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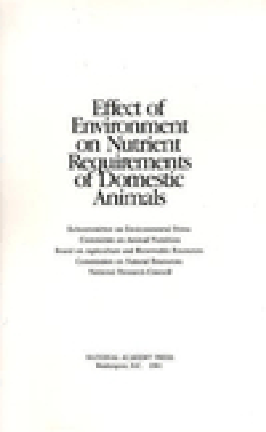

Effect of Environment on Nutrient Requirements of Domestic Animals

Subcommittee on Environmental Stress, National Research Council

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Effect of Environment on Nutrient Requirements of Domestic Animals

Subcommittee on Environmental Stress
Committee on Animal Nutrition
Board on Agriculture and Renewable Resources
Commission on Natural Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report attempts to bring into focus the effects of environmental stresses on nutrient requirements of cattle (beef and dairy), sheep, swine, and poultry. The term environmental stress used herein includes both physical and psychological aspects of the animal's surroundings, although most available data relating environment and nutrition involve the climatic environment and, in particular, the effects of thermal stress.

The goal of this report is to create an awareness of the numerous and varied interactions between environment and nutrition. There are expectations that NRC committees preparing nutrient requirement tables will find the report valuable in documenting environmental effects on nutrient requirements. Researchers should benefit from the report when conducting and analyzing experiments where environmental effects are evident. Students of both nutrition and physiology should find the discussions valuable in explaining environment-nutrition interactions. Extension workers and technical personnel including producers may apply principles discussed herein to make management decisions.

The report includes documented data dealing with animal responses to environmental stressors but is not limited to a review of pertinent literature. The authors have projected topics beyond the scope of "textbook" materials in an attempt to describe new and imaginative approaches to the complex problems involved in adjusting nutrient requirements to meet demands imposed by adverse environments. The authors have the conviction that assembling and interpreting data in this way will stimulate research that will strengthen present knowledge and fill voids that now exist in the understanding of this most important topic.

The CAN Subcommittee on Environmental Stress expresses its appreciation to Gerald H. Stott, L. E. Mount, Minoru Hironaka, and Robert R. Oltjen, who reviewed the manuscript, and M. W. A. Verstegen, who made valuable contributions to the report. Also reviewing this report were the members of the Committee on Animal Nutrition of the National Research Council. The Subcommittee is indebted to Philip Ross, Executive Secretary, and Selma P. Baron, Staff Officer, of the Board on Agriculture and Renewable Resources, for their assistance in the production of this report.

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INTRODUCTION

Nutrient requirements have been commonly established in an environment protected from climatic extremes. For that reason, such requirements are most relevant during optimum environmental conditions and are less appropriate when animals are exposed to stressful environments. Despite the general awareness that energy demands are increased by cold and that the magnitude of those demands is moderated by total body insulation, few quantitative data exist relating environment, nutrient need, and productive efficiency. The latter relationship is particularly important since, in an era of limited resources, it may be necessary to identify the trade-offs between improved production of meat, milk, or eggs in a controlled environment and the capital investment and energy input necessary to create an optimum environment. It may, in fact, be more sensible to settle for something less than maximum performance if such performance does not justify the cost.

Only recently have objective bases been developed to guide livestock producers in altering nutrient inputs in response to environmental change for optimizing productivity or economic return. Existing nutrition-environment models are rudimentary but can be used to compare the cost of extra feed to maintain body temperature in cold weather versus the cost of providing a warm building, bedding, or other alternatives. Such models include the "operational characteristic" of growth for beef cattle, swine, and poultry related to feed energy levels (Teter *et al*., 1973), the "lower critical temperature" model for beef cattle to estimate lower critical temperatures in still air and wind (Webster, 1974), and the "BOSCOM" model for growth of beef cattle during the finishing phase, which estimates dietary energy requirements in relation to diurnal and seasonal fluctuations in temperature (Paine *et al*., 1974). The "effective temperature" model for pigs estimates heat production required to maintain body temperature by adjusting ambient temperature for air velocity, mean radiant temperature, and the type of contact surface (Mount, 1975). The "production" model for laying hens (Emmans, 1974) and the "protein-energy-temperature" model for turkeys (Waibel, 1977) estimate nutrient requirements for egg production and growth, respectively, as they vary with temperature. Limited data are available to evaluate trade-offs during hot weather, and existing nutrition environment models do not account for temporary excursions from the thermoneutral zone, which may be of little consequence because of adaptive and compensatory mechanisms (Hahn, 1981).

The general purpose of this report is to collect, interpret, and integrate research findings to develop a foundation of information pertinent to nutritional-environment interaction. Then species-specific discussions of current concepts of nutritional management during environmental stress are presented. Although attempts have been made to unify terminology, contributions of different authors have not been molded to any particular scheme. It is hoped this approach will be valuable in gaining a thorough understanding of adjusting nutrient requirements to deal with existing environments and will therefore aid in developing rational managerial decisions.

I

FARM ANIMALS AND THE ENVIRONMENT

Animal-Environment Interactions

Livestock live within an environment complicated by a multitude of factors encompassing both physical and psychological aspects of the animal's surroundings. The thermal environment has a strong influence on farm animals with air temperature having the primary effect, but altered by wind, precipitation, humidity, and radiation. Ideally, the impact of the thermal environment can be described in terms of effective ambient temperature (EAT), which combines the various climatic events. Animals compensate within limits for variations in EAT by altering food intake, metabolism, and heat dissipation, which in turn alter the partition of dietary energy by the animal. The net result is an altered energetic efficiency, which can require dietary changes in nutrient-to-energy ratios.

THERMAL BALANCE

Homeothermic animals maintain a relatively constant core temperature by balancing the heat gained from metabolism against that gained from or given up to the environment. This heat balance is achieved through the concerted effects of physiological, morphological, and behavioral thermoregulatory mechanisms (Monteith, 1974; Robertshaw, 1974). Too rapid a rate of heat loss leads to hypothermia; too slow a loss to hyperthermia. Neither can be tolerated for an extended time. Under most conditions there is a continual net loss of sensible heat from the body surface by conduction, convection, and radiation, and under all conditions there is a continual loss of insensible (evaporative) heat from the respiratory tract and skin surface. The net rate of heat loss depends upon the thermal demand of the surrounding environment and the resistance to heat flow of the tissue, skin, and its cover (pelage or plumage). This environmental heat demand is a function of meteorological factors and reflects the cooling power of the surroundings. (Under unusual circumstances where environmental temperature exceeds core temperature, animals may gain net heat from the environment, but then expend energy to rid themselves of heat via evaporation.) Environmental heat demand equals the rate of heat flow from an animal to a particular environment.

EFFECTIVE AMBIENT TEMPERATURE

Because animals are always exposed to and affected by several components of the climatic environment, there are advantages to evaluating responses of the animals to an index value representing the collective thermal impact of the animal's total environment.

EAT is one such index described in terms of environmental heat demand: the temperature of an isothermal environment without appreciable air movement or radiation gain that results in the same heat demand as the environment in question. Several attempts have been made to formulate a means of quantifying EAT. Most have fallen short of expectations, usually because of the resourcefulness of animals in combatting thermal stress by physiological and behavioral reactions, which in turn influence the environmental heat demand. Specific formulas for calculating EAT for each species have not been developed, although the combined effect of selected environmental variables have been reported, e.g., wind-chill factors and the temperature-humidity index (THI).

EAT is, however, a useful concept when predicting the effect of the thermal environment on animals. Several factors, in addition to air temperature, influence environmental heat demand. Examples that have been documented for livestock include:

1. *Thermal radiation*. Thermal radiation received by an animal has two primary sources: solar radiation (direct, or reflected from clouds and surrounding surfaces) and terrestrial or long-wave radiation (emitted from all surfaces constituting the surroundings). The net impact of thermal radiation on an animal depends on the difference between the combined solar and long-wave radiation received and the long-wave radiation emitted by the animal. Shades, nearby structures and other animals, ground cover, clouds, surface characteristics of the animal, and insulation along with interior surfaces of housing are examples of factors influencing the net impact of thermal radiation. For animals in sunlight, a net gain of heat by thermal radiation usually ex

ists, resulting in an increased EAT of 3 to 5°C. In winter, the increased EAT is beneficial; in summer, it is detrimental.

2. *Humidity. The* air's moisture content influences an animal's heat balance, particularly in warm or hot environments where evaporative heat loss is crucial to homeothermy. The higher the ambient vapor pressure, the lower the vapor-pressure gradient from the skin or respiratory tract to the air, and hence the lower the rate of evaporation. An increase in ambient vapor pressure generally has less impact on the heat balance of species that depend more on panting (and less on sweating) to lose heat during heat stress. Hence, different weightings are given dry-bulb and wet-bulb air temperatures in calculating temperature-humidity indices for different species. For cattle, which sweat in response to heat stress, one index is calculated as:

   [(0.35) (dry-bulb temperature) + (0.65) (wet-bulb temperature)],

   whereas, in an index for swine, a nonsweating species, wet-bulb temperature is given less weight and temperature-humidity index is calculated as:

   [(0.65) (dry-bulb temperature) + (0.35) (wet-bulb temperature)].

3. *Air movement*. Air movement affects rate of convective and evaporative heat exchange. However, the magnitude of this effect is moderated somewhat by the reduction in skin temperature because vasoconstriction reduces the animal—environmental temperature gradient. The increase in rate of heat loss or gain per unit increase in air velocity is greatest at low air velocities because disruption of the boundary layer of still air surrounding the body requires relatively little air movement. Above 6 km/h, increased air velocity results in little additional increase in convective heat transfer. By means of a wind-chill index, the combined effect of ambient temperature and air speed on environmental heat demand is represented by a single value. Wind-chill indices have been developed for various species in cool and cold environments. In extremely hot environments (when ambient temperature exceeds animal surface temperature), animals gain heat convectively.

4. *Contact surfaces*. The nature and temperature of the floor or other contact surfaces determines rate of conductive heat flow from an animal. Although this is ordinarily a small part of total heat exchange, it can be significant in some situations such as piglets on a floor with high thermal conductivity, such as concrete. An animal may respond behaviorally to change its posture and thus its orientation to specific environmental components such as area of contact with a cool or warm floor, orientation to radiation sources and sinks, and orientation to drafts and winds.

5. *Precipitation*. Animals are sometimes exposed to inclement weather. A combination of low temperature, wind, and rain or wet snow can adversely affect an animal's heat balance. Water accumulates in an animal's pelage, displacing still air, thereby reducing external insulation. In addition, rain may flatten the pelage, thereby reducing its depth and thus insulative value. Snow or cold rain increase conductive heat loss, and drying of the pelage cools the animal by evaporative heat loss.

The continued effort to improve and develop criteria for determining EAT should be a goal of continued research even though it presently has limitations for practical application as discussed by McDowell (1972). Although this report occasionally includes the use of EAT as described above for discussion purposes, the reader is expected to use the best description of the environment available in terms of environmental heat demand. In some instances, that may be limited to mean daily or monthly dry-bulb temperature.

THERMAL ZONES

Evaluation of the relationship between animals and their thermal environment begins with the thermoneutral zone (TNZ). The concept of thermoneutrality may have varied meanings depending on the viewpoint of the describer. For farm animals, this topic was reviewed by Mount (1974), where the following definitions evolved:

1. The range of EAT* over which metabolic heat production remains basal.
2. The range of EAT over which the body temperature remains normal, sweating and panting do not occur, and heat production remains at a minimum. (This is sometimes referred to as the zone of minimum thermal regulatory effort.)
3. The range that provides a sensation of maximum comfort. (This is also defined as the thermal-comfort zone.)
4. The EAT selected by an animal offered an unrestricted range in environments. (This is also called the preferred thermal environment.)
5. The optimum thermal environment from the standpoint of the animal, which is the environment that promotes maximum performance and least stress (including disease) for the animal.

While these definitions are not totally synonymous, they are in general agreement. The preferred definition is based upon one's interest or reason for

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* Mount (1974) actually used the term, "operative environmental temperature," which is defined similarly to our use of EAT in this report.

describing the TNZ. It must be emphasized that thermal comfort for the stockman may be different from the TNZ of the animal; therefore, selection or assessment of animal environments must not be based on human comfort.

In this report, TNZ is defined as the range of effective ambient temperatures (EAT) within which the heat from normal maintenance and productive functions of the animal in nonstressful situations offsets the heat loss to the environment without requiring an increase in rate of metabolic heat production (Figure 1). Figure 2 shows expected zones of thermoneutrality for several species; however, it should be noted that shifts in the TNZ occur as a result of acclimation by the animal to cold or hot environments (e.g., for the cow, the TNZ can be shifted downward as much as 15°C through cold acclimation during a winter season).

At temperatures immediately below optimum, but still within the TNZ, there is a cool zone (Figure 1) where animals invoke mechanisms to conserve body heat. These are mainly postural adjustments, changes in hair or feathers, and vasoconstriction of peripheral blood vessels. As EAT declines within this zone, metabolic rate of the fed animal remains at the thermoneutral level.

The effectiveness of various insulative and behavioral responses to cold stress are maximal at the lower boundary of the TNZ, a point called the lower critical temperature (LCT). Below this point is the cold zone (Figure 1) where the animal must increase its rate of metabolic heat production to maintain homeothermy. Increases in metabolic heat production parallel increased envi

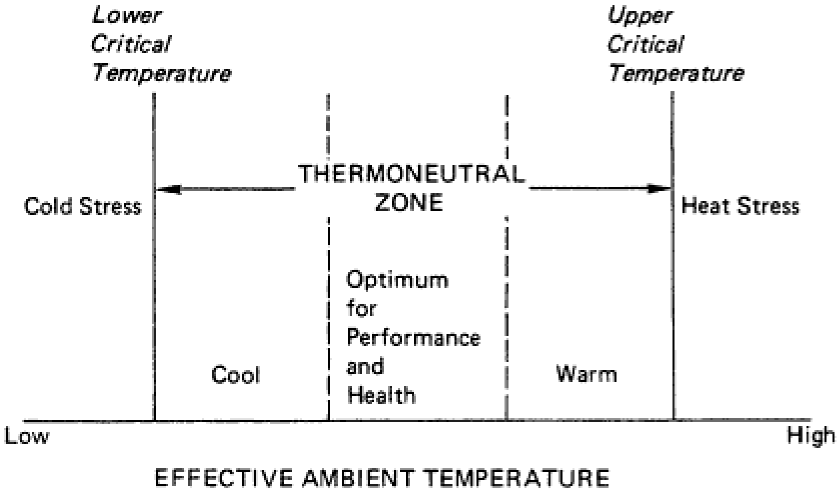

Figure 1.
Schematic representation showing relationship of thermal zones and temperatures.

ronmental heat demand in this zone for animals capable of maintaining constant body temperature.

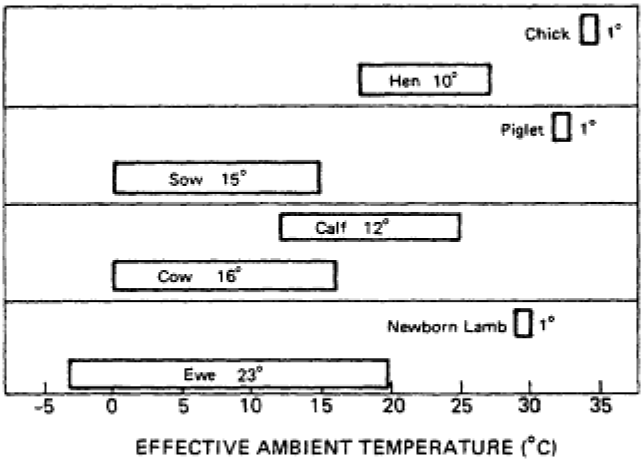

Figure 2.
Estimated range in thermoneutral temperature for newborn and mature animals of different species (adapted from Bianca, 1970).

In general, initial responses of animals to cold stress rely more on increasing metabolic heat production, but long-term exposure to cold gradually results in adaptive responses through physiological and morphological change. Increased insulation, for example, is an added barrier to heat flow in animals and influences the rate at which sensible heat is exchanged with the environment. Insulation includes tissue insulation (fat, skin), external insulation (hair coat, wool, feathers), and insulative value of the air surrounding the animal. These insulative barriers are additive and are a major factor in establishing LCT and rate of heat loss below LCT. Of course, as an animal's insulation changes, so do the limits of its thermal zones described in Figures 1 and 2.

Lower critical temperature can be predicted from the thermoneutral heat production and thermal insulation (Blaxter, 1962; Monteith, 1974; Webster *et al.*, 1970). A summary of estimated LCT's for typical classes of livestock is found in Table 1. These values should be considered only as indicators of cold-susceptibility as, in practice, the actual LCT may vary considerably depending upon specific housing and pen conditions, age, breed type, lactational state, nutrition, time after feeding, history of thermal acclimation, hair or wool coat, and behavior; estimated effects for some of these are shown in Table 1. For example, a group of pigs has an LCT several degrees less than a single pig (Close *et al.*, 1971), because huddling behavior of the pig in a

TABLE 1 Estimates of Lower Critical Temperatures for Sheep, Cattle, Swine, and Poultry

Species	Lower Critical Temperature (°C)	Source
Sheep		
Shorn, maintenance feeding	25	Ames, 1969
Shorn, full feed	13	Brink and Ames, 1975
5 mm fleece, maintenance	25	Blaxter, 1967.
5 mm fleece, fasting	31	Blaxter, 1967
5 mm fleece, full feed	18	Blaxter, 1967
1 mm fleece, maintenance	28	Blaxter, 1967
10 mm fleece, maintenance	22	Blaxter, 1967
50 mm fleece, maintenance	9	Blaxter, 1967
100 mm fleece, maintenance	-3	Blaxter, 1967
Cattle		
8 mm hair, fasting	18	Blaxter, 1967
8 mm hair, maintenance	7	Blaxter, 1967
8 mm hair, full feed.	-1	Blaxter, 1967
Newborn calves	9	Webster, 1974
One-month-old calves	0	Webster, 1974
Fat stock, 0.8 kg gain/day	-36	Webster, 1974
Fat stock, 1.5 kg gain/day	-36	Webster, 1974
Beef cow, maintenance	-21	Webster, 1974
Dairy cow, dry and pregnant	-14	Webster, 1974
Dairy cow, 2 gal/day	-24	Webster, 1974
Dairy cow, 8 gal/day	-40	Webster, 1974
Swine		
45 kg	23.3	Heitman *et al*., 1958
100 kg	20.2	Heitman *et al*., 1958
25-50 kg, fasting	25	Close and Mount, 1975
2 kg, maintenance (single weight)	31	Holmes and Close, 1977
2 kg, maintenance (group of pigs)	27	Holmes and Close, 1977
20 kg, maintenance	26	Holmes and Close, 1977
60 kg, maintenance	24	Holmes and Close, 1977
100 kg, maintenance	23	Holmes and Close, 1977
2 kg, 3X maintenance	29	Holmes and Close, 1977
20 kg, 3X maintenance	17	Holmes and Close, 1977
60 kg, 3X maintenance	16	Holmes and Close, 1977
100 kg, 3X maintenance	14	Holmes and Close, 1977
Poultry		
Chick	34	Richards, 1971
Five-week-old chick	32	Sturkie, 1965
Adult	18	Sturkie, 1965

cold environment reduces the exposed surface and thus heat loss to the environment.

The predicted LCT for large ruminants on high feeding levels are considerably lower than for poultry, swine, and young animals. The extremely low values for the feedlot animal and dairy cow result from the large amounts of heat produced as an inevitable consequence of digestion and metabolism at high levels of production, from the small surface area to mass ratio of these relatively large animals, and from their large amount of insulative tissue. In contrast, the pig has a poorly developed hair coat and utilizes dietary energy more efficiently, thus producing less metabolic heat; hence it has a higher LCT.

Measures of LCT have proven to be quite useful in determining nutrient requirements, in establishing design criteria for housing, and in guiding practical husbandry decisions, particularly for coldsusceptible animals such as swine, sheep, and calves. However, the importance of LCT to cold-acclimated feedlot and dairy cattle is less direct. These animals have predicted LCT's that rarely occur in agricultural regions; for them, it appears that the influences of the thermal environment are largely through seasonal acclimation and metabolic and digestive adjustments to the environment.

As EAT rises above optimum, the animal is in the warm zone (Figure 1) where thermoregulatory reactions are limited. Decreasing tissue insulation by vasodilation and increasing effective surface area by changing posture are major mechanisms used to facilitate rate of heat loss. When EAT exceeds the upper critical temperature (UCT), animals must employ evaporative heat loss mechanisms such as sweating and panting. The animal is then considered heat stressed.

In a hot environment, animals are faced with dissipating metabolic heat in a situation where there is a reduced thermal gradient between the body core and the environment, resulting in a reduced capacity for sensible heat loss. The immediate response of animals to heat stress is reduced feed intake, to attempt bringing metabolic heat production in line with heat dissipation capabilities. The higher producing animals with greater metabolic heat (from product synthesis) tend to be more susceptible to heat stress. This is different from cold conditions where high-producing animals with their higher metabolic heat production are in a more advantageous position than low or non-producing animals. In hot conditions, there may also be avenues of heat gain from the environment, such as direct or indirect solar radiation, long-wave radiation, conduction, and convection. (Gains from the latter three occur only if the temperature of the surroundings or air temperature is higher than animal surface temperature.) Evaporation of moisture from the skin surface or respiratory tract is the primary mechanism used by animals to lose excess body heat in a hot environment: this mechanism is limited by air vapor pressure but enhanced by air movement.

Environment—Nutrition Interactions

Conventionally, measures of energy have been the basis of most animal feeding systems, feed composition tables, and nutrient recommendations for livestock. Because energy in the form of heat is intimately involved with thermal balance, it is convenient to use energy as the common denominator when describing the interaction between animals and the environment.

Nutrient requirement tables list values for animals in conditions presumed to be relatively free of environmental stress and where animals are expected to perform near their genetic potential. In practice, environmental conditions are not always ideal and as a result animal performance often falls short of genetic potential. Contributing factors responsible for reduced productivity include naturally occurring climatic factors as well as those attributable to man (managerial). The latter arise largely through the confinement of animals in intensive production systems. Of the many stresses affecting rate and efficiency of animal productivity, more is known of the consequences of the thermal environment and associated factors of humidity, radiation, and air movement than factors such as altitude, sound, animal density, confinement, chemical or biological contamination, etc. Individual stressors may independently reduce animal performance, or may interact with other factors creating complex stressful situations whose origin may be at times difficult to assess. Animal shelters and housing are intended to eliminate or moderate the impact of the macroenvironment, but, simultaneously, may create a new array of microenvironmental stresses with which the animal must contend.

PARTITIONING OF FEED ENERGY

Figure 3 illustrates schematically the partitioning of feed energy within animals and is a useful basis for identifying the modes of influence of the environment on the nutrient requirements of animals. Where possible the terminology of the report *Nutritional Energetics of Domestic Animals* (NRC, 1981) has been used.

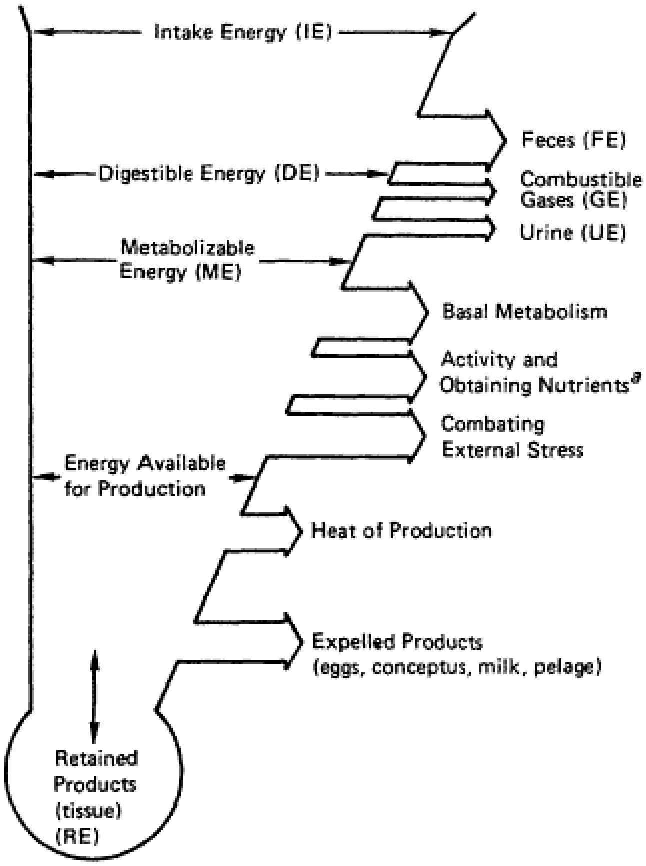

Figure 3.
Partition of feed energy within the animal (after Young, 1975c). [a]Heat increments of voluntary activity, fermentation, digestion, absorption, and nutrient metabolism for maintenance and productive functions contribute to body heat and in cold environments aid in maintenance of body temperature. However, in hot conditions these heat increments may be a liability to the thermal balance of the animal.

Intake energy (IE) is the combustible energy ingested per day and is determined from the combustible energy density of the feed, its Opportunity for ingestion, and the appetite of the animal. Feed is not completely digested or absorbed. The nonabsorbed fraction is voided as feces and its combustible energy is referred to as fecal energy (FE). Digestible energy (DE) may be calculated as IE - FE. However, as feces also contain endogenous material, not all of the combustible energy of feces arises directly from the nonabsorbed fraction of feed. Because of the endogenous component the calculated value (IE - FE) is more correctly termed the apparent digestible energy. Similarly, metabolizable energy (ME) intake may be calculated by subtracting from the intake energy the energy losses occurring in feces, urine (UE) and the gaseous products of digestion (GE), viz., ME = IE - FE - UE - GE. Therefore, by definition, the metabolizable energy intake is that which is available to an animal for maintenance and productive functions.

Maintenance functions involve the utilization and oxidation of metabolizable energy for (1) basal metabolism that is represented by the heat energy evolved in sustaining body integrity by the vital life processes, (2) voluntary activity and obtaining nutrients including the muscular activity of seeking and obtaining food, the processes of digestion, absorption, conversion of food into metabolizable forms, and the formation and excretion of waste products, and (3) combating of external stressors related to an immediate and direct imposition of stress or stresses on the animal. With respect to the latter, animals are consistently faced with various types and magnitudes of stress to which they must continually adjust both behaviorally and physiologically. Although the physiology of stress is still poorly understood (Stott, 1981), some stressors, such as exposure to a cold environment, are known to increase the rate of oxidation of feed or body energy to produce heat. The energetic costs of stressors such as parasites or pathogens are recognized but not well defined. The ME oxidized for the various maintenance processes is released in the animal as heat (maintenance heat) and is ultimately disposed to the environment through physical avenues of heat exchange.

Metabolizable energy for production is available after the maintenance needs of the animal are met. Because of the inefficiencies of product synthesis (heat of production), energy available for production is not entirely incorporated into animal products, be it retained in tissue growth or fattening, or expelled in a product, such as milk, pelage, eggs, or offspring. The latter includes inefficiencies of product synthesis as well as the costs of retaining or expelling the product.

Typically, animals retain energy as glycogen, lipids, and (or) protein when metabolizable energy intake exceeds immediate needs. Likewise, retained energy is mobilized when the animal's demand is greater than the energy available from feed. For example, dairymen allow their cows to accu mulate body fat (energy) when not lactating, expecting it to be mobilized and utilized during peak lactation when maximum intake may be insufficient to meet the cow's immediate needs for both maintenance and maximum levels of lactation.

In summary, Figure 3 represents the intake of feed energy and its partition through the major routes of energy disposed of as wastes, as expelled products, and as heat or retained as tissue. Heat is dissipated via several pathways under the control of thermoregulatory mechanisms to prevent a rise or decline in body temperature. During cold stress, heat from maintenance and productive processes may be of immediate value to the animal in maintaining body temperature, reducing the need of the animal to produce extra body heat by shivering or other cold-induced thermogenic processes. On the other hand, during heat stress thermoregulatory mechanisms are activated to dissipate excess heat from the body to maintain homeothermy. Thus heat that may be beneficial during cold exposure may be a burden to the animal during heat stress. For example, heat evolved during productive functions effectively lowers the thermoneutral zone resulting in a greater magnitude of heat stress at a given temperature for producing compared with nonproducing animals.

Behavioral and physiological adjustments by the animal arising from external stressors affect energy intake and its partition within the animal, the amount of energy available for production, the level of productivity, and the efficiency of utilization of feed. The influences of the environment are therefore much broader in scope than simply implied in the single component of "combating external stress" in Figure 3.

DIGESTIBILITY AND METABOLIZABILITY

Digestibility and metabolizability are biological measures of energy or nutrient value assigned to feeds and depend not only on the physical and chemical nature of the feed itself but also on the animal ingesting the feed, the physiological state of the animal, and the amount of feed ingested (NRC, 1981).

Recognized differences, particularly in digestive processes, among species to which ingested feeds have different nutrient values have led to the development of somewhat independent feeding systems, including lists of feed composition tables for various species.

Independent of any influence of the environment on plant growth and the composition or quality of animal feed per se there is a growing body of evidence indicating that the environment directly influences digestive and metabolic functions in animals. Although the extent and nature of the physiological changes in the animal are, as yet, not resolved, the possible consequences to applied animal nutrition are important. However, within temperate climatic zones, the ability of animals to digest roughages increases with warmer temperatures and decreases with colder ambient temperatures, although in the severe heat stress of the tropics an animal's ability to digest feed may be depressed (Bhattacharya and Hussain, 1974; Sharma and Kehar, 1961). Results summarized in Table 2 indicate the effect of ambient temperature on digestibility values. There has been hesitation in accepting the premise that the nutrient value of a feed could be influenced by the environment to which the animal is exposed (Fuller, 1965; Graham, 1965), because with sudden changes in the thermal environment there are transient changes in rate of passage of digesta and volume of the gastrointestinal tract that are of sufficient magnitude to bias short-term estimates of apparent digestibility (Degen and Young, 1980; Graham, 1965). Thus, caution needs to be exercised when interpreting feed digestibility estimates made during periods where there have been changes in the thermal environment or during constant heat or cold stress. Although possibly related to appetite changes occurring with exposure to hot or cold environments (see page 27), the observed changes in feed digestibility are not solely dependent on feed intake since the effects are also observed when feed intake is equalized, restricted, and controlled (Christopherson, 1976; Kennedy *et al*., 1977; Lippke, 1975; Warren *et al*., 1974). Most data on effect of ambient temperature on the ability of animals to digest feedstuffs are for ruminant animals consuming roughages. In the few trials with sheep receiving concentrate (grain based) feeds, digestibility values have generally not been influenced by ambient temperature.

Investigations of possible direct thermal effects on gastrointestinal tract temperature or on microbial populations have failed to show the significance of these routes of action (Cunningham *et al*., 1964).

The importance of rate of digesta passage in ruminants on diet digestibility is clearly evident (Balch, 1950; Blaxter *et al*., 1956; Mertens and Ely, 1979). Several recent studies indicate that ambient temperature may affect feed digestibility by altering the volume of the gastrointestinal tract and rate of digesta passage. During heat exposure, rumen motility of cattle decreases (Attebery and Johnson, 1969) and there is a concomitant increase in the retention time of digesta that should increase digestibility (Warren *et al*., 1974). Virtually opposite responses have been reported for cold-exposed sheep and cattle, i.e., an increase in reticulorumen motility and rumination activity, an increase in rate of passage of digesta (decreased retention time), and a decrease in the apparent digestibility of feeds (Buckebusch and Marquet, 1964; Christopherson, 1976; Gonyou *et al*., 1979; Kennedy *et al*., 1977; Westra and Christopherson, 1976).

Studies on nonruminant animals have shown that the gastrointestinal tract motility is reduced by hypothyroidism and increased by the administration of thyroid hormones, as reviewed by Levin (1969). In 1974 Miller *et al*. reported that cows with damaged thyroid glands had a reduced rate of passage that could be restored to normal rate by feeding thyroprotein. Similarly,

TABLE 2 Influence of Ambient Temperature on the Ability of Cattle, Sheep, and Swine to Digest Feed

		Temperature Range		Change in Digestibility Coefficient per 1°C	
Species	Feed Component	Low (°C)	High (°C)		Source
Cattle					
Friesian calves	Dry matter	17	38	+0.17	Colditz and Kellaway, 1972
Crossbred calves	Dry matter	17	38	+0.16	Colditz and Kellaway, 1972
Brahman calves	Dry matter	17	38	+0.13	Colditz and Kellaway, 1972
Beef calves	Dry matter	-10	19	+ 0.18	Christopherson, 1976
Beef calves	Dry matter	-4	17	+ 0.25	Christopherson, 1976
Steers	Dry matter	10	20	+ 0.02	Wohlbbiet and Schneider, 1965
Steers	Dry matter	-9	17	+ 0.09	Christopherson, 1976
Beef cows	Dry matter	-11	20	-0.01	Christopherson, 1976
Dairy cows	Dry matter	20	32	+0.09	McDowell *et al*., 1969
Friesian calves	Energy	17	38	-0.04	Colditz and Kellaway, 1972
Crossbred calves	Energy	17	38	+ 0.03	Colditz and Kellaway, 1972
Brahman calves	Energy	17	38	0.00	Colditz and Kellaway, 1972
Beef calves	Energy	-4	17	+0.31	Christopherson, 1976
Beef cows	Energy	-11	20	+ 0.03	Christopherson, 1976
Dairy cows	Energy	20	32	+ 0.25	McDowell *et al*., 1969
Steers	ADF	17	32	+0.38	Warren *et al*., 1974
Steers	ADF	-9	17	+0.16	Christopherson, 1976
Dairy cows	ADF	20	32	+ 0.32	McDowell *et al*., 1969
Beef calves	Nitrogen	-10	19	+ 0.17	Christopherson, 1976
Beef calves	Nitrogen	- 4	17	+ 0.14	Christopherson, 1976
Steers	Nitrogen	17	33	+ 0.17	Warren *et al*., 1974
Steers	Nitrogen	-9	17	-0.02	Christopherson, 1976
Beef cows	Nitrogen	-11	20	0.00	Christopherson, 1976
Dairy cows	Nitrogen	20	32	+ 0.21	McDowell *et al*., 1969

Sheep					
Shorn wethers	Dry matter	0	20	+0.16	Kennedy *et al.*, 1976
Shorn wethers	Dry matter	1	18	+0.21	Westra and Christopherson, 1976
Shorn wethers	Dry matter	1	18	+0.20	Westra and Christopherson, 1976
Shorn wethers	Dry matter	4	24	+0.18	Kennedy *et al.*, 1977
Shorn wethers	Dry matter	4	24	+0.28	Kennedy and Milligan, 1978
Shorn sheep	Dry matter	1	21	+0.17	Westra and Christopherson, 1976
Fleeced rams	Dry matter	−10	20	+0.29	Christopherson, 1976
Wethers	Dry matter	−8	14	+0.15	Nicholson *et al.*, 1980
Wethers	Dry matter	−8	14	+0.14	Nicholson *et al.*, 1980
Shorn wethers	Organic matter	0	20	+0.17	Kennedy *et al.*, 1976
Shorn wethers	Organic matter	4	24	+0.27	Kennedy and Milligan, 1978
Growing lambs	Energy	0	23	0.00	Moose *et al.*, 1969
Growing lambs	Energy	0	23	−0.16	Moose *et al.*, 1969
Growing lambs	Energy	5	29	+0.05	Moose *et al.*, 1969
Growing lambs	Energy	5	29	+0.10	Moose *et al.*, 1969
Shorn wethers	Energy	1	18	+0.21	Westra and Christopherson, 1976
Shorn wethers	Energy	1	18	+0.08	Westra and Christopherson, 1976
Shorn wethers	ADF	1	18	+0.22	Westra and Christopherson, 1976
Shorn wethers	ADF	1	18	+0.25	Westra and Christopherson, 1976
Shorn wethers	NDF	4	24	+0.39	Kennedy and Milligan, 1978
Shorn wethers	Nitrogen	1	18	+0.07	Westra and Christopherson, 1976
Shorn wethers	Nitrogen	1	18	+0.15	Westra and Christopherson, 1976
Shorn wethers	Nitrogen	0	20	−0.04	Kennedy *et al.*, 1976
Shorn wethers	Nitrogen	4	24	+0.11	Kennedy and Milligan, 1978
Fleeced rams	Nitrogen	−10	20	+0.26	Christopherson, 1976
Swine					
Growing hogs	Dry matter	6	20	+0.24	Phillips *et al.*, 1980
Growing hogs	Energy	6	20	+0.27	Phillips *et al.*, 1980
Growing hogs	Energy	5	23	+0.12	Fuller and Boyne, 1972
Growing hogs	Nitrogen	10	30	+0.15	Fuller, 1965
Growing hogs	Nitrogen	6	20	+0.48	Phillips *et al.*, 1980

Kennedy *et al.* (1977) found thyroidectomized sheep had reduced rate of digesta passage that could be restored by thyroid therapy. That warm temperatures decrease thyroid activity and cold temperatures increase thyroid activity in animals is documented for several species (de Andrade *et al.*, 1977; Gale, 1973; Johnson, 1976). This suggests that the shift in thyroid activity in animals because of exposure to different ambient temperatures may be associated with both a change in gut motility and rate of digesta passage. The result is a shift in ration digestibility. More research is needed to more clearly understand the sequence of physiological mechanisms involved and the importance of diet type and level of feeding.

Effects of the thermal environment on the dry matter and DE value of feed would also alter its ME value. However, the ME value of a feed is also dependent upon the losses of urinary energy and combustible gases from microbial fermentation. These losses, like fecal loss, are also dependent on the environment. There are during cold exposure increases in urinary energy and nitrogen output, especially where there is substantial tissue protein degradation to provide substrate for thermogenesis (Blaxter and Wainman, 1961; Graham *et al.*, 1959), which would lower calculated ME value (as defined). Such a bias is an ambiguity arising from the definition of metabolizable energy rather than a true penalty that should be placed against the energy value of the diet. However, the slight reduction in methane production observed in cold-exposed sheep (Kennedy and Milligan, 1978), probably reflecting a reduction in microbial activity, would improve slightly the ME value of the diet consumed during periods of cold exposure. However, this improvement is insignificant relative to the reduction in digestibility observed during cold exposure.

The above evidence indicates an influence of the thermal environment on digestive function and suggests a need to develop appropriate adjustment factors for roughage-based diets for ruminants. However, any adjustment factors suggested at this stage can only be preliminary estimates that should be refined by further research. Although information on the thermal environment is generally not available for the estimates of biological measures of feeds presently listed in feed composition tables, the data are generally assumed to be based on studies with animals in thermoneutral conditions.

The effect of ambient temperature on digestion of feedstuffs by growing hogs has also indicated a decrease in energy and nitrogen digestibility when the animals are exposed to cold (Fuller, 1965; Fuller and Boyne, 1972; Phillips *et al.*, 1979). Observed changes in digestibility values have ranged from 0.12 to 0.48 digestibility units per °C change in ambient temperature. At present there are, however, insufficient data for a recommendation to be made for adjusting swine diets for the effect of ambient temperature on feedstuff digestibility.

Metabolizability rather than digestibility values of feeds are more readily measured in poultry. There is, however, no clearcut evidence that ambient temperature affects the ME value of diets fed to chickens. Swain and Farrell (1975) observed an increase in metabolizable energy value of diets when chickens were exposed to warmer temperatures, while other researchers (Matterson, 1970; Olson *et al.*, 1972) have not detected a significant change. Davis *et al.* (1972) noted that ME declined during the first 3 weeks but returned to normal during the second 3 weeks in hens kept at 30°C.

Basal Metabolism

Basal metabolism (H_eE) is the result of chemical change that occurs in the cells of an animal in the fasting and resting state using just enough energy to maintain vital cellular activity, respiration, and circulation. For the measurement of basal metabolism (basal metabolic rate), the animal must be in a thermoneutral environment, a postabsorptive state, resting, but conscious, quiescent, and without stress. (There is difficulty, determining when ruminant animals reach the postabsorptive state.)

The H_eE established under minimal heat output may have the connotation that values have plateaued, when actually, as fasting continues, H_eE is in a slow decline. Thus, length of time for the fast is an important criterion to specify. There is much confusion and disagreement as to when resting metabolism ends and basal metabolism begins for each species. Passage rate of food through the tract could be a factor on which to base this decision. In all cases, the length of the fasting period should be specified. A common benchmark of fasting metabolism is when the respiratory quotient (RQ) reflects the catabolism of fat. Experimentally this requires from 48 to 144 h fasting to achieve.

Generally H_eE is determined when the animal is not thermally stressed (no panting, no gular response, no sweating, no shivering) and is technically where heat production has plateaued at a minimal level. Thus a range of temperatures may exist over which H_eE can be determined.

The formula for calculating rate of metabolic heat production by ruminants via indirect calorimetry (Brouwer, 1965) is as follows:

$$H_eE\ (\text{kcal}) = 3.866 \times O_2\ (\text{liters}) + 1.200 \times CO_2\ (\text{liters}) - 0.518 \times CH_4\ (\text{liters}) - 1.431\ N\ (\text{grams in urine})$$

Although O_2 measurements alone are not as accurate as adjusting for CO_2 production and the other factors, calculations using 4.7 kcal/liter O_2 are acceptable because of a minimal technical error in the calculated value (Whittow, 1976). This assumes an RQ for a fasting animal of 0.71, and ignores the losses of methane (CH_4) and nitrogen (N) in nonruminants.

Recent studies, based on oxygen consumption, have failed to establish a TNZ in poultry. Heat production (HE) was found to decline continuously as the ambient temperature increased (O'Neill *et al.*, 1970; Romijn and Vreugdenhil, 1969; van Kampen, 1974). Using 20°C as a baseline, the HE of chickens was 13.4 percent higher at 15°C and 7.5 percent lower at 25°C (Figure 4), temperatures that are, respectively, presumably outside and within the TNZ. In all cases chickens were exposed to constant temperature environments. Similar data for beef cows are shown (Figure 4), although resting metabolic rate here is based on the previous month's average ambient temperature. The use of this temperature is necessary because cattle, unlike chickens, are usually exposed to widely fluctuating natural environments.

There is supportive data for growing calves (Christopherson *et al.* , 1979; Webster *et al.*, 1969) of a shift in resting thermoneutral heat production as a consequence of prior cold exposure. Data from sheep (Slee, 1968; Webster *et al.*, 1969) also suggest that resting metabolic rate is influenced by temperature to which the animals were exposed prior to the metabolic measurement. Data from two cows (Young, 1975a) in controlled temperature chambers with 8 weeks exposure to a near-constant temperature are shown in Figure 4 with each point representing results from a single animal as an average of measurements made over several weeks. Other data to support the overall effects were from groups of cows, one group housed (4 cows) and one group outside (8 cows) during the Alberta winter. Measurements are group averages, and prior exposure temperature is average outside temperature during the month prior to metabolic rate measurements.

On the basis of metabolic heat production, there appears to be no obvious plateau that can be easily identified as thermoneutral. This creates doubts about using minimum metabolic heat production to define thermoneutrality.

The equation for estimating H_eE appears to be readily solvable, but its derivation and meaning are complex. Surface area of an animal is an important component because of its role in heat loss, and surface area is positively correlated to heat production. In turn, the H_eE is empirically highly correlated to metabolic body weight, i.e., W^x, where x is the exponential power to which the value W is raised. For a detailed discussion on the derivation of $H_eE = aW^x$, the reader is referred to Kleiber (1961) and Mount (1968).

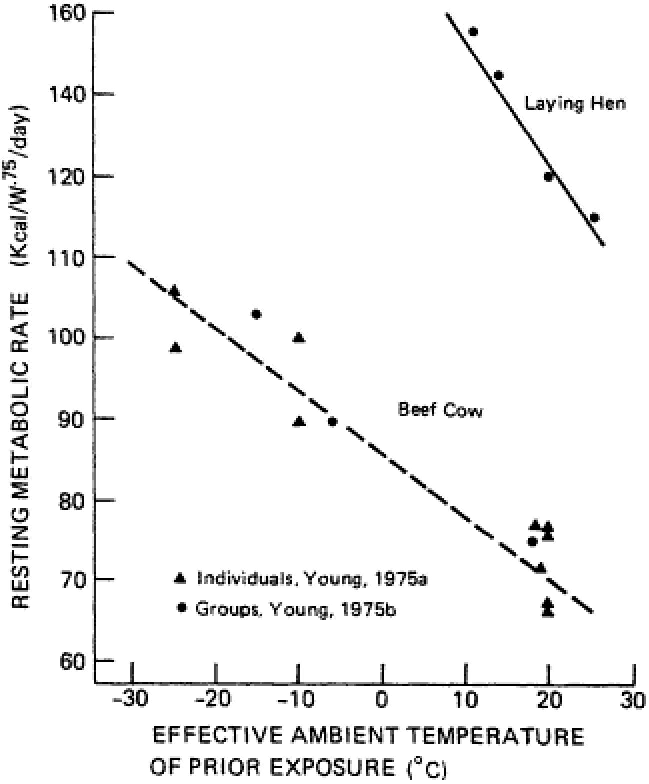

Figure 4.
Basal metabolic heat production for laying fowl (van Kampen and Romijn, 1970) and resting metabolic heat production at 22 h fasting for the beef cow (Young, 1975a).

Values for H_eE have considerable variability even among similar breeds within species. Table 3 lists H_eE values from numerous sources determined by several experimental approaches, including gaseous exchange, heat output measurements, and comparative slaughter. Kleiber (1961) determined that *M* (as a measure of H_eE) = 70 kcal/$W^{0\ 75}$/day as the best approximation of H_eE for homeotherms, where *M* = kcal and *W* = body weight in kilograms. The European Association for Animal Production adopted in 1964 the three-quarters power of body weight as the interspecies reference base (Mount, 1968).

Recognizing the many routes by which energy transfer can occur in animals, one can foresee that many factors influence H_eE, such as prior plane of nutrition, rate of feed intake, environment, age, activity, disease and infec tion, sex, breed, species, type and extent of pelage, and others. Even in homeotherms body temperature tends to rise as the animal has greater difficulty removing heat, and with the rise in core temperature comes a progressively increasing O_2 utilization, which increases on the basis of $Q_{10} = 2.0$ (Ames *et al.*, 1971). Thus, a rise of 10°C in body temperature theoretically results in a twofold increase in oxygen utilization, as revealed by a linear plot on a semi-log scale of O_2 utilization (log) versus core temperature (arithmetic). Obviously, animals succumb should the core temperature rise several degrees above normal, but the expression of Q_{10} reveals how increasingly more difficult it is for the animal to rid itself of excess heat when relatively small rises in core temperature increase heat production. However, certain breeds of animals are more efficient in coping with heat, and their resistance depends to some extent on how much of a burden is H_eE. For example, light breed chickens (White Leghorns) have a higher UCT and greater heat loss at ambient temperatures of - 5 to 32.5°C than heavy breeds such as Barred Rocks (Ota and McNally, 1961) and appear to be more tolerant of heat. The greater resistance of light breeds to hot weather is partially explained by a reduced H_eE (Burman and Snaper, 1965).

TABLE 3 Basal Metabolic Rates of Various Farm Species from Various Sources to Indicate Older and Contemporary Values in the Literature

Species	$H_eE = aW^x$/day	Source
Rabbit	64.7 $W^{0\ 75}$	Kleiber, 1961
Goat	54.4 $W^{0\ 75}$	Kleiber, 1961
Sheep	72.4 $W^{0\ 75}$	Kleiber, 1961
Cow	69.8 $W^{0\ 75}$	Kleiber, 1961
Cattle, beef heifer	75.4 $W^{0\ 75}$	Kleiber, 1961
Pig	68.1 $W^{0\ 75}$	Mount, 1968
Sheep, old wether	58.5 $W^{0\ 73}$	Blaxter, 1962
Cattle, beef	77.0 $W^{0\ 75}$	Lofgreen and Garrett, 1968
Cattle, dairy	117.0 $W^{0\ 75}$	Cited by Mount, 1968
Cattle, several breeds	93.0 $W^{0\ 75}$	Blaxter and Wainman, 1961
Poultry	78.0 $W^{0\ 75}$	Whittow, 1976

Minimizing the proportion of metabolizable energy expended for H_eE would be advantageous in maximizing energy available for product synthesis. As an example, a diurnal fluctuation of H_eE in poultry is well documented, since heat production at night may be as much as 18-30 percent less for the chicken (King and Farner, 1961). By offering laying chickens their diets as single meals in the evening rather than in the morning, efficiency of production is higher (Simon, 1973), attributed to the lower H_eE at that time (Balnave, 1974). Based on O_2 consumption, cold-acclimated animals gener ally have higher heat production at temperatures above those at which acclimation occurred (Young, 1975a,b). This is a response to acclimation in animals with a lower UCT. Such information has practical application in a consideration of alternatives for maximizing efficiency of energy expenditure for maintenance and weight gain in colder climates where shelter versus feed or fuel weigh heavily in farming budgets. Verstegen and Van der Hel (1974) showed that heat loss is less and LCT lower for pigs raised on asphalt or straw, than on concrete, when cold environments are encountered. Thus, the animal tends to adjust its metabolism to tolerate colder environments.

Basal metabolism is as much as 45 percent higher in molting hens (Perek and Sulman, 1945), and this expenditure of energy accounts for up to 82 percent of the ME intake. Unfeathered male chickens have H_eE threefold greater than males at 22°C, while at 29 and 34°C, the unfeathered birds had H_eE values 1.5 and 1.0 times, respectively, those of leathered males (O'Neill *et al.*, 1971).

Apparently, prior plane of nutrition influences H_eE. Male chickens previously fed a high-energy diet have a higher H_eE than those given low-energy diets (Mellen *et al.*, 1954), and the effect persists for some time after dietary energy is lowered (Freeman, 1963). High-energy diets generally produce greater weight gain with greater efficiency, so their use for broiler production, despite a higher H_eE, has received greater acceptability.

Dukes (1947) reported that chickens with transmissible lymphomatosis had a slight increase in H_eE but that a marked increase was detected in two cases of lymphocytoma. A febrile condition in animals that raises the core temperature would be reflected in the H_eE.

The behavior component of animals is closely related to the level of basal functions, and the interplay of behavior with the stage of the reproductive cycle and managerial systems also modifies H_eE. Such husbandry practices as shearing sheep and the molting of hens are similar in influencing heat production at basal conditions. Thus, there are many parallels of responses among the wide diversity of animals that serve mankind.

Feed Intake

That environmental conditions affect level of voluntary feed intake and the utilization of the metabolizable energy (ME) ingested is widely accepted, but it is difficult from existing knowledge to systematically relate environmental fluctuations to changes in nutritive requirements of animals. Much of the research on changes in feed intake with fluctuations in climatic conditions, such as temperature, relative humidity, and rate of air movement, have been conducted under controlled conditions in laboratories usually with only one variable under study. Most of the laboratory studies have demonstrated rather dramatic modifications in feed intake at high and low temperatures, but transfer of this knowledge to farm practice has been difficult mainly because climatic conditions on farms are considerably more variable than when evaluated in the laboratory. Those who consider the direct effects of heat or cold stress on feed intake and performance important for farm feeding should also be aware of the influence of summer temperatures on changes in forage quality.

DAIRY COWS

When lactating dairy cows are fed free choice a diet consisting of 60-65 percent high-quality roughage and 35-40 percent concentrates and exposed to constant temperature conditions, feed intake will increase approximately 35 percent at - 20°C over the level at 10-20°C (Figure 5). Also, lactating cows under continuous heat stress begin to show a decline in intake at 25-27°C with a marked decline occurring above 30°C. At 40°C intake is usually no more than 60 percent of the 18-20°C level. Rate of feed intake increases during cold exposure because it minimizes discomfort from cold (Church *et al.*, 1974). Efficiency of the utilization of ME for production may actually rise at temperatures down to -5 or -10°C but thereafter efficiency declines due to high rate of heat loss (Williams, 1959). The rate of rise or decline in feed intake at the extremes in temperature is influenced by level of milk yield and to some extent by breed (Ragsdale *et al.*, 1950, 1951).

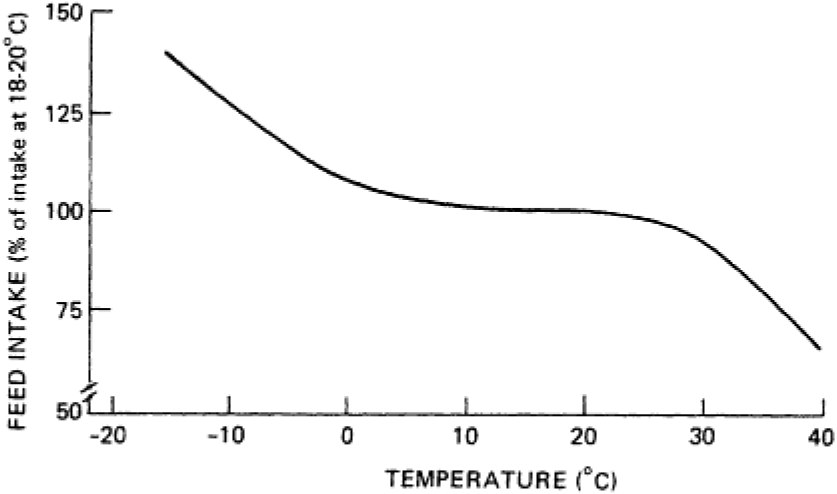

Figure 5.
Effect of environmental chamber temperature on feed intake in cattle using 18-20°C as baseline (adapted from Johnson *et al.*, 1963; McDowell *et al.*, 1969).

In general, lactating cows grazing high-quality pastures in either warm or cool climates and receiving concentrate supplement will tend to have a lower level of total dry matter intake than when fed a drylot diet of 60 percent roughage and 40 percent concentrates because of the difference in the water content of the forages (Yazman *et al.*, 1979). But, when daily maximum temperature is in the range of 8-22°C, the performance of grazing cows receiving concentrate supplement at the rate of 1:2 will be nearly equal to that for cows on the 60:40 diet (Van Soest, 1981). When maximum daily temperature exceeds 25°C, the rate of dry matter intake from grazing may decline rapidly due in part to the direct effects of thermal stress on the cow causing suppression of activity and the indirect decline due to the quality of the forage. Frequently, the lowering of forage quality brought about by the effects of high-temperature conditions on the growth and composition of forages may be as important, or more so, in determining intake than the direct effects of thermal stress on the cow. Raising the proportion of concentrates fed to

1:1.5 for grazing cows will slow the decline in intake energy with rising temperature but not to the same extent as changing to 80:20 for pen feeding systems because of a decline in walking to graze caused by the thermal stress (Yazman *et al.*, 1979).

DAIRY HEIFERS

After about 6 months of age, heifers can at times become fastidious eaters under almost any environmental conditions; hence, it is difficult to predict the influence of temperature on their nutritive requirements. Several short-term studies conducted in a temperature-controlled chamber at the University of Missouri during the 1950's (Johnson and Ragsdale, 1959) suggested mild to marked influence of high and low ambient temperatures on the feed intake and growth rate of heifers. Later, longer-term studies in the same laboratory showed compensatory growth to overcome short-term growth suppression from high temperature when the animals were returned to moderate temperatures (Baccari *et al.*, 1980). Strachan and Marnson (1963), McDowell (1977), and Yazman (1980) did not find any significant correlation between ambient temperature during field tests and growth rate over extended periods (more than 12 months). For example, Yazman (1980) found that during 7-day periods of above-average ambient temperatures in Puerto Rico average daily gain declined by 50 percent, but gains following high-temperature periods were 50 to 70 percent greater even though average daily maximum temperature was only 0.5°C lower. Similar behavior has been observed in hot controlled environment rooms. When dairy heifers were moved from 18 to 29°C, daily gain declined during the first 20 days but recovered during the second 20 days (Johnston *et al.*, 1961).

Preliminary results from Maracay, Venezuela, a tropical area, showed that Holstein heifers on high feeding, but exposed each day throughout life to a maximum temperature equal to or exceeding 27°C, were 50 kg lighter at 24 months than paternal half-sibs in Maryland even though all heifers were fed similar levels of energy (C. Schneeberger, Cornell University, personal communication, 1980). The differences in weight for the two locations were not statistically significant, but the Venezuela heifers were significantly shorter in length wither to pins (-3.2 cm) and lower in height at wither (-2.1 cm). The Venezuelan heifers carded considerably more body fat. The conclusion was that the high-temperature conditions in Venezuela possibly created an unidentified imbalance in the utilization of the feeds offered, which may have affected rate of skeletal development.

Although several laboratory tests (Colditz and Kellaway, 1972) have indicated that heat stress results in smaller changes in feed intake of *Bos indicus* heifers than *Bos taurus* heifers, the percentage decline in both types is approximately the same.

The general conclusion is that temperature conditions on farms may create disturbances that will affect efficiency of feed utilization by growing heifers, but temperature effects are of much less economic significance than for lactating cows or feedlot cattle.

FEEDLOT CATTLE

Generally, growing and fattening cattle have a slightly lower dry matter intake per unit of metabolic size than lactating dairy cows, but feeding × temperature interactions appear similar for the two groups (Figure 6 versus Figure 5). Estimates of change in feed consumption with temperature by feedlot cattle were derived from feeding experiments simulating farm conditions. Complete diets with at least 70 percent digestibility were used. Intake rose from 10°C to below -10°C in a near linear fashion. Below -10°C variation among animals was high, possibly because of individual differences in response to cold or variation in acclimation, which resulted in large differences among animals at the same ambient temperature. Although the standard deviation for the mean level in intake increased showing high variability among animals and days, there was a trend for intake to increase to at least -15°C. In some cases intake declined at the very low EAT because behavioral patterns, such as standing to shiver, caused the animals to spend less time eating. For instance, under feedlot conditions for mid-winter in Canada daily gain of steers decreased 70 percent when temperature reached -17°C and ME intake per unit of gain was 140 percent greater than from March to Novem

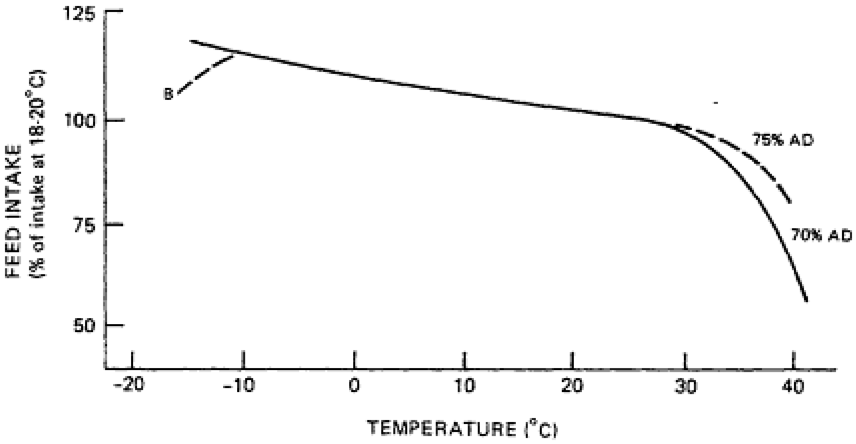

Figure 6.
Estimated changes in dry matter intake of feedlot cattle on a ration with 70 percent apparent digestibility or at temperatures above 27°C, 75 percent apparent digestibility. "B" indicates behavioral changes (adapted from Leu *et al.*, 1977; Milligan and Christison, 1974).

ber (Milligan and Christison, 1974). In this test ADG and feed per unit of gain had correlations of -0.85 to 0.74 with ambient dry-bulb temperature. The marked reduction in daily gain indicates both intake and efficiency of utilization of *ME* for gain are lowered.

From 10°C to approximately 25°C there was little change in feed consumption; however, on a 70 percent digestibility diet daily intake declined rapidly when the cattle were exposed to more than 6 h per day of temperature above 30°C (Figure 6). Increasing the energy value of the ration to 75 percent apparent digestibility appeared to help animals maintain intake (Figure 6). Even so, it is more difficult to maintain intake with beef cattle in feedlots than with lactating cows under extreme temperatures.

There is some evidence from studies with dairy cattle (Ruvuna *et al.*, 1976) that the appetite of crossbred cows is influenced less by summer heat stress than for purebreds. With the high use of crossbreeding in the beef industry, possible advantages of crossbreds in feed efficiency during periods of stress should receive attention. At 27°C total daily IE of Brahman, Santa Gertrudis, and Shorthorn heifers was less depressed than that of Brown Swiss and Holstein heifers (Johnson *et al.*, 1958). The level of intake of the beef breed heifers was lower, however, both under cool and warm conditions. When change in IE was calculated as percentage at 27°C versus 10°C, the decline was similar in all breeds, thus species differences for IE resulting from heat stress are not clearly defined at this time.

The conclusion is that above 25°C and below -10°C type of ration and level of temperature markedly affect intake but from near 0 to 25°C digestibility of ration is more important than ambient temperature. Even though temperature is the environmental variable most frequently associated with feed intake, lot surface and space per animal and their interaction effects are also important to feed intake (Elam, 1971; McDowell and Hemandez-Urdaneta, 1975).

SHEEP

Values for prediction of temperature-feed intake interactions for farm feeding of sheep are limited, mainly because the vast majority of sheep are kept under extensive grazing conditions. It is well accepted that body covering (length of fleece) and level of feeding will affect the response of sheep to temperature conditions (Armstrong *et al.*, 1959). In general, the decline in feed intake under hot room conditions of unshorn sheep is similar to that for lactating cows (Figure 5), and shorn sheep respond approximately as do dry cows.

The values in Table 4 indicate that both level of roughage in the diet and temperature influence feed intake. Because of lower IE at 27-32°C, the total ME per unit of gain will be expected to rise when sheep are stressed by heat.

TABLE 4 Effect of Alfalfa Hay-to-Concentrate Ratio on Feed Intake of Sheep Under Cool and Hot Conditionsa

	Intake (g/day)	
Hay: Concentrate Ratio	Cool (11-22°C)	Hot (27-32°C)
25:75	1,000	820
50:50	1,180	1,032
75:25	1,050	1,016
75:25 + fat	879	868
Average	1,027	934

[a] Adapted from Bhattacharya and Uwayjan, 1975.

SWINE

The estimated relationship of feed intake to ambient temperature for pigs of two weight ranges are shown in Figure 7. The associations of temperature with feed intake were developed largely from studies under controlled temperature conditions. Since commercial swine-rearing systems often include some temperature modification, the laboratory data should parallel that observed under farm systems. The temperature at which intake rises or declines

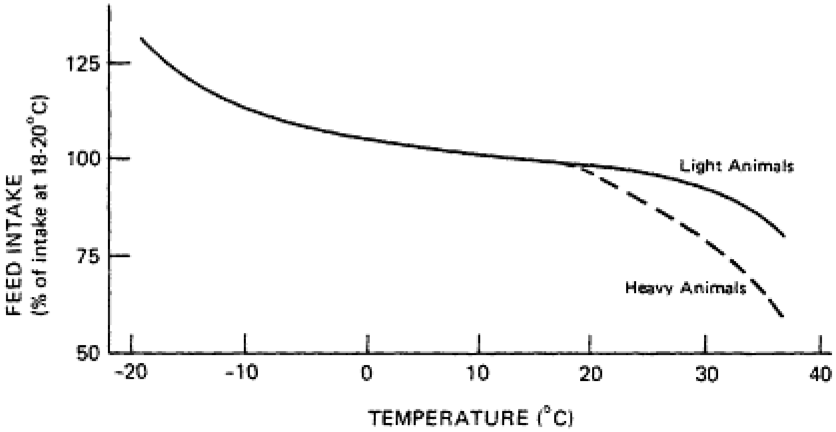

Figure 7.
Effect of environmental temperature on feed intake of swine. (Solid lines are 40-70-kg animals; dashed lines are 70-120-kg animals) (adapted from Heitman and Hughes, 1949; Verstegen *et al.*, 1978).

is approximately the same for light and heavy pigs; however, heavy pigs (above 70 kg) do appear to have a lower response threshold to heat stress than smaller pigs (Figure 7). In fact, the absolute feed intake of young pigs (8 weeks of age) may be higher at 25°C (1.82 kg/day) than at 20°C (1.74 kg/ day). Growth rate of young pigs is moderately reduced under both cool (10°C) and hot (30°C) conditions; however, the percent of the energy retained may be higher at 30°C (43 percent) than at 10°C (34 percent) (Vetstegen *et al.*, 1978). Experimental evidence to date clearly shows there is an important interaction effect of size of pig and EAT.

POULTRY

Laying hens will acclimate to a fairly wide range of temperature conditions, e.g., Davis *et al.* (1972) showed laying hens reared at 18°C required only 2-3 weeks to reach a new equilibrium of 160 kcal ME/kg 0.75/day after change to a 35°C environment (Figure 8). When the hens were shifted from 18 to 7°C, their ME intake was lowered for approximately 1 week due to behavioral adaptation before feed intake returned to a level of about 102 percent of the amount consumed before the shift.

The estimated changes in feed intake for laying hens acclimated to the environmental temperature and fed a diet of 3.17 kcal ME/g DM is shown in Figure 9. Below 5°C an increase in feed intake is required to provide for higher maintenance requirements. Data are limited on intake for temperatures as

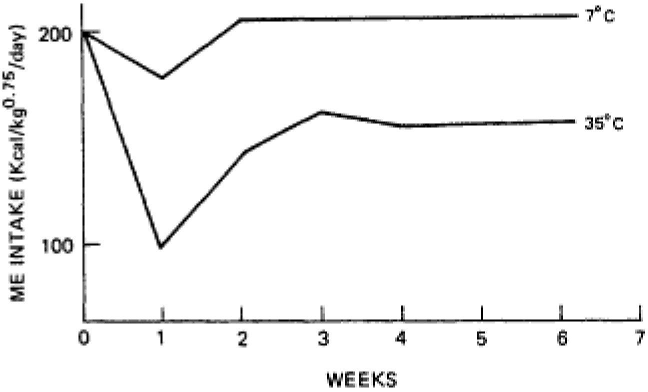

Figure 8.
ME intake of laying hens after being moved from an 18°C environment to a 35 or 7°C environment (adapted from Davis *et al.*, 1972).

low as 0°C. Similar to other species, level of intake at low temperatures is erratic due to behavior changes to alleviate rapid heat loss; hence, the intake curve is represented by a broken line below 5°C and represents an extrapolation of needs for thermal equilibrium.

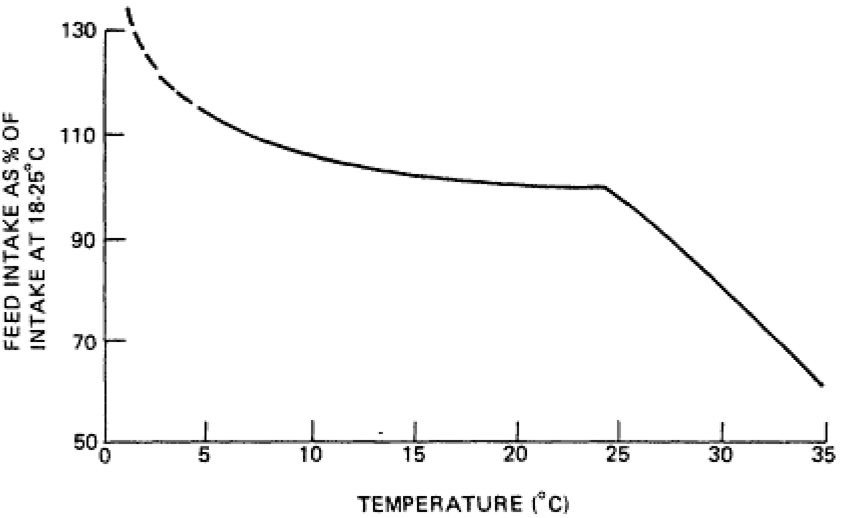

Figure 9.
Estimated change in feed intake for laying hens. Based on data in Table 38.

Under commercial production systems, where temperature inside the house may range from 20-37°C, the feed intake of laying leghorns will decrease by 1.0 to 1.5 g per day per 1°C from 25 to 34°C but by 4.2 g per 1°C from 32 to 36° C (Davis *et al.*, 1973). Level of protein in the diet appears to have an interaction effect on feed intake of laying hens under thermal stress (McNaughton *et al.*, 1978). For summer feeding in temperate areas and throughout the year in hot climates, a crude protein of 25 percent or higher in the ration is recommended for good efficiency, whereas less than 25 percent CP, is satisfactory at temperatures below 25°C for laying hens.

Forage-Temperature Interaction on Feed Intake

During the summer months grazing ruminants often show signs of distress with only short periods of grazing from mid-morning to late afternoon. The restricted grazing is usually attributed to the direct effects of temperature and solar radiation on the animal, but this is not necessarily the case as climate-forage interaction also contributes to animal distress.

TEMPERATURE EFFECTS

High ambient temperatures bring about rapid rate of maturity of forages and a rise in cell wall content (CWC), as illustrated in Figure 10. This occurs in the stems and leaves of both temperate and tropical grasses, but the change is more pronounced in tropical grasses. The rate of plant maturation rises with temperature, e.g., alfalfa grown at 17°C took 52 days to reach early bloom but only 21 days at 32°C (Faix, 1974). As forages mature, there is an increase in CWC and a decrease in the digestibility of the cell wall (DCW). As ambient temperature increases, the digestibility of the dry matter (DDM) of a forage decreases due to a rise in CWC and decrease in DCW as illustrated in Figure 11 (Minson and McLeod, 1970).

LIGHT INTENSITY

High light intensity increases the content of water-soluble carbohydrates (WSC), whereas, high temperature decreases WSC (Deinum, 1966). With high light intensity CWC decreases (Deinum *et al.*, 1968). When there is heavy

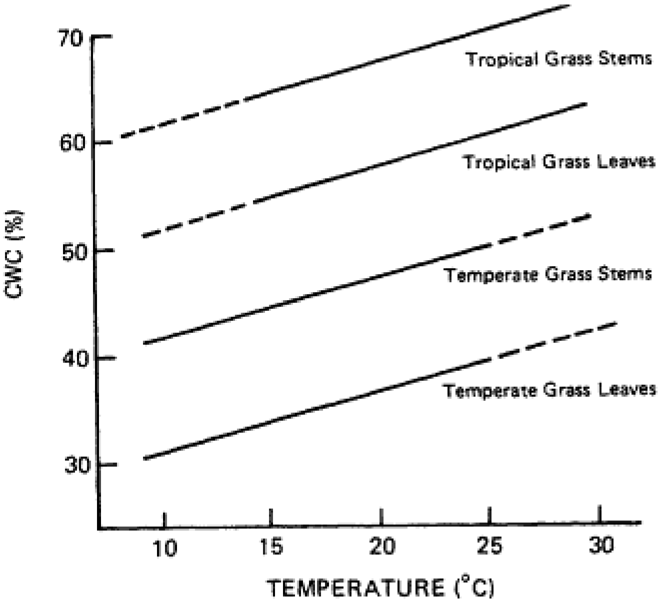

Figure 10. The effect of temperature on the cell wall content (CWC) of grasses of the same maturity (adapted from Van Soest, 1981).

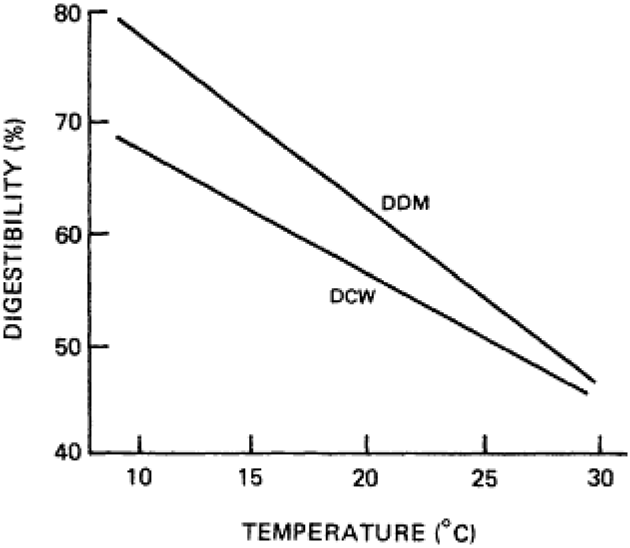

Figure 11. Changes in the digestibility percentage by ruminants of plant digestibility of dry matter (DDM) and digestibility of cell wall (DCW) with changes in ambient temperature from 10 to 28°C (adapted from Deinum, 1976; Minson and McLeod, 1970).

cloud cover, such as occurs in the United States during summer or in tropical areas during the rainy season, both temperature and light contribute to high CWC, which results in lower DDM and lowered intake by grazing ruminants.

FORAGE QUALITY

Seasonal variations in temperature and light intensity markedly affect the DDM and CWC of both grasses and legumes. During the spring, alfalfa grows under longer daylength and lower temperature, thus its CWC is lowest and DDM highest (Kalu, 1976). The higher temperature during mid-summer causes an increase in CWC with a corresponding decrease in DDM; therefore, alfalfa harvested at this time is at its lowest quality. Grasses tend to follow a similar pattern (Jolliff *et al.*, 1979).

The percent CWC of forages has a negative correlation (-0.83) to daily dry matter intake (DMI), as illustrated for temperate forages in Figure 12 (Osbourn *et al.*, 1974; Van Soest, 1971). Another important relationship is the positive association of DMI and DDM; however, this relationship declines for forages grown under high temperature conditions (Laredo and Minson, 1973).

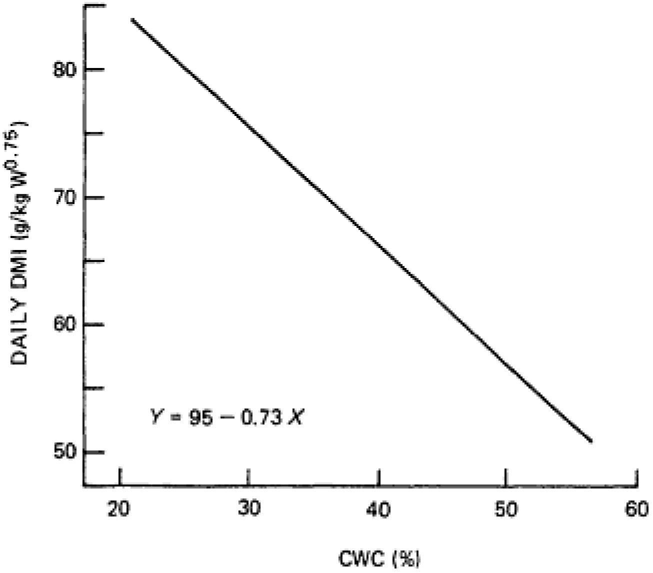

Figure 12.
Relationship between daily dry matter intake (DMI) by ruminants and cell wall with increasing percentage of cell wall content (CWC) of temperate forages (adapted from Osbourn *et al.*, 1974).

Forages grown under high temperatures have a higher stem to leaf ratio. Grazing animals prefer leaves (McDowell, 1972). When the animals select leaves instead of consuming the whole plant, bite size and the rate of intake are decreased; hence, morphological characteristics of forages, such as leaf to stem ratio, are negatively related to CWC. A higher CWC due to high temperature has a negative influence on DMI and DDM of plants. Also, feeds that have high CWC have higher heat increment even at similar IE; thus, the higher CWC of forages grown during summer or in tropical areas results in poorer utilization of energy (Van Soest, 1971). The reasons for the decline in efficiency as cell wall intake rises is not entirely clear but it is associated with a linear increase in rumination time (Welch and Smith, 1969). This implies an increase in the energy costs associated with the digestion of CWC, but the efficiency of utilization of the end products of CWC digestion, i.e., increased acetate, is an alternative explanation.

The decrease in forage quality resulting from seasonal changes in temperature has a negative effect on intake, digestibility, and efficiency of utilization of ME. As a result, the interaction effects of climatic conditions on forages complicates deriving estimates of the direct effects of temperature on intake of grazing ruminants.

Water-Environment Interactions

Water, a nutrient, is essential for life, and intake is subject to marked interaction effects with environment. Little is known about actual requirements for normal physiological functions within the TNZ or at thermal extremes. Most estimates of water needs are based on free water consumed under *ad libitum* offerings.

WATER SOURCES

The water needs of livestock are filled from three major sources: (1) free drinking water, (2) water contained in feed, and (3) metabolic water produced by oxidation of organic nutrients. The catabolism of 1 kg of fat, carbohydrate, or protein produces 1190, 560, or 450 g of water, respectively. Metabolic water is important to all animals, particularly those residing in dry environments, such as the kangaroo rat (Church *et al.*, 1974). The first two sources are of major concern in the management of livestock, although in periods of negative energy balance, i.e., when depot fat and tissue protein are being utilized, metabolic water would be important.

Water contained in or on the feed is extremely variable. It may range from a low of 5 percent in dry grains to about 90 percent in young, fast-growing grasses. In addition, the amount of dew or precipitation on the grass at the time of grazing is subject to wide fluctuations. In the case of swine and poultry, diets are blended from dry ingredients and intake of water in a feed accounts for about 10 percent of the total feed intake.

WATER LOSSES

Water losses by animals are principally through: (1) urine, (2) feces, and (3) evaporation from the body surface and respiratory tract, although under severe stress cattle and other species may lose a significant amount through drooling (McDowell and Weldy, 1967). Unless animals are on a water restricted diet, urinary excretion rate can usually be reduced without impairing the ability of the kidneys to excrete body wastes (Church *et al.*, 1974).

In ruminants the loss of water through feces is substantial, approximately equal to urinary losses. The high-fiber nature of ruminant diets requires proportionately more water to carry the ingesta through the gastrointestinal tract than for nonruminants. Level of fiber is not, however, sufficient reason to explain the level of fecal water, e.g., cattle feces contain 75-85 percent water, while sheep and goat feces have 60-65 percent water. The ability to reabsorb water in the lower gut and excrete drier fecal pellets instead of wet, loose feces is presumably one mechanism of water conservation.

Water loss from the respiratory tract is extremely variable, depending on relative humidity and respiration rate. Expired air is over 90 percent saturated; hence, under conditions of low relative humidity, respiratory losses are high. Conversely, losses are low when inspired air is near saturation. When respiration rate increases in response to high temperatures or other behavioral stimulus, the rate of respiratory water loss is increased, e.g., cattle may lose 23 ml/m^2/h at 27°C and up to 50 ml/m^2/h under severe heat stress (Roubicek, 1969).

Cutaneous evaporation of water is the major means of heat loss in cattle and sheep at high temperatures (McDowell and Weldy, 1967; Robertshaw, 1966). There are large differences among species in the importance of sweating with domestic livestock ranked in the descending order of horses, donkeys, cattle, buffaloes, goats, sheep, and swine (McDowell, 1972). The threshold skin temperature for sweating varies among species with cattle reacting at about 25° C (McDowell *et al.*, 1954). Zebu cattle may secrete up to 15 g/m^2/min when heat stressed (McDowell, 1972), but during cold conditions only 0.6-1.0 g/m^2/min are lost (Murray, 1966).

Swine and poultry are examples of species that depend more on the respiratory than cutaneous route for water loss. Total evaporative water loss in poultry increases markedly with temperature rising from 10 to 40°C. As noted in Table 5, cutaneous water loss plays a decreasing role in heat loss as temperature rises and heat dissipation occurs predominantly through respiratory water loss.

TABLE 5 Heat Loss from White Leghorn Fowl by Respiratory and Cutaneous Evaporative Heat Loss at Different Environmental Temperaturesa

Ambient Temperature (°C)	Body Weight (kg)	Heat Produced (kcal/h)	Cutaneous Evaporation (kcal/h)	Respiratory Evaporation (kcal/h)	Total Evaporation (kcal/h)
10	1.70	6.55	0.166	0.251	0.417
20	1.66	5.09	0.201	0.277	0.478
30	1.69	4.43	0.323	0.482	0.805
35	1.67	5.27	0.597	1.561	2.158
40	1.65	5.33	0.995	3.443	4.438

[a] Adapted from van Kampen, 1974.

FACTORS AFFECTING WATER INTAKE

There are numerous factors that influence the intake of free water, such as animal species, physiological condition of the animal, level of dry matter intake, physical form of the diet, water availability, quality of water, temperature of the water offered, and ambient temperature.

Differences Among Species

Zebu cattle may have a lower intake of water than European breeds (Colditz and Kellaway, 1972; Johnson *et al.*, 1958; Ragsdale *et al.* , 1950; Winchester and Morris, 1956), but there is conjecture over whether observed values are directly attributable to genotype (Figure 13) due to sampling variance, differences in body size, or level of dry matter intake. When data from these experiments are adjusted to a constant body size and dry matter intake, species differences become negligible.

Water intake per kilogram of dry matter consumed may be as much as 40 percent less for sheep than cattle (ARC, 1965). Over the temperature range -17 to 27°C, the estimated requirements for cattle were 3.5 to 5.5 kg water/ kg DM, whereas in about the same temperature range sheep needed only 2.0 to 3.0 kg water/kg DM. The estimated water needs for swine are near that for sheep, 2.0-2.5 kg/kg DM.

Differences in water consumption among sheep, swine, poultry, and cattle could be largely due to some of the factors already discussed, but further testing will be required to discern potential species differences between *Bos indicus* and *Bos taurus* and between cattle and buffalo.

Physiological State

Young calves generally have higher intakes of water per kilogram of DM consumed (5.0-7.0) than the 3.5 to 5.5 kg recommended for older cattle (ARC, 1965; Pettyjohn *et al.*, 1963). During the last 4 months of pregnancy, cows may consume 30 percent more water than when dry and open (ARC, 1965) and under barn feeding conditions the estimated intake of free water for lactating cows is 0.87 kg water/kg milk produced (Winchester and Morris, 1956).

The kg water/kg DM consumed by pregnant ewes increases from about 2.0 in the first month to 4.3 in the fifth month (Head, 1953). Ewes carrying twins will consume over twice the amount of water of nonpregnant ewes and those carrying single lambs, 138 percent above nonpregnant ewes. When corrected for water content of milk, lactating ewes consume 100 to 164 percent more water than dry ewes (Forbes, 1968).

Weanling pigs will consume approximately 20 kg water daily per 100 kg of body weight, but those near market weight much less, 7 kg/100 kg of

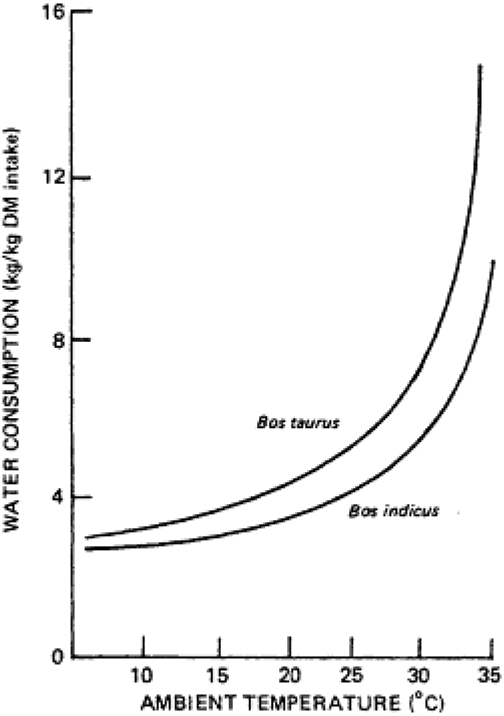

Figure 13.
Water intake of two species of cattle as a function of environmental temperature (adapted from Winchester and Morris, 1956).

body weight. Water intake for nonpregnant sows is estimated at 5 kg/day, 5-8 kg during pregnancy, and 15-20 kg while lactating (ARC, 1966).

Frequency of Watering

When cattle on grazing have water available free choice, they drink 2 to 5 times per 24 h (Castle *et al.*, 1950; Hancock, 1953). Cattle grazing pasture with forage DM of 17.8 percent under cool conditions (13°C) will drink about 4 times daily with a rate of intake of 0.26 to 0.45 kg/second (Castle, 1972). In general, water intake, particularly of lactating cows, will depend upon availability (Table 6). Under extensive grazing systems in dry tropical areas, water intake of sheep or cattle will decline as distance to water sources increases. Water intake of sheep declined significantly, about 7.85 g/kg, when distance between feed and water increased from 2.4 to 5.6 km (Daws and Squires, 1974).

Physical form of the diet influences water consumption (Table 7). When the same forage crop was made into both hay and silage, Holstein heifers on the silage diet had higher total water intake (free + feed) and secreted more urine than heifers on hay alone. Others have made similar observations (Calder *et al,*, 1964; Forbes, 1968). Protein and salt levels in the diet will also influence water consumption (ARC, 1965; Kwan *et al.*, 1977; Pierce, 1962; Ritzman and Benedict, 1924; Sykes, 1955; Weeth and Haverland, 1961).

Water Temperature

Findings on the effect of temperature on water intake are variable. When Hereford cattle were kept in drylot where daily maximum temperature was 38° C, reducing the water temperature from 31.0 to 18.3°C caused a decline in consumption of water, but daily gains increased (Ittner *et al.*, 1951). However, at 31°C maximum daily temperature there was no effect of cooling the water for finishing cattle (Harris *et al.* , 1967). When heated water

TABLE 6 The Effect of Water Availability on Water Consumption by Lactating Grazing Cowsa

Treatment	Water Consumed (kg)
Water in barn 2.8 h/day	10.1
Water in field 21.2 h/day	15.3
Both sources	15.5

[a] Adapted from Castle and Watson, 1973.

(39.4°C) was presented to cows in a cold environment (-12°C), intake increased, but at this low temperature, heating the water to 30°C did not influence consumption by sheep (Bailey *et al.*, 1962).

TABLE 7 Effect of Some Diets on Water Intake of Holstein Heifers[a]

	Experiment I			
	Hay	Pellets	Hay-Grain	Silage
Water consumed, kg/kg feed dry matter				
Water in feed	0.14	0.14	0.14	1.40
Water drunk	3.57	3.10	3.16	2.84
Total water intake	3.71	3.24	3.30	4.24
	Experiment 2			
	Hay		Silage	
	Ad lib.	Maint.	*Ad lib.*	Maint.
Water consumed, kg/kg feed dry matter				
Water in feed	0.11	0.12	3.38	3.38
Water drunk	3.36	3.66	1.55	1.38
Total intake	3.48	3.79	4.93	4.76
Urine, kg/kg feed dry matter	0.93	1.14	1.85	1.68

[a] Data from Waldo *et al.*, 1965.

Water temperature does not appear to alter rate of digestion. Under two ambient temperatures, 3°C and 12°C, water temperatures of 1, 14, 27, and 39°C did not have a detectable effect on digestion of Holstein cows even though ingestion of 21 kg of water at 1°C depressed lower, middle, and upper rumen temperatures by 13, 6, and 1°C within 10 rain (Cunningham *et al.*, 1964).

Air Temperature

The concept that water intake of livestock is related to air temperature is well recognized. Numerous experiments have shown significant positive correlations between water intake and ambient temperature. Although water intake may be related to ambient temperature, several other factors are important in decision making on water needs.

Cattle

Under controlled temperature conditions it has been demonstrated that cattle tend to increase water intake as temperature rises (Figure 13 and

Table 8), with 27°C being the temperature where marked changes in intake by lactating cows is noted (Table 8). Below that point water consumption is considered largely a function of dry matter intake (Bianca, 1970; Brody *et al.*, 1954; McDowell and Weldy, 1967; McDowell *et al.*, 1969; Ragsdale *et al.*, 1949, 1950, 1951; Winchester and Morris, 1956).

TABLE 8 Intake of Drinking Water and TDN of Brown Swiss, Holstein, and Jersey Heifers Under Various Temperature Conditionsa

Air Temperature (°C)	kg Water/ kg TDN	kg TDN/Day	kg Water/ Day
2	4.7	4.7	22.1
10	5.2	4.2	22.1
21	7.2	4.2	28.0
27	9.0	4.0	34.7
32	22.2	3.0	53.7
35	24.8	2.9	60.3

[a] Average body weight 361 kg (range 263-417 kg).
SOURCE: Adapted from Johnson and Yeck, 1964.

Under controlled environmental conditions no appreciable effect has been shown by changing rate of, ir movement from 0.64 to 12.9 kph on water consumption at -8, 10, 18, and 27°C. Changing the radiation level from 0.02 to 0.84 cal/cm^2/min had no effect on the intake of water at 7°C but had significant effects at 21 or 27°C (Brody *et al.*, 1954; Thompson *et al.*, 1954).

The correlation of water consumption of cattle and ambient temperature under field conditions is less clear because of confounding factors. However, at ambient temperatures from -37 to 7°C, water intake of Herefords in feed-lots was positively correlated with air temperature on the same day (r = 0.27) and with feed intake the previous day (r = 0.25) (Williams, 1959). The correlations were statistically significant with the conclusion that observations on water intake made at low constant temperatures were only in general related to intakes under low fluctuating temperatures.

For average daily temperatures around 8°C in Britain, water intake of lactating cows was significantly correlated with daily milk yield and dry matter content of the forage but was not significantly related to either air temperature or relative humidity. Average intake was 3.70 kg/kg DM consumed after adjustment for water in the milk (Castle and Macdaid, 1975). When maximum daily temperatures for grazing cattle are in the range of 13 to 28°C, water consumption is positively correlated with maximum temperature, forage DM and daily hours of sunshine but negatively correlated with rainfall and relative humidity as illustrated in Table 9. Even though the correlation between water and intake was not significant, it is similar to the correlation for maximum air temperature and water.

TABLE 9 Correlation Coefficients Between Intake of Drinking Water and Various Climatic and Production Variables for Lactating Holstein Cowsa

Variable	Correlation Coefficient	Significance (P value)
Maximum air temperature	+0.57	<0.05
Rainfall	-0.57	<0.05
Relative humidity	-0.82	<0.01
Sunshine	+0.86	<0.01
Forage DM	+0.52	n.s.
Milk yield	+0.36	n.s.

[a] Adapted from Cowan *et al.*, 1978.

When maximum daily temperature exceeds 30°C, free water intake tends to rise more rapidly than from 25 to 30°C, but variation among individuals increases markedly. It is, therefore, difficult to characterize water needs because of confounding with changes in animal behavior and the possibility that animals may use high water intake to maintain a sensation of fill that may result in lowered feed intake (McDowell, 1972). The data in Table 8 illustrate the point. The kg water/kg TDN consumed rose very rapidly above 27°C and so did total water intake, but kg TDN had decreased by 30 percent. The marked decline in TDN intake per day is not likely to occur under field conditions, thus the estimates of water based on this experiment and that in Figure 13 appear abnormally high for general recommendations.

Figure 14 shows that "previous temperature exposure" of the animals will markedly affect level of water intake. The Shorthorn heifers switched from a cold environment in January (6°C) to a 32°C control room had a more rapid rise in water intake than similar heifers changed from outside to a 32°C continuous temperature in August. After both groups had become adjusted to the 32°C (approximately 10 weeks), water intake became steady at a level of 1.8 times the level of the control group under cool conditions. After the third week of exposure, feed intake was at the preexposure level, but rate of live-weight gain was 12.5 percent less than for the control group (0.81 kg/day).

Figure 15 portrays the estimated water intake of nonlactating cattle expressed as kg water/kg DM intake. From -10 to 20°C there is a slight progressive rise. Above 25°C consumption rises more sharply due to the initiation of sweating and increased respiration rate. At 35°C or higher it is virtually impossible to keep feed intake up. The estimated physiological needs are 10 kg/kg DM at 40°C, but usually the cattle are so distressed that behavior becomes variable, in which case water intake may rise markedly

(B_1) or even decline (B_2). Seldom does the stress level suggested at above 35°C occur throughout the day; hence, the major concern is below 35°C on a daily basis. The extreme rise of water consumption in Figure 13 and Table 8 appears as much a function of reduced DM intake as the direct effects of stress. When temperature falls below -10°C, physiological needs may decline slightly (Point P, Figure 15), but due to the high degree of stress behavior may vary as indicated by Point B, Figure 15.

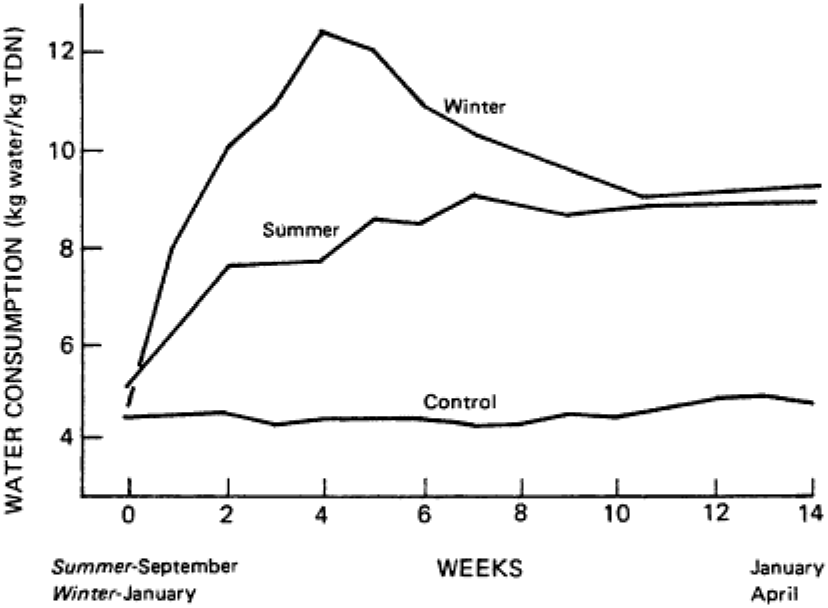

Figure 14.
Intake of drinking water of Shorthorn heifers kept in an open barn January-April (control), or changed from outside to 32°C in January (winter), or to 32° C in September (summer) (adapted from Bond and McDowell, 1972).

Sheep

The relation of drinking water intake to ambient temperature for sheep appears to parallel that for cattle. From 0 to 15°C water intake of growing and fattening sheep is 2.0 kg/kg DM consumed, increased to 2.5 kg at 15-20°C and 3.0 kg above 20°C (ARC, 1965). Up to approximately 38°C daily maximum temperature, water intake appears positively related to temperature, but at 40°C or higher, water intake may decline or rise rapidly, as in Figure 15 for cattle (Daws and Squires, 1974). When temperature declines to -12°C, the temperature of the rumen, rectum, and subcutaneous tissues decreases, resulting in a decline of about 50 percent in water intake from the 15°C level (Bailey *et al.*, 1962).

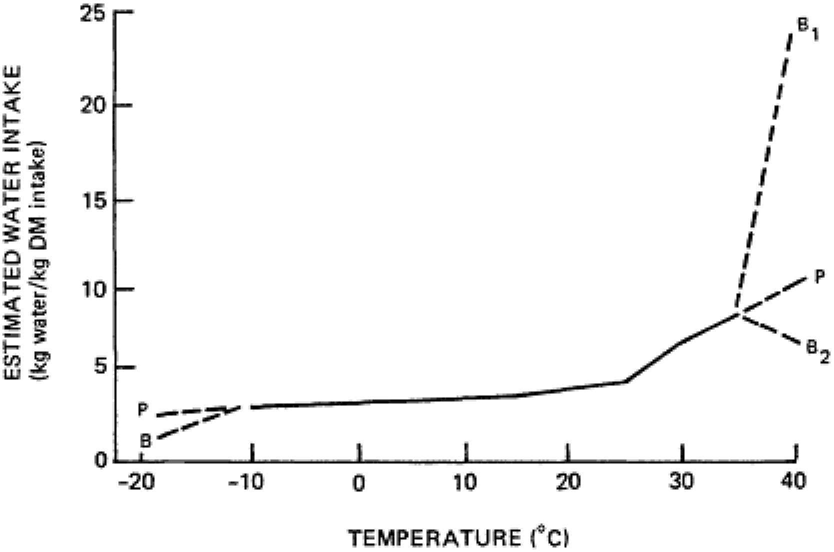

Figure 15.
Estimated *ad libitum* water intakes for nonlactating cattle over the temperature range -10 to 35°C; solid line with extensions "P" at high and low denoting "physiological needs"; "B_1" and "B_2" indicate behavior patterns at extreme temperature.

In tropical Australia and other areas a number of tests have been made on the influence of drought and temperature on the tolerance of various types of sheep to dehydration. Merino sheep seem to have a higher tolerance than European breeds to water deprivation (Macfarlane *et al.*, 1958). It has also been suggested that type of body covering may influence water needs with hair sheep having the least need, followed by coarse wool sheep and fine wool sheep (Hafez, 1968).

Swine

Experiments under controlled temperature conditions have shown an inconsistent relation between ambient temperature and water intake. At 7, 12, 20, and 30°C, water intakes were 2.88, 2.76, 2.74, and 4.28 kg/kg of DM. The corresponding values, when measured as kilograms of water consumed daily per kilogram of body weight, were 0.136, 0.122, 0.123, and 0.181 (Close *et al.*, 1971). The major increase in water consumption between 20 and 30°C, when expressed as a function of DM intake, is primarily a function of the reduced DM intake with increasing temperature above 25°C (Fuller, 1965). Presently, the needs for water at temperatures lower than 10°C are not identified, mainly because of the current production environments.

Poultry

Laying hens deprived of water survive 8 days at an ambient temperature of 14°C, but only 6 days when the temperature is 29°C (Bierer *et al.*, 1966). At 35°C White Leghorn fowl lose, by respiratory evaporation, 2.6 g of water per hour as compared to 0.5 g/h at 20°C (van Kampen, 1974). Thus, rising ambient temperatures increase the need for water. Water is lost from poultry as a fluid (excretory water loss through urinary and digestive systems) or as a vapor (respiratory water loss). Another major route of water loss for laying poultry is eggs. About two-thirds of the egg is water.

Poultry derive water from three sources: feed, which contains about 10 percent water by weight; metabolism of proteins, carbohydrates, and fats (metabolic water); free water consumption. The latter is the primary source of water, comprising about 74 percent of the total daily intake (Table 10).

The secondary source of water is metabolic water, at only 18 percent of the total intake. There is a close correlation between metabolic water and calories produced: 0.135 g H_2O per converted kcal (Kerstens, 1964). Therefore, a hen consuming 100 g of feed per day that has a caloric value of 3 kcal/g produces about 40 g of metabolic water per day. The hen drinks water at a ratio of 2 to 3 g of water per gram of diet. So, the intake of water is, at temperatures of 21-22°C, typically 250 g water per 100 g feed during egg production. Laying hens consume more water on days when an egg is formed and laid than on nonlaying days, 225 g versus 115 g, respectively (Howard, 1975).

As ambient temperatures rise, chickens consume increasing amounts of water; intake is 2.0-fold at 32°C, and 2.5-fold at 37°C greater than intake at 21°C.

Water availability for poultry is important for survival under heat stress. Hens allowed ample drinking water in containers large enough for their

TABLE 10 Water Intake by Broiler Chickens[a]

			Percent of Total		
Age (weeks)	Ambient Temperature (°C)	Total H_2O Intake (g/bird)	H_2O in feed	Metabolic H_2O	Drinking H_2O
1	31	16	9	19	72
3	25	32	11	23	66
5	22	91	7	14	79
7	20	140	6	16	78
9	20	163	6	16	78
Mean			8	18	74

[a] Adapted from Kerstens, 1964.

heads to be dunked survive longer during hot stressful conditions (Vo and Boone, 1978). Thus, the water serves as a coolant for external evaporation or to absorb heat from the head during drinking positions. In corroboration of these observations, hens were noted to withstand high ambient temperatures when allowed unlimited access to water, as compared to those given equivalent amounts by syringe directly in the crop (Lee *et al.*, 1945). The connotation of these data is that water presumed to be drunk during heat stress may actually have been lost to the surroundings when shaken off the head. The impact of such losses on total water intake is not known.

Because of the many factors that may influence the needs for drinking water, the real needs for water are difficult to characterize. That a positive relation exists between temperature and the amount of water consumed by animals when water is available free choice is undisputed. On the other hand, it is very unlikely that real water needs rise by 400 to 500 percent at 30°C or above. Most likely, the quick rise in water consumption at high temperature is used by animals as a stopgap measure to maintain heat balance until physiological processes can adjust to the new environment. No doubt ingested water is used as a heat sink in the rumen and may also be used by animals under acute thermal stress to replace feed at least on a temporary basis. In addition, what is sometimes measured as water consumption, because water disappeared from a container, may have been lost by animals immersing part of their body in response to heat or from evaporation.

In general, drinking water intake per unit DM intake remains nearly constant up to about 27°C. At that point, water intake seems to rise rather rapidly in response to stress, but after an acclimation period of perhaps several weeks, intake may decline to near the lower temperature level. When making estimates of water requirements under different environmental conditions, one should remember that animals on farms rarely encounter constant thermal stress throughout a 24-h period.

Nutritional Efficiency

Efficiency is the comparison of output to input. There are numerous schemes for measuring efficiency of converting ingested feedstuffs to animal product. For livestock, total (gross) efficiency is calculated as follows:

$$\text{Total efficiency} = \frac{\text{Total output}}{\text{Total input}} \times 100.$$

The most common "feed efficiency" term used by stockmen relates weight of feed ingested to weight of animal product output (feed to gain ratio) and may at times be confusing because it relates weights that in essence are not really comparable. For example, dry matter content of both feedstuffs and animal product are highly variable, which may result in from 3 to 25 units of feed by weight required to produce a unit of body weight gain. However, feed to gain ratio is an accepted way of describing total efficiency and is a useful term in practical situations since ultimately it is weight of feed that must be grown or purchased and fed and weight of product sold.

It is more meaningful when relating environment and efficiency to calculate total efficiency in caloric terms to obtain an energetic efficiency term as shown below:

$$\text{Total energetic efficiency} = \frac{\text{Total energy gain (RE)}}{\text{Total energy intake (IE)}} \times 100.$$

Partial efficiency is defined as the observed change in gain for a given change in feed intake expressed as a percentage:

$$\text{Partial efficiency} = \frac{\Delta\text{Energy gain (RE)}}{\Delta\text{Energy intake (IE)}} \times 100.$$

Since by definition, gains do not occur at or below maintenance, the maintenance level of feeding can be used as a baseline from which to calculate partial efficiency:

$$\text{Partial efficiency} = \frac{\text{Gain (RE)}}{\text{Intake (IE)} - \text{Maintenance (HE)}} \times 100.$$

Partial efficiency is simply the ability to convert the energy surplus above maintenance to stored chemical energy in terms of growth or product. Animal gains can vary considerably depending on the fat:protein ratio; thus efficiency of energy retention (partial efficiency) will vary with composition of gain since the cost of fat synthesis is different than protein. When the efficiency of producing product from energy surplus to maintenance (partial efficiency) is altered, then total efficiency is also affected. Some data suggest a lipogenic effect of cold (Fuller and Boyne, 1971), while other studies (Hacker *et al.*, 1973) suggest leaner carcasses during cold exposure. Magnitude of cold and availability of food are major determinants of composition of growth for animals. exposed to thermal stress. Seasonal variation in composition of expelled product such as butterfat content of milk are well known. However, when all factors are considered, environment has little effect on partial efficiency.

Changes in total efficiency do not infer changes in partial efficiency. Generally, environment influences total efficiency by affecting rates of intake and maintenance energy requirement. Adverse environments alter the efficiency of converting feedstuffs to animal product and therefore are economically important to study. The fact that climatic environment alters the relationship of output per unit input has led to varied studies designed to describe effect of environment or environmental modification on efficiency of convening feed to product. Henderson and Geasler (1969) summarized several studies comparing the value of modifying both summer and winter environments with natural environments for the beef cattle studies. In general, for the locations included in the studies, environmental modification resulted in improved efficiency of feed conversion although economic advantage was not always positively correlated with efficiency.

For specific effects of climatic factors several workers have reported decreased feed efficiency of swine exposed to either heat (Hazen and Mangold, 1960; Jensen, 1971) or cold (Fuller and Boyne, 1971; Mangold *et al.*, 1967), although there is some evidence that finishing hogs exhibiting compensatory growth after removal from heat stress are as efficient as nonstressed animals (Hahn *et al.*, 1975). Ames and Brink (1977) reported reduced feed efficiency for lambs exposed to either heat or cold when compared with thermoneutrality for temperatures ranging from -5 to 35°C when estimated lower critical temperature was 15°C. Again both heat and cold result in reduced efficiency of milk production (McDowell *et al.*, 1976) when compared as kilograms of milk per megacalorie feed energy. Under heat stress, feed efficiency (megacalories of ME per kilogram of milk) declines rapidly above 27°C (Moody *et al.*, 1967).

An example of an environmental effect on rate of performance and energetic efficiency of food animals is illustrated by data shown in Table 11 collected from similar swine grown in temperatures ranging from cold stress (0° C) to heat stress (35°C). The energetic efficiency was reduced during both cold and heat stress and was highest during the TNZ. While the temperature and efficiency values may differ for animals with different insulation, diets, etc., or for different species and products, the same general pattern of reduced energetic efficiency is consistent among animals exposed to stressful environments. This reduced energetic efficiency, in turn, causes an economic loss. Livestock producers are usually willing to incorporate management systems to improve energetic efficiency when that is advantageous economically.

There are some reports (Holme and Coey, 1967; Sugahara *et al.*, 1970) of improved efficiency of swine during mild cold compared with thermoneutral conditions. Figure 16 suggests this may happen if rate of increased voluntary intake is more rapid than rate of increased energy requirement for heat production during cold. When exposed to heat, the combination of reduced in

TABLE 11 Effect of Temperature on Intake, Growth Rate, and Efficiency of Energy Conversion for Swine

Temperature (°C)	Caloric Intake (kcal DE/ day)	Growth Rate (kg/ day)	Product (kcal GE)[a]	Caloric Efficiency (%)[b]
0	15,377	0.54	2,991	19.4
5	11,404	0.53	2,936	25.7
10	10,616	0.80	4,432	41.7
15	9,554	0.79	4,376	45.8
20	9,766	0.85	4,709	48.2
25	7,976	0.72	3,988	50.1
30	6,703	0.45	2,493	37.1
35	4,579	0.31	1,717	37.4

[a] Estimated caloric value of gain for an 80-kg pig is 5.54 kcal GE/g (Thorbeck, 1975).

[b] Calculated: (kcal GE in product ÷ kcal DE intake) × 100.

SOURCE: Ames, 1980.

take and increased heat production result in reduced efficiency for growing animals.

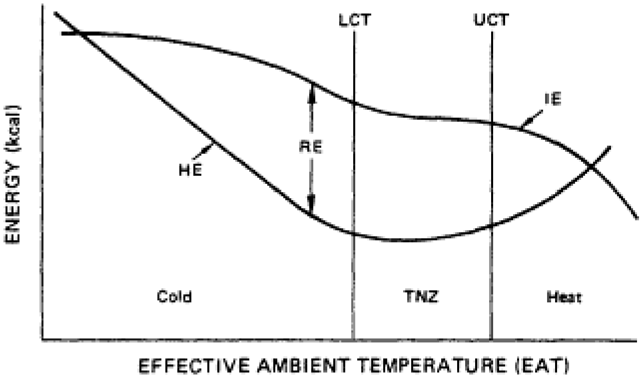

Figure 16.
Schematic relationship of heat production (HE), intake energy (IE), and energy for production (RE = IE - HE) with temperature zones.

In contrast to most data for growing animals, total energetic efficiency of producing expelled products such as eggs and milk have been reported to be improved during heat by Davis *et al.* (1972) and Johnson (1965), respectively. This apparent difference in efficiency of an expelled product compared with tissue growth is explained by catabolism of body stores to meet energy demands during heat when intake is reduced. (See page 112 for a detailed description of energetic efficiency of egg production). Consequently, caloric efficiency of producing an expelled product is improved primarily because of mobilization of tissue reserves while only ingested energy is used to calculate caloric efficiency. Of course, original costs of depositing depot fat are not considered, and, therefore, caloric efficiency of producing an expelled product such as the egg during heat must be taken within the context of short-term utilization of stored energy. Conversely, catabolism of tissue stores in animals where growth is the end point of production is self-defeating and results in lowered efficiency, although a lower percent carcass fat may be considered a desirable result. There may, however, be instances of management systems that rely on the ability of animals to withstand periods of reduced feed quantity or quality and then recover tissue stores through compensatory growth when the diet is more favorable. There appear to be two additional reasons for improved efficiency of producing eggs during heat. First, efficiency of using body fat as an energy source is high compared with using energy from feed sources, which results in higher efficiency of egg production during heat exposure. And second, van Kampen (1974) re ported lowered H_eE, while McDonald (1978) reported lowered "existence energy" during heat as a result of lowered intake and reduced activity of laying hens.

Reports of energetic efficiency for animals exposed to fluctuating environments compared with constant temperature are conflicting. Bond *et al.* (1963) found that pigs exposed to a constant 21°C environment had higher total efficiency than pigs exposed to cyclic 10 to 32°C or 4 to 38°C environments. Giacomini (1979), working with lambs, and Sorensen and Moustgaard (1961) and Hahn *et al.* (1975), with pigs, found no difference in efficiency of growth when cyclic environments were compared with constant temperature environments of the same mean temperature. The variety of differences in fluctuating environments (i.e., duration, magnitude of change, etc.) will require much more data before conclusions can be drawn.

Numerous studies suggest that specific climatic variables change total efficiency. Morrison *et al.* (1966) found no effect of 45, 70, and 95 percent relative humidity on hogs when temperature was considered optimum, but a significant effect was noted when studied during heat (Morrison *et al.*, 1969). Berry *et al.* (1964) reported declines in milk production with an increasing THI value. Morrison *et al.* (1971) indicated lower total efficiency of gain for cattle exposed to rain but improved total efficiency with wind during mild winter conditions in California. Further examples of effects of specific climatic variables only substantiate the need to use effective ambient temperature when relating effects of the climatic environment to performance.

Measurement of efficiency in the short term can lead to erroneous conclusions because of differences in an animal's previous nutritional background. For example, animals that have received restricted intake will compensate with improved feed efficiency when allowed *ad libitum* intake. Hens formerly on restricted diets gradually renew their lipid reserves (Polin and Wolford, 1972) by depositing lipid in the carcass more efficiently than non-restricted birds. Allden (1968) reported that feed consumption and feed utilization were not affected in the long term following a period of nutrient restriction although compensation was observed early in the recovery period. Searle and Graham (1975) reported no difference in body composition of animals held at constant weight for up to 6 months by restricted feeding and then fed *ad libitum* compared with lambs fed *ad libitum*. Short-term changes in efficiency during heat stress may occur, but studies show (Hahn *et al.*, 1975) that animals convert feed more efficiently after relief from heat stress compared with unstressed animals subjected to restricted nutrition and tend to equalize in the long run with little effect on long-term efficiency. Degen and Young (1980) reported that rapid changes in live weight during and following cold exposure can be largely attributed to losing and gaining of body fluids.

The impact of climatic environment on energy flow in terms of both energy intake and that available for growth may directly affect the utilization of other nutrients because in many cases nutrient requirement is a function of available energy. For example, protein efficiency ratio (grams of gain per gram of CP,) is lowered during both heat and cold stress in sheep (Ames and Brink, 1977), and Fuller and Boyne (1971) and Roy *et al.* (1969) have reported lowered nitrogen retention during thermal stress in swine and cattle, respectively. These examples emphasize the need to consider available energy in the light of environmental stress and to adjust rations to enhance efficient utilization of all nutrients.

II

APPROACHES FOR PRACTICAL NUTRITIONAL MANAGEMENT

Beef Cattle

INTRODUCTION

Beef cattle are kept in many climatic regions and, except for some intensive production systems, are largely exposed to naturally occurring climatic conditions. In intensive beef production systems such as feedlots with shelters or confinement barns, there may be some modulation and protection from climate, but other stress factors, such as gaseous contaminants, dust, mud, or crowding, may be generated that have a detrimental influence on animal performance.

The following presentation on adjustment factors for the feeding of beef cattle is based on the Fifth Revised Edition of *Nutrient Requirements of Beef Cattle* (NRC, 1976a) and the adjustment factors pertain to the values and tables presented in that publication. Some modification may be necessary to adapt the suggested adjustment factors to other feeding systems. The adjustment factors relate primarily to the effects of thermal stress, both hot and cold, on energy requirement and utilization by beef cattle. Where information is available, consideration is given to nonthermal stress factors as well as to protein and other dietary components. In developing adjustment factors, it has been necessary to assume that the recommendations contained in *Nutrient Requirements of Beef Cattle are* for cattle exposed to conditions relatively free of thermal stress or an ambient temperature range of about 15 to 25°C. The midpoint, 20°C, has been adopted as a reference point for thermal adjustments. The reference temperature is reasonable since it represents thermal conditions where beef cattle of various ages and physiological states should exhibit little or no thermal discomfort (Johnson, 1976; Monteith, 1974; Robertshaw, 1974). Of course, some data forming the basis of *Nutrient Requirements of Beef Cattle* are from field trials where temperatures were outside the 15 to 25°C range. Unfortunately, for many of these studies a description of the thermal environment is not available.

The complexity of climatic factors would preferably be expressed in the composite unit of effective ambient temperature (EAT; see page 6). However, sufficient information is not presently available for estimation of EAT for beef cattle under practical commercial conditions. Instead, mean air temperature will be used with the understanding that while it is not the ideal description of environmental conditions, it is usually available and does provide a reasonable index. The reader should use the best-available information and should not refrain from making nutrient adjustments through the lack of a precise measure of EAT.

Extremes in ambient temperature influence the behavior, function, and productivity of animals by complex and involved processes (see Part I). To develop adjustment factors for beef cattle, simplification is necessary and three areas of influence are identified. These are: (1) voluntary feed and water intake, (2) nutrient value of ingested feedstuffs, and (3) the maintenance energy requirement of the animal. The last is really two components, one associated with longer-termed acclimatization to thermal stress and the other

TABLE 12 Summary of Voluntary Food Intake of Beef Cattle in Different Thermal Environments

Thermal Environment	Intakes Relative to Values Tabulated in *Nutrient Requirements of Beef Cattle*
> 35°C	Marked depression in intake, especially with high humidity and/or solar radiation and where there is little night cooling. Cattle on full feed—10 to 35 percent depression. Cattle near maintenance—5 to 20 percent depression. Intakes depressed less when shade or cooling available and with low fiber diets.
25 to 35°C	Intakes depressed 3 to 10 percent.
15 to 25°C	Preferred values as tabulated in *Nutrient Requirements of Beef Cattle.*
5 to 15°C	Intakes stimulated 2 to 5 percent.
-5 to 5°C	Intakes stimulated 3 to 8 percent. Sudden cold snap or storm may result in digestive disturbances in young stock.
-15 to -5°C	Intakes stimulated 5 to 10 percent.
< - 15°C	Intakes stimulated 8 to 25 percent. Intakes during extreme cold (< -25°C) or during blizzards and storms may be temporarily depressed. Intake of high roughage feeds may be limited by bulk.

with acute metabolic responses associated with an immediate hot or cold stress. Until more research data are available, rectilinear responses have been assumed, and, therefore, caution should be exercised in utilizing the suggested adjustment factors in extreme conditions.

TABLE 13 Summary of Voluntary Food Intake of Beef Cattle Exposed to Nonthermal Stress

Stressor	Estimated Effect on Intake and Adjustment Values Tabulated in *Nutrient Requirements of Beef Cattle*
Rain	Temporary depression of 10 to 30 percent.
Mud	
Mild, 10 to 20 cm deep	Intakes depressed 5 to 15 percent.
Severe, 30 to 60 cm deep	Intakes depressed 15 to 30 percent. Mud effects are greatest when access to feed is limited and when there is a lack of a suitable bedded area.
Illness or disease (nonspecific)	Usually accompanied with severe depression in voluntary intake.

VOLUNTARY FOOD INTAKE

In general, voluntary intakes of food tend to decrease as ambient temperature increases and increase when ambient temperatures decrease. Tables 12 and 13 provide summaries of changes in voluntary food and water intake due to various stressors and are presented relative to the estimated dry matter intakes tabulated in *Nutrient Requirements of Beef Cattle*. Estimates of feed intake both within and among animals become more variable and less predictable as ambient temperatures vary further from the 20°C reference temperature. Furthermore, a predictable response in an animal's food intake is not always possible following a sudden or abrupt change in the environment, especially where the change is beyond the animal's adaptive range. In practice, a predicted intake based upon the general state of the environment, for example, on mean weekly or monthly temperature, is generally more useful than one based on daily or within-day variations. However, in diurnally fluctuating conditions where, for example, night cooling may relieve an animal of the severity of hot daytime temperatures, both voluntary intake and performance may be higher than would be predicted from the mean daily or weekly temperature.

WATER NEEDS

Water is consumed by cattle as free water and water with feed. Total water requirement varies with live weight, feed intake, physiological state, and en vironmental temperature. The need for water increases with increased intakes of protein or salt, and in lactating cows. Relationships between ambient temperature and water requirement of cattle are detailed on page 39 and summarized in Table 14. Water quality is important to cattle, especially with respect to the content of salts and toxic compounds (NRC, 1974).

TABLE 14 Water Requirements of Beef Cattle in Different Thermal Environments

Thermal Environment	Water Requirements
> 35°C	8 to 15 kg water per kg DM intake.
25 to 35°C	4 to 10 kg water per kg DM intake.
15 to 25°C	3 to 5 kg water per kg DM intake. Young and lactating animals require 10-50 percent more water.
-5 to 15°C	2 to 4 kg water per kg DM intake.
< -5°C	2 to 3 kg water per kg DM intake. Increases of 50-100 percent occur with a rise in ambient temperature following a period of very cold temperature, e.g., a rise from -20 to 0° C.

NUTRIENT VALUES OF FEEDSTUFFS

It is evident from data presented in Table 2 that the ability of ruminants to digest roughage diets depends upon the thermal environment. Roughages tend to be more highly digested during warm conditions than when the same diet is fed to cattle exposed to cold temperatures. While research data are still rather limited on the physiological mechanism of this influence of the environment, the effect appears to be associated with rate of passage of digesta, metabolic acclimation, and thyroid hormone activity. Until more research data are available, a rectilinear adjustment is suggested that can be applied directly to roughage feeds in Table 11 of the Feed Composition Table in *Nutrient Requirements of Beef Cattle* (NRC, 1976a). Adjustments for thermal effect on digestibility can be made to diet component values for feeds or diets by the following general formula:

$$A = B + B[C_f(T - 20)],$$

where
A = value adjusted for environment,
B = diet component value from NRC feed composition table,
C_f: correction factor (see below), and
T = effective ambient temperature (°C).

Correction Factor for Effect of Temperature on Diet Digestibility (Cf)

Diet Component	
Dry matter	0.0016
Energy components (ME, NE, TDN)	0.0010
Acid detergent fiber	0.0037
Nitrogen (crude protein)	0.0011

Table 15 provides examples of the effect of the thermal environment on the estimated nutrient value of alfalfa hay.

Evidence from sheep (see Table 2) indicates that the above adjustment for the effect of temperature on diet digestibility is of more importance for roughage than for concentrate diets. Presently, no adjustment is recommended for concentrate diets fed to beef cattle.

ADJUSTMENTS TO MAINTENANCE ENERGY REQUIREMENT

Thermal environment influences maintenance energy requirements of cattle two ways: first, that due to acclimatization as a consequence of prolonged exposure to a thermal environment, and second, that due to an immediate increase in heat production necessary for maintenance of homeothermy when the animal is exposed to an acute heat or cold stress. The acclimatization component is associated with hormonal and metabolic functional changes that develop as a consequence of prolonged exposure and, therefore, is more associated with seasonal changes in the thermal environment than with daily or short-term weather fluctuations. In making adjustments for metabolic acclimatization, mean monthly temperatures would be an appropriate basis for adjustment. On the other hand, acute response to heat or cold as a consequence of exposure to extreme temperatures requires an immediate response,

TABLE 15 Example of Adjustment to the Feeding Value of Alfalfa Hay for Feeding to Beef Cattle Exposed to Warm, Thermoneutral, and Cold Environmental Conditions

	Environmental Temperature (°C)		
	30	20	- 5
ME (Mcal/kg)	1.94	1.92[a]	1.87
NE_m (Mcal/kg)	1.14	1.13	1.11
NE_g (Mcal/kg)	0.40	0.40	0.39
TDN (%)	53.5	53.0	51.7
Digestible protein (%)	11.5	11.4	11.1

[a] From Table 11, NRC, 1976a.

and, therefore, daily weather fluctuations would be the more appropriate basis for adjusting beef cattle diets. When considering any feeding adjustment that requires a change in diet type, caution should be exercised to avoid possible disturbance to rumen microbial functions.

Adjustment to Maintenance Energy Requirements for Metabolic Acclimatization

This adjustment is necessary because the basal or resting metabolism of animals is to some extent dependent upon the thermal environment to which they are partially or fully acclimatized (see page 22). Basal metabolic rates tend to be lower in animals with prior exposure to warm and elevated in animals with prior exposure to cold conditions. The continually variable seasonal conditions of the natural environment result in continuous changes in the state of animal acclimatization. In beef cattle, adjustments based on seasonal changes in the thermal environment (mean monthly temperature) would be most appropriate, although it is likely that cattle never fully acclimatize to the extremes in regions where there are marked seasonal fluctuations in ambient temperature.

In *Nutrient Requirements of Beef Cattle* (NRC, 1976a), the estimates for net energy requirement for maintenance (NE_m) is based on the relationship

$$NE_m = aW^{0.75},$$

where
NE_m = net energy for maintenance (Mcal/day),
a = 0.077 for TNZ,
W = live weight (kg).

By assuming a rectilinear relationship between basal or resting metabolism and temperature of prior exposure, the above equation can be modified to account for metabolic changes associated with acclimatization. For each °C prior exposure to ambient temperatures above or below 20°C, 0.0007 should be subtracted or added respectively to a in the above equation. Thus, for cattle with prior exposure to temperatures of 30, 20, 10, and 0°C, the value a becomes 0.070, 0.077, 0.084, and 0.091, respectively.

An alternative exists to adjusting maintenance requirement by the above equation and then having to calculate adjusted NE_m values for tables in *Nutrient Requirements of Beef Cattle*. Adjustments can be made directly to the NE_m and maintenance energy requirement values expressed in terms of ME or TDN by decreasing (for heat) or increasing (for cold) the tabulated values by 0.91 percent for each °C the cattle have had prior extended exposure to conditions above or below 20°C.

Adjustment in Maintenance Energy Requirements for Immediate Heat or Cold Stress

Heat Stress

Adjustments to maintenance energy requirement for heat stress should be based on the severity of heat stress, which can vary considerably among animals depending upon acclimatization, diet, level of productivity, and diurnal fluctuations in radiant heat load. During severe heat stress maintenance requirements increase through the increased cost of panting and alterations in tissue metabolism because of increased tissue temperatures (Q_{10} law). The type and intensity of panting can provide an index for an appropriate adjustment in maintenance requirements. The percentage increase in oxygen consumption, and thus maintenance requirement, increases about 7 percent while the animal is in first-phase panting, i.e., rapid shallow panting, but 11 to 25 percent during second-phase open-mouth panting (Hales, 1973; Hales and Findlay, 1968; Kibler and Brody, 1951). However, with severe heat stress, appetite is usually lowered, which results in reduced productivity and metabolic heat production.

Cold Stress

Adjustments for acute cold stress apply when cattle are exposed to thermal environments below their lower critical temperature (LCT). The LCT tends to be lower in beef cattle compared with other domestic animals (Table 1), and direct cold stress is generally not a practical nutritional problem except in areas with extremely cold winters or through the chilling effects of moisture and wind on young stock or animals with poor resistance to cold. The overall cold hardiness of beef cattle is a consequence of their large size, their usually effective thermal insulation, and the relatively large amounts of heat that arise from normal digestion and metabolic processes (heat increments). Often more important than the immediate increase in energy requirements during a severe cold stress, such as from a winter storm or blizzard, can be the challenge to animal survival. The severity of the challenge to survival is not only dependent upon the environmental conditions, but also upon the animal's level of acclimatization to cold. Cold acclimatized cattle not only have an increased metabolic rate, but also an enhanced capacity to increase their rate of metabolic heat production (summit metabolism) to prevent hypothermia when severely cold stressed, i.e., acclimatized cattle may therefore survive in situations where nonacclimatized cattle may succumb.

Increased heat production during cold stress requires an immediate utilization of energy substrates from either the diet or from tissue reserves. Nutritional adjustments can be estimated to maintain animal productivity. It is then a relatively simple step to estimate the increase in maintenance energy requirements for exposure to temperatures below the animal's lower critical temperature (LCT). But, to calculate such adjustments it is necessary to first establish the LCT of the animal.

LCT of cattle can be estimated from the equation:

$$LCT = T_c - I\,(HE - H_e),$$

where
LCT = lower critical temperature (°C),
T_c = core temperature (°C) (39°C satisfactory assumption),
I = total insulation, i.e., tissue plus external, see Table 16 (°C/Mcal/m^2/day),
HE = heat production (Mcal/m^2/day), and
H_e = heat of evaporation (Mcal/m^2/day).

For beef cattle the value HE is conveniently estimated from values in *Nutrient Requirements of Beef Cattle* as the metabolizable energy intake (ME) and the net energy required for production (NE_p), as shown below:

$$HE = (ME - NE_p)/A,$$

where
HE = heat production (Mcal/m^2/day),
ME = metabolizable energy intake (Mcal/day),
NE_p = net energy for production (Mcal/day), and
A = surface area (m^2).

NOTE: Surface area may be calculated from body weight according to the general formula $A(m^2) = 0.09\ kg^{0\ 75}$.

The increased energy requirement to maintain productivity in an environment colder than the animal's LCT is given by the formula:

$$ME^* = A(LCT - T)/I,$$

where
ME^* = increase in maintenance energy requirement (Mcal/day),
A = surface area (m^2),
LCT = lower critical temperature (°C),
T = effective ambient temperature (°C), and
I = total insulation, i.e., tissue plus external, see Table 16 (°C/Mcal/m^2/day).

TABLE 16 Estimates of Tissue and External Insulation for Beef Cattle

Tissue Insulation (I_t)[a]	I_t (°C/Mcal/m^2/day)			
Newborn calf	2.5			
Month-old calf	6.5			
Yearling	5.5 to 8.0			
Adult cattle	6.0 to 12.0			
External Insulation (I_e)[b]	I_e(°C/Mcal/m^2/day) in Relation to Coat Depth			
Wind Speed(mph)	<5 mm	10 mm	20 mm	30 mm
<1	7	11	14	17
4	5	7.5	10	13.5
8	4	5.5	8	9
16	3	4	5	6.5

[a] Cattle in thin or emaciated body conditions and breeds with thin skins (dairy breeds and *Bos indicus*) have lower values than fat stock and breeds with thick skins (e.g., Hereford). With acclimation to cold I_t increases.

[b] Presence of moisture, wet snow, or mud in the coat could reduce I_e in affected areas by 50 to 80 percent.

SOURCE: Composite of data from Webster (1974, 1976) and Blaxter (1977).

Typical LCT values for cattle and estimated increase in feed energy requirements as a consequence of exposure to subcritical temperatures are shown in Table 17. Evident from these examples are the low LCT values for cattle in dry conditions free from wind and the impact of mud or moisture on I_e. In cold climates wind is sometimes a problem, but because of the intense cold there is usually little moisture. At these cold temperatures snow tends to remain dry and powdery and does not reduce the insulative value of the hair coat as much as wet snow or rain. From the estimates in Table 17 there are obvious advantages for providing cattle with protection from wind and, in wet cold climates, overhead shelter and dry bedding. The economics of providing such protection must be calculated for each specific situation.

ADJUSTMENTS TO NONENERGY COMPONENTS

While environmental stress has direct consequences on the dietary energy requirements of cattle, there is at present considerable uncertainty as to desirable adjustments for the nonenergy components of diets. As an example, the dietary energy requirements of cattle increase to compensate for the increased heat production during cold exposure, but do protein, mineral, and vitamin needs increase proportionately? There is some evidence that vitamin

TABLE 17 Estimates of Lower Critical Temperature (LCT) of Beef Cattle and the Increase in Energy Requirements to Compensate for Exposure to Temperatures Below Their Lower Critical Temperature

		Thermal Insulation (°C/Mcal/m^2/day)		Heat Production Without Direct Cold Stress		Lower Critical Animal Temperature[a] (°C)	Increased Energy Requirement per °C below LCT[b]	
Animal and Conditions	Liveweight (kg)	I_t	I_e	Mcal/day	Mcal/m^2/day		Mcal ME/day	%
Calf, I week old dry, low wind	50	3	12	2.93	2.37	7.7	0.083	2.83
Heifer, 6 months old gaining 0.5 kg/d dry, low wind	100	6	14	5.91	3.05	- 17.0	0.097	1.64
wet, 10 mph wind	100	6	4	5.91	3.05	9.9	0.194	3.28
Yearling steer gaining 1.1 kg/d dry, low wind	300	8	12	15.62	3.87	- 34. I	0.202	1.30
wet snow, mud, 10 mph wind	300	8	5	15.62	3.87	-9.5	0.310	1.99
Dry pregnant cow —middle third of pregnancy dry, low wind	500	9	15	16.4	2.89	-25.0	0.237	1.45
wet snow, 10 mph wind 500	9	8	16.4	2.89	-7.3	0.334	2.04	

[a] LCT in terms of effective ambient temperature.

[b] For estimate in term of NE$_m$, multiply ME by efficiency of use of ME for maintenance, approximately 0.58 for concentrate feed and 0.68 for roughage feeds.

A requirements may increase in cattle during cold exposure (Hidiroglou and Lessard, 1971; Jones *et al*., 1962). A recent report by Ames *et al*. (1980) indicates that protein as a percentage of the diet can be reduced during winter without affecting the growth rate of feedlot cattle. Any decrease in protein-in the ration should only be proportioned to the increase in food intake such, that the absolute amount of protein intake is maintained. Any adjustment in ration composition should consider economics and the possible effect of feeding excesses of some ration components. Most protein supplements fed in excess of immediate animal needs are catabolized and utilized as an energy source.

Increasing percentage roughage in cattle diets results in a slight increase in heat production because of increased heat increment of feeding. Under hot environmental conditions this increased heat production can result in reduced voluntary food intake. It is therefore advantageous to feed. diets of low roughage content during hot weather. On the other hand, for restricted fed cattle in a cold climate an increase in roughage may at times be advantageous. However, if feed is not restricted in cold conditions substituting roughage for concentrate feeds may limit the total available energy intake and reduce rate of productivity.

There is clearly an urgent need for further research into the interaction between protein, mineral, and vitamin needs of cattle and the array of environmental stressors encountered in commercial beef cattle systems.

SUMMARY OF ADJUSTMENTS FOR ENVIRONMENTAL STRESS FOR BEEF CATTLE

1. Voluntary Feed Intake

a. Adjust values tabulated in *Nutrient Requirements of Beef Cattle* (1976a) in accord with adjustment factors indicated in Tables 12 and 13.

2. Nutrient Value of Feedstuffs

a. Adjust the nutrient value of roughage feeds for the ambient temperature to which the consuming animal is exposed, see page 62.

3. Maintenance Energy Requirement

a. Adjust by either the NE_m equation or the percentage factor method the maintenance energy requirement estimates for animals tabulated in *Nutrient Requirements of Beef Cattle* downward 0.91 percent for each °C cattle have prior exposure to seasonal temperatures above 20°C and upward 0.91 percent for each °C below 20°C, see page 64.

b.

(i) *Heat stress*: Using type and intensity of panting as an index, increase the estimated maintenance energy requirements by up to 7

TABLE 18 NCm and NE8 in Diet for Example I (Finishing Steer) Adjusted for Effects of the Thermal Environment

			Amount in Diet on Dry Matter Basis[a]							
			NE_m (Mcal)				NE_8 (Mcal)			
Ingredient	Reference Number	Percent	a (Nonstressful)	b (Hot Dry)	c (Cold Wet)	d (Cold Dry)	a (Non-stressful)	b (Hot Dry)	c (Cold Wet)	d (Cold Dry)
Corn, aerial part, ensiled	3-08-153	55	0.86	0.87	0.84	0.83	0.54	0.55	0.53	0.52
Corn, ears, ground	4-02-849	40	0.89	0.89	0.89	0.89	0.56	0.56	0.56	0.56
Supplement		5	0.08	0.08	0.08	0.08	0.05	0.05	0.05	0.05
TOTAL (Mcal/kg diet DM)		100	1.83	1.84	1.81	1.80	1.15	1.16	1.14	1.13

[a] a,b,c,d—Environmental situations described in text.

percent for rapid shallow breathing and 11 to 25 percent for deep open-mouth panting, see page 65.

(ii) *Cold stress*: The adjustment for direct cold stress applies only if animals are exposed to temperatures below their LCT. If a direct cold stress is suspected, first determine the thermal insulation and LCT values of the cattle, then apply an adjustment to the maintenance energy requirements of the cattle for each °C the effective ambient temperature is below the LCT of the cattle, see page 66.

EXAMPLES OF ENVIRONMENTAL INFLUENCES ON NUTRITION OF BEEF CATTLE

The following examples illustrate the use of the above suggested adjustments and are based on formulation of an adequate ration as presented in *Nutrient Requirements of Beef Cattle* (NRC, 1976a).

Example 1

Evaluation for a 300-kg finishing steer (Charolais-Angus cross) with anticipated gain of 1.1 kg per day. In this example a simple diet formulation from corn silage, ground ear corn, and a supplement is used as presented in Formulating Diets (page 21 and Table 6 of *Nutrient Requirements of Beef Cattle*, NRC, 1976a). Four environmental situations have been considered:

a. Nonstressful conditions.
b. A hot dry environment with an average ambient temperature of 30° C, but where for a short duration daily mean temperatures rise to 35°C, resulting in rapid shallow breathing.
c. A cold wet environment with an average temperature of 0°C and with the presence of mud and wet snow. There is also a lack of a suitable bedding area.
d. A cold dry environment with an average ambient temperature of -15°C and where there is a dry bedding area and effective protection from wind.

Estimated NE_m and NE_g values for the diet are presented in Table 18. Table 19 summarizes estimates of the adequacy of the diet and expected performance of the steer in the four environments.

Example 2

Evaluation for a 500-kg dry pregnant mature cow (Hereford breed) in the last third of pregnancy on a diet of brome hay (1-00-890). Four environmental situations have been considered:

TABLE 19 Estimated Adequacy of Diets and Performance of a 300-kg Finishing Steer (Example 1) Illustrating Expected Influences of the Thermal Environment

		Environmental Conditions[a]				
		a (Non-stressful)	b (Hot Dry)	c (Cold Wet)	d (Cold Dry)	Data Source and Explanation
Daily feed consumption	kg dry matter	7.60	6.84	7.98	8.36	*Nutrient Requirements of Beef Cattle*—Table 1
Daily NE_m required	Mcal					*Nutrient Requirements of Beef Cattle*—Table 3 Adjusted for acclimatization to thermal environment.
i. Adjusted for acclimatization temperature		5.55	5.04	6.56	7.32	Seven percent increase for heat stress. No adjustment necessary for direct cold exposure.
ii. Added adjustment for direct heat or cold stress		0	0.35	0	0	
	TOTAL	5.55	5.39	6.56	7.32	
Feed need for maintenance	kg dry matter	3.03	2.93	3.62	4.07	NE_m required ÷ NE_m/kg diet DM
Feed left for gain	kg dry matter	4.57	3.91	4.36	4.29	Feed consumption—feed for maintenance
NE_8 available for deposit in gain	Meal	5.26	4.54	4.97	4.85	Feed left for gain × NE_8/kg DM
Expected liveweight gain	kg/day	1.20	1.06	1.13	1.10	Interpolated from Table 3 of *Nutrient Requirements of Beef Cattle*
Feed dry matter/unit gain		6.3	6.5	7.1	7.6	Feed consumption ÷ weight gain

[a] a,b,c,d—Environmental conditions as described in text.

w. Nonstressful conditions.
x. A hot dry environment with an average ambient temperature of 30° C, but where for a short duration daily mean temperatures rise to 35°C resulting in rapid shallow breathing.
y. A cold dry environment with an average ambient temperature of -25°C and where there is a dry bedding area and effective protection from wind.
z. A cold dry environment with seasonal temperatures of usually - 15° C, but estimates are required for a period of several days of a winter storm with air temperatures of -25°C, 10 mph winds, drifting snow, and lack of suitable bedding or shelter.

Estimates of daily maintenance requirement in terms of ME and kilograms of hay are shown in Table 20 (p. 74).

TABLE 20 Estimated Maintenance Requirements for a 500-kg Pregnant Beef Cow During the Last Third of Pregnancy (Example 2) Illustrating the Influences of Environmental Stress

	Environmental Conditions[a]			
	w (Nonstressful)	x (Hot Dry)	y (Cold Dry)	z (Winter Storm)
Maintenance energy requirements (Mcal ME/day)				
1. Adjusted for acclimatization temperature	16.4	14.9	23.1	21.6
2. Added adjustment for direct heat or cold stress	0.0	1.0	0.0	5.9
TOTAL	16.4	15.9	23.1	27.5
Diet on dry matter basis[b]				
1. Energy content adjusted for environmental conditions (Mcal ME/kg)	1.87	1.90	1.79	1.79
2. Feed requirement for maintenance (kg/day)	8.8	8.4	12.9[c]	15.4[c]

[a] w,x,y,z—Environmental conditions as described in text.

[b] Brome hay (1-00-890) diet.

[c] Bulk of diet may limit intake of brome hay.

Dairy Cattle

INTRODUCTION

The thermoneutral zones depicted in Figure 2 indicate that neonatal calves possess a wider range of temperature tolerance than either lambs or piglets. Adult cows are second only to sheep with full fleece with respect to thermal tolerance.

That efficiency of performance of dairy cattle of all ages is influenced to an extent by both high- and low-temperature conditions is generally recognized. However, due to variability in systems of management employed on dairy farms, there is a tendency to only generalize on alterations in feeding to meet the nutritive requirements for maximum performance under hot or cold conditions. The major reasons are that dairy cattle are not usually fed for maximum growth rate or full genetic potential for milk production, and the management systems create either micro- or macroenvironments that affect maintenance needs of the animals. Dairy animals are generally kept: (1) on pasture with full exposure to the weather elements, (2) in drylot or pasture with access to tree shade or a constructed shelter free choice, or (3) confined within a barn or shelter with or without engineering inputs to control temperature. With few exceptions, dairy cattle will be subjected to all three systems during their life. Frequently they undergo exposure to two of the systems daily. Lack of environmental modifications to reduce the impact of the weather during either mid-summer or mid-winter may have both short -and long-range effects on energy needs for maintenance (R. E. McDowell, Cornell University, personal communication). For instance, maintenance needs on a daily basis may be 30 percent greater from about noon to 6 p.m. than for 2 to 10 a.m. Correspondingly, total daily requirements may be 30 percent or more greater for the periods July-August and. January-February than during other seasons. A lactation period frequently covers nearly the full range of the seasonal effects. The nutritive requirements are also confounded by stage of lactation effects on milk yield.

THERMAL ZONES FOR DAIRY CATTLE

Except for the neonatal calf, the estimated range of temperature for highest efficiency of energy utilization is about 13-18°C; however, significant changes in feed intake or in numerous physiological processes will not usually occur within the range of 5-25°C (McDowell, 1972). Above 25°C or below 5°C appetite will be influenced by the thermal environment (Figure 5). The degree of this effect depends upon numerous factors, e.g., type of feed, quantity of feed offered, level of atmospheric humidity, length of pelage, and for lactating cows the stage of lactation and daily milk yield. From 0 to 60 days of lactation, appetite and feed intake are more affected by the thermal environment than in later stages of lactation (McDowell *et al.*, 1976).

Little is known about the relationship of pelage to appetite or maintenance requirements in dairy cattle, but estimates indicate that growing longer hair during winter, shedding to short coat in summer, or even changing the position of the hairs from flat to erect can alter the rate of heat dissipation by a factor of three to five (McDowell, 1980). Wetting of the hair coat by snow or rain, wind speeds in excess of 6 km/h, relative humidity less than 30 or greater than 80 percent, or exposure to direct solar radiation in excess of 700 langley per day will also affect the rate of heat exchange and indirectly affect the critical temperatures.

Some researchers have estimated important differences among European dairy breeds in lower critical temperature, e.g., Johnson and Ragsdale (1959) and Ragsdale *et al.* (1950), but in most of the studies the interaction effects of body weight, level of milk yield, and other factors have confounded true estimates of breed effects. Since the thermoneutral zone is to a large extent controlled by the balance of heat production and rate of heat loss, numerous factors need consideration in ascertaining the best level of feeding for maximizing efficiency under various environmental situations.

FEED INTAKE AND ENERGY REQUIREMENTS DURING COLD STRESS

Calves

Calves usually attain a reasonably stable body temperature within a few hours after birth (Williams, 1967); hence, they rapidly develop a rather wide tolerance to temperature (Figure 2). Elevated humidity levels in closed housing for neonatal calves appear much more important than temperature to their well being. For example, Bates (1974) found lung damage in nearly all of 50 veal calves grown in individual metal stalls in a well insulated barn with temperature and humidity controls. Seldom are female dairy calves fed for maximizing growth rate. Young calves (0-30 days) are usually fed milk at the rate of 10 percent of body weight, and after a few days concentrates are offered free choice. It may be that additional milk feeding under cold conditions would stimulate gain, but this is expensive and increased risk of health disorders may arise (Hollon and Branton, 1970; McDowell and McDaniel, 1968).

The recommended practices for feeding calves are projected to double birth weight by 3 months of age. Delay of doubling birth weight until 6 months will not deter attainment of normal size later; but when birth weight is not increased 100 percent by 8 to 9 months, there will be permanent effects on both mature weight and skeletal size (McDowell, 1972). Calves that encounter a serious health problem, such as pneumonia, during the first 30 days of life are about three times more likely than normal calves to encounter a health problem later in life (Hollon and Branton, 1973; McDowell and McDaniel, 1968). It appears, therefore, that level of feeding and care to ensure thriftiness in female dairy calves is more important than maximizing rate of growth. When male calves of dairy breeds are fed to maximize growth rate, the guidelines on requirements for various environments described for beef cattle appear appropriate.

Heifers (6 Months to First Parturition)

The normal management system for development of dairy heifers is to have them attain 50 percent of their expected mature size by 15 to 17 months of age and to reach 75-80 percent of expected mature weight at the time of first parturition, around 24 to 28 months. Since birth weight is ordinarily about 8 percent of mature weight, a modest rate of gain, approximately 0.5 kg/day, is required to reach 80 percent of mature weight and about 95 percent of maturity in skeletal dimensions by 28 months (Matthews *et al.*, 1975). Level of feeding needs adjustment to ensure sufficient energy to maintain normal heat balance during the various seasons. The exception would be the last 3 months of pregnancy. Should this period coincide with mid-winter, it would be desirable to have about a 30 percent increase in energy intake to ensure a normal size fetus and some store of body fat (Williams, 1967).

Lactating Cows

The relative changes in maintenance requirements and dry matter intake for a 600-kg Holstein cow expected to produce 27 kg of milk with 3.7 percent fat content are shown in Figure 17 and tabulated in Table 21.

The solid portion of the dry matter intake (DM) in Figure 17 was derived from a study of approximately 85,000 data sets of average daily yields of milk for 10-day periods under field conditions over a 12-year period when lactating Holsteins consumed a diet of alfalfa hay, corn silage, and concentrates at a ratio of approximately 60 percent roughage and 40 percent concentrates (McDowell, personal communication). The temperature-feed intake classes from 10-40°C were at 3°C intervals with the class limits set at a lower limit of 6 h above the class mean and not more than 12 h exceeding the class mean. When the hours for the class mean of temperature exceeded 12 h, the day was shifted to a higher class. For the low-temperature classes (- 10 to 20°C), a similar procedure was used to classify the days with a lower limit of at least 6 h per 24 h below the class mean and not exceeding 12 h.

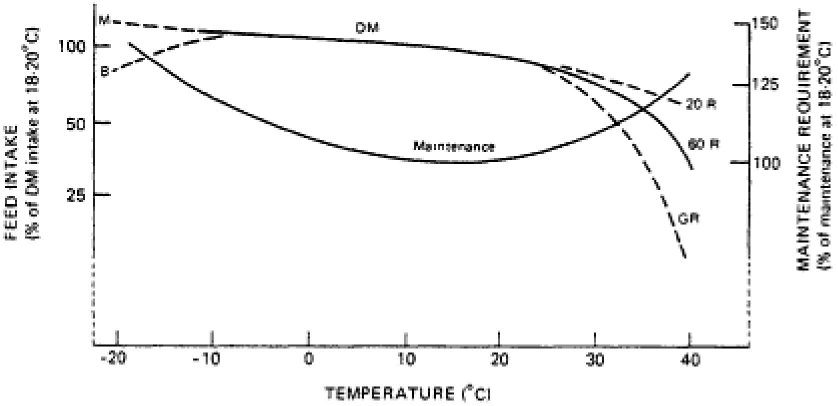

Figure 17
Estimated maintenance requirements for a 600-kg cow over a temperature range of - 15 to + 40°C; percentage changes intake of dry matter under low and high temperatures expressed as percentage of level at 18-20°C for cows consuming ration of 60 percent roughage and 40 percent concentrates (60 R); and percent decline from 20°C for cows on 20 percent roughage, 80 percent concentrates (20 R) or on grazing alone (GR); "M" depicts estimated need at - 15 to -20°C with "B" indicating most likely intake level due to changes in behavior to conserve body heat.

From - 10 to 25°C there was a gradual decline in feed intake (Figure 17). Intake decreased rapidly when the daytime temperatures were 6 h or more above 30°C per day (60 R, Figure 17). The declines in feed intake at the extreme high and low temperatures were attributed to changes in animal behavior, i.e., standing to shiver in cold and resting to minimize heat production under thermal stress. At the very low temperatures, frozen silage influenced intake. The dashed line (M, Figure 17) is the estimated intake of the 60:40 ration at -15 to -20°C, while "B" represents the more general pattern, i.e., a reduction in feed intake because of behavioral changes directed towards conservation of body heat and often less palatable feed.

Using 18-20°C as a base point of 100 percent, intake increased with decreasing temperature, reaching about 150 percent at -20°C. The estimated daily dry matter intake to maintain the 27-kg daily milk yield would increase from 18.2 kg to 21.3 kg (Table 21). But because of the need to maintain heat balance, behavior (limited movement and shivering), coupled with usually lowered palatability of such feeds as frozen silage at - 15 to - 20°C, the expected dry matter intake will increase to only 20.4 kg per day. With rising

TABLE 21 Relative Changes in Maintenance Requirements and Dry Matter for 600-kg Cows Producing 27-kg 3.7 Percent Fat Milk at Various Ambient Temperatures Along with Estimates of Actual Intakes of DM and Water

Requirement for 27-kg Production			Expected[c]		
Temperature (°C)[a]	Maintenance (% 18-20°C)	DM[b] (kg)	DM Intake (kg)	Milk (kg)	Water Intake (kg)
- 20	151	21.3	20.4	20	51
- 15	133	20.2	20.0	23	55
- 10	126	19.8	19.8	25	58
- 5	118	19.3	19.3	27	63
0	110	18.8	18.8	27	64
5	103	18.4	18.4	27	67
10	100	18.2	18.2	27	67
15	100	18.2	18.2	27	67
20	100	18.2	18.2	27	68
25[c]	104	18.4	17.7	25	74
30	111	18.9	16.9	23	79
35	120	19.4	16.7	18	120
40	132	20.2	10.2	12	106

[a] Values for 25°C and higher temperature are for days with at least 6 h exceeding the temperature class but not more than 12 h.

[b] Estimated requirements of DM intake for maintenance and 27-kg milk.

[c] Estimates of intakes of DM and water and milk yield on water-free choice and *ad libitum* feeding of ration of 60 percent hay and corn silage with 40 percent concentrates.

maintenance requirements 20.4 kg or less intake will leave less ME available for milk synthesis resulting in approximately 20 kg of milk at -20°C instead of 27 kg (Table 21). Limitations on estimated water intake may also contribute to the milk yield projected for -20°C.

From 10 to - 10°C, cows will eat more to make up for an increased rate in heat loss, thus consumption of the 60:40 ration will rise provided additional feed is offered (McDowell *et al.*, 1976). At - 10 to - 15°C or lower, poorer performance may be offset by increasing the proportion of concentrates in the ration or providing closed housing in order that the body heat from the cows will maintain the environmental temperature above - 10°C.

There are three options that may be utilized individually or in combination to reduce the environmental effects on ME intake: provide shelter or protection for the cattle to at least partially alleviate the stress of extreme temperatures; increase the proportion of concentrates in the diet, e.g., 20 percent roughage-80 percent concentrate; or use a combination of the two measures. Shifting of the concentrate ratio will enable cows to maintain ME intake nearer the level required to maintain 600-kg body weight and 27-kg milk yield per day over a wider temperature range than on diets higher in roughage content (Figure 17, 20 R).

FEED INTAKE AND ENERGY REQUIREMENTS DURING HEAT STRESS

Calves

There are no data available at this time for recommending changes in calf feeding under hot conditions. As already indicated, researchers and dairymen have been more concerned with economics of feeds and thriftiness than in rapid growth for female calves.

Heifers

Above latitude 38°N in the United States, the birth weight for Holstein females is in the range of 40-45 kg and they average 350 to 370 kg at 15-17 months (time of breeding), 450-500 kg at 24-26 months, and 600-640 kg at maturity (Matthews *et al.*, 1975). At latitudes of less than 34°N in the United States and in the Caribbean region, Holstein females weigh 6 to 10 percent less at birth (38-41 Kg) and average approximately 16 percent lower in weight at maturity (510-540 kg) than in the northern latitudes. These differences in weight occur even when the heifers are sired by the same bulls and quantity of feed is not limiting (Hollon and Branton, 1970; McDowell, 1972; Yazman *et al.*, 1981). In these warm climate areas, daily maximum temperature exceeds the upper critical temperature of 27°C during 6 to 12 months of the year. Exposure to heat stress will increase maintenance energy requirements for at least a portion of each day. Correspondingly, appetite is depressed, resulting in smaller fetuses and slower rate of growth after birth. As indicated previously, lower quality forages with reduced digestibility are no doubt an additional factor. It appears, therefore, that it could be prohibitively expensive to produce 600-kg or more Holsteins at maturity in warm climates. Seasonal changes in temperate areas will usually result in heifers calving from July to September being 3 to 4 percent lighter at time of parturition than paternal half-sibs calving in January and February. Further evaluations of seasonal effects on the nutritive requirements for heifers is desirable.

Lactating Cows

According to the values in Figure 17 and Table 21, maintenance requirements for a 600-kg Holstein will rise markedly when exposed for 6 h or more per day to temperatures above 30°C, a relative humidity of 70 percent or higher, and solar radiation exceeding 700 langleys per day. In order to maintain an output of 27 kg of milk per day, dry matter intake should increase from 18.2 to 20.2 kg when temperature rises above 35°C. However, heat stress will suppress appetite (Figure 5); hence, reduced rather than increased feed intake must be accepted. At 35°C, dry matter consumption will be about 16.7 kg per day (Table 21). With reduced intake and increased maintenance needs, milk yield will decline by 33 percent at 35°C and by over 50 percent at 40°C. Water intake will be high at 35°C but will show some decline for most cows at 40°C due to a much lower dry matter intake.

Increasing the proportion of concentrates in the ration will raise the upper critical temperature on intake (Figure 17), but in spite of type of feeding, intake will decline. Efficiency of utilization of the feed may also decline. As rate of feed intake declines because of heat stress, the rate of rumen motility declines, which slows rate of passage. The data in Table 22 illustrate the impact of time of exposure to temperatures above 27°C on gross efficiency (kg milk/Mcal NE) for Holsteins. Irrespective of stage of lactation, gross efficiency remained high with exposure to no more than 20 days of maximum temperature above 27°C. Up to 40 days exposure depressed efficiency significantly in the early and late stages of lactation. Cows exposed 40 to 87 days showed marked depression (-27 percent) in efficiency from the cows exposed 20 days or less.

The approximate range of correlations between climatic variables and daily milk yield under field conditions has been -0.35 to 0.30, with most from -0.1 to 0.2. The variance has ranged from 3 to 10 percent, depending on stage of lactation, e.g., 14 percent for cows 0-100 days in lactation, 8 percent 101-200 days, and 10 percent 201-300 days (McDowell, 1974).

TABLE 22 Gross Efficiency (kg milk/Mcal/NE) for Holsteins in First Lactation When Maximum Daily Temperature Did Not Exceed 27°C or Exceeded 27°C 21 to 40 or 40 to 87 Days per 100 Days of Lactation

	Number of Days, Maximum > 27°C		
Stage of Lactation (days)	0 to 20	21 to 40	40 to 87
0 to 100	0.85[a]	0.74[b]	0.62[c]
101 to 200	0.82	0.77	0.75
201 to 300	0.87	0.78	0.72

[a b c] Values in the same row with a common superscript are not significantly different, but do differ from those not having the same superscript ($P < 0.05$).
SOURCE: McDowell *et al.*, 1976.

Correlations between ME intake and weather conditions have been highest for conditions occurring on the same day or one day previous, whereas milk yield was most highly correlated with EAT the preceding 2-5 days. Several experiments (Guthrie *et al.*, 1968; Johnson *et al.*, 1962; Maust *et al.*, 1972; Razdan and Ray, 1968; Thomas and Razdan, 1973) showed that given the opportunity, cattle made a day-to-night shift in feeding during summer, e.g., 12.4 percent more DM consumed during the night while in winter cows ate 8.5 percent more DM during the day. In none of these experiments were there significant depressions in total daily DM intake or milk yield, even though daily maximum temperature exceeded 27°C.

On farms near San Juan, P.R., a warm, humid area, Holsteins offered feed at the rate of 2.5 multiples of maintenance in ME averaged 16 kg milk per day. For 16 h the temperature exceeded 27°C with a low of 25°C, which permitted little opportunity for the animals to cool off (Table 23). When near the same level of ME was offered, Holsteins in New Iberia, La., also warm and humid in July, milk yield was 17 kg; 26 kg at Phoenix, Ariz., (hot, dry); and 23 kg at Ithaca, N.Y. The average mean daily temperature was 28°C in San Juan, New Iberia, and Phoenix (Table 23), but hours above 27°C ranged from 13 to 16. Although the Phoenix area cows were exposed to the highest temperatures, the low humidity and rapid cooling of the environment after sunset permitted restoration of heat balance and higher feed intake. The New York cows were exposed to the fewest hours above 27°C, but feed intake was markedly affected by high humidity and poor acclimatization to the heat stress due to only short periods of high temperatures.

Environmental modifications, such as confined housing, can be utilized to modulate the nutritive requirements of lactating cows outside the TNZ. Confined housing has the advantage of reducing heat production resulting from walking to graze but there are limitations which must be kept in mind. For example, the humidity may rise above the critical level and foot problems from wet floors may offset the reduction in energy needs from walking and changing the thermal environment (McDowell, 1974).

TABLE 23 Average Hourly and Daily Temperature During the Month of July for Tropical (San Juan), Subtropical (New Iberia), Semiarid (Phoenix), and Temperate (Ithaca) Areas

Hour of Day	Sau Juan, Puerto Rico	New Iberia, Louisiana	Phoenix, Arizona	Ithaca, New York
00	26	24	22	20
01	26	24	21	19
02	26	23	21	19
03	26	23	20	18
04	26	22	20	18
05	25	22	19	17
06	25	22	22	17
07	26	23	25	18
08	27	26	28	19
09	28	27	29	20
10	29	28	30	22
11	29	29	32	25
12	29	31	33	27
13	30	32	35	30
14	30	32	36	32
15	30	32	38	31
16	29	32	37	30
17	29	32	36	29
18	28	31	35	28
19	28	30	33	26
20	27	28	30	24
21	27	27	28	23
22	27	26	26	22
23	27	25	23	21
Daily average	28	28	28	23

SUMMARY

The feasibility both from the standpoint of economics and biological efficiency for supplying additional feed for higher maintenance needs of calves and heifers of dairy breeds under hot or cold conditions is not clear at this time. It seems that except under extreme circumstances for calves or heifers in later stages of pregnancy, added feed is not practical as compensatory gains in other periods will occur. The lactating cow producing over 6,000 kg of milk per lactation becomes the real target for adjustments in feeding, but here again practical solutions have limitations. As long as the kilogram of milk per megacalories of estimated net energy consumed exceeds 0.8, the offering of more feed will usually pay. This means it is practical to increase feeding when environmental temperature is below 0°C but of questionable value during midsummer or in warm climate regions since the output of milk per megacalorie of energy may decline to 0.6 or less.

Environmental modifications to alleviate or reduce the stress of cold or hot conditions offer promise as an alternative to higher intakes of ME but caution must be exercised to ensure the interaction effects are not negative. An additional alternative to more feed or housing is to change the genotype of the animals. Heritability of feed efficiency appears greater than zero; estimates for dairy breeds range from 0.12 to 0.48, indicating genetic progress could be made in selection for increased gross feed efficiency (Freeman, 1975). Data for appropriate estimates on which to base selection are very costly to obtain. Milk yield and changes in body weight are joint responses to feed intake. These traits are correlated both phenotypically and genetically to feed efficiency (phenotypic correlation fat corrected milk (FCM) yield and FCM per megacalorie estimated net energy = 0.82), thus yield and efficiency are not individually controlled by independent sets of genes. Researchers have, therefore, given emphasis to selection for total milk yield as the most practical means of increasing gross efficiency. Use of breeds smaller than Holstein or crossbreds may give the appearance of improved efficiency under extreme thermal conditions; but when considered on the input—output ratio per unit of metabolic size, the validity of changing breeds to increase gross efficiency becomes less convincing. The general conclusion is that improved information is needed to provide more accurate guidelines on feeding dairy cattle in various environments, particularly under field situations.

Sheep

INTRODUCTION

Comparatively speaking, sheep are more tolerant of climatic extremes than other farm animals. For example, Alexander (1974) calculated from data of Bennett (1972) that adult sheep when dry, in a calm wind, and with 10 cm of fleece could withstand -120°C ambient temperature. However, calculated cold tolerance for freshly shorn adult sheep (7 mm of fleece) would be only -15°C, and, when wet and exposed to a 7 m/s wind, similar sheep could withstand only 13°C. For lambs, Alexander (1968) suggested that heat loss would exceed summit metabolism at 23°C when a small lamb with a short fleece was wet and exposed to a 5.5 m/s wind. For a large lamb in the same condition, metabolism would match heat loss at approximately 4°C. Obviously, survival during cold is highly variable, depending on both the animal's ability to increase heat production and aspects of the environment affecting effective ambient temperature (EAT).

Heat tolerance is even less defined than cold tolerance for sheep. Mount (1979) reports that sheep will survive acute periods of 40-60°C dry-bulb temperature, but successful growth and reproduction at that temperature has not been demonstrated and is unlikely. Since homeotherms must rely more on evaporative heat loss when exposed to effective ambient temperatures (EAT) in the hot zone, factors affecting rate of evaporation (wind and humidity) are of major importance in determining survival during heat.

THERMAL ZONES FOR SHEEP

The thermal zones for sheep depend largely on amount of external insulation provided by the fleece. As noted in Table 1, shorn growing lambs on a maintenance ration have a lower critical temperature (LCT) of about 25°C, but LCT is estimated as low as - 20°C in similar fleeced animals (Blaxter, 1967; Webster *et al*., 1969). Calculation of lower critical temperature indicates that increased intake and the concurrent increase in heat production reduces LCT as much as -20°C from *ad libitum* feeding to fasting. Clearly, LCT can be influenced by wetting of fleece because insulatory value is reduced by wetting (Bennett, 1972). Wind increases rate of heat loss (Joyce and Blaxter, 1964) and has an additive effect when sheep are wetted (Blaxter. *et al*., 1966). Since TNZ is, in fact, a descriptive term relating balance of heat production and loss, it is obvious that any factor affecting either of these two determinants will consequently alter TNZ and LCT.

ENVIRONMENTAL EFFECTS ON FEED ENERGY INTAKE

Many factors affect the amount of metabolizable energy (ME) available to the animal. These include digestibility of the foodstuff, amount of the foodstuff consumed, and/or the ability of the animal to acquire food. In general, factors influencing amount of metabolizable energy available for consequent use may be considered as feed intake.

Exposure to heat reduces voluntary intake in sheep as it does in other species (see page 31). Bhattacharya and Hussain (1974) reported that high ambient temperatures coupled with high humidity during the day, reaching a maximum of 32°C and 98 percent, respectively, reduced *ad libitum* intake in sheep, with depression most severe when the diets contained high levels of roughage. However, a later report from the same laboratory (Bhattacharya and Uwayjan, 1975) showed conflicting results when temperature was coupled with low humidity. The diversity of those findings supports the need to discuss results in terms of EAT rather than separating the effects of temperature and humidity during heat stress.

In general, voluntary intake increases during cold compared to TNZ. Webster *et al*. (1969) reported increased food intake of sheep housed indoors as still air temperature fell. Soderquist and Knox (1967) reported higher dry matter intake at 0°C compared to 23°C in growing lambs. Ames and Brink (1977) reported increased dry matter consumption in lambs, whose critical temperature was 13°C, to be statistically higher at 10, 5, and 0°C, but no further increase was noted at -5°C. Those data clearly show that voluntary intake is increased above thermoneutral values during mild cold, but that a limit in voluntary intake was reached before animals were severely cold stressed.

For shorn lambs whose lower critical temperature was 13°C, Brink (1975) related dry matter consumption over a wide range of ambient temperatures (- 5 to 35°C) and found the following linear relationship:

$$DMI = 111.3 - 0.52\,T,$$

where
DMI = daily intake (g/$W^{0\ 75}$),
T = temperature (°C).

The impact of fluctuating temperatures and the validity of mean daily temperature when the standard deviation of daily temperature is high has been recently studied by Giacomini (1979) where lambs exposed to a constant thermoneutral temperature (15°C) were compared with lambs in fluctuating environments with a mean temperature of 15°C. When fluctuations were from 10 to 20°C, 5 to 25°C, or 0 to 30°C, feed intake was not different from constant 15°C temperature. Certainly the area of fluctuating temperature deserves more study. This is particularly important in the design of confinement systems where constant temperatures may result in patterns of feed intake different from those established during fluctuating temperatures.

Assuming some nutrient (e.g., vitamin and mineral) requirements are constant over wide ranges in temperature raises a concern that difference in intake can have a major effect on vitamin and mineral intake. When these nutrients represent a constant percentage of the diet, it is obvious that reduced intake may lead to deficiency. Care must be taken (and adjustments made when necessary) to meet the animal's requirement when intake varies. The same consideration must be made for various nonnutrient additives (antibiotic premixes, growth promotants, etc.) when they are to be ingested at a constant rate daily. Obviously, diet adjustment for components that are not affected by the thermal environment should be altered in proportion to changes in rate of feed consumption. For this reason it is important that accurate estimates of voluntary intake during thermal stress be established.

NUTRIENT DIGESTIBILITY

Many authors have reported a positive relationship between ambient temperature and nutrient digestibility for ruminants (see Table 2). A general discussion is found on page 31.

Although information relating diet digestibility to heat stress is not in total agreement, most data tend to support the hypothesis that digestibility is increased during heat stress. Some believe this results from decreased voluntary intake rather than from a direct effect of increased EAT. Ames and Brink

(1977) used shorn lambs fed in controlled environmental chambers to determine the effect of ambient temperature on the digestibility of diet components. This study showed increased digestibility of dry matter, crude protein, and nitrogen-free extract as temperature rose from 15°C to 35°C (LCT was 13°C). Crude fiber digestibility increased when temperature rose from 15 to 30°C, but was not increased at 35°C. No difference was found in ether extract digestibility during heat stress. Bhattacharya and Hussain (1974) reported that during heat stress sheep diets had lower digestibilities except for crude fiber and nitrogen-free extract. They found that higher roughage (75 percent) diets were most affected. Perhaps variations in findings relating heat stress to diet digestibility are altered by roughage to concentrate ratio. Obviously, more knowledge is needed for different rations.

Several authors (Blaxter and Wainman, 1961; Christopherson, 1976; Kennedy and Milligan, 1978; Young and Christopherson, 1974) indicate lowered dry matter digestibility during cold. Examples of depressed digestibility during cold are shown in Table 2. Consequently, when increased intake during cold is considered in combination with decreased digestibility, the advantages of the former would be partially offset by the latter. For example, increased consumption per unit of metabolic size from 10 to 0°C is 5.3 percent, but with decreased digestibility the net increase in digestible energy was only 2.7 percent. Christopherson (1976), who conducted extensive studies of digestibility during prolonged cold with both sheep and cattle, also found a temperature effect independent of level of intake. He reported that dry matter digestibility had a 0.31, 0.21, and 0.08 percent decline per °C cold stress for sheep, calves, and steers, respectively. Kennedy and Milligan (1978) suggest that cold effect on digestibility is greater with higher levels of food intake.

ENERGY REQUIREMENT DURING COLD STRESS

When exposed to effective ambient temperatures (EAT) below the cool zone, energy expenditure must compensate for increased energy loss. Increased heat production during cold stress has been measured by several authors (Alexander, 1962; Bennett, 1972; Blaxter *et al.*, 1966; Graham *et al.*, 1959). Wind (Joyce and Blaxter, 1964), rain (Panaretto *et al.*, 1968), and wind and rain combinations (Blaxter *et al.*, 1966) have been shown to increase further the rate of heat loss of sheep exposed to cold. These findings suggest an apparent reduction in external insulation and result in increased rate of sensible heat loss when measured at a given thermal gradient. Use of effective ambient temperature measures such as wind-chill temperature (Ames and Insley, 1975) and insulatory value of the wetted fleece should provide similar estimates of heat loss.

When sheep are exposed to temperatures below the LCT, there are two factors that determine rate of heat loss: (1) thermal gradient between core temperature and ambient temperature, and (2) amount of insulation provided by tissue, fleece, and air. These factors can be used to estimate rate of heat loss, and therefore maintenance energy requirement for animals exposed to cold, by the following equation:

$$ME_m = aW^{0.75} + b\frac{\Delta T}{I},$$

where

ME_m = metabolizable energy for maintenance corrected for effective temperature (kcal ME/day),

T = magnitude of cold (°C), i.e., difference between animal's lower critical temperatures and effective temperature,

I = total insulation (°C/kcal/m^2/day),

a = coefficient of maintenance requirement for animal in zone of thermoneutrality (kcal ME/day),

b = surface area of animal (m^2).

NOTE: Coefficient a is 127.8 kcal ME/day for sheep.

Table 24 shows the percentage increase in maintenance energy requirements at seven levels of insulation for five different weights. The system to estimate the listed values does have shortcomings and cannot be calculated without some error. First, the insulative value of the animal is not uniform over its entire surface. Indeed, small errors in estimating insulative value will lead to relatively large differences in energy required during cold. For example, Blaxter *et al*. (1959) reported conductive value of fleece (in similar sheep) ranges from 122 to 149 kcal/m^2/24 h/°C/cm. That variation would result in a 111 percent error for a 50 kg lamb with 0.04°C/kcal/m^2/day total insulation when estimating additional heat loss during cold. Second, the animal's ability to shunt blood to and from specific areas of the body reduces the accuracy of the estimates of insulation. Third, calculations assume that the animal is a sphere with no facing surfaces.

When the system presented in Table 24 is compared to observed increases in heat production for rather well defined sheep, the utility of the system can be assessed (Table 25). Variations of up to 19.7 percent are noted; however, in each case insulative value was estimated, and increased metabolic heat production during cold exposure was measured for a relatively short period. While more work is obviously needed to improve estimates of insulation, in a general sense these data support increasing energy requirements of sheep based on estimated insulation and body weight.

TABLE 24 Percent Increase in Maintenance Energy Cost per Degree Centigrade Below Lower Critical Temperature

Insulation (°C/kcal/m^2/day)[a]	Sheep Weight (kg)				
	40	50	60	70	80
0.01	5.8	5.4	5.2	4.7	4.6
0.02	2.9	2.7	2.6	2.4	2.3
0.03	1.9	1.8	1.7	1.6	1.5
0.04	1.4	1.3	1.3	1.2	1.2
0.05	1.2	1.1	1.0	0.9	0.9
0.06	1.0	0.9	0.8	0.8	0.7
0.07	0.8	0.7	0.7	0.7	0.6

[a] Wool provides about 0.007°C/kcal/m^2/day per cm depth (Blaxter *et al.*, 1959).

The options for increasing energy intake for animals fed *ad libitum* are more limiting than for those where adjustment can be accomplished by simply providing more feed. In this situation increasing caloric density by addition of fat or increasing relative amounts of feedstuffs with higher caloric densities (i.e., replacing roughages with concentrates) are possibilities. The former approach, however, is contrary to the notion of increasing heat increment during cold since fat is lower in heat increment compared with most feedstuffs. However, its high caloric density may still be used advantageously. The value of heat increment during cold has been mentioned previously, and, while this may prove valuable, it should be understood that heat increment for each unit of weight of roughages and concentrates is similar. However, heat increment is a higher percentage of digestible energy for roughages as compared with concentrates, so that calories supplied by the heat increment of a roughage may be less expensive than those from a con

TABLE 25 Comparison of Measured and Estimated Heat Loss (kcal/m2/ day/°C) During Cold

Measured	Estimated	Difference (%)	Data Source[a]
115	96	+ 11.9	Graham *et al.*, 1959
77	96	- 19.7	Webster *et al.*, 1969
84.2	75	+ 11.2	Webster and Blaxter, 1966

[a] Description of sheep used in these studies were used to obtain estimated values from Table 24.

centrate source. Consequently, from an economic standpoint energy costs may be reduced during cold by increasing roughages at the expense of concentrates. Moose *et al*. (1969) reported that feeds with high heat increments fed during cold have a sparing effect on net energy for production, thus allowing their use for gain. Brokken (1971) developed a model using the data of Lofgreen and Garrett (1968) to blend rations to improve performance during cold stress. This model is based on maximum use of heat increment and concludes that economic advantages do exist for altering rations during cold. The magnitude of this advantage is dependent upon relative ingredient prices, magnitude of cold, and the effect of cold on intake.

ENERGY REQUIREMENT DURING HEAT STRESS

Expected increases in heat production during heat exposure of sheep have been reported, but little quantification of increased energy needs is available. During heat exposure, energy requirement increases because of energy expended during panting (Kibler, 1957), sweat gland activity (Macfarlane, 1964), and the calorigenic effect of hormones (Whittow and Findlay, 1968). An additional factor when core temperature rises is the Q_{10} effect (Schmidt-Nielsen *et al*., 1967). Whittow and Findlay (1968) calculated that the effect of increased rectal temperature accounted for as much as 62 percent of increased O_2 consumption in cattle, and Ames *et al*. (1971) measured a 41 percent increase in O_2 consumption of sheep assuming $Q_{10} = 2.0$. It is apparent that increases during heat are nonlinear (Graham *et al*., 1959) as opposed to linear increases during cold. Nonlinearity is to be expected because of the decreased efficiency of evaporative mechanisms and increased Q_{10} effect as heat stress becomes more severe (Ames *et al*., 1971). More precise estimates of increased energy requirement during heat are further confounded by depressed appetite.

The adjustment of diets during heat stress can be a practical approach toward minimizing the effect of heat even though increased maintenance requirement during heat is difficult to estimate accurately. McDowell (1972) and Brink and Ames (1978a) have reported nonlinear increases in maintenance energy during heat when maintenance is calculated as the difference between intake and gain.

Lofgreen (1974) confirmed the validity of formulating diets for relief of heat stress. His adjustment involved lowering heat increment of the diets while keeping net energy constant. These adjustments were accomplished by reducing the roughage content of the diets, adding dried beet pulp, and increasing fat content. Moose *et al*. (1969) found that low-concentrate diets (35 percent) had lowered heat increment than higher-concentrate diets (70 percent) when fed to lambs and reported that at temperatures above 25°C high heat increment can seriously impair the efficiency of diets containing higher percentages of roughage. Rea and Ross (1961), in a growing trial with lambs, concluded that lambs gain more rapidly in warm temperatures when given diets of 60 percent concentrate as compared to 40 percent concentrate.

THERMAL EFFECTS ON PROTEIN REQUIREMENT OF SHEEP

Protein requirement includes both that necessary to maintain nitrogen equilibrium (maintenance protein) and that needed for productive function. Ideally, dietary protein exceeding that needed for maintenance is used only for production (growth, wool, or milk); however, growth and other productive functions may be limited by available energy because of increased energy for maintenance during thermal stress. When energy is limiting, protein may then be catabolized and serve as an energy source (Crampton and Harris, 1969).

Because of the relationship between energy and protein requirement, the direct effect of climate on energy requirement has a subsequent effect on protein required for growth or production. Data suggest no effect of thermal environment on protein required to maintain nitrogen equilibrium (Brink and Ames, 1978b). The frequently used protein-to-energy ratio for formulation of animal diets is not appropriate for describing diets during thermal stress when maintenance energy requirement and intake vary unless only protein and calorie values surplus to maintenance are used to calculate a ratio. Instead, when formulating diets with respect to the thermal environment, both energy and protein should be included to meet requirements for each nutrient separately, and the protein-to-energy ratio of the diet should be ignored.

When energy requirement for maintenance increases (i.e., cold stress). less energy is available for production, and consequently the protein-to-calorie ratio above maintenance levels increases. Ames and Brink (1977) have reported reduced protein efficiency. ratio of lambs-during both cold and heat compared to TNZ. Ames *et al.* (1980) have suggested a system for adjusting protein above maintenance to match expected growth rate of lambs exposed to thermal stress. When protein is adjusted, growth rate during thermal stress is not altered, but protein efficiency ratio is improved. When protein is a more expensive nutrient than energy, cost of gain is decreased. Table 26 indicates protein adjustments for a 27-kg lamb receiving a diet that is expected to result in 272-g ADG.

ENVIRONMENTAL EFFECTS ON LAMB PERFORMANCE

Exposure of sheep to thermal stress affects voluntary food intake and maintenance requirement as discussed previously. Obviously, average daily gain and feed required per unit of gain are also affected by thermal stress. Few studies have reported the effect of temperature on performance of growing lambs, but Ames and Brink (1977) conducted growth and efficiency studies for shorn lambs exposed to a wide range (- 5 to 35°C) of ambient temperatures. These lambs received a 50 percent concentrate (grain sorghum), 50 percent roughage (alfalfa) diet. Table 27 relates temperature with ADG and feed efficiency.

TABLE 26 Protein Adjustment for Growing Lambs

Deviation from Critical Temperature	Expected ADG (g)[a]	Maintenance Protein (g)[b]	Protein for Growth (g)	CP in Ration (%)[c]
20	54	33.2	17.0	2.4
15	132	33.2	41.0	5.8
10	195	33.2	60.8	8.6
5	236	33.2	73.6	10.4
Critical temperature	272	33.2	84.9	12.0
- 5	222	33.2	69.3	9.8
- 10	181	33.2	56.6	8.0
- 15	136	33.2	42.5	6.0
- 20	95	33.2	29.7	4.2

[a] Ames *et al*., 1975.

[b] Preston, 1966.

[c] Constant intake.

Daily gain for lambs receiving a grain sorghum (50 percent), alfalfa (50 percent) ration can be predicted for the range of temperatures above by the equation:

$$ADG(\text{g}) = 129.94 + 9.27\,T - 0.35\,T^2,$$

where

T = temperature in °C.

This equation suggests 13°C as the temperature for maximum ADG of shorn lambs. For lambs with fleece, temperature for maximum growth and efficiency would be lowered.

MISCELLANEOUS ENVIRONMENTAL FACTORS AFFECTING NUTRITION OF SHEEP

Knowltoh *et al*. (1969) studied effects of high carbon dioxide levels on nutrition of sheep. They reported reduced feed intake when exposed to 4 percent

CO_2, but intake was inversely related to CO_2 concentration at exposure levels of 8, 12, 16, and 18 percent. Nutrient digestibility was not influenced by CO_2 levels up to 16 percent, but variable decreases were measured at 16 and 18 percent CO_2.

TABLE 27 ADG and Feed Efficiency of Lambs Grown at Different Ambient Temperatures and Fed Ad Libitum

Temperature (°C)	ADG (g)	Feed Efficiency (gain/feed)
- 5	73	0.04
0	130	0.08
5	170	0.11
10	192	0.15
15	197	0.14
20	184	0.13
30	107	0.08
35	41	0.04

SOURCE: Ames and Brink, 1977.

Blaxter (1978) studied the effect of simulated altitude on sheep and found no difference in heat production or heat increment values when oxygen concentration in air was 150 ml/liter compared to 200 ml/liter.

Confinement rearing of sheep has been estimated to reduce energy requirements by 30 percent (Parker, 1976). Direct measurement of heat production in commercial confinement management systems has not been done, but Young and Corbett (1972) reported that maintenance requirements were generally 60-70 percent greater for grazing sheep compared to housed animals. The need for a more precise estimate of effect of confinement on energy required for maintenance is needed.

Harbers *et al*. (1975) reported that sheep acclimate to sound of 100 dB or less; however, intermittent noise was shown to increase nutrient digestibility during short-term exposure.

Allden (1968) reported that feed consumption and utilization for weight gain were not affected in the long term by prolonged periods of undernutrition. They reported that lambs subjected to restricted feed levels during the first 6 months of life failed to fully recover (in terms of weight) compared with lambs receiving adequate nutrition. However, when unlimited feed was available, when lambs were 6-12 months old, they completely recovered earlier weight loss. Graham and Searle (1975) held 4-month-old wethers at 20 kg live weight for 4 or 6 months then fed *ad libitum* to recover weight for age. They reported increased voluntary food intake during rehabilitation compared to controls. While heat production per unit metabolic size fell during weight stasis, it rose in the first month of recovery but remained less than controls. Gross efficiency was higher during the first week of recovery then returned to control values. Except for acute changes in intake and consequent efficiency during the first week of recovery following undernutrition, there appear to be no long-lasting nutritional differences in sheep receiving restricted levels of nutrition.

SUMMARY

Sheep are probably most tolerant of environmental extremes compared with swine, cattle, and poultry. They are unique because of the potentially large insulatory value of the fleece. Responses of sheep to thermal stress in terms of intake, maintenance energy requirement, and rate of performance are typical. Nutrient adjustments for changes in voluntary intake, energy adjustments for cold stress, and protein adjustments for differences in thermally induced changes in rate of growth are presented but are based on limited research data. More basic information is needed to accurately predict the impact of environment on nutrient requirements of sheep.

Swine

INTRODUCTION

Stresses from the thermal environment influence productivity of swine by altering their heat exchange with the environment, feed intake rate, average daily gain, and dietary protein-concentration requirement, among other things. Effects on dietary requirements for other nutrients are less important. Cold stress and heat stress will be considered separately.

LOWER CRITICAL TEMPERATURE

In thermoneutral conditions, heat-production rate depends mostly on feed intake and metabolic body size. Physical activity is a lesser factor. By definition, within the thermoneutral zone, ambient temperature does not affect heat-production rate (Blaxter, 1977). By expressing lower critical temperature (LCT) in terms of effective ambient temperature (EAT), effects of various combinations of thermal-environmental factors on the pig can be evaluated and compared.

Holmes and Close (1977) summarized data from several sources regarding swine energetics. They concluded that thermoneutral heat-production rate of pigs weighing 20 to 180 kg can be predicted as:

$$HE = 64.5 + 0.32\,ME$$

where
HE = heat production (kcal/$W^{0\ 75}$/day),
ME = metabolizable energy intake (kcal/$W^{0\ 75}$/day).

When conditions change the animal's maintenance requirement, the factor 64.5 in this formula may have to be changed.

Maintenance energy requirement (HE) is defined as the metabolizable energy needed for the animal to maintain a constant body-energy content. At thermoneutrality, the maintenance-fed animals' heat-production rate is equal to ME intake, so the latter may be calculated using the above formula by substituting it for both heat production and rate of ME intake. Thus,

$$ME_m = 64.5 + 0.32\ ME_m = 95 \text{ kcal}/W^{0.75}\text{/day}$$

where
ME_m = maintenance metabolizable energy (kcal/$W^{0\ 75}$/day).

Recent reviews by Van Es (1972) and Close *et al.* (1973) show that a more accurate estimate for growing-finishing hogs, based on the average of various data, is about 100 kcal/$W^{0\ 75}$/day.

Values for the lower critical temperature when pigs are at maintenance level of intake are given in Table 28. Pigs in groups huddle in the cold, so their heat-loss rate is less (and their LCT lower) than that of those held singly. If specific alterations in animal activity or productivity raise or lower metabolizable energy intake at maintenance, the lower critical temperature will

TABLE 28 Lower Critical Temperatures (LCT) in Pigs of Different Body Weights Fed at Maintenance (100 kcal/W0 75/day), 2 Times Maintenance, and 3 Times Maintenance

			Lower Critical Temperature (°C)		
			Feeding Level		
Kind of Animal		Weight (kg)	1 × Maintenance	2 × Maintenance	3 × Maintenance
Baby pig	(single)	2	31	29	29
	(group)	2	27	24	24
Growing pig	(single)	20	26	21	17
	(group)	20	24	19	15
Finishing pig	(single)	60	24	20	16
	(group)	60	23	18	13
Finishing pig	(single)	100	23	19	14
	(group)	100	22	17	12
Sow	(thin)	140	25	20	14
	(fat)	140	23	18	12

SOURCE: Holmes and Close, 1977.

change accordingly. Moreover, it should be observed that these estimates are derived from relatively short-term exposures to cool temperatures (up to 3 weeks at an EAT of 5 to 10°C below LCT). Long-term exposure to much colder conditions may engender further acclimation and result in a much lower value (Irving, 1964).

A pig normally consumes feed at a rate 2 to 4 times the maintenance level. As a consequence, its heat-production rate is higher and its LCT is lower than at maintenance intake. The lower critical temperature of pigs in groups fed at 2 or 3 times maintenance is also given in Table 28. According to these values, for each extra 100 kcal ME consumed per kg$^{0\ 75}$ per day, LCT falls by 1 or 2°C in sows.

Lower critical temperature (Table 28) can be assumed to be the lowest effective ambient temperature for optimal management of pigs at the feed intake rate specified. This can be estimated for *ad libitum*-fed animals only if their actual feed intake rate is known. Assuming the feed contains 2.8 kcal ME/g, feed intake rate for which the LCT estimates in Table 28 are valid are given in Table 29.

According to NRC requirements, a pig fed *ad libitum* in thermoneutral surroundings will have an average feed-intake rate of 2.8 kg per day over the weight range 20 to 100 kg. Lighter pigs, of course, eat less; heavier ones more. For example, those weighing 20 to 35 kg will eat about 1.7 kg of feed per day, which is about 3.2 times maintenance, according to NRC standards. In the weight range 60 to 100 kg, feed-intake rate is about 3.5 kg daily, or 3.7 times maintenance. The LCT of *ad libitum*-fed pigs is thus 1 to 4°C, still lower than that of pigs with a feed-intake rate 3 times maintenance (Table 28), provided they eat the amount of feed predicted by NRC.

For the average lower critical temperature of pigs in a group on a well-insulated floor, one can expect 13 to 14°C in the growing period and 10 to

TABLE 29 Amounts of Feed (g/day) Given Pigs of Various Weights at 1 to 3 Times Maintenance (Assuming Feed Contains 2.87 kcal ME/g)

Weight (kg)	Metabolic Weight (kg$^{0\ 75}$)	1 × Maintenance	2 × Maintenance	3 × Maintenance
20	9.46	330	660	989
40	15.91	554	1,109	1,663
60	21.56	751	1,502	2,254
80	26.75	932	1,864	2,796
100	31.62	1.102	2,703	3,305
140 (sow)	40.70	1,418	2,836	4,254

11°C during finishing. If the pigs are kept on a slotted floor, 3 or 4°C must be added to the LCT to account for the extra heat-loss rate to the floor (Mount, 1975; Verstegen and van der Hel, 1974). A wet floor increases LCT even further. In Table 30 a survey of the effects of some environmental factors on LCT, derived mainly from Mount (1975), is given.

It may be assumed that the lower critical temperature of *ad libitum* -fed pigs on a partly wet, slotted floor will be about 18 to 19°C during the growing phase and 14 to 15°C for finishing hogs. Thus, 18°C will be used as the reference point for effects of cold stress on *ad libitum*-fed growing pigs and 14° C on *ad libitum*-fed finishing hogs.

Yet another factor is that individual pigs eat different amounts of feed, and those with a relatively low feed-intake rate have higher LCT and therefore are especially vulnerable to cold stress. Also, since many studies are carried out

TABLE 30 Changes in Lower Critical Temperature (LCT) in Pigs at Various Housing, Management, and Climatic Conditions

Condition	Specification	Weight (kg)	Change in LCT (°C)	Reference
Air speed (km/h)				
2.4	individual pigs	—	+ 4	Mount, 1975
1.8	individual pigs	—	+ 7	Mount, 1975
5.5	individual pigs	—	+ 10	Mount, 1975
1.6	group of nine	40	+ 1.5	Verstegen and van der Hel, 1976
Floor				
Concrete vs. straw	at 10°C	piglet	+8	Stephens, 1971
Concrete vs. straw	at 30°C	piglet	+2	Stephens, 1971
Straw	group of nine	35	-4	Mount, 1975
Concrete slats	group of nine	35	+5	Mount, 1975>
Wet surface	group of nine	35	+5 - + 10	Mount, 1975
Draft				
Draft	insulation	—	+6	Mount, 1975
Draft	uninsulated (winter)	—	+8	Mount, 1975
No draft	uninsulated (winter)		+2	Mount, 1975
No draft	uninsulated with straw	—	-4	Mount, 1975
Radiant temperature				
+ 1°C	individual	piglet	- 1	Mount, 1964
Reflective wall and ceiling	group	11	- 2	Holmes and McLean, 1977

with relatively fat hogs, meat-type pigs are more sensitive to cold stress (Comberg *et al.*, 1967).

Further, vapor pressure is a consideration. Significant effects of high humidity on pig performance at low environmental temperatures are not expected. However, some negative effects can nonetheless occur. High vapor pressure reduces the evaporation of water, so floor and walls tend to be wetter. This may influence the pigs' heat balance, because their body surfaces may be wetter, and it may indirectly reduce performance because it favors survival of pathogenic microbes in the environment.

COLD STRESS

The cold-stressed pig's extra thermoregulatory heat-production rate is based on data in Table 28 and the formula given on page 96. From measurements of heat-production rate in both cold and thermoneutral conditions, Holmes and Close (1977) calculated the extra feed needed to compensate for the increased rate of heat loss. They made separate calculations based on measurements near the lower critical temperature, as well as at 10°C of coldness. (Coldness is a term used to describe the magnitude of difference between lower critical temperature and existing thermal conditions.) The latter condition—an EAT only a few degrees above the freezing point—is often encountered in practice. These data can be used to calculate the extra feed required to compensate for the heat needed to keep the body warm.

In Table 31 estimates are given of this extra heat to keep the body warm and the extra feed requirement. There is a difference in the additional feed needed per °C of coldness between grouped pigs and those kept singly. Those in groups can huddle, thereby reducing body-surface exposure and

TABLE 31 Extra Heat Required per °C Coldness and Feed Equivalent Required to Compensate (Assuming Feed Contains 2.9 kcal ME/g)

Kind of Animal	Weight (kg)	Extra Heat (kcal/°C/day)	Feed Equivalent (g/°C/day)
Baby pig	2	11	4
Individual	20	39	14
Group	20	38	13
Individual	100	103	36
Group	100	100	35
Sow: thin	140	170	59
Sow: fat	140	98	34

SOURCE: Holmes and Close, 1977.

heat loss to the cold environment. One can conclude that a pig weighing 20 kg should consume additional feed at the rate of 13 g/day/°C of coldness, and for pigs weighing 100 kg up to 35 g/day/°C. In Table 32 are given some examples of the extra feed requirement. Of course, compensation for coldness by extra feed intake as outlined results. in an average daily gain comparable to that at thermoneutrality only if body composition is not influenced by environmental conditions.

Extra feed intake is required during cold to compensate for reduced gain in restricted-fed pigs. For example, if ME intake remains the same, body energy gain is reduced at environmental temperatures below the lower critical temperature due to extra heat to keep the body warm. However, daily gain—even with extra feed-intake rate—still may not be the same in the cold as at thermoneutrality.

Fat, protein, water, and ash gains, which together comprise body weight gains, may be reduced in several ways. Fat gain will be more reduced in the cold than protein gain, because fat is used primarily' as fuel (Masoro, 1966). In growing pigs, the same has been found by Hacker *et al.* (1973), Verstegen *et al.* (1973), and Brown *et al.* (1976). Close and Mount (1976) showed that reduction in protein gain in the cold depended on feeding level. Sorensen's data (1962), on the other hand, suggest that protein gain was reduced more than fat gain in severe cold (below 8°C). Also, the proteingain/water-gain ratio is increased in young pigs in the cold (Brown *et al.*, 1976). Consequently, body weight gain may be less than expected from protein- and fat-deposition measurements alone (Verstegen *et al.*, 1973).

From results of a number of growth trials in various environmental conditions, calculations show average daily gain is reduced from 13 to 19 g/°C of coldness over the entire growing-finishing period (Fuller and Boyne, 1971). From review of many trials, Verstegen *et al.* (1978) concluded that average daily gain is depressed by 15 g/°C of coldness when feed-intake rate remains constant. When the feed requirement needed to compensate for this reduction in gain was calculated from results of growth trials, values of 30 to 45 g/°C

TABLE 32 Estimates of Extra Feed Required at Various Temperatures (g/day)

	Effective Ambient Temperature (EAT)		
	15°C	10°C	°5C
Animals of 20 kg (LCT = 18°C)	39	104	169
Animals of 100 kg (LCT = 14°C)	0	144	334

of coldness per day were obtained (Verstegen *et al.*, 1977, 1978). There was, however, much variation in this extra feed requirement across experiments; these values are averages from numerous investigations.

For *ad libitum*-fed pigs, additional feed must be consumed during cold to maintain daily gain. There is, however, less information on voluntary feed-intake rate in pigs under standardized environmental conditions than on heat-production rate. In some experiments, cold-stressed pigs ate so much additional feed that daily gain was actually higher than at thermoneutrality. Sugahara *et al.* (1970) found this with pigs weighing 6 to 35 kg. Holme and Coey (1967) noted the same thing in heavier pigs. Seymour *et al.* (1964), who studied protein-concentration/environmental-temperature interaction, noticed that pigs had, if any, only a slight reduction in gain, but increased feed intake at environmental temperature below 16.5°C.

Ultimately, there are three possibilities in regard to feed intake and gain in *ad libitum*-fed pigs in the cold. Each is supported to some extent by reports in the literature. These are:

1. A small change, if any, in gain, but an increase in feed intake. Seymour *et al.* (1964) found an increase in daily feed intake amounting to 11 to 16 g/°C of coldness between 16 and 2.5°C (three pigs in a group). Mangold *et al.* (1967) calculated from three winter trials that extra feed requirement per °C of coldness below 15.5°C increased with body weight (Table 33), but they worked with fluctuating temperature. Jensen *et al.* (1969) reported similar findings with pigs in groups of 7 to 12.
2. A reduced gain accompanied by no change or an increased feed intake. In trials of 1 week's duration, Heitman and Hughes (1949) found an increased feed intake in the cold. In weight ranges of 32 to 65 kg and 75 to 100 kg, they observed increased daily feed intake of about 53 and 41 g/°C of coldness, respectively, when environmental temperature fell from 15.5 to 4.5°C. However, despite the higher rate of feed intake, there remained a reduction in daily gain of about 12 and 54 g/°C of coldness per day, respectively.

From a review of the literature, Verstegen *et al.* (1978) calculated a reduction in daily gain of 8.1 g/°C of coldness below 15°C, with an increase in daily feed intake of 19.5 g/°C. Corrected toward a daily gain comparable to that at thermoneutrality (assuming a gain/feed ratio of 0.31), this would require approximately 19.5 + (8.1/0.31), or 46 g/°C per day.

Mangold *et al.* (1967) found only a small change, if any, in feed intake in pigs weighing about 65 kg over the environmental-temperature range, 9 to 15.5° C. They noticed a decrease in daily gain of 13 g/°C of coldness. In an earlier report, Hazen and Mangold (1960) also used this approach to deter mine that during cold pigs are able to increase feed intake so that body weight gain remains the same as at thermoneutrality.

TABLE 33 Extra Feed Intake and Reduction in Gain per ° Temperature Change in the Cold

Temperature Range (°C)	Weight (kg)	Increase in Intake (g/°C)		Reference
Constant gain, but increase in feeding level				
15.5-2.5	7-92	11-16		Seymour *et al.*, 1964
15.5-6.5	13.6	4		Mangold *et al.*, 1967
15.5-5.5	34	20		Mangold *et al.*, 1967
15.5-5.5	65	37		Mangold *et al.*, 1967
16—1	50-86	33		Jensen *et al.*, 1969
22—10	14-48	14		Jensen *et al.*, 1969
Constant feed intake, but decrease in body weight gain				
Temperature Range (°C)	Weight (kg)	Decrease in gain (g/°)		
15.5-9.0	65	13		Marigold *et al.*, 1967
15.5-5.5	22-92	9-11		Hazen and Mangold, 1960
13.0-5.0	22-90	17.8		Fuller and Boyne, 1971
Changes in both intake and gain (g/°C)				
Temperature Range (°C)	Weight (kg)	Decrease in gain (g)	Increase in intake (g)	
15.0-5.0	20-110	8.1	19.1	Verstegen *et al.*, 1978
15.5-4.5	32-64	12	53	Heitman and Hughes, 1949
15.5-4.5	75-95	54	41	Heitman and Hughes, 1949

Another factor that affects estimates of extra feed required by cold exposure is a small, but consistent, reduction of dietary-energy digestibility in cold-stressed animals. From the data of Hicks (1966) and Fuller and Boyne (1971) on pigs, Ames and Brink (1977) on lambs, and Young and Christopherson (1974) on cattle, a digestibility coefficient drop of 0.1 to 0.4 percent per °C may be expected. Lowered digestibility is less predictable for swine, since some investigations did not find a significant alteration in digestibility with temperature in pigs (Table 2).

In summary, the extra feed intake required by cold-stressed pigs when rate of gain remains comparable to that at thermoneutrality can be calculated from results of a few *ad libitum* feeding trials (Table 33) and averages about 25-30 g/°C of coldness per day for pigs weighing between 20 and 100 kg.

On the basis of energy balance trials, 25 g of feed intake per °C coldness for the growing-finishing period may be the best estimate. However, in growth trials with relative short-term cold exposure, a much higher value is obtained. This value would, of course, vary directly with body weight. From a more extensive review of the literature, when data were corrected to a constant daily gain basis, the estimate of extra feed required was 45 g of feed per °C of coldness per day (Verstegen *et al.*, 1978).

From all this evidence, it seems justifiable to estimate arbitrarily that the extra feed requirement for pigs under cold stress in practical conditions averages in the range of 30 to 40 g/°C of coldness per day for the growing-finishing period when body weight ranges from 20 to 100 kg.

In 1968, NRC estimated that *ad libitum*-fed pigs weighing from 20 to 100 kg have an average daily gain of 800 g and a gain/feed ratio of 0.29, provided they have a daily feed intake of 2.8 kg under optimal conditions. Recommended crude-protein concentration averages 13.52 percent. There is no clear evidence that total dietary crude-protein requirement varies with environmental temperature. Data of Seymour *et al.* (1964) showed similar reduction in gain in the cold when pigs were fed diets with high (16 percent) or low (13 percent) crude-protein levels. Thus, crude-protein concentration in the diet may be reduced when the pigs are cold-stressed. Example calculations for adjusting crude-protein concentration for cold-stressed pigs follow.

Assume extra daily feed intake per pig required per °C of coldness is 40 g. (This amounts to 40/2,800, or 1.4 percent extra feed per °C of coldness.) Assume further that dietary crude-protein concentration is adjusted by diluting a basic corn-soy diet, containing 13.5 percent crude protein, with corn, containing 8 percent crude protein. [Crude-protein intake at optimal conditions would be (2,800 g/day)(0.135) = 378 g/day.]

If, for example, a practical environment is at 5°C of coldness (in the range of 5 to 10°C), each pig will need an extra feed intake of (40 g/°C)(5°C) = 200 g daily. In such a case, total feed intake would be 2,800 + 200 = 3,000 g/day. If total crude-protein intake is to remain equal (378 g/day), the adjusted dietary-crude-protein concentration (X) would be calculated as:

$$\begin{aligned}(2{,}800)(0.135) &= (3{,}000)(X)\\ X &= 12.6 \text{ percent}\end{aligned}$$

And the replacement (Y) of the basic diet by corn to achieve this would be calculated as:

$$\begin{aligned}[(3{,}000)(1 - Y)(0.135)] + [(3{,}000\ Y)(0.08)] &= (2{,}800)(0.135)\\ Y &= 0.164.\end{aligned}$$

That is, the adjusted diet would contain 16.4 parts corn and 83.6 parts basic diet. A similar approach for cattle and sheep exposed to both heat and cold stress has not altered daily gain but improved protein efficiency ratio (Ames *et al.*, 1980).

HEAT STRESS

Various definitions and concepts have been used to describe the reactions of pigs to heat stress. From the concept of thermoneutrality, as proposed by Mount (1974), the upper critical temperature is defined as the effective ambient temperature above which total heat-production rate at a given feed intake will rise. As a working hypothesis, Holmes and Close (1977) described upper critical temperature as that point at which a pig with dry skin can maintain maximal rate of heat loss. One may also use the point at which there is a rise in core temperature or frequency of respiration, as suggested by Heitman and Hughes (1949).

Since the pig must rely on evaporative heat loss in the heat, vapor pressure is more important during heat stress than in the cold. When considering heat loss, it has been suggested by Holmes and Close (1977) that at 30°C an increase of 18 percent in relative-humidity value is equivalent to an increase in air temperature of 1°C for swine. One may extract various other values of the temperature equivalence of relative humidity from other data. Morrison *et al.* (1967) pointed out that at 22.8°C, an increase in relative humidity from 45 to 95 percent was comparable in its effect on the pigs' heat balance of 2.2°C temperature increase. Using rise in core temperature as an index, one can calculate a value for EAT when relative humidity is greater than 30 percent as:

$$\text{EAT} = (0.35)\ (\text{wet-bulb temperature}) + (0.65)\ (\text{dry-bulb temperature})$$

However, to be useful, such indices must be predictive of feed intake and weight gain. Thus, effects of air speed, thermal radiation, housing and equipment factors, and group size must ultimately be accounted for and should be included to improve the accuracy of calculating EAT.

Data relating heat-induced decreases in feed intake and rate of gain in groups of pigs to effective ambient temperature and body weight are shown in Table 34. Compared with cold stress, much less information is available relating effects of heat stress on production traits. Houses for swine production during hot weather have been only partially evaluated in terms of effects on specific performance characteristics. For these comparisons, EAT, including at least dry- and wet-bulb temperatures, should be used as the standard. If not stated otherwise, EAT is assumed in the following discussion.

From data on short-term exposure to hot conditions (Heitman and Hughes, 1949; Heitman *et al.*, 1958), it can be calculated that pigs ate about 60 to 100 g less feed each day per °C of heat stress (32 as opposed to 21°C). This decline in feed intake resulted in a reduction in daily gain of 35 to 57 g/°C of heat stress.

TABLE 34 Decrease in Feed Intake and Rate of Gain During Heat Stress

		Decrease		
Temperature (°C)	Weight (kg)	Intake (g/°C)	Gain (g/°C)	Reference
21-32	35-65	60	33	Heitman and Hughes, 1949
21-32	75-100	120	57	Heitman and Hughes, 1949
24-32	45	—	38	Heitman *et al.*, 1958
22-32	68	—	60	Heitman *et al.*, 1958
22-27	91	—	60	Heitman *et al.*, 1958
19-27	114	—	60	Heitman *et al.*, 1958
18-32	20-100	30	7	Hazen and Mangold, 1960
16.5-32	7-92	14	3	Seymour *et al.*, 1964
22-38	13.5	8	4	Seymour *et al.*, 1964
22-38	35	33	8	Seymour *et al.*, 1964
22-38	65	41	12	Seymour *et al.*, 1964
23-33	6-35	42	21	Sugahara *et al.*, 1970

Heavier pigs are more sensitive to heat stress than lighter ones (Ingram, 1974). Performance data bear this out. In one experiment, finishing hogs did not grow at all in a 39°C environment, whereas those weighing around 45 kg continued to gain weight (Heitman and Hughes, 1949). Mangold *et al.* (1967) found the same thing in their three summer trials: heavy pigs showed greater reduction in both intake and gain than did growing pigs. Previous Iowa studies had also shown that pigs weighing less than 20 kg had much less decrease in feed intake than older pigs (Hazen and Mangold, 1960). They reported figures from which a reduction of 30 and 7 g/°C of heat load in intake and gain, respectively, in the body weight range of 20 to 100 kg were calculated when 32 and 18°C were compared. Of course heavier pigs are usually fatter and have a lower UCT. Consequently, heavier pigs are more heat stressed at the same temperature because they are exposed to a greater heat load.

It is logical that adding fat to swine diets may be advantageous during heat stress, because fat has a lower heat increment than either carbohydrate or protein. In addition, fat has a high caloric density that helps offset lowered caloric intake during heat exposure. Stahly *et at*. (1979a) have reported advantages for adding fat to diets of heat-stressed pigs. These same workers

(1979b) report an advantage for feeding synthetic lysine instead of natural protein, which reduces heat increment of the diet.

Some investigators have found that dietary vitamin and mineral concentrations may need to be increased under heat-stress conditions. But there is little evidence indicating that total daily requirements for these nutrients are affected by effective ambient temperature. Of course, as high temperatures reduce feed intake, it may be advisable to increase the concentration of certain vitamins and minerals in the diet to compensate. Peng and Heitman (1974) found that dietary thiamine requirement may be greater at 30 and 35°C compared with thermoneutral. Holmes and Grace (1975) found more potassium in the urine of heat-stressed pigs, but calcium retention was not affected.

Holmes and Grace (1975) and Gray and McCracken (1974) noticed an increase in the nitrogen content of the urine of pigs held at relatively high ambient temperatures, suggesting protein retention may be decreased somewhat in heat-stressed pigs. There has also been the suggestion that backfat thickness is increased at high temperatures (Holmes, 1971). Information on the magnitude and cause of body-composition changes in pigs in hot conditions is far from complete. Yet, with some exceptions (Filmer and Curran, 1977), there is reason to believe an increase in dietary crude-protein content during hot periods may be justified.

To get some idea of the normal magnitude of environmental heat stress during hot weather, one must know both the optimum temperature range and the average EAT. Most investigators have found the range, 18 to 21°C, optimal for growing-finishing pigs. Heat exposures have mostly been made at 32 to 38° C. However, these temperatures more likely reflect daily maximums in practice rather than daily means. It has been found that cyclic temperatures have about the same effect on physiological responses and performance traits as the mean of the cycle. Mean daily temperature is usually less than 30°C (Bond *et al.*, 1967; Morrison *et al.*, 1975); therefore, it seems justifiable for illustrative purposes to assume a mean heat load (difference between EAT and the pig's UCT) of 5°C during summertime. Of course, not all animals will always be under this much heat stress. By facilitating wallowing, providing shade, increasing air velocity (Bond *et al.*, 1965), and taking other measures, heat load can be varied, and this in turn influences feed intake and daily gain. Quantitative effects of environmental modifications are difficult to evaluate for practical situations, thus the 5°C heat load seems reasonable.

During heat stress dietary crude protein may require adjustment. If the averages of the data of Hazen and Mangold (1960), Mangold *et al.* (1967), and Heitman *et al.* (1958) are used, daily feed intake will decrease about 40 g/°C of heat stress, and this is paralleled by a daily gain depression of 10 to 20 g/ °C. In pigs held at 5°C above optimum, daily intake will be (40 g/°C)(5°C) = 200 g lower (2,800 - 200 = 2,600 g/day), but the animals should still consume a total of 375 g of digestible crude protein daily (NRC, 1973).

For example calculations, two feeds will be considered: a basic corn-soy diet, containing 13.5 percent crude protein, and a supplement containing 40 percent crude protein. Combination of the two is expected to yield a daily intake of 375 g of crude protein at the specified feed-intake rate (2,600 g/day). The crude-protein content (*X*) of the adjusted diet will be greater than 13.5 percent:

$$\begin{aligned}(2{,}800)(0.135) &= (2{,}600)(X)\\ X &= 14.42 \text{ percent.}\end{aligned}$$

And the replacement (*Y*) of the basic diet by protein supplement to achieve this would be calculated as:

$$\begin{aligned}[(2{,}600)(1 - Y)(0.135)] + [(2{,}600\ Y)(0.40)] &= (2{,}800)(0.135)\\ Y &= 0.039.\end{aligned}$$

That is, the adjusted diet would contain 3.9 parts protein supplement and 96.1 parts basic diet.

In summary, dietary crude protein should be provided in accordance with requirement for gain and not simply fed as a constant percentage of a temperature-dependent daily intake.

SUMMARY

Swine, like other species, are sensitive to changes in the effective thermal environment. Size is highly correlated with fatness and therefore related to rate of heat loss. Consequently, responses of swine to specific environmental conditions are largely dependent on size. Increased heat loss during cold stress reduces rate of performance unless compensation is made by increasing rate of feed intake. During heat stress, rate of intake is depressed, resulting in lowered performance. Dietary adjustments designed to provide each nutrient as required but to avoid over- or underfeeding when intake varies with environmental condition are discussed. Although more quantitative data are needed for accurate nutrient adjustments in response to thermal stress, swine producers should consider the impact of environmental conditions when developing diets for pigs.

Poultry

INTRODUCTION

Environmental factors are generally recognized to have a major impact on the production of meat and eggs from poultry. These include temperature, humidity, light (length of day and intensity), altitude (air pressure and partial pressures of oxygen and carbon dioxide), wind velocity (air movement), solar energy, quality of air and water, and density of population. During the last decade, the influence of environmental factors on poultry have received greater attention so that more reliable baseline values are available. Most studies have dealt with only one environmental factor—with other factors presumably held constant. Yet, we recognize that in husbandry practices, be it in- or outdoors, poultry are subjected to a multiple of factors, none held completely constant, and all interrelated. At times these factors could be reinforcing or counteracting the impact each has on the bird. Another complication, often ignored, has been the animal's acclimatization to environmental forces that tend to allow poultry to withstand sudden short-term excursions from the norm, which produce havoc to a nonacclimatized bird. A crucial factor that appears to govern the TNZ and responses to hot or cold is acclimation (Harrison and Biellier, 1969; Shannon and Brown, 1969; van Kampen, 1974; Waxing and Brown, 1967).

POULTRY ENVIRONMENT

The use of shelter to shield poultry from the macroenvironment is an approach to enhance productivity and thus justify such expenditures. The struc ture creates around the bird a meso- and microenvironment (Charles, 1974) that moderates but does not alleviate environmental impact. In temperature-nutrition studies, it is important to consider the environment in the cage (microenvironment) and to avoid use of measurements taken within the building (mesoenvironment).

A "perfect" environment to the nutritionists for rearing poultry could be defined as those ambient conditions that maximize gain in weight or egg output with the least expenditure of nutrients. Unfortunately, the "perfect" environment may not be economically feasible. A compromise is reached, and the direction of management is to achieve an "optimum" environment, one in which the ambient situation is efficiently obtainable in terms of productivity and nutrient intake with a minimum of sacrifices. For example, if a low ambient temperature reduces productivity, then supplying a mesoenvironment at a higher temperature will be rewarding if the increased productivity equals or exceeds the expenditure required to supply the higher ambient temperature.

An example of such consideration is the evaluation of nutrient costs to raise turkeys for maximum profits (Waibel, 1977). When protein (soybean meal) sources are relatively cheap, one apparently should feed the usually recommended levels of protein to stimulate maximum gain in weight; but when protein is expensive, the cost-accounting approach justifies lower levels of dietary protein and less than maximum weight gain. And, to complicate the situation, the ambient temperature at which the turkeys grow has an impact on the profit-efficiency-weight gain output (Waibel, 1977).

Although the final accounting for productivity is meat, eggs, and/or reproductive output (young stock from hatching facilities), there are several instances where environment affects nutrient utilization. Consider the discussion on basal metabolism (page 27). A shift toward a higher environmental temperature reduces energy expenditure of poultry (O'Neill *et al*, 1970; Romijn and Vreugdenhil, 1969; van Kampen, 1974). Thus, where higher ambient temperatures are available birds expend less of their metabolizable energy for maintaining a constant body temperature and appear to have the option of shifting this savings of energy to production or improving feed efficiency.

FEED INTAKE AND NUTRIENT REQUIREMENTS

At this point, a differentiation must be noted between the environmental effect on nutrient intake versus its effect on nutrient requirements. Inherent in this recognition is that when nutrient intakes are altered by the environment, an adverse effect on the animal should be alleviated by correspondingly adjusting dietary levels of the nutrients to compensate for altered daily intake. If equal daily intakes of nutrients at different environmental conditions do not produce comparable productive outputs and/or efficiency, then we would assume that the nutrient requirements were altered.

To illustrate this concept, consider the data in Figure 18 adapted from a study by March and Biely (1972). Chicks were reared at 20 and 31.1°C using diets with graded levels of lysine covering the range from levels that are deficient to those in excess. Two separate response lines Were obtained when feed intake was related to body weight gain in the two temperatures. The slopes of the lines are nearly parallel, and the difference between the two levels of intake indicates that chicks in the 31.1°C ambient temperature ate about 20 percent less feed. Thus, the high temperature reduced feed intake and consequently reduced gain. However, when the data are plotted on the basis of lysine intake versus body weight gain, note that one response line can describe the relationship despite the two environments (Figure 19). Thus, environmental effect on growth was not from a change in nutrient requirements for growth, but instead was a consequence of an environmental effect to reduce feed intake and thus lower the daily intake of lysine (and other nutrients), which resulted in reduced growth rate. Note that at equal lysine intakes, growth was comparable in both environments (Figure 19).

In warmer environments, a decline in feed intake may or may not influence egg production or quality. How drastically feed intake is depressed and for how long are what apparently determines the hen's response. Even in the thermoneutral zone, a decline in feed intake of up to 15 percent may not af

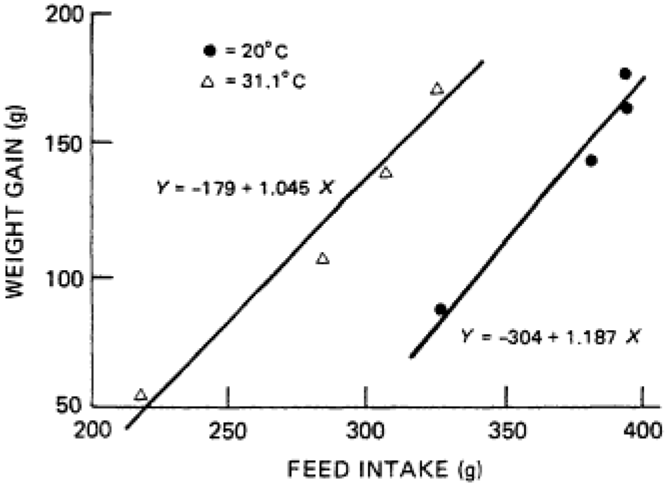

Figure 18.
Relationship between total feed intake and total weight gain of White Leghorn chicks fed for 15 days diets with lysine levels of 0.73, 0.88, 1.03, and 1.33 percent at two ambient temperatures (adapted from data by March and Biely, 1972).

feet production or quality of eggs (for reviews, see Polin and Wolford, 1972; Snetsinger and Zimmerman, 1974) if the bird mobilized body reserves to replace the nutrient deficit (Davis *et al.*, 1972; Polin and Wolford, 1972, 1973; Snetsinger and Zimmerman, 1974).

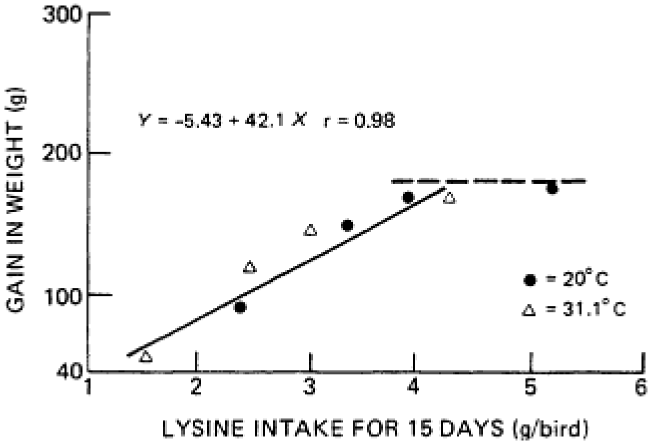

Figure 19.
Relationship between accumulative intake of lysine and accumulative growth of chicks reared at 20 or 31.1°C and fed diets for 15 days containing 0.73, 0.88, 1.03, or 1.33 percent lysine (adapted from March and Biely, 1972).

In early studies, Wilson (1949) and Payne (1966) recognized that a drop in egg production by chickens in hot environments was partially due to lower energy intake. Recently, Dale and Fuller (1980) reported that high fat or high fat-high density diets alleviate to some extent the weight loss of broilers at 31° C. Other studies, to be discussed, indicate that lesser amounts of feed result in submarginal intakes of all nutrients and that their replacement does not necessarily ensure a return to normal production. Warmer temperatures reduce basal metabolic rate (Shannon and Brown, 1969) and maintenance energy, the latter at an estimated 4 percent with each 1°C rise above thermoneutrality (Leeson *et al.*, 1973). For example, White Leghorn and Rhode Island Red hens at 33-34°C have a heat loss which is 58 and 51 percent, respectively, of the values at 18.3°C (Ota and MeNally, 1961). Part of the decline is also accounted for by less activity to eat as extrapolated from studies on laying hens restricted in feed intake (Jackson, 1972) or those more efficient in feed utilization (Morrison and Leeson, 1978).

EFFICIENCY OF EGG PRODUCTION

The energetic equivalent of egg weight is generally accepted as 1.66 kcal per gram of egg, including the shell. Recently, Sibbald (1979) related egg weight to caloric value by the equation:

$$Y = 19.7 + 1.81\,X,$$

where
X = weight of egg (g),
Y = energy value (kcal/egg).

Egg shell is about 98 percent mineral and has a caloric value of about 0.24 kcal per gram (Bolton, 1958) or 1.2 kcal for a 5 g shell. Shell protein and membranes account for almost all of this energy. The value of 1.66 is obtained by combustion of an aliquot of blended egg in a bomb calorimeter (Bolton, 1958) and is approximated from data presented by Cotterill *et al.* (1977) showing that an average egg of 60.8 g contains 6.36 g of protein (5.7 kcal per gram of protein) and 6.52 g of lipid (9.4 kcal per gram of lipid) with a caloric value of 96.9 kcal, which, added to the 1.2 kcal for shell, equals 98.1 kcal. (The yield of calories by combusting an egg is 37 percent from its protein and 63.8 percent from its fat.) A flock laying at an average rate of 70 percent and producing eggs weighing an average 61 g is producing 42.7 g of egg per bird per day, equivalent to 70.9 kcal. If these birds were consuming each day 110 g of feed containing 2.85 kcal of ME per gram, then the energetic efficiency is 22.6 percent:

$$[70.9 \text{ kcal}/(110 \text{ g feed} \times 2.85 \text{ kcal ME/g feed})] \times 100 = 22.6 \text{ percent.}$$

Tables 35 and 36 contain a series of values in which the energetic efficiencies are given for the range of egg weights from 50 to 65 g, a range of feed intakes of 80 to 150 g per day, a range of egg production values of 60 to 75 percent, and, for two dietary levels of ME, 2.85 and 3.00 kcal/g. Therefore, a decline or improvement in any of the above values, other than ME, as a result of environmental factors, can be estimated from the change in energetic efficiency of egg production obtained from the values in Table 35. If egg weight remains constant at 65 g, egg production at 70 percent, and no change occurs in body weight while feed intake declines from 110 to 100 g, then the caloric efficiency has improved from 24.1 to 26.4 percent (Table 35), or an increase of 9.5 percent.

A change in body weight complicates the situation. To consider the impact of such an event, consider the following. Metabolizable energy values of feedstuffs do not appear to be different for laying hens when in cold, warm, or hot environments (Brown *et al.*, 1967; Davis *et al.*, 1972). Thus, the digestive, absorptive, and excretion processes leading to retention of energy from the diet were not affected in hens held at ambient temperatures ranging from 7 to 35°C for as long as 6 weeks. Davis *et al.* (1972) noted that feed intake was almost 26 percent less by the hens in the 35°C environment, but

TABLE 35 The Efficiency of Converting Feed to Egg in Energetic Equivalents Assuming a Diet Containing ME = 2.85 kcal per g

	Feed Intake (g/bird/day)							
Average Egg Weight (g)	80	90	100	110	120	130	140	150
	60% egg production							
50	21.8	19.4	17.5	15.9	14.6	13.4	12.5	11.6
55	24.0	21.4	19.2	17.5	16.0	14.8	13.7	12.8
60	26.2	23.3	21.0	19.1	17.5	16.1	15.0	14.0
65	28.4	25.2	22.7	20 7	18.9	17.5	16.2	15.1
	65% egg production							
50	23.7	21.0	18.9	17.2	15.8	14.6	13.5	12.6
55	26.0	23.1	20.8	18.9	17.4	16.0	14.9	13.9
60	28.4	25.2	22.7	20.7	18.9	17.5	16.2	15.1
65	30.8	27.3	24.6	22.4	20.5	18.9	17.6	16.4
	70% egg production							
50	25.5	22.7	20.4	18.5	17.0	15.7	14.6	13.6
55	28.0	24.9	22.4	20.4	18.7	17.2	16.0	14.9
60	30.6	27.2	24.5	22.2	20.4	18.8	17.5	16.3
65	33.1	29.4	26.4	24.1	22.1	20.4	18.9	17.7
	75% egg production							
50	27.3	24.3	21.8	19.9	18.2	16.8	15.6	14.6
55	30.0	26.7	24.0	21.8	20.0	18.5	17.2	16.0
60	32.8	29.1	26.2	23.8	21.8	20.2	18.7	17.5
65	35.5	31.5	28.4	25.8	23.7	21.8	20.3	18 9

they continued to lay at a high rate at the expense of body tissue stores. The energy retention (metabolizable energy), which they determined to be 205 kcal per hen per day, was equivalent to 141 kcal per kg $^{0\ 75}$ per day. Egg energy of 70.5 kcal per day was equivalent to 48.6 kcal per day per kg$^{0\ 75}$, yielding an energetic efficiency of 34.4 percent at 35°C. The hens weighed only 1.55 kg at the end of 21 days, down from 1.83 at the start of the experiment. Using equations given by Davis *et al.* (1972) based on carcass analyses, the energetic values of the hen's carcass contain 5,543 and 4,310 kcal at the start and end of the experiment, respectively. The difference of 1,233 kcal for 280 g weight loss during 21 days yields a value of 4.41 kcal per gram of body weight loss. The daily weight loss of 13.3 g, equivalent to 59.1 kcal (40.8 kcal per kg$^{0\ 75}$), contributed to energy available to the hen. Therefore, the calories available to the hens each day were the sum of metabolizable energy and that obtained from body tissues, a total value of 181.8 kcal per kg$^{0\ 75}$. Egg energy was 26.7 percent of this total, as compared to 26.4 or 24.4 percent obtained in environments of ambient temperature and

7°C, respectively. Therefore, the improved energetic efficiency of egg production at 35°C, originally calculated as 34.4 percent, was only 26.7 percent when the hen's bodily stores were included in the accounting. This example illustrates two factors: (1) that temperature did not, per se, have an influence on the partial efficiency of egg production and that (2) accounting only for feed in the production of an egg can lead to misleading results as compared to a more inclusive accounting of energy balance.

TABLE 36 The Efficiency of Convening Feed to Egg in Energetic Equivalents, Assuming a Diet Containing ME = 3.00 kcal per g

	Feed Intake (g/bird/day)							
Average Egg Weight (g)	80	90	100	110	120	130	140	150
	60% egg production							
50	20.8	18.4	16.6	15.1	13.8	12.8	11.9	11.1
55	22.8	20.3	18.3	16.6	15.2	14.0	13.0	12.2
60	24.9	22.1	19.9	18.1	16.6	15.3	14.2	13.3
65	26.9	24.0	21.6	19.6	18.0	16.6	15.4	14.4
	65% egg production							
50	22.5	20.0	18.0	16.3	15.0	13.8	12.8	12.0
55	24.7	22.0	19.8	18.0	16.5	15.2	14.1	13.2
60	27.0	24.0	21.6	19.6	18.0	16.6	15.4	14.4
65	29.2	26.0	23.4	21.3	19.5	18.0	16.7	15.6
	70% egg production							
50	24.2	21.5	19.4	17.6	16.1	14.9	13.8	12.9
55	21.6	23.7	21.3	19.4	17.8	16.4	15.2	14.2
60	29.1	25.8	23.2	21.1	19.4	17.9	16.6	15.5
65	31.5	27.9	25.2	22.9	21.0	19.4	18.0	16.8
	75% egg production							
50	25.9	23.1	20.8	18.9	17.3	16.0	14.8	13.8
55	28.5	25.4	22.8	20.8	19.0	17.1	16.3	15.2
60	31.1	27.7	24.9	22.6	20.8	19.1	17.8	16.6
65	33.7	30.0	27.0	24.5	22.5	20.8	19.3	18.0

Other nutrients should be considered in their conversion to eggs and meat. For example, hens at 100 percent production are estimated to be about 37 percent efficient in transferring protein from diet to amino acids in eggs (Cotterill *et al.*, 1977). At 70 percent production the value is 25.9 percent. The value 25.9 percent is derived from 110 g of feed at 15.5 percent crude protein, yielding 6.36 g of amino acids in the egg:

$$[6.36 \text{ g amino acids}/(110 \text{ g feed} \times 0.155 \text{ g CP/g feed})] \times 100 = 37 \text{ percent},$$

$$37 \text{ percent} \times 0.7 \text{ production} = 25.9 \text{ percent}.$$

In terms of dietary true protein (amino acids in feed), the efficiency value would be higher because the level of true protein in feed is less than the crude protein (nitrogen) level.

Referring again to data by Davis *et al.* (1972), the efficiency of amino acid deposition into the egg appears to be enhanced by higher temperature. This conclusion is arrived at by calculating the efficiency values of 29.6 and 40.6 percent at environmental temperatures of 7 to 10°C and 35°C, respectively (Table 37). In this experiment, body weight declined 235 g, with 9 percent, or 21.2 g, attributed to a loss of protein (Davis *et al.*, 1972). The daily loss of body protein averaged 0.5 g/day. This protein, if assumed to be available for eggs, when added to the 11.2 g obtained from the diet, yielded a total availability of 11.7 g/day. Based on this value, the efficiency of protein deposition into egg at 35°C was 40.3 percent, similar to values found when the contribution of body protein was excluded. Unlike caloric efficiency, which was corrected to a major extent upon accounting for body reserves, the efficiency for transfer of protein from diet to eggs appears to be improved at warmer temperatures. Considerably more data are needed to substantiate this conclusion, since it is possible that protein was utilized for energy. If the latter is so, then feed formulation of energy to protein ratios may have to be shifted upward in cold environments.

Another example for consideration is based on calculations from data by Adams *et al.* (1962) and depicted in Figure 20. Clearly, two effects are noted: one, which shows that feed intake of broiler-type chicks was reduced at 31.2°C, and two, that high-energy diets reduced feed intake more than the lower-energy diets fed at this high temperature.

Figure 21 reveals that gain in weight per unit of protein consumed versus energy concentration in the diet is positively correlated and that this relation

TABLE 37 The Effect of Environmental Temperature on the Efficiency of Protein Deposition in Chicken Eggsa

	Environmental Temperature (°C)	Egg Mass per Day (g)	Crude Protein Intake/ Day (g)	Amino Acids per Egg (g)[b]	Percent of Feed Protein in Egg
Expt. #1	10	45.9	16.8	4.82	28.7
Expt. #2	35	43.7	11.2	4.59	41.0
Expt. #3	7	49.7	17.2	5.22	30.4
Expt. #4	35	44.9	11.8	4.71	39.9

[a] Derived from data of Davis *et al.*. 1972.

[b] Amino acids comprise 10.5 percent of egg weight (Cotterill *et al.* 1977)

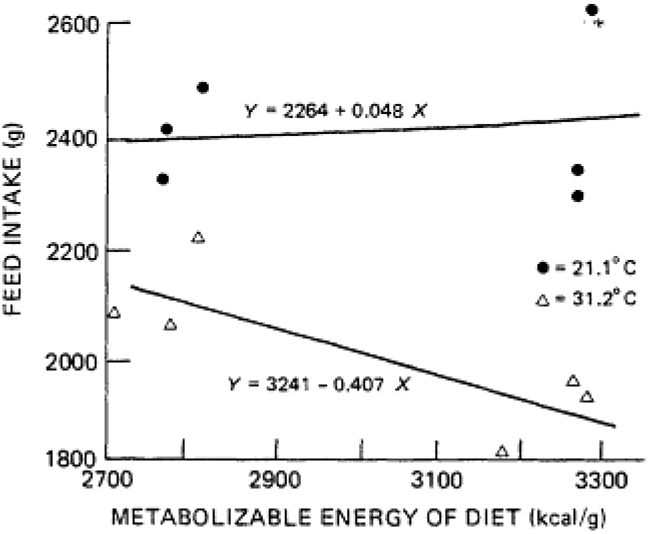

Figure 20.
Relationship between dietary ME, feed intake, and ambient temperature for broiler-type chicks 6-10 weeks of age (adapted from Adams *et al.* , 1962).

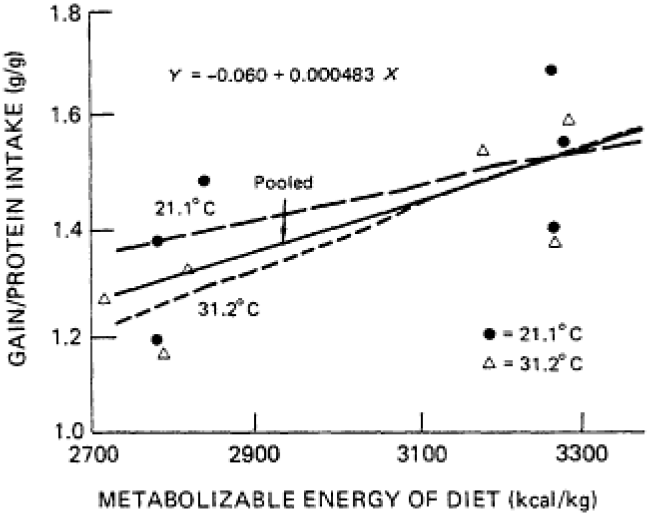

Figure 21.
Relationship between gain, percent protein, and ME of the diet fed to broiler-type chicks 6-10 weeks of age (adapted from data by Adams *et al.*, 1962).

TABLE 38 Lysine Intake and Body Weights of Broilers Reared at Temperatures of 15.6 and 29.6°C (Adapted from Data by McNaughton et al., 1978)

	Experiment No. 1				Experiment No. 2			
	15.6°C		29.6°C		15.6°C		29.6°C	
Dietary Lysine (%)	Lysine Intake (g) (0–4 wk)	4-Wk Body[a] Weight (g)	Lysine Intake (g) (0–4 wk)	4-Wk Body Weight (g)	Lysine Intake (g) (0–4 wk)	4-Wk Body Weight (g)	Lysine Intake (g) (0–4 wk)	4-Wk Body Weight (g)
0.80	7.40	480^{d}	6.32	401^{c}	—	—	—	—
0.85	7.45 ←	482^{d}	6.89	424^{c}	9.39	502^{d}	6.94	385^{a}
0.90	8.08 ←	510^{cd}	→ 7.47	469^{b}	11.34 ←	656^{c}	8.88	542^{b}
0.95	9.17	545^{bc}	→ 8.13	522^{a}	12.27 ←	680^{c}	10.03	640^{c}
1.00	9.49 ←	558^{ab}	8.83	535^{a}	14.02	738^{b}	→ 11.51	706^{d}
1.05	11.42	588^{a}	→ 9.40	546^{a}	13.68 ←	749^{b}	→ 12.22	714^{d}
1.10	12.18	595^{a}	10.15	542^{a}	14.23	752^{ab}	13.16	748^{d}
1.15	12.54	574^{a}	10.58	535^{a}	15.76	792^{a}	13.22	714^{d}
1.20	—	—	—	—	15.73	771^{ab}	→ 13.67	721^{d}

[a-d] Values with the same superscript letters within a column are not significantly different.

NOTE: The arrows indicate body weights at comparable lysine intake.

ship for growth seems to be unaffected by ambient temperature at 31.2°C versus 21.1°C. Additional evidence indicating a lack of temperature influence on growth from protein is reported by March and Biely (1972), who fed chicks diets deficient or adequate in lysine at 18.3, 22.2, or 29.4°C. The response line is characteristic of lysine levels versus gain and is independent of temperature. A review of data by McNaughton *et al.* (1978) on body weights of broiler-type chicks at 4 weeks of age also reveals that at equal lysine intakes body weight was similar at 15.6 and 29.6°C (Table 38).

FEED INTAKE

Estimations of the effect on feed intake of laying hens by temperature were made by numerous investigators. Their data are given in Table 39, converted to express the effect as a percentage change from controls kept at 18-25°C. The variability is excessive for any definite mathematical equation to be established. This should not be too surprising when one considers the heterogeneity of the factors, such as strain, length of time under heat stress, percentage production, weight of eggs, and ME values of the diet that existed among these experiments. Obviously, one all-encompassing equation would appear to be difficult to establish. However, within certain limits there is a possibility of obtaining a measure of feed intake related to temperature. These data (Table 38) show a relationship of:

$$Y = 24.5 - 1.58\,T,$$

where
T = ambient temperature (°C),
Y = percentage change of feed intake from controls in the thermoneutral zone.

This is a decline in feed intake of 1.58 percent per 1°C rise in temperature referenced to the intake value at temperatures in the 18-25°C range. Payne (1967) calculated for laying hens a decline in feed intake of 1.5 percent for each 1°C rise in temperature through the range of 5 to 30°C. Emmans (1974) calculated metabolizable energy on a daily basis to decline 4.3 kcal per 1°C rise for white and brown egg layers. This value for a diet with metabolizable energy of 2.9 kcal per gram represents 1.5 g of diet. Regression equations, derived from data by Jones and Barnett (1974), reveal that turkey hens show a decline in feed intake of 3.2 g or 1.5 percent for each 1°C rise between the temperatures of 4.5 to 35°C. Thus, an overall estimate for relating feed intake to temperature change appears to be 1.5 percent/°C with 20-21°C as a baseline.

PERFORMANCE

An improvement in growth performance may be observed upon a decline in ambient temperature as a result of an increase in feed consumption (Khalil *et al.*, 1968). The response seems to occur as a result of an increased intake of diet, even though marginal in some nutrient rather than a response to temperature, per se. The former is the more likely reason, as March and Biely (1972) showed that a lysine deficiency at 31°C is not observed at 20°C because of the greater amount of diet consumed at the lower temperature. Similarly, calculations based on data by Bray and Gesell (1961) reveal that hens at 5.5°C consume an average 23 percent more diet and, although fed diets with protein levels below normal, produced 18 percent more egg than their counterparts at 24.4°C on similar diets.

Data by Bray and Gesell (1961) analyzed for response relationships between daily egg mass produced (Y) and percentage protein in the diet (X) reveal that for dietary protein levels ranging from 6 to 14 percent, $Y = 11.7 + 4.06\,X$ for hens kept at 30°C, and $Y = 10.4 + 2.94\,X$ for hens kept at 24.4°C. The slope ratio of 2.94/4.06 indicates that hens kept at 30°C ate 25 percent less diet, which attributed to the reduction in egg mass over the range of protein insufficiency. Based upon the slope of the response curves, each 1 percent decline in protein level below the dietary level of 12 percent results in a 4 g loss in egg weight. However, when egg mass is related to daily pro

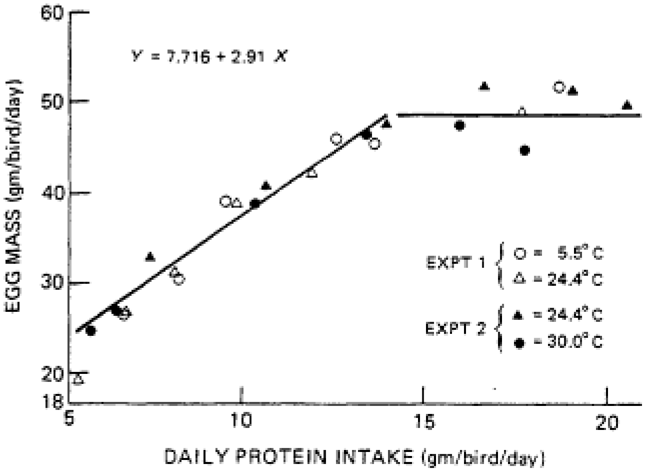

Figure 22.
Relationship between dietary protein level and daily egg mass from White Leghorn hens at 5.5. 24.4. and 30°C (adapted from Bray and Gesell. 1961).

tein intake rather than protein level in the diet, then a decline of 2.9 g of egg occurs for each 1 g of reduced protein intake below 14 g (Figure 22), regardless of the temperature. At adequate protein intakes, moderately high temperatures do not affect egg mass output, provided energy intake is also comparable.

In cyclic environments chickens appear to take advantage of the cooler phase of the cycle to undo to some extent the adverse effect on production and quality caused by the extreme heat (de Andrade *et al.*, 1977; Miller and Sunde, 1975; Squibb, 1959; Table 38). Temperatures in the lethal range, especially those in tropical climates, are tolerated so that egg production is maintained, but only if cooler temperatures occur at the lower range of the daily fluctuations (Squibb, 1959). However, chickens in heated chambers lay smaller eggs with thinner shells (Clark and Amin, 1965). Miller and Sunde (1975) noted that some hens shifted from cyclic cold to cyclic hot died, while others had several days of producing shell-less eggs. During hot summer days when poultry are under stress to remove body heat and eat less diet, shifting the photoperiod to include cooler temperatures of the night would be appropriate to allow access to feed.

ACCLIMATION

Miller and Sunde (1975) noted that laying hens took 7 days to adjust to a shift of cyclic cold to cyclic hot. Jones *et al.* (1976) observed that chickens stabilized at lower values of feed intake within 24 hours when shifted to warmer temperatures. However, as long as 21 to 28 days were noted by other investigators (Davis *et al.*, 1972; Shannon and Brown, 1969) for acclimation to occur. Turkey hens appear to be acclimated, based on feed intake, in 8 to 14 days when shifted from cold to hot environments (Jones and Barnett, 1974), or, as long as 21 days, if the temperature is as high as 37.8°C (Parker *et al.* , 1972). If they are moved stepwise every 2 weeks into 5°C hotter environments starting at 20°C, each time there are dramatic declines in productivity, feed intake, egg and shell quality, and estrone levels in plasma with the move into 30 and 35°C temperatures (Kohne and Jones, 1976). Evidently short-term exposure to a warmer environment does not acclimate turkeys to a subsequently hotter environment.

Unfortunately we have not taken advantage in everyday husbandry procedures of inducing acclimatization or acclimation as an approach to buffer an expected environmental impact. Most research has emphasized long-term constant exposure to a particular environmental factor, perhaps assuming exposure time would overcome the short-comings of our inability to study a multiple of variable factors.

CARCASS COMPOSITION

The effect of temperature on carcass composition is not an established certainty. Fat levels in carcasses were shown to be unchanged (Adams *et al.*, 1962; Mickelberry *et al.*, 1966) or increased (Kubena *et al.* , 1972; Winchester and Kleiber, 1938) as temperatures increase above 29°C. When lipid levels of the carcasses were increased, then investigators found the moisture levels decreased, a widely recognized phenomenon. Rearing chicks at 29°C did not alter the fatty acid composition of tissue (Fisher *et al.*, 1962; Mickelberry *et al.*, 1966), but rearing them at 32°C did make them more saturated (Fisher *et al.*, 1962). The trend for cold temperatures is that chickens (Fisher *et al.*, 1965), turkeys (Hellickson *et al.*, 1966), and ducks (Scott *et al.*, 1959) have less fat. The chickens were noted to have fat that was more unsaturated (Fisher *et al.*, 1965). Protein levels in the carcass may be unchanged (Kubena *et al.*, 1972) or slightly lower (Olson *et al.*, 1972) in hot ambient temperatures. Where chickens are restricted in their intake at cool cyclic temperatures ranging from 13 to 24° C, daily, to the amount consumed by birds at the hot temperatures (cyclic 26.5-40.5°C), then the difference in energy per unit gain (protein plus fat) could be considered that amount attributed to the effect of temperature on feed intake. Olson *et al.* (1972) noted that those hot cyclic temperatures caused a decline of 49 percent in carcass energy gain when a diet with an ME of 3.22 kcal/g was fed, as compared to a decrease of 38 percent for a diet with ME of 3.69 kcal/g. In other words, temperature appears to influence carcass composition partially by its effect on feed intake and partially by altering the response of the animal. In hot environments, feed intake is less than normal, creating a nutrient deficit that may be severe enough to alter the metabolism of the liver, causing excess fat to accumulate in the carcass; whereas in cold temperatures, the demand for energy may force depletion of adipose reserves for energy. Furthermore, increasing the energy density of the diet in cold weather will alleviate to some extent the demand to match intake with expenditure of energy and thus tend to maintain carcass composition at a status quo. During heat stress, when feed intake is reduced, the need for nutrients is alleviated to some extent by increasing nutrient density (Dale and Fuller, 1980), thus assuring less of a chance for a nutrient deficit, which can cause fat to accumulate in liver and carcass.

NUTRIENT ADJUSTMENTS

The heat increment of a hen's diet is lowest when a greater percentage of ME is in the form of lipid than when carbohydrates or protein dominate the caloric supply (Polin and Wolford, 1976). Presumably, diets with minimal heat increment may be beneficial during periods of heat. The approach of adding fat to poultry diets during thermal stress has not been consistently successful. Reid (1979) achieved some success by adding up to 9 percent tallow in diets fed to laying hens reared at 29°C. Their ME intake per day increased, and this improved their energy balance, considering both egg production and body weight gain. On the other hand, Sell (1979) reported that increased caloric efficiency in laying hens fed added dietary fat during heat was due to tissue deposits of fat while egg energy per unit of ME consumed declined. Fat supplementation for broiler chickens has not been consistently beneficial during thermal stress. Fuller and Rendon (1977) and Dale and Fuller (1980) obtained beneficial results feeding high fat (29-33.2 percent of ME from fat) compared to low fat (7-12.6 percent of ME from fat) diets, but Cerniglia *et al.* (1978) found there was no advantage for adding dietary fat in diets fed to broilers during heat.

Attempts to overcome the expected loss in feed intake and resultant adverse effects from high temperatures by adjusting nutrient density of the diet have met with partial success (Mowbray and Sykes, 1971; Payne, 1967). Stockland and Blaylock (1974) fed one of three diets to maintain protein intake of hens relatively constant. Hens at 29.4°C produced at 66.4 percent versus 70.6 percent at ambient (March-July), or 68 percent at 18.3°C, despite a 19 percent decline in feed intake. The experiment lasted 26 weeks. Table 40 summarizes data (de Andrade *et al.*, 1976, 1977) that compare diets whose nutrients were increased 20-25 percent and the energy density by 10 percent over that of a diet typically used at thermoneutrality. All three diets were fed to laying chickens in three different environments. The higher nutrient densities prevented a major decline in egg production, moderated a decline in egg weight, markedly improved efficiency of feed conversion to egg, but were unable to prevent the loss in shell quality (Table 39). Part of the reason for the latter's decline is attributed to a 6.5-13.5 percent lower calcium intake (Table 39). Another reason for poor shell quality during heat stress appears to be lower circulating levels of hormones, for chickens (Bell and Freeman, 1971; de Andrade *et al.*, 1977; Erb *et al.*, 1978) and turkeys (Kohne and Jones, 1976), and the physiological stress of respiratory alkalosis (Mongin, 1968). Just having adequate calcium intake without an adequate intake of other nutrients does not overcome the effect of temperature on shell calcium (Kohne and Jones, 1976). At equal calcium intakes, the hot temperatures lower shell quality (Figure 23).

Overall, the indication is that nutrient intake alone is not going to solve completely the adverse effect of heat stress. There is that physiological stress on laying birds during initial heat exposure that dietary changes do not appear to moderate. Miller and Sunde (1975) observed shell-less eggs and some mortality within 24 hours after subjecting laying hens to cyclic or constant hot environments. They detected an effect on shell quality of those eggs in the shell gland within the few hours after heat exposure. In time some ac

TABLE 39 Effect of Temperature on Feed Intake of Laying Hens, Regardless of Value for Metabolizable Energy in Diet. Feed Intake at 18-25°C Serves as Control Value. All Assume Chronic Exposure. Y = 24.5 - 1.58 T, where T = Ambient Temperature and Y = Percent of Control

	Feed Intake (% of Control)										
Ambient Temperature (°C)	Vo *et al.*, 1978[a]	de Andrade *et al.*, 1976[a]	de Andrade *et al.*, 1977[a]	Ahmad *et al.*, 1974[a]	Miller and Sunde, 1975[a]	Stockland and Blaylock, 1974[a]	van Kampen, 1974[a]	Jones and Barnett, 1974[a]	Jones *et al.*, 1976[b]	Kohne and Jones, 1976[b]	Mean
4-5					+8.7%			+26.8%	+ 3.3%		(4) 15.4%
13								+ 5.3%			(1) 5.3%
18-25	100%	100%	100%	100%	100%	100%	100%	100%,	100%	100%	—
27								- 6.7%			(1) - 6.7%
29.4	-22%					- 17%					(2) - 19.5%
30				- 8%						- 18.6%	(2) - 13.3%
31		- 26%	- 26%								(2) - 26.0%
32					- 25%						(1) - 25.0%
35	- 32%						- 56%	- 18.6%	- 43%	- 32%	(6) - 34.6%[d]

[a] Chickens, adult female.

[b] Turkeys, adult female.

[c] Linear regression used to calculate feed intake at 21°C, and then A percent calculated.

[d] Includes value of Davis *et al.*, 1972.

[e] Includes values of Bray and Gesell, 1961.

climation occurred and egg production returned to near normal levels with some improvement in shell quality, even though dietary nutrients were not increased. In cyclic environments a return toward normal shell quality occurred because a greater percentage of the eggs were laid after 0900 hours (Miller and Sunde, 1975), an indication of a longer stay in the shell gland. Despite the shell-less eggs and poor shell quality of hens in hot environments, bone mineralization remained at normal levels throughout.

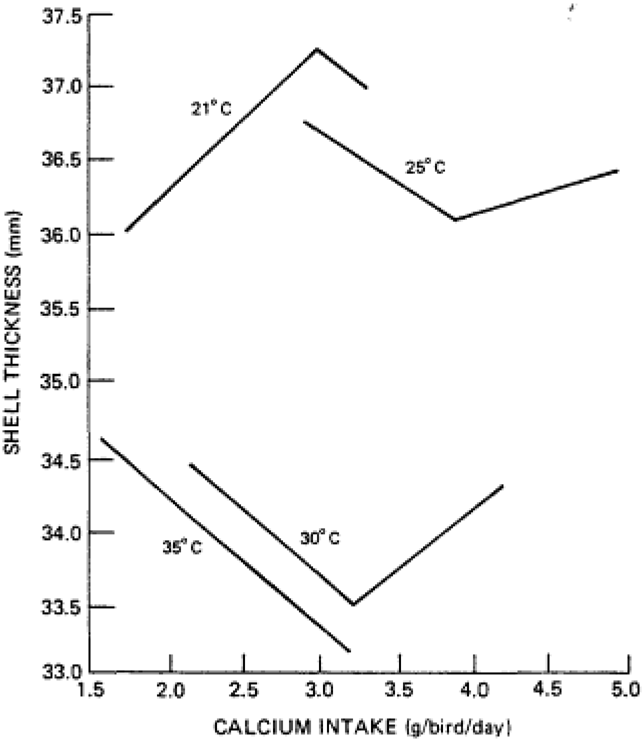

Figure 23.
The relationship between daily calcium intake and shell thickness by turkeys fed 1.54, 2.01, or 2.48 percent dietary calcium at each of four environmental temperatures (after Kohne and Jones, 1976).

ESTIMATING ME REQUIREMENT FOR LAYING HENS

Many equations are available to estimate the ME requirements of laying hens exposed to different temperatures (for review, see McDonald, 1978). Basically, such estimates depend on three factors: maintenance energy, energy related to a change in body weight (energy is demanded for gain, energy is

TABLE 40 The Effect of Diets with Nutrients Increased 20 to 25 Percent and ME 10 Percent on the Response of Chickens to High Temperature. Adapted from de Andrade et al. (1976, 1977). The Control Diet Contained 15 Percent Crude Protein and ME = 2.95 kcal per g

	Relative to Control at 21°C								
	Δ Egg Production (%)			A Feed Intake (%)			Δ (kg egg/kg feed) (%)		
Environmental Temperature (°C)	Cont.	HND + 20[a]	HND + 25[b]	Cont.	HND + 20	HND + 25	Cont.	HND + 20	HND + 25
Constant 21°C	± 0	-0.1	+0.9	± 0	- 7.7	- 13.7	± 0	- 12.1	- 16.8
Cyclic 31°C avg.	- 6.5	—	-2.8	-22.1	—	-31.1	- 13.8	—	-28.0
Constant 31°C	- 18.2	-9.2	-2.3	-26.1	-20.8	-25.3	- 2.5	- 8.7	-22.4
	Δ Egg Weight (%)			Δ Shell Thickness (%)			Δ Calcium Intake (%)		
	Cont.	HND + 20	HND + 25	Cont.	HND + 20	HND + 25	Cont.	HND + 20	HND + 25
Constant 21°C	± 0	+5.1	+1.4	± 0	+4.6	+ 0.3	± 0	+ 9.0	+ 7.6
Cyclic 31°C avg.	-6.4	—	-3.4	- 8.5	—	- 7.8	-22.2	—	- 13.8
Constant 31°C	-8.7	-3.6	-2.7	- 11.5	-6.7	- 11.9	-26.1	- 13.6	- 6.5

[a] HND + 20 = a diet with an increase of 20 percent of all nutrients, except energy that is greater by 10 percent, as compared to the control diet.

[b] HND + 25 = same as footnote[a] except nutrients are 25 percent higher.

released when weight is lost), and the energy for egg production. Thirteen equations were recently presented (McDonald, 1978), along with the capability of each to predict the actual ME encountered from 16 published reports from eight countries. None of the equations allows for an estimate of the environmental effect on maintenance requirements. Nevertheless McDonald's equation predicted daily ME requirements within 1.6 percent of observed values (Table 41). Emmans (1974) derived equations to estimate ME requirements for light and mid-weight hens, and included a correction for temperature. In the assumption that the temperature at each of the areas in the published report by McDonald was 21°C, Emmans' equation overestimates daily ME by 18.5 percent (Table 40), and the overestimates increase as the assumed temperature is raised. However, changing the equations by Emmans to estimate maintenance energy based on $W^{0\ 75}$ rather than $W^{1.0}$ at 21°C improves the overestimation down to only 3 percent (Table 40). Balnave *et al.* (1978) estimates that maintenance energy for laying hens changes at the rate of 1.4 percent per °C. Note that this value approximates the rate of change (1.55 percent) obtained from the estimated effect of temperature on feed intake (Table 37). Based on reviews by Grimbergen (1974) and Balnave (1974), maintenance energy for light breeds is estimated to range between 126 and 135 kcal per $W^{0\ 75}$ at 25°C. Grimbergen (1974) estimated poultry generally need 113 kcal/$W^{0\ 75}$/day for maintenance energy.

Combs (1968) predicted energy requirements for hens exposed to different environmental temperatures as follows:

$$ME = (1.78 + 0.012\,T)(1.45\,W^{0\ 653}) + 3.13\,\Delta W + 3.15\,E,$$

where
ME = metabolizable energy (kcal/day),
T = environmental temperature (°C),
ΔW = body weight (g),
W = body weight change (g), and
E = daily egg mass (g).

This equation does not account for differences in feather cover. To make that correction the data by Emmans and Charles (1977) can be used. Their estimate indicates that maintenance energy increases about 9 percent for each unit increase of a score denoting loss of feathers; a score ranging from one to six.

By assuming a correction of 1.5 percent per °C, compounded for maintenance energy, an efficiency of 80 percent for energy to be converted into weight gain or eggs, and calorigenic values of 4.4 kcal per gram of tissue (derived in the previous section) and 1.66 kcal per gram of egg (presented earlier), the following equation may be derived:

TABLE 41 Observed and Estimated ME Intakes of Various Experiments from the Review by McDonald (1978), Using the Equation ME = 130 W0 75 (1.015) t + 5.50 W + 2.07 EE and those by Emmans (1974) and McDonald (1978)

Location	Observed ME Intake	Emmans, 1974 (~ 21°C)	Emmans, 1974 ($W^{0\ 75}$ ~ 21°C)	McDonald, 1978	This Report
Belfast	319.0	378,0 (+ 18.5%)	339.8 (+ 6.5%)	314.9 (- 1.3%)	307.5 (- 3.6%)
Q.A.C.	294.6	405.0 (+37.5%)	350.2 (+ 18.9%)	318.0 (+ 8.0%)	313.0 (+ 6.2%)
Old Random	290.4	368.0 (+ 26.7%)	326.0 (+ 12.2%)	329.1 (+ 13.3%)	292.5 (+ 0.7%)
Israel	326.5	389.8 (+ 19.4%)	348.0 (+ 6.6%)	321.5 (- 1.5%)	315.0 (- 3.5%)
Beltsville	359.3	376.0 (+ 4.7%)	334.1 (- 7.0%)	327.9 (- 8.7%)	300.7 (- 16.3%)
Minnesota	313.6	379.4 (+21.0%)	332.7 (+ 6.1%)	313.4 (- 0.1%)	297.3 (- 5.2%)
Guelph	281.7	382.9 (+ 35.9%)	341.4 (+21.2%)	320.5 (+ 13.8%)	308.2 (+ 9.4%)
Vancouver	356. 1	423.3 (+ 18.9%)	360.9 (+ 1.4%)	327.5 (- 8.0%)	321.7 (- 9.7%)
Czechoslovakia[a]	445.9	565,0 (+ 26.7%)	442.1 (- 0.8%)	457.3 (+ 2.6%)	462.4 (+ 3.7%)
Norway	357.5	367,4 (+ 2.8%)	332.8 (- 6.9%)	328.2 (+ 8.2%)	301.9 (- 15.5%)
Florida[a]	442.4	495.7 (+ 12.1%)	406.2 (- 8.2%)	438.2 (- 0.9%)	425.0 (- 3.9%)
Texas	319.8	346.8 (+ 8.4%)	319.6 (± 0.0%)	307.3 (- 3.9%)	290.6 (- 9.1%)
Colorado	300.1	358.1 (+ 19.3%)	323.8 (+ 7.9%)	312.3 (+ 4.0%)	292.5 (- 2.5%)
N. Maryland[a]	393.3	419.7 (+ 6.7%)	344.7 (- 12.4%)	370.0 (- 5.9%)	360.1 (- 8.4%)
Seven Hills	330.6	422.7 (+ 27.9%)	364.9 (+ 10.4%)	345.5 (+ 4.5%)	327.8 (- 9.8%)
Reading[a]	372.6	408.4 (+ 9.6%)	344.4 (- 7.6%)	377.8 (+ 1.4%)	359.9 (- 3.4%)
		Mean = +18.5%	+ 3.0%	+ 1.6%	- 3.2%
		± 10.6%	± 9.9%	± 6.8%	± 6.3%

[a] Heavy breed.

$$ME = 130\ W^{0.75}\,(1.015)^{\Delta t} + 5.50\ \Delta W + 2.07\ EE,$$

where
W = body weight (kg),
ΔW = growth rate or rate of loss in grams per day,
EE = egg mass (g), and
Δt = difference between 25°C and ambient temperature (°C).

The above equation assumes a temperature of 22°C at all experimental stations listed in Table 40, a most unlikely probability; yet the equations underestimated the observed ME values by only 3.2 percent. Seven values were within ±5 percentage units of observed values. Unfortunately, experiments available in the literature do not have details on ambient temperatures and state of acclimation for the hens. Also to be noted is that heavy breeds were included in the estimates of Table 40. Emmans (1974) considered these separately. Nevertheless, the formula is a start, and the challenge is obvious.

Forced molting is practiced in the poultry industry. Less feed would be required to hold birds through a molt if buildings are kept warmer than usual. Those occasions when ambient temperatures allow this are favorable periods for the husbandry practice of forced molting. Use of fuel to attain desired feed-saving temperatures is minimized. In open housing, molted hens are stressed less at these warmer times of the year. The forced molting procedure is not practiced with ambient temperature considered in the cost-accounting of feed versus fuel. According to van Kampen (1974), an ambient temperature of 35°C reduces the H_eE of feathered poultry to 57 kcal/$W^{0\ 75}$. Although a savings of feed at higher temperatures appears to be possible, and feed efficiency is markedly improved, fuel costs and adverse physiological and nutritional factors make high-temperature rearing of birds uneconomical.

WATER

Water is a nutrient essential for life. Free water consumption accounts for 74 percent of the total daily intake. Metabolic water is a secondary source, accounting for 18 percent of the water intake. Temperature influences the proportional accounting of the total water intake (see Table 10). Also, as ambient temperatures rise, chickens consume increasing amounts of water (Figure 24). Such water intake is 2-fold and 21/2-fold at 32°C and 37°C, respectively, above that at 21°C. Increasing ambient temperatures appear to cause body temperature to rise slightly until ambient temperatures attain 38-39° C; then higher air temperatures cause a marked rise in body temperature (Figure 24) as the gradient between these two becomes less. The body heat is more difficult to remove, and physiological mechanisms (e.g., panting) are utilized to assist heat loss, but these, in turn, generate heat from their activity, thereby aggravating the situation. In domestic fowl, thermal polypnea increases steadily with increasing heat load, and energy utilized to remove heat reduces energy available for productivity. In addition, less feed is consumed as ambient temperatures rise, and this also reduces net energy for production. As the burden of heat stress becomes greater, the evaporative route (use of water) for heat loss from poultry becomes more dominant.

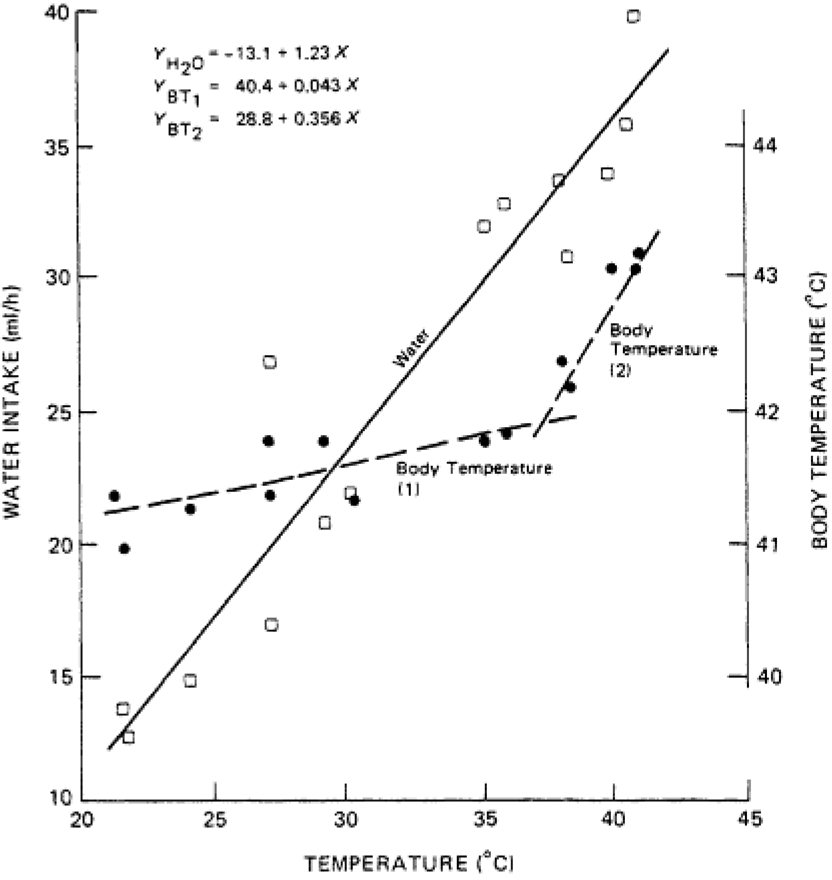

Figure 24.
The relationship between ambient temperature and water intake or body temperature of White Leghorn hens in chambers for 6 hours (adapted data from Wilson, 1948).

Hyperventilation is used to increase evaporative heat loss. During such situations, the exchange of gases in the lungs increases with a concomitant reduction in the level of CO_2 in the blood. This lowers the bicarbonate concentration of the blood, resulting in an adverse effect on shell formation. Heat stress produces its adverse effect on egg-shell quality in three ways: (1) by interfering with calcium carbonate formation for shell, (2) by reducing feed intake and thus calcium needed for shells, and (3) by upsetting the acid-base balance of the blood. Water plays an indirect role through its need to reduce heat stress by allowing greater evaporative heat loss and as a media for salt loss through secretory processes. Thus, poultry suffer even more when unable to obtain adequate water supplies during thermal stress.

Neither sweat glands nor sabaceous glands are found in the skin of poultry (Jenkinson and Blackburn, 1968). Nevertheless, loss of cutaneous heat accounts for 40-42 percent of the evaporative heat loss at ambient temperatures of 10-20° C and 27 percent of the loss at 35°C (van Kampen, 1974). The relative humidity of the air has an influence on the effectiveness of evaporative heat loss. Hot, humid environments are particularly stressful for poultry unless they are acclimatized or acclimated to such conditions. However, relative humidities of 52 to 90 percent at temperatures of 12.6 or 23.8°C have no effect on feed intake or weight gain (Prince *et al.*, 1965).

The availability of water for poultry is important for survival during heat stress. Hens allowed ample drinking water in containers large enough to dunk their heads survive longer during hot stressful conditions (Vo and Boone, 1978). Thus, the water serves as a coolant for external evaporation or to absorb heat from the head during drinking positions. In corroboration of these observations, hens were noted to withstand high ambient temperatures when allowed unlimited access to water, as compared to those given equivalent amounts by syringe directly into the crop (Lee *et al.*, 1945). The connotation of these data is that water presumed to be drank during heat stress may actually have been lost to the surroundings when shaken off the head. The impact of such losses on total water intake is not known.

VITAMIN A

High ambient temperatures reduce the intake of diets by young chickens (Ascarelli and Bartov, 1963; Kurnick *et al.*, 1964; Squibb *et al.*, 1958) and laying hens (Heywang, 1952). In all experiments, these investigators noted that the requirements of vitamin A did not change (Ascarelli and Bartov, 1963; Heywang, 1952; Kurnick *et al.*, 1964) or that absorption appeared to be unaffected (Squibb *et al.*, 1958) by higher temperatures. Instead the adjustment of vitamin A levels in diets is required because of the reduced intake of feed caused by high ambient temperatures.

SUMMARY

The optimum environment for rearing poultry is not necessarily that which allows maximal gain in weight or egg output. Efficiency of productivity, including cost factors, must also be considered. As environmental temperatures vary, so do efficiency and cost of productivity. For example, diets high in protein levels for maximum weight gain of turkeys seem most appropriate when protein is relatively cheap, but lower levels are justified when protein is expensive. The ambient temperature influences feed intake and thus must be considered in the profit-efficiency-weight gain output.

When nutrient intake is shifted by environmental influence on feed intake, an adverse effect on productivity (growth or egg output) ought to be alleviated by adjusting nutrient density to compensate for the altered intake of feed. Nutrient requirement was considered to be altered when such adjustments to give equal nutrient intake at different environmental conditions did not yield comparable productive outputs and/or efficiency. Research with poultry reveals that environmental temperatures over the range of 4 to 31°C do not affect nutrient requirement for protein, lysine, or vitamin A, as measured by growth or egg production.

A review of experimental data revealed that feed intake of poultry appears to change 1.5 percent per °C over the range of 5-35°C with 20-21°C as a baseline. It decreases as temperatures rise, and vice versa. Maintenance energy is less at temperatures above 21°C and higher at lower temperatures. Thus productive efficiency generally tends to improve as environmental temperatures increase and be less efficient at colder temperatures. Energetic efficiency of egg production considers such factors as weight of eggs produced, percentage egg production, amount of feed consumed, and caloric density of the diet. Tables are presented to allow the energetic efficiency to be determined from a set of values for each of the factors involved. These values are based on how the energy value of an egg is calculated, and this is discussed. The impact of body weight on energetic efficiency is noted, as well as how a change in ambient temperature can influence energetic efficiency by influencing a change in body weight.

Prediction equations are presented for estimating ME requirements of laying hens subjected to different ambient temperatures. One such derived equation is based upon a review of data in the literature. It differs from earlier equations by adjustments of constants to reflect additional information gathered during more recent experiments. These equations are expected to be a challenge for future research to improve their predictability.

In cold environments hens are stimulated to eat more. Under such conditions marginal deficiencies in nutrients appear to be overcome by the increase in daily nutrient intake. On the other hand, hot environments may produce nutrient deficiencies for marginally adequate diets because of the decline in feed intake. Making allowances for these situations by adjustment of nutrient density appears to alleviate some, but not all, of the adverse effects from very hot conditions. Shell quality seems to be one of those in the latter category.

Acclimation of poultry to continuous hot environments must be a consideration in accounting for nutrient requirements. As little as 7 days, and as long as 28 days, were reported for poultry to acclimate. Differences in adjustment appear to be associated with such factors as age, species, temperature of stressful situations, and the type of productivity being measured.

Carcass composition will change during shifts in environmental temperatures, and much of the change is related to the effect on feed intake and, thus, nutrient intake.

As ambient temperatures rise, poultry consume increasing amounts of water. Such water intake is 2-fold at 32°C, and 21/2-fold at 37°C greater than the intake at 21°C. The water plays an important role in evaporative heat loss and to influence appetite, which accounts for less feed consumed as temperatures rise. Thus energy used to dissipate the heat load, and a decline in energy available from the lower feed intake, reduces net energy available for productivity. Availability of water for poultry is important for survival under heat stress. There is some indication that poultry use the water as a coolant for external evaporation, or to absorb heat from the head during drinking positions.

EPILOGUE

Part I of this report provided a foundation of information relating nutrition and environment. Both direct and indirect influences of the environment are shown to have a major impact on nutrient intake, requirement, and utilization. Clearly, the role of environment in livestock and poultry nutritional management is a valid consideration.

Discussions describing the impact of environment on different species and suggested techniques for nutritional management to deal with different environments are presented in Part II. Some species differences in the depth of understanding of nutrition-environment interactions are evident. For example, for poultry a more quatitative approach is possible, whereas a more estimated approach is described for dairy cattle. Differences are also apparent when schemes for maximizing efficiency of growth are compared with efficiency of expelled products, i.e., eggs and milk. Yet, many similarities among species exist. All species are affected by the influence of environment on rate of feed intake and maintenance energy requirement. And, all are concerned with maximizing caloric efficiency to conserve energy resources. Effect of environment on rates of energy flow is important in all cases and is the basis for most observed nutrition-environment interactions.

The authors have projected their best estimates of nutrient adjustments for livestock exposed to adverse environments. In some cases these adjustments are based on limited research data and plagued with uncertainty. That is especially evident for ruminants. Research data are more abundant for poultry, but still much is unknown. It is hoped that the material presented will be of immediate value, but perhaps more importantly that it will stimulate additional research.

Research areas that need immediate study are numerous. Initially, a more accurate system for characterizing the total environment is needed. Further development of effective ambient temperature (EAT) is necessary to accurately assess environmental impact. Basic research to establish accurate and reliable patterns of voluntary feed intake for animals in different environments is needed so that nutrient adjustments can more readily be incorporated in management systems. Maintenance energy requirement needs to be known for varying degrees of thermal stress. This need is particularly lacking for heat stress. An understanding of mechanisms and ramifications of acclimatization to environment would enhance the development of management strategies to deal with changing environments. More research must be conducted to predict responses to fluctuating temperatures similar to those encountered under natural conditions. The impact of nonclimatic variables such as psychological stressors and management systems on nutrient requirement should be investigated. And, unknown subtle effects of environment await discovery.

An integrated systems approach to managing livestock must include the effects of environment if maximum utilization of resources is to be realized. It is hoped this report will aid in achieving that goal.

REFERENCES

Adams, R. L., F. N. Andrews, J. C. Rogler, and C. W. Carrick. 1962. The protein requirement of 4-week old chicks as affected by temperature. J. Nutr. 77:121.

Abroad, M. M., F. B. Mather, and E. W. Gleaves. 1974. Effect of environmental temperature and dietary energy on dwarf and normal hens and normal roosters. Poult. Sci. 53:927.

Alexander, G. 1962. Temperature regulation in the new-born lamb. V. Summit metabolism. Aust. J. Agric. Res. 13:100.

Alexander, G. 1968. The environment and neonatal survival in sheep in Australia. Proc. Ecol. Soc. Aust. 3:125.

Alexander, G. 1974. Heat loss from sheep. *In* J. L. Monteith and L. E. Mount, eds.. Heat Loss from Animals and Man. Butterworth, London.

Allden, W. G. 1968. Undernutrition of the Merino sheep and its sequelae. I. Growth and development of lambs following prolonged periods of nutritional stress. Aust. J. Agric. Res. 19:621.

Ames, D. R. 1969. Normal responses of sheep to acute thermal stress. Unpublished Ph.D. Thesis. Michigan State University, East Lansing.

Ames, D. R. 1980. Thermal environment affects livestock performance. BioScience 30:457.

Ames, D. R., and D. R. Brink. 1977. Effect of temperature on lamb performance and protein efficiency ratio. J. Anita. Sci. 44:136.

Ames, D. R., and L. W. Insley. 1975. Wind-chill effect for cattle and sheep. J. Anim. Sci. 40:161.

Ames, D. R., J. E. Nellor, and T. Adams. 1971. Energy balance during heat stress in sheep. J. Anim. Sci. 32:784.

Ames, D. R., D. R. Brink, and R. R. Schalles. 1975. Relationship of temperature and ADG. J. Anita. Sci. 41:263. (Abstr.)

Ames, D. R., D. R. Brink, and C. L. Willms. 1980. Adjusting protein in feedlot rations during thermal stress. J. Anim. Sci. 50:1.

ARC. 1963. The nutrient requirements of' farm livestock. No. 1 (Poultry). Agric. Res. Counc., London.

ARC. 1965. The nutrient requirements of farm livestock. No. 2 (Ruminants). Agric. Res. Counc., London.

ARC. 1966. The nutrient requirements of farm livestock. No. 3 (Pigs). Agric. Res. Counc., London.

Armstrong, D. G., K. Blaxter, N. McC. Graham, and F. Wainman. 1959. The effect of environmental conditions on food utilization by sheep. Anim. Prod. 1:1.

Ascarelli, I., and I. Bartov. 1963. Vitamin A requirements of chicks at moderately elevated temperature. Poult. Sci. 42:232.

Attebery, J. T., and H. D. Johnson. 1969. Effect of environmental temperature, controlled feeding and fasting on tureen motility. J. Anita. Sci. 29:727.

Baccari, F., H. D. Johnson, and G. L. Hahn. 1980. Compensatory growth of young dairy heifers subjected to heat stress. J. Anita. Sci. 51:4. (Abstr.)

Bailey, C. B., R. Hironaka, and S. B. Slen. 1962. Effects of the temperature of the environment and the drinking water on the body temperature and water consumption of sheep. Can. J. Anim. Sci. 42:1.

Balch, C. C. 1950. Factors affecting the utilization of food by dairy cows. 1. Rate of passage of food through the digestive tract. Br. J. Nutr. 4:361.

Balnave, D. 1974. Biological factors affecting energy expenditure, p. 25-46. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

Balnave, D., D. J. Farrell, and R. B. Cumming. 1978. The minimum metabolizable energy requirement of laying hens. World's Poult. Sci. J. 34(3): 149.

Bates, D. W. 1974. Future direction of dairy cattle environment research and needs for additional knowledge. Proc. Intern. Livestock Environ. Symp., p. 416. Am. Soc. Agric. Eng., St. Joseph, Mich.

Bell, J., and B. M. Freeman. 1971. Physiology and Biochemistry of the Domestic Fowl. Academic Press, Inc., Ltd., London.

Bennett, J. W. 1972. The maximum metabolic response of sheep to cold: Effects of rectal temperature, shearing, feed consumption, body posture and body weight. Aust. J. Agric. Res. 23:1045.

Berry, I. L., M.D. Shanklin, and H. D. Johnson. 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans. ASAE 7:329.

Bhattacharya, A. N., and F. Hussain. 1974. Intake and utilization of nutrients in sheep fed different levels of roughage under heat stress. J. Anim. Sci. 38:877.

Bhattacharya, A., and M. Uwayjan. 1975. Effect of high ambient temperature and low humidity on nutrient utilization and on some physiological responses in Awasi sheep fed different levels of roughage. J. Anim. Sci. 40:320.

Bianca, W. 1970. Animal responses to meteorological stress as a function of age. *In* Biometeorology, vol. 4. Part I: Proceedings of The Fifth International Biometeorological Congress held at Montreux, Switzerland, ed. by S. W. Tromp and W. H. Weihe, published as a Supplement to vol. 14 of the International Journal of Biometeorology, 1970, by Swets and Zeitlinger, Amsterdam. Pages 119-131.

Bierer, B. W., W. T. Carll, and T. H. Eleazer. 1966. A comparison of the survival time and gross pathology in producing and non-producing White Leghorn hens deprived of water. Poult. Sci. 45:65.

Blaxter, K. L. 1962. The fasting metabolism of adult wether sheep. Br. J. Nutr. 16:615.

Blaxter, K. L. 1967. The Energy Metabolism of Ruminants. Hutchinson and Co., London.

Blaxter, K. L. 1977. Environmental factors and their influence on the nutrition of farm livestock, p. 1. *In* W. Haresign, H. Swan, and D. Lewis, eds., Nutrition and the Climatic Environment. Butterworth, London.

Blaxter, K. L. 1978. The effect of simulated altitude on the heat increment of feed in sheep. Br. J. Nutr. 39:659.

Blaxter, K. L., and F. W. Wainman 1961. Environmental temperature and the energy metabolism and heat emission of steers. J. Agric. Sci. (Camb.) 56:81.

Blaxter, K. L., N. McC. Graham, and F. W. Wainman. 1956. Some observations on the digestibility of food by sheep, and on related problems. Br. J. Nutr. 10:69.

Blaxter, K. L., N. McC. Graham, and F. W. Wainman. 1959. Environmental temperature, energy metabolism and heat regulation in sheep. III. Metabolism and thermal exchanges of sheep with fleeces. J. Agric. Sci. 52:41.

Blaxter, K. L., J. L. Clapperton, and F. W. Wainman. 1966. The extent of differences between six British breeds of sheep in their metabolism, feed intake and utilization, and resistance to climate stress. Br. J. Nutr. 20:283.

Bolton, W. 1958. The efficiency of food utilization for egg production by pullets. J. Agric. Sci. (Camb.) 50:97.

Bond, J., and R. E. McDowell. 1972. Reproductive performance and physiological responses of beef females as affected by a prolonged high environmental temperature. J. Anim. Sci. 35:820.

Bond, T. E., C. F. Kelly, and H. Heitman, Jr. 1963. Effect of diurnal temperature on heat loss and well-being of swine. Trans. ASAE 6:132.

Bond, T. E., H. Heitman, and C. F. Kelly. 1965. Effects of increased air velocities on heat and moisture loss and growth of swine. Trans. ASAE 8:167.

Bond, T. E., C. F. Kelly, and S. R. Morrison. 1967. Physiological response of swine to cycling environmental conditions. Anim. Prod. 9:453.

Bray, D. J., and J. A. Gesell. 1961. Studies with corn soya diets. Environmental temperature— a factor affecting performance of pullets fed diets sub-optimal in protein. Poult. Sci. 40:1328.

Brink, D. R. 1975. Effect of ambient temperature on lamb performance. M.S. Thesis. Kansas State University, Manhattan.

Brink, D. R., and D. R. Ames. 1975. Effect of ambient temperature on lamb performance. J. Anim. Sci. 41:264. (Abstr.)

Brink, D. R., and D. R. Ames. 1978a. Thermal stress and NE_m, of lambs. 11th Annual Midwest ASAS. (Abstr.)

Brink, D. R., and D. R. Ames. 1978b. Effect of thermal stress on protein for maintenance. 70th ASAS, p. 407.

Brody, S., A. Ragsdale, N. Thompson, and D. Worstell. 1954. The thermal effects of radiation intensity (light) on milk production, feed and water consumption, and body weight in Holstein, Jersey, and Brahman cows at air temperatures 45°, 70°, and 80°F. Mo. Agric. Exp. Stn. Bull. 556.

Brokken, R. F. 1971. Formulating beef rations for improved performance under environmental stress. Am. J. Agric. Econ. 53:79.

Brouwer, E. 1965. Report of sub-committee on constants and factors, pp. 441-443. *In* K. L. Blaxter, ed., Energy Metabolism. Academic Press, London.

Brown, D. E., R. R. Hacker, and G. J. King. 1976. Growth and ACTH responses to cold stress of young pigs fed *ad libitum*. Can. J. Anita. Sci. 56:365.

Brown, W. O., J. J. Waring, and R. F. Addison. 1967. The utilization of energy by the laying hen, pp. 77-97. *In* Progress in Livestock Nutrition. U.S. Feed Grain Council, London.

Buckebusch, Y. and J.P. Marguet. 1964. Recherches surle comportement alimentaire, chez les ruminants. 2. Influence de la temperature ambiante. Rev. Med. Vet. 115:397.

Burman, A., and N. Snaper. 1965. The relation of fasting and resting metabolic rates to heat tolerance in the domestic fowl. Br. Poult. Sci. 6:207.

Calder, F., J. Nicholson, and H. Cunningham. 1964. Water restrictions for sheep on pasture and rate of consumption with other feeds. Can. J. Anita. Sci. 44:266.

Castle, M. E. 1972. A study of the intake of drinking water by dairy cows at grass. J. Br. Grassl. Soc. 27:207.

Castle, M. E., and E. Macdaid. 1975. The intake of drinking water by dairy cows at grass. J. Br. Grassl. Soc. 30:7.

Castle, M. E., and J. N. Watson. 1973. The intake of drinking water by grazing dairy cows. The effect of water availability. J. Br. Grassl. Soc. 28:203.

Castle, M. E., A. Foot, and R. Holley. 1950. Some observations on the behaviour of dairy cattle with particular reference to grazing. J. Dairy Res. 17(3):215.

Cerniglia, G., K. L. Koonce, and A. B. Watts. 1978. Effects of ambient temperature on broilers. La. Agric. 21:14.

Charles, D. R. 1974. The definition and measurement of the climatic environment in poultry houses, pp. 73-77. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

Christopherson, R. J. 1976. Effects of prolonged cold and the outdoor winter environment on apparent digestibility in sheep and cattle. Can. J. Anim. Sci. 56:201.

Christopherson, R. J., R. J. Hudson, and M. K. Christopherson. 1979. Seasonal energy expenditures and thermoregulatory response of bison and cattle. Can. J. Anim. Sci. 59:611.

Church, D. C., G. E. Smith, J. P. Fontenot, and A. T. Raison. 1974. Water metabolism and requirements. *In* Digestive Physiology and Nutrition of Ruminants, vol. 2 (Nutrition). O&B Books, Corvallis, Oreg.

Clark, C. E., and M. Amin. 1965. The adaptability of chickens to various temperatures. Poult. Sci. 44:1003.

Close, W. H., and L. E. Mount. 1975. The rate of heat loss during fasting in the growing pig. Br. J. Nutr. 34:279.

Close, W. H., and L. E. Mount. 1976. Gains in protein and fat in the growing pig in relation to environmental temperature. 7th Symposium on Energy Metabolism. EAAP Publ. No. 15, p. 173. Vichy INRA.

Close, W., L. Mount, and I. Start. 1971. The influence of environmental temperature and plane of nutrition on heat losses from groups of growing pigs. Anim. Prod. 13:285.

Close, W. H., M. W. A. Verstegen, and L. E. Mount. 1973. The energy costs of maintenance and production in the growing pig. Proc. Nutr. Soc. 32:72A.

Colditz, P. J., and R. C. Kellaway. 1972. The effect of diet and heat stress on feed intake, growth and nitrogen metabolism in Friesian, Fl Brahman x Friesian, and Brahman heifers. Aust. J. Agric. Res. 23:717.

Cornberg, G., H. F. Wolfermann, and H. Rundefeldt. 1967. The influence of temperature and relative humidity on weight gain and feed utilization in finishing swine. Z. Tierz. Zuchts Biol. 83:240.

Combs, G. F. 1968. Amino acid requirements of broiler and laying hens. Proc. Md. Nutr. Conf., p. 86.

Cotterill, O. J., W. W. Marion, and E. C. Naber. 1977. A nutrient reevaluation of shell eggs. Poult. Sci. 56:1927.

Cowan, R. T., D. Shackel, and T. M. Davison. 1978. Water intakes, milk yield and grazing behaviour of Friesian cows with restricted access to water in a tropical upland environment. Aust. J. Exp. Agric. Anita. Hush. 18:190.

Crampton, E. W., and L. E. Harris. 1969. Applied Animal Nutrition, 2nd ed. W. H. Freeman and Co., San Francisco.

Cunningham, M. D., F. A. Martz, and C. P. Merilan. 1964. Effect of drinking water temperature upon ruminant digestion, intraruminal temperature, and water consumption of nonlactating dairy cows. J. Dairy Sci. 47:382.

Dale, N. M., and H. L. Fuller. 1980. Effect of diet composition on feed intake and growth of chicks under heat stress. II. Constant vs. cycling temperatures. Poult. Sci. 59:1434.

Davis, R. H., O. E. M. Hassan, and A. H. Sykes. 1972. The adaptation of energy. utilization in the laying hen to warm and cool ambient temperatures. J. Agric. Sci. (Camb.) 79:363.

Davis, R. H., O. E. Hassan, and A. Sykes. 1973. Energy utilization in the laying hen in relation to ambient temperature. J. Agric. Sci. (Camb.) 80:173.

Daws, G. T., and V. R. Squires. 1974. Observations on the effects of temperature and distance to water on the behavior of Merino and Border Leicester sheep. J, Agric. Sci. (Camb.) 82:383.

de Andrade, A. N., J. C. Rogler, and W. R. Featherstone. 1976. Influence of constant elevated temperature and diet on egg production and shell quality. Poult. Sci. 55:685.

de Andrade, A. N., J. C. Rogler, W. R. Featherstone, and C. W. Alliston. 1977. Interrelationships between diet and elevated temperatures (cyclic and constant) on egg production and shell quality. Poult. Sci. 56:1178.

Degen, A. A., and B. A. Young. 1980. Effect of cold exposure on liveweight and body fluid compartments in sheep. Can. J. Anim. Sci. 60:33.

Deinum, B. 1966. Influence of some climatological factors on the chemical composition and feeding value of herbage. Proc. X Intern. Grassl. Cong., p. 415.

Deinum, B. 1976. Effect of age, leaf number, and temperature on cell wall and digestibility of maize. Carbohydrate Research in Plants and Animals. Miscellaneous Papers 12. Landbouwhogeschool, Wageningen, The Netherlands.

Deinum, B., A. van Es, and P. J. Van Soest. 1968. Climate, nitrogen and grass. II. The influence of light intensity, temperature and nitrogen on *in vivo* digestibility of grass and the prediction of these effects from some chemical procedures. Neth. J. Agric. Sci. 16:217.

Dukes, H. H. 1947. The Physiology of Domestic Animals, 6th ed. Comstock Publishing Co., Ithaca, N.Y.

Elam, C. J. 1971. Problems related to intensive indoor and outdoor production systems. J. Anim. Sci. 32:554.

Emmans, G. C. 1974. The effects of temperature on the performance of laying hens, pp. 79-90. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

Emmans, G. C., and D. R. Charles. 1977. Climatic environment and poultry feeding in practice, p. 31. *In* W. Haresign, H. Swan, and D. Lewis, eds., Nutrition and the Climatic Environment. Butterworth, London-Boston.

Erb, R. E., A. N. de Andrade, and J. C. Rogler. 1978. Interrelationships between diet and elevated temperatures (cyclic and constant) on concentrations of progesterone, estradiol-17β and testosterone in blood plasma of laying hens. Poult. Sci. 57(4):1042.

Faix, J. F. 1974. The effect of temperature and day length on the quality of morphological components of three legumes. Unpublished Ph.D. Thesis. Cornell University, Ithaca, N.Y.

Filmer, D. G., and M. K. Curran. 1977. Climatic environment and practical nutrition of the growing pig, p. 25. *In* W. Haresign, H. Swan, and C. Lewis, eds., Nutrition and the Climatic Environment. Butterworth, London.

Fisher, H. K., G. Hollands, and H. S. Weiss. 1962. Environmental temperature and composition of body fat. Proc. Soc. Exp. Biol. Med. 110:832.

Fisher, H., P. Griminger, and H. S. Weiss. 1965. Body composition and atherosclerosis in cocks after long exposure to heat and cold. J. Appl. Physiol. 20:591.

Forbes, J. 1968. Water intake of ewes. Br. J. Nutr. 22:33.

Freeman, A. E. 1975. Genetic variation in nutrition of dairy cattle, pp. 19-46. *In* The Effect of Genetic Variance on Nutritional Requirements of Animals. National Academy of Sciences, Washington, D.C.

Freeman, B. M. 1963. The gaseous metabolism of the domestic chicken. III. The oxygen requirements of the chicken during the period of rapid growth. Br. Poult. Sci. 4:169.

Fuller, H. L., and M. Rendon. 1977. Energetic efficiency of different dietary fats for growth of young chicks. Poult. Sci. 56:549.

Fuller, M. F. 1965. The effect of environmental temperature on the nitrogen metabolism and growth of the young pig. Br. J. Nutr. 19:531.

Fuller, M. F., and A. W. Boyne. 1971. The effect of environmental temperature on the growth and metabolism of pigs given different amounts of food. I. Nitrogen metabolism, growth, and body composition. Br. J. Nutr. 25:259.

Fuller, M. F., and A. W. Boyne. 1972. The effects of environmental temperature on the growth and metabolism of pigs given different amounts of food. 2. Energy metabolism. Br. J. Nutr. 28:373.

Fuquay, J. W. 1981. Heat stress as it affects animal production. J. Anim. Sci. 52:164.

Gale, C. C. 1973. Neuroendocrine aspects of thermo-regulation. Annu. Rev. Physiol. 35:391.

Giacomini, G. E. 1979. Effect of fluctuating temperature on lamb performance. Unpublished M.S. Thesis. Kansas State University, Manhattan.

Gonyou, H. W., R. J. Christopherson, and B. A. Young. 1979. Effects of cold temperature and winter condition on some aspects of behaviour of feedlot cattle. Appl. Anita. Ethol. 5:113.

Graham, N. McC. 1965. Metabolism of the pregnant ewe and some effects of thermal stress, p. 387. *In* K. L. Blaxter, ed., Energy Metabolism. Academic Press, London.

Graham, N. McC., and T. W. Searle. 1975. Studies of weaner sheep during and after a period of weight stasis. I. Energy and nitrogen utilization. Aust. J. Agric. Res. 26:343.

Graham, N. McC., F. W. Wainman, K. L. Blaxter, and D. G. Armstrong. 1959. Environmental temperature, energy metabolism, and heat regulation in sheep. I. Energy metabolism in closely clipped sheep. J. Agric. Sci. (Camb.)52:13.

Gray, R., and K. J. McCracken. 1974. Utilization of energy and protein by pigs adapted to different temperature levels, p. 161. 6th Symposium on Energy Metabolism EAAP Publ. No. 14. Stuttgart University, Hohenheim.

Grimbergen, A. H. M. 1974. Energy expenditure under productive conditions, p. 61. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

Guthrie, L. D., J. B. Frye, Jr., and J. A. Lee. 1968. Effects of exposure to shade or sun and level of fiber on the efficiency of energy utilization by lactating Holstein cows. J. Dairy Sci. 51:969.

Hacker, R. R., M. P. Stefanovic, and T. R. Batia. 1973. Effects of cold exposure on growing pigs: Growth, body composition and 17-ketosteroids. Can. J. Anita. Sci. 37:739.

Hafez, E. S. E. 1968. Adaptation of Domestic Animals. Lea & Febiger, Philadelphia.

Hahn, G. L. 1981. Housing and management to reduce climatic impacts on livestock. J. Anim. Sci. 52:175.

Hahn, G. L., N. F. Meador, D. G. Stevens, and M. D. Shanklin. 1975. Compensatory growth in livestock subjected to heat stress. Paper 75-4008. Am. Soc. Agr. Eng., St. Joseph, Mich.

Hales, J. R. S. 1973. Effects of heat stress on blood flow in respiratory and nonrespiratory muscles in the sheep: An explanation of the apparent high efficiency of panting. Pfluger Arch. 344:119.

Hales, J. R. S., and J. D. Findlay. 1968. The oxygen cost of thermally-induced and CO_2-induced hyperdilation in the ox. Resp. Physiol. 4:353.

Hancock, J. 1953. Grazing behavior of cattle. Anita. Br. Abstr. 21:1.

Harbers, L. H., D. R. Ames, A. B. Davis, and M. B. Ahmed. 1975. Digestive responses of sheep to auditory stimuli. J. Anim. Sci. 41:654.

Harris, R., H. Yates, and J. Barnett. 1967. Refrigerated water for fattening steers. J. Anita. Sci. 26:207.

Harrison, P. C., and H. V. Biellier. 1969. Physiological response of domestic fowl to abrupt changes of ambient air temperature. Poult. Sci. 48:1034.

Hazen, T. E., and D. W. Marigold. 1960. Functional and basic requirements of swine housing. Trans. ASAE 41:585.

Head, M. J. 1953. The effect of pregnancy and lactation in the ewe on the digestibility of the ration with a note on the partition of nitrogen in the foetus at full term. J. Agric. Sci. 43:214.

Heitman, H., and E. Hughes. 1949. The effects of air temperature and relative humidity on the physiological well being of swine. J. Anim. Sci. 8:171.

Heirman, H., C. F. Kelley, and T. E. Bond. 1958. Ambient air temperature and weight gain in swine. J. Anim. Sci. 17:62.

Hellickson, M. A., A. F. Butchbaker, R. L. Witz, and R. L. Bryant. 1966. Performance of growing turkeys as affected by environmental temperature. Proc. Annu. Meet. Am. Soc. Agric. Eng. Chicago, Ill.

Henderson, H. E., and M. R. Geasler. 1969. Effect of environment and housing on performance of feedlot cattle under midwest conditions. Mich. State Univ. Bull. AH-BC-48, p. 1.

Heywang, B. W. 1952. The level of vitamin A in the diet of laying and breeding chickens during hot weather. Poult. Sci. 31:294.

Hicks, A. M. 1966. Physiological responses of growing swine to low temperatures. Unpublished Ph.D. Thesis. University of Saskatchewan, Saskatoon.

Hidiroglou, M., and J. R. Lessard. 1971. Some effects of fluctuating low ambient temperatures on beef cattle. Can. J. Anim. Sci. 51:111.

Hollon, B. F., and C. Branton. 1970. Growth rate of purebred Holstein versus purebred-sired crosses and crossbred-sired dairy cattle. J. Dairy Sci. 53:665.

Hollon, B. F., and C. Branton. 1973. Health and viability of purebred Holsteins compared to crosses among Brown Swiss, Holsteins, Jerseys and Red Sindhis. J. Dairy Sci. 56:309.

Holme, D. W., and W. E. Coey. 1967. Effects of environmental temperature and method of feeding on performance and carcass composition of bacon pigs. Anim. Prod. 9:209.

Holmes, C. W.1971. Growth and backfat depth of pigs kept at a high ambient temperature. Anim. Prod. 13:521.

Holmes, C. W., and W. H. Close. 1977. The influence of climatic variables on energy metabolism and associated aspects of productivity in the pig, p. 51. *In* W. Haresign, H. Swan, and D. Lewis, eds., Nutrition and the Climatic Environment. Butterworth, London.

Holmes, C. W., and N. D. Grace. 1975. A note on the metabolism of Ca, P, Mg, Na and K by pigs growing at a high ambient temperature. Anim. Prod. 21:341.

Holmes, C. W., and N. R. McLean. 1977. The heat production of groups of young pigs exposed to reflective or non-reflective surfaces on walls and ceilings. Trans. ASAE 77:527.

Howard, B. R. 1975. Water balance of the hen during egg formation. Poult. Sci. 54(4):1046.

Ingram, D. L. 1974. Heat loss and its control in pigs, p. 233. *In* J. L. Monteith and L. E. Mount, eds., Heat Loss from Animals and Man. Butterworth, London.

Irving, L. 1964. Terrestrial animals in cold: birds and mammals, p. 361. *In* Handbook Of Physiology, Section 4, Adaptation to the Environment. Am. Physiol. Soc., Washington, D.C.

Ittner, N., C. Kelly, and H. Guilbert. 1951. Water consumption of Hereford and Brahman cattle and the effect of cooled drinking water in a hot climate. J. Anim. Sci. 10:742.

Jackson, N. 1972. Effect of restricting energy intake of the laying hen, directly and by dilution of the diet, on egg production and the efficiency of energy utilization. J. Sci. Food Agric. 23:413.

Jenkinson, D. McE., and P. S. Blackburn. 1968. The distribution of nerves, monamine oxidase, and cholinesterase in the skin of poultry. Res. Vet. Sci. 9:429.

Jensen, A. H. 1971. Biological implication of intensive swine mating systems. J. Anim. Sci. 32:560.

Jensen, A. H., D. E. Kuhlman, D. E. Becker, and B. G. Harmon. 1969. Responses of growing-finishing swine to different housing environments during winter seasons. J. Anim. Sci. 29:451.

Johnson, H. D. 1965. Environmental temperature and lactation. Int. J. Biomet. 9:103.

Johnson, H. D., ed. 1976. Progress in Biometeorology, vol. 1, part 1, div. B. Swets and B. V. Zeithlinger, Amsterdam.

Johnson, H. D., and A. C. Ragsdale, 1959. Effects of constant environmental temperatures of 50° and 80°F on the growth responses of Holstein, Brown Swiss, and Jersey calves. Mo. Agric. Exp. Stn. Bull. 705.

Johnson, H. D., and R. G. Yeck. 1964. Age and temperature effects on TDN, water consumption and balance of dairy calves and heifers exposed to environmental temperatures of 35 to 95° F. Mo. Agric. Exp. Stn. Bull. 865.

Johnson, H. D., A. C. Ragsdale, and R. G. Yeck. 1958. Effects of constant environmental temperatures of 50° and 80°F on the feed and water consumption of Brahman, Santa Gertrudis, and Shorthorn calves during growth. Mo. Agric. Exp. Stn. Bull. 683.

Johnson, H. D., A. C. Ragsdale, I. Berry, and M. Shanklin. 1963. Temperature-humidity effects including influence of acclimation in feed and water consumption of Holstein cattle. Mo. Agric. Exp. Stn. Bull. 846.

Johnson, J. C., Jr., B. L. Southwell, R. L. Givens, and R. E. McDowell. 1962. Interrelationships of certain climatic conditions and productive responses of lactating dairy cows. J. Dairy Sci. 45:695.

Johnston, J. E., G. A. Hindry, D. H. Hill, and A. Guidry. 1961. Factors concerned in hot weather effects on growth and feed efficiency of dairy heifers. J. Dairy Sci. 44:976.

Jolliff, G. D., A. Garza, and J. M. Hertel. 1979. Seasonal forage nutritive value variation of Coastal and Coastcross-1 bermudagrass. Agron. J. 71:91.

Jones, J. E., and B. D. Barnett. 1974. Effect of changing dietary energy and environmental temperature on feed consumption of large broad breasted White turkey hens. Poult. Sci. 53:335.

Jones, J. E., B. L. Hughes, and B. D. Barnett. 1976. Effect of changing dietary energy levels and environmental temperatures on feed consumption and egg production of single comb White Leghorns. Poult. Sci. 55:274.

Jones, T. J., R. M. Hough, and W. T. Gerard. 1962. Vitamin A studies in the dairy calf. Can. Vet. J. 3:248.

Joyce, J. P., and K. L. Blaxter. 1964. The effect of air movement, air temperature and infrared radiation on the energy requirements of sheep. Br. J. Nutr. 18:5.

Kalu, B. A. 1976. Age and time of year effects on alfalfa (*Medicago satira L.*) quality and morphological development. Unpublished M.S. Thesis. Cornell University, Ithaca, N.Y.

Kennedy, P.M., and L. P. Milligan. 1978. Effect of cold exposure on digestion, microbial synthesis and nitrogen transformations in sheep. Br. J. Nutr. 35:105.

Kennedy, P. M., R. J. Christopherson, and L. P. Milligan. 1976. The effect of cold exposure of sheep on digestion, rumen turnover time and efficiency of microbial synthesis. Br. J. Nutr. 36:231.

Kennedy, P. M., B. A. Young, and R. J. Christopherson. 1977. Studies on the relationship between thyroid function, cold acclimation and retention time of digesta in sheep. J. Anita. Sci. 45:1084.

Kerstens, R. 1964. Investigation of the production of heat and water vapour and the influence of environment on the growth rate of broiler chicks. Funki Information, Funki Ltd., Aerhus, Denmark.

Khalil, A. A., O. P. Thomas, and G. F. Combs. 1968. Influence of body composition, methionine deficiency or toxicity and ambient temperature on feed intake in the chick. J. Nutr. 96:337.

Kibler, H. H. 1957. Environmental physiology and shelter engineering, with special reference to domestic animals. XLIII. Energy metabolism and cardio-respiratory activities in Shorthorn, Santa Gertrudis, and Brahman heifers during growth at 50 and 80°F temperatures. Mo. Agric. Exp. Stn. Bull. 643.

Kibler, H. H., and S. Brody. 1951. Environmental physiology. XIII. Influence of increasing temperature 40 to 105 F on heat production and cardio-respiratory activities in Brown Swiss and Brahman cows and heifers. Univ. Mo. Res. Bull. 473.

King, J. R., and D. S. Farner. 1961. Energy metabolism, thermo-regulation, and body temperature. *In* A. J. Marshall, ed., Biology and Comparative Physiology of Birds, vol. II. Academic Press, New York.

Kleiber, M. 1961. The Fire of Life. John Wiley & Sons, Inc., New York.

Knowltoh, P. H., W. H. Hoover, and B. R. Poulton. 1969. Effects of higher carbon dioxide levels on nutrition of sheep. J. Anim. Sci. 28:554.

Kohne, H. J., and J. E. Jones. 1976. The relationship of circulating levels of estrogen, corticosterone, and calcium to production performance of adult turkey hens under conditions of increasing ambient temperature. Poult. Sci. 55:277.

Kubena, L. F., B. D. Lott, J. W. Deaton, F. N. Reece, and J. D. May. 1972. Body composition of chicks as influenced by environmental temperature and selected dietary factors. Poult. Sci. 51:517.

Kurnick, A. A., B. W. Heywang, B. J. Hulett, M. G. Vavich, and B. L. Reid. 1964. The effect of dietary vitamin A, ambient temperature, and rearing location on growth, feed conversion, and vitamin liver storage of White Leghorn pullets. Poult. Sci. 43:1582.

Kwan, K., C. E. Coppock, G. Blake, M. J. Fettman, L. E. Case, and R. E. McDowell. 1977. Use of urea by early postpartum cows. J. Dairy Sci. 60:1706.

Laredo, M. A., and D. J. Minson. 1973. The voluntary intake, digestibility and retention time by sheep of leaf and stem fractions of fine grasses. Aust. J. Agr. Res. 24:875.

Lee, D. H. K., K. W. Robinson, N. T. M. Yeates, and M. I. R. Scott. 1945. Poultry husbandry in hot climates—experimental enquiries. Poult. Sci. 24:195.

Leeson, S., D. Lewis, and D. H. Shrimpton. 1973. Multiple linear regression equations for the prediction of food intake in the laying fowl. Br. Poult. Sci. 14:595.

Leu, B. M., M. P. Hoffman, and H. L. Self. 1977. Comparison of confinement, shelter and no shelter for finishing yearling steers. J. Anim. Sci. 44:7171.

Levin, R. J. 1969. Review. The effect of hormones on the absorptive, metabolic and digestive functions of the small intestines. J. Endocrinol. 45:315.

Lippke, H. 1975. Digestibility and volatile fatty acids in steers and wethers at 21 and 32 C ambient temperatures. J. Dairy Sci. 58:1860.

Lofgreen, G. P. 1974. Ration formulation for relief from heat stress, p. 81. *In* 13th Calif. Feeders Day, Imperial Valley. Exp. Stn., El Centro, Calif.

Lofgreen, G. P., and W. W. Garrett. 1968. A system for expressing net energy requirements and feed values for growing and finishing beef cattle. J. Anim. Sci. 27:793.

Macfarlane, W. V. 1964. Terrestrial animals in dry heat: Ungulates, p. 509. *In* Handbook of Physiology, Section 4, Adaptation to the Environment. Am. Physiol. Soc., Washington, D.C.

Macfarlane, W. V., R. H. J. Morris, and B. Howard. 1958. Heat and water in tropical Merino sheep. Aust. J. Agric. Res. 9:217.

Mangold, D. W., T. E. Hazen, and V. W. Hays. 1967. Effect of air temperature on performance of growing-finishing swine. Trans. ASAE 10:370.

March, B. E., and J. Biely. 1972. The effect of energy supplied from the diet and from environmental heat on the response of chicks to different levels of dietary lysine. Poult. Sci. 51:665.

Masoro, E. J. 1966. Effect of cold on metabolic use of lipids. Physiol. Rev. 46:67.

Matterson, L. D. 1970. Factors influencing energy utilization. *In* R. W. Seedy, ed., Specific Nutrients in Animal Nutrition. Southern Regional Educational Board, Atlanta, Ga.

Matthews, C. A., W. W. Swett, and R. E. McDowell. 1975. External form and internal anatomy of Holsteins and Jerseys. J. Dairy Sci. 58:1453.

Maust, L. E., R. E. McDowell, and N. W. Hooven. 1972. Effect of summer weather on performance of Holstein cows in three stages of lactation. J. Dairy Sci. 55:1133.

McDonald, M. W. 1978. Feed intake of laying hens. World's Poult. Sci. J. 34:209

McDowell, R. E. 1972. Improvement of Livestock Production in Warm Climates. W. H. Freeman & Co., San Francisco.

McDowell, R. E. 1974. Effect of environment on the functional efficiency of ruminants, p. 220. *In* Livestock Environment, Proc. Int. Livestock Environ. Syrup. Am. Soc. Agric. Eng., St. Joseph, Mich.

McDowell, R. E. 1977. Performance of lactating cows and heifers on tropical grass pastures with and without supplement. Proc. 11th Conf. on Livestock and Poultry in Latin America. Univ. of Fla., Gainesville, p. C4.

McDowell, R. E. 1980. The influence of environment on physiological functions. *In* H. H. Cole and W. N. Garrett, eds., Animal Agriculture, 2nd ed. W. H. Freeman & Co., San Francisco.

McDowell, R. E., and A. Hemandez-Urdaneta. 1975. Intensive systems for beef production in the tropics. J. Anim. Sci. 41:1228.

McDowell, R. E., and B. T. McDaniel. 1968. Interbreed matings in dairy cattle. II. Herd health and viability. J. Dairy Sci. 51:1275.

McDowell, R. E., and J. R. Weldy. 1967. Water exchange of cattle under heat stress. Biometeorol. 2:414.

McDowell, R. E., D. H. K. Lee, and M. H. Fohrman. 1954. The measurement of water evaporation from limited areas of a normal body surface. J. Anim. Sci. 13:405.

McDowell, R. E., E. G. Moody, P. J. Van Soest, R. P. Lehmann, and G. L. Ford. 1969. Effect of heat stress on energy and water utilization of lactating cows. J. Dairy Sci. 52:188.

McDowell, R. E., N. W. Hooven, and J. K. Camoens. 1976. Effect of climate on performance of Holsteins in first lactation. J. Dairy Sci. 59:956.

McNaughton, J. L., J. D. May, F. N. Reece, and J. W. Deaton. 1978. Lysine requirement of broilers as influenced by environmental temperatures. Poult. Sci. 57(1):57.

Mellen, W. J., F. W. Hill, and H. H. Dukes. 1954. Studies on the energy requirements of chickens. 2. Effect of dietary energy level on the basal metabolism of growing chickens. Poult. Sci. 33:791.

Mertens, D. R., and L. O. Ely. 1979. A dynamic model of fiber digestion and passage in the ruminant for evaluating forage quality. J. Anim. Sci. 49:1085.

Mickelberry, W. C., J. C. Rodger, and W. J. Stadelman. 1966. The influence of dietary fat and environmental temperature upon chick growth and carcass composition. Poult. Sci. 45:313.

Miller, J. K., E. W. Swanson, W. A. Lyke, B. R. Moss, and W. F. Byrne. 1974. Effect of thyroid status on digestive tract fill and flow rate of undigested residue in cattle. J. Dairy Sci. 57:193.

Miller, P. C., and M. L. Sunde. 1975. The effects of precise constant and cyclic environments on shell quality and other lay performance factors with Leghorn pullets. Poult. Sci. 54:36.

Milligan, J. D., and G. Christison. 1974. Effects of severe winter conditions on performance of feedlot steers. Can. J. Anita. Sci. 54:605.

Minson, D. J., and M. M. McLeod. 1970. The digestibility of temperate and tropical grasses. Proc. XI Intern. Grassl. Cong., p. 719.

Mongin, P. 1968. Role of acid-base balance in the physiology of egg shell formation. World's Poult. Sci. J. 24:200.

Monteith, J. L. 1974. The concept of thermal neutrality, p. 425. *In* J. L. Monteith and L. E. Mount, eds., Heat Loss from Animals and Man. Butterworth, London.

Moody, E. G., P. J. Van Soest, R. E. McDowell, and G. L. Ford. 1967. Effect of high temperature and dietary fat on performance of lactating cows. J. Dairy Sci. 50:1909.

Moose, M. G., C. V. Ross, and W. H. Pfander. 1969. Nutritional and environmental relationships with lambs. J. Anim. Sci. 29:619.

Morrison, S. R., H. Heitman, T. E. Bond, and P. Finn-Kelcey. 1966. The influence of humidity on growth rate and feed utilization of swine. Int. J. Biometeorol. 10:163.

Morrison, S. R., T. E. Bond, and H. Heitman. 1967. Skin and lung moisture loss from swine. Trans. ASAE 10:691.

Morrison, S. R., H. Heitman, and T. E. Bond. 1969. Effect of humidity on swine at temperatures above optimum. Int. J. Biometeorol. 13:135.

Morrison, S. R., R. L. Givens, W. N. Garrett, and T. E. Bond. 1971. Effects of mud, wind, and rain on beef cattle performance in feedlot. Calif. Agric. 24:6.

Morrison, S. R., H. Heitman, and R. L. Givens. 1975. Effect of diurnal air temperature cycles on growth and food conversion in pigs. Anim. Prod. 20:287.

Morrison, W. D., and S. Leeson. 1978. Relationship of feed efficiency to carcass composition and metabolic rate in laying birds. Poult. Sci. 57:735.

Mount, L. E. 1964. Radiant and convective heat loss from the new-born pig. J. Physiol. 173:96.

Mount, L. E. 1968. The Climatic Physiology of the Pig, p. 271. G. W. Harris, H. Davison, A. D. M. Greenfield, and R. Whittam, eds. Williams & Wilkins Co., Baltimore.

Mount, L. E. 1974. Concepts of thermal neutrality. *In* J. L. Monteith and L. E. Mount, eds., Heat Loss from Animals and Man. Butterworth, London.

Mount, L. E. 1975. The assessment of thermal environment in relation to pig production. Livestock Prod. Sci. 2:381.

Mount, L. E. 1979. Adaptation to Thermal Environment. University Park Press, Baltimore.

Mowbray, R. M., and A. H. Sykes. 1971. Egg production in warm environmental temperatures. Br. Poult. Sci. 12:25.

Murray, D. 1966. A comparison of cutaneous evaporation rates in cattle exposed to heat in a climate laboratory and in the field. J. Agric. Sci. 66:175.

Nicholson, J. W. G., R. E. McQueen, and P. L. Burgess. 1980. Effect of cold on digestibility of chopped or pelleted hay by sheep. Can. J. Anim. Sci. 60:571.

NRC. 1968. Nutrient Requirements of Swine, 6th rev. ed. National Academy of Sciences, Washington, D.C.

NRC. 1973. Nutrient Requirements of Swine, 7th rev. ed. National Academy of Sciences, Washington, D.C.

NRC. 1974. Nutrients and Toxic Substances in Water for Livestock and Poultry, National Academy of Sciences, Washington, D.C.

NRC. 1976a. Nutrient Requirements of Beef Cattle, 5th rev. ed. National Academy of Sciences, Washington, D.C.

NRC. 1976b. Climate and Food: Climatic Fluctuation and U.S. Agricultural Production. National Academy of Sciences, Washington, D.C.

NRC. 1977. Nutrient Requirements of Poultry, 7th ed. National Academy of Sciences, Washington, D.C.

NRC. 1978. Nutrient Requirements of Dairy Cattle, 5th ed. National Academy of Sciences, Washington, D.C.

NRC. 1981. Nutritional Energetics of Domestic Animals and Glossary of Energy Terms. National Academy Press, Washington, D.C.

Olson, D. W., M. L. Sunde, and H. R. Bird. 1972. The effect of temperature on metabolizable energy determination and utilization by the growing chick. Poult. Sci. 51:1915.

O'Neill, S. J. B., D. Balnave, and N. Jackson. 1970. The influence of feathering and environmental temperature on the heat production of the cockerel. 14th World's Poult. Sci. Congr., Madrid, Section 4, 918. (Abstr.)

O'Neill, S. J. B., D. Balnave, and N. Jackson. 1971. The influencing of leathering and environmental temperature on the heat production and efficiency of utilization of metabolizable energy by the mature cockerel. J. Agric. Sci. (Camb.) 77:293.

Osbourn, D. J., R. A. Terry, G. E. Outen, and S. B. Cammell. 1974. The significance of a determination of cell walls as the rational basis for the nutritive evaluation of forages. Proc. XII Intern. Grassl. Cong. 3:374.

Ota, H., and E. H. McNally. 1961. Poultry respiration calorimeter studies on laying hens, Single Comb White Leghorn, Rhode Island Reds, and New Hampshire Cornish Crosses. Agric. Res. Serv. U.S. Dep. Agric., p. 42.

Paine, M. D., J. A. Witz, A. F. Butchbaker, C. M. Bacon, and J. E. McCroskey. 1974. Mathematical simulation of energy metabolism in beef animals. Trans. ASAE 17:102.

Panaretto, B. A., J. C. D. Hutchinson, and L W. Bennett. 1968. Protection afforded by plastic coats to shorn sheep. Proc. Aust. Soc. Anim. Prod. 7:264.

Parker, C. F. 1976. Feeding and breeding ewes in confinement housing. Ohio Sheep Day Report.

Parker, J. T., M. A. Boone, and J. F. Knechtges. 1972. The effect of ambient temperature upon body temperature, feed consumption, and water consumption using two varieties of turkeys. Poult. Sci. 51:659.

Payne, G. C. 1966. Practical aspects of environmental temperature for laying hens. World's Poult. Sci. J. 22:126.

Payne, G. C. 1967. Environmental temperature and egg production, pp. 235-241. *In* C. Horton-Smith and E. C. Amoroso, eds., Physiology of the Domestic Fowl. Oliver and Boyd, Edinburgh.

Peng, C. L., and H. Heitman. 1974. The effect of ambient temperature on the thiamin requirement of growing-finishing pigs. Br. J. Nutr. 32:1.

Perek, M., and F. Sulman. 1945. The basal metabolic rate in molting and laying hens. Endocrinol. 36:240.

Pettyjohn, J., J. Everett, and R. Mochrie. 1963. Responses of dairy calves to milk replacer fed at various concentrations. J. Dairy Sci. 46:710.

Phillips, P. A., B. A. Young, and J. B. McQuitty. 1980. Weight responses of growing-finishing swine to acute cold stress. Can. J. Anim. Sci. 60:557.

Pierce, A. 1962. Studies on salt tolerance of sheep. IV. The tolerance of sheep for mixtures of sodium chloride and calcium chloride in the drinking water. Aust. J. Agric. Res. 13:479.

Polin, D., and J. H. Wolford. 1972. The effect of meal-eating on egg production and body weight of White Leghorn chickens. Poult. Sci. 11(4):1109.

Polin, D., and J. H. Wolford. 1973. Factors influencing food intake and caloric balance in chickens. Fed. Proc. 32(6):1720.

Polin, D., and J. H. Wolford. 1976. Various types of diets, sources of energy, and positive energy balance in the induction of fatty liver hemorrhagic syndrome. Poult. Sci. 55:325.

Preston, R. L. 1966. Protein requirements of growing-finishing cattle and lambs. J. Nutr. 90:157.

Prince, R. P., J. H. Whitaker, L. D. Matterson, and R. E. Luginbuhl. 1965. Response of chickens to temperature and relative humidity environments. Poult. Sci. 44:73.

Ragsdale, A. C., D. M. Worstell, H. J. Thompson, and S. Brody. 1949. Influence of temperature, 50° to 0°F and 50° to 95°F, in milk production, feed and water consumption and body weight in Jersey and Holstein cows. Mo. Agric. Exp. Stn. Bull. 449.

Ragsdale, A. C., H. J. Thompson, D. M. Worstell, and S. Brody. 1950. Milk production and feed and water consumption responses of Brahman, Jersey, and Holstein cows to changes in temperature, 50° to 105°F and 50° to 8°F. Mo. Agric. Exp. Stn. Bull. 460.

Ragsdale, A. C., H. J. Thompson, D. M. Worstell, and S. Brody. 1951. Influence of increasing of temperature, 40° to 105°F on milk production in Brown Swiss, and on feed and water consumption and body weight in Brown Swiss and Brahman cow. s and heifers. Mo. Agric. Exp. Stn. Bull. 471.

Razdan, M. N., and S. N. Ray. 1968. Physiological behavior of Tharparkar cattle under different environments. I. Feed consumption and growth. Indian J. Dairy Sci. 21:75.

Rea, J. C., and C. V. Ross. 1961. Effect of energy-protein relationship, physical form of feed and environmental temperature on lambs. J. Anim. Sci. 20:948. (Abstr.)

Reid, B. L. 1979. Feeding and management practices for improving performance in hot weather. Fla. Nutr. Conf., p. 61.

Richards, S. A. 1971. The significance of changes in the temperature of the skin and body core of the chicken in the regulation of heat loss. J. Physiol. 216:1.

Ritzman, E., and F. Benedict. 1924. The effect of varying feed levels on the physiological economy of stress. N.H. Agric. Exp. Stn. Tech. Bull. 26.

Robertshaw, D. 1966. Sweat gland functioning of the domestic ruminants. Proc. 4th Biometeorol. Cong. Rutgers, N.J.

Robertshaw, D. 1974. Environmental Physiology. Physiology series 1, vol. 7. University Park Press, Baltimore.

Romijn, C., and E. L. Vreugdenhil. 1969. Energy balance and heat regulation in the White Leghorn fowl. Neth. J. Vet. Sci. 2:32.

Roubicek, D. 1969. Water metabolism, pp. 353-373. *In* E. Hafez and I. Dyer, eds., Animal Growth and Nutrition. Lea & Febiger, Philadelphia.

Roy, C. R., M. V. N. Rao, and D. P. Sadhu. 1969. Effect of climate on the metabolism of nutrients in growing Hariana cattle. I. Metabolism of proximate principles. Indian J. Dairy Sci. 22:248.

Ruvuna, F., B. T. McDaniel, J. C. Johnson, Jr., B. F. Hollon, R. E. McDowell, and G. W. Brandt. 1976. Interactions of breed and heterosis with hot and cold seasons for milk yield. Proc. 71st Meet. Am. Dairy Sci. Assoc., p. 72.

Schmidt-Nielsen, K., E. C. Crawford, Jr., A. E. Newsome, K. S. Rawson, and H. T. Hammel. 1967. Metabolic rate of camels: Effect of body temperature and ehydration. Am. J. Physiol. 212:341.

Scott, M. L., F. W. Hill, E. H. Parsons, Jr., and J. H. Bruchner. 1959. Studies on duck nutrition. 7. Effect of dietary energy: Protein relationships upon growth, feed utilization and carcass composition in market ducklings. Poult. Sci. 38:497.

Searle, T. W., and N. McC. Graham. 1975. Studies of weaner sheep during and after a period of weight stasis. II. Body composition. Aust. J. Agric. Res. 26:343.

Sell, J. L. 1979. Use of supplemental fat to improve productive efficiency of poultry. Fla. Nutr. Conf., p. 43.

Seymour, E. W., V. C. Speer, V. W. Hays, D. W. Mangold, and T. E. Hazen. 1964. Effects of dietary protein level and environmental temperature on performance and carcass quality of growing-finishing swine. J. Anim. Sci. 23:275.

Shannon, D. W. F., and W. O. Brown. 1969. The period of adaptation of the fasting metabolic rate of the common fowl to an increase in environmental temperature from 22°C to 28°C. Br. Poult. Sci. 10:13.

Sharma, D. S., and N. D. Kehar. 1961. Effect of environmental temperature and humidity on intake and digestion of nutrients. J. Appl. Physiol. 16:611.

Sibbald, I. R. 1979. The gross energy of avian eggs. Poult. Sci. 58(2):404.

Simon, J. 1973. Influence d'un temps d'alimentation limite' a' deux heures per jour chez' la poulette et chez la pondeuse de souche ponte. 4th Europ. Poult. Conf., London, p. 203.

Slee, J. 1968. Body temperature regulation and vasomotor responses in Scottish Blackface and Tasmanian Merino sheep subjected to slow cooling. Anim. Prod. 10:265.

Snetsinger, D. C., and R. A. Zimmerman. 1974. Limiting the energy intake of laying hens, pp. 185-199. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

Soderquist, H. G., and K. L. Knox. 1967. Temperature-energy relationships in fattening lambs. J. Anim. Sci. 26:930. (Abstr.)

Sorensen, P. H. 1962. Influence of climatic environment on pig performance, p. 88. *In* J. T. Morgan and D. Lewis, eds. Nutrition of Pigs and Poultry. Butterworth, London.

Sorensen, P. H., and J. H. Moustgaard. 1961. Der einfluss der stallklimas auf das washstrum die futterverwertung und slachtqualitat yon schweinen scheusbericht. VIII. Int. Tierzuchtkongress, Hamburg, p. 127.

Squibb, R. L. 1959. The relation of diurnal temperature and humidity ranges to egg production and feed efficiency of New Hampshire hens. J. Agric. Sci. (Camb.) 52:217.

Squibb, R. L., J. E. Braham, and G. Arroyave. 1958. Rate of vitamin A absorption in New Hampshire laying hens subjected to 20°C and 36°C temperature. Poult. Sci. 37:932.

Stahly, T. S., G. L. Cromwell, and M. P. Aviotti. 1979a. The effect of environmental tempera ture and dietary fat supplementation on the performance and carcass characteristics of growing and finishing swine. J. Anim. Sci. 49:1478.

Stahly, T. S., G. L. Cromwell, and M. P. Aviotti. 1979b. The effect of environmental temperature and dietary lysine source and level on the performance and carcass characteristics of growing swine. J. Anim. Sci. 49:1242.

Stephens, D. B. 1971. The metabolic rates of newborn pigs in relation to floor insulation and ambient temperature. Anim. Prod. 13:303.

Stockland, W. L., and L. G. Blaylock. 1974. The influence of temperature on the protein requirement of cage reared replacement pullets. Poult. Sci. 53:1174.

Stott, G. H. 1981. What is animal stress and how is it measured? J. Anim. Sci. 52:150.

Strachan, R. T., and W. F. Marnson. 1963. Growth of Jersey calves in the tropics. Anim. Br. Abstr. 31:1035.

Sturkie, P. D. 1965. Arian Physiology, 2nd ed. Cornell University Press, Ithaca, N.Y. 200 pp.

Sugahara, M., D. H. Baker, B. G. Harmon, and A. H. Jensen. 1970. Effect on ambient temperature on performance and carcass development in young swine. J. Anim. Sci. 31:59.

Swain, S., and D. J. Farrell. 1975. Effects of different temperature regimens on body composition and carry-over effects on energy metabolism of growing chickens. Poult. Sci. 54:513.

Sykes, J. F. 1955. Animals and Fowl and Water. Yearb. Agric. Water, pp. 14-18. USDA, Washington, D.C.

Teter, N. C., J. A. DeShazer, and T. L. Thompson. 1973. Operational characteristics of meat animals: Part II. Beef. Trans. ASAE 16(4):740.

Thomas, C. K., and M. N. Razdan. 1973. Adaptability of 1/2 Sahiwal-1/2 Brown Swiss cattle to subtropical conditions. I. Feeding behavior. Indian J. Dairy Sci. 43:5.

Thompson, H. J., R. G. Yeck, D. M. Worstell, and S. Brody. 1954. The effect of wind on evaporative cooling and surface temperature in dairy cattle. Mo. Agric. Exp. Stn. Bull. 548.

Thorbeck, G. 1975. Studies on energy metabolism of growing pigs. No. 434 Beretning Fra Stat Husdyrbrugs Forsog, Kobenhavn.

Van Es, A. J. H. 1972. Hanbuch der Tierernahrung. Paul Parey, Hamburg.

van Kampen, M. 1974. Physical factors affecting energy expenditure. *In* T. R. Morris and B. M. Freeman, eds., Energy Requirements of Poultry. Br. Poult. Sci. Ltd., Edinburgh.

van Kampen, M., and C. Romijn. 1970. Energy balance and heat regulation in the White Leghorn fowl, p. 213. *In* A. Schürel and C. Wenk, eds., Energy Metabolism of Farm Animals. Juris Druck Verlag, Zurich.

Van Soest, P. J. 1971. Estimation of nutritive value from laboratory analysis. Proc. 1971 Cornell Nutr. Conf., Buffalo, N.Y. p. 106.

Van Soest, P. J. 1981. Nutritional Ecology of the Ruminant. Ruminant Metabolism, Nutritional Strategies, The Cellulolytic Fermentation and the Chemistry of Forages and Plant Fibers. O&B Books, Inc., Corvallis, Oreg.

Verstegen, M. W. A., and W. van der Hel. 1974. Effects of temperature and type of floor on metabolic rate and effective critical temperature in groups of growing pigs. Anim. Prod. 18:1.

Verstegen, M. W. A., and W. van der Hel. 1976. 7th Symposium on Energy Metabolism EAAP Publ. No. 15. INRA, Vichy.

Verstegen, M. W. A., E. W. Brascamp, and W. van der Hel. 1978. Growing and fattening of pigs in relation to temperature of housing and feeding level. Can. J. Anim. Sci. 58:1.

Verstegen, M. W. A., W. H. Close, I. B. Start, and L. E. Mount. 1973. The effects of environmental temperature and plane of nutrition on heat loss, energy retention and deposition of protein and fat in groups of growing pigs. Br. J. Nutr. 30:21.

Verstegen, M. W. A., W. H. van der Hel, and G. E. J. M. Willems. 1977. Growth depression and food requirements of fattening hogs at low environmental temperature when housed either on concrete slats or straw. Anim. Prod. 24:253.

Vo, K. V., and M. A. Boone. 1978. Effect of water availability on hen survival time under high temperature stress. Poult. Sci. 56(1):375.

Vo, K. V., M. A. Boone, and W. E. Johnston. 1978. Effect of three lifetime ambient temperatures on growth, feed and water consumption and various blood components in male and female Leghorn chickens. Poult. Sci. 57:798.

Waibel, P. E. 1977. Progress in defining the requirement of market turkeys. Proc. 1977 Ga. Nutr. Conf., p. 42.

Waibel, P. E. 1978. Dietary protein and fat for turkeys is relative to environmental temperature. 1978 Midwest Poult. Fed. Conv.

Waldo, D., R. Miller, M. Ikamoto, and L. A. Moore. 1965. Ruminant utilization of silage in relation to hay, pellets, and hay plus grain. II. Rumen content, dry matter passage and water intake. J. Dairy Sci. 48:1473.

Waring, J. J., and W. O. Brown. 1967. Calorimetric studies on the utilization of dietary energy by the laying White Leghorn hen in relation to plane of nutrition and environmental temperature. J. Agric. Sci. (Camb.) 68:149.

Warren, W. P., F. A. Martz, K. H. Asay, E. S. Hildenbrand, C. G. Payne, and J. R. Vogt. 1974. Digestibility and rate of passage by steers fed tall fescue, alfalfa and orchard grass hay at 18 and 32°C ambient temperatures. J. Anim. Sci. 39:93.

Webster, A. J. F. 1974. Heat loss from cattle with particular emphasis on the effects of cold , p. 205. *In* J. L. Monteith and L. E. Mount, eds., Heat Loss from Animals and Man. Butterworth, London.

Webster, A. J. F. 1976. Principles of Cattle Production, p. 103. *In* H. Swan and W. H. Broster, eds. Butterworth, London.

Webster, A. J. F., and K. L. Blaxter. 1966. The thermal regulation of two breeds of sheep exposed to air temperatures below freezing point. Res. Vet. Sci. 7:466.

Webster, A. J. F., and B. A. Young. 1970. Breed and strain differences in the cold tolerance of cattle raised in different environments. Univ. Alberta Feeders Day Rep. 49:37.

Webster, A. J. F., A. M. Hicks, and F. L. Hays. 1969. Cold climate and cold temperature induced changes in the heat production and thermal insulation of sheep. Can. J. Physiol. Pharmacol. 47(6):553.

Webster, A. J. F., L Chlumecky, and B. A. Young. 1970. Effects of cold environments on the energy exchange of young beef cattle. Can. J. Anim. Sci. 50:89.

Weeth, H., and L. Haverland. 1961. Tolerance of growing cattle for drinking water containing sodium chloride. J. Anim. Sci. 20:518.

Welch, J. G., and A. N. Smith. 1969. Influence of forage quality on rumination time in sheep. J. Anim. Sci. 28:813.

Westra, R., and R. J. Christopherson. 1976. Effects of cold on digestibility, retention time of digesta, reticulum motility and thyroid hormones in sheep. Can. J. Anim. Sci. 56:699.

Whittow, G. C. 1976. Regulation of body temperature, chap. 7. *In* P. D. Sturkie, ed., Avian Physiology, 3rd ed. Springer-Verlag, New York.

Whittow, G. C., and J. D. Findlay. 1968. Oxygen cost of thermal panting. Am. J. Physiol. 214:94.

Williams, C. M. 1959. Influence of winter conditions on the feed and water intake of feedlot steers. J. Anim. Sci. 18:1155.

Williams, C. M. 1967. Livestock production in cold climates. *In* R. H. Shaw, ed., Ground Level Climatology. AAAS Publ. 86. American Association for the Advancement of Science, Washington, D.C.

Wilson, W. O. 1948. Some effects of increasing environmental temperatures in pullets. Poult. Sci. 27:813.

Wilson, W. O. 1949. High environmental temperatures as affecting the reaction of laying hens to iodized casein. Poult. Sci. 28:581.

Winchester, C. F., and M. Kleiber. 1938. The effect of environmental temperature on mortality, rate of growth, and feed utilization of food energy in White Leghorn chicks. J. Agric. Res. 57:529.

Winchester, C. F., and M. J. Morris. 1956. Water intake rates of cattle. J. Anim. Sci. 15:722.

Wohlbbiet, W., and W. Schneider. 1965. A preliminary report on the metabolism of steers kept under different environmental temperatures, p. 405. *In* K. L. Blaxter, ed., Energy Metabolism. Academic Press, London.

Yazman, J. A. 1980. Feeding systems for lactating cows and growing heifers in a tropical environment. Unpublished Ph.D. Thesis. Cornell University, Ithaca, N.Y.

Yazman, J. A., R. E. McDowell, H. Cestero, F. Roman-Garcia, and J. A. Arroyo-Aguilu. 1979. Supplementation of dairy cows grazing intensively managed tropical grass pastures at two stocking rates. J. Agr. Univ. P.R. 63:281.

Yazman, J. A., R. E. McDowell, J. A. Arroyo-Aguilu, H. Cestero, and F. Roman-Garcia. 1981. Efficiency of utilization of tropical grass pastures by lactating cows with and without supplement. J. Agr. Univ. P.R. 66:229.

Young, B. A. 1975a. Effects of winter acclimatization on resting metabolism of beef cows. Can. J. Anim. Sci. 55:619.

Young, B. A. 1975b. Temperature-induced changes in metabolism and body weight of cattle (*Bos taurus*). Can. J. Physiol. Pharmacol. 53:947.

Young, B. A. 1975c. Some physiological costs of cold climates. Univ. Mo. Agr. Exp. Stn. Spec. Rep. 175.

Young, B. A. 1981. Cold stress as it affects animal production. J. Anim. Sci. 52:154.

Young, B., and R. Christopherson. 1974. Effect of prolonged cold exposure on digestion and metabolism in ruminants, p. 75. Proc. Intern. Livestock Environ. Symp. Lincoln, Nebr.

Young, B. A., and J. L. Corbett. 1972. Maintenance energy requirement of grazing sheep in relation to herbage availability. Aust. J. Agric. Res. 23:57.