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INDIRECT AND DIRECT CALORIMETRY IN A COMMERCIAL TURKEY FACILITY

by

CARL PATRICK MCDERMOTT

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled INDIRECT AND DIRECT CALORIMETRY IN A COMMERCIAL TURKEY FACILITY submitted by CARL PATRICK MCDERMOTT in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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Abstract

All animals produce heat as a product of their metabolic processes. The measurement of this heat production is called calorimetry and may be categorised into two methods, direct and indirect. Direct calorimetry measures sensible and latent heat separately. Sensible heat losses are determined by measuring the change in temperature across any medium surrounding the subject. Latent or evaporative heat losses are determined by measuring the rise in the moisture content of the air leaving the building or chamber that houses the subject. Indirect calorimetry measures the gaseous exchange caused by the oxidation of foodstuffs in the body. Knowledge of heat production is vital to the design of confinement facilities and environmental control systems in turkey housing. Data for design are limited and are often estimated from calorimetric data for other types of poultry. Both direct and indirect calorimetric methods have been utilised for obtaining data in laboratory studies. The main objective of this study was, to measure heat production from turkeys using both the direct and indirect calorimetric methods and to compare the results.

This study was carried out on a commercial turkey farm, consisting of a brooder and a grower barn. Both female (hen) and male (tom) turkeys were studied. The hens were studied for 24-hour periods once a week in the brooder barn and once every two weeks in the grower barn. Toms were monitored only in the grower barn for a 24-hour period once a week. All data necessary for calculating heat production were obtained using a data acquisition system for monitoring livestock facilities developed by the Department of Agricultural Engineering, University of Alberta. Hourly feed and water consumption data also were recorded.

Mean daily heat production from toms, measured directly, ranged from 21.4 W/bird at 64 days old to 69.3 W/bird at 106 days. Heat production from hens ranged from 3.0 W/bird at 16 days and 36.4 W/bird at 79 days. Direct calorimetry measured a higher value for heat production for 13 monitoring periods. Indirect calorimetry gave higher results on 4 occasions. Direct measured 4% higher than indirect calorimetry averaged over all the monitoring periods. Heat production varied directly with feed consumption rate and indirectly

with ambient temperature. Ambient temperatures were found to be lower than those recommended. This did not effect the growth rate adversely as the turkeys reached market weight four weeks earlier than normal. Feed consumption rates were higher than previously reported values.

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Table of Contents

List of Tables

List of Figures

Figure | Page

1. Introduction

We would not recommend any further direct experiments: the determination of heat production by indirect calorimetry is sufficiently accurate for most purposes of research (Benedict and Lee, 1937).

The shift from rural to urban lifestyle has caused a high demand for food and has led to traditional extensive livestock and poultry systems being replaced by highly efficient intensive ones. Livestock husbandry has become an industry with much emphasis placed on efficiency. This industry requires knowledge of all factors effecting production rates and therefore interactions between the animal and its environment must be known. Housing schemes must be comfortable for both operator and animal and designed for high production. Turkey producton has become intensified in recent years and the need for reliable data has increased.

Environmental control is critical in confinement turkey housing. To maintain ambient temperatures within the thermoneutral range, a ventilation system is used to control temperature during summer and a supplemental heating system is used to maintain minimum temperatures during winter. The ventilation system must dilute moisture, gases and aerial contaminants to acceptable levels during winter conditions to maintain an environment that is conducive to maximum growth. Reliable heat production data are necessary for designing systems that provide both adequate ventilation rates in summer and supplemental heat in winter. The assumption that minimum winter ventilation rates should be based on moisture control has been questioned (McQuitty, 1985). Carbon dioxide (CO_2), ammonia (NH_3) and dust levels in a barn can effect the health of both the operator and livestock. Therefore, knowledge of contaminant production, as well as moisture production, is important for determining the minimum ventilation rate.

Turkeys generate heat in both sensible and latent forms. Sensible heat is lost to the environment by convection and thermal radiation. Latent heat is derived from respiration however, some sensible heat can be converted to latent heat when it is used to evaporate moisture from the litter and waterers. This conversion depends mainly on ambient temperature, relative humidity and floor covering. Therefore, building latent heat includes both animal heat and evaporation from wet surfaces. Building latent heat depends on management practices and can only be measured accurately in a whole-house situation. Accurate measurement of animal latent and sensible heat values have been obtained using direct calorimeters, the adiabatic and gradient layer being the most favoured types. These calorimeters have become highly advanced and can measure heat and moisture production with an accuracy of ±1% (McLean, 1987).

Open and closed circuit indirect calorimeters have also been used to calculate heat production. Indirect calorimeters measure the oxygen (O_2) consumption and carbon dioxide (CO_2) production associated with metabolism. Different substrates have different CO_2 and O_2 contents thus the ratio of CO_2 production to O_2 consumption varies with food type. This ratio is known as the respiratory quotient (RQ). The RQ is indicative of the metabolic processes taking place in the body. For example, if an animal were starving and metabolising body energy stores, the RQ would be approximately 0.7, which is the RQ of fat.

Laboratory calorimetry is useful for many studies but does not account for environmental and management conditions imposed in the field. Sensible to latent heat conversion cannot be simulated in a laboratory accurately. With the improvement of data acquisition systems and instrumentation in recent years, it is possible to undertake studies on a whole-house basis. Heat, moisture, gas and aerial contaminant levels may now be measured in commercial housing operations to obtain reliable design data and to evaluate existing designs. Whole-house calorimetry has become more prevalent in recent years and research has been undertaken on a variety of poultry barns and on pig barns. To date there have been no studies on commercial turkey barns. Instrumentation for indirect calorimetry have also improved. Highly accurate and portable electronic gas analysers have made it possible to conduct indirect calorimetric measurements on housing units. Direct and indirect methods have compared favourably in laboratory tests, though, they have never been compared in field tests.

2. Literature Review

2.1 Calorimetry

2.1.1 History of Calorimetry

Organisms consume and digest foodstuffs in order to convert nutrients into energy. Some of this energy is excreted in the feces and urine, some is retained for growth and some is converted into heat. The measurement of this heat energy is called calorimetry and is important in animal energetics experiments. An accurate knowledge of sensible and latent heat production is required to design livestock buildings and environmental control systems that will provide an environment conducive to optimum livestock production. Both direct and indirect measurement techniques can be used to obtain data. Direct calorimetry requires the physical measurement of heat loss (by conduction, convection, radiation and as latent heat of water vaporisation) while the indirect technique measures the respiratory exchange to calculate energy production (Kleiber 1961; Blaxter 1967; Flatt 1969).

The first calorimeter was designed by Crawford (1778, as cited by Kleiber, 1975) and consisted of an insulated water bath. Heat production was calculated from temperature changes in the water. Two years later, Lavoisier and LaPlace (1780, as cited by Kleiber, 1975) designed a calorimeter which consisted of a chamber surrounded by ice which was then surrounded by an adiabatic jacket. The weight of the melted ice water was used to calculate the heat production. They also noted the similarity between the combustion of material and animal respiration. Calorimetric and respiration trials were carried out and indicated that combustion took place inside the body as well as outside. Lavoisier and Laplace concluded that fire and metabolism produced the same amount of heat per unit of carbon dioxide (CO_2) produced. Although the process is more complicated when substrates are metabolised rather than combusted directly, this theory proved to be correct and is the basis for indirect calorimetric techniques used to this day.

Rubner (1894, as cited by Flatt, 1969) designed a respiration chamber that was neither insulated nor adiabatic but was surrounded by two separated air spaces. Heat production was found by measuring the temperature change across the walls and the O_2 consumption and CO_2 production. In an experiment with dogs, Rubner found that the heat of combustion of the organic material in the urine plus the heat produced by the dogs was within one percent of the heat of combustion of the foodstuffs consumed by the dogs. Atwater and Rosa (1899, as cited by Flatt, 1969) designed a respiration calorimeter for human subjects in which both heat production and respiratory exchange could be measured simultaneously. This apparatus indicated good correlation between the O_2 consumed and the CO_2 produced and the heat produced.

Respiration calorimeters became more popular than direct calorimeters since they were easier to operate and gave more precise measurements. In recent years, indirect calorimetry has become more popular in laboratory studies since the equipment used for measuring gaseous exchange has become more accurate and easier to handle. Direct calorimetry, which measures the temperature gradient across the building wall, the change in the condition of the ventilated air and supplemental heating to calculate the heat production of the animals in the building, is preferred in whole-house calorimetry.

2.1.2 Direct Calorimeters

Early adiabatic direct calorimeters were cumbersome and difficult to operate. These consisted of a double-walled chamber which housed the animal. To prevent heat from flowing through the walls, the temperature of the outer wall was maintained at the same level as the inner wall by heating and cooling. A liquid-cooled heat exchanger removed the sensible heat and maintained equality between the air entering and leaving the chamber. Once the coolant flow rate and temperature rise were measured, the sensible heat from the animal could be calculated. Latent heat was calculated by measuring the ventilation rate and change in moisture content of the ventilating air.

Armsby (1904, as cited by McLean and Tobin, 1987) built an adiabatic chamber to accomodate cattle. The temperature of the outer wall was controlled by heating or cooling in such a way that no heat flowed from the inner to the outer wall. On the inner walls, heat given off by the animals was collected by water circulating in copper pipes. Thermocouple readings were taken every minute. Similarily, temperature and flow rates of cooling water were measured throughout the twenty-four hour period. This calorimeter proved to be labour intensive and difficult to use. Capstick (1921) and Deighton (1926) built slightly less complicated calorimeters using cooling pipes at the chamber surface as a heat exchanger. These were still very time consuming and expensive.

Benzinger and Kitzinger (1949) developed a gradient layer calorimeter which they claimed had a fast response time and gave accurate, precise results. The calorimeter consisted of a chamber and two platemeters (heat exchangers) all surrounded by a water jacket. The inside surfaces of these three components were lined with an insulating material. Thickness and thermal conductivity of the lining were made uniform so that the heat flow across the plates would be proportional to the temperature gradient between the inside and outside surfaces of the lining. This temperature gradient was measured by thermocouples interwoven in the plastic insulating material. The thermocouples were connected in series and placed at regular intervals in the lining, integrating the electrical outputs over the entire layer. The total voltage was then proportional to the sensible heat output of the subject.

Air entering the calorimeter was first cooled to a prescribed temperature T_2 and saturated with water vapour. It then passed through the first platemeter which raised the temperature to that of the chamber T_1. The heat gained being measured by the heat sensitive material lining the platemeter. Air then entered the chamber at T_1 with a dewpoint of T_2. The sensible heat being generated in the chamber passed through the heat sensitive material, exiting at the same temperature but with a higher moisture content, due to the evaporative heat from the animal. The air passed through the second platemeter, where the temperature was lowered to T_2 and the extra water produced by the animal was condensed out. Thus, sensible heat was calculated from the heat sensitive layer in the chamber. The difference between the heat gained by the air in the first platemeter and heat lost in the second platemeter was attributed to latent heat production.

In operating this calorimeter, only the output voltages from the thermocouples were necessary for calculating both sensible and latent heat. The majority of direct calorimeters built in recent years operate on either adiabatic or gradient layer principles (McLean and Tobin, 1987). A partitional calorimeter, based on the gradient layer principle which measures both convective and radiant heat production, was built at the University of Nebraska (Olson *et al.*, 1974). Sensible heat loss in this unit is measured continuously with a gradient layer thermopile, while radiative heat loss is measured by a 4-Pi radiometer lining the walls of the calorimeter. Conductive heat loss becomes negligible when the animal is suspended in a cage inside the calorimeter. Convective heat losses are found by subtracting the radiative heat from the total heat losses. The only major difference between this calorimeter and Benzinger and Kitzinger's gradient layer design is that latent heat production is calculated from the dewpoint temperature in the chamber. Considerable work has been carried out on laying hens in this calorimeter (DeShazer *et al.*, 1970; Riskowski *et al.*, 1977)

A calorimeter for studies on large farm animals was built at the Hannah Research Institute, Aberdeen and is described in detail by McLean and Tobin (1987). This calorimeter uses platemeters to measure evaporative heat loss; however, only approximately 1/16 of the ventilating air passes through the platemeters. This is done to limit the size of the platemeters whose heat sensitive layer must be then 16 times more sensitive than that in the chamber. Most of the sensible heat is detected in the chamber using a thermopile to measure the temperature of the exhausted air. If there is any difference between the inlet and exhaust air, this represents sensible heat from the animal not detected by the sensitive gradient layer in the chamber but by the platemeters. Temperature is measured by thermojunctions between a ribbon of copper and constantan soldered together at regular intervals and wound around strips of Tufnol insulation. This calorimeter can operate within a temperature range of 10 to 40 °C and has an accuracy of approximately ±1%.

2.1.3 Whole-house Calorimetry

Whole-house calorimetry is based on direct calorimetry principles and heat production is calculated from the difference in temperature and moisture of air entering and leaving a building. The general equation for direct whole-house calorimetry is:

$$\text{Heat produced} = \text{Building} + \text{Ventilation} - \text{Supplemental} \qquad (2.1)$$

The measured quantities in the heat balance are heat losses through the building structure and the ventilation system, and the supplemental heat added to the building. Building heat losses through the floor, footing, walls and ceiling can become heat gains during warm periods with high solar radiation. This value depends on the type of structure and the thermal conductivity of the building components. When the heat produced by the animals is not sufficient to maintain building temperature within the animals' thermoneutral zone, supplemental heat is required. In very warm conditions, supplemental heat may be in the form of air chilling and is expressed by a positive value in the above equation. Supplemental heat is usually provided by hot air furnaces or hot water pipes running along the interior walls of the building.

Both sensible and latent heat are lost through ventilation. Minimum ventilation rates are based on controlling concentrations of moisture, and other airborne contaminants, while maximum rates are based on temperature control during hot summer conditions (McQuitty, 1985). Interior and exterior dry-bulb temperatures and dewpoints must be measured accurately. This is usually done with thermistors and some form of humidity sensor. Supplemental heat provided by black-steel water pipes, may be calculated by measuring the temperature differential across the heater and the circulation rate of the hot water (Feddes *et al.*, 1984a). Fan-speed sensors are used for measuring ventilation rates and these are correlated to the mass air-flow rate which can be measured manually using, for example, a hot wire anemometer (Clark *et al.*, 1984). The heat loss across the walls, ceiling, footing and floor also must be measured. Heat loss can be calculated when all the thermal resistances and temperature gradients are known for a structural component. Alternatively, use of heat flux plates as described by DeShazer *et al.* (1982) can be used to measure the heat flow through the building structure.

Whole-house calorimetry has proved very useful in measuring heat and moisture production in livestock and poultry. With the use of data acquisition systems and computers, data can be collected at short intervals over long periods of time with little manual effort. Feddes *et al.* (1984) measured the heat and moisture production from broilers using instrumentation that recorded data every 4 minutes and less transient data every 20 minutes for a period of 24 hours. Feddes *et al.* (1985) undertook similar tests on three egg laying units under winter conditions in Alberta. Heat and moisture production rates were measured during light and dark periods. Whole-house calorimetry includes data on local effects such as housing type, management practices and environmental conditions which are unobtainable in laboratories and therefore provides more accurate information for maximum productivity.

2.1.4 Indirect Calorimetry

There are two basic methods of indirect calorimetry. The first requires the calculation of heat production from respiratory exchange data and the second relies on carcass analysis combined with energy balance studies. Most animal metabolic experiments use respiratory calorimetry which involves the measurements of O_2 consumption and CO_2 and urine production. General procedures have been established (Kleiber, 1961). Gaseous exchange is the most widely-used form of indirect calorimetry because of its ease of operation and accurate results.

Respiratory exchange calorimetry calculates heat production from O_2 consumption and CO_2 production when organic compounds are converted into energy by animals. These organic compounds may include feed or any body stores being oxidised at the time. The ratio of mols or volume of CO_2 produced to mols or volume of O_2 consumed is known as the respiratory quotient (RQ). Different substances have different carbon (C) and O_2 contents and so the relative amounts of O_2 consumed and CO_2 produced will vary depending on the substance. Heat production calculations from animals are based on the assumption that O_2 consumption, CO_2 production and nitrogen (N) excretion result from the oxidation of carbohydrates, fats and proteins. Blaxter (1967) gave a detailed description of the processes involved in the oxidation of these substances. This description is summarised below.

Carbohydrate Oxidation:

The oxidation of a carbohydrate such as glucose would be:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + 2817\ kJ \qquad (2.2)$$

1 mol glucose	134 L	134 L	Heat of combustion
180 g	191 g	264 g	

For every mol of glucose oxidised, 6 mols of O_2 (134 L or 191 g) are consumed and 6 mols of CO_2 are produced (134 L or 264 g). This reaction will produce 2817 kJ of heat which means that, for every litre of O_2 consumed and CO_2 produced, 21 kJ of heat will be produced. In this instance, the respiratory quotient is 6/6 or unity. Blaxter (1967) conducted a study to investigate whether these values can be applied to all carbohydrates consumed by animals. Blaxter measured the heat of combustion of compounds likely to be found in food and compared these values to that used for glucose. Table 2.1 shows the actual heat of combustion determined by a bomb calorimeter, the calculated value and the percentage error in using the glucose equation. For most substances the error was less than 1% with glycogen, starch and cellulose being the exceptions. Errors of up to 6.4% will occur with these compounds, however; these are minor food constituents.

Fat Oxidation:

As with carbohydrates, the oxidation of fats involves the consumption of O_2 and the production of CO_2 and water. For example, the oxidation of palmitic acid would be:

$$CH_3(CH_{12})_{14}COOH + 23O_2 = 16CO_2 + 16H_2O + 10037\ kJ \qquad (2.3)$$

1 mol palmitic	515 L	358 L	heat of combustion
256 g	736 g	704 g	

Thus, for every mol of palmitic acid oxidised (256 g), 23 mols (515 L. or 736 g) of O_2 will be consumed, 16 mols (358 L or 704 g) of CO_2 and 10037 kJ of heat will be produced. Therefore, for every litre of O_2 consumed 19.5 kJ of heat will be produced and for every litre of CO_2 produced 28 kJ of heat will be produced. In this case, the respiratory quotient is 16/23 or 0.7. Table 2.2 shows the determined values for the oxidation of different fats, the calculated values using palmitic acid as the reference equation and the % error.

Table 2.1 Actual heat of combustion of carbohydrates in food, calculated heat using glucose as a representative and the bias (calculated/determined)x100 (Blaxter, 1967).

Compound	Determined Heat kJ/mol	Calculated Heat kJ/mol	Bias
Glucose	2817	2817	100.0
Galactose	2807	2817	100.3
Fructose	2828	2817	99.6
Sucrose	5649	5633	99.7
Lactose	5654	5633	99.6
Maltose	5651	5633	99.7
Raffinose	8478	8450	99.7
Glycogen (/g)	17.23	16.38	95.0
Starch (/g)	17.49	16.38	93.6
Cellulose (/g)	17.5	16.38	93.6

The Oxidation of Protein:

The oxidation of protein in the body is an incomplete process. Nitrogen is not completely oxidised but is excreted from mammal's bodies as urea. In calculating the heat of combustion of an amino acid, the heat of urea oxidation must be subtracted from the value for the heat produced by a completely oxidised amino acid. The associated O_2 consumption and CO_2 production with urea oxidation must also be subtracted from the amino acid equation. For example, when analine is oxidised in the body the reaction is:

$$2CH_3CH(NH_2)COOH + 6O_2 = 5CO_2 + 5H_2O + CO(NH_2)_2 + 2611\ kJ \qquad (2.4)$$

2 mols analine	134 L	112 L	1 mol urea	heat of combustion
178 g	192 g	220 g	60 g	

This equation gives the heat of reaction when analine is oxidised into CO_2, water and urea. Thus, for every two mols of analine oxidised 6 mols of O_2 are consumed, 5 mols of CO_2 and one mol of urea are produced. The thermal equivalents are 19.4 kJ/L O_2 consumed and 23.3 kJ/L CO_2 produced. The RQ becomes 0.83 and will be different for various amino acids. Likewise, the heat equivalents for O_2 and CO_2 will be different.

Table 2.2 Actual heat of combustion of fats in food, calculated heat using palmitic acid as a representative and the bias (calculated/determined)x100 (Blaxter, 1967).

Compound	Determined Heat kJ/mol	Calculated Heat kJ/mol	Bias
Formic	272	289	106.1
Acetic	876	939	107.1
Propionic	1537	1589	103.2
n-butyric	2194	2239	102.0
n-valeric	2853	2889	101.3
Caproic	3478	3539	101.7
Lauric	7416	7439	100.3
Myristic	8730	8738	100.1
Palmitic	10037	10037	100.0
Stearic	11350	11338	99.9
Arachidic	12665	12639	99.8
Behenic	13973	13938	99.8
Oleic	11121	11158	100.3

Calculating thermal equivalents based on representative samples will create inaccuracies. Blaxter (1967) stated that for most studies, constants based on mixed fats, proteins, starch and cellulose can be used. In 1958, the First Symposium on Energy Metabolism, sponsored by the European Association for Animal Production was held in Copenhagen, Denmark. A committee was appointed at this meeting to consider and recommend factors for use in metabolic calculations (as cited by McLean and Tobin, 1987). Values recommended by the committee are shown in Table 2.3 (Brouwer 1965). This table shows the O_2 consumption and the heat and CO_2 production per gram of substance oxidised. If these factors are not sufficiently accurate for a particular experiment, reference compounds typical of the substances being oxidised can be used (Blaxter, 1967).

The respiratory quotients are indicative of metabolic processes. For example, if an animal were only oxidising fat, then the RQ value would be expected to be 0.7 or, if only carbohydrates were being consumed, then the RQ value would be 1.0. Other substances can also be oxidised and give different RQ's; alcohol yields an RQ of 0.667 and glyceronic acid yields an RQ of 1.2 (Swan, 1974). Synthesis of fat from carbohydrate can give rise to a maximum of 1.3 (Blaxter, 1967). However, Benedict and Lee (1938) found RQ values as high as 1.47 in force-fed geese. Kleiber (1975) reports that RQ values less than 0.7 may be taken as an index of the formation of carbohydrate from fat.

Table 2.3 Constants for typical protein, fat and CHO oxidation by animals (Brouwer 1965).

Compound	O_2 Consumed per gram		CO_2 Produced per gram		Heat Produced	RQ
	g	L	g	L	kJ	
Protein	1.366	0.957	1.520	0.774	18.42	0.81
Fats	2.875	2.013	2.810	1.431	39.76	0.71
Starch	1.184	0.829	1.629	0.829	17.58	1.00
Saccharose	1.122	0.786	1.543	0.786	16.57	1.00
Glucose	1.066	0.746	1.746	0.746	15.65	1.00

Calculation of heat production:

The data in table 2.3 were based on the breakdown of carbohydrates, proteins and fats as given by Lusk (1928) and Carpenter (1948). These data did not take into account the incomplete combustion of carbohydrates and the formation of combustible gases mainly in the form of methane (CH_4). These combustible gases must be considered in calculating heat production by indirect calorimetry. Different equations have been derived based on varying assumptions (Weir, 1949; Boyd, 1953; Brouwer, 1958; Hoffman, 1958). The Committee on Constants and Factors, whose report was prepared by Brouwer (1965), recommended the use of a multiple regression equation which takes CH_4 production and urinary N into account. This formula which recommended for use with ruminants and was adopted at the Third

Symposium on Energy Metabolism held in 1964 at Troon, Scotland (Brouwer, 1965), and is as follows:

$$HP = 3.866\ O_2 + 1.200\ CO_2 - 0.518\ CH_4 - 1.431\ N \tag{2.5}$$

where:

HP = heat production, kcal,

O_2 = oxygen consumed, L,

CO_2 = carbon dioxide produced, L,

CH_4 = methane produced, L, and

N = urinary nitrogen, g.

Equations that require only the measurement of O_2 consumption also have been derived and are useful in certain experiments (Weir, 1949; McLean, 1971). However equation 2.5 is the most widely used in experiments on man and mammals.

2.1.5 Indirect Calorimetry for Poultry

The equation for indirectly calculating heat production will be slightly different for poultry than for mammals. In the latter, the excretion of N in the urine is in the form of urea while in poultry it is mainly in the form of uric acid. Uric acid has a greater O_2 content than urea, thus the RQ of protein catabolism in poultry is lower than in mammals. Coulson and Hughes (1931) showed that 65.8% of N in the fowl's urine is present as uric acid and only 6.45% as urea. The remainder is made up of ammonia, creatin-creatinin, purin and allantoin. Barrot *et al.* (1938, as cited by Romijn and Lokhorst, 1964) derived a formula for heat production in poultry by calculating the heat equivalent of protein in the fowl as well as the O_2 consumption and CO_2 production when protein is metabolised:

$$HP = 3.871\ O_2 + 1.194\ CO_2 - 2.375\ N \tag{2.6}$$

The only significant difference between equations 2.5 and 2.6 is that the coefficient for protein metabolism is higher in the avian equation than in the mammilian equation. If protein is entirely ignored, an error of only 0.6% results (Romijn and Lokhorst, 1964), so the formula in its simplistic form becomes:

$$HP = 3.871\ O_2 + 1.194\ CO_2 \tag{2.7}$$

Mitchell *et al.*, (1935) showed that indirect calorimetry is only applicable when dealing with RQ values between 0.707 (fat) and 1.00 (carbohydrates). When dealing with fowl many researchers have found RQ's of less than 0.707 and slightly above 1.00 (Dukes, 1937; Farrell, 1974; Morrison and Leeson, 1978) and so this casts some doubt on the validity of indirect calorimetry in poultry. However, the instances of low or high RQ values have been declining, partly due to the advent of more sophisticated and accurate instrumentation.

2.1.6 Comparison of Direct and Indirect Calorimetry

Indirect calorimetry is an inexact method for measuring heat production as it depends upon certain approximations. However, these errors are small and in most cases give estimates close to that of direct measurement (Blaxter, 1967). All comparisons of direct and indirect calorimetry have been undertaken in laboratories with calorimetric chambers. There are no reported comparisons involving whole-house calorimetry in the literature. The first laboratory comparison was made by Rubner (1894, as cited by Flatt, 1969), who measured the total heat production of dogs in a respiration chamber. This heat production was compared to the estimated metabolisable energy of the food eaten by the dogs. The average heat production from the two methods agreed within less than 1%. Atwater and Rosa (1899) compared the two methods on human subjects using carbon and nitrogen balance experiments. Their results agreed so well that they concluded that the law of conservation of energy applies to living organisms.

Armsby and Moulton (1925, as cited by Flatt, 1969) constructed an adiabatic respiration calorimeter to study the energy metabolism of cattle. In studies with steers and lactating cows, agreement was obtained within 1% between the direct and indirect methods. Forbes *et al.* (1928) used the same calorimeter for later tests on steers and found a comparison between the two methods to be within 3%. However, not all comparisons have provided such good results. Pullar *et al.* (1967) described a number of experiments where discrepancies of up to 31% were encountered. The first experiment used human subjects and based calculations on CO_2 production and O_2 consumption. Direct measurements were higher than indirect estimates by an amount varying between 6 and 31%. A later experiment using paramagnetic and infrared analysers for O_2 and CO_2, respectively gave discrepancies varying between -12.2% and 22%. The differences in the latter experiment were attributed to inaccurate calibration procedures, and in the former experiment to poor experimental design. A further experiment with chickens showed discrepancies between 3% to 12%. In this case, the direct method was a gradient layer calorimeter and the indirect method was based on carcass analysis. Direct measurements were lower than indirect measurements.

2.2 Heat Production by Livestock and Poultry

2.2.1 Partitioning of Energy

Animals obtain energy from a number of sources. Energy in the form of light is converted by the eye to chemical energy. Sound produces mechanical energy in the ear which eventually becomes electrical energy (Blaxter, 1967). These events, however, are insignificant compared to food, the main source of energy. All living beings must consume food and convert this food to energy necessary for survival, growth and production. The partitioning of energy in the body was described by Young (1986) and is summarised here. Intake Energy (IE) is the total combustible energy of the food, absorbed by the body and used for a variety of functions. However, some of this energy will be excreted in the feces. Apparent Digestible

Energy is the IE intake minus the Fecal Energy (FE). This is referred to as 'Apparent' because not all energy in the feces comes directly from the energy in the food, as feces also contains endogenous material. Energy is also lost in the urine (UE) and in the form of CH_4 as Gaseous Energy (GE). The remaining energy is Metabolisable Energy (ME) and is utilised for maintenance functions and production. The equation for energy partitioning is :

$$IE = ME + FE + GE + UE \quad (2.8)$$

Esmay (1977) noted that between 70% and 90% of IE in poultry was available for metabolism. ME is first used for maintenance functions such as finding food, eating, digesting, maintaining body functions and adapting to environmental changes. The remainder of the ME is then available for growth or animal products such as milk or reproduction (Blaxter, 1967). Figure 2.1 shows the partitioning of energy through a ruminant's body (McLean and Tobin, 1987).

Poultry have similar pathways for energy in the body, gaseous energy losses are lower and the expelled products are eggs and feathers instead of milk and wool. Metabolic Heat Production (MHP) is the release of heat as the maintenance requirements and production processes in the body take place. McLean (1973) stated that MHP from mammals is a function of surface area while Monteith (1973) noted that MHP is a function of age, diet and weight. Kleiber (1961) calculated that heat production was proportional to body weight raised to the power of 0.75. Monteith (1973) found that surface area is proportional to body weight raised to the power of 0.66.

2.2.2 Zone of Thermoneutrality

Poultry are homeothermic, that is they maintain a constant body temperature despite changes in their surrounding thermal environment. The surrounding thermal environment includes all the influences of wet- and dry-bulb temperature and of air-velocity. These factors all effect the rate of heat loss or gain by the body and their combined effect is termed

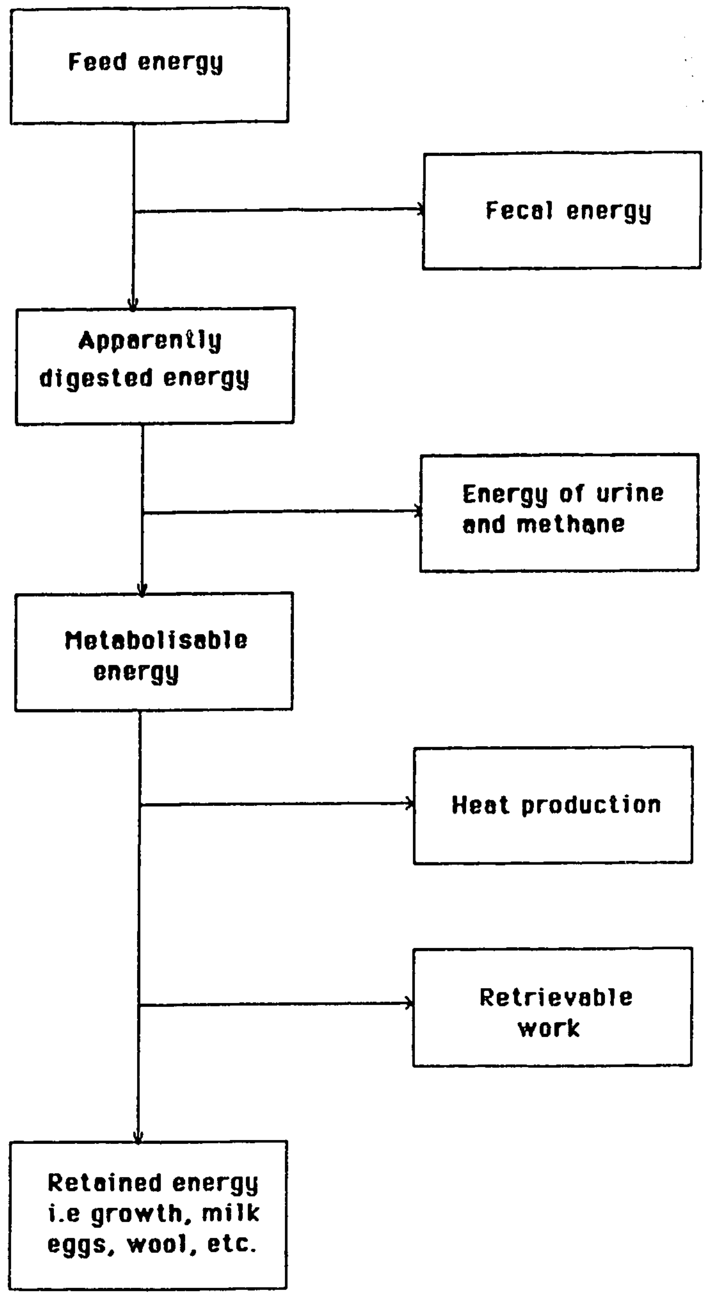

Figure 2.1 Partitioning of energy in the body (adapted from McLean and Tobin, 1987).

effective environmental temperature. The more energy that poultry use to maintain their body temperature, the less energy is available for growth. If the digestible energy intake were less than the maintenance energy requirements, energy stores will be depleted from fat and muscle until death occurs. Every animal has a zone of thermoneutrality, this being a temperature zone where the MHP of the animal is at a minimum. The range is dependant on the ability of the animal to adjust its heat production both physiologically and behaviourally. In a thermally-neutral environment, the MHP will be a function of body size and diet. Figure 2.2 shows the basic relationship between the rates of heat production and the effective environmental temperature.

This diagram shows that the thermoneutral zone lies between the critical temperature and the temperature of incipient hyperthermal rise. Clark *et al.* (1981) showed that heat production in this zone is independent of effective environmental temperature. Below this lower critical temperature (LCT), heat production rises as the environmental temperature drops, this heat production being a sensible heat loss only. The evaporative, or latent, heat losses remain at a minimum. Above the critical temperature, sensible heat production drops to zero while latent heat production increases. Poultry lose latent heat through their respiratory system by panting. Figure 2.2 shows that once the temperature rises above the temperature of incipient hyperthermal rise, heat production increases until eventually death occurs. This is correct if feed consumption were to remain constant. In practice, the bird will decrease feed consumption and heat production will decrease.

2.2.3 Thermoregulatory Mechanisms

Thermoregulatory mechanisms are behavioural and physiological. Humans regulate their temperature by exercising, shivering or moving to a warmer area. Poultry also can regulate their temperature by activity. However, in intensive production there is not much room for excessive movement so huddling is the best method of conserving heat. Heat losses can very greatly with posture. DeShazer *et al.* (1970) found an increase in sensible heat loss of between 20 and 40% for a hen in a standing rather than a sitting position. Esmay (1977) noted a 12% decrease in heat loss for chicks when they had their heads under their wings.

Physiological thermoregulatory mechanisms involve the regulation of the MHP. All homeotherms have some type of temperature sensor that triggers the body to create, conserve or waste heat. Benzinger (1961) stated that a thermostat existed which sensed the temperature of the blood entering the anterior hypothalmus and that this sensor was extremely sensitive, being capable of noticing changes as low as 0.01°C. Cutaneous sensations of heat or cold in the environment and changes in skin temperature are also inputs to the thermostat control (Corbit, 1969). In addition, Rawson *et al.* (1969) stated that there were some other deep

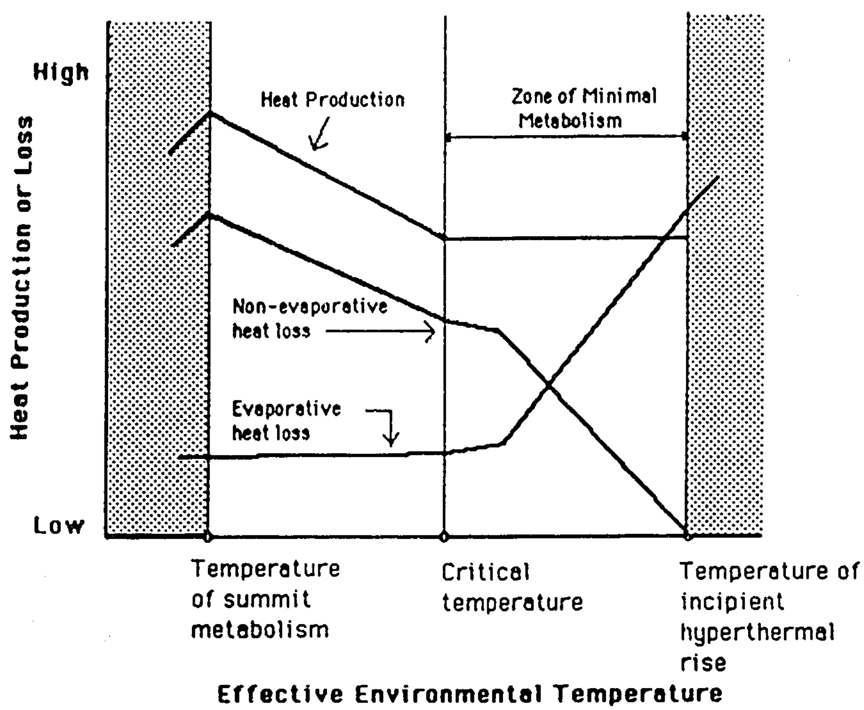

FIGURE 2.2 Schematic diagram of the relationship between MHP and environmental temperature (adapted from Baxter, 1984).

tissue or blood vessel thermoreceptors. Information from all these sensors is accumulated and thermoregulation is then activated by one or more of five processes (Benzinger, 1969, as cited by Swan, 1984). They were as follows:

1. excitation of sweating by central warm reception
2. dilation of blood vessels caused by central warm reception
3. suppression of thermogenesis by central warm reception
4. inhibition of sweating by peripheral cold reception
5. excitation of metabolic thermogenesis by peripheral cold reception.

When temperatures are below the thermoneutral zone, poultry can increase their heat production to between 3 or 4 times that at thermoneutrality (Esmay, 1977). This large increase of heat production is brought about mainly through shivering (Scott, 1976). Heat production from poultry has been measured both directly (Ota and McNally, 1961) and indirectly (Farrell, 1971) in laboratories. Direct whole-house calorimetry also has been carried out more recently by some researchers (Reece *et al.*,1969; Feddes *et al.*, 1984). However, heat production values for turkeys are very limited. When designing turkey barns the use of heat production data from heavy chickens is recommended (ASHRAE, 1981).

2.2.4 Heat Losses in Poultry

Heat losses from birds and mammals can be categorised into two types. The first is termed sensible heat loss, which involves losing heat through radiation, convection and conduction. The second type is called latent heat loss, which involves using sensible heat supplied by the animal to vapourise water from the skin and respiratory passages. Latent heat losses are much more predominant in hot temperatures as can be seen from Figure 2.2. Sensible heat losses are usually in the form of convective and radiant heat transfer when turkeys are housed in a barn. Conductive heat losses or gains require the turkey to be in contact with a body having a different temperature. In commercial conditions, conductive losses occur through contact with the earthen floor of the barn.

Sensible heat losses depend mainly on the covering of feathers, which provide very good thermal insulation. This insulation value can be increased if the birds increase the surface area of insulation by fluffing their feathers. Wathes and Clark (1981) found that heat production could be decreased by 50% with good feather covering. For areas not covered by feathers, sensible heat is lost from the surface of the skin. This loss is proportional to the temperature gradient between this surface and the ambient air and is also related to the air speed over the skin. Convective heat losses will increase in draughty conditions.

3. Objectives

Turkey production has become highly intensified in recent years and so the necessity for heat production data has become important. In order to provide an acceptable environment for the turkeys, heat production must be measured in a field situation. If indirect methods of measuring heat production and examining metabolic activity under different environmental conditions are to be carried out on a whole-house basis, then indirect calorimetry results must be compared to direct results. The data acquisition system developed in the Department of Agricultural Engineering, University of Alberta, and built for whole-house direct calorimetric measurements, was equipped with an O_2 and CO_2 analyser. Using this system which was housed in a mobile laboratory, a commercial turkey facility was monitored with the following objectives:

1. To compare direct and indirect calorimetry on a whole-house basis.
2. To determine the total heat production of toms in the grower barn and of hens in both the brooder and grower barns.
3. To study the dynamic aspects of heat production in terms of the diurnal patterns, changes in metabolic activity throughout the life cycle, and response to different ambient temperatures.
4. To compare different RQ values between toms and hens.
5. To establish whether the ventilation system was adequate for maintaining acceptable air quality in the brooding and growing facilities.
6. To establish if the supplemental heating system was adequate in severe winter conditions.

4. Experimental Methods and Equipment

4.1 Facilities

4.1.1 Barn Studied

This study began on January 8, 1988 and was completed on May 19, 1988. A 5000-bird turkey farm situated in Neerlandia, 150 km northeast of Edmonton, Alberta, was studied. The turkey housing facilities were less than two years old and consisted of a brooder barn and a grower barn. Both barns had automatic feeders and waterers which were accessed *ad libitum*. Supplemental heating was controlled thermostatically. Each barn, was monitored separately. Figure 4.1 shows a floor plan of the housing facilities.

The brooder barn was 12 by 51 metres and had a solid concrete floor that was initally covered with sawdust. Supplemental heat was provided by a hot water heater and 51-mm black steel pipes running along the east and west walls and under the concrete floor. Figure 4.2 shows a cross-section of the barn with the heating pipes and some ventilation details. The ventilation system consisted of five variable-speed fans, which were blocked and insulated until required. Only one fan was required when the one day old poults were first placed, due to high ambient temperature requirements and low moisture and contaminant production. After two weeks, a second fan was required to compensate for increased moisture production as the poults grew. One week later a third fan was switched on. Two of the fans were not operated during the entire study period as minimum ventilation rates were in effect. The fans were controlled by thermostats, one thermostat controlling two fans at the north end and two fans at the south end of the barn and a third controlling the central fan. Air entered the barn via an adjustable fresh air inlet situated along the full length of the west wall opposite the fans. Thermal resistance of the walls was calculated from the construction components and verified by measurements of heat flux during the data acquisition period. The estimated thermal resistance was 7.1 $(m^2 \cdot {}^\circ C)/W$ for the walls and 10.6 $(m^2 \cdot {}^\circ C)/W$ for the ceiling.

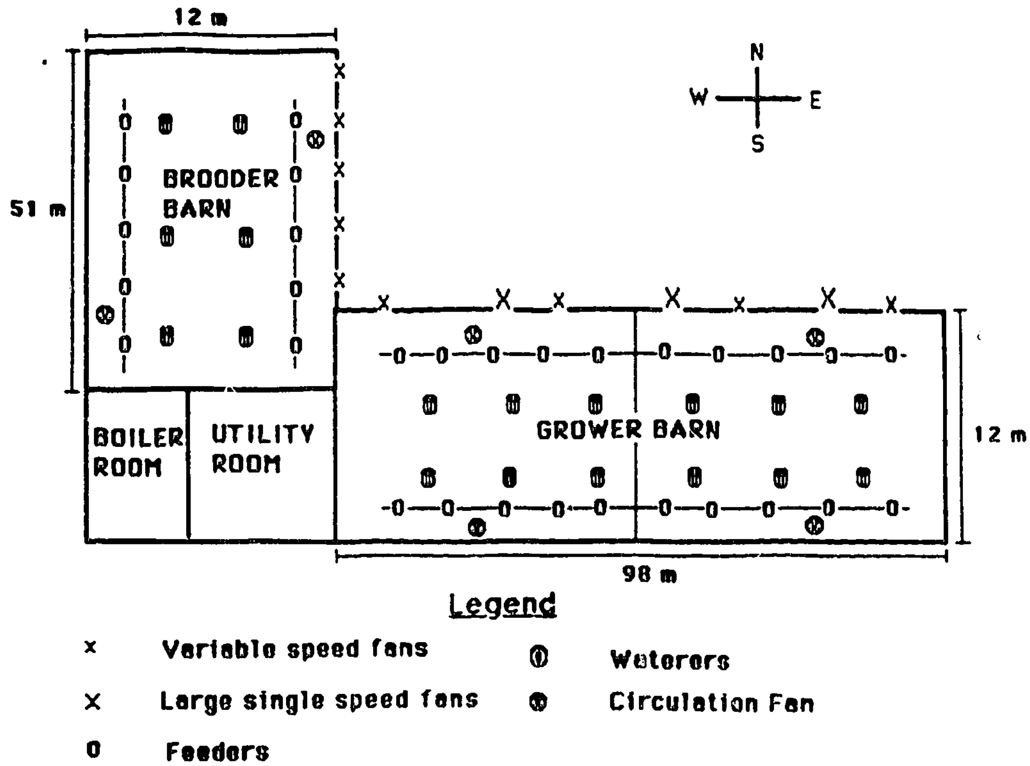

Figure 4.1 Plan view of the housing facilities with waterers and feeders (not to scale).

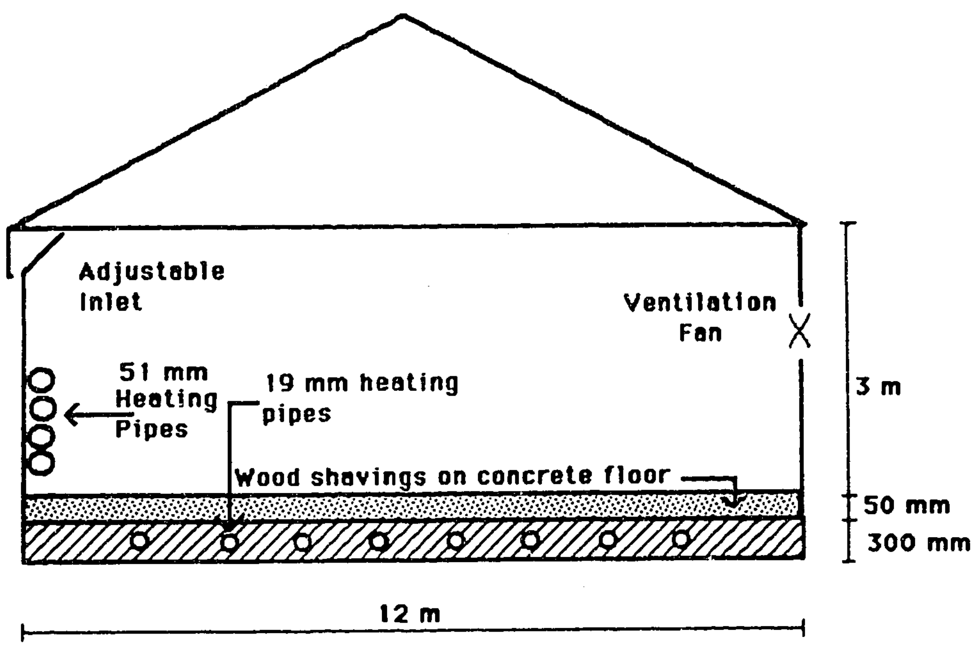

Figure 4.2 Cross-sectional view of the brooder barn showing heating pipes and inlet location (not to scale).

Turkeys were housed in this barn from one day to 8 weeks of age.

Figure 4.3 shows a plan view of the brooder barn with the locations of the sensors and sampling tubes. Of the five fans in this barn, three were used during the period of the study. PVC gas sampling tubes 6 mm in diameter were run from each of these fans to the mobile laboratory which was placed halfway along the west wall of the barn. Sampling tubes also were placed at three ambient locations within the barn along the centreline of the north-south axis (Figure 4.3). In addition, outside air was sampled and assumed representative of the air entering the barn. Thermistors were placed at each operating fan, at four ambient locations and on the inlet and outlet heating pipes. In order to monitor the area surrounding the birds ambient locations were defined as being at turkey height, approximately 0.5 m above the ground. Fan-speed sensors built in the Department of Agricultural Engineering, University of Alberta, monitored the voltage going to each of the operating fans. Heat-flux plates were placed on the floor, footing, wall and ceiling in the centre of the barn. Finally, a sensor was placed on the feed auger motor to monitor feed entering the barn. This sensor, also built in the Department of Agricultural Engineering, University of Alberta, converted voltage going to the feed auger motor from 110 V to 9 V which was then sent to the data acquisition system.

The grower barn, approximately 12 by 98 metres, was divided into two equal sections 12 by 49 metres. This was done to facilitate another concurrent experiment monitoring airborne dust and ammonia (NH_3) levels (Licsko and Feddes, 1988). A "fogging device", which sprayed a fine mist across the barn to reduce airborne dust particles was installed in the west section. Dust concentrations in both sections were then compared and the fogging system evaluated. The partition which isolated the two sections consisted of a wood frame and plastic sheeting.

Supplemental heating was provided in the grower barn by a hot-water boiler and 51-mm black-steel pipes which were hung along the south wall of the building. Figure 4.4 shows a cross-sectional view of the barn with heating pipes and the location of the inlet. The

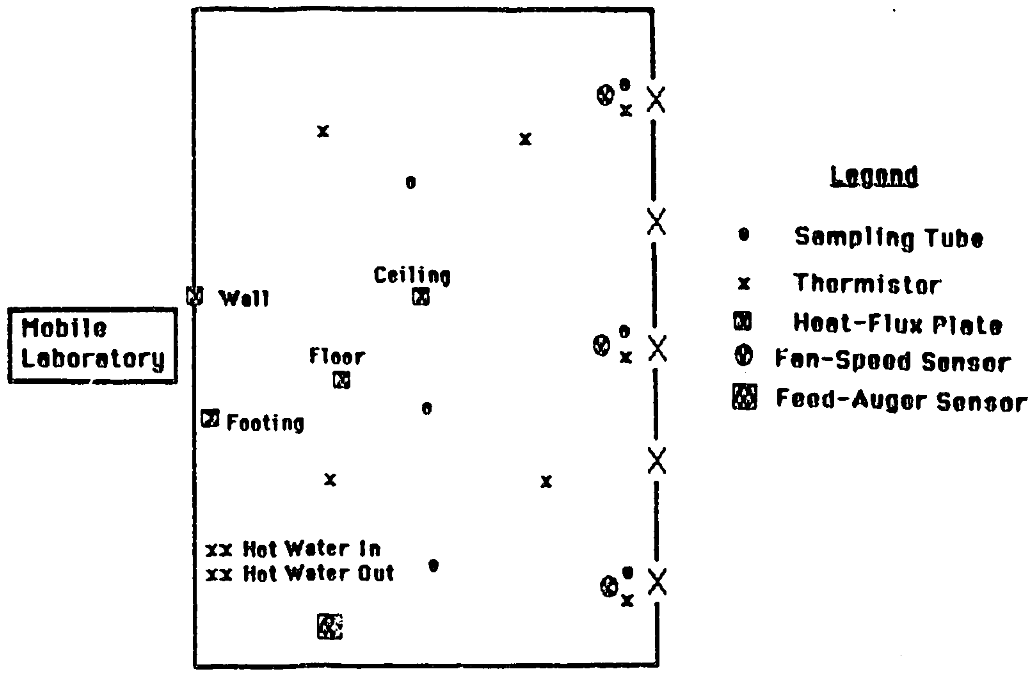

Figure 4.3 Locations of sampling, tubes and sensors in brooder barn.

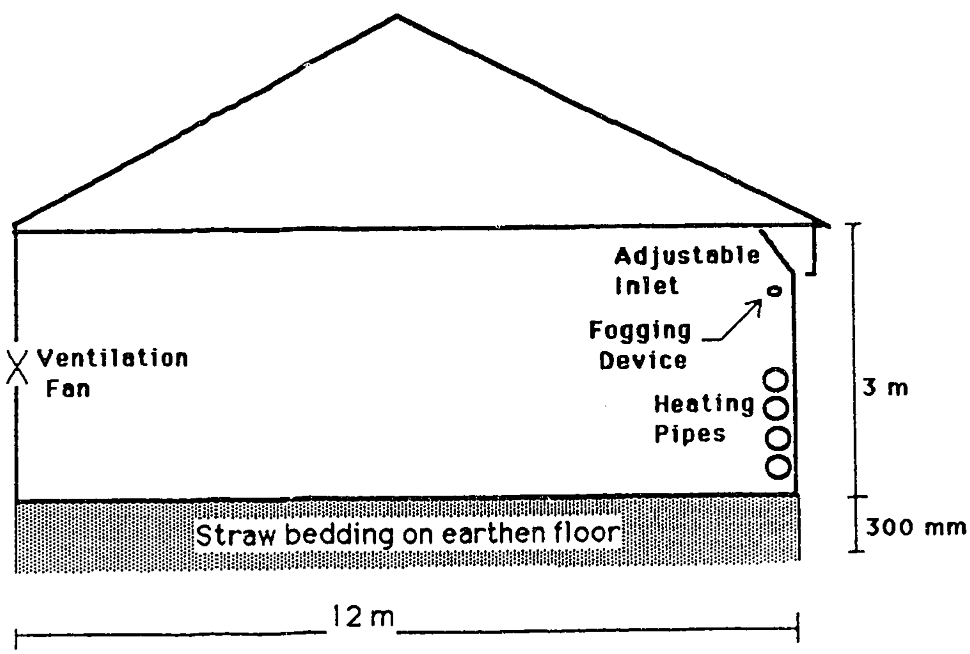

Figure 4.4 Cross-sectional view of the grower barn showing heating pipes and inlet location (not to scale).

ventilation system consisted of four variable-speed fans used for minimum ventilation and three large single speed fans for temperature control (Figure 4.4). The four variable-speed fans were 500 mm in diameter and continuously in use. Two thermostats controlled fan-speed, one controlling the two fans on the west end of the grower barn with a second controlling the two on the east side. The single speed fans were 650 mm in diameter and controlled by separate thermostats. Being similar in construction to that of the brooder barn, a continuous adjustable inlet also was located along the wall opposite the fans.

Figure 4.5 shows locations of sensors and sampling tubes for the two halves of the grower barn. Sampling tubes were placed at each of the variable-speed fans and at two

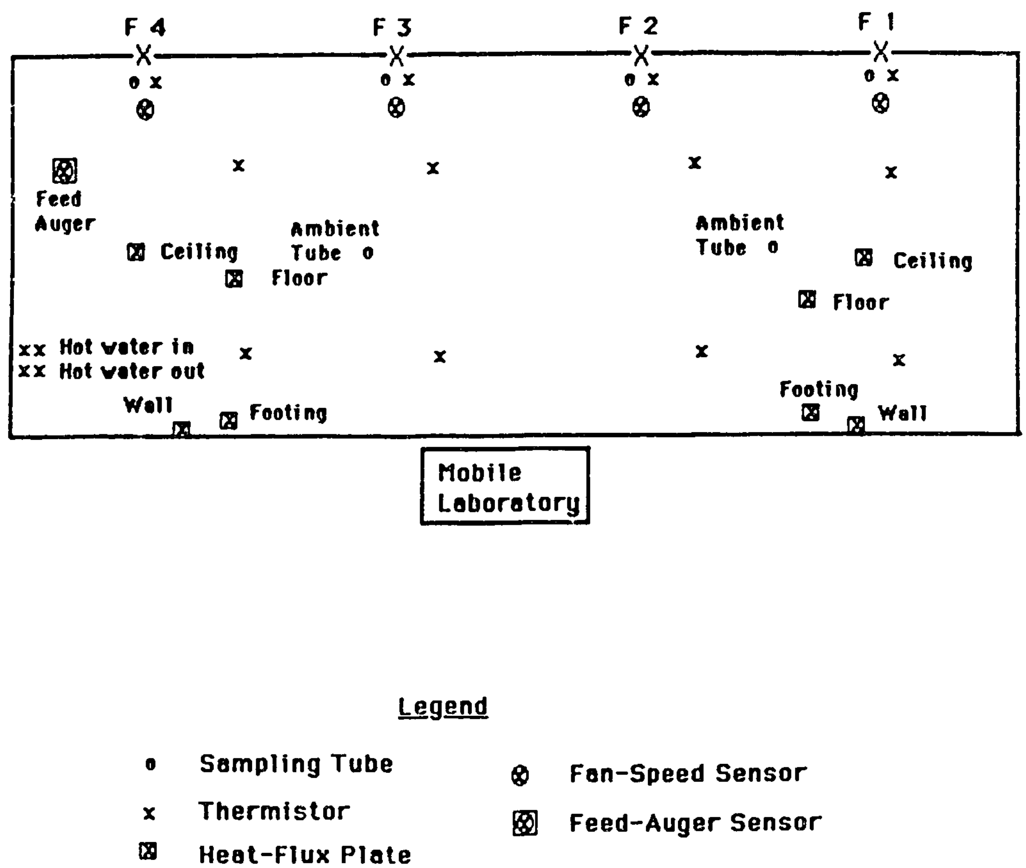

Figure 4.5 Locations of sampling tubes and sensors in grower barn.

ambient locations along the east-west axis of the barn. Outside air was also sampled to measure the condition of the air entering the barn. Temperature sensors were placed at eight ambient locations, at the variable speed fan locations and on the inlet and outlet heating pipes. Each half of the barn had four heat-flux plates, which were placed at the midpoint on each of the floor, footing, wall and ceiling. The feed sensor used in the grower barn was the same as used in the brooder barn. Fan-speed sensors, similar to those used in the brooder barn measured the voltage going to each variable-speed fan. Single-speed fans were not running continuously. For this reason a sensor, similar to that used for the feed auger in the brooder and grower barns monitored the time and duration of the operation of the fan.

The monitoring began on January 12, 1988 with a batch of 8-week Large White toms that were moved from the brooder barn to the grower barn. The batch consisted of 2710 birds, which were monitored weekly until marketed (Table 4.1). A new batch of 5400 Large White hens were placed in the brooder barn on February 1. Monitoring began one week later and continued on a weekly basis until they were moved to the grower barn (Table 4.1). In the grower barn monitoring of the hens took place every two weeks due to financial constraints. Each barn was monitored continuously over a 24-hour period for each run.

The numbers of birds are only approximate since the barn charts did not agree with the number of birds marketed to the processing plant. The barn charts estimated that the number of toms shipped was 140 more than actually were shipped, which is an error of 4.5% as 3100 birds were originally placed. For the hens, the number shipped was 105 less than the charts indicated, which is an error of 1.9% of the 5400 that started. This error lay either in the number of birds alleged to have started or in the counting of the dead birds. The mortality records are more likely the cause of the discrepancy, since hundreds of male and female chicks died in the first three weeks of life. For this reason, the bird numbers for each monitoring period were calculated by adding the mortality from that period to the number marketed. This lessens the error for the later runs as mortality was very small then and easily counted.

Table 4.1 Dates of monitoring the three barns, the number of birds and their ages.

Date	Run ID	Age, days	No. of Birds
	Toms in Grower Barn		
88-01-12	TBC2	64	2710
88-01-18	TBC3	70	2692
88-01-25	TBC4	77	2673
88-02-01	TBC5	84	2658
88-02-09	TBC7	92	2636
88-02-16	TBC9	99	2610
88-02-23	TBC1	106	2575
88-02-26	Marketed		2560
	Hens in Brooder Barn		
88-02-08	TA1	7	4913
88-02-17	TA2	16	4692
88-02-22	TA3	21	4665
88-03-01	TA4	29	4616
88-03-08	TA5	36	4595
88-03-16	TA7	44	4579
	Hens in Grower Barn		
88-03-29	TBCH1	57	4562
88-04-12	TBCH2	71	4544
88-04-20	TBCH3	79	4537
88-05-05	TBCH5	94	4526
88-05-18	TBCH6	108	4512
88-05-19	Marketed		4512

4.1.2 Equipment and Instrumentation

The mobile laboratory owned by the University of Alberta that houses the data acquisition system described by Feddes and McQuitty (1977) was utilised for this experiment. The laboratory was moved between the two barns and connected up to the sampling lines and sensor wires that had been installed previously. The laboratory positions are shown in Figures 4.3 and 4.5. The sample tubes and sensor cables were run from their various locations inside and outside the barn through an electrically-heated pipe. This maintained the sample temperatures above the dewpoint which was crucial for accurate moisture readings.

Temperatures were measured using thermistors (Fenwall Electronics, Framingham, MA). These were placed at the fans to measure the exhaust air temperatures and within the barns to measure ambient temperatures (Figures 4.3, 4.5). Thermistors, sandwiched between the heating pipes and a layer of insulation also were used to measure the temperature of the hot water. All ambient thermistors were placed at bird height. A thermistor to measure the temperature of the incoming air also was placed outside the barn at a point protected from solar radiation. Moisture content of air was calculated from the dewpoints which were measured with a cooling mirror dewpoint hygrometer (Model 880, Cambridge Systems, MA). This hygrometer was cleaned before each run and calibrated before and after each run by internal electronic calibration.

Conductive heat losses were calculated from the estimated thermal resistance values of the building walls, ceiling and floor and were validated by measuring the heat flow through structural components. The heat flow was measured with 50 mm x 50 mm x 5 mm heat-flux plates. The design, testing and calibration of similar plates was described by DeShazer *et al.* (1982). Sites for the heat flux plates were the floor, footing, wall and ceiling (Figures 4.4, 4.5).

Oxygen content was measured using a paramagnetic O_2 analyser (Model 540A, Servomex, Sussex, England). This measures the relative magnetic susceptibility of the sample and relates this to O_2 content. Due to the high value of paramagnetism exhibited by O_2, analyses virtually are unaffected by changes in background gas composition. However, water vapour will affect the O_2 concentration measurement. In order to correct for this, the dewpoint of the sample was used to convert the O_2 content to a dry basis. Since barometric pressure also has a significant affect on paramagnetic analysers (McLean and Watts, 1976), the unit was purchased with a built-in pressure compensator. Carbon dioxide was measured using a non-dispersive infrared analyser with a linerisation circuit (Model 870, Beckman Industrial, La Habra, CA).

Both analysers were calibrated before and after each run. The O_2 analyser was calibrated using nitrogen as zero gas and spanned with 21.2% certified gas and outside air. This gave three points for the calibration line. Because the range of interest was approximately 20 - 20.5% the O_2 analyser was operated at a 20% offset. This offset was obtained by means of a zero suppression module (521) which provided suppression over the 0-99% O_2 range in increments of 1% O_2. The required offset was selected by dual ten position thumb wheel switches located on the front panel of the module. The CO_2 analyser also was calibrated with 99.9% pure nitrogen as zero and two standards were used for span, 0.151% and 0.6%. Flow rates to the analysers were kept constant with control valves.

In order to measure the ventilation rate from the variable-speed fans, voltage to each fan was correlated with the measured air-flow rate. Discharge ducts, approximately 0.5 m x 0.5 m x 3.0 m were mounted downstream from each fan. Air straighteners were placed inside each duct to stop turbulent flow according to specifications (Jorgenson, 1983). These ducts were insulated with 25-mm styrofoam. Flow rates were measured twice a day by a hot-wire anemometer (Kurz Instruments Inc., Carmel Valley, CA). A 25-point traverse of the air speeds within each duct was obtained. The mean air speed then was multiplied by the cross-sectional area of the duct to obtain a mass air-flow rate. A regression then was used to correlate the voltages and the measured air-flow rate. This equation is shown in Appendix B. The hot-wire anemometer was calibrated periodically in a small scale, air-velocity calibrator located in the Department of Mechanical Engineering, University of Alberta.

Air-flow rates from the single-speed fans were measured in the same way as the variable speed fans and were measured at the beginning and end of each run. A constant rate was assumed for the duration. An event recorder monitored the time of operation of each fan during each 4-minute period. The product of operation time and rate was the mean hourly ventilation rate for that fan. Total ventilation was the sum of the air-flow rates from each fan.

Mass air-flow rates were measured at STP conditions (25 °C and 760 mm Hg) for which the anemometer was calibrated. Therefore, for direct calculations of heat production, ventilation rates were corrected to local conditions of temperature and pressure. Equation 2.7 for the indirect calculation of heat production was derived at a temperature of 0 °C and a pressure of 760 mm Hg. Ventilation rates used in calculating indirect heat production were therefore corrected to these standards.

Originally, supplemental heat was to be measured by measuring the inlet and outlet temperatures of the hot-water heating pipes in the barn and the water flow rates through the pipes. However, precise readings of water flow were impossible to attain. As a result, an equation derived for the calculation of heat transfer from black-steel hot-water pipes was used to calculate supplemental heat input (Turnbull and Bird, 1981; Feddes *et al.*, 1984). This equation predicted heat output as a function of temperature difference between the ambient air and the hot water and pipe dimensions. This equation is also shown in Appendix B.

The feed augers were monitored by event recorders which measured the time the auger was operated during each 4-minute period. The auger then was calibrated manually by measuring the auger output over four 30-second and four 15-second durations. A water meter (Model 13411, Neptune) was used to measure the quantity of water going to the waterers over each 24-hour period. This meter was read at the start and end of each run.

All the instruments were checked at the beginning and end of each run to ensure they were operating well. Wet- and dry-bulb temperatures were used to check the behaviour of the dewpoint hygrometer. Ambient temperatures were periodically measured using a hand-held electronic thermometer to check the accuracy of the thermistors. Draeger tubes were used to get an indication of the CO_2 concentration in the barn. These tubes are only accurate within ±15%.

Figure 4.6 shows a diagram of the sampling, analysing and data acquisition system for the grower barn. The system for the brooder barn is similar but with different sampling locations. The seven gas sampling tubes from the different locations were attached to an automatic sequencing sampler (Feddes and McQuitty, 1977) that sampled air from each tube for four minutes and distributed the sample to the dewpoint, O_2 and CO_2 analysers. The data acquisition system scanned the electronic output from these analysers every four minutes, the overall result being that every location was analysed twice per hour, with one 4-minute rest period every hour. The fan-speed sensors and event recorders were recorded every four minutes, as was the feed auger sensor. Static pressure was measured with by a low-range differential pressure transducer (Validyne, Model DP45, Sierra Instruments, CA). The pressure differential was calibrated with an inclined manometer. Hot water temperatures and dry-bulb temperatures at the exhaust fans also were recorded every 4 minutes in order to monitor any sudden changes in supplemental heat and outlet temperatures. All other thermistors were monitored at 20-minute intervals as this was deemed sufficient for recording changes within the barn. Likewise, outside temperature was recorded every 20 minutes.

Output from all the analysers, thermistors, event recorders, fan-speed sensors and heat-flux plates were scanned by a data logger designed and built by the Technical Services Department, University of Alberta and sent to an IBM personal computer. The data for each run of 24 hours duration were saved on a diskette and analysed on a Lotus spreadsheet.

4.2 Data Analysis

Data in their raw form consisted of voltage readings from each channel on the data logger for each run. The voltages from the 20-minute thermistor channels first were separated using an editing program (Personal Editor 1.0, IBM). They then were processed on a Lotus

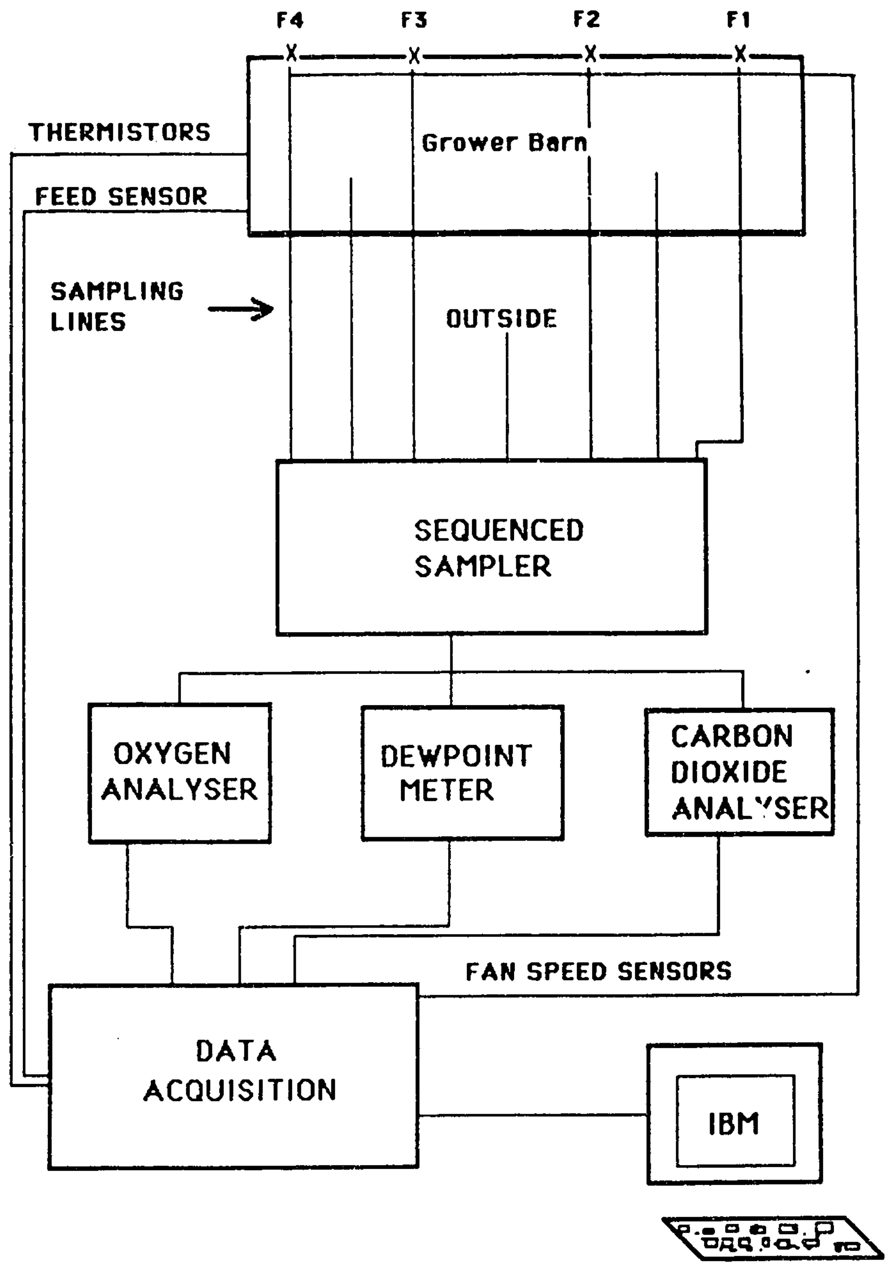

Figure 4.6 Sampling, analysing and data acquisition system in the grower barn.

worksheet using appropriate calibration equations for thermistors (Appendix B). Data from the analysers then were divided into seven files, one for each sampling location. These files were processed on a worksheet where voltage readings were converted into concentrations and dewpoints. The algorithms are shown in Appendix B. Ventilation and supplemental heat raw voltages were processed on a different worksheet. Output from these three separate worksheets, in the form of hourly averages, went to files and were then called to a worksheet programmed to calculate heat produced directly and indirectly.

The final worksheet processed inside and outside gas concentrations, calculated RQ values and heat production per litre of ventilated air (kJ/L) (equation 2.7). Rate of heat production (kW) was calculated as the product of ventilation rate (L/s) and heat produced per litre (kJ/L). Utilising basic psychrometric equations (ASHRAE, 1981), heat and moisture losses through each fan were calculated. The sum of these was added to the heat lost through the structural components to give the total heat loss. This worksheet calculated supplemental heating using an equation derived by Feddes *et al.*, (1984a) which uses the temperature difference between the inlet and outlet hot-water pipe to calculate heat released from black-iron pipes (Appendix B). Bird heat production then was calculated as the total heat loss minus supplemental heat input.

Two similar spreadsheets were used, one for the brooder barn and one for the grower barn. To regulate the size of the spreadsheet for the grower barn, data from the east and west sections were processed separately and the results averaged. Appendix E gives a sample data output from the west section of the grower barn. These results were calculated from data collected while monitoring the grower barn housing 84-day old toms.

4.3 Preliminary Investigation

Using the data acquisition system described above, a preliminary experiment was undertaken in September 1987, to validate the accuracy of the equipment (McDermott and Feddes, 1988). Animal heat production was simulated by three propane burners. Three different burning rates were tested using one, two or three of the burners. The combustion of propane involved the consumption of O_2 and the production of CO_2 in which every 44 grams (one mol) of combusted propane consumed 160 grams (5 mols) of O_2 and produced 132 grams of CO_2 (3 mols) and 2200 kJ of heat energy. Propane yielded a RQ of 0.6. Thus, for every mol (32 g or 22.4 L.) of O_2 consumed, 440 kJ of heat were produced. Similarily, for every mol (44 g or 22.4 L.) of CO_2 produced, 733 kJ of heat were produced.

A known quantity of propane was combusted over a 3-hour period. Inlet and outlet gas concentrations, temperatures, and dewpoint were measured as described above. Ventilation rates were measured directly in a discharge duct using a hot-wire anemometer (Model TA3000, Airflow Developments Ltd., High Wycombe, England) and assumed to be constant throughout the run. Thus, heat production was calculated by measuring the O_2 consumption, measuring the CO_2 production and by a direct calorimetric method. These three methods then were compared to the actual heat production of the propane. The chamber used for the simulation and measurements is described by Leonard and McQuitty (1984).

Indirect calculations gave higher values for heat output than direct calculations. The average deviation for the nine runs was 1.9% and ranged from 0.1% to 4.1%. All three methods deviated from the theoretical heat production by 9% over the entire measurement period. This deviation from the theoretical value was attributed to inaccuracies in the ventilation readings which can be above 5% (Leonard and McQuitty, 1984). Errors in ventilation will cause errors of the same magnitude in both direct and indirect heat production calculations. The RQ value ranged from 0.55 to 0.64 with an overall average of 0.6. This indicated that readings from the gas analysers were accurate.

5. Results and Discussion

5.1 Environmental conditions

5.1.1 Toms in Grower Barn

Monitoring the grower barn during occupancy by toms occurred between January 12 and Feburary 23, 1988. During this period, recognised normally as the coldest during an Albertan winter, hourly outside temperatures varied from -29.5 °C to 7.9 °C. Ventilation rates were at a minimum to control moisture and aerosol contaminants to acceptable levels while maintaining desirable temperatures. Table 5.1 shows the mean temperatures outside and within the grower barn during the monitoring periods, along with the maximum and minimum temperatures measured. The largest fluctuation in any 24-hour monitoring period during this study was an increase in temperature of 24 °C, from -16 °C to 8 °C. The average daily range was 13 °C. The average ambient temperature over all the runs was 12.8 °C, ranging from 6 °C to 20 °C. The minimum value and the ambient temperature indicated that the supplemental heating system was not adequate for severe winter conditions. All the mean temperatures were well below the recommended ambient temperature of 18 °C (ASHRAE, 1981) and in some cases below the lower critical temperature of 13 °C.

No noticeable temperature differences greater than 1 °C occurred among the sampling locations of the respective barns. This is partly due to four ceiling mounted circulation fans in the grower barn and two in the brooder barn. Figure 5.1 shows the relationship between ambient temperatures and outside temperatures for the grower barn. Recommended temperatures are also shown. Ideally, a profile of ambient temperatures would be a straight line somewhere within the thermoneutral zone of the turkey regardless of temperature. However, the ambient temperature followed the outside temperature in many cases. Exhaust temperatures measured at the fans were slightly higher than ambient temperatures, which were measured at bird height. Again the difference did not exceeded 1 °C.

Table 5.1 Summary of environmental conditions for toms and hens in brooder and grower barns.

Age (days)	Temperature °C Outside	Range	Ambient	Range	Relative Humidity % Ambient	Range
			Toms in Grower Barn			
64	-18.0	-23/-8	14.0	12/17	68	60/79
70	-12.2	-17/-2	12.1	9/16	63	54/72
77	-1.4	-10/4	12.8	8/18	70	57/77
84	-18.0	-22/-17	11.0	6/16	81	59/92
92	-23.8	-30/-17	13.2	12/16	85	66/100
99	1.4	-2/5	15.8	12/20	62	54/68
106	-9.1	-16/8	11.3	8/14	73	54/87
			Hens in Brooder Barn			
7	-23.9	-29/-14	33.8	31/35	36	32/40
16	-0.3	-5/6	27.2	26/28	38	35/43
21	-12.0	-20/-5	24.5	22/26	46	42/52
29	-2.7	-8/6	22.2	20/25	66	55/90
36	6.4	2/13	23.0	21/26	59	51/68
44	-0.2	-6/9	19.6	20/26	66	53/78
			Hens in Grower Barn			
57	0.0	-7/7	16.3	11/21	63	74/48
71	6.6	-3/18	17.8	14/22	47	59/33
79	5.6	2/12	18.0	17/20	73	83/52
94	10.3	6/16	16.3	12/20	52	72/38

Table 5.1 also shows the mean relative humidity and ranges during the monitoring periods. The mean humidity in the barn for all measurements was 72% which is in good agreement with the recommended level of 70% (ASHRAE, 1981). The range, however varied from 54% to 100% in one run when the outside temperature was at its minimum for the period. This indicated that the minimum ventilation rate was not sufficient for moisture control when the supplemental heating system was at maximum.

5.1.2 Hens in Brooder and Grower Barn

Monitoring the brooder barn began on Feburary 8, 1988 when the hens were 7 days old and continued on a weekly basis until 44 days old. The hens were moved to the grower barn 10 days later. Monitoring the grower barn began when the hens were 57 days old and continued twice weekly until they were marketed. Due to a power failure, the data recorded on May 19 were lost. As a result, data for the hens only exists until May 5. The hens were 94 days old at this time. During this period, both winter and spring conditions prevailed, resulting in a wider range of temperatures than during the period that the toms were monitored. When the hens were in the grower barn outside temperatures varied from -29 °C to 16 °C, with the largest range in 24 hours being from -3 °C to 18 °C. While monitoring the brooder barn the maximum 24-hour range in outside temperature was 15 °C.

Mean outside and ambient temperatures with their ranges are given in Table 5.1. ASHRAE (1981) recommends that the ambient temperature in a brooder barn be 38 °C initally and decrease 3 °C per week until 18 °C is reached. The temperature in the brooder barn was found to be less than this for the first four monitoring periods by approximately 3 °C. Figure 5.2 shows outside, ambient and recommended temperatures.

During the first four weeks in the brooder barn, the requirements for supplemental heating were high since ambient temperatures were high and outside temperatures were low. The system was inadequate to provide the desired high temperatures. Consequently, a propane heater was used in conjunction with the heating system to increase temperatures at the early

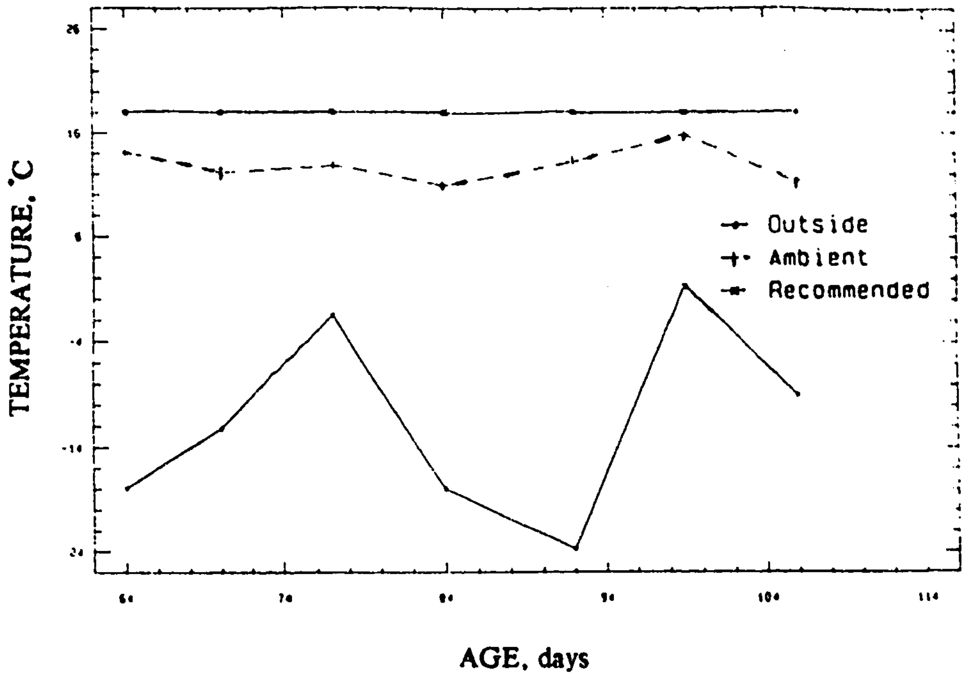

Figure 5.1 Recommended ambient, measured daily outside and ambient temperatures during the monitoring period of the toms.

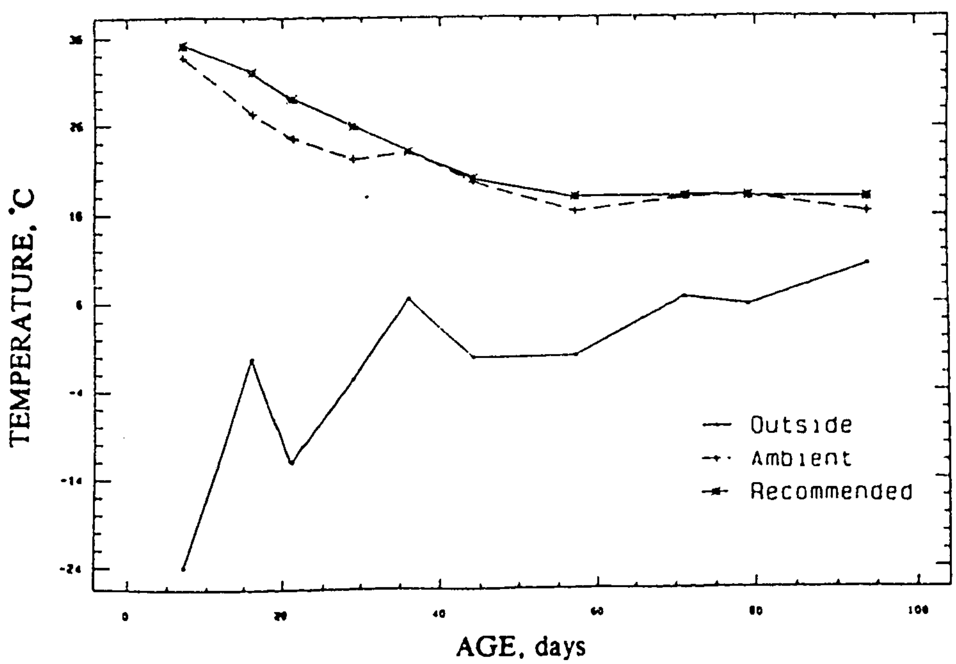

Figure 5.2 Recommended ambient, measured daily outside and ambient temperatures during the monitoring period of the hens.

stages of poult life. The poults suffered high mortality in these few weeks, possibly due to these adverse conditions. Figure 5.2 shows only the mean temperatures in the barn, the ranges are shown in Table 5.1. When superimposing the daily range of temperatures for each run on Figure 5.2, ambient temperatures were lower than those recommended for the major part of the day.

Means and ranges of relative humidity also are given in Table 5.1. In general, the relative humidity remained at an acceptable level with the exception of one reading of 90%. Minimum ventilation was used in the brooder barn as high temperatures were required and outside temperatures were low. This ventilation was sufficient for removing moisture since the birds were small and not producing much moisture. As stated earlier, ambient temperatures were lower than recommended. This may have resulted in an increased sensible, rather than latent, heat loss. Relative humidity in the grower barn was acceptable; ventilation rates were generally for temperature control and were sufficient for adequate moisture removal.

5.2 Carbon Dioxide Production

5.2.1 Carbon Dioxide Production for Toms

Carbon dioxide concentrations of the air entering and leaving the barn were measured by an infrared analyser. The product of this concentration difference and the ventilation rate gave production rate. Carbon dioxide concentrations that were measured at two ambient locations did not differ from the exhaust air values. Mean CO_2 concentrations and CO_2 production rates from the toms in the grower barn are presented in Table 5.2. As expected, production rates rose as the birds matured due to increased metabolic activity and feed consumption.

The threshold limit value (TLV) for CO_2 is 5000 ppm (ACGIH, 1984). This is the maximum average allowable concentration for a normal 8-hour working day. Any concentrations above this are considered a potential health risk to the operator. This value was

Table 5.2 Carbon dioxide levels ambient concentrations (ppm) and production rates (L/h.bird) in the grower and brooder barn for toms and hens.

Age (days)	CO_2 Produced L/(h.bird)	Ambient CO_2 ppm	Ventilation Rate L/(s.bird)	Static Pressure mm H_2O
		Toms in Grower Barn		
64	3.39	2594	0.43	0.4
70	4.33	1880	0.80	0.6
77	6.63	1584	1.54	0.1
84	7.75	2681	0.95	0.1
92	9.76	3616	0.84	0.2
99	10.59	1858	1.92	0.3
106	11.90	2113	1.85	0.9
		Hens in Brooder Barn		
07	N/A	1635	N/A	0.1
16	0.50	1558	0.11	0.1
21	1.12	2542	0.16	0.1
29	1.54	2514	0.20	0.4
36	1.93	1772	0.38	0.8
44	3.02	2709	0.37	0.6
		Hens in Grower Barn		
57	4.05	2030	0.66	0.3
71	5.19	1764	1.07	0.5
79	5.61	1888	1.03	0.6
94	5.40	1238	1.70	1.5

N/A Not Available

not exceeded in the grower barn. Mean ambient concentrations of CO_2 were below 3000 ppm as recommended by the Scottish Farm Buildings Investigation Unit (SFBIU, 1984) with one exception, where the mean level rose to 3616 ppm during run 5 with a variation of ±990 ppm. Mean CO_2 concentrations for the previous run were 2681 ppm with a variation of ±1800 ppm. These high concentrations occurred during very cold weather when the ventilation rate was minimal. These concentrations were not considered to be a health hazard, but suggested that air quality control could be improved. Figure 5.3 shows mean hourly ambient CO_2 concentrations over a 24-hour monitoring period when the toms were 92 days old. Concentrations of CO_2 rose from late evening to early morning.

Carbon dioxide production rates are shown in Figure 5.4. The production rates increased at night resulting in the higher nightly concentrations of CO_2 in the grower barn. Carbon dioxide production is influenced by many factors such as feed intake, activity and ambient temperature. Feed intake in this study was ***ad libitum*** and did not cause any major changes in CO_2 production rates. Typically, bird activity would be greater during daylight hours due to activity on the farm so CO_2 production rates should have fallen at night. However, during this monitoring period ambient temperatures decreased at night (Appendix D.9). This decrease was caused by a decrease in outside temperature which was not compensated for by the heating system. Consequently, turkey heat production increased. Appendix D.10 shows mean hourly heat production measured by direct and indirect calorimetry for the same period. Since CO_2 production depends on metabolic rate diurnal variations in CO_2 and heat production were similar.

The CO_2 production rate was found to be a function of turkey age. Utilising daily averages for each run, a regression equation was calculated to equate CO_2 production with age. This equation, valid for Large White tom turkeys between 64 to 106 days old, is:

$$Y = -18.91 + 0.429X - 0.00131X^2 \qquad (5.1)$$

$$R^2 = 0.99$$

where:

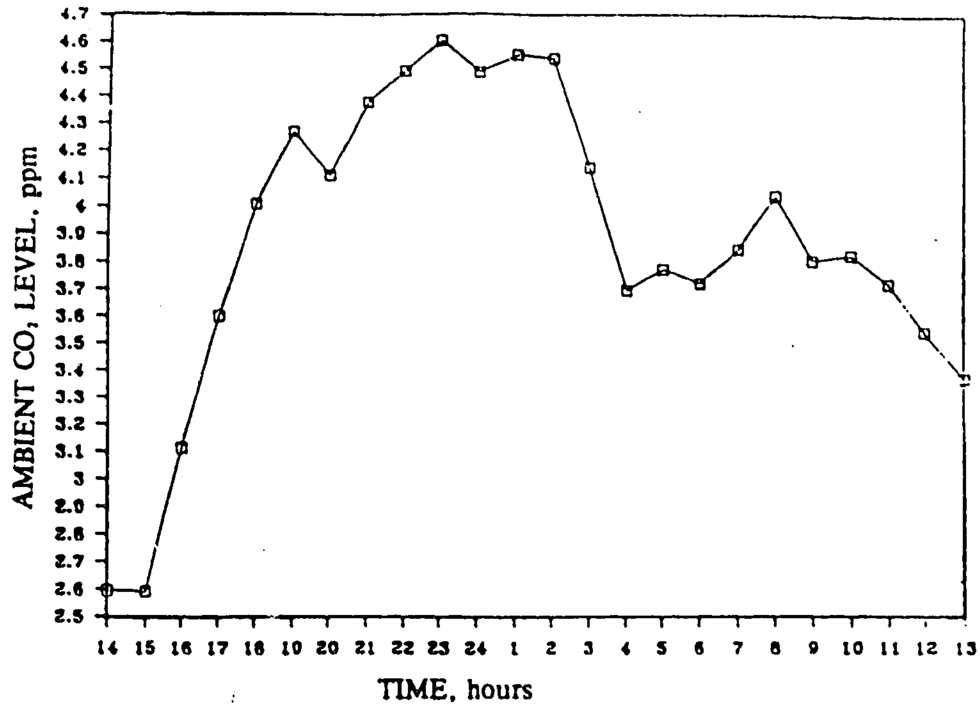

Figure 5.3 Ambient carbon dioxide concentrations for toms at 92 days of age.

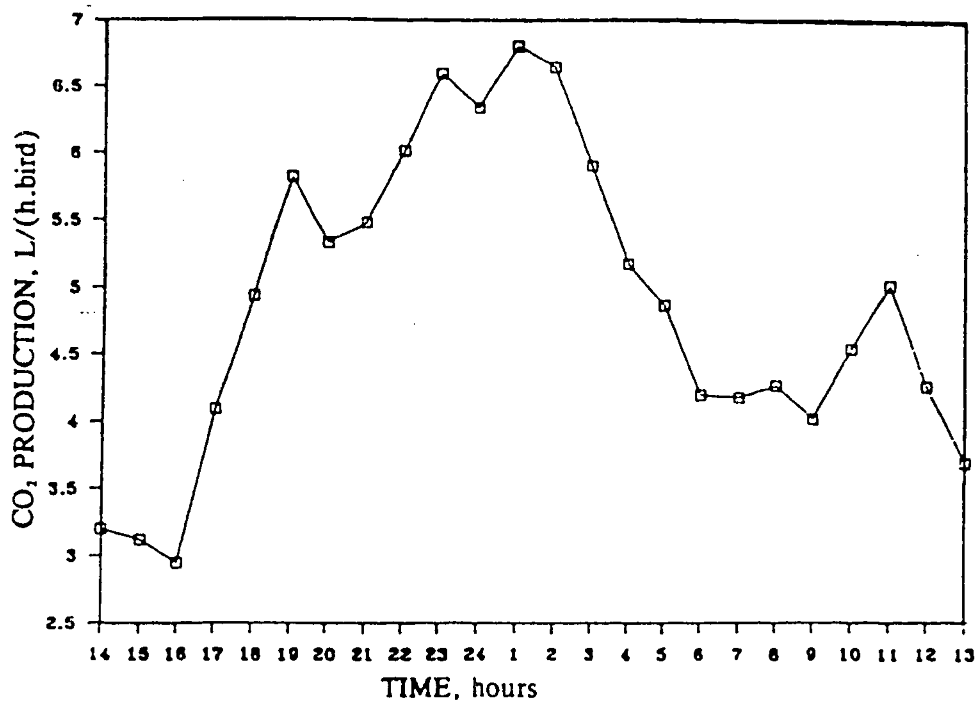

Figure 5.4 Carbon dioxide production rates in the grower barn for 92-day old toms.

X = age of toms, days, and

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

5.2.2 Carbon Dioxide Production for Hens

Carbon dioxide was measured at the three exhaust fans and at three ambient locations in the brooder barn. At no time did CO_2 concentrations rise above 3000 ppm in either the brooder barn or the grower barn while housing the hens. When the outside temperature was low, the birds were too small to produce enough CO_2 to yield high concentrations. Production rates increased with age to a maximum of 5.4 L/(h.bird) at 94 days old, when the birds were mature.

Table 5.2 shows the mean CO_2 concentrations and production rates over a 24-hour period for all monitoring of hens. With the exception of the last two runs, the production rates for the hens were higher than those for the toms at a comparable age. Toms were heavier than hens of the same age and had faster growth rates. Consequently, a higher CO_2 production would have been expected from the toms at a given age. An explanation for this apparent discrepancy may be that the toms utilised more metabolisable energy intake for growth than the hens. Therefore, the hens would have had a greater CO_2 production rate due to this lower efficiency of conversion.

Ventilation rates were so low when the hens were seven days old that flow rates were impossible to measure. Temperatures in the brooder barn were lower than recommended, while moisture and CO_2 concentrations were well below acceptable upper limits. As a result the possibility exists that ventilation in the brooder barn could have been lowered to increase temperature. Figure 5.5 shows the ambient CO_2 concentrations in the barn when the hens were 71 days old while figure 5.6 shows CO_2 production rate. Carbon dioxide production rose at night and fell during daylight hours with the concentration following the production rate. Appendix D.27 shows heat production measured directly and indirectly for that 24-hour period. Diurnal variations in heat production rates are similar to variations in CO_2 production

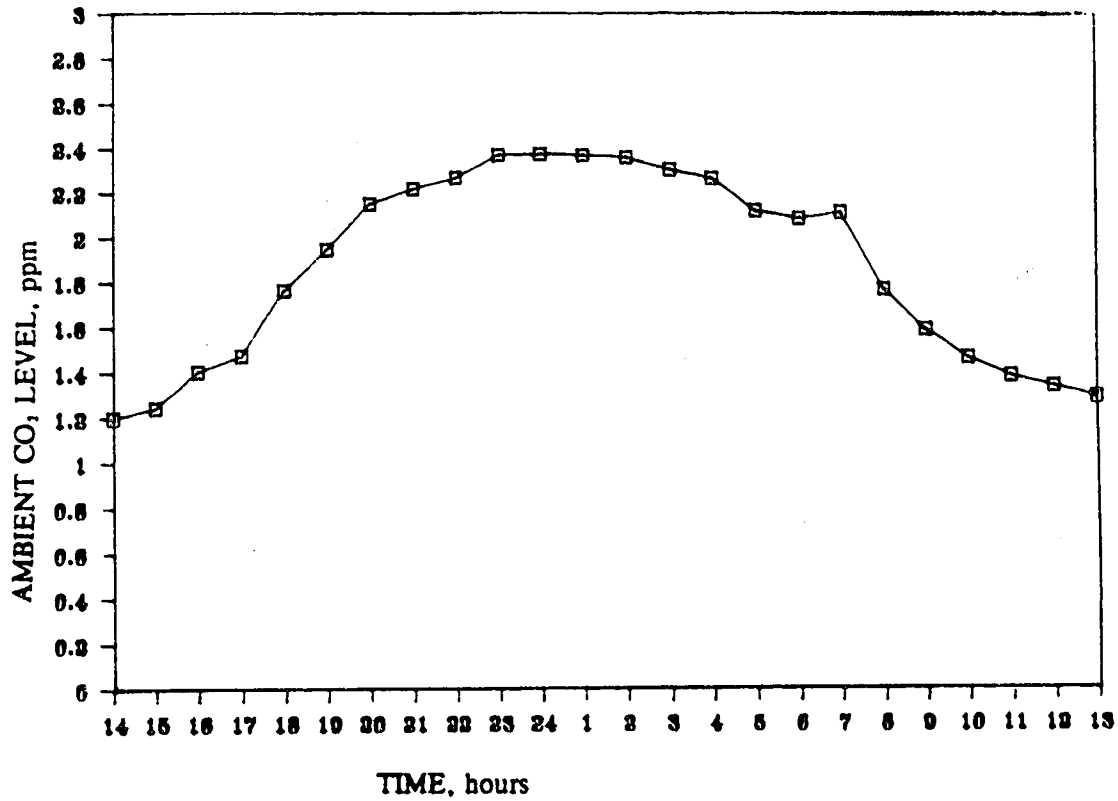

Figure 5.5 Ambient carbon dioxide concentrations for hens at 71 days of age.

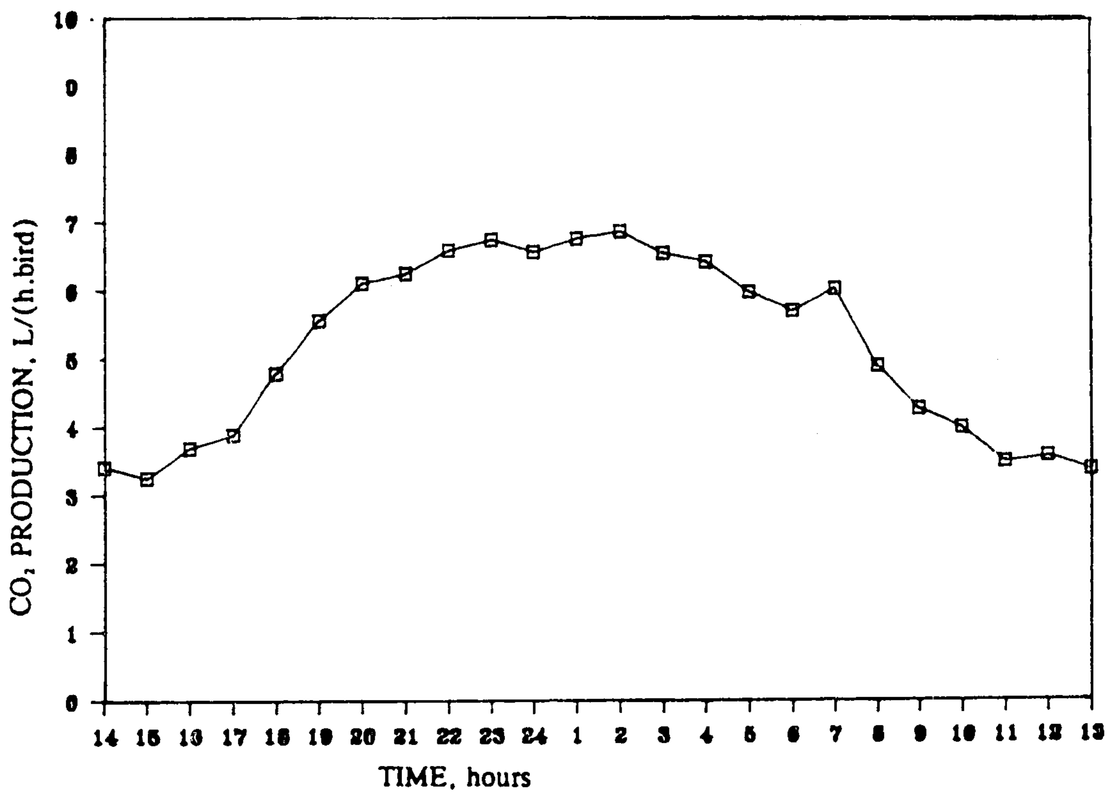

Figure 5.6 Carbon dioxide production rates in the grower barn for 71-day old hens.

rates.

A regression equation equating CO_2 production with age was calculated. The equation is valid for the entire growth cycle of the hen and is:

$$Y = -1.67 + 0.134X - 0.000586X^2 \qquad (5.2)$$

$$R^2 = 0.97$$

where:

X = age of hen, days, and

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

Ventilation rates and static pressures are also shown in Table 5.2. Static pressure is an indicator of air mixing. Turnbull and Bird (1981) recommend a minimum pressure differential of 1.3 mm of H_2O for good air mixing. In only one instance was this pressure attained, indicating that poor air mixing would have occurred for all other cases. Ventilation rates were low and insufficient to maintain proper air inlet velocity. However, as stated earlier temperature differences between different locations in the barn were small as a result of the ceiling mounted circulation fans.

5.3 Direct Calorimetry

5.3.1 Heat Balance

A heat balance in a barn consists of building shell heat losses, ventilation heat losses, supplemental heat gain and animal heat gain to the building. Supplemental heat gain arises mainly from the heating system, with a small fraction from lighting. Ventilated heat consists of two components, sensible and latent heat. The sensible component comes from the heating system and from the birds. Latent heat arises from evaporative heat production from the birds and from the evaporation of moisture from wet or damp surfaces. Once heat losses are measured, total heat production from the turkeys may be calculated using equation 2.1.

Figure 5.7 shows the heat balance over 24 hours for one monitoring period of 70-day old toms. Ventilation heat losses were the greatest with building shell losses constantly being the smallest factor in the heat balance. Supplemental heat input became higher than heat production from the birds during night. Supplemental heat should have been at a maximum at this time since, as shown earlier (Table 5.1), outside temperatures varied from -17 °C to -2 °C while the ambient temperature did not reach the recommended 18 °C. Shell heat losses remained relatively constant throughout the period. Bird heat production was erratic during the day and became relatively constant at night. As stated previously, the turkeys were fed ***ad libitum*** and were exposed to continuous lighting. These two factors indicate that any diurnal fluctuations must have been due to environmental conditions. Heat production in the barn was observed to increase when the birds were disturbed and would explain the constant heat production at night and the increase in morning. Figure 5.8 shows mean hourly ambient temperature variations. Ambient temperatures and heat production dropped during the night. This was not typical as heat production was observed to increase as temperature decreased for the majority of runs.

Figure 5.9 shows a similar balance for a 24-hour monitoring period in the brooder barn. Figure 5.10 shows the temperature profile for that same period. The hens were 36 days old for this run. Table 5.1 shows that that outside temperatures were relatively high during this period and the average ambient temperature was within recommended values. Again, ventilated heat loss was the largest component in the heat balance followed by bird heat production. Shell heat losses were the smallest. Shell and supplemental heat were constant while ventilated and bird heat fluctuated slightly. This graph shows how fluctuations in bird heat production followed the ventilated heat losses. Bird heat production showed no diurnal patterns for this period.

Table 5.3 shows the mean heat balance values for each run in all barns. Shell heat losses were dependant on outside temperature with decreasing temperatures resulting in increased losses. This was due to a higher temperature gradient across the building structure.

Table 5.3 Daily mean heat balance data for the hens and toms.

Age (days)	Building Losses	Supplemental Gains	Ventilation Heat	Bird Heat
	....	........W/bird........	....	
		Toms in grower barn		
64	10.5	14.6	25.5	21.4
70	7.9	15.2	32.9	25.6
77	4.8	11.8	48.4	41.4
84	10.5	12.8	51.2	48.9
92	11.6	4.4	54.1	61.3
99	4.8	5.7	63.7	62.8
106	7.4	5.6	67.5	69.3
		Hens in brooder barn		
16	2.5	6.4	6.9	3.0
21	3.3	6.8	11.7	8.2
29	2.2	3.7	13.1	11.6
36	1.5	3.6	15.8	13.7
44	1.8	2.4	21.1	20.5
		Hens in grower barn		
57	3.0	4.4	25.8	24.4
71	2.2	0.0	28.6	30.8
79	2.4	0.0	34.0	36.4
94	1.0	0.0	28.7	29.7

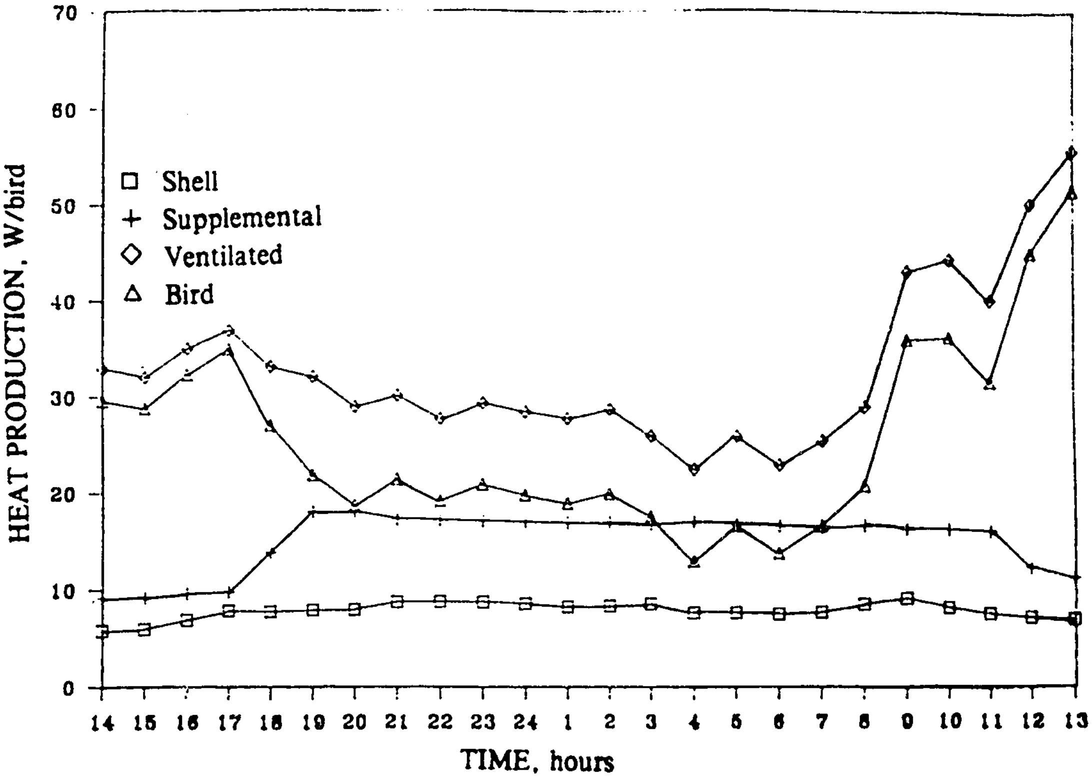

Figure 5.7 Heat balance in grower barn for 70-day old toms.

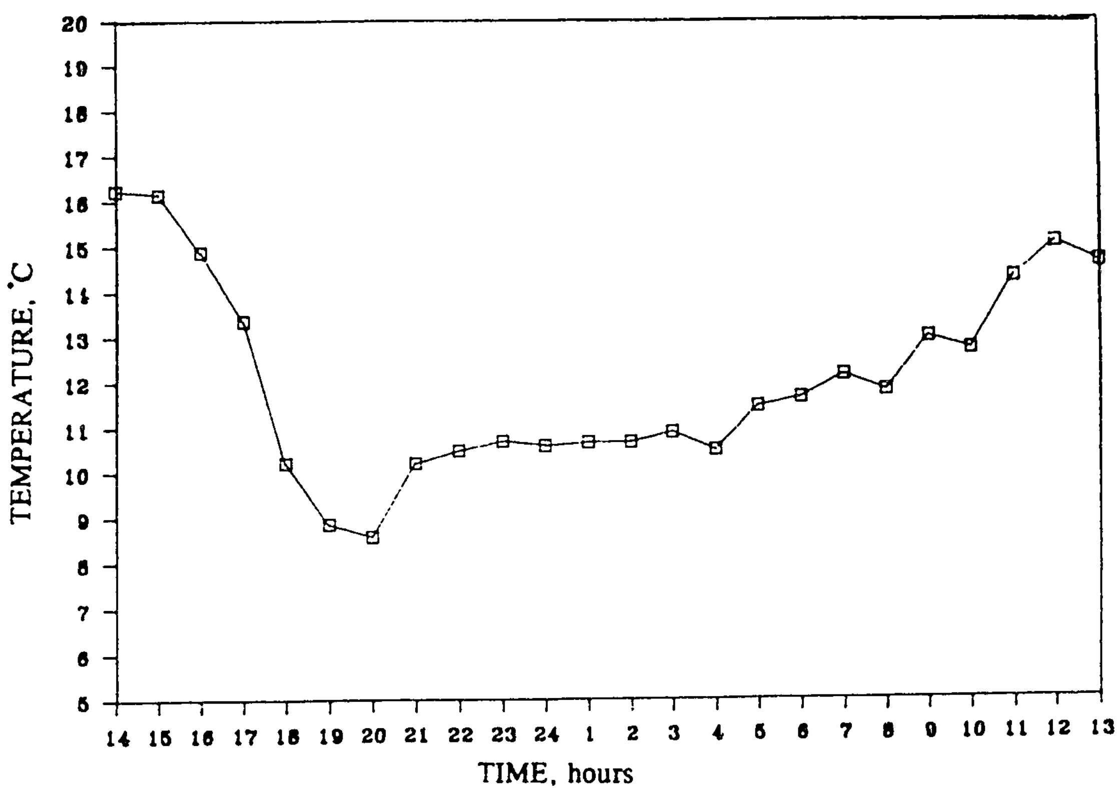

Figure 5.8 Ambient temperature in the grower barn for 70-day old toms.

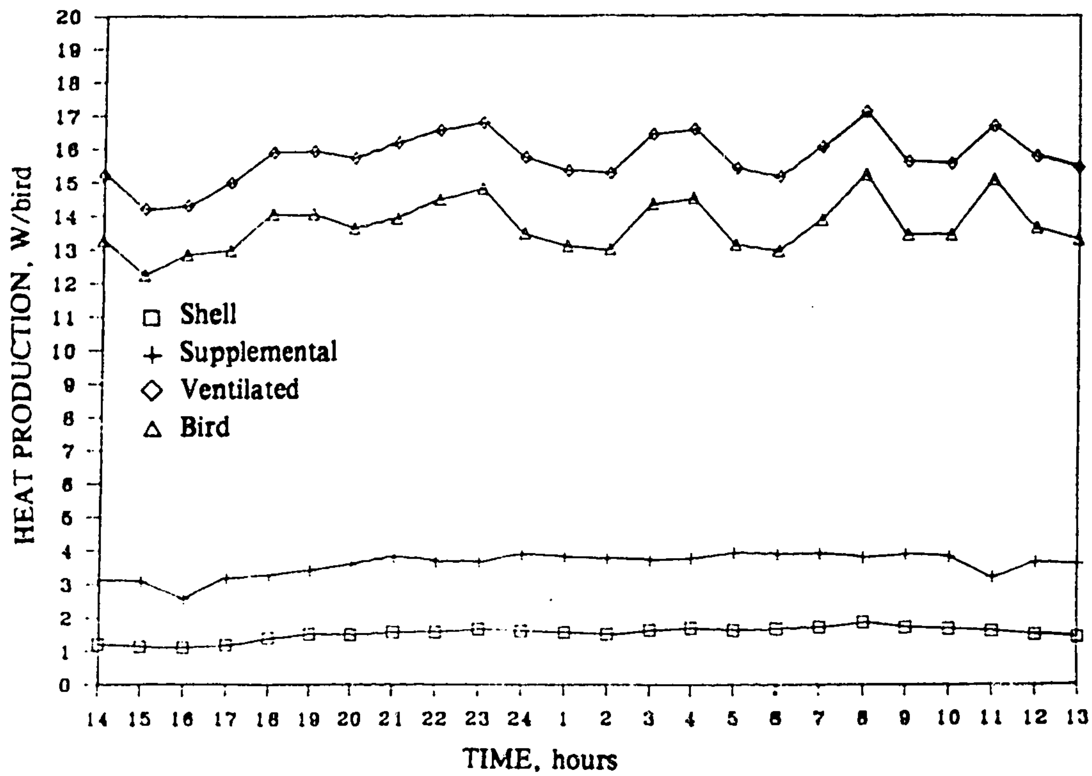

Figure 5.9 Heat balance in brooder barn for 36-day old hens.

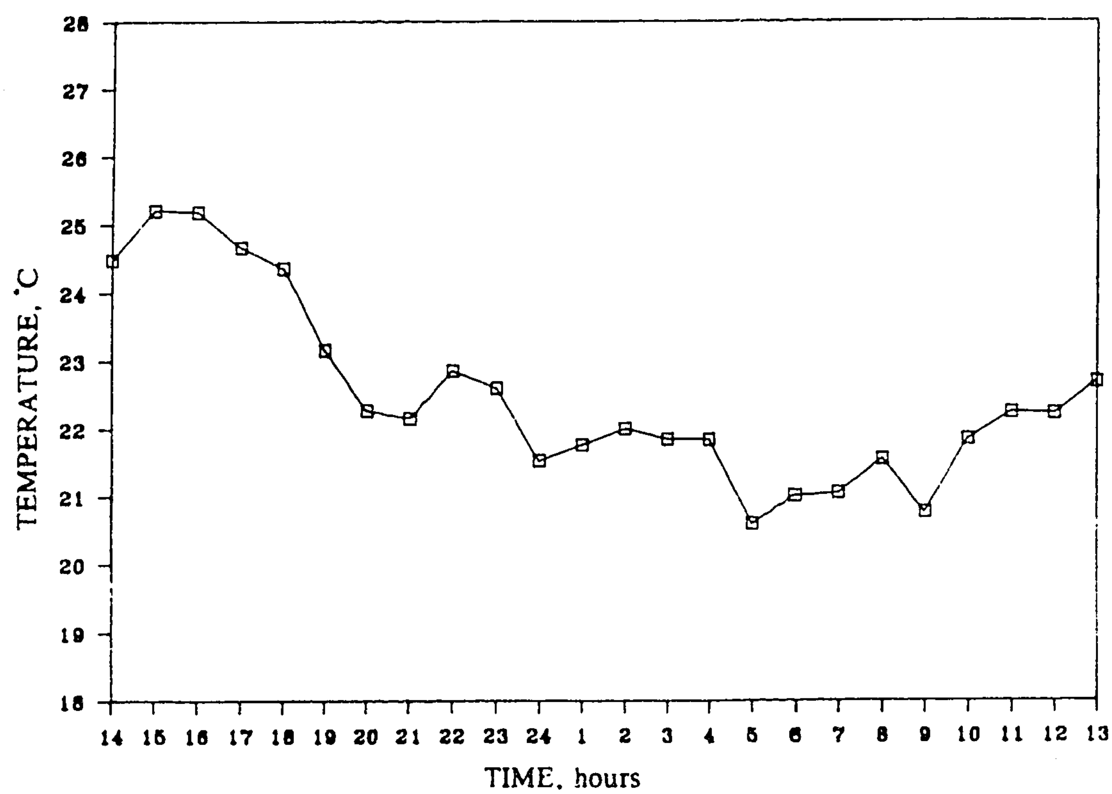

Figure 5.10 Ambient temperature in the brooder barn for 36-day old hens.

The heating system was expected to produce more heat as outside temperature decreased. This occurred in most instances with some noticeable exceptions. The coldest period while monitoring the grower barn housing the toms was when they were 92 days old, when outside temperatures ranged from -30 °C to -17 °C. Supplemental heat output for this period was considerably less than it had been in earlier periods with higher outside temperatures. Ambient temperatures for this run were, in fact, relatively higher since turkey heat production increased considerably. They produced approximately the same amount of heat at 92-days old as they did a week later when their body size was greater. The low supplemental heating and outside temperatures may have caused an increase in turkey activity giving rise to higher heat production rates.

Similarily, when the toms were 106 days of age, outside temperatures only decreased to -16 °C with an average temperature of -9.1 °C for the entire period. Supplemental heat was much less than in previous runs under similar conditions. In this case, ambient temperature dropped to 8 °C at one stage which is well below recommended temperatures for turkey barns.

During cold spells brooder barn supplemental heat did not appear to control ambient temperature well. As shown in Figure 5.2, temperature in the brooder barn was below recommended values for the first four runs. Supplemental heat input decreased for the last of these runs, suggesting that there may have been a fault in the control system. Outside temperatures rose while monitoring the grower barn during occupancy by the hens and supplemental heating was only required during one run. Shell losses in the grower barn were much less for the hens than for the toms due to higher outside temperatures. With the exception of the first two runs on the brooder barn, heat supplied to the building by the birds was greater than that supplied by the heating system.

5.3.2 Heat Production

Appendix D shows the 24-hour heat production rates, measured directly and indirectly, in all barns for each monitoring period with the exception of the first measurements on the brooder barn. Ambient temperatures for all monitoring periods are also shown in Appendix D. Due to a power failure, data for the hens in the grower barn at 79 days old were incomplete. A definite relationship between heat production and ambient temperature can be seen. Generally, as the temperature in the barn decreased, usually at night, direct and indirect heat production from the birds increased. With the exception of two runs heat production peaked during the night while in all cases, ambient temperatures dropped at night. This increase in heat production resulted either from a decrease in body weight gain or an increase in feed consumption. Heat production from 70-day and 84-day old toms dropped at night despite a decrease in ambient temperatures (Appendix D.3 and D.7). The birds appeared to adjust to the lower temperatures.

Heat production from the hens was equally dependant on ambient temperature. When the hens were in the grower barn, ambient temperatures were higher than they were for the toms. As a result, fluctuations in heat production were not as large. However, there were still noticeable changes in production as temperature varied, even though the variations occurred within the thermoneutral zone. When the hens were 79 days old, ambient temperatures remained relatively constant (Appendix D.29). Only 12 hours data were collected for this run. For the first 9 hours, the ambient temperature was 18 °C and heat production remained constant. Fluctuations in temperature seemed to affect heat production regardless of whether they were within the thermoneutral zone or not.

Table 5.4 shows the feed consumption (g/d.bird kg), water consumption (L/d.bird) and bodyweight of the birds for each monitoring period. For two runs in the grower barn the feed auger was out of order and so no values for feed consumption could be obtained. Feed consumption data for two runs in the brooder barn were also unobtainable. Previously reported feed consumption data are also shown in Table 5.4 (Jensen, 1975). These data were also with Large White turkeys, though growth rates measured by Jensen were lower than those measured in this study. For this reason feed consumption is on a bird weight basis rather than an age basis. While toms in this study weighed 11.1 kg at 106 days of age, the reported mean

Table 5.4 Measured and reported feed consumption, water consumption and body weight of toms and hens.

Age (days)	Measured Feed g/(d.bird kg)	Reported Feed ** g/(d.bird kg)	Water L/(d.bird)	Bird Weight kg
		Toms in Grower Barn		
64	78	63	N/A	5.1*
70	99	57	N/A	5.9*
77	97	53	N/A	7.0*
84	N/A	66	N/A	7.8*
92	N/A	47	N/A	8.8
99	54	45	0.67	10.0*
106	74	46	0.61	11.1
		Hens in Brooder Barn		
7	N/A	N/A	N/A	0.13*
16	251	124	0.1	0.33*
21	185	190	0.14	0.67*
29	106	126	0.19	0.99
36	N/A	81	0.22	1.54
44	75	71	0.27	2.00
		Hens in Grower Barn		
57	71	62	0.38	3.14
71	67	56	0.44	4.50*
79	50	46	0.50	6.63*
94	50	45	0.48	6.86

* Estimated from Summers and Leeson (1985)

** Reported by Jensen (1975)

N/A Not Available

weight for 106-day old Large White toms was 8.3 kg. The mean hen weight at 94 days old in this study was 6.86 kg, while the reported mean weight for 94-day old Large White hens was 4.86.

Feed consumption per kilogram of bird weight was higher than reported values in most cases. Reported consumptions were slightly higher on two occasions. Total feed consumed from birth to market weight was less than reported values despite the higher feed consumption. Mean total feed consumption for the toms was 27.3 kg/bird. Jensen (1975) reported a total feed consumption of 33.1 kg/bird for a similar weight. The average total feed consumption per hen in this study was 20.9 kg. Jensen reported a total feed consumption of 21.4 kg per hen. This results in an 18% and 2.5% saving in feed costs for the toms and hens, respectively. This difference resulted from the toms and hens reaching market weight four weeks earlier than usual. Feed consumption per unit weight decreased with increasing age in the brooder barn. Toms in the grower barn consumed more food per unit weight at 106 days old than at 99 days. Table 5.1 shows that the mean ambient temperature was 4.5 °C lower at 106 days old. Similarily, feed consumption per unit weight at 64 days old was less than at 70 and 77 days. Mean ambient temperatures were lower for the latter runs. Total hen feed consumption as measured by the feed auger sensor was 90250 kg; barn charts indicated that the actual consumption was 94100 kg, giving an error in feed consumption data of 4.1%.

Feed consumption appeared to increase with decreasing temperatures. The increase in heat production associated with the low ambient temperatures caused an increase in feed consumption. However, this increase in energy intake was not purely for heat production as growth rates were also high. Summers and Leeson (1985) also reported feed consumption and growth rates for Large White turkeys; their values were lower than those measured by Jensen (1975).

Water consumption was measured for two runs with toms and all but one monitoring period with hens. Water consumption was also higher than previously reported values. Due to experimental error, bodyweights were only measured on seven occasions and had to be estimated in nine cases using the difference between the known weights and previously reported weights (Summers and Leeson, 1985).

Figure 5.11 shows the quantities of feed entering the grower barn every hour over a 24-hour period. Figure 5.12 shows hourly heat production for that same period. In this run the heat production decreased as the temperature decreased. The relationship between feed consumption and heat production shows that the early evening heat production was high when consumption was also high. Heat production then decreased with a decrease in rate of food consumption. Figures 5.13 and 5.14 show feed consumption and heat production measured in the brooder barn when the hens were 29 days old. Heat production remained relatively constant throughout with only one sharp increase in early evening. Similarily, feed consumption stayed constant, with the auger being activated every four hours for comparable lengths of time. The trend was similar for all the other runs, with heat production increasing as food consumption increased. Figures 5.11 and 5.13 show only the feed entering the barn. This feed was not necessarily consumed at the times shown on the graphs.

Maximum daily direct heat production data are given in Table 5.3. Bird heat is the total sensible and latent heat produced by the turkeys. The maximum mean heat production from the toms was 69.3 W, the highest recorded hourly average being 93.9 W. Ranges varied as much as ±30% for both toms and hens. As expected production rates increased with maturity for the toms with one exception at the age of 84 days. As explained earlier, this increase in heat production occurred because the supplemental heating system did not compensate for extremely cold outside conditions.

Heat production from hens was higher than from toms at a given age despite the fact that the toms were heavier. This may have been due to cold stress, with the hens utilising metabolisable intake energy for growth to a lesser extent than toms. Teter *et al.* (1976) developed a model for predicting turkey growth rates. They reported that mature toms appeared to be much more resistant to cold weather than hens. The maximum rate of heat production averaged over 24 hours for the hens was 36.4 W. This occurred during the second

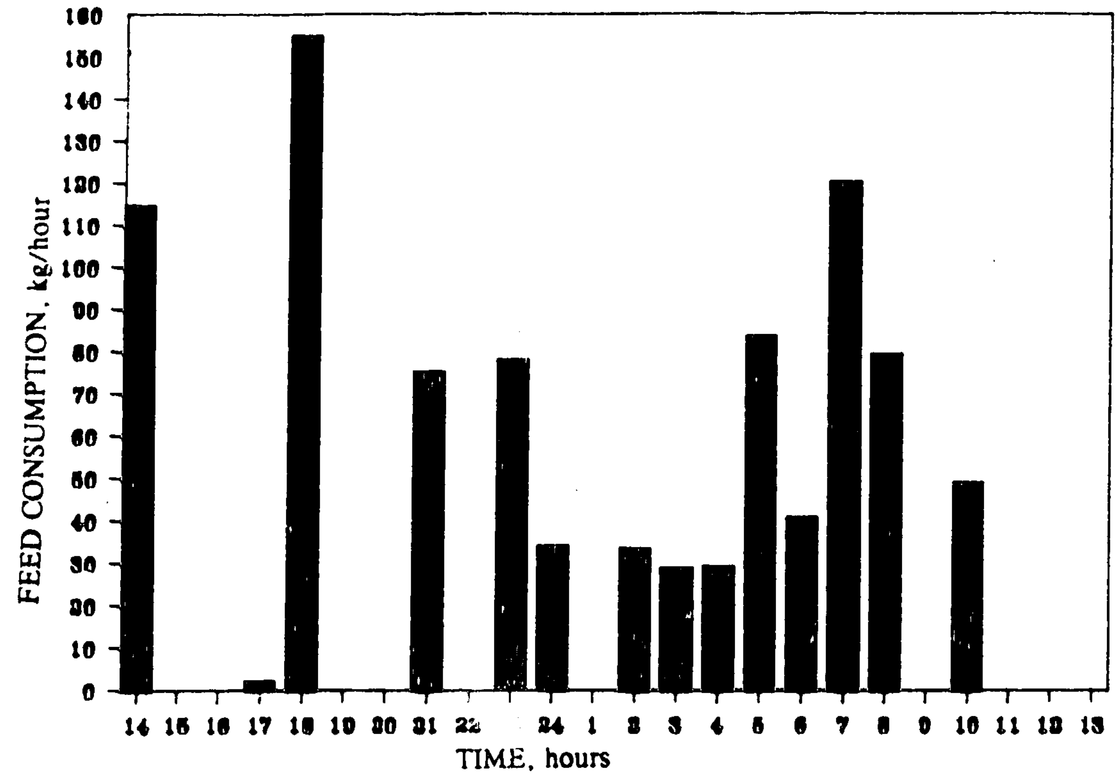

Figure 5.11 Hourly feed consumption in grower barn for 70-day old toms.

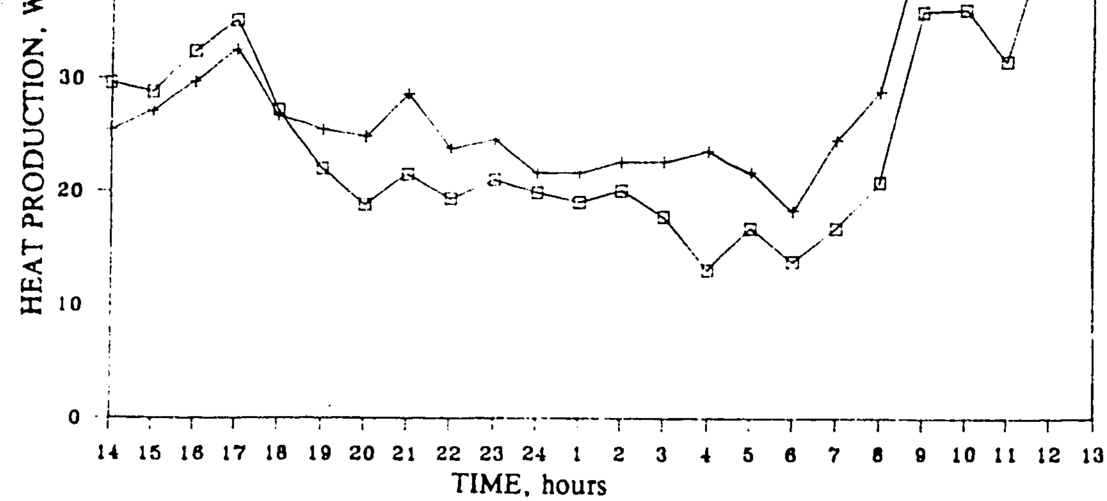

Figure 5.12 Heat production from 70-day old toms in grower barn.

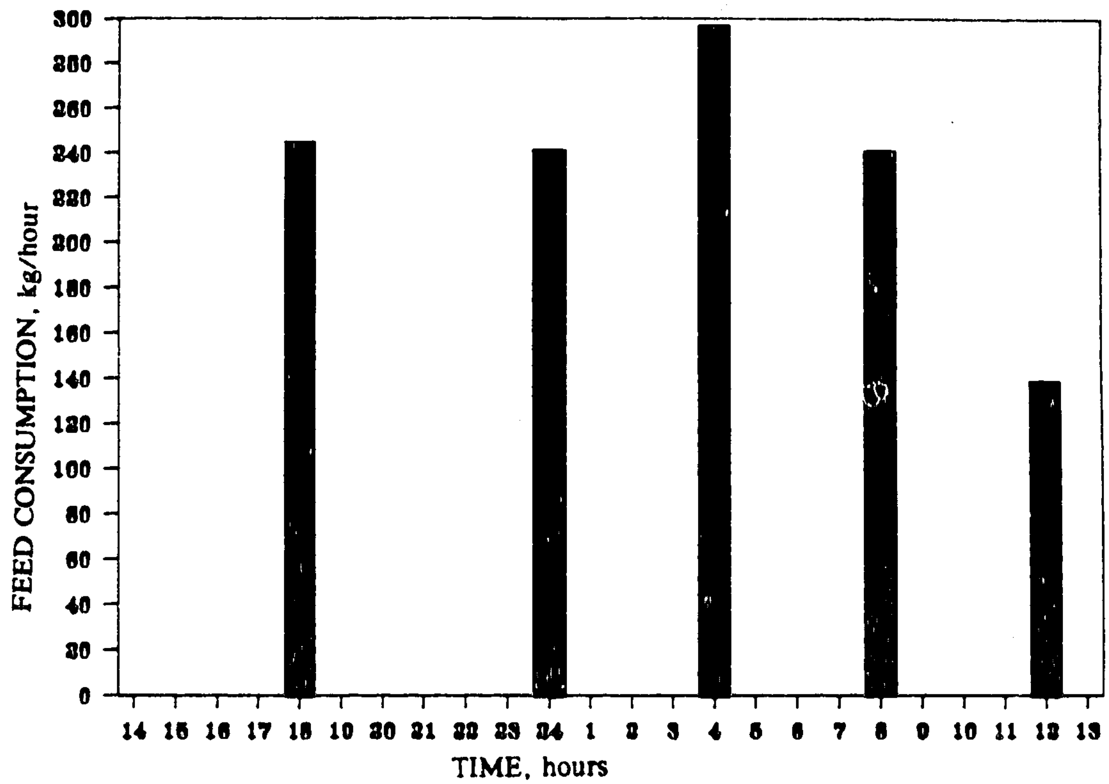

Figure 5.13 Hourly feed consumption in brooder barn for 29-day old hens.

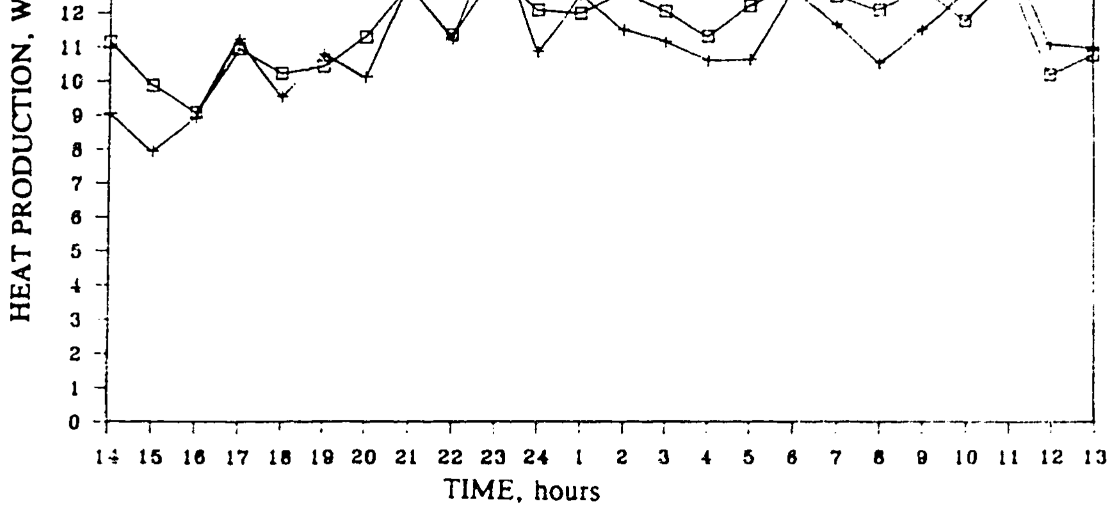

Figure 5.14 Heat production from 29-day old hens in brooder barn.

last run rather than the last run as was expected. The largest hourly value was 73.6 W measured during the last run. This run also had the largest range over an entire monitoring period, the lowest production rate was 10.51 W.

Feed consumption and heat production were related closely as were CO_2 production and heat production. The more food the birds metabolised, the more energy and CO_2 they produced. In most cases, temperature was the controlling factor dictating heat production from the birds and, subsequently, feed consumption. If ambient temperatures were higher and more constant, the birds could have produced less heat and retained this feed energy as growth. However, if temperatures had been higher, activity in the barn and subsequently feed consumption would have decreased, so that growth rate may also have decreased. The toms and hens reached market weight four weeks earlier than normal, so the low and fluctuating temperatures apparantly did not have an adverse effect and may in fact have contributed to rapid growth. The birds appeared to adjust their lower critical temperature to the ambient temperature by increasing feed consumption at lower temperatures. The feed to bodyweight conversion for the toms was 2.52 kg/(kg bodyweight), higher than a previously reported value of 2.13 (Summers and Leeson, 1985) Equations relating heat production to bird age were calculated. The relationship for the toms is only valid for the time they spent in the grower barn. Equations for the hens are valid throughout their entire life cycle.

a. Toms;

$$Y = -158.19 + 3.72X + 0.0148X^2 \qquad (5.3)$$

$$R^2 = 0.98$$

b. Hens;

$$Y = -11.14 - 0.9456X - 0.00512X^2 \qquad (5.4)$$

$$R^2 = 0.96$$

where:

X = bird age, days, and

Y = heat production, (W/bird).

5.3.3 Sensible to Latent Heat Production

Bird total heat production included both sensible and latent heat components. Sensible heat output was used in the evaporation of moisture from the litter and any other moisture source in the barn. Therefore, the calculated sensible heat is not the true sensible heat output from the turkeys. In order to calculate the proportion of sensible heat converted to latent heat in the barn, latent heat output from the turkeys was estimated. This value was then subtracted from the total latent heat production. Data on the latent heat production of turkeys are limited. DeShazer *et al.* (1974) measured evaporative heat losses from Large White toms from 6 to 36-days of age. They found that evaporative heat loss remained constant as environmental temperatures decreased with increasing age. Evaporative heat losses ranged from 1.5 W/bird to 3.3 W/bird. ASAE standards 1988 cite latent heat production of 2.2 W/kg for 15 kg Large White toms and 2.4 W/kg for 8.2 kg Large White hens. These data are the only available data for latent heat production therefore, data for young hens were taken from DeShazer *et al.* (1974). A value of 2.2 W/kg was assumed for the older hens and toms. Latent heat production was dependant on ambient temperature therefore assuming a constant value for evaporative heat losses does not give accurate results. However, the assumed value was the only one possible from the limited data in the literature.

Table 5.5 shows total, sensible and latent turkey heat production in the barn for each monitoring period. Estimated bird latent heat production was higher than total latent heat for four runs on the grower barn housing toms and for one run on the grower barn housing hens. The estimated values were too high. Environmental temperature effects latent heat production. DeShazer *et al.* (1974) showed that a 5 °C difference in ambient temperature could cause up to 50% change in latent heat output. Temperatures in the grower barn were low during occupancy by the toms and sensible heat production is the usual way for maintaining body temperature in cold environments. In order to predict the quantity of sensible heat converted into latent more data are required for latent heat production from turkeys at different weights and at different temperatures.

Table 5.6 Indirect and direct heat production measurements, average RQ values and the ratio of direct to indirect for the hens and toms.

Age (days)	Indirect (W/bird)	Direct (W/bird)	Ratio	RQ
	Toms in grower barn			
64	19.0	21.4	1.13	1.01
70	28.8	25.6	0.88	0.80
77	37.0	41.4	1.12	1.03
84	48.0	48.9	1.02	0.87
92	60.4	61.3	1.01	0.89
99	64.7	62.8	0.97	0.92
106	66.8	69.3	1.04	1.00
	Hens in brooder barn			
7	N/A	N/A	N/A	N/A
16	2.6	3.0	1.15	1.07
21	6.8	8.2	1.21	1.05
29	11.2	11.6	1.04	0.97
36	12.0	13.7	1.14	0.93
44	17.6	20.5	1.16	1.02
	Hens in grower barn			
57	23.8	24.4	1.03	1.02
71	35.1	30.8	0.88	0.85
79	35.0	36.4	1.04	0.94
94	33.9	29.7	0.88	0.95

N/A Not Available

Sensible heat losses were the largest in the grower barn housing toms. However, latent losses predominated for the hens in the brooder barn. For the hens in the grower barn sensible losses were higher for the last three runs.

5.4 Indirect Versus Direct Calorimetry

Direct calorimetry involves a heat balance as shown in the previous section. Indirect measurements also were carried out by measuring O_2 consumed and CO_2 released in the production of energy. These values then were used in equation 2.7 derived by Romijn and Lockhorst (1964). Ventilation rates were corrected to a temperature of 0 °C and a pressure of 760 mm of mercury (Hg) as these were the conditions used in developing the equation. Table 5.6 shows the total heat production measured directly and indirectly for hens and toms, respectively. Respiratory quotients also are given in this table. As stated earlier, this is the ratio of CO_2 produced to O_2 consumed. Direct calorimetry values on average were 4% higher than indirect. Direct measured higher heat production than indirect in 13 runs while, indirect gave higher values in four runs. The difference between direct and indirect for all the runs varied from -12% to 21%. Maximum heat production measured indirectly was 66.2 and 35.1 W from the toms and hens, respectively. The maximum value for heat production from the hens was during the third last run in the grower barn. Deviations of indirect from direct were greatest in the brooder barn with the exception of the fourth run. Figures 5.15 and 5.16 show the differences between indirect and direct graphically for the toms and hens, respectively.

Appendix D shows hourly mean heat production as measured directly and indirectly for all the runs. Appendix D.23 shows measurements for 44 day-old hens, deviations between direct and indirect increase at night. Direct calorimetry measured an increase in heat production from the hens at night while, indirect measurements indicated a decrease in heat production. Appendix D.24 shows the hourly temperature profile for that same period. Temperatures decreased at night and so an increase in heat production would be expected. This indicated that direct calculations were more likely to be representative of actual values.

Table 5.6 Indirect and direct heat production measurements, average RQ values and the ratio of direct to indirect for the hens and toms.

Age (days)	Indirect (W/bird)	Direct (W/bird)	Ratio	RQ
	Toms in grower barn			
64	19.0	21.4	1.13	1.01
70	28.8	25.6	0.88	0.80
77	37.0	41.4	1.12	1.03
84	48.0	48.9	1.02	0.87
92	60.4	61.3	1.01	0.89
99	64.7	62.8	0.97	0.92
106	66.8	69.3	1.04	1.00
	Hens in brooder barn			
7	N/A	N/A	N/A	N/A
16	2.6	3.0	1.15	1.07
21	6.8	8.2	1.21	1.05
29	11.2	11.6	1.04	0.97
36	12.0	13.7	1.14	0.93
44	17.6	20.5	1.16	1.02
	Hens in grower barn			
57	23.8	24.4	1.03	1.02
71	35.1	30.8	0.88	0.85
79	35.0	36.4	1.04	0.94
94	33.9	29.7	0.88	0.95

N/A Not Available

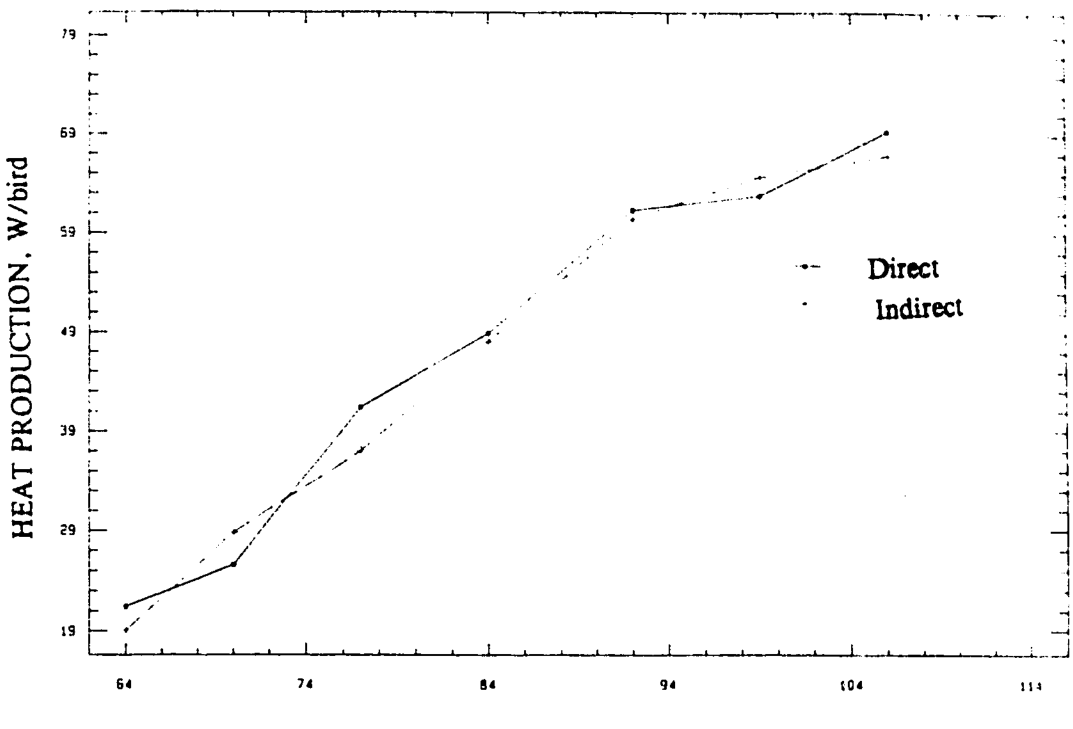

Figure 5.15 Heat production as measured directly and indirectly for the toms.

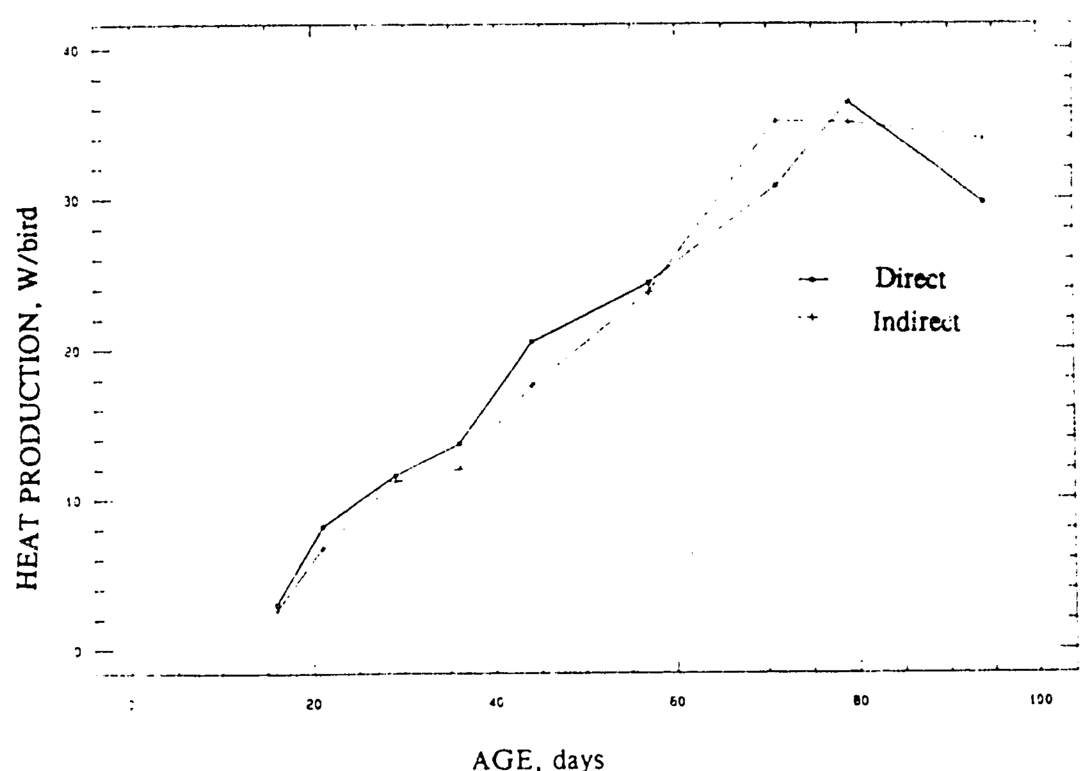

Figure 5.16 Heat production as measured directly and indirectly for the hens.

In all other runs, direct and indirect production profiles were similar. Hourly values show that direct calorimetry did not always give higher values than indirect despite the fact that the mean daily value was higher.

Heat and CO_2 produced by the anerobic metabolism in the litter was considered to be negligible. Anaerobic heat production was not measured directly. Litter temperature as measured by the thermistors in the heat-flux plates on the floor underneath the litter indicated that litter temperature was similar to room temperature. Also the low level of ammonia production suggested that biological activity was low in the litter. Most of the litter was dry with the exception of the area near the drinking fountain and under the mister nozzles in the grower barn.

Appendix C gives an error analysis for all the sensors and analysers. The O_2 analyser was accurate to within ± 100 ppm or 1% of full scale (2250 ppm), whichever was largest. Considerable drift occurred over the 24-hour monitoring periods in some cases up to 1000 ppm. Despite the fact that the O_2 analyser was equipped with a pressure compensator changes in barometric pressure have been found by other researchers to effect the readings slightly. This was discovered through personal communication at the University of Alberta. Measurement of O_2 consumption required the measurement of the difference between outside and inside O_2 concentrations therefore, any error incurred measuring outside concentration was compensated for by a similar error in ambient concentration measurement. Therefore an accuracy of ±100 ppm was used for outside and inside measurements. This gave a total accuracy of ±200 ppm in calculating the difference between inside and outside O_2 concentrations.

Errors in temperature measurement only effect direct calculations. These errors were relatively small compared to ventilation, dewpoint and O_2 concentration measurements. Carbon dioxide measurements were accurate within ±1% of full scale (50) ppm. This gave a total accuracy of ±100 ppm when measuring the difference in CO_2 concentrations. The error analysis showed that O_2 concentration measurements were most likely to cause error in heat production calculations and differences between direct and indirect.

Using certified span gases for O_2 calibration is not recommended because these gases have an analytical accuracy of 1%. In this experiment, a span of 21.2% was used, this gave an accuracy of 0.212% or 2120 ppm. This was not sufficiently accurate for this experiment. However, this was not likely to cause any errors in heat calculations because any calibration error in measuring outside concentration was compensated for by a similar error in measuring ambient CO_2.

Accurate measurement of dewpoint is critical for both direct and indirect calorimetry. Because the sample was not dried before entering the O_2 analyser, a correction factor for moisture was used. The percentage of moisture in the sample was calculated and O_2 readings were adjusted to a dry basis. The partial vapour pressure of the sample air was calculated and used to calculate the percentage water vapour content of the sample. Once water content was known the O_2 measurement was corrected to a dry basis (Appendix B). If dewpoint measurements were underestimated, then O_2 readings would be lower than the actual concentration. Because outside temperatures were lower than inside for all monitoring periods and changes in moisture were not as extreme at the lower end of the psychrometric chart, outside measurements would not be effected to the same extent as inside. This would have the effect of increasing the value for O_2 consumption and subsequently the heat production value. The effect on direct calorimetry would be to decrease the value for moisture content and so give a decreased value for heat production.

Similarily, if dewpoint was overestimated indirect values would have been lower than the actual value and the direct values would have been higher. Appendix C shows that an error of 0.5 °C in dewpoint would result in a 3% and 7% error in direct and indirect, respectively. These errors would be additive to give a total discrepancy between indirect and direct calorimetry of 10%. Oxygen consumption played a major role in the calculation of heat production from gaseous exchange, contributing approximately 75% to equation 2.7. For this reason, indirect calorimetry was much more susceptible to errors in dewpoint than direct. If the samples had been dried before entering the O_2 analyser errors caused by dewpoint meter malfunctions would have been less.

In the course of this experiment, some difficulties were experienced with the dewpoint readings. On some occasions, ice settled on the cooling mirror overnight which rendered the instrument useless for the remainder of the run. In order to obtain dewpoint readings in these cases, a relationship between ambient temperatures and dewpoints for other runs was used to estimate dewpoint from this. This, however, was very approximate and so these readings were suspect. Dewpoint readings, therefore may have caused a considerable portion of the difference between direct and indirect calorimetry. Errors in measuring ventilation rate caused similar errors in both direct and indirect methods however, these errors canceled out the difference between the methods. It should be noted that other factors such as inaccuracies in equation 2.7 or indirect energy expended in raising food to body temperature caused small discrepancies between the two methods, however, these were negligible.

The error analysis was carried out on data from the brooder barn housing 36-day old hens. Total heat production was relatively low compared to data from the grower barn. The percentage error was higher here than it would have been in a later run. Differences between direct and indirect calorimetry were greatest for the brooder barn where heat production values were smallest. Therefore, instrument error appeared to cause less discrepancy at higher heat production values.

5.5 Respiratory Quotient

Respiratory quotient (RQ) is the ratio of the volume of CO_2 produced to the volume of O_2 consumed when a substrate is oxidised. This ratio is indicative of the metabolic processes taking place in the body. An RQ of 0.7 suggests that only fat in the body is being oxidised and, if only carbohydrates were being oxidised the RQ would be 1.0. Table 5.6 gives the respiratory quotients measured for each run. The average RQ for all the measurements was 0.96 with means of 0.93 and 0.97 for the toms and hens, respectively. Research on turkeys is limited, so these results can only be compared with measurements on other types of fowl. Lundy et al. (1978) measured RQ's between 0.95 and 1.03 from laying hens. The measurements in this experiment ranged from 0.80 to 1.07; however Lundy et al. conducted their experiment in a chamber with controlled conditions. Both toms and hens achieved market weight four weeks earlier than average with a very high feed conversion of 2.52 kilograms of feed per kilogram of weight gain. These high RQ's are consistent with such fast growth.

If O_2 consumption was overestimated, then the RQ value would have been lower than it actually was. Although RQ values are well within the accepted range the O_2 consumption value may still be inaccurate. As explained earlier, a small inaccuracy in O_2 consumption will cause a large error in heat production. No diurnal patterns in RQ could be found.

Conclusions

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

1. Mean daily heat production values from direct calorimetric measurements were 4% higher than indirect measurements. Differences between methods ranged from -12% to 21%.
2. Maximum mean heat production measured directly was 69.3 W for the toms and 36.4 W for the hens for 106 days and 79 days, respectively. Maximum indirect values for the toms and hens were 66.8 and 35.1 W/bird, respectively. Heat production was found to be greater from hens than toms for similar ages.
3. Feed consumption rate was found to be higher than reported values for Large White turkeys. However, total feed consumption was less than reported as a result of less time required to attain market weight.
4. Ambient temperatures were approximately 3 °C less than those recommended. The cooler temperatures stimulated additional feed consumption, thus lowering the lower critical temperature to that of the ambient temperature. This may explain the higher rate of gain.
5. Ambient CO_2 concentrations were generally below the recommended concentrations of 3000 ppm. The maximum recorded level was 4606 ppm.
6. The hens were found to have a higher CO_2 production rate than the toms at a similar age. This was attributed to toms utilising more energy for growth energy.
7. Carbon dioxide production was found to be a function of the ambient temperature in the barn. As temperature decreased both heat production and food consumption increased thus causing an increase in CO_2 production.
8. Minimum ventilation rates were not sufficient for maintaining recommended relative humidity levels in the grower barn. The ventilation system in the brooder barn controlled moisture adequately.
9. Pressure differentials between inside and outside the barn were considerably lower than recommended values indicating poor air mixing in the barn if other methods of recirculation were not available.

10. Errors in dewpoint were found to have opposite effects on direct and indirect calorimetry, thus increasing the discrepancy between the two methods. A 0.5°C error in dewpoint caused a 10% difference between the measurement methods. Indirect calorimetry was found to be more susceptible to errors in dewpoint than direct.
11. Average RQ for all the runs was 0.97 with a range from 0.80 to 1.07. Mean RQ for the toms and hens were 0.93 and 0.97, respectively. No pattern could be found between RQ and age. Diurnal variations in RQ were not noticable.

Recommendations

The data collected in this experiment show that, for this farm, the supplemental heating system was not sufficient to maintain an environmental temperature at the recommended value. Brooder barn temperatures were lower than recommended and may have been the cause of high mortality in the first few weeks of the hens life. Increased heating, especially in the brooder barn is required. Minimum ventilation rates were found insufficient for removing moisture and CO_2 from the grower barn. Both tom and hen mortality in this barn were over 16% with respiratory problems appearing to play a major role. These problems may have been caused by high moisture or dust levels both of which can be controlled by increasing the minimum ventilation rate. Despite the low ambient temperatures, feed consumption rates were high with corresponding higher growth rates.

The indirect methods of calorimetry compared favourably with the direct for field conditions, however, improvements can be made. Accurate moisture measurements are critical for oxygen determinations and for direct calculations. Frequent checks on wet and dry bulb temperatures can ensure the dewpoint meter is functioning properly. Because indirect calorimetry is so sensitive to moisture readings gas samples should be dried before they enter the oxygen analyser rather than correcting for moisture afterwards. More accurate results are required to examine changes in RQ due to sex and age.

The following recommendations are made as a result of this study:

1. Investigate further the effects of low temperatures on turkey production.
2. Cyclic rather than low ambient temperatures may stimulate feed consumption. An experiment to measure feed consumption and growth rates at cyclic temperatures is recommended.
3. Measure the latent heat from turkeys in calorimeters at different temperatures and different ages. If latent heat production values were known sensible to latent heat conversion could be calculated from the data reported here.
4. Investigate further the effect of anaerobic litter breakdown on RQ values in whole-house

indirect calorimetry. The heat input from the litter should also be measured. This would be possible by measuring heat production in the barn after the turkeys are removed.

5. A system calibration is recommended with a known heat input. This calibration should be repeated in order to ascertain accuracy and repeatability of the system.
6. Investigate the effects of changes in barometric pressure on the O_2 analyser.

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Appendix A

1. Psychrometric Equations:

$$P = (10^{**}(10.79586(1 - TT) + 5.0282Ln(TT)$$

$$+ 1.50474E\text{-}4(1 - 10^{**}(8.29692((1 - TT) - 1)))$$

$$+ 0.42873E\text{-}3(10^{**}94.76955(1\text{-}TT)) - 2.21958)(760)$$

$$W = 0.622\ P/(Pa - P)$$

$$H = T + W(2501 + 1.86T)$$

$$Vs = 2.16(T + 273.16)/(Pa - W(Pa)/(0.622 + W))$$

$$Ws = 0.622\ Ps/(Pa - Ps)$$

$$RH = (100\ W/Ws)/(1 - ((1 - W/Ws)(Ps/Pa)$$

where:

P = vapour pressure, mm Hg

T = temperature, °C

TT = temperature, K, T + 273.16 K

W = humidity ratio, kg moisture/kg dry air

Pa = atmospheric pressure, mm Hg

H = enthalpy, kJ/kg dry air

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

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

Ps = vapour pressure of saturated air, mm Hg, and

RH = relative humidity, %

2. Ventilation Rate:

$$Q = V A$$

where:

Q = ventilation Rate, m^3/s

V = air speed averaged over 25 readings, m/s, and

A = duct area, m^2.

3. Ventilated Heat Losses:

$$THL = Q(Hin - Hout)/Vs(1000)$$

$$LHL = Q(Win - Wout)/Vs(1000)$$

$$SHL = THL - LHL$$

where:

THL = total heat loss from building, W

LHL = latent heat loss, W

SHL = sensible heat loss, W

Q = ventilation rate, m^3/s

Hi = enthalpy of incoming air, kJ/kg dry air

Hout = enthalpy of exiting air, kJ/kg dry air

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

Wi = inside humidity ratio, kg moisture/kg dry air, and

Wout = outside humidity ratio, kg moisture/kg dry air.

4. Building Heat Losses:

$$C = U\ (Tin - Tout)\ N/3.6$$

where:

C = conductive heat loss, (W)

U = exposure factor, kJ/(h.°C.bird)

Tin = inside temperature, °C

Tout = outside temperature, °C, and

N = number of birds

Appendix B - Calibration Equations

1. Gas Analysers:

a. Oxygen Analyser;

$$O = (((AV + B)10000) \times 100)/(100 - Pv/Pa)$$

where:

O = oxygen concentration (dry basis), ppm

V = voltage output from analyser, volts

A = regression coefficient, 0.247

B = regression coefficient, 20.0

Pv = vapour pressure, mm Hg, and

Pa = atmospheric pressure, mm Hg.

b. Carbon Dioxide Analyser;

$$C = AV - B$$

where:

C = carbon dioxide concentration, ppm

V = voltage output from analyser, volts

A = regression coefficient, 2.4307, and

B = regression constant, 15.6519.

c. Dewpoint Meter;

$$T = AV - B$$

where:

T = dewpoint temperature, °C

V = voltage output from analyser, volts

A = regression coefficient, 16.3591, and

B = regression constant, 32.7322.

2. Feed Auger Sensor:

Brooder Barn and Grower Barn;

$$F = AT$$

where:

F = feed entering barn, g/s

T = time auger runs, s, and

A = rate of feed flow, 277 g/s

3. Anemometer Calibration:

$$F = 1.27V$$

where:

F = air flow rate, m/s, and

V = voltage reading from anemometer, volts.

4. Thermistors:

$$X = \text{Ln } R$$

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

where:

T = temperature, °C

R = sensor resistance, ohms

A = regression coefficient, $0.209099055/10^6$

B = regression coefficient, $0.275851225/10^3$, and

C = regression coefficient, $0.137958851/10^2$.

5. Supplemental Heat Input:

$$\dot{H} = L(A(((Tin + Tout)/2) - Tamb) + B)$$

where:

H = supplemental heat input, (W)

L = length of heating pipe, m

Tin = inlet water temperature, °C

Tout = outlet water temperature, °C

Tamb = ambient temperature, °C

A = regression coefficient, 2.1794, and

B = regression coefficient, 12.044

Appendix C - Error Analysis

An error analysis was carried out on the measurements made by the analysers and sensors necessary to calculate heat production. Representative mean values from one run were analysed. These data were then varied according to the absolute error specified by the manuals for each measurement. The effect of each error on heat production measured both directly and indirectly was calculated. Maximum possible error in heat production was calculated as the sum of the individual errors.

The table lists the representative mean data used and the accuracy of each instrument. The heat production error caused by each instrument is also given. Inaccuracies in dewpoint and ventilation caused subsequent errors in both direct and indirect. All other instruments caused errors in one method only. Dewpoint errors caused opposite effects on direct and indirect, so the discrepency was the sum of the individual errors. Ventilation was adjusted to 0 °C and 760 mm Hg for indirect calculations. Therefore an error in ventilation would cause a difference between direct and indirect.

Table F Error Analysis of Instruments Used for Determining Heat Production Directly and Indirectly.

Measurement	Representative Value	Accuracy	Error Direct W/bird	Error Indirect W/bird	RQ
Oxygen	1523 ppm	± 200 ppm	N/A	2.9	0.1
Carbon Dioxide	1431 ppm	± 100 ppm	N/A	0.2	0.06
Inside Dewpoint	13.5°C	± 0.5	0.4	0.8	0.09
Outside Dewpoint	-1.2°C	± 0.5	≤0.1	0.2	0.02
Ventilation	633 L/s	± 5%	0.5	0.4	N/A
Inside Temperature	23 °C	± 0.2	≤0.1	N/A	N/A
Outside Temperature	6 °C	± 0.2	≤0.1	N/A	N/A
Hot Water Temperature	69 °C	± 0.2	0.1	N/A	N/A

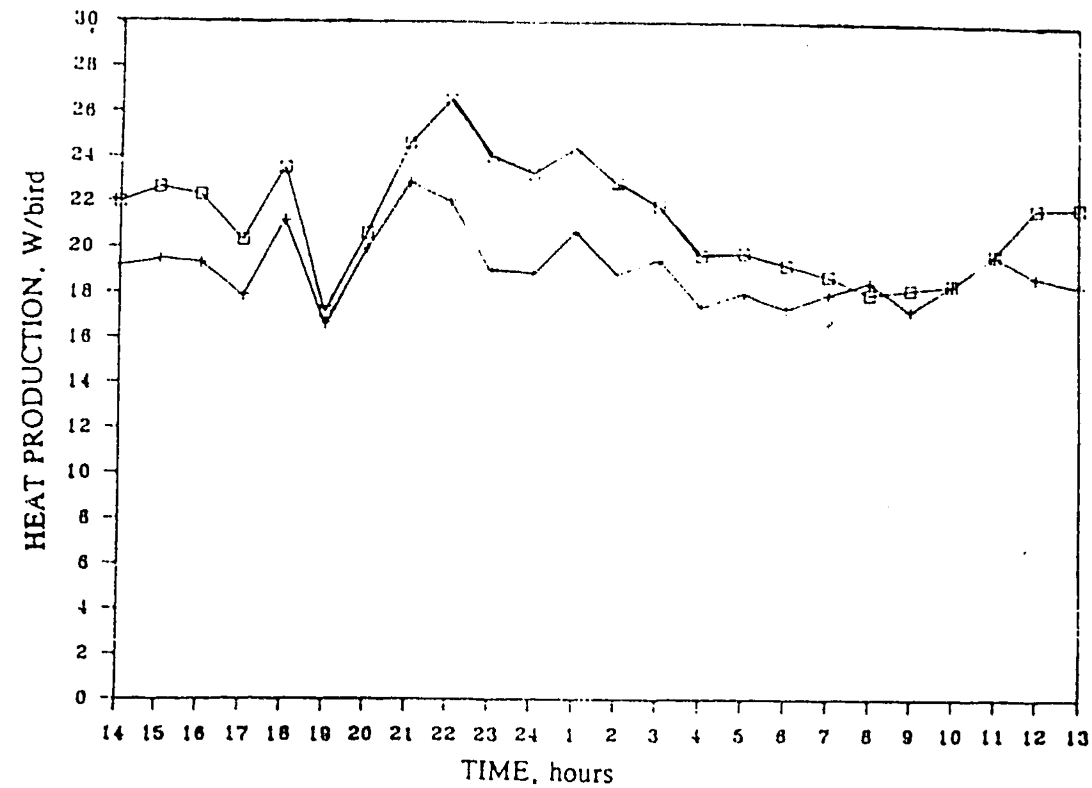
	Direct Mean	Direct Worse Case	Direct % Error	Indirect Mean	Indirect Worse Case	Indirect % Error
Heat Production, W/bird	13.7	12.7	7.3	12.0	7.5	37.4
Respiratory Quotient				0.93	0.66	25.8

Appendix D - 24-Hour Heat Production and Temperature Variations

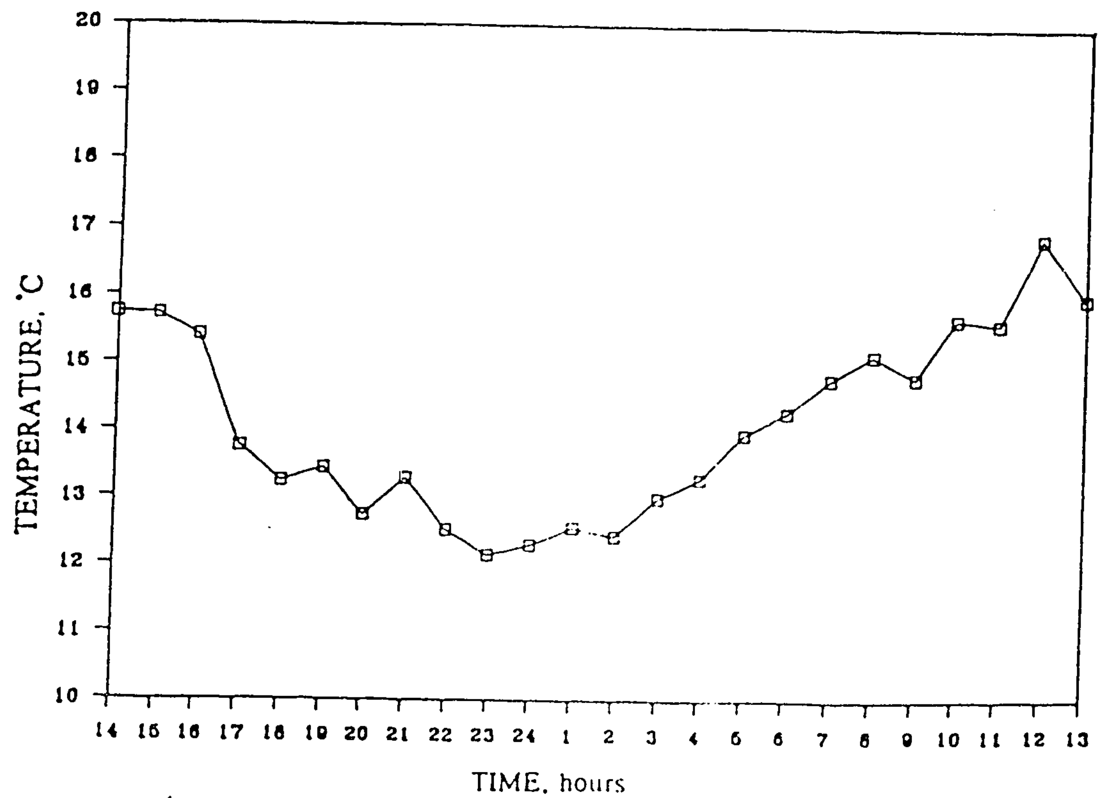
Heat production over a 24-hour period appeared to be closely linked with the temperature in the barn. In cold weather, ambient temperatures went as low as 6 °C due to insufficient supplemental heat being added. The trend was for ambient temperatures in the barn to decrease at night during very cold spells. Heat production followed this pattern, production increased as ambient temperatures went below the thermoneutral zone of the turkeys. This appendix shows the relationship between ambient temperature and heat production measured directly and indirectly. The symbols used on the heat production plots are:

Direct calorimetry - □

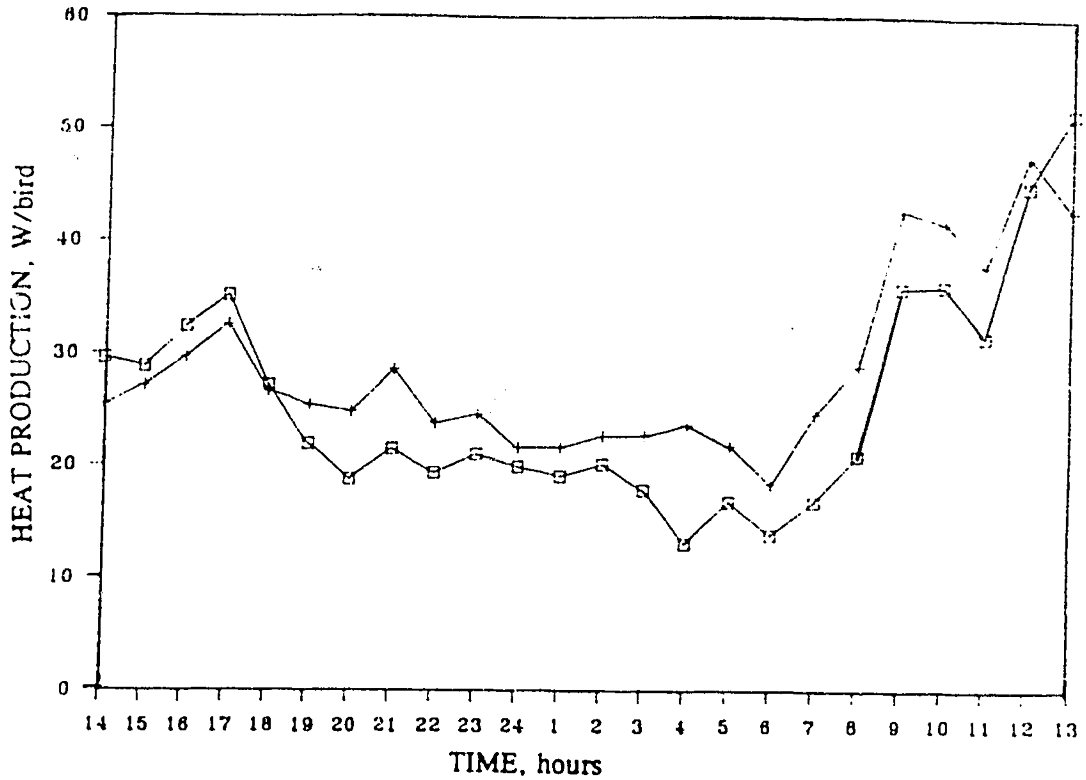
Indirect Calorimetry - +



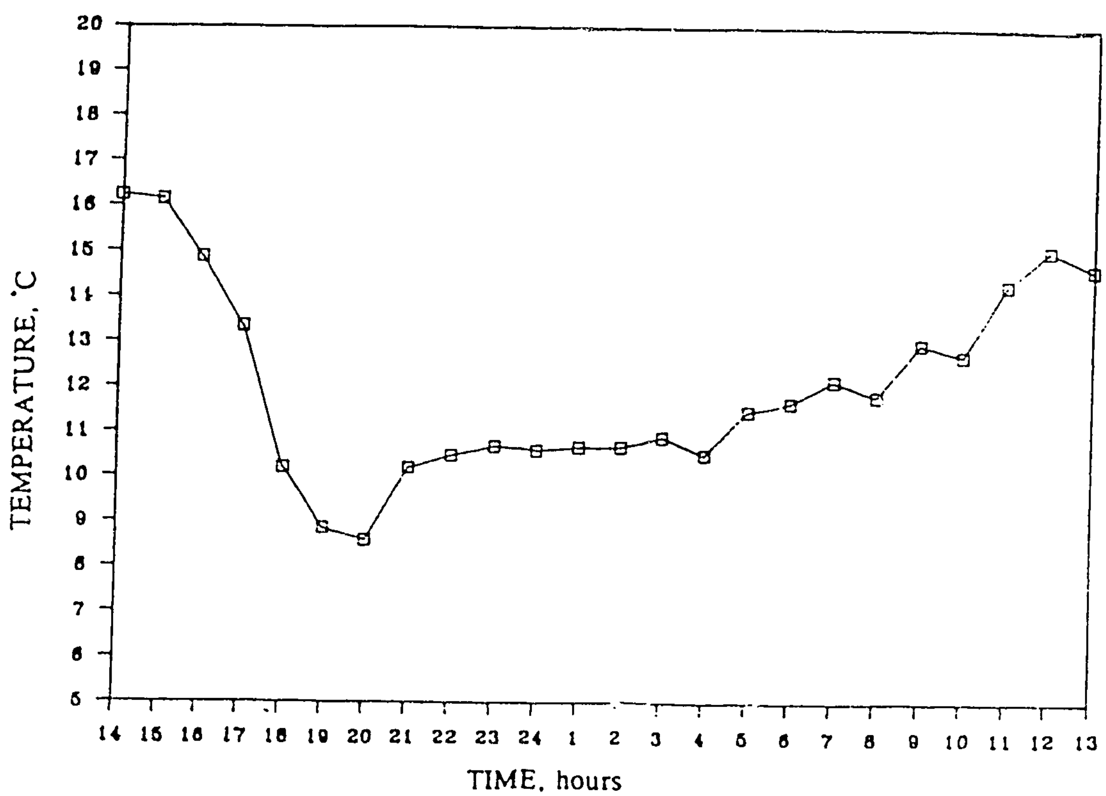
D.1 Heat production of toms measured directly and indirectly at 64 days of age.



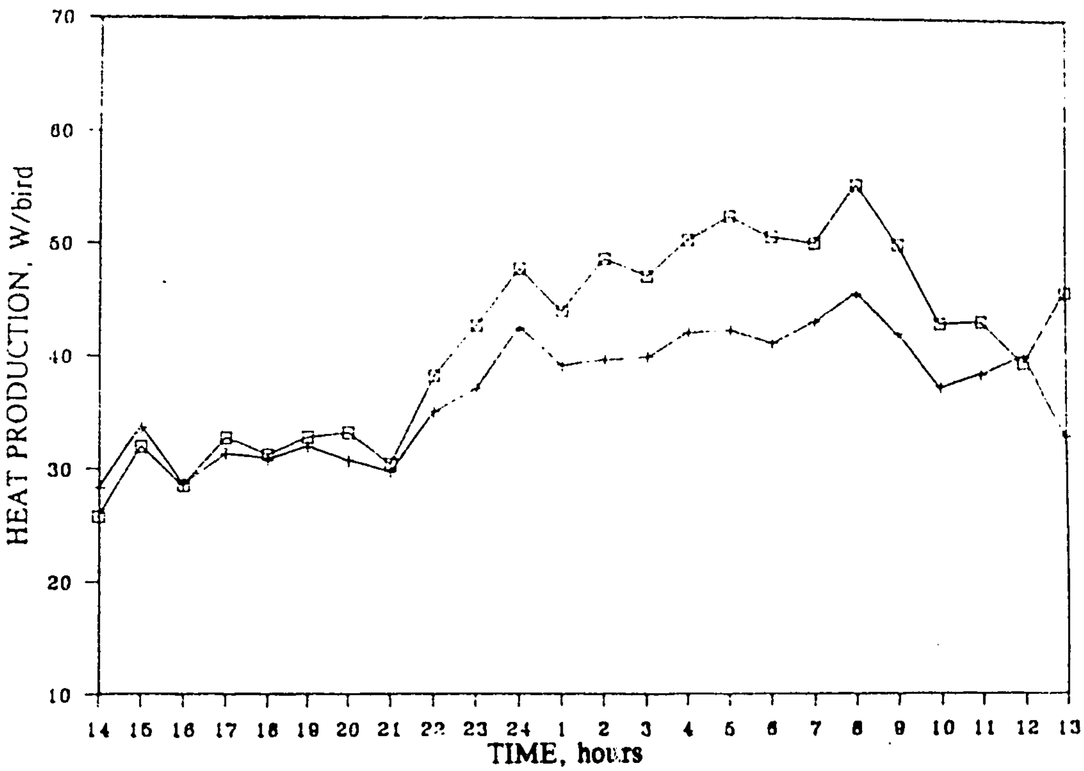
D.2 Ambient temperature in grower barn for 64-day old toms.



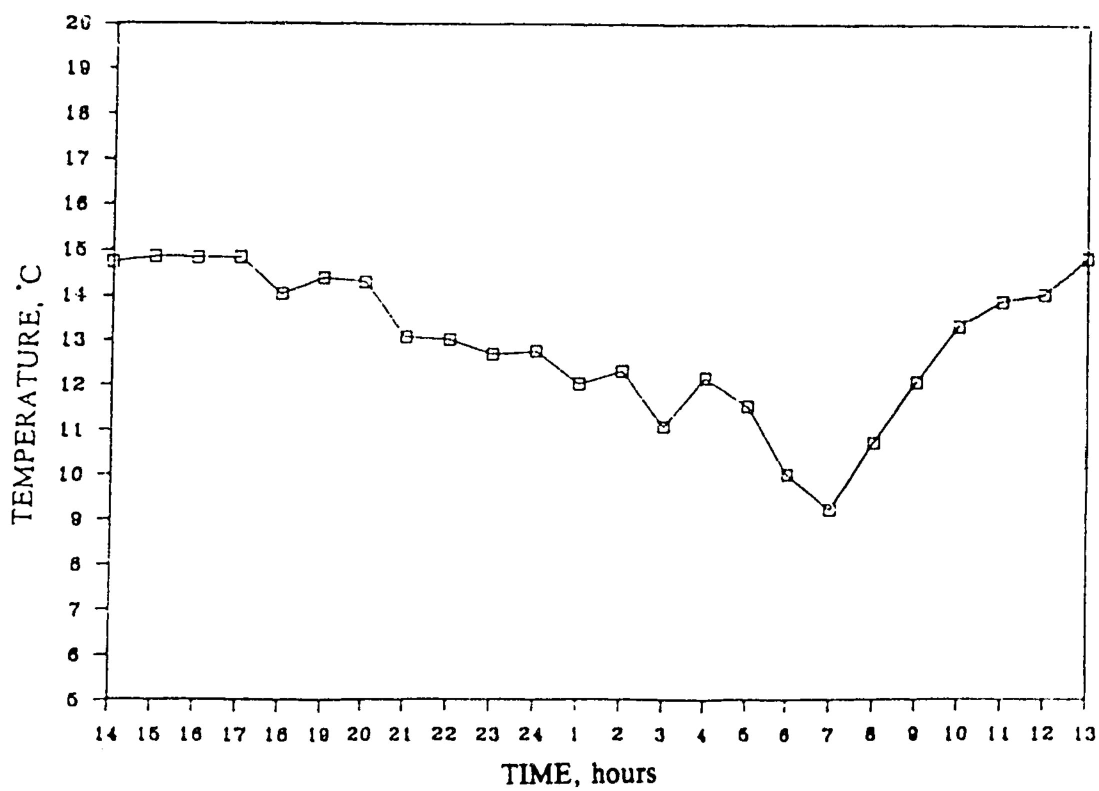
D.3 Heat production of toms measured directly and indirectly at 70 days of age.



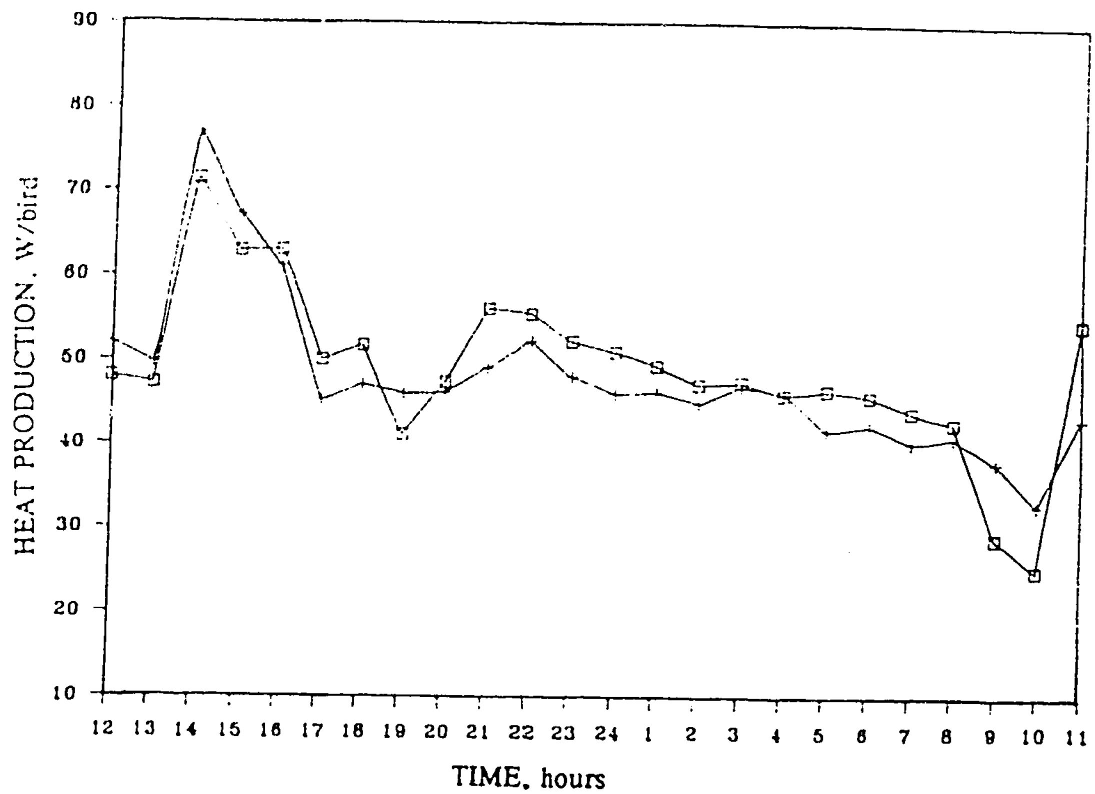
D.4 Ambient temperature in grower barn for 70-day old toms.



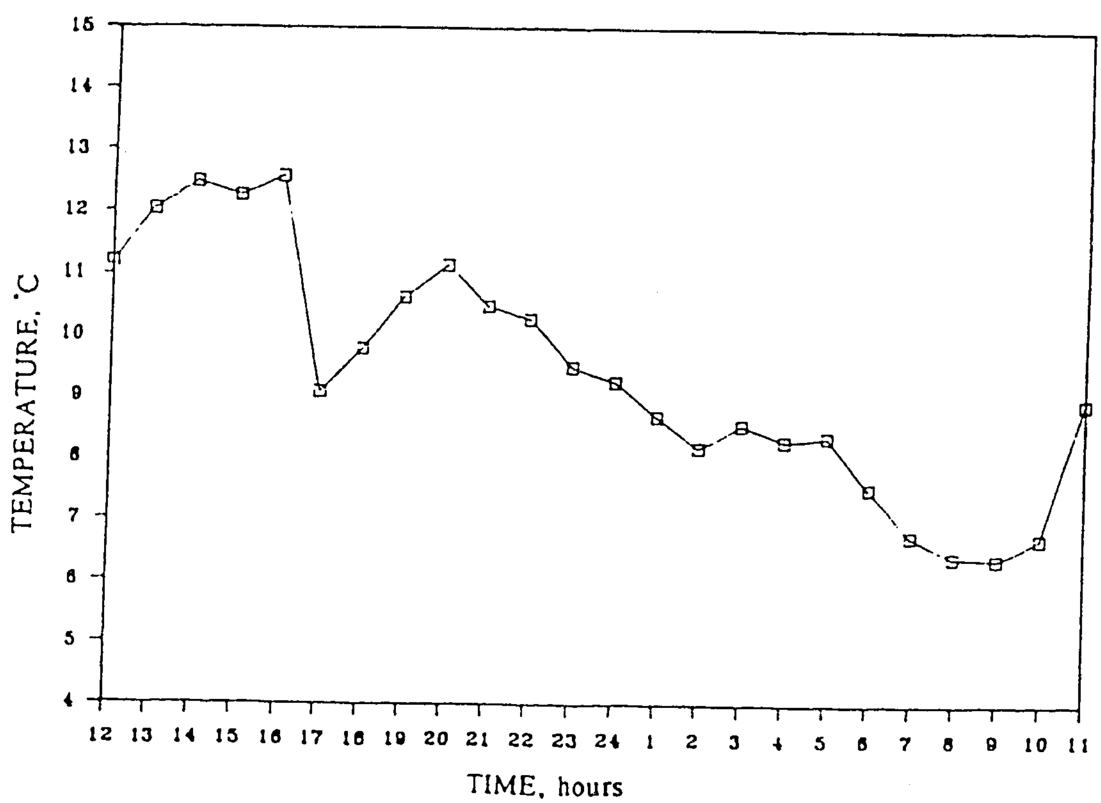
D.5 Heat production of toms measured directly and indirectly at 77 days of age.



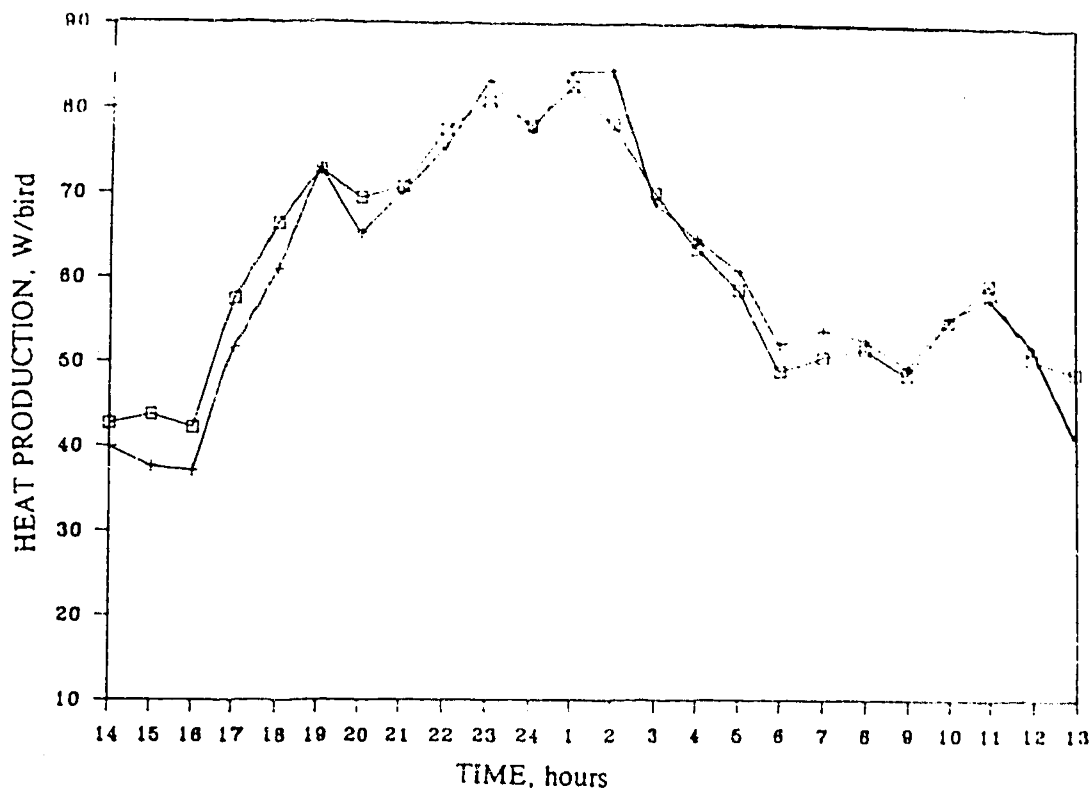
D.6 Ambient temperature in grower barn for 77-day old toms.



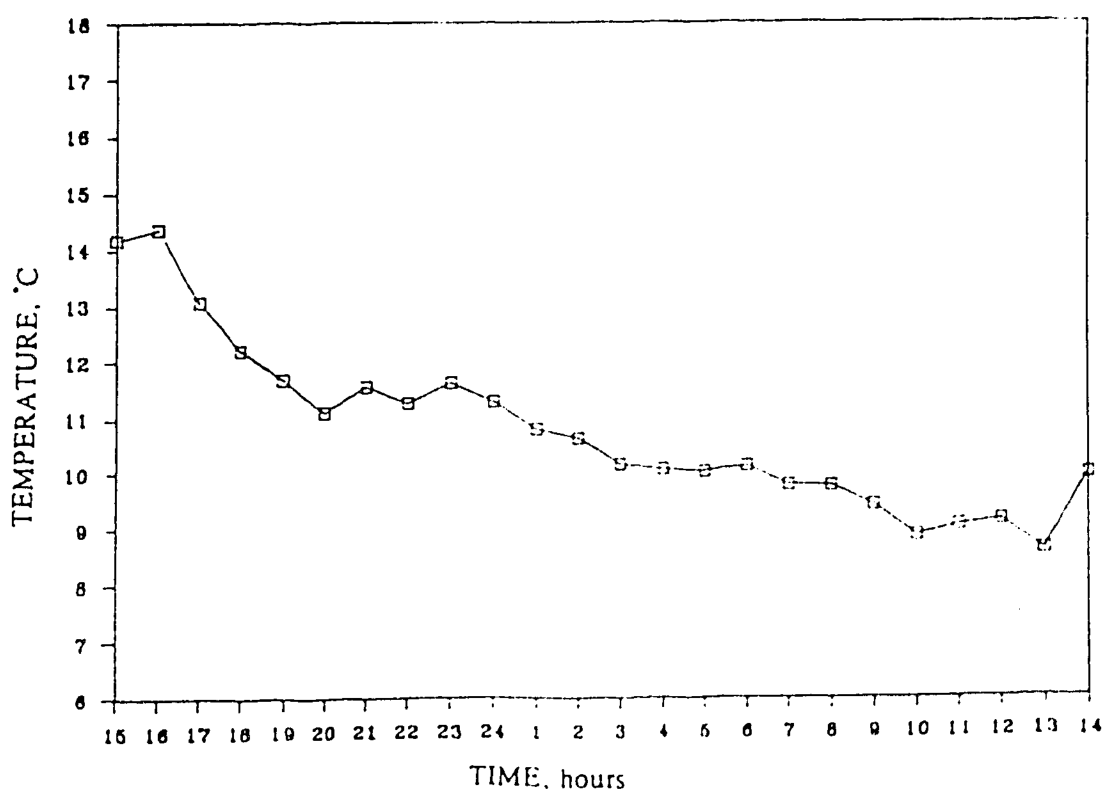
D.7 Heat production of toms measured directly and indirectly at 84 days of age.



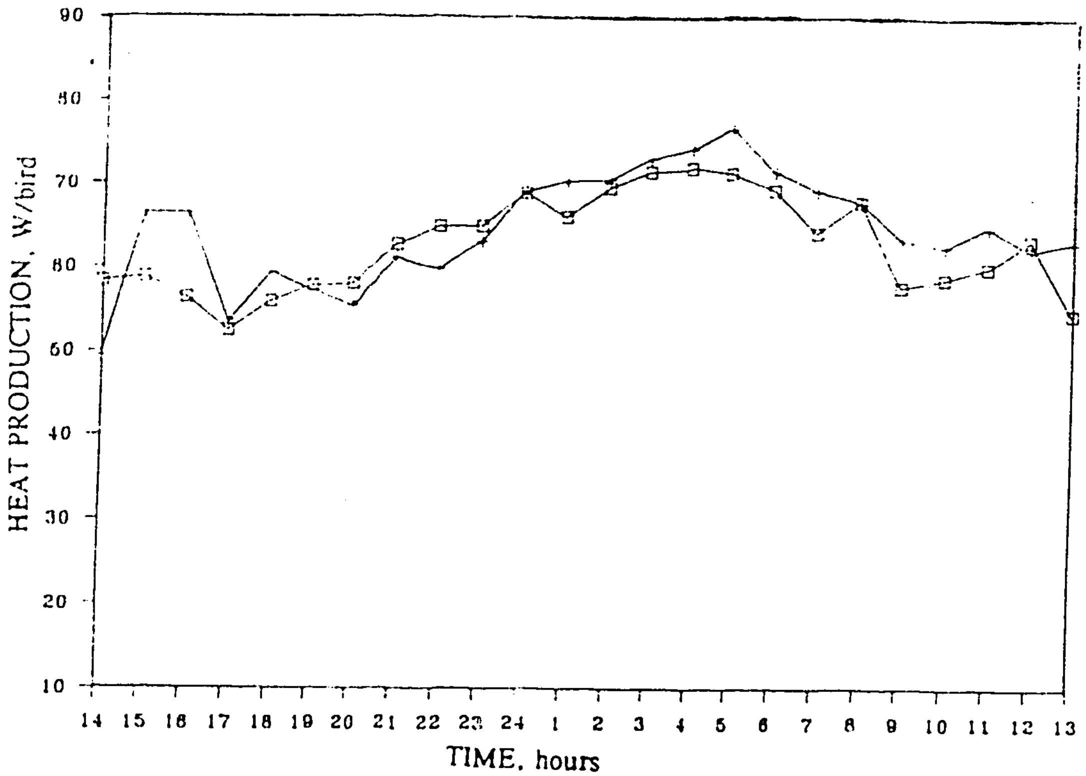
D.8 Ambient temperature in grower barn for 84-day old toms.



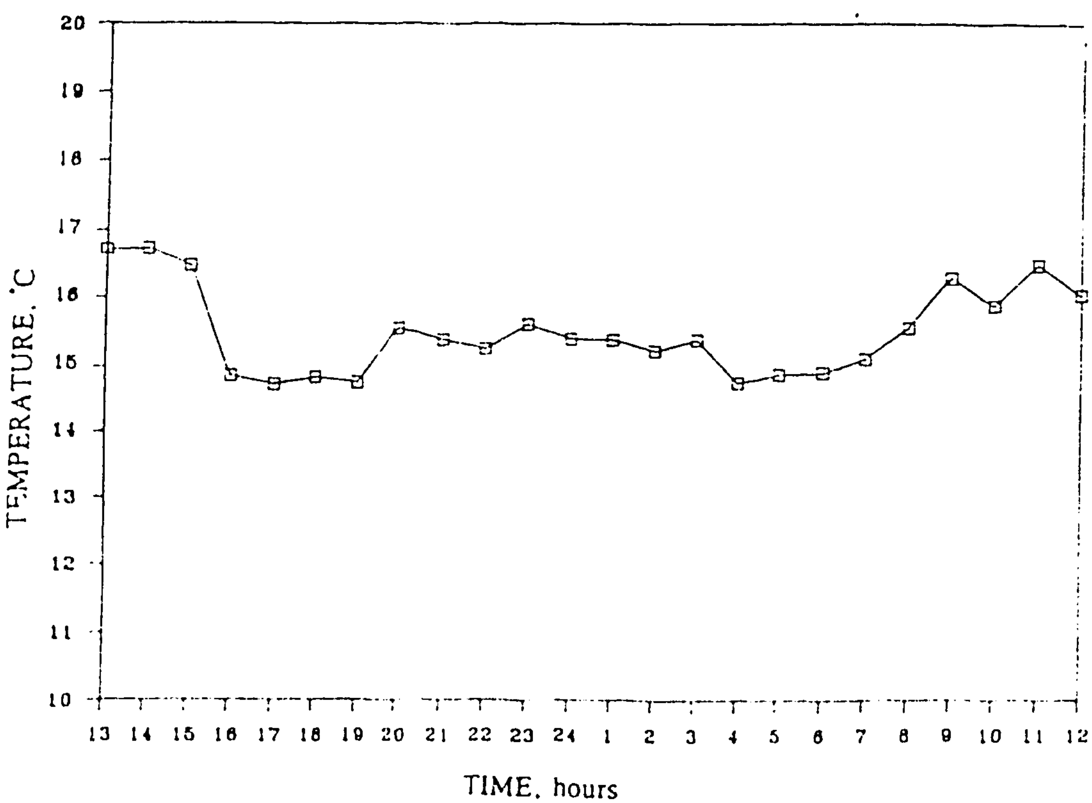
D.9 Heat production of toms measured directly and indirectly at 92 days of age.



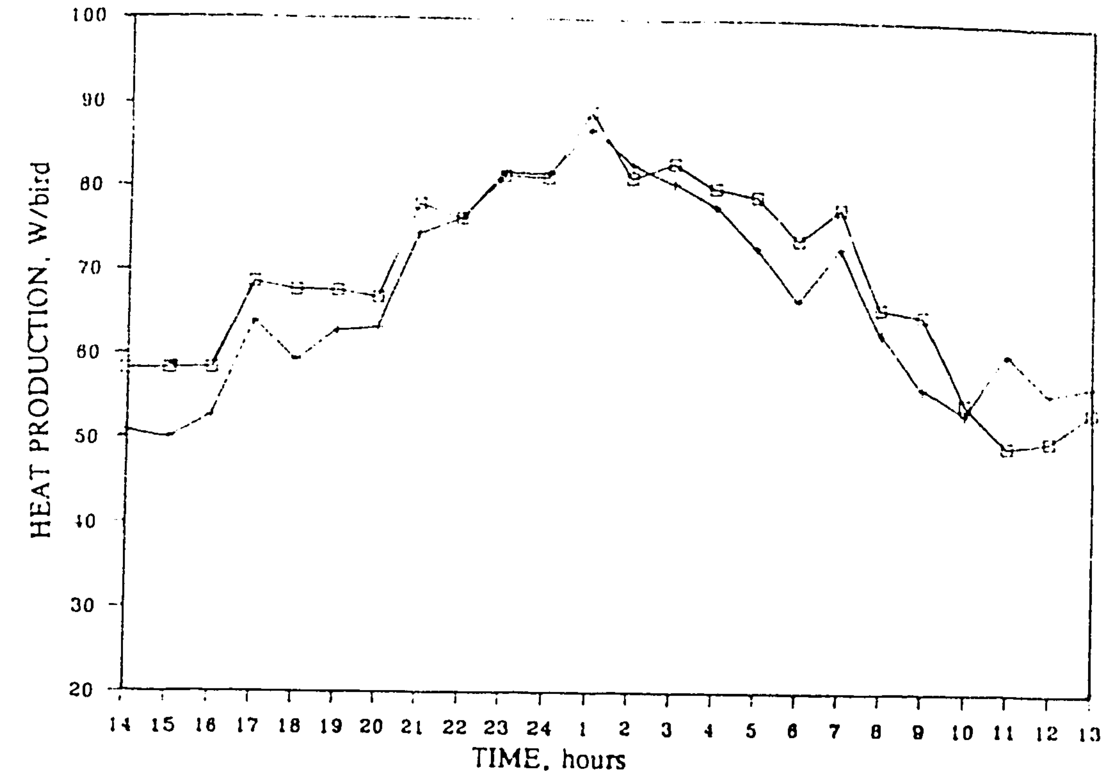
D.10 Ambient temperature in grower barn for 92-day old toms.



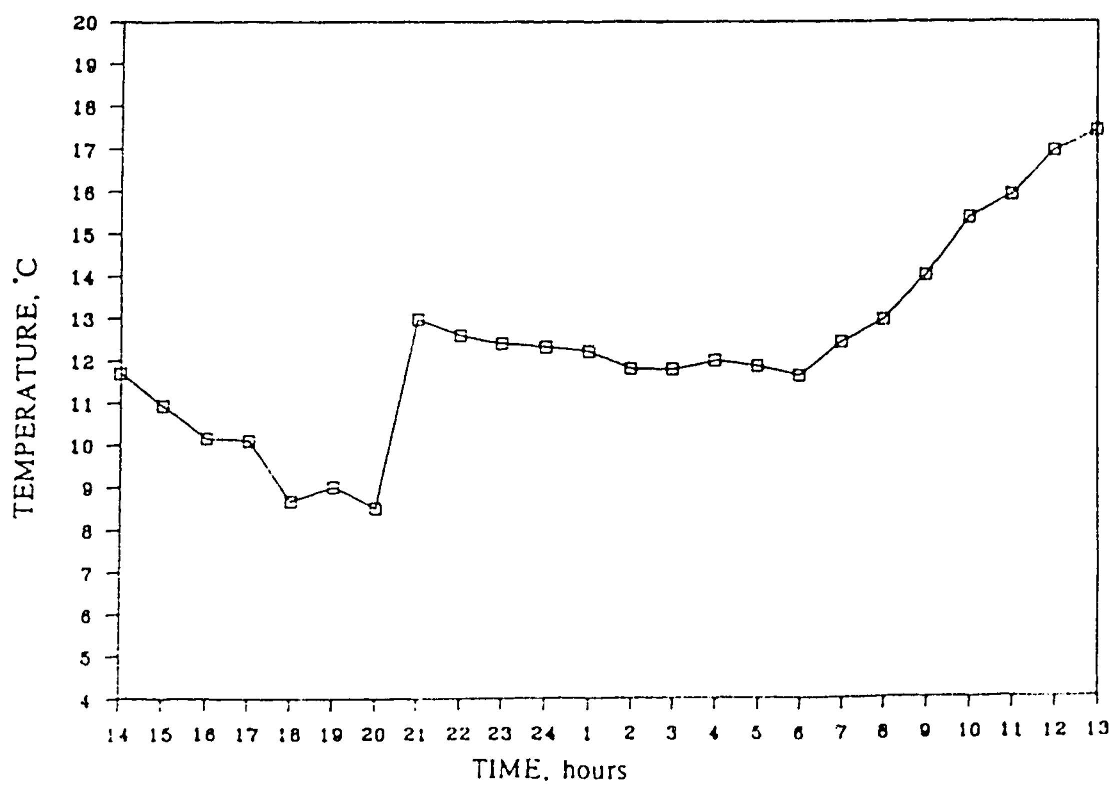
D.11 Heat production of toms measured directly and indirectly at 99 days of age.



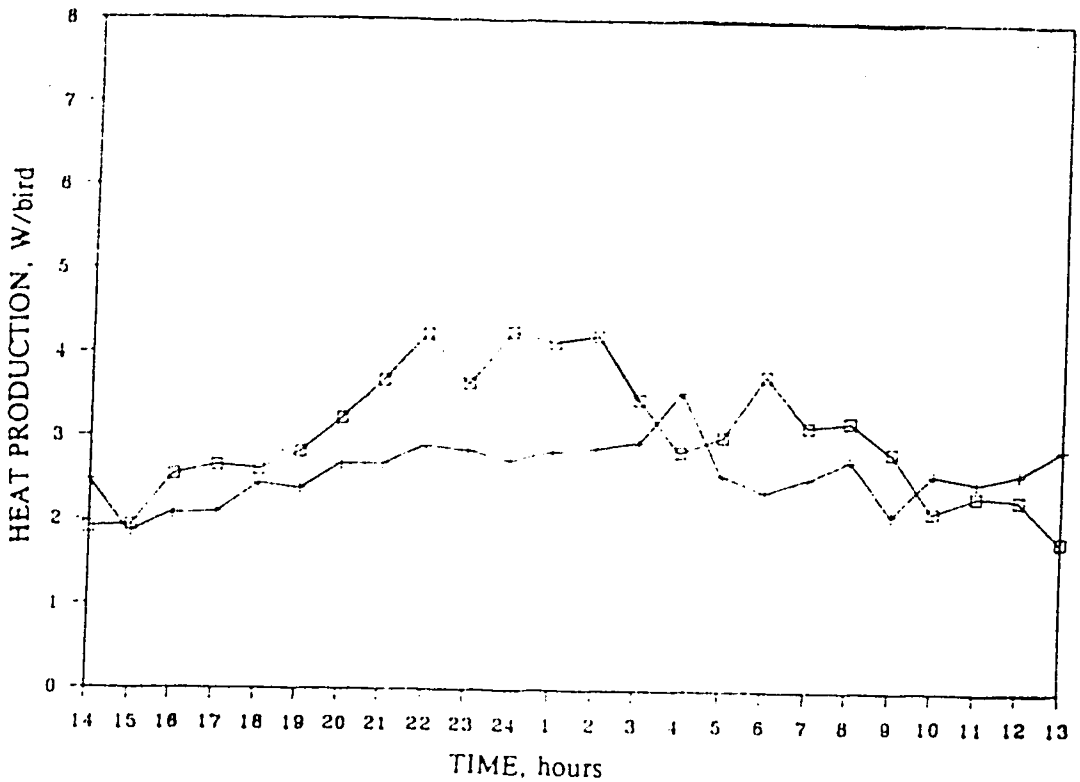
D.12 Ambient temperature in grower barn for 99-day old toms.



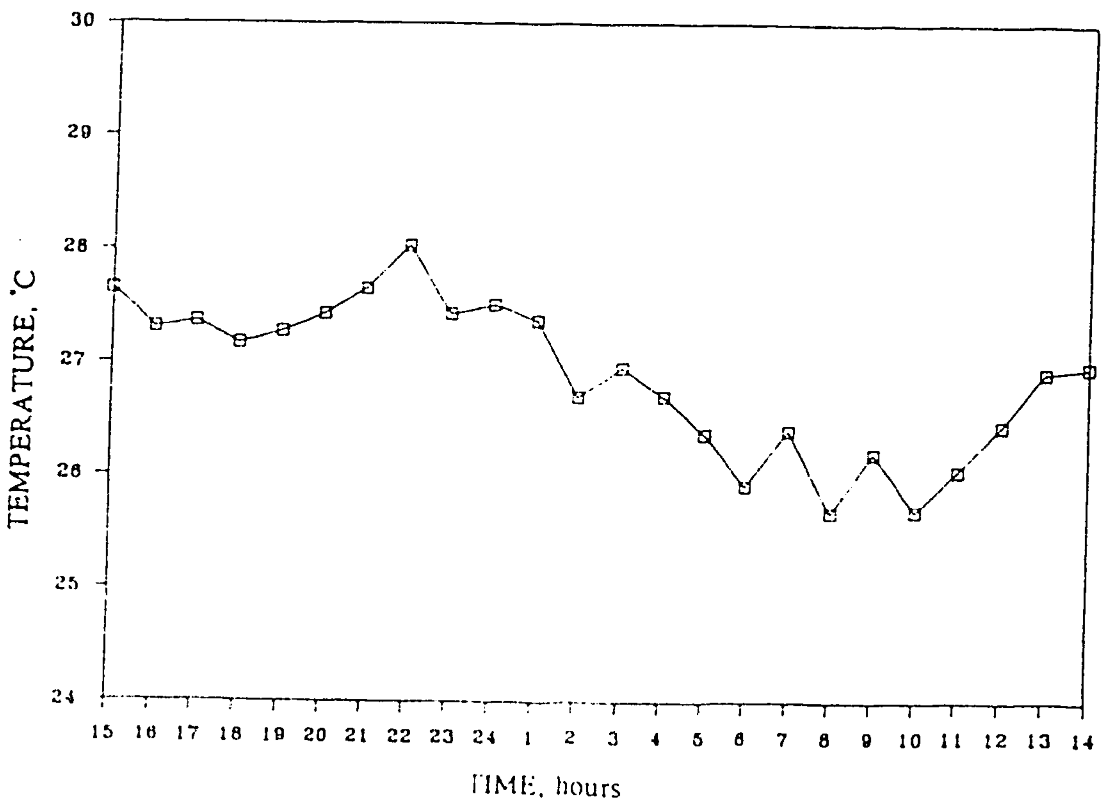
D.13 Heat production of toms measured directly and indirectly at 106 days of age.



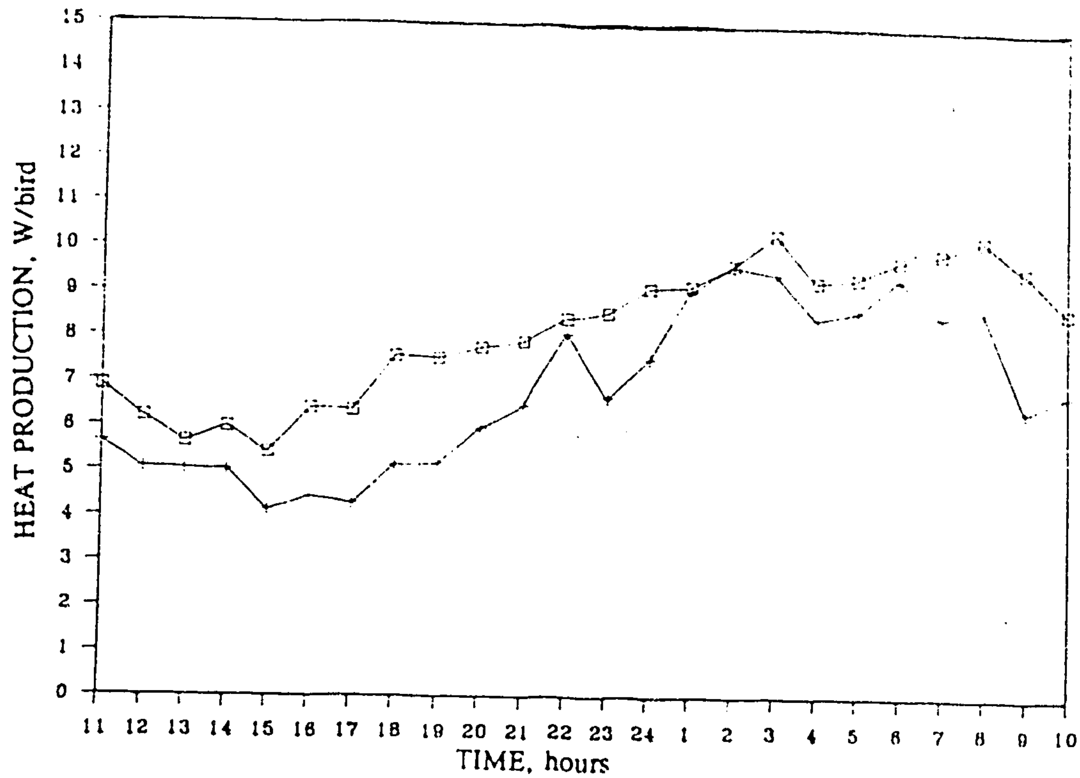
D.14 Ambient temperature in grower barn for 106-day old toms.



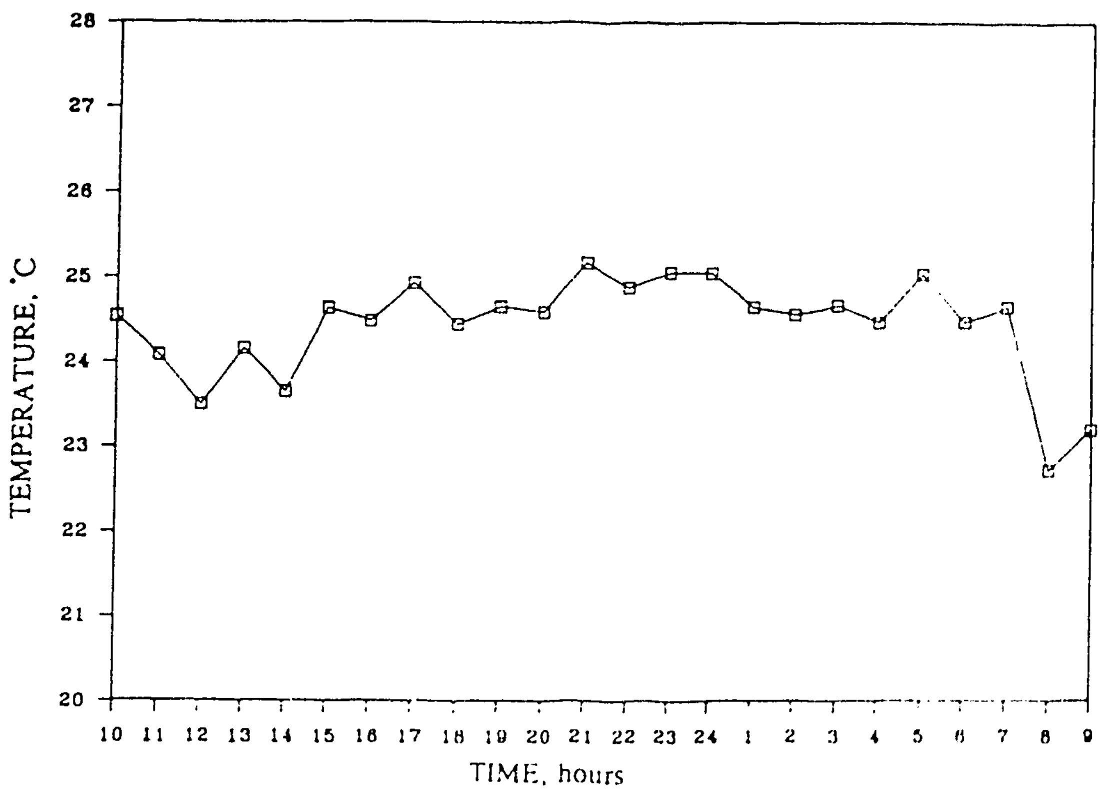
D.15 Heat production of hens measured directly and indirectly at 16 days of age.



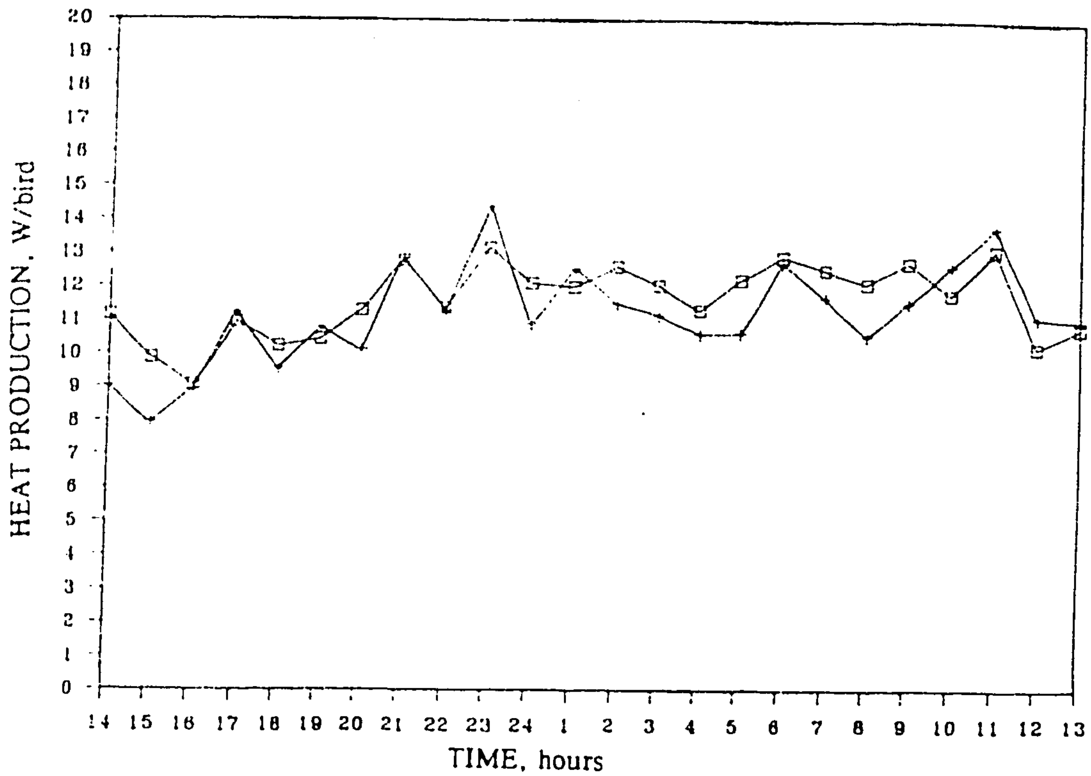
D.16 Ambient temperature in brooder barn for 16-day old hens.



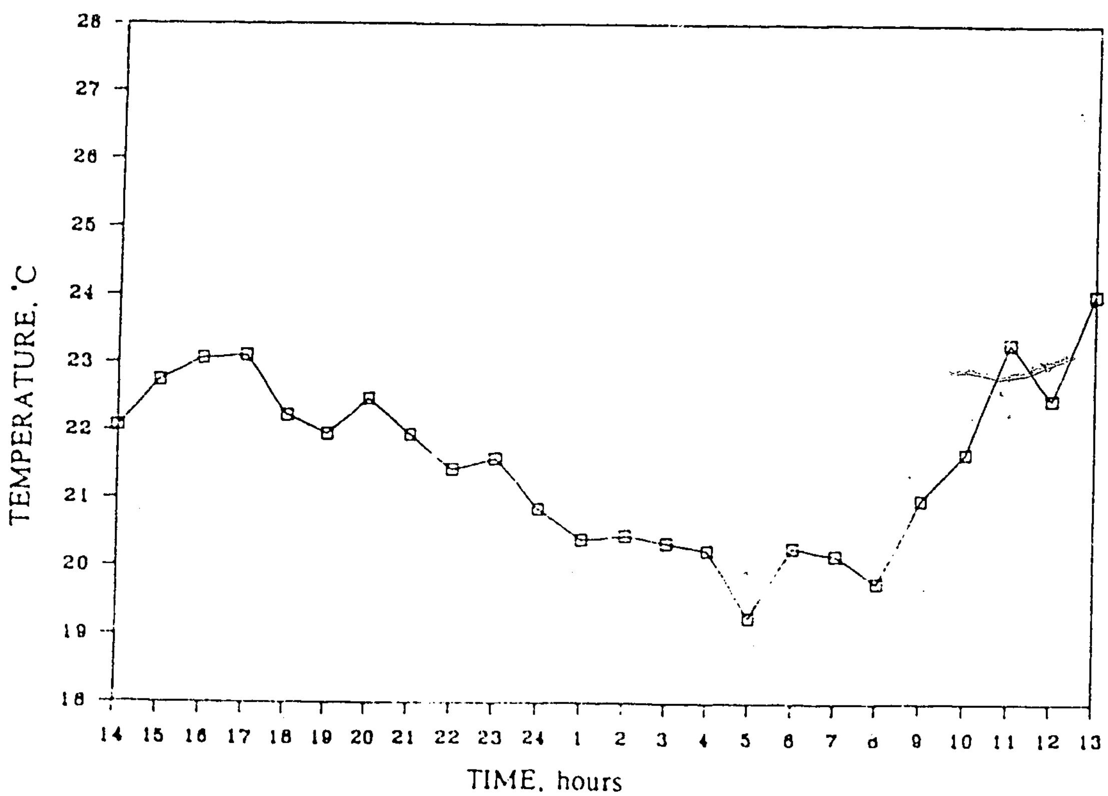
D.17 Heat production of hens measured directly and indirectly at 21 days of age.



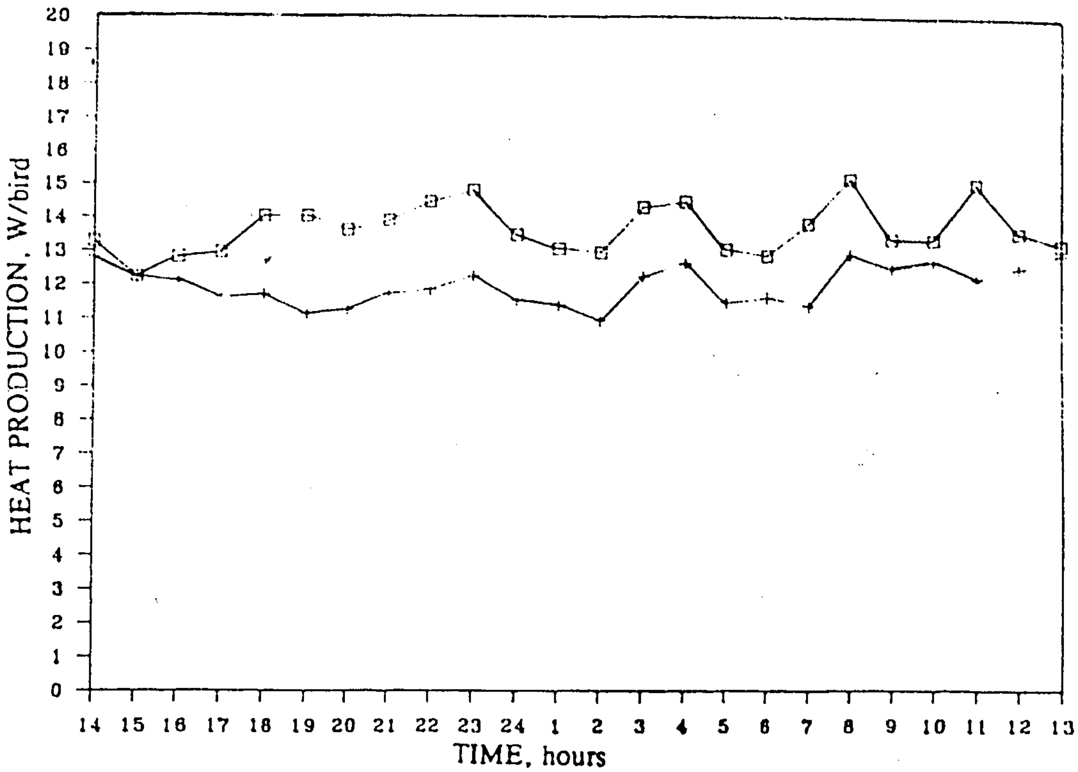
D.18 Ambient temperature in brooder barn for 21-day old hens.



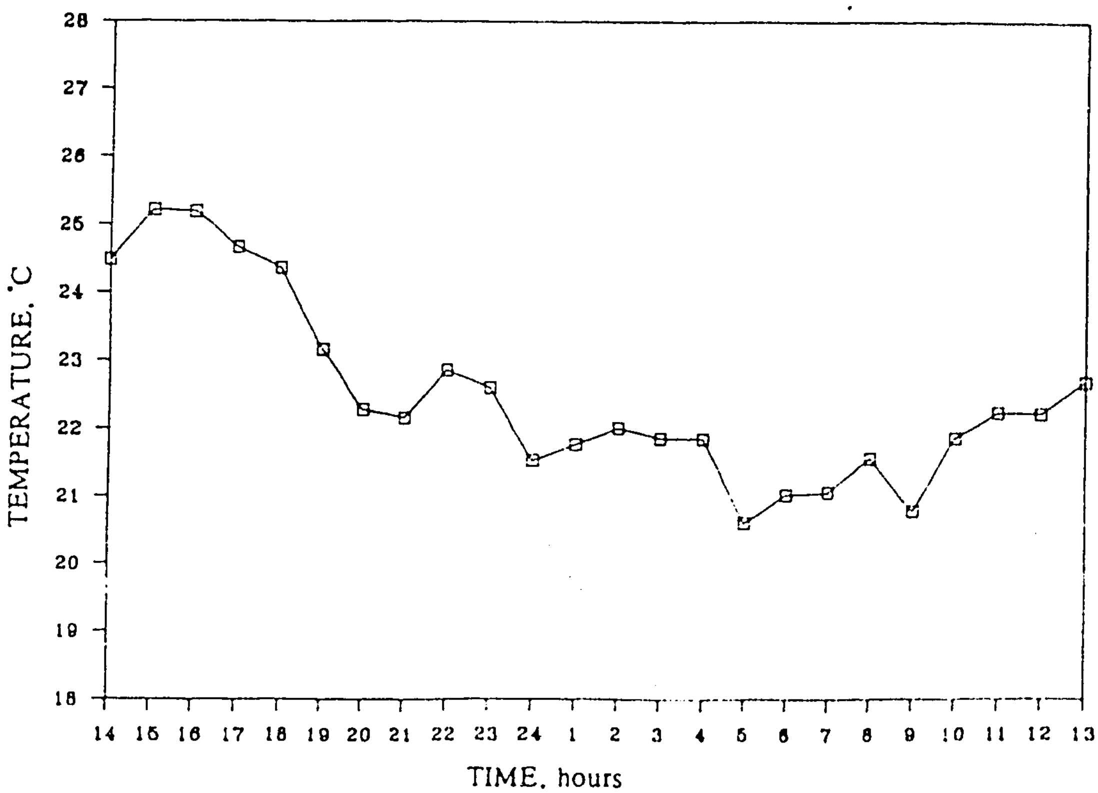
D.19 Heat production of hens measured directly and indirectly at 29 days of age.



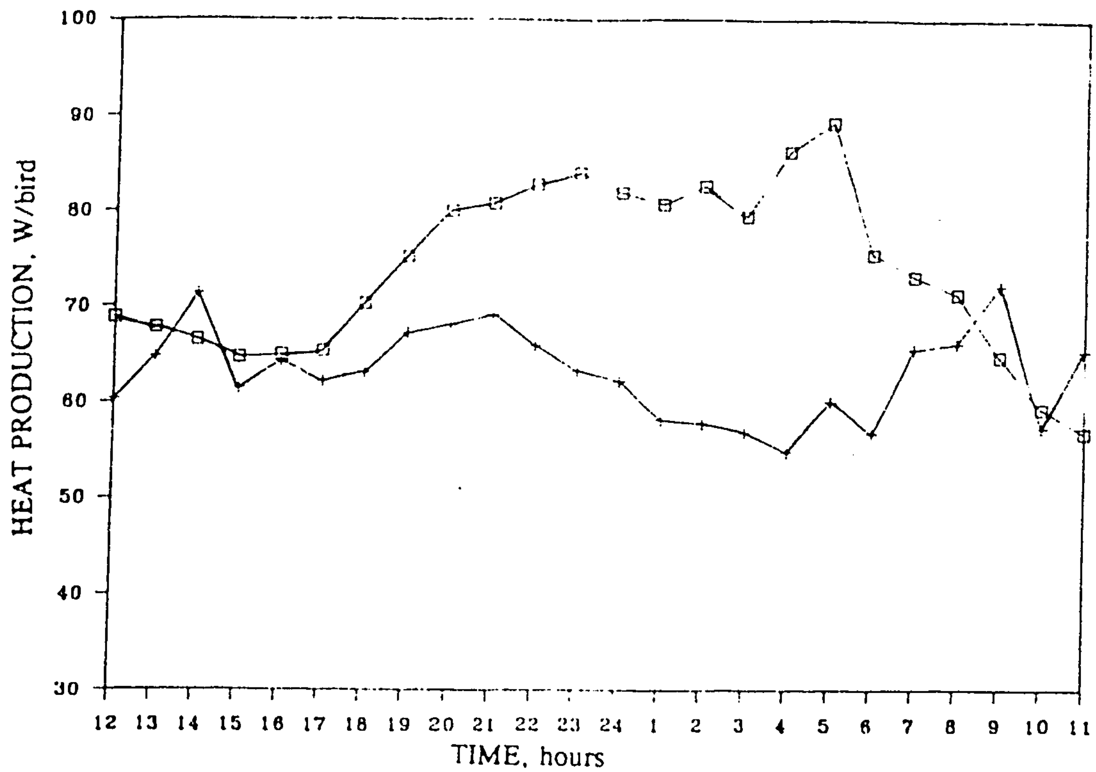
D.20 Ambient temperature in brooder barn for 29-day old hens.



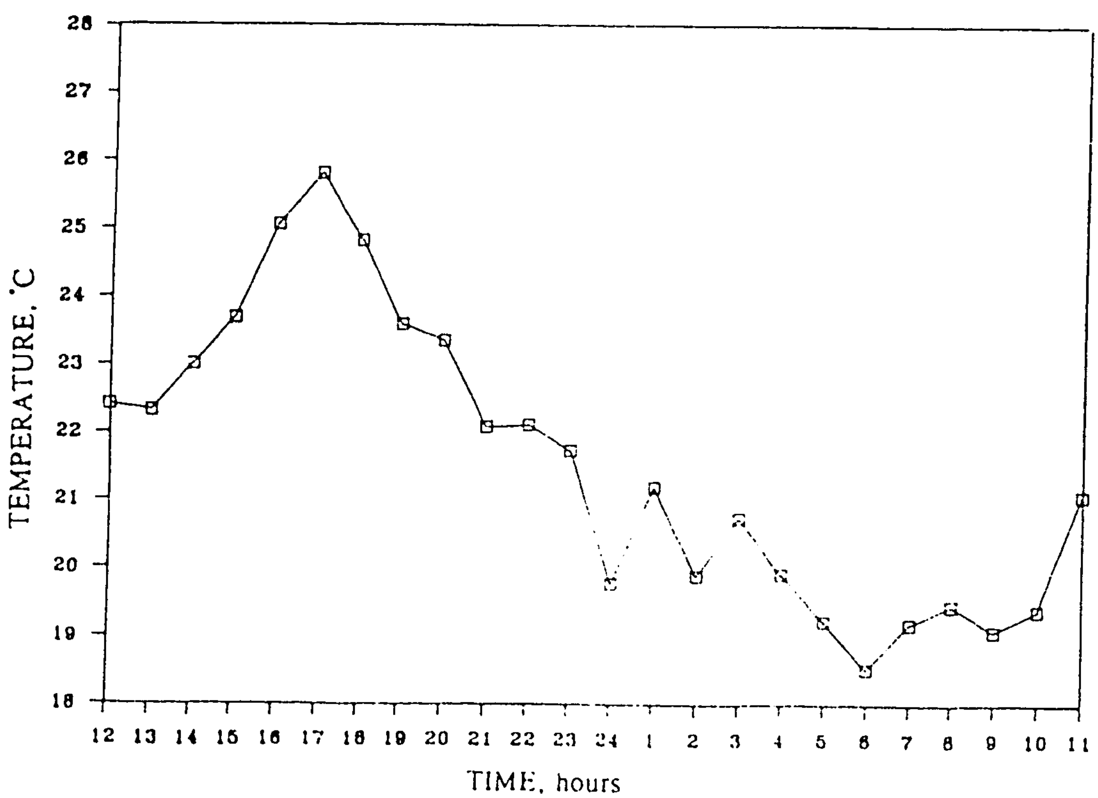
D.21 Heat production of hens measured directly and indirectly at 36 days of age.



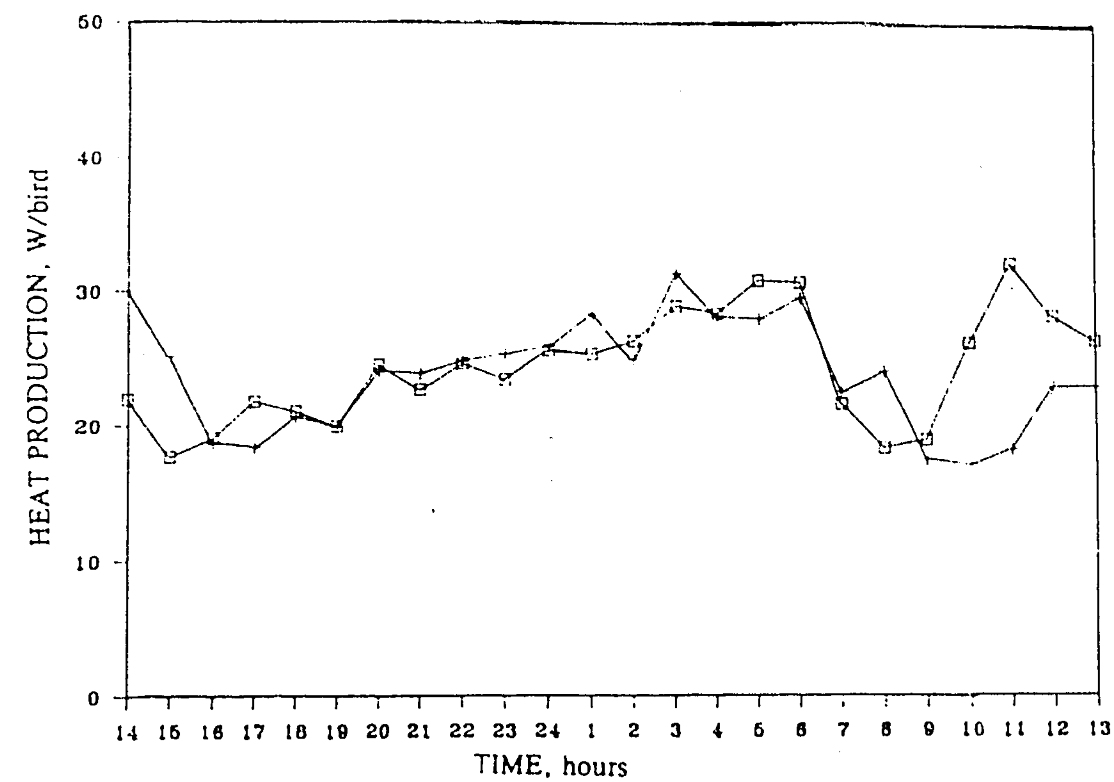
D.22 Ambient temperature in brooder barn for 36-day old hens.



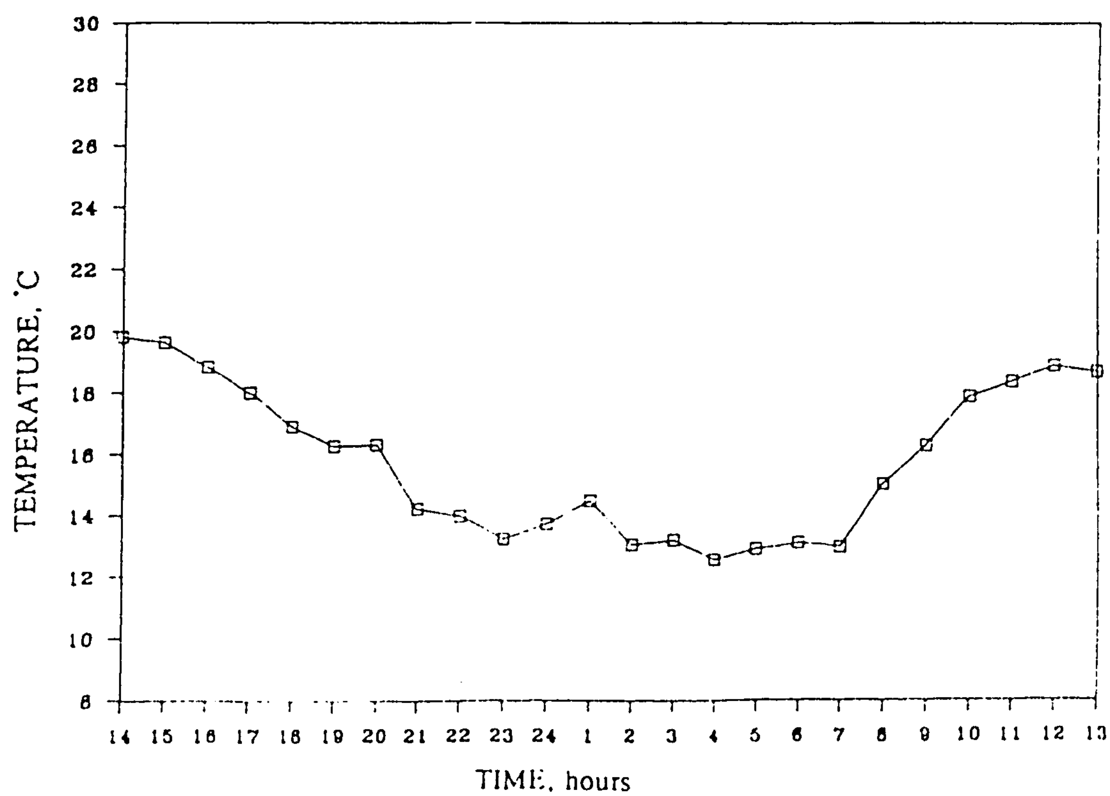
D.23 Heat production of hens measured directly and indirectly at 44 days of age.



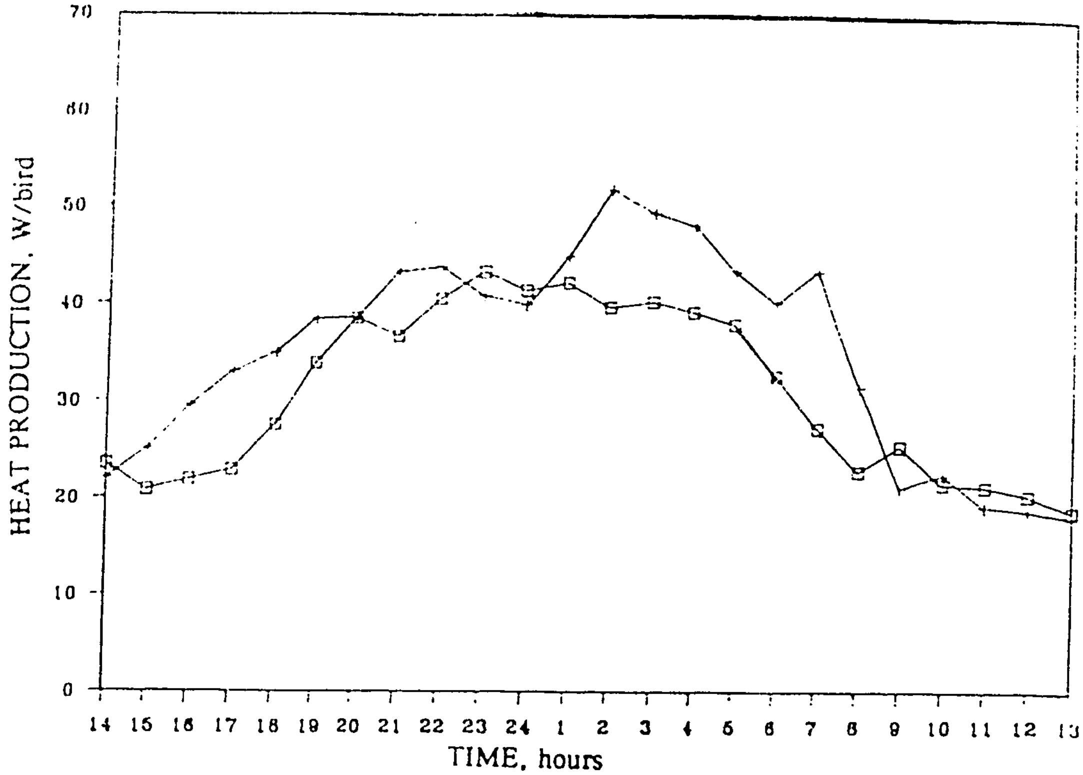
D.24 Ambient temperature in brooder barn for 44-day old hens.



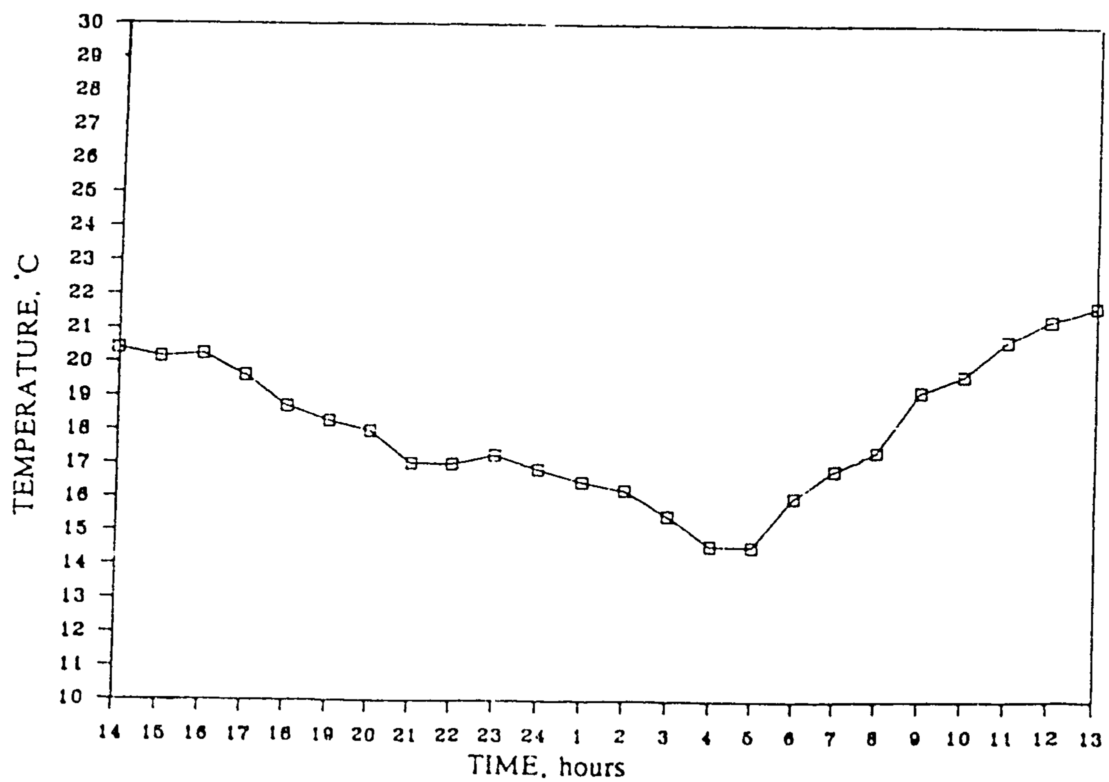
D.25 Heat production of hens measured directly and indirectly at 57 days of age.



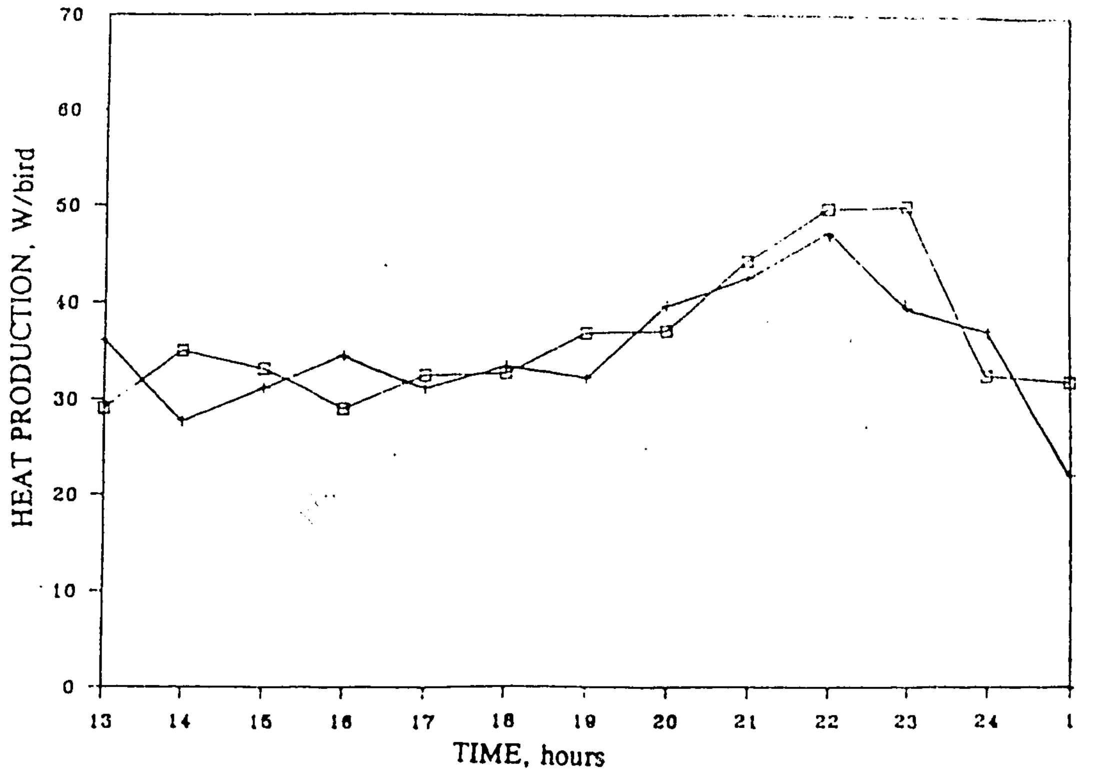
D.26 Ambient temperature in grower barn for 57-day old hens.



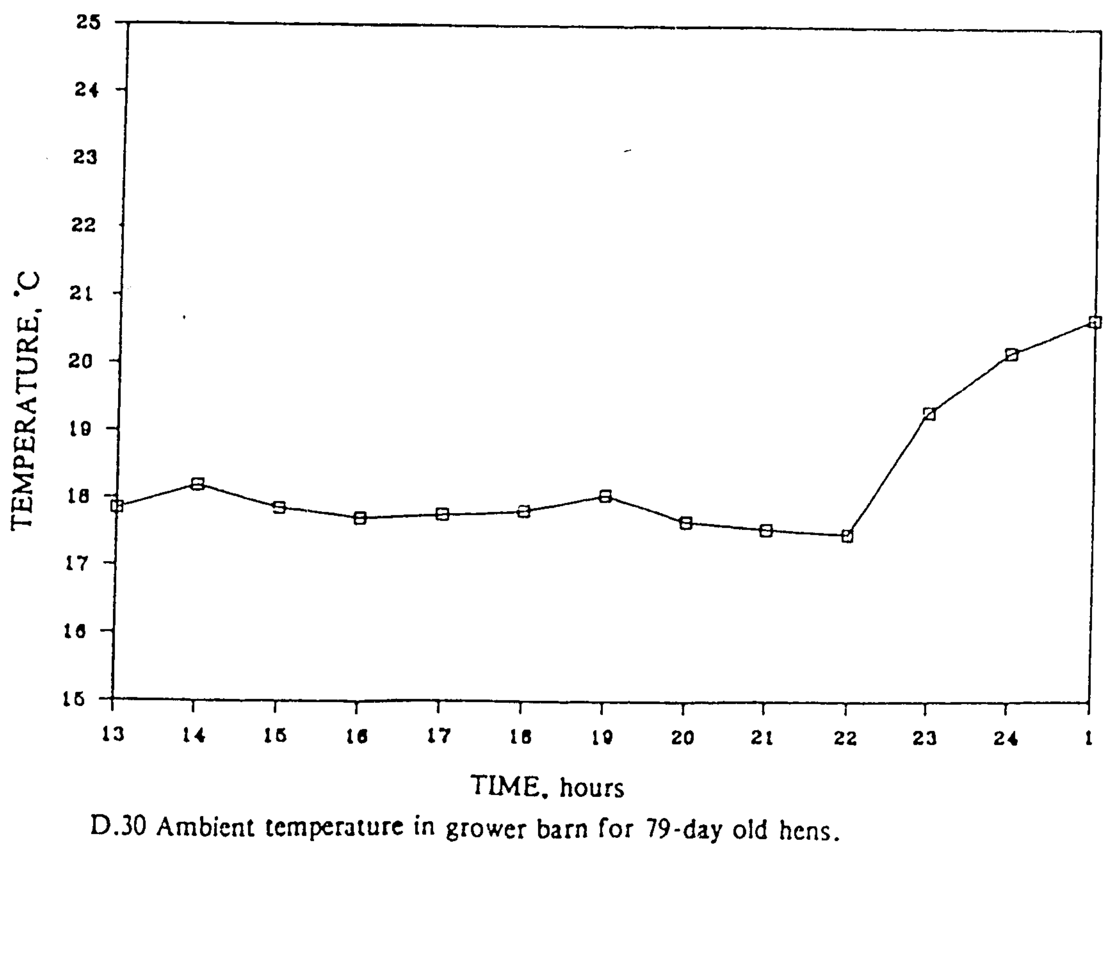
D.27 Heat production of hens measured directly and indirectly at 71 days of age.



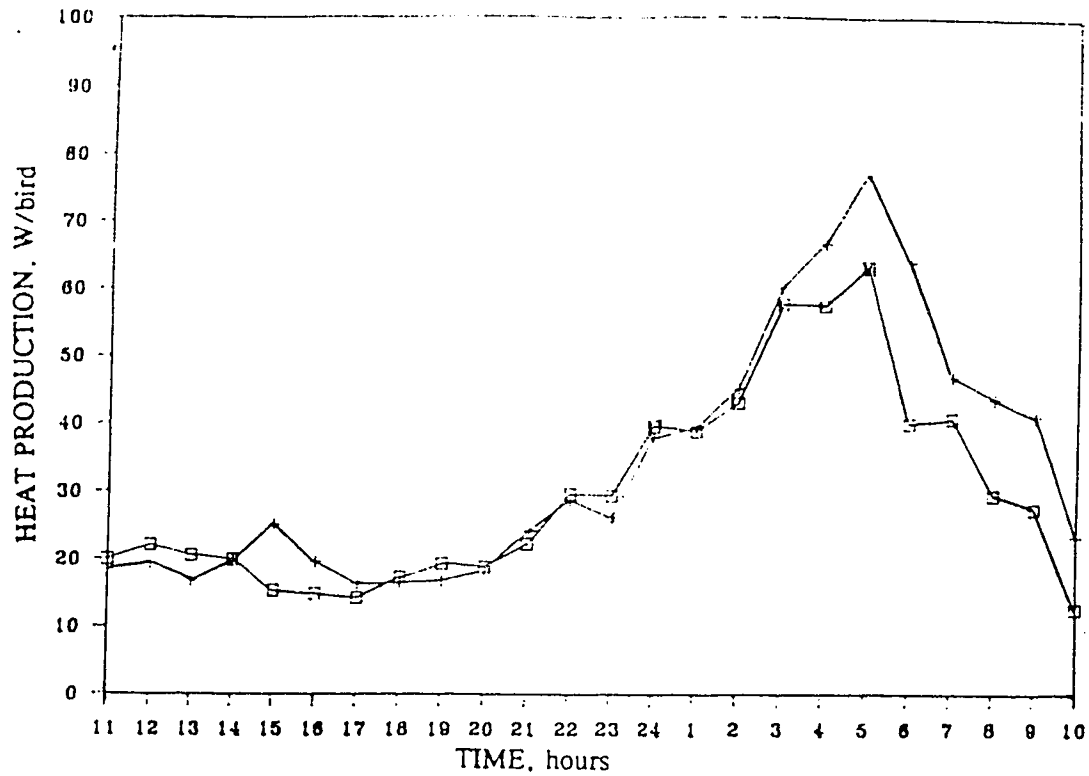
D.28 Ambient temperature in grower barn for 71-day old hens.



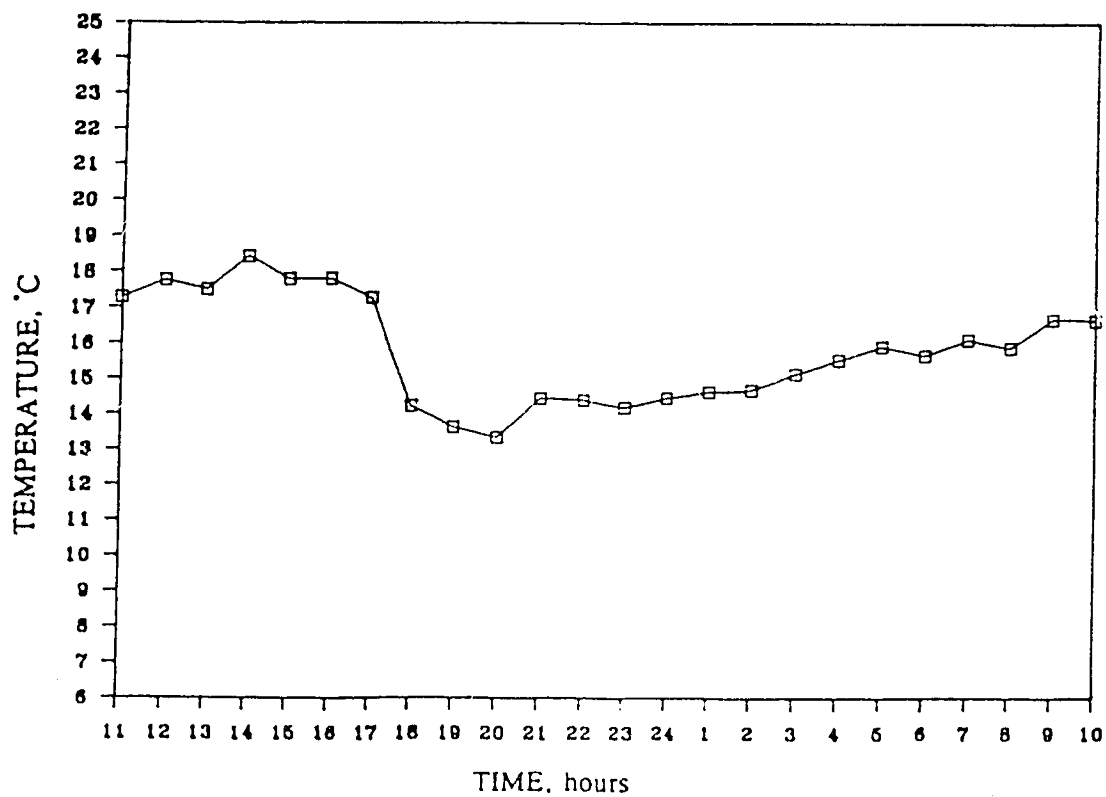
D.29 Heat production of hens measured directly and indirectly at 79 days of age.



D.30 Ambient temperature in grower barn for 79-day old hens.



D.31 Heat production of hens measured directly and indirectly at 94 days of age.



D.32 Ambient temperature in grower barn for 94-day old hens.

Appendix E - Sample Data Output

A sample of the output from the Lotus spreadsheet is given here. Much of the output, data involved in the intermediatry stages of calculating heat production and are not shown here. Other data not shown here are, ammonia, ambient temperatures, static pressure, sensible and latent heat. All data are hourly averages from either the 4 or 20 minute readings. The headings for each item in the output and their units are:

EF = exposure factor, W/°C

Temp = temperature, °K

CO_2 = carbon dioxide level, ppm

O_2 = oxygen level, ppm

DP = dewpoint temperature °C

Pipe = length of heating pipe, m

Atmpress = atmospheric pressure, kPa

Shell Heat = heat lost through building structure, W

Supp Heat = Supplemental heat added to the building, W

Ventilation = ventilation rate, L/h

Relhum = relative humidity, %

Airvol = Specific volume, L/kg

Enthalpy = energy content of air, kJ/kg dry air

RQ = ratio of CO_2 produced to O_2 consumed,

Direct Heat = bird heat production calculated from heat balance, W/bird

Indirect Heat = bird heat production calculated from respiratory exchange, W/bird

Barn: Barn B EF = 420.57 Pipe (m) = 275
Run #ID TBC5 #Birds = 1291 Atmpress (kPa) = 93.3

	Outside Conditions				Exhaust Conditions: Fan 1			
Time	Temp	CO_2	O_2	DP	Temp	CO_2	O_2	DP
12	254.6	366	209525	-10.2	288.1	4420	205424	10.6
13	255.9	385	209617	-11.8	288.7	4329	205512	11.5
14	255.8	391	209664	-15.1	288.7	4194	205629	13.4
15	255.3	389	209748	-14.0	288.8	4130	205629	13.3
16	255.3	383	209795	-13.0	288.3	3878	206041	12.3
17	255.3	381	209836	-11.9	283.6	2436	207568	8.9
18	254.4	383	209890	-11.0	284.9	2391	207651	8.5
19	253.9	381	209964	-9.8	285.0	2373	207185	4.0
20	253.0	381	210057	-8.8	285.2	2481	207556	7.2
21	252.2	383	209924	-11.6	284.4	2394	207697	6.7
22	251.2	368	209914	-12.2	284.5	2510	207577	7.0
23	250.7	377	209948	-11.6	283.7	2448	207667	6.2
24	249.9	367	209954	-12.5	283.6	2442	207708	6.0
01	249.2	371	210027	-11.0	283.3	2436	207708	5.8
02	249.7	373	210026	-11.1	282.8	2374	207731	5.2
03	250.2	377	210083	-10.2	283.2	2433	207687	5.5
04	249.3	368	210231	-7.9	282.6	2312	207810	4.9
05	247.9	368	210054	-11.0	282.6	2365	207752	5.3
06	245.8	368	210155	-9.7	281.9	2324	207878	5.4
07	244.4	371	210089	-10.8	281.5	2359	207680	4.5
08	243.1	365	210173	-10.2	281.7	2439	207561	4.5
09	248.5	366	210229	-9.0	280.4	2437	207590	3.7
10	252.6	362	210175	-8.9	282.3	2318	207763	4.4
11	242.8	366	210088	-9.9	282.8	2261	207842	4.2

Temp	Exhaust Conditions: Fan 2 CO_2	O_2	DP	Shell Losses	Suppl. Heat	Ventilation Fan 1	Fan 2
289.9	4498	205309	8.8	13996	04615	411	404
289.8	4459	205320	10.3	13684	03933	391	380
289.8	4296	205517	10.4	13825	04099	618	603
289.9	4227	205438	11.4	13975	04365	533	521
289.3	3850	206399	16.4	14089	04341	534	538
284.8	2557	207461	10.4	12052	09818	648	617
286.3	2419	207646	10.0	12778	18921	688	680
286.4	2433	207734	10.4	13164	18950	601	586
286.6	2531	207815	11.5	13708	18978	619	607
285.7	2452	207673	8.7	13768	19185	727	710
285.9	2531	207583	8.2	14097	19299	707	702
285.0	2507	207611	6.9	13983	19647	686	670
285.1	2511	207643	6.8	14260	19759	662	644
284.5	2533	207615	6.6	14445	19913	654	628
284.2	2450	207699	5.9	14017	20022	651	630
284.7	2501	207631	6.7	13909	19902	647	630
284.2	2394	207727	5.8	14089	20121	641	619
284.1	2431	207691	6.2	14777	19747	604	588
283.3	2421	207669	5.2	15371	20389	597	573
282.7	2417	207618	4.8	15555	20495	558	545
283.2	2489	207522	4.6	16009	20831	525	514
281.3	2386	207648	3.8	13554	21339	479	490
283.8	2362	207783	5.9	12369	20598	452	444
284.3	2347	207792	4.7	16929	21042	636	612

Exhaust Conditions Fan 1			Exhaust Conditions Fan 2		
Relhum %	Airvol	Enthalpy	Relhum %	Airvol	Enthalpy
75	898.7	36.8	60	902.5	36.0
76	901.4	38.8	66	903.7	38.0
87	903.2	41.9	66	903.9	38.2
86	903.4	41.8	71	904.9	39.7
83	900.9	39.7	100	908.1	48.2
90	883.3	29.8	92	888.2	33.1
80	887.0	30.6	81	892.4	33.9
58	884.7	25.7	83	893.2	34.7
72	887.0	29.3	88	894.8	36.6
73	884.4	27.9	77	889.7	31.7
74	884.9	28.4	74	890.0	31.2
74	881.8	26.6	72	886.4	28.8
74	881.4	26.3	71	886.5	28.7
74	880.2	25.7	72	884.6	27.9
74	878.4	24.6	71	883.0	26.7
73	879.7	25.3	72	885.1	28.1
73	877.5	24.1	70	883.0	26.7
75	877.8	24.5	73	883.1	27.1
79	875.9	24.0	72	879.8	25.1
77	873.9	22.6	72	877.9	24.2
75	874.7	22.8	69	879.3	24.4
78	870.0	20.6	74	872.9	21.7
72	876.4	23.3	72	882.0	26.4
69	877.9	23.6	64	882.8	25.6

RQ1	RQ2	Ventilated Heat Fan 1	Ventilated Heat Fan 2	Direct Total (W/bd)	....Indirect Heat (W/bd)..... Fan 1	Fan 2	Total
0.99	0.98	23339	22469	42.5	27.4	27.6	55.0
0.96	0.95	22715	21680	41.7	25.9	26.3	52.3
0.94	0.94	38730	35296	64.5	40.1	40.3	80.4
0.91	0.89	33439	31402	57.3	35.1	35.7	70.7
0.93	1.02	32117	37131	60.8	32.2	29.9	62.1
0.91	0.92	32328	32883	51.9	23.4	23.4	46.9
0.90	0.91	35224	37170	51.0	24.5	24.3	48.9
0.72	0.92	27562	32529	41.8	25.4	20.9	46.4
0.84	0.96	31163	35262	47.1	24.3	22.0	46.3
0.90	0.92	37120	39072	54.5	25.8	25.6	51.4
0.92	0.93	37467	39163	55.0	26.4	26.3	52.7
0.91	0.91	35327	35949	50.5	25.0	25.0	50.0
0.92	0.93	34654	35230	50.0	23.9	23.9	47.7
0.89	0.90	34024	34098	48.2	24.1	24.1	48.2
0.87	0.89	32771	33083	46.1	23.6	23.3	47.0
0.86	0.87	32448	33381	46.1	24.5	24.4	48.9
0.80	0.81	31277	31839	44.0	24.2	24.2	48.3
0.87	0.87	31578	32276	45.3	22.0	22.0	44.0
0.86	0.83	32066	31364	45.0	21.4	22.3	43.7
0.83	0.83	30251	30376	42.9	21.1	21.1	42.1
0.79	0.80	29208	29430	41.4	21.3	21.2	42.5
0.78	0.78	22377	23374	29.2	19.6	19.6	39.2
0.81	0.84	20180	21230	25.5	17.0	16.7	33.7
0.84	0.86	35973	35812	52.1	22.4	22.2	44.6