the CO_2 production rates for Barn BC and for those in Barns BA and BB.

The minimum daily mean CO_2 production of 3.1 L/(h.bird) occurred in Barns BA and BB when ambient temperatures were low. The relatively low calculated total heat production rates for these particular monitoring cycles indicate that deep-body temperatures were maintained by non-physiological thermoregulatory mechanisms such as huddling and fluffing out of the feathers, resulting in decreased poultry sensible heat loss. The low CO_2 production rates could be attributed to the decrease in activity levels associated with huddling behaviour. Indeed, these depressed CO_2 production rates were similar to the mean CO_2 production rates during the dark periods, when activity levels were at their lowest.

Figures 5.3 shows typical hourly CO_2 production rates over a 24-hour monitoring cycle for Barns BC. Because of the association of CO_2 production rates with ventilation, the hourly variations in CO_2 production were due, in part, to

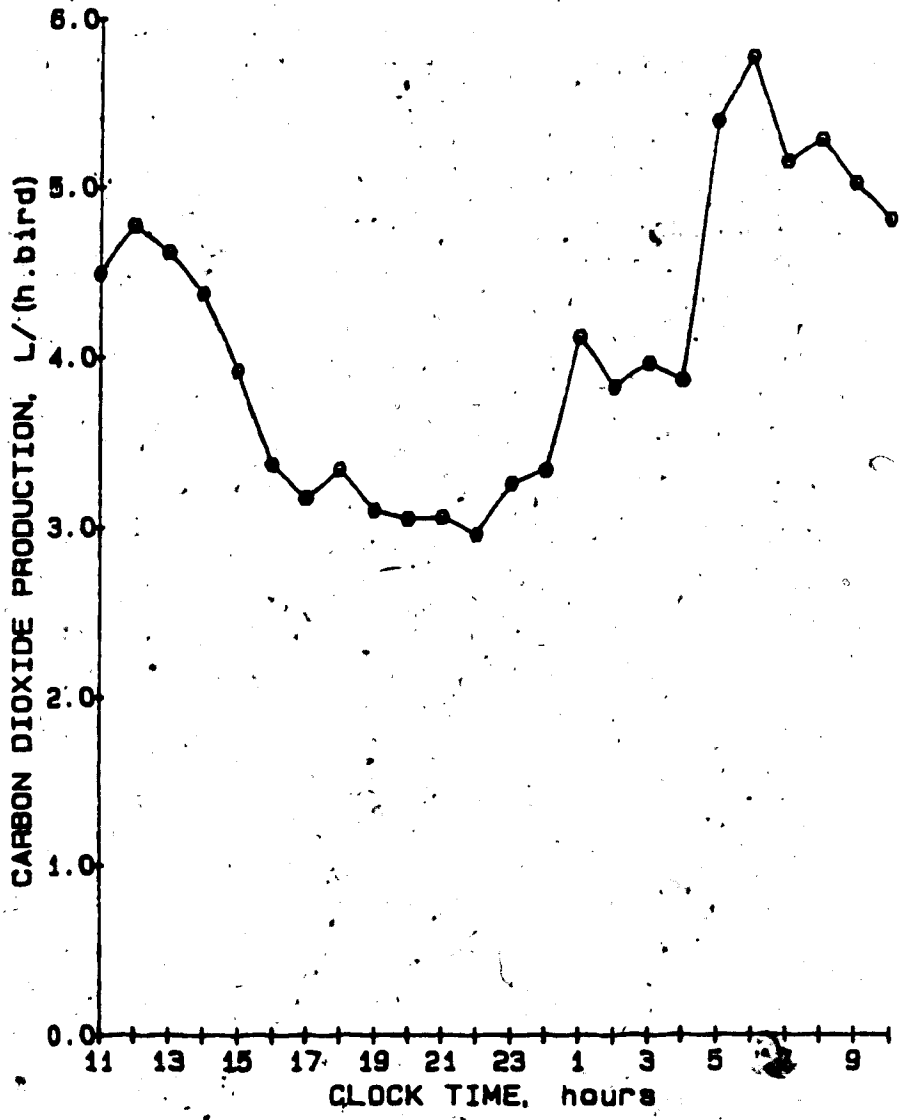


Figure 5.3 Carbon dioxide production throughout a 24-hour period in Barn BC with 39-week old breeders.

changes in the ventilation rate. Carbon dioxide production shows the same diurnal variations as poultry heat production because of its dependence on metabolic rate. However, the hourly variations also could be explained in terms of metabolic rate and activity levels, with peaks in CO_2 production occurring when marked increases in bird activity were observed, for example, when the feeders were operated or when egg collection was taking place.

The means for daily CO_2 production also were expressed as means for the light and dark periods and ranged from 4.76 to 3.46 L/(h.bird) for the light hours and from 3.50 to 2.51 L/(h.bird) during the dark hours. These means were averaged further to give overall means of CO_2 production, detailed in Table 5.10, for the light and dark hours over the whole production cycle. The magnitude of the reduction in CO_2 production was similar for all three barns, with a 26% reduction for Barn BA and 28% reductions for Barns BB and BC.

5.5 Ammonia Production

Concentrations of NH_3 were measured three times every hour at the seven sampling locations in each of the barns. Production rates for NH_3 were determined in the same way as CO_2 production rates, with the daily means being detailed in Table 5.11. Although the evolution of NH_3 gas into ambient air is primarily a function of the stored droppings, the rate of NH_3 production is dependent on the volume of the

TABLE 5.9 OVERALL MEAN CARBON DIOXIDE PRODUCTION AND CONCENTRATION DATA DURING THE LIGHT AND DARK PERIODS DURING THE BREEDER PRODUCTION CYCLE.

	Barn BA		Barn BB		Barn BC	
	Light	Dark	Light	Dark	Light	Dark
CO_2 production L/(h.bird)	4.07	3.01	4.28	3.08	4.25	3.05
range	(3.5 /4.6)	(2.5 /3.5)	(3.6 /4.8)	(2.4 /2.5)	(3.7 /4.7)	(2.9 /3.3)
% reduction, day to night	26		28		28	
CO_2 ambient, ppm	2089	1763	2406	2017	2135	1843
CO_2 exhaust, ppm	2058	1841	2423	1898	1979	1659

TABLE 5.10 MEAN AMMONIA PRODUCTION AND CONCENTRATION DATA AND VENTILATION RATES FOR THE THREE BREEDER BARNS.

Bird age, weeks	Production mL/(h.bird)	NH_3 Exhaust ppm	NH_3 Ambient ppm	Ventilation Rate L/(s.bird)
		Barn BA		
31	75	33	26	0.66
34	127	20	23	1.78
37	64	24	31	0.76
45	66	29	28	0.72
48	68	24	36	0.79
52	27	16	35	0.45
57	88*	29	42	0.76*
Mean	73	25	32	0.85
		Barn BB		
27	45	14	17	0.90
31	148	58	75	0.71
36	158*	85	100	0.52*
40	96	56	73	0.45
43	172*	84	104	0.57*
48	160	84	123	0.53
51	145	67	89	0.61
55	104	38	44	0.76
Mean	129	61	78	0.63
		Barn BC		
33	95	36	53	0.74
36	105	38	51	0.76
39	97	36	43	0.76
43	98*	31	44	0.90*
46	89*	27	33	0.98*
Mean	97	34	45	0.83

* Denotes corrected air quality parameters.

stored litter which, in turn, is a function of the number of birds. Ammonia production rates, therefore, were expressed on a per bird basis in mL/(h.bird) to account for the differences in bird densities.

Barn BC had relatively constant mean daily NH_3 production rates, ranging from 89.3 to 104.6 mL/(h.bird). The means for Barns BA and BB, on the other hand, showed considerable variation over the production cycle, with ranges of 27.0 to 126.5 mL/(h.bird) for Barn BA and 45.3 to 171.8 mL/(h.bird) for Barn BB. The relatively constant rate of moisture removal as well as the small fluctuations in house temperatures resulted in the constant NH_3 production rates for Barn BC. The mean daily production rates were further averaged to overall means for the entire production cycle. These were 73.4, 128.5 and 96.7 mL/(h.bird) for Barns BA, BB and BC, respectively, with Barn BB having the highest overall mean, despite the lowest mean ventilation rate.

Examination of NH_3 production rates showed little variation to exist between rates measured during a 24-hour monitoring cycle. This was to be expected because only small diurnal fluctuations in thermal parameters occurred in all three barns. For this reason, means were expressed on a daily basis only.

In close confinement poultry housing, NH_3 production is a function of the litter properties, with litter temperature, aeration, moisture content and pH having the greatest influence on the production of NH_3. The uric acid

content of the feces was assumed to be the same for all three barns due to the utilization of similar feed compositions and manure storage times. Barn BA had the highest overall mean moisture production rates and the lowest mean relative humidities, resulting in the relatively dry litter conditions. Consequently, Barn BA had the lowest overall mean NH_3 production rate, its value being close to 50% of that for the overall mean for Barn BB. In general, high NH_3 production rates tended to coincide with high ambient temperatures in Barns BA and BB, which both utilised shallow-pit manure storage. The lower overall mean ambient temperatures in Barn BA, along with the previously-mentioned dry litter conditions, partly explained the difference in the NH_3 production rates for the two shallow-pit systems.

Bearing in mind that temperatures within the deep pit of Barn BC were, on average, 3°C cooler than temperatures above the slats, the combination of higher relative humidities and greater aeration of the stored litter resulted in the second highest overall NH_3 production rate. The air patterns set up in the pit area probably affected the rate of transfer of NH_3 into the house environment by increasing the NH_3 partial pressure gradients.

Determination of the influence of manure storage system on NH_3 production was difficult because of the differences in prevailing environmental conditions in the three barns. Because of the relatively large difference in production rates for the two shallow-pit barns, one might conclude that

the effect of the manure storage system on NH_3 production is not as marked as the effects due to small changes in environmental conditions. In comparison with shallow-pit storage, NH_3 production rates for the deep-pit storage system were depressed due to the low pit temperatures but elevated due to the effects of more efficient aeration and higher relative humidites, the net effect being to maintain NH_3 production rates between the rates measured for Barns BA and BB.

The daily means of the NH_3 concentrations in the vicinity of the animals as well as at the outlets are given in Table 5.11. Except for the first monitoring period in Barn BA, ambient concentrations were higher than those at the fans in all three barns, regardless of the ventilation rate. The more distinct differences in NH_3 distributions do not substantiate the previously-established trends in temperature and CO_2 distributions, except in Barn BC. Although differences between ambient and exhaust temperatures and CO_2 concentrations in Barn BC were not considered significant, the larger differences between NH_3 concentrations point to the occurrence of incomplete mixing in this barn. High ventilation rates and pressure differentials, together with a narrow building width could have resulted in short circuiting of the ventilating air, with the exhausted air stream undergoing only partial mixing.

The greatest variations between ambient and exhaust NH_3 concentrations occurred in Barn BB where mean NH_3 concentrations were higher and mean ventilation rates lower than those in other barns. The high static pressure differentials, however, also indicate the possibility of short circuiting in this barn, despite the relatively low ventilation rates and large building width.

The overall means of the ambient NH_3 concentrations were 33, 78 and 45 ppm for Barns BA, BB and BC, respectively (Table 5.12). Based on the human TLV of 25 ppm, recommended by the ACGIH (1984) for time-limited exposures, and the upper limit of 20 ppm recommended by the SFBIU (1984), the NH_3 concentrations measured in this study indicated the existance of a potential health hazard to operators exposed to the poultry environment for extended periods of time. Indeed, the short term exposure limit TLV of 35 ppm (ACGIH, 1984), based on a 15-minute exposure time not repeated more than four times daily, was exceeded throughout much of the production cycles in all three barns, suggesting the existance of a potential hazard to operators exposed to the environment for even short periods of time. Based on the accecptable upper limit of 20 ppm (Sainsbury, 1980; SFBIU, 1984), concern must also be expressed for bird health and performance, because of the continuous exposures to high NH_3 concentrations. With the exception of the first monitoring cycle in Barn BB, mean daily ambient concentrations in all cases were in excess of 20 ppm. The concentrations recorded

TABLE 5.11 OVERALL MEAN AMMONIA PRODUCTION AND CONCENTRATION DATA FOR BARNS BA, BB AND BC.

	Barn BA	Barn BB	Barn BC
NH_3 production, mL/(h.bird)	73.4	128.5	96.7
NH_3 ambient concentration, ppm	33	78	45
NH_3 exhaust concentration, ppm	25	61	34

in Barn BB give particular cause for concern, with the mean daily values reaching as high as 123 ppm. Although production was maintained at a high level in Barn BB, the same producer obtained better performances in Barn BC, possibly due to the lower NH_3 concentrations in that barn.

Although no data are presently available on the quality of the air environment in broiler breeder facilities, the overall mean NH_3 concentration in Barn BB was shown to exceed the overall mean NH_3 concentrations in layer barns under winter conditions in Alberta, as reported by McQuitty et al. (1985).

The existence of such high ambient NH_3 concentrations in all of the barns monitored, despite ventilation rates in excess of those recommended by Winchell (1982), demonstrates the inadequacy of these recommended values for NH_3 control. The maintenance of satisfactory relative humidities by the ventilation systems indicates that NH_3 control rather than moisture control should have been the criterion on which the design of minimum ventilation rates was based.

To eliminate potential hazards to operator health due to long-term and short-term exposures to high NH_3 concentrations as well as to optimise bird health and performance requires either (a) increasing the ventilation rate, causing an associated increase in supplemental heating demand or (b) reducing the rate of NH_3 production. The latter possibility could be achieved by increasing the frequency of manure removal which, in turn, could only be

achieved through the redesign of the traditional methods of manure storage in broiler breeder barns.

5.6 Hydrogen Sulphide Production

Because H_2S is not considered a primary contaminant in close confinement poultry housing, periodic monitoring of H_2S concentrations was carried out by a total sulphur analyser. During each monitoring day, the air was sampled for approximately 20 minutes.

The maximum detected H_2S concentration was 40 ppb during the first monitoring cycle in Barn BB. Only traces of H_2S (less than 20 ppb) were detected in subsequent monitoring cycles, with similar levels being detected in Barn BA and BC. Such concentrations were not considered hazardous, being far below the TLV of 10 ppm proposed by the ACGIH (1984) and the maximum cencentration of 5 ppm recommended by the SFBIU (1984).

The association of high H_2S concentrations with the disturbance of liquid manures seems to rule out the possibility of the occurrence of high concentrations during cleaning of the manures pits. However, no measurements were taken on the subject during the course of this study, prohibiting the formulation of recommendations in this regard.

5.7 Dust Concentrations

Dust particle counts were grouped into two overall size ranges to best describe the potential of the poultry environment as a health hazard to both operators and birds. Particles were classified as being either respirable (aerodynamic diameters less than 5 μm) or non-respirable (aerodynamic diameters greater than 5 μm), according to their ability to penetrate the lung tissue. The lower limit on particle counts was 0.5 μm, as this was the smallest size capable of being detected by the particle counter.

The mean concentrations of respirable and non-respirable dust particles for the light and dark hours of each monitoring cycle are given in Table 5.13. Because of the high dust concentrations encountered and the adhesive nature of poultry house dust, some instrument failure was expected and so, dust particle counts were not available for all data collection cycles. In all cases, the night time dust concentrations were found to be lower for both size ranges than the corresponding day-time values. As dust production in poultry housing is strongly dependent on the level of bird activity and since activity levels were lower during the dark hours, night-time dust production had been expected to be lower. Indeed maximum dust concentrations did correspond to times of peak bird activity, such as times when the mechanical feeders were activated or egg collection was being carried out or when the lights were switched on. Figures 5.4 and 5.5 demonstrate the diurnal fluctuations in respirable dust concentrations at 36 and 48 weeks for all

TABLE 5.12 MEAN RESPIRABLE AND NON-RESPIRABLE DUST CONCENTRATIONS FOR BARNS BA, BB AND BC (PARTICLES/mL).

Bird age, weeks	Light <5 μm	Light >5 μm	Dark <5 μm	Dark >5 μm	Mean Daily <5 μm	Mean Daily >5 μm
			Barn BA			
31	11.3	2.4	0.6	0.8	6.4	1.7
34	3.0	6.5	0.7	0.3	1.9	4.1
37	43.2	10.5	6.7	1.1	26.5	6.2
45	68.7	30.5	25.7	5.0	49.0	18.8
48	57.5	16.5	17.9	2.6	39.4	10.1
52	56.6	24.5	20.6	4.4	40.1	15.3
57	-	-	-	-	-	-
			Barn BB			
27	8.6	9.1	0.7	0.6	5.3	5.5
31	32.8	10.3	8.7	1.7	22.8	6.7
36	55.2	20.7	22.0	5.6	41.3	14.4
40	-	-	-	-	-	-
43	41.8	10.9	10.1	1.9	28.6	7.2
48	47.1	11.3	12.0	2.0	32.5	7.4
51	39.5	9.4	11.0	1.9	27.6	6.3
55	-	-	-	-	-	-
			Barn BC			
33	27.0	3.7	4.3	0.6	16.7	2.3
36	30.8	6.6	6.4	1.2	19.6	3.8
39	1.7	3.7	0.4	0.9	1.1	2.5
43	-	-	-	-	-	-
46	7.0	1.9	3.8	0.3	10.9	1.2

- No data taken due to instrument failure.

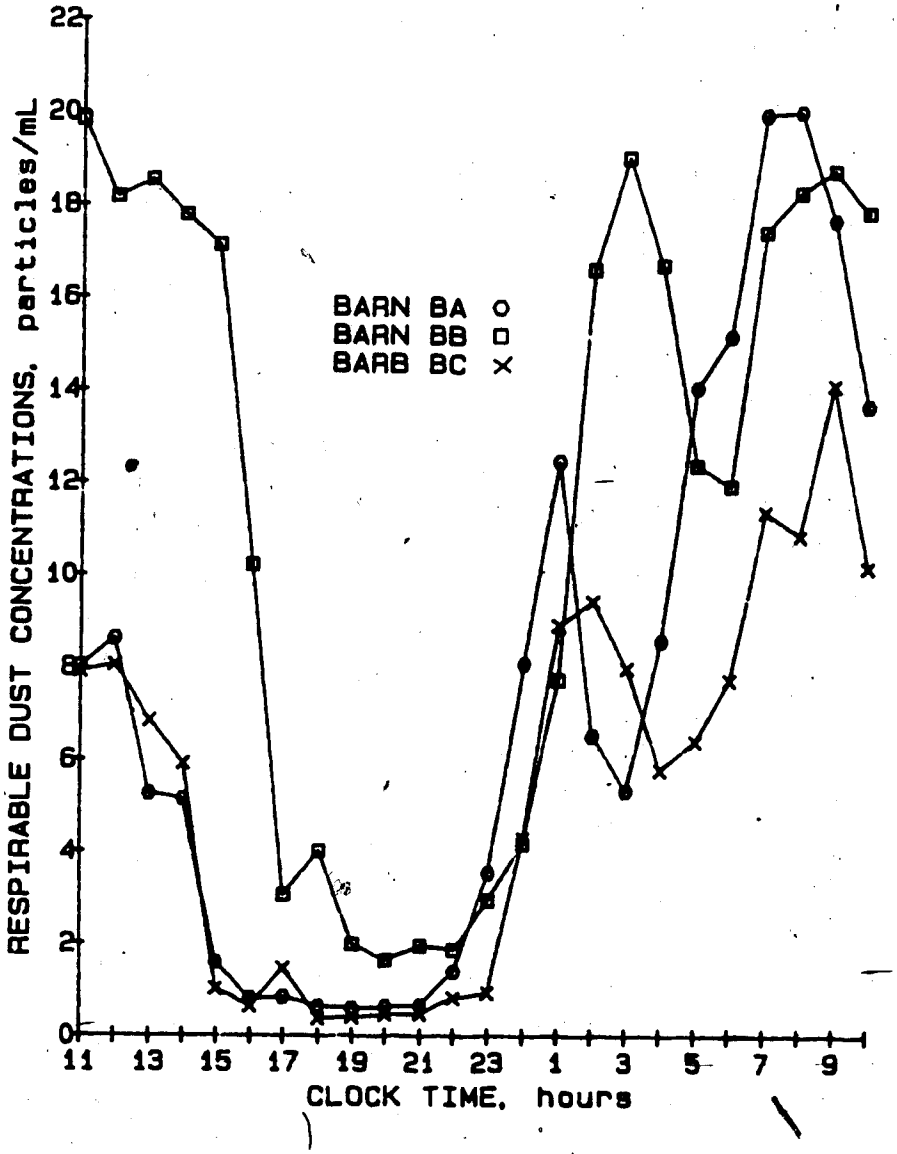


Figure 5.4 Respirable dust concentrations for a 24-hour period in three broiler breeder barns at 36 to 37 weeks into the production cycle.

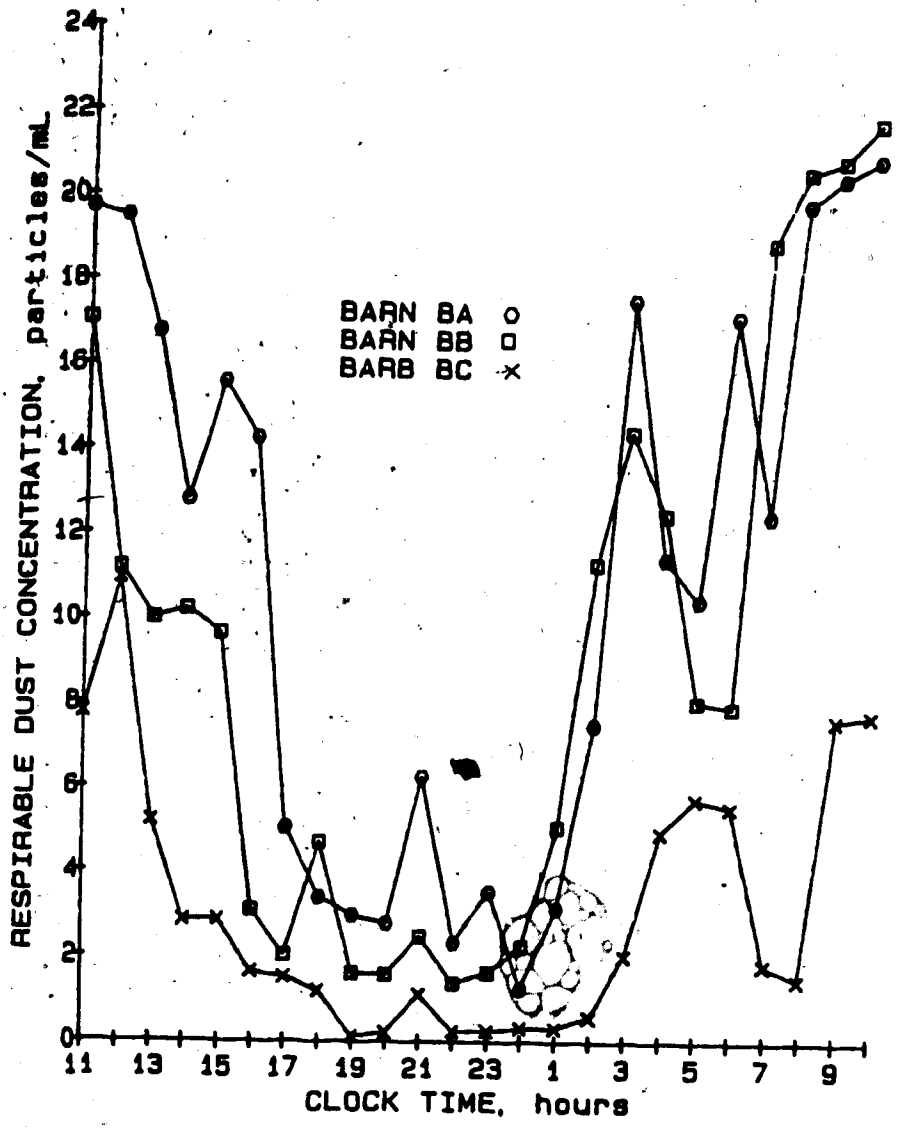


Figure 5.5 Respirable dust concentrations for a 24-hour period in three broiler breeder barns at 48 weeks into the production cycle.

three barns. The reduction in dust concentrations over the dark hours is clearly illustrated, with relatively sharp increases in dust production when lights were switched on, followed by another peak as feeders were activated. Figures 5.4 and 5.4 also illustrate the reduction in dust concentrations which occurred in Barn BC due to the increase in ventilation rates as the production cycle progressed.

Barn BA had the highest mean concentrations of particles less than 5 μm for both light and dark periods over the entire production cycle. Barn BA also had the maximum respirable dust concentration of 80 particles/mL, recorded during data collection at 45 weeks of age and corresponding to the time when feeders were activated. The same barn also had the highest non-respirable dust concentrations indicating higher overall dust production for this barn. Low ambient relative humidities and dry litter conditions, together with the more aggressive bird behaviour observed in this barn, may explain the higher dust production, while the low static pressure differentials and bad fan location for minimum ventilation requirements could have contributed to the high concentrations by prohibiting the exhausting of excess dust.

Barn BC had the lowest mean concentrations of both respirable and non-respirable dust over its production cycle due to the higher ventilation rates utilised in this barn. Although Barn BA had the highest mean overall ventilation rate, this value was misleading due to the extremely high

ventilation rates utilised during one 24-hour monitoring cycle. In practise, mean daily ventilation rates were much lower than the overall mean value.

The influence of manure storage system on dust production was difficult to determine because of the many different variables involved. The higher relative humidities in Barn BC, partly due to the increased evaporative efficiency of the deep pit system, probably resulted in lower dust production, while the location of the litter in deep pit storage could have prevented the transmission of dust particles generated in the litter into the poultry environment.

Leonard et al. (1984) and McQuitty et al. (1985) reported maximum values of mean dust concentrations over 24-hours of 7.5 and 39.7 particles/mL in broiler and layer facilities, respectively. These studies were carried out in Alberta under similar climatic conditions and the data were recorded using the same experimental procedures and equipment as used in this study. Comparisons of these values with the data in Table 5.13 demonstrate the lower quality of the breeder environment compared to the broiler environment, while dust concentrations in the breeder facilities tended to be lower than the overall mean concentration for the layer barns.

The dust concentrations found in the breeder environment did not exceed the TLV of 420 respirable particles/mL recommended by the ACGIH (1984). Using a

procedure developed by Jacobson and Tomb (1967), as cited by the ACGIH (1984), to convert particle count concentrations to respirable mass concentrations, the respirable dust concentrations measured in this study were found not to exceed the 4 mg/m^3 recommended by O'Blenis et al. (1984), with the maximum mean daily respirable dust concentration of 49 particles/mL occurring in Barn BA being equivalent to a respirable dust concentration of 0.23 mg/m^3. The dust concentrations were such, however, that working inside the breeder facilities for long periods became uncomfortable without the use of a dust mask.

Because of the lack of threshold limits on dust concentrations for poultry housing, no conclusions can be drawn on the effects of the dust concentrations encountered in this study on broiler breeder health and performance. Barn BA, however, with the highest mean respirable dust concentrations, also had the highest rate of bird mortality. Furthermore, the effects of the various combinations of particulate and non-particulate contaminants encountered cannot be assessed because of the lack of information pertaining to the consequences of such contaminant loads on the health and performance of both operators and poultry. The high NH_3 concentrations and substantial dust concentrations, however, in these three barns were, in the opinion of the author, an unpleasant and unacceptable combination.

6. Summary and Conclusions

Based on the results of this study, the following conclusions were drawn.

1. Overall bird total heat production rates ranged from 67.7 to 75.4 kJ/(h.bird), with mean daily values ranging from 44.3 to 112.9 kJ/(h.bird).
2. Overall means of the latent heat removed by ventilation ranged from 25.7 to 36.2 kJ/(h.bird), corresponding to a moisture removal rate of 10.0 to 11.9 g/(h.bird).
3. The ratio of latent heat to total heat in the exhaust air from the barns ranged from 0.34 to 0.42, with the highest value occurring in the deep-pit barn.
4. The proportion of bird sensible heat converted to latent heat in the evaporation of moisture ranged from 24 to 37%.
5. The effect of the manure storage system on bird total heat production was not considered significant.
6. Overall mean carbon dioxide production rates ranged from 3.6 to 3.8 L/(h.bird), with mean daily values ranging from 3.1 to 4.1 L/(h.bird).
7. RQ values obtained from bird total heat and carbon dioxide production data were in agreement with expected results.
8. Overall mean ammonia production rates ranged from 73.5 to 128.5 mL/(h.bird), with the highest values occurring in a barn utilizing shallow-pit manure storage.

9. Carbon dioxide concentrations were considered to be low in terms of health hazards (range of 1294 to 2727 ppm).
10. Ammonia concentrations in all three barns (range of 17 to 123 ppm) were considered to pose a potential health hazard to operator health even for short exposure times as well as being hazardous to poultry health.
11. The high ammonia concentrations measured in all three barns together with low measured relative humidities (range of 55 to 60%) suggests that ammonia control rather than moisture control should have been the criterion on which minimum ventilation rates were based.
12. The occurrence of high ammonia concentrations in the breeder barns studied suggests that management practices, such as the frequency of manure removal, should be altered to eliminate the potential health risks to operator and poultry health.
13. Hydrogen sulphide did not pose a problem in any of the barns monitored, the maximum concentration measured being 40 ppb.
14. Dust concentrations showed appreciable diurnal variations in all three barns, with the maximum recorded respirable dust concentration being 80 particles/mL, and, although below acceptable limits, were considered a major contributor to an unpleasant work environment in each instance.

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8. Appendix A - Processing Equations

The following equations were used in the Fortran program to convert raw voltage data to real units.

1. Thermistor-based Measurements:

a. Thermistor constant-current circuit;

$$R = E/I - L(RES)$$

where R = sensor resistance, ohms

E = output to data logger, volts

I = constant current of 0.5 mA

L = length of thermistor lead wire, m, and

RES = resistance of wire per 30.5-m-length

b. Temperature determination from resistance;

$$1/T = AX^3 + BX^2 + C$$

where T = temperature, °C

X = ln R

A = regression coefficient, $.209099055/10^6$

B = regression coefficient, $.275851225/10^3$

C = regression coefficient, $.137958851/10^2$

2. Dewpoint Measurement:

Dewpoint determination - (dewpoint hygrometer);

$$DP = 1.36D - 28.6$$

where DP = dewpoint, °C

D = output to data logger, volts

AA = regression coefficient, 1.36, and

BB = regression coefficient, 28.6

3. Air Quality Measurements:

a. Carbon Dioxide;

$$C = AK^2 + BK + C$$

where C = CO_2 concentration, ppm

A = regression coefficient, 0.038

K = output voltage, volts

B = regression coefficient, 0.4132

C = regression coefficient, 0.0424

b. Ammonia;

$$N = AD/2000$$

where N = NH_3 concentration, ppm

A = regression coefficient, 140.0

D = output voltage, volts

c. Hydrogen Sulfide;

$$H = 2.52\ D/1000$$

where H = H_2S concentration, ppm

4. Water Flow Measurements:

a. Doppler calibration;

$$F = AX + B$$

where F = water flow, m/s

A = regression coefficient, 0.315

X = Doppler reading, m/s

B = regression coefficient, -0.019

b. Flow calibration for bypass controller;

$$F = AV + B$$

where F = water flow, m/s

A = regression coefficient, 0.566

V = output from rectifier circuit, volts

B = regression coefficient, -0.927

5. Anemometer calibration:

Hot-wire:

$$Y = -3.179 + 0.999X$$

where Y = actual air velocity, m/s

9. Appendix B - Error Analysis

An error analysis was performed on the primary measurements made by the data acquisition system that were necessary to carry out a heat and moisture balance. A BASIC computer program was used to perform a simplified building heat and moisture balance. Initially, mean data for each of the three breeder barns were used to give representitive values for the heat and moisture parameters. These data were then varied according to the absolute errors associated with their measurement and the resultant deviations in the heat and moisture parameters from the representitive values were maximised by using different error combinations. This resulted in the maximum possible error in the heat and moisture parameters. Table B lists the data used in the determination of representitive heat and moisture balance parameters, along with the absolute error associated with the measurement of these data.

Barn BA:

Representative bird sensible heat production: 75.6 kJ/(h.bird).

Worst case error combination: 101.3 kJ/(h.bird)

Resultant error: 34.0%.

TABLE B PRIMARY DATA AND ABSOLUTE ERRORS FOR EACH OF THE THREE BARNS, USED IN THE DETERMINATION OF WORST CASE ERRORS FOR HEAT AND MOISTURE PARAMETERS.

Parameter	Barn BA	Barn BB	Barn BC	Absolute error
Ambient temperature, °C	17.5	18.9	18.8	0.2
Exhaust temperature, °C	18.1	18.0	18.2	0.2
Inlet temperature, °C	-3.5	-2.6	2.7	0.3
Outside temperature, °C	-3.1	-2.2	1.7	0.3
Dewpoint inside, °C	8.5	10.0	10.0	1.0
Dewpoint outside, °C	-5.0	3.6	3.4	1.5
Ventilation rate, L/s	2100	3015	3970	10%
Pipe in temperature, °C	52.7	56.9	32.9	0.2
Pipe out temperature, °C	57.9	66.3	46.7	0.2

Representative latent heat production: 41.9 kJ/(h.bird).

Worst case error combination: 54.1 kJ/(h.bird).

Resultant error: 29.1%.

Barn BB

Representative bird total heat production: 65.0 kJ/(h.bird).

Worst case error combination: 86.0 kJ/(h.bird).

Resultant error: 32.3%.

Representative latent heat production: 20.1 kJ/(h.bird).

Worst case error combination: 30.2 kJ/(h.bird).

Resultant error: 50.2%.

Barn BC

Representative bird total heat production: 66.2 kJ/(h.bird).

Worst case error combination: 88.5 kJ/(h.bird).

Resultant error: 33.7%.

Representative latent heat production: 25.8 kJ/(h.bird).

Worst case error combination: 37.0 kJ/(h.bird).

Resultant error: 43.4%.

10. Appendix C - Energy Balance Equations

1. Psychrometric Equations:

```
P = (10**(10.79586(1.0-TT)+5.0282ALOG(TT)+
    1.50474E-4(1.0-10**(8.29692((1.0/TT)-1.0))
    +0.42873E-3(10**94.76955(1.0-TT))
    -2.21958)(760)
W = 0.622 P/(B-P)
H = T + W(2501+1.86T)
SV = 2.16(T=273.16)/(B-W(B)/(0.622+W))
WS = 0.622 PS/(B-PS)
RH = (100W/WS)/(1.0-((1.0-W/WS)(PS/B)
```

where P = vapor pressure, mm Hg

TT = 273.16°K/(dewpoint °K)

W = humidity ratio, kg moisture/kg dry air

B = barometric pressure, mm Hg

H = enthalpy, kJ/kg dry air

SV = specific volume, m^3/kg dry air

WS = saturation humidity ratio, kg moisture/ kg dry air

PS = vapor pressure of saturated air, mm Hg, and

RH = relative humidity, %

2. Ventilation Rate:

```
Q = V A
```

where Q = ventilation rate, m^3/s

V = Exhausted air speed, m/s

A = duct area, m^2

3. Conductive Heat Losses:

C = E (TI-TO) N

where C = heat loss, kJ/h

E = exposure factor, kJ/(h.°C.bird)

TI = inside temperature, °C

TO = outside temperature, °C

N = number of birds

4. Supplemental Heat Input:

a. Using water flow rate;

H = (HWI-HWO) F A

where H = heat input, kJ/h

HWI = inlet water temperature, °C

HWO = outlet water temperature, °C

F = water flow rate, L/h

A = specific heat capacity of water,

= 4.187 (kJ/(°C.L)

b. Using coefficient of heat transfer;

H = L K (((HWI+HWO)/2)-TAMB)*3.6

where H = heat input, kJ/h

L = length of black-iron pipe, m

K = coefficient of heat transfer, W/(m.°C)

TAMB = ambient teperature, °C

5. Ventilated energy losses:

THL = Q(HI - HO)(3600)/SV

LHL = Q(WI - WO)(3600)/SV

SHL = THL - LHL

where THL = total heat loss, kJ/h

LHL = Latent heat loss, kJ/h

SHL = sensible heat loss, kJ/h

Q = ventilation rate, m^3/s

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

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

SV = specific volume, m^3/kg dry air

11. Appendix D - Data Output

The following is an example of the output from the energy balance program for a 24-hour monitoring period. Only the critical thermal and air quality parameters are detailed in this section. Other data not shown here include temperatures, dewpoints, enthalpies, static pressure differentials, as well as concentration data for CO_2 and NH_3.

TABLE D TYPICAL DATA OUTPUT FROM ENERGY BALANCE PROGRAM.

T	VHT	HTP	LHP	CO_2	V	EHT	NH_3
13	78.29	75.44	40.29	4.49	0.77	83.19	100.07
14	79.09	81.19	40.22	4.77	0.77	88.27	94.65
15	81.34	78.25	39.71	4.61	0.76	85.39	105.65
16	83.02	74.56	37.81	4.37	0.72	80.98	93.34
17	90.22	66.54	36.67	3.92	0.70	72.56	90.44
18	94.33	73.69	36.55	3.37	0.70	62.47	91.06
19	97.07	77.08	37.13	3.17	0.71	58.72	92.99
20	98.80	79.50	36.72	3.34	0.70	61.90	99.84
21	98.22	79.19	36.37	3.10	0.69	57.48	97.92
22	100.63	81.02	36.73	3.05	0.70	56.45	93.79
23	100.86	81.35	36.86	3.06	0.70	56.61	97.59
00	102.91	83.72	37.44	2.96	0.71	54.76	94.68
01	104.28	85.70	37.56	3.26	0.72	60.31	99.89
02	106.17	87.10	37.49	3.34	0.71	61.85	99.01
03	113.76	95.58	39.23	4.12	0.75	76.29	101.61
04	110.55	85.15	39.49	3.83	0.75	70.99	94.09
05	104.67	84.87	38.59	3.97	0.73	73.47	101.01
06	101.82	82.53	37.22	3.87	0.71	71.64	92.89
07	110.32	87.82	38.25	5.40	0.73	99.87	88.18
08	112.12	89.67	39.45	5.78	0.75	106.91	82.49
09	101.79	84.11	39.56	5.16	0.75	95.61	95.20
10	88.47	77.01	39.32	5.29	0.75	97.84	92.70
11	79.29	80.27	39.37	5.03	0.75	93.14	90.83
12	73.46	68.27	38.52	4.82	0.74	89.31	86.31

where T = time elapsed in hours with ~~the~~ starting time in the first column

VHT = ventilation heat loss, kJ/(h.bird)

HTP = bird total heat production, kJ/(h.bird)

LHP = latent heat production, kJ/(h.bird)

CO_2 = carbon dioxide production, L/(h.bird)

EHT = estimated heat production, kJ/(h.bird)

NH_3 = ammonia production, mL/(h.bird)

12. Appendix E - Heat Balance Components and Correction Factors

The relevant components of the heat balance for the data collection periods considered in error are presented here in uncorrected form, together with the correction factors applied to these data:

TABLE E HEAT BALANCE COMPONENTS AND CORRECTION FACTORS FOR THOSE MONITORING RUNS DEEMED TO BE IN ERROR.

Ventilation Rate L/(s.bird)	Ventilation Heat Loss kJ/(h.bird)	Bird Total Heat Production kJ/(h.bird)	CO_2 Production L/(h.bird)	CO_2 Correction Term
		Barn BA, Run No. 8		
0.93	129.75	79.15	4.09	0.822
		Barn BB, Run No. 3		
0.72	98.62	88.63	5.29	0.723
		Barn BB, Run No. 5		
0.68	102.97	93.48	4.36	0.836
		Barn BC, Run No. 4		
1.01	95.45	86.69	4.10	0.887
		Barn BC, Run No. 5		
1.12	81.47	81.66	4.01	0.871

13. Appendix F - Regression Analysis Relating Heat Production to Temperature

Based on the analysis of the calculated heat and contaminant production rates in broiler breeder barns, the following regression equations were considered the most applicable to predict these rates.

Y = heat or contaminant production rate, and

X = bird age, weeks

Bird total heat production, kJ/(h.bird):

Barn BA: $Y = -2742.47 + 197.06X - 4.45X^2 + 0.03X^3$

($R^2 = 0.85$)

Barn BB: $Y = 569.46 - 37.83X + 0.93X^2 - 0.01X^3$

($R^2 = 0.36$)

Barn BC: $Y = 2267.83 - 167.35X + 4.24X^2 - 0.04X^3$

($R^2 = 0.97$)

Bird sensible heat production, kJ/(h.bird):

Barn BA: $Y = -1385.49 + 98.27X - 2.16X^2 + 0.02X^3$

($R^2 = 0.86$)

Barn BB: $Y = 263.05 - 15.63X + 0.36X^2 - 0.01X^3$

($R^2 = 0.48$)

Barn BC: $Y = 196.86 - 4.72X - 0.07X^2 + 0.01X^3$

$(R^2 = 0.99)$

Bird latent heat production, kJ/(h.bird):

Barn BA: $Y = -1356.98 + 98.79X - 2.28X^2 + 0.02X^3$

$(R^2 = 0.78)$

Barn BB: $Y = 293.09 - 21.13X + 0.54X^2 - 0.01X^3$

$(R^2 = 0.15)$

Barn BC: $Y = 2208.12 - 172.67X + 4.55X^2 - 0.04X^3$

$(R^2 = 0.98)$

CO_2 production, L/(h.bird):

Barn BA: $Y = 7.14 - 0.13X + 0.001X^2$

$(R^2 = 0.83)$

Barn BB: $Y = 5.00 - 0.06X + 0.001X^2$

$(R^2 = 0.15)$

Barn BC: $Y = 6.77 - 0.11X + 0.001X^2$

$(R^2 = 0.99)$