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Environmental Physiology And Shelter Engineering

With Special Reference to Domestic Animals

XX. Comparative Physiological Reactions of European and Indian Cattle To Changing Temperature

D. M. WORSTELL AND S. BRODY

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TABLE OF CONTENTS

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Grateful acknowledgments are made to all persons (both of the U. S. Department of Agriculture and the University of Missouri) associated with this project, and particularly to Professor A. C. Ragsdale without whose encouragement this bulletin would not have been prepared.

This bulletin is a report on the Department of Dairy Husbandry research project No. 100, entitled "Influence of Climatic Factors on Productivity."

Some of the material in this bulletin was presented at the following meetings: (1) "Discussion Group on Temperature Regulation" at the New York meeting of the Federation of American Societies for Experimental Biology, April, 1952. (2) "Biostatistical Conference" of the Biometric Society, Ames, Iowa, July 18, 1952. (3) South Carolina Dairy Association Meeting at Clemson College, November 19, 1952. (4) Symposium on "Nutrition Under Climatic Stress," National Research Council, Washington, D. C., December 5, 1952.

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XX. Comparative Physiological Reactions of European and Indian Cattle To Changing Temperature

D. M. WORSTELL* and S. BRODY

INTRODUCTION

This is an attempt to integrate the more significant physiological data obtained on the effect of temperature (while holding the other climatic conditions constant) during five separate experiments (Fig. 1) in the Climatic, or Psychroenergetic, Laboratory. The detailed data have been previously published in Missouri Research Bulletins (listed in the Appendix), each reporting on a specific research during the given period.

Our basic interest is in the physiological reactions associated with changing temperature and time and in the mechanisms involved in maintaining normal the internal body temperature in the face of changing environmental temperature. We are especially interested in the sequences and causal relations of the homeothermic mechanisms, that is, which occurs first and why; and in estimating the breed differences in the reactions to changing temperatures, especially between European and Indian-evolved cattle.

In an integration study covering data reported by so many workers it is difficult to give due recognition to each worker. This is true because all their results are here combined in order to show the interrelations of *all* physiological reactions. Although the preceding publications, including their authors, are listed in the Appendix it seems desirable to outline the division of labor and to list the senior authors on the resulting publications: A. C. Ragsdale (selection and management of the experimental animals; milk and butterfat production, feed consumption, and body weight); H. H. Kibler (heat production, respiratory vaporization, pulse rate, respiration rate, pulmonary ventilation rate, and rectal temperature); H. J. Thompson, Agricultural Engineer, BPISAE, U.S.D.A., (control of the Psychroenergetic Laboratory; skin and hair temperature, water consumption, total moisture vaporization and overall heat loss from the chambers); Clifton Blincoe (thyroid activity and blood analyses).

*Resident Statistician of BPISAE, U. S. Dept. of Agriculture.

Samuel Brody and H. J. Thompson served as project leaders of the physiological and engineering phases, respectively.

MATERIALS AND METHODS

As previously mentioned, the data here reported have been published and were all obtained under the controlled conditions of the Climatic Laboratory. This laboratory (described in detail by H. J. Thompson and R. E. Stewart in Agric. Engr., *33*, 201-204, 206, April 1952) consists of two independently-controlled chambers, each 26 x 18 x 9 feet. Each chamber houses six animals in 4-foot wide standard dairy barn stalls. These two chambers are, in turn, housed in an insulated 60 x 40-foot building covered with galvanized steel. A mixture of fresh and recirculated air was moved through each chamber at about 45 feet per minute, or about 180 cubic feet per cow, or about 900 lbs. dry air per hour per cow. The relative humidity was maintained at about 65 per cent. The overall chamber light intensity was about 17 foot-candles (from six 200-watt bulbs). The air, surrounding walls, ceiling and floor had approximately the same temperature.

The animals used in the experiments consisted of both European- and Indian-evolved cattle, lactating and non-lactating, mature cows and yearling heifers. Jersey, Holstein and, in one experiment, Brown Swiss represented the European-evolved cattle. A Texas-bred light grey "Barzee Brahman" (probably of the Guzarat breed) represented the Indian-evolved cattle. As shown in Table 1, there were considerable differences in age, weight, milk yield, stages of lactation and gestation, as well as breed.

Although the first four experiments (Fig. 1) included control animals, no data on the controls are given in this report. Only the data obtained during the periods of increasing temperature from 50° to 105°F (except the last phase of the Winter 1948-49 period at which time the temperature was raised following a period of exposure to declining temperature), and of decreasing temperature 50° to 5°F were included. With one exception (Spring 1950, when the initial temperature was 40°F) the experimental periods began at 50°F environmental temperature. The temperatures were increased (or decreased) from the base level by 5° or 10°F intervals. Except at the high temperatures, where shorter intervals were necessary, the cows were kept at each temperature level for about two weeks to allow sufficient time for repeating the measurements. Details regarding the laboratory measurements and animals are given in the preceding progress reports. (See list on pages 35 and 36.)

INTERPRETATION OF DATA

Methods of Analysis and Interpretation: In the previous bulletins, listed in the Appendix, the data were presented graphically on arithmetic paper in absolute values and also, frequently, as percentages of the initial temperature level (50°F). In this report semi-logarithmic paper, which has an arithmetic

TABLE 1 -- VITAL STATISTICS ON EXPERIMENTAL ANIMALS

	At Beginning of Experiment			At End of Experiment			At Beginning of Experiment			At End of Experiment	
Cow No.	Age Years	Body Wt. Lbs.	Milk Yield* Lbs./day	Stage of Lactation	Stage of Gestation	Cow No.	Age Years	Body Wt. Lbs.	Milk Yield* Lbs./day	Stage of Lactation	Stage of Gestation
	Summer 1948 Rising Temperature 50° to 105°F. 153 days (March 6 to Aug. 6, 1948)						Winter 1948 Declining Temperature 50° to 5°F.† 91 days (Oct. 25, 1948, to Jan. 23, 1949)				
Jersey 212	3.2	895	31.6	6	2 1/2	Jersey 502	4.0	820	16.6	8	6 1/2
Jersey 202	3.6	850	29.0	8	6	Jersey 508	3.8	850	14.0	7	4 1/2
Jersey 994	4.5	728	25.8	6 1/2	3	Jersey 933	9.8	840	18.8	8 1/2	4 1/2
Holstein 83	5.5	1260	46.2	5 1/2	1	Holstein 136	4.0	1220	33.6	7	not bred
Holstien 118	4.3	1125	38.4	6	4	Holstein 109	5.0	1200	36.0	8 1/2	6 1/2
Holstein 106	4.6	1085	dry	18	Farrow	Holstein 14	9.8	1450	dry	23 1/2	Farrow
	Summer 1949 Rising Temperature 50° to 105°F. 80 days (May 23 to Aug. 11, 1949)						Winter 1949 Declining Temperature 50° to 8°F. 95 days (Oct. 4, 1949, to Jan. 6, 1950)				
Jersey 994	5.6	770	32.5	6	not bred	Jersey 957	8.8	840	23.6	7	not bred
Jersey 212	4.5	990	34.0	5 1/2	1	Jersey 977	6.8	920	19.8	6	4
Brahman 190	2.5	750	**	3 1/2	not bred	Brahman 190	3.0	850	dry	8 1/2	4
Brahman 209	2.0	710	**	3 1/2	not bred	Brahman 209	2.3	820	dry	8 1/2	4
Holstein 109	5.8	1250	36.3	3 1/2	not bred	Holstein 118	5.8	1200	38.8	4 1/2	not bred
Holstein 7	10.0	1270	47.7	5 1/2	not bred	Holstein 154	3.8	1200	39.1	6 1/2	11
	Spring 1950--Rising Temperature 40° to 105°F.										
	Cows 102 days (Feb. 6 to May 18, 1950)						Heifers 109 days (Feb. 6 to May 25, 1950)				
Brown Swiss 16	6.0	1350	48.7	5 1/2	not bred	Brown Swiss 1	0.5	410			
Brown Swiss 20	6.5	1270	49.7	5	not bred	Brown Swiss 2	0.5	340			
Brown Swiss 24	6.2	1410	42.6	6	4	Brown Swiss 3	0.5	370			
Brahman 189	3.0	940	dry	12 1/2	6	Brahman 1	0.8	500			
Brahman 190	3.0	980	dry	12 1/2	8	Brahman 2	0.8	410			
Brahman 209	2.8	930	dry	12 1/2	8	Brahman 3	0.8	410			

*Milk yield is average for month before start of experiment.
**Not milked before placed in Laboratory.
†Although the actual test continued to another phase, 50° to 95°F, none of the data are included in this report.

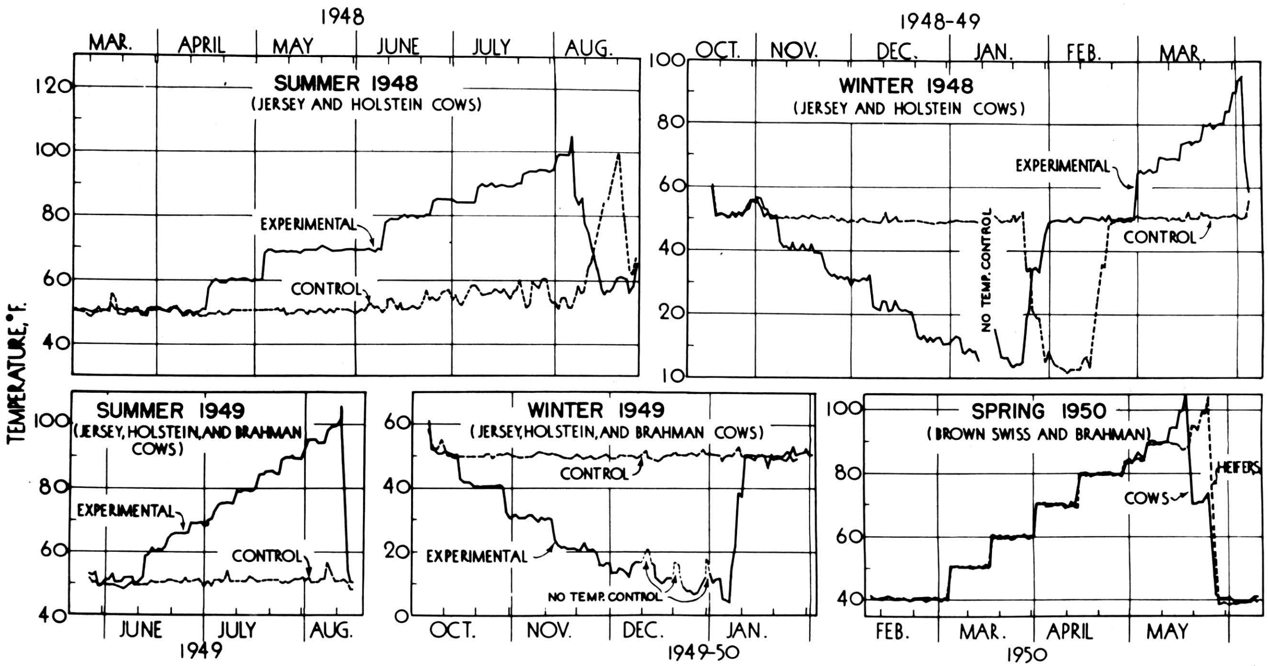

Fig. 1.—The temperature calendar for the five experimental periods from which data were taken for this report.

horizontal scale and a logarithmic vertical scale, was used as it offered a method of plotting the absolute values of the many physiological reactions all on the same graph without distortion; it provided a true relative comparison of all the physiological reactions as function of temperature since equal slopes on semi-logarithmic paper represent equal relative changes; it offered a means of determining the percentage changes of the curves directly from the charts as explained below. (See Fig. 17.)

Readers desiring to know the numerical values of percentage changes (increase, decrease, or comparison) may read them direct from the scales that have been placed in the inside back cover (Fig. 17). As Figs. 3 to 7 and Figs. 9 to 16 were all plotted on the same scale, these scales can be used with any of these charts except for rectal temperature.

Semi-logarithmic paper is not suitable for plotting body temperature as the different temperature scales—Centigrade or Fahrenheit—give different slopes, that is, different percentage increases for a given absolute temperature change. Furthermore, a very narrow change in rectal temperature corresponds to very wide changes in other physiological reactions. For instance, increasing the environmental temperature from 40° to 105°F raised the rectal temperature in the Brown Swiss cows from 100.4° to 107.7°F, and the respiration rate from 22 to 150 (Table 3). Hence, rectal temperature has been shown throughout this bulletin on a separate arithmetic grid alongside the other reactions on the semi-logarithmic grid.

Our data are not, at present, suitable for estimating the conventional statistical parameters because: the number of animals used was small; the animals were not selected at random and not always comparable; estimates of parameters would be based on the assumption that the distribution of the deviations from the mean accords with Gauss's Law of Errors, and this law may not be applicable to these rate-of-progress data (development of acclimatization and of deterioration, advances in the stages of lactation, gestation, and age) conditioned by many genetic and environmental elements.

The analyses and integrations were, therefore, carried out mostly by plotting on semi-logarithmic paper the time-temperature trends for the individual cows (exemplified by Fig. 9) and for averages of the various breeds (Figs. 12 to 16). Only tentative conclusions were drawn from each curve. Comparisons of physiological reactions were made on individual cows (Figs. 10 and 11) and on breed averages (Figs. 3 to 7).

Tables 2 to 6 characterize the physiological reactions—their absolute "normal", maximal, and minimal values and percentage changes; Tables 7 and 8 present the "critical temperatures" for the individual animals and for the breed averages.

The term "critical temperature" here refers to a marked change in slope of a curve for a given reaction. For example, if the milk production curve for a given animal shows a marked decrease in slope after 80°F, this temperature is called the "critical temperature" for the *given* animal.

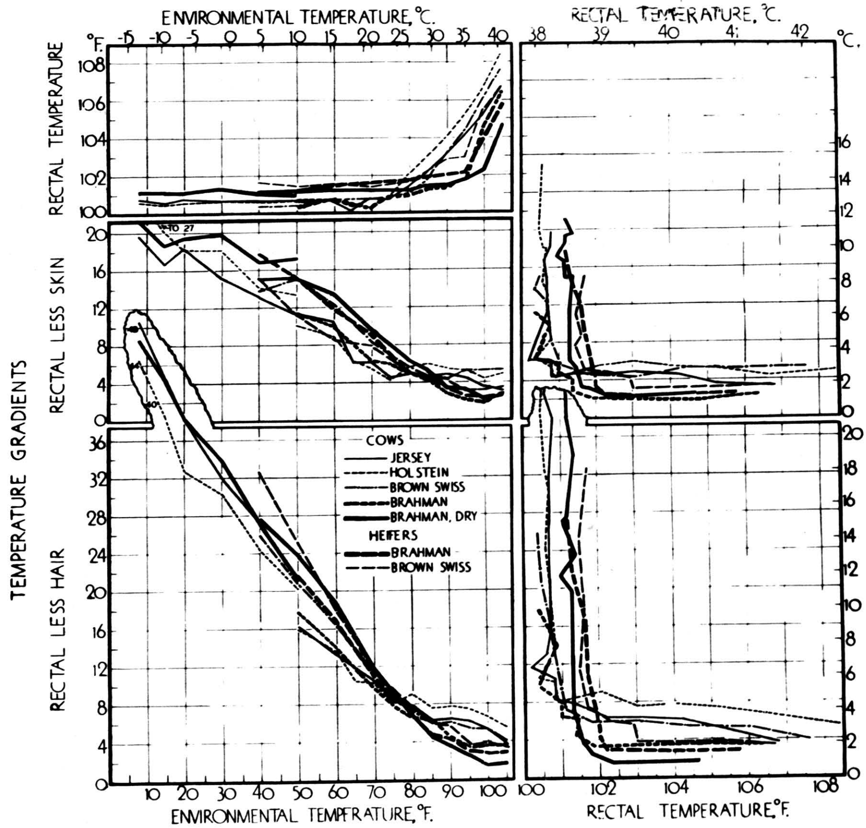

Fig. 2a.—Temperature gradients (rectal less hair and rectal less skin temperatures) plotted against both environmental temperature (left-hand sections) and against rectal temperature (right-hand sections). The rectal temperatures in the upper left-hand section are shown for comparison.

Different physiological reactions have different critical temperatures and other individual peculiarities. Some curves appear to have more than one "critical temperature"; for example, some curves, as respiration rate, increase in slope to a maximum point following which there is a decline in slope or, at least, no further rise.

When an increase in slope occurs at a relatively low temperature, it is interpreted as the beginning of an adjustment of the involved homeothermic mechanisms to counteract the effects of environmental-temperature increase. When a change occurs at a later temperature the change is interpreted to reflect an inability to adjust to further temperature, often indicating deterioration of the involved function. The position of the critical temperature varies not only with the particular reaction, but also with age, weight, breed, and the productive level of the animal. While the following values for breed dif-

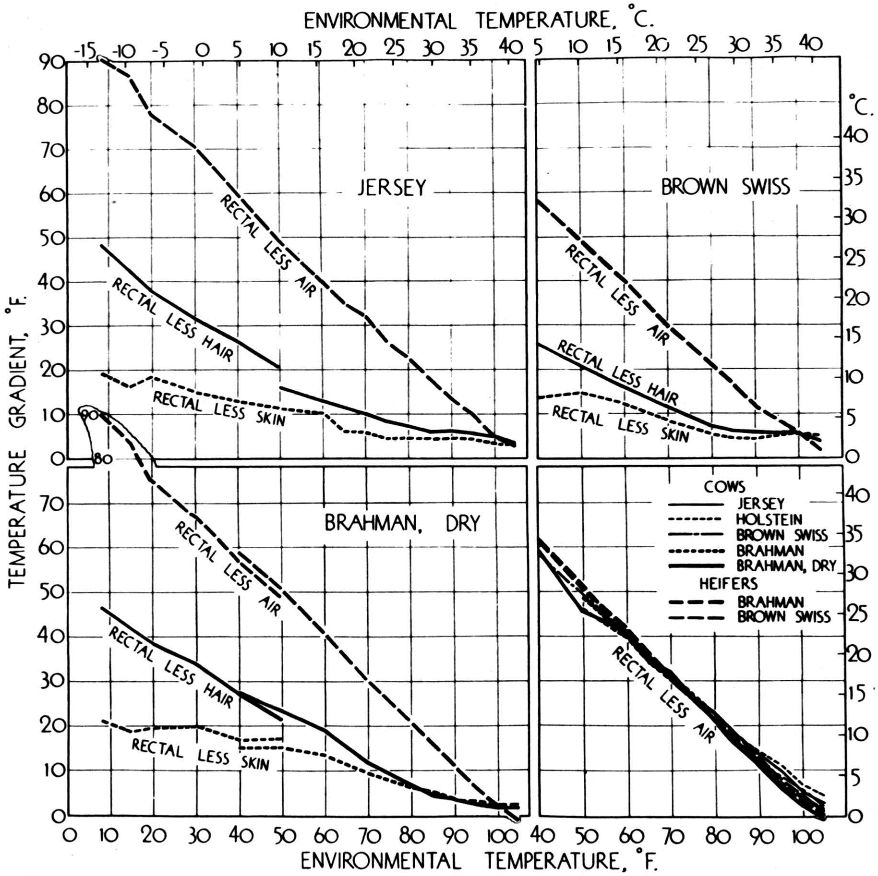

Fig. 2b.—Left side: Temperature gradients (rectal less air, rectal less hair, and rectal less skin temperatures) of Jersey and Brahman dry cows plotted against chamber temperature 8° to 105°F. Upper right: Similar data for the Brown Swiss cows during the temperature range 40° to 105°F. Lower right: Comparison of rectal less air temperature for all cattle categories. Fig. 2a presents comparison for all the cattle categories for the temperature gradients rectal less hair and rectal less skin. The rectal-less-air gradient most nearly approaches a linear course.

ferences may be generally true, the statistical significance of the differences may be slight because of wide variation in the physiological status of the animals between and within the breeds.

Environmental Temperature vs. Rectal Temperature as Independent Variables and the Temperature Gradient Problem: Table 2 shows that the normal rectal temperature was about 100.6° for lactating and about 101.4° for the non-lactating cows and the heifers. The upper section of Fig. 2, as also lower sections of Figs. 3 and 4, indicates that the rectal temperature in the cows was approximately constant prior to 70°F environmental tempera-

TABLE 2 -- NORMAL[1] VALUES FOR SOME PHYSIOLOGICAL REACTIONS

Reaction	Lactating					Heifers (dry)	
	Jersey	Holstein	Brown Swiss	Brahman	Dry Brahman	Brahman	Brown Swiss
Rectal Temperature, °F	100.6	100.8	100.5	100.6	101.2	101.4	101.6
°C	38.1	38.2	38.0	38.1	38.4	38.5	38.6
Respirations/min.	25	27	25	18	14	14	25
Pulse Rate	62	66	58	68	64	78	74
Body Weight[2], lbs.	830	1220	1340	730	950	485	420
kg.	376	553	608	331	431	220	190
Pulmonary Ventilation, lit/min.	80	110	120	70	65	35	45
$lit/m^2/min.$	19	21	22	16	13	10	16
Respiratory Vaporization, gms/hr.	80	130	130	50	50	30	38
$gms/m^2/hr.$	19	25	24	12	10	9	13
Total Vaporized Moisture, gms/hr.	250	350	380	290	220	180	190
$gms/m^2/hr.$	60	68	70	66	44	52	66
Milk Production, lbs/day	22	40	44	8	0	0	0
Butterfat, %	5.9	3.5	3.8	5.4	----	----	----
FCM Production, lbs/day (milk corrected to 4% fat)	28	36	43	10	0	0	0
Water Consumption, gals/day	12	20	20	8	5	4	4
TDN Consumption,[3] lbs/day	16	25	26	11	11	7	6
$Cal/m^2/hr.$	290	350	360	190	165	155	185
Heat Production, Cal/hr.	620	850	900	490	500	330	350
$Cal/m^2/hr.$	150	165	166	114	100	96	123
CO_2-Combining Capacity, vol. %	58	58	60	58	57	61	60
Creatinine, mg. %	1.1	1.2	1.3	1.5	1.5	1.4	1.3
Ascorbic Acid, mg.%	0.6	0.6	0.6	0.7	0.6	0.8	0.8

[1]By "normal" is meant the average values (for each breed) between 40° and 60°F environmental temperature --the apparent "comfort zone" for our cows. This "comfort zone" is the temperature range during which there is no apparent physiological adjustment to changing environmental temperature.

[2]Surface area for the European breeds was computed from the equation: Surface area in square meters. $= 0.15$ (weight in kg) $^{0.56}$ (see Mo. Res. Bul. 89, p. 10). The surface area of the Brahman was considered to be 12% greater than for the European breeds (see Mo. Res. Bul. 464, p. 14).

[3]Assuming that one lb. TDN (Total Digestible Nutrients) is equivalent to 1814 Calories.

ture. Increasing the temperature above 75°F affected differently the rectal temperature of the various cattle categories, depending on breed, age, productivity, and body size.

The critical temperature for rectal temperature was 70° for the Holstein, 75° for the Jersey, 80° for the Swiss, and 95° for the Brahman (Table 8). The steepest rise as well as the highest value of rectal temperature at 105° environmental temperature occurred in the Holsteins, followed by the other lactating cows. At 105°F environmental temperature the rectal temperature of the heifers was below that of the cows, and the dry Brahman cows had the lowest rectal temperature.

Since most of the physico-chemical reactions of the body—outside those concerned with such processes as vaporization and respiration rates and hair growth—are probably influenced more directly by the internal (rectal) than by the environmental temperature, it seemed desirable to plot the various physiological reactions as function of rectal as well as of environmental temperature.

The appearance of the curves were quite different when plotted against rectal temperature than when plotted against environmental temperature. Fig. 2 shows that when plotted against environmental temperature the temperature gradient curves decline gradually with rising environmental temperature until the rise in rectal temperature begins; but when plotted against rectal temperature, the temperature gradient curves fall precipitously during the initial 1°F rectal temperature rise (due to the approximate constant rectal temperature prior to 75°F in the European and 95°F in the Brahmans). After the sudden fall the gradients remain nearly constant for the Indian cows and decline slightly for the European cows.

The temperature gradient at 105°F environmental temperature is, of course, dependent on the rectal temperature level. The rectal temperature at 105°F environmental temperature tends to be highest in the largest animals (lowest ratio of surface area to body weight) and in the highest producers; and lowest in the smallest and least productive animals. Therefore, as shown in the following tables (and in Figs. 2a and 2b), the highest gradients between rectal and surface temperature are in the largest and most productive cows (Holsteins, Brown Swiss, and Jerseys) and the lowest in the Brahmans (the highest surface area per unit weight and lowest producers) and in the heifers.

Cattle Categories	Rectal Temp. at 105° Envir. Temp.	Temperature Gradient, °F					
		At 105° Envir. Temp.			At 105° Rectal Temp.		
		Rectal Less Air*	Rectal Less Hair	Rectal Less Skin	Rectal Less Air*	Rectal Less Hair	Rectal Less Skin
Holstein	108.4	4.5	5.5	4.9	12.0	7.4	5.3
Brown Swiss	107.6	2.0	4.0	5.3	8.0	5.4	5.2
Jersey	106.8	2.8	3.6	3.2	6.2	5.2	3.8
Brahman Lactating	106.4	1.2	3.7	2.7	3.6	3.6	2.0
Brahman Dry	104.7	–0.7	1.9	2.7	–0.7	1.9	2.7
Brown Swiss Heifer	106.7	1.3	3.4	3.4	5.4	3.8	3.2
Brahman Heifer	105.8	0.7	3.0	2.8	2.0	3.0	2.6

*Chamber air as measured with the touch thermocouple during the 105°F temperature level.

One aspect of Figs. 2a and 2b relates to the meaning and significance of the concept "temperature gradient". Since the rectal temperature of cattle apparently remains constant on lowering the temperature 70°F down to –40°F (as occurs in the mountain states) the rectal-less-air temperature gradient simply represents the decline in environmental temperature. However, the temperature gradients of rectal-less-hair and rectal-less-skin reflect changes in conductivity with changing environmental temperature of the many categories of peripheral tissues under the skin, of the skin, and of the hair. The concept, "temperature gradient", used in Figs 2a and 2b is physiologically very significant, but it is somewhat confused by the many component gradient categories. The following quotations from several investigators may be helpful in this connection.

Hart[1] reported that in quiet mice heat production—and therefore heat loss—below the critical temperature is proportional to the temperature gradient. Scholander[2] *et al.* reported that the "heat loss essentially follows Newton's Law of Cooling—it is essentially proportional to the body-to-air gradient" below the zone of thermoneutrality. Hardy[3] *et al.* reported that in man "the conductance of the peripheral tissues, measured by dividing the heat loss by the thermal heat established between the internal organs and the skin, changed linearly with calorimeter temperature lower than 28.5°C. . . . The rate of cooling, according to Newton's Law, was constant through the experimental range, 5.3 Cal/m^2/hr. per degree difference in skin and calorimeter temperature".

It thus appears from the literature and from our material (Missouri Res. Bul. 481 and 489) that the heat loss from the body as a whole tends to follow Newton's Law. The heat flow from the body interior to the body surface tends to be proportional to the peripheral tissues conductance, which is vasocontrolled by the blood flow. Scholander's[2] gull did not lose much heat at –40° from its long, thin, naked legs because of the greatly reduced blood flow by vasoconstriction which reduced the conductance of the peripheral tissue, and also lowered the surface temperature to slightly above freezing; this reduced to a minimum the temperature gradient between surface and environment, and therefore reduced to a minimum the overall heat loss from the surface to the environment. The surfaces of our cows' feet were similarly cold. This, incidentally, calls attention to the fact that while the rectal temperature of warm-blooded species is constant at environmental temperature 75°F down to –40°F, the temperature of some peripheral tissues, such as of the feet, may drop down to near freezing— but not below in arctic animals— without injury or apparent discomfort.

[1]Hart, J. S., Effect of temperature and work on metabolism, body temperature, and insulation. Results with mice. Canadian J. Zool. *30*, 90-98, 1952.

[2]Scholander, P. F., Walters, V., Hock, R., and Irving, L., Body insulation and heat regulation in relation to body temperature and metabolic rate in arctic and tropical mammals and birds. Biol. Bull. *99*, 225-271, 1950.

[3]Hardy, J. D., Milharat, A. T., and Du Bois, E. F., Heat loss and heat production in woman (and man) under basal conditions at temperatures from 23° to 35°C, in *Temperature, Its Measurement and Control in Science and Industry*, Reinhold, New York, 1941, p. 531.

As will be explained, the rise in rectal temperature reflects, or coincides with the cessation of increase in evaporative cooling with rising environmental temperature. It, however, also reflects the attainment of a critically low level in the temperature gradient, that is, a temperature at which the temperature gradient curve deviates from its downward linear course, towards the horizontal. The change in slope occurs when the difference between rectal and skin temperature is reduced to about 4°F, or 8°F between rectal and hair temperature (Fig. 2).

The curves for the other physiological reactions have been plotted in similar manner, against both environmental (Figs. 3, 4, and 5) and rectal (Figs. 6 and 7) temperature. When the reactions were plotted against rectal temperature, the resulting curves appeared to be of two types.

(1) Some curves showed a very steep initial rise and flattened out with increase in rectal temperature above 102°F. This type included total and respiratory vaporization, respiration rate, and pulmonary ventilation rate. The changes in these reactions reflect homeothermic adjustments to rising environmental temperature, that is, attempts to maintain the internal body temperature normal in the face of rising environmental temperature. When the upper limit in these mechanisms was obtained, the rectal temperature began to rise.

(2) Other curves were unchanged prior to 101.5° or 102°F rectal temperature but showed a gradual decrease, or increase, with increasing rectal temperature above 101.5° or 102°F. This type included milk production, feed consumption, heat production, pulse rate, creatinine, and CO_2-combining capacity. The changes in these reactions resulted from an increased internal body temperature. They may reflect adjustments to or, more often, deterioration resulting from the increasing internal temperature. The following sections discuss these two types of curves in more detail.

Physiological Adjustments to Rising Environmental Temperature at Constant Rectal Temperature: The temperature trends for the various physiological reactions (Figs. 9 to 16) indicate that there is virtually no call on the homeothermic mechanisms for physiological adjustments between about freezing and 60°F environmental temperature. This range may, then, be termed the "comfort zone" for cattle under our laboratory conditions (which is not identical with the zone of thermoneutrality) and the numerical values for the physiological reactions during this temperature range are called "normal values" in Table 2.

Decreasing the environmental temperature from 40° down to 8°F affected but slightly the physiological reactions, particularly of the European lactating cows. Respiration rate and moisture vaporization declined gradually with declining temperature; feed consumption (paralleled by water consumption) increased 36 per cent in the non-lactating Brahmans, 26 per cent in the lactating Jerseys and 8 per cent in the Holsteins; heat production showed a correspondingly greater increase in the Brahmans—56 per cent compared to 12 and 2 per cent in the Jersey and Holsteins, respectively (Table 6). Body weight tended to increase somewhat (stimulated by the increased feed consumption); milk production appeared to decline somewhat with declining temperature (and advancing lactation) in the Jerseys. The Holsteins, however,

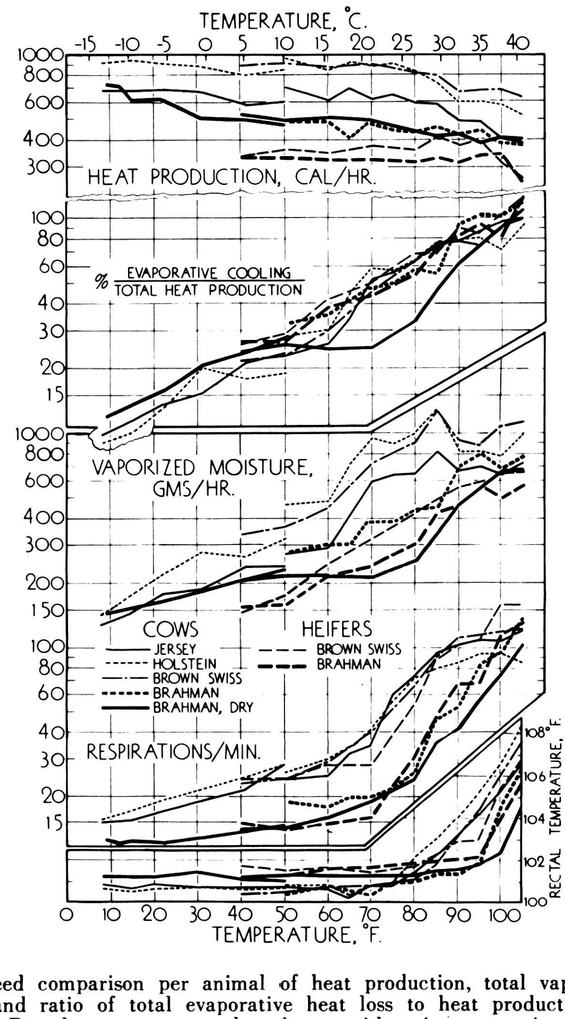

Fig. 3a.—Breed comparison per animal of heat production, total vaporized moisture, respiration rate and ratio of total evaporative heat loss to heat production on semi-logarithmic paper. Rectal temperature, plotted on arithmetic paper, is shown for comparison. Note the virtual identity in all groups, except dry Brahman, of the ratio levels at a given temperature. In combining the data for a breed comparison it should be noted from Fig. 1 that while 65° and 75°F temperature periods were maintained for the lactating Jersey, Brahman, and Holstein cows (summer 1949), there were no 65° and 75°F periods for the lactating Brown Swiss and dry Brahman cows and heifers (spring 1950).

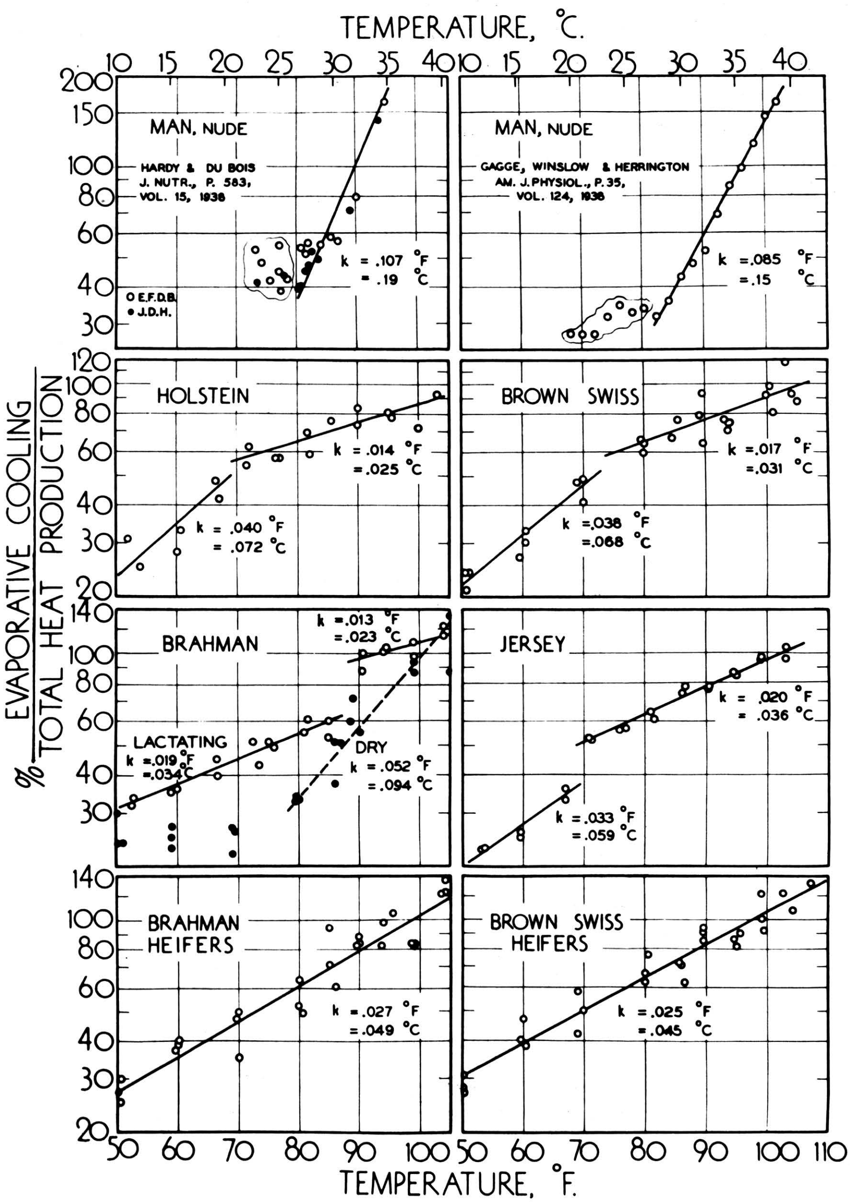

Fig. 3b.—The same data (from 50° to 105°F) as in the second segment of Fig. 3a but shown separately for the different breeds with approximate slopes, *k*, for each. Man is shown in the top segments for comparison (data points encircled disregarded in determining slope). Note the difference in the steepness of the slopes for man and for the cows. The value of *k* multiplied by 100 is percentage rise in the ratio of evaporative cooling to heat production.

maintained a fairly stable level of milk production throughout the period of declining temperature. The significance of the milk yield decline in the Jerseys with declining temperature is problematical because no correction was made for the declines normally associated with the advancing periods of lactation and gestation.

Increasing the environmental temperature above 60°F, on the other hand, affected profoundly most of the physiological reactions. The major mechanism for maintaining the body temperature normal prior to rise in rectal temperature is the rate of vaporization. This is demonstrated by the following

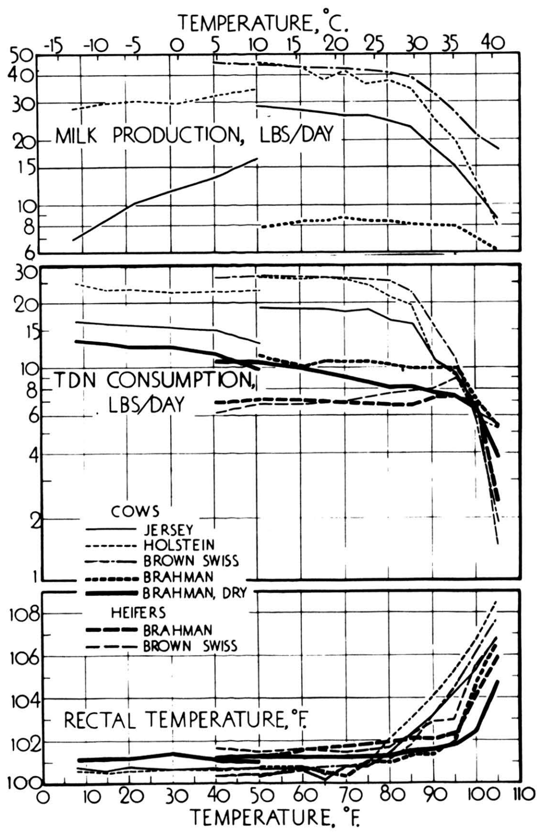

Fig. 4.—Breed comparison in the temperature course of milk production and feed (TDN) consumption on semi-logarithmic paper, and of rectal temperature on arithmetic paper.

observations: 1) The vaporization rate was the first reaction to show a dramatic rise with increasing temperature [above 60°F in European and above 70°F in Indian-evolved cattle (Tables 7 and 8)]; 2) Termination of the rise in vaporization rate led to a prompt rise in rectal temperature (Fig. 3).

At low environmental temperature, heat dissipation is mostly by convection and radiation. Rising environmental temperature reduces the temperature gradient between body and environment with consequent reduction in convective and radiative cooling and shifting of the heat dissipation to evaporative cooling. When the environmental temperature approaches the body-

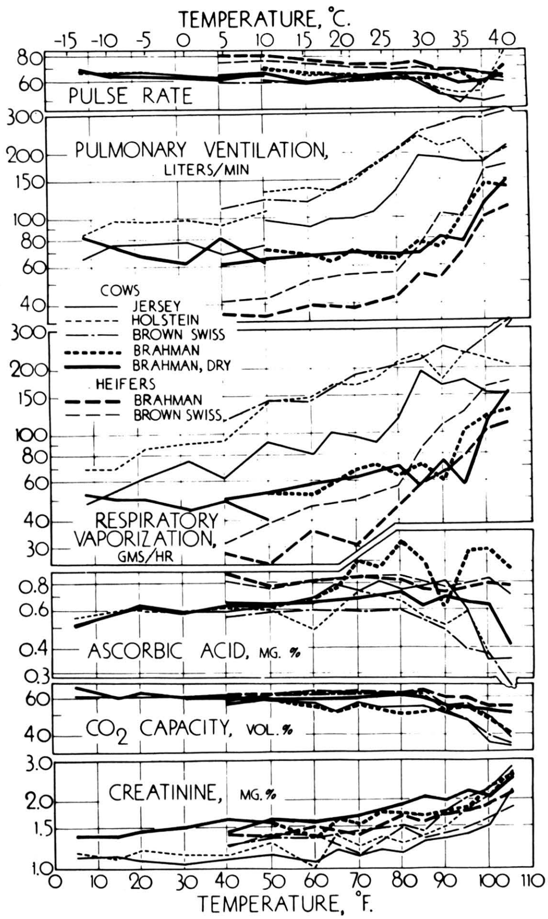

Fig. 5.—Breed comparison of pulse rate, pulmonary ventilation rate, respiratory vaporization and of some blood constituents on semi-logarithmic paper.

TABLE 3 -- RANGE[1] OF SOME PHYSIOLOGICAL REACTIONS BETWEEN TEMPERATURE 50° to 105°F.

	Lactating					Heifers (dry)	
Reaction	Jersey	Holstein	Brown Swiss	Brahman	Dry Brahman	Brahman	Brown Swiss
TDN Consumption, lbs/day							
Maximum	20	26	28	12	11	8	12
Minimum	5	5	1	5	2	2	1
Milk Production, lbs/day							
Maximum	31	50	50	11	---	---	---
Minimum	4	7	8	5	----	---	---
Heat Production, Cal/hr.							
Maximum	720	1000	960	520	560	360	460
Minimum	360	490	610	370	310	250	290
Respirations/min.							
Minimum	22	23	22	17	11	13	24
Maximum	132	114	150	146	148	132	160
Pulse Rate							
Minimum	41	49	46	55	57	54	60
Maximum	72	85	67	73	70	85	76
Total Vaporized Moisture, gms/hr.							
Minimum	270	430	350	260	200	140	160
Maximum	740	1070	1250	820	720	630	790
Respiratory Vaporization, gms/hr.							
Minimum	74	120	120	52	40	22	29
Maximum	200	270	390	130	170	120	180
Pulmonary Ventilation Rate, lit/min.							
Minimum	88	115	105	60	45	28	36
Maximum	230	260	350	150	170	120	190
Per Cent of Heat Production Lost by Vaporization							
Minimum	23	25	21	32	22	25	27
Maximum	105	93	119	123	133	134	132
Creatinine, mg. %							
Minimum	0.7	0.7	1.0	1.3	1.3	1.1	0.9
Maximum	2.4	2.6	2.9	2.6	3.0	2.1	2.0
CO_2-Combining Capacity, vol. %							
Maximum	66	67	65	61	67	67	68
Minimum	34	35	34	39	44	51	34
Rectal Temperature,							
Minimum, °F	100.0	100.2	100.4	100.2	101.2	101.0	101.2
°C	37.8	37.9	38.0	37.9	38.4	38.3	38.4
Maximum, °F	106.9*	108.5	107.7	106.5	106.4	106.3	107.2
°C	42.6	42.5	42.0	41.4	41.3	41.3	41.8

[1]The range as given is the maximum and minimum values of the individual animals (of a given breed) between the temperature levels of 50° and 105°F., inclusive.

*With the exception of one Jersey cow whose rectal temperature was measured to be 108.6° at 105°F enviromental temperature.

surface temperature, convective and radiative cooling approach zero, and vaporization takes over as virtually the sole means for heat dissipation. Hence, the ability to withstand high temperatures is proportional to the ability to dissipate heat by vaporization. Cattle are peculiar in that, unlike man, their heat dissipation by vaporization reaches an upper limit at the rather low environmental temperature—about 70°F in the Holstein and Jersey, 85°F in the Brown Swiss, and 95°F in the Brahmans. Fig. 7—particularly its segments showing the ratios of vaporization calories to heat production calories—shows that after the rectal temperature begins to rise (after 75°F in European and after 95°F in Brahman cattle) there is little breed difference in evaporative cooling ability.

TABLE 4 -- RANGE[1] OF SOME PHYSIOLOGICAL REACTIONS BETWEEN TEMPERATURES 50° to 80°F.

Reaction	Lactating Jersey	Lactating Holstein	Dry Brahman
TDN Consumption, lbs/day			
Minimum	13	18	10
Maximum	19	27	14
Milk Production, lbs/day			
Maximum	18	37	---
Minimum	2	23	---
Heat Production, Cal/hr.			
Minimum	530	760	450
Maximum	780	990	780
Respirations/min.			
Maximum	44	30	15
Minimum	10	15	12
Pulse Rate			
Minimum	58	58	61
Maximum	73	70	71
Total Vaporized Moisture, gms/hr.			
Maximum	280	370	240
Minimum	90	100	120
Respiratory Vaporization, gms/hr.			
Maximum	120	180	64
Minimum	35	40	39
Pulmonary Ventilation Rate, lit/min.			
Maximum	96	118	94
Minimum	53	68	54
Per Cent of Heat Production Lost by Vaporization			
Maximum	25	27	30
Minimum	7	6	10
Creatinine, mg. %			
Minimum	0.8	0.9	1.3
Maximum	1.3	1.5	1.6
CO_2-Combining Capacity, vol. %			
Minimum	55	55	54
Maximum	63	73	70
Rectal Temperature,			
Maximum, °F	101.4	101.2	101.5
°C	38.5	38.4	38.6
Minimum, °F	100.2	99.8	101.0
°C	37.9	37.6	38.3

[1]The range as given is the maximum and minimum values of the individual animals (of a given breed) between the temperature levels of 50° and 80°F, inclusive.

Unlike man, cattle increase the rates of respiration, pulmonary ventilation, and respiratory vaporization with increasing environmental temperature. The increase in respiratory vaporization supplements the inadequate outer-surface vaporization in cattle. The increasing pulmonary ventilation also increases the respiratory heat loss by convection (significantly at the lower environmental temperatures but insignificantly at the higher temperatures). Respiratory vaporization appears to be a function of pulmonary ventilation rate as indicated by the horizontal trend in the ratio curves of respiratory moisture exhaled per liter (Fig. 6). The peculiarities in the ratio of respiratory to total

TABLE 5 -- VALUES AT 105°F AS PERCENTAGES OF VALUES AT 50°F ON SOME PHYSIOLOGICAL REACTIONS AVERAGED FOR THE DIFFERENT BREEDS (Values at 50°F = 100%)

	Lactating					Heifers (dry)	
Reaction	Jersey	Holstein	Brown Swiss	Brahman	Dry Brahman	Brahman	Brown Swiss
TDN Consumption	28	20	7	46	35	33	22
Milk Production	30	18	24	73	---	---	---
Heat Production	63	64	70	78	83	79	89
Respiration Rate	515	340	510	730	750	940	650
Total Vaporized Moisture	270	230	300	280	310	360	370
Respiratory Vaporization	170	170	250	230	300	450	460
Pulmonary Ventilation Rate	220	170	250	200	240	320	410
Creatinine	190	210	210	170	150	160	140
CO_2-Combining Capacity	61	61	59	68	86	86	61
Ratio: Total Vaporization, Cal. / Heat Production, Cal.	440	370	440	360	400	460	420
Ratio: Respiratory Vaporization, Cal. / Heat Production, Cal.	280	270	290	310	390	560	540
Ratio: Respiratory Vaporization / Total Vaporization	62	74	83	83	106	125	120
Ratio: Respiratory Vaporization / Ventilation Rate	77	101	89	118	130	145	114

TABLE 6 -- VALUES AT 8°F AS PERCENTAGES OF VALUES AT 50°F ON SOME PHYSIOLOGICAL REACTIONS AVERAGED FOR THE DIFFERENT BREEDS (Values at 50°F = 100%)

	Lactating		Dry
Reaction	Jersey	Holstein	Brahman
TDN Consumption	126	108	136
Milk Production	42	82	---
Heat Production	112	102	156
Respiration Rate	54	55	86
Total Vaporized Moisture	52	50	62
Respiratory Vaporization	54	44	105
Pulmonary Ventilation Rate	96	86	130
Creatinine	98	92	90
CO_2-Combining Capacity	106	106	100
Ratio: Total Vaporization, Cal. / Heat Production, Cal.	42	46	44
Ratio: Respiratory Vaporization, Cal. / Heat Production, Cal.	48	42	66
Ratio: Respiratory Vaporization / Total Vaporization	102	98	190
Ratio: Respiratory Vaporization / Ventilation Rate	56	52	80

TABLE 7 -- THE CRITICAL TEMPERATURE[1] (°F) OF THE VARIOUS PHYSIOLOGICAL REACTIONS OF INDIVIDUAL ANIMALS.
(Mature Lactating Animals Except Where Indicated)

Reaction	Jersey Cows					Holstein Cows					Brahman Cows		Dry Brahman Cows			Brown Swiss Cows			Brown Swiss Heifers			Brahman Heifers		
	Summer 1948			Summer 1949		Summer 1948			Summer 1949		Summer 1949		Spring 1950			Spring 1950			Spring 1950			Spring 1950		
	994	212	202	994	212	118	83	106 (dry)	109	7	190	209	189	209	190	16	20	24	1	2	3	1	2	3
Feed Consumption																								
No Increase After																			85	80	85	85	*	*
Decrease After	80	80	80	75	85	70	70	70	85	70	95	95	95		95	80	80	85	95	95	95	95	95	95
Milk Production																								
Decrease After	85	85	85	85	85	80	85		85	85	95	95				85	80	85						
Heat Production																								
No Increase After																			70	70	50	70	60	50
Decrease After	85	85	80	85	85	80	80	80	80	75	95	85	70	60	70	70	80	70	100	95	95	100	100	100
Pulse Rate																								
Decrease After	80	85	85	80	80	80	80	80	85	85	95		85	85	90	85	85	85						
Increase After				100	100	95	90	90	100		100				100	95	95	95						
Gradual Increase to												80							95	80	80	100	90	95
Body Weight																								
No Increase After								90			70	70							90	90	90	95	95	95
Decrease After	80	*	85	75	85	85	70		80	80			*	*	*	80	80	85	100	100	100	100	100	100
Butterfat %																								
Increase After	90	100	90	100	95	80	85		90	85	100	*				90	95	90						
Respiration Rate																								
Increase After	60	60	60	65	60	70	60	60	70	60	75	70	80	80	80	60	60	50	70	70	70	70	70	70
Decrease After	80	85	80	85	85	80	80	90	80	75						85	90	90	85	85	85			100
Vaporized Moisture																								
Increase After				60	60				60	60	85	85	85	70	70	50	60	50	40	50	50	70	60	60
Decrease After				70	70				70	70	95	90	100	90	100	85	85	85	90	90	100	95	85	95
Respiratory Vaporization																								
Increase After				75	75				75	70	90	90	100	85		60	70		80	70	80	70	70	90
Decrease After				85	85				85	80	95	100		100	90	90	100	85	100	95	100	105	100	100
Pulmonary Ventilation Rate																								
Increase After				75	75				70	65	90	90	100	85	60	60	70	80	80	85	80	70	80	90
Decrease After				85	85				85	80	100	100		100	95	90	100	85	100	100	100	100	105	100
Water Consumption																								
Increase After	*	70	80		80	80	80				85	85	85	95	85	85	80	90	70	70	50	70	70	80
Decrease After		100	100	75	100	90	95	85	85	75	100		100		100	85	80	85	95	90	95	100	100	100
Rectal Temperature																								
Increase After	80	70	70	80	75	70	70	70	70	70	95	95	100	90	95	70	80	80	80	80	80	95	95	95

*Indicates no change in slope.

[1] "Critical temperature" refers to the approximate environmental temperature after which marked changes occur in the slopes of the physiological reactions of animals subjected to rising environmental temperature 50° to 105°F. In comparing the critical temperatures for the various breeds it should be noted (from Fig. 1) that while 65° and 75°F temperature periods were maintained for the lactating Jersey, Brahman, and Holstein cows, there were no 65° and 75°F periods for the lactating Brown Swiss and dry Brahman cows and heifers.

vaporization curves reflect the fact that the respiratory vaporization curve has a higher critical temperature than outer surface, or total, vaporization (Tables 7 and 8).

TABLE 8 -- THE CRITICAL TEMPERATURE[1] (°F) OF THE VARIOUS PHYSIOLOGICAL REACTIONS FOR BREED AVERAGES

	Lactating					Heifers	
Reaction	Jersey	Holstein	Brown Swiss	Brahman	Dry Brahman	Brahman	Brown Swiss
Feed Consumption							
No Increase After						95	85
Decrease After	75	70	80	95	95	95	95
Milk Production							
Decrease After	85	85	85	95			
Heat Production							
No Increase After						60	70
Decrease After	85	75	70	95	70	100	95
Pulse Rate							
Decrease After	80	80	85	95	85		
Increase After	100	90	95	100	100		
Gradual Increase to						95	80
Body Weight							
No Increase After						95	90
Decrease After	85	80	80	*	*	100	100
Butterfat, %							
Increase After	90	85	90	*			
Respiration Rate							
Increase After	60	60	60	75	80	70	70
Decrease After	85	80	90				100
Vaporized Moisture							
Increase After	60	60	50	85	70	70	50
Decrease After	70	70	85	95	95	95	90
Respiratory Vaporization							
Increase After	75	75	60	90	95	70	80
Decrease After	85	85	90	100		100	100
Pulmonary Ventilation Rate							
Increase After	75	65	60	90	95	70	80
Decrease After	85	85	85	100	100	100	100
Creatinine							
Increase After	80	80	85	95	100	95	85
CO_2-Combining Capacity							
Decrease After	85	85	85	95	85	85	85
Ascorbic Acid							
Decrease After	90	80	80	95	80	80	80
Rectal Temperature							
Increase After	75	70	80	95	95	95	80

[1]"Critical temperature" refers to the approximate environmental temperature after which marked changes occur in the slopes of the physiological reactions of animals subjected to rising environmental temperature 50° to 105°F. In comparing the critical temperatures for the various breeds it should be noted (from Fig. 1) that while 65° and 75°F temperature periods were maintained for the lactating Jerseys, Brahman, and Holstein cows, there were no 65° and 75°F periods for the lactating Brown Swiss and dry Brahman cows and heifers.

*Indicates no change in slope.

Physiological Changes Associated with Rising Rectal Temperature: After the upper limit of heat dissipation has been nearly reached with resulting increase in rectal temperature, there is decline in feed consumption, milk production, and apparently thyroid activity, with consequent decline in the heat increments (SDA, etc.) of those processes and, therefore, in total heat production. The declines in feed (hay, TDN[4]) and milk production may be considered as reflecting deterioration of the animal, and/or as homeothermic mechanisms reducing the thermal stress associated with feeding and lactation.

The curves plotted against rectal temperature (Fig. 6), and also against environmental temperature (Fig. 4), show greater decreases in feed consumption than in milk production. This is also brought out by the ratio curves of TDN consumed to FCM (4% fat corrected milk) produced (Fig. 6). The greater decline in feed consumption than in milk production leads to loss in body weight. The decline in body weight, however, is rather slight due, in part, to replacement of the body fat by water and, in part, to decline in the maintenance cost (decrease in heat production).

The decline in pulse rate paralleled the decline in feed consumption, milk production, and heat production.

The decline in CO_2-combining capacity appears to have been caused mostly by loss of carbon dioxide following increase in pulmonary ventilation rate. The rise in blood creatinine (Fig. 5) apparently reflects the accelerated endogenous nitrogen catabolism following the decline in feed consumption as well as of some other reactions associated with increasing temperature. The creatinine curves increase with increasing rectal temperature (Fig. 6) as well as declining feed consumption. The changes in ascorbic acid (Fig. 5) apparently reflect the reaction of the adrenal cortex to heat stress.

[4]While Figs. 4 and 6 and Tables 2 to 6 present TDN (Total Digestible Nutrients) consumption, Figs. 2, 9 to 12 and 16 show the actual hay consumed. It was thought that hay consumption was the better curve to present since hay was fed *ad libitum* and it more nearly reflected the effect of changing temperature on appetite than did the TDN consumption, which included the grain, since grain was fed in proportion to the amount of milk produced (see Missouri Res. Bul. 425), and the cows consumed all that was placed before them—except at the very high temperatures. The amount of grain fed, however, influenced the amount of hay consumed and often the same amount of grain was fed to a given animal throughout the experiment (this was especially true for the Brahmans). But regardless of whether the curve is TDN or hay, the decline occurred at the same temperature although the hay consumption decreased to practically nothing at 105°F whereas the TDN curves were less steep and less abrupt at the point where the change in slope occurred.

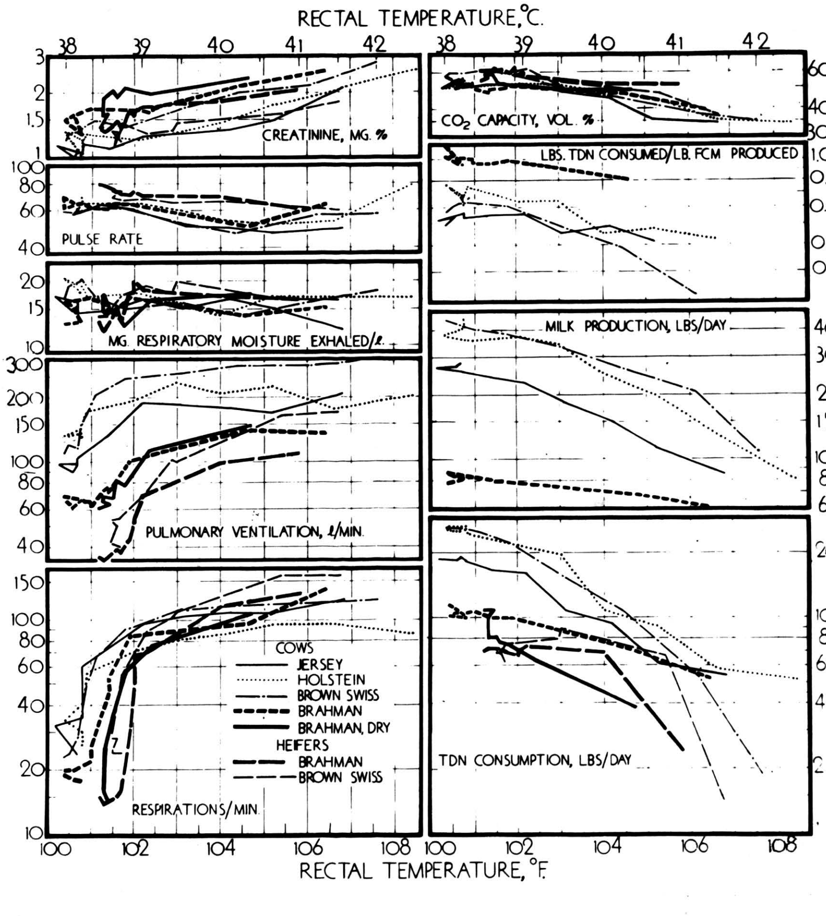

Fig. 6—Curves of the various physiological reactions, and ratios of some physiological reactions, plotted against rectal temperature on semi-logarithmic paper. The data are plotted in a time, or environmental temperature, sequence from 50°F or 40°F up to 105°F environmental temperature. (Data from the declining temperature periods, 50° to 8°F, are not included.)

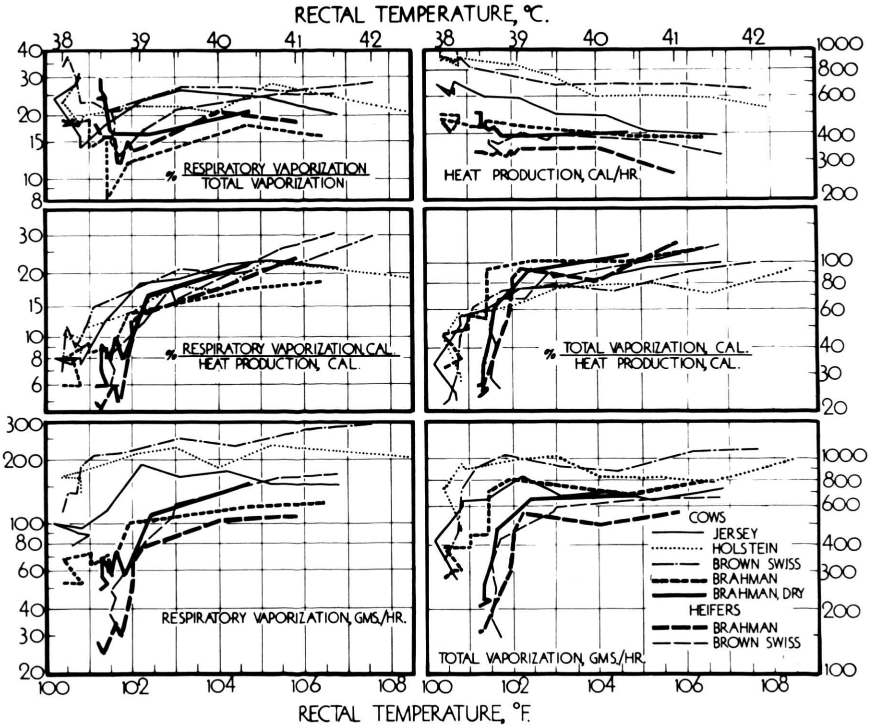

Fig. 7.—Same as Fig. 6, for additional reactions and ratios.

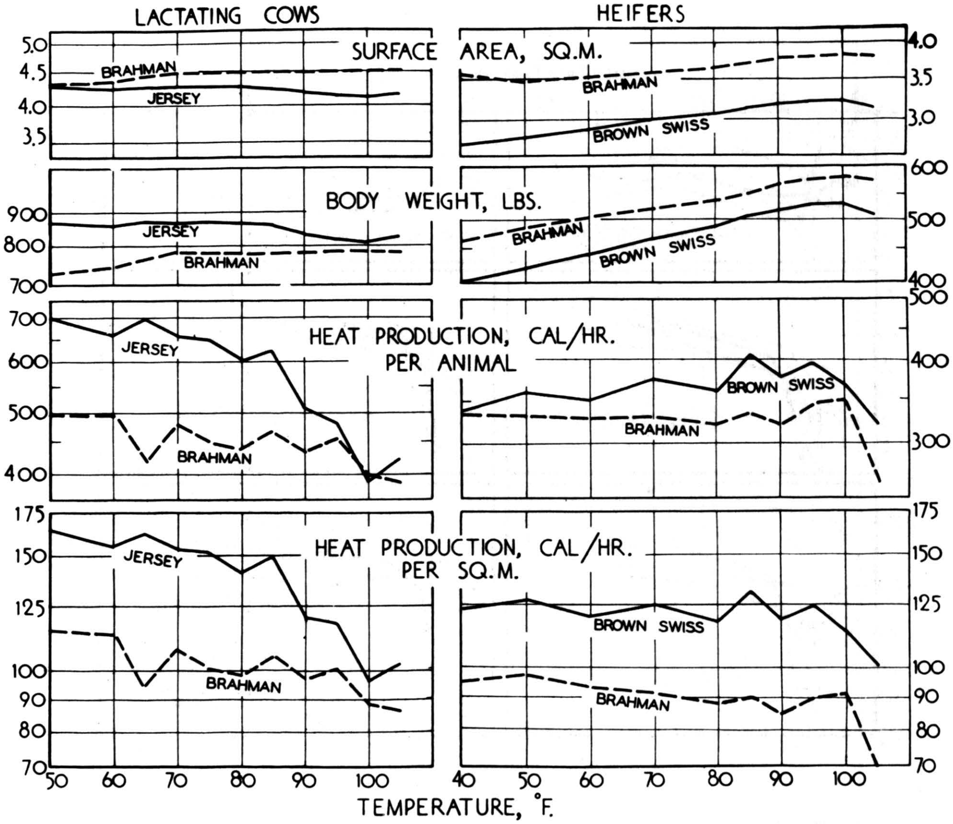

Fig. 8.—Heat production per animal and per square meter surface area of Brahman and Jersey lactating cows (left) and Brahman and Brown Swiss heifers (right). The body weights and surface areas are also given. While the Brahman heifers were heavier, their heat production per animal—as well as per unit surface area—was much less than in the Brown Swiss heifers. At 100°F when feed consumption was reduced to near zero, the heat production per animal was nearly the same in the Jersey and Brahman cows; but per unit surface area it was less in the Brahman than in the Jersey. The major portion of the breed difference in heat production in the cows appears to be due to differences in productive level.

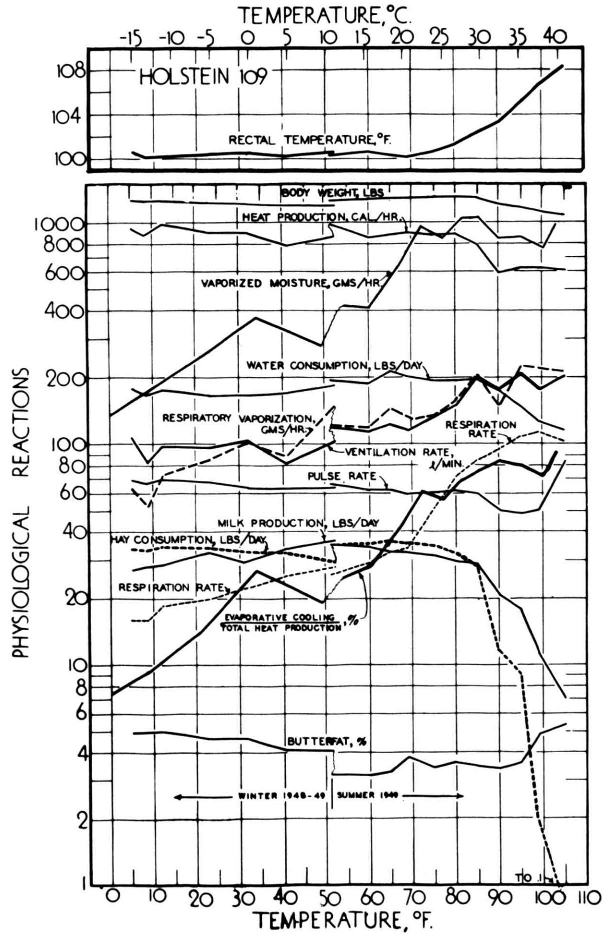

Fig. 9.—Temperature trends on Holstein cow 109 of 12 physiological reactions plotted on semi-logarithmic paper and rectal temperature (upper section) plotted on arithmetical coordinate paper. Data from 50° to 105°F were obtained during the summer 1949 period and data for 50° to 0°F were obtained during the winter 1948 period.

Individual Differences in Water Consumption: Although individual variations occurred in the critical temperature and in the slopes of the various physiological reactions, most of the temperature-trend curves for individual curves (of the same breed) were found to be very similar (Figs 10 and 11). The one great exception was water consumption which varied enormously between individual cows (lower section of Figs. 10 and 11).

The most intriguing water consumption pattern occurred in Jersey 212; she increased her consumption of water from 11 gallons at 50°F to 43 gallons at 100°F. Since the water temperature was about 50°F in contrast to the chamber temperature of 80°F to 105°F, Jersey 212, which consumed enormous amounts of water, maintained a lower rectal temperature and a higher milk yield than those cows which did not consume so much water. Cow 212 which drank more, also urinated more. Which is the cause and which the

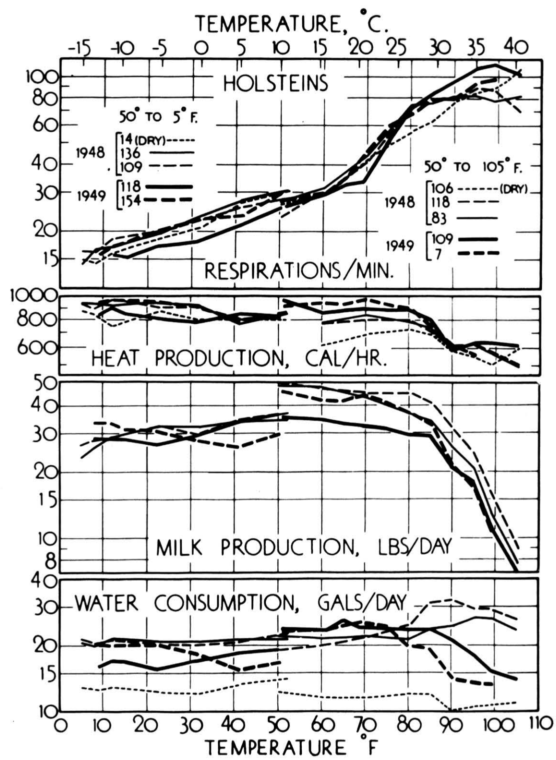

Fig. 10.—Individual differences in response to changing temperature in lactating Jersey cows plotted on semi-logarithmic paper. (Different groups of animals were used for the rising and for the declining temperature trials; those in the declining temperature trials were lower milk producers and were further advanced in the periods of gestation and lactation.)

effect? Was the heavy water drinking the cause of heavy urination, or the heavy urination the cause of heavy water drinking? The physiological mechanisms involved in the higher water consumption of 212 would obviously be different in the two cases. If higher urination were the "cause" of higher water consumption, the involved mechanism would probably be depression of anti-diuretic hormone secretion by the posterior pituitary. Then the other cows would also have been induced to drink more by the administration of diuretic which could also render them more heat tolerant.

Fig. 16 shows that while the water consumption declined in the milking Brown Swiss cows, it increased in the Brown Swiss heifers. This leads to the conclusion that, with the exception of Jersey 212, decline in water consumption

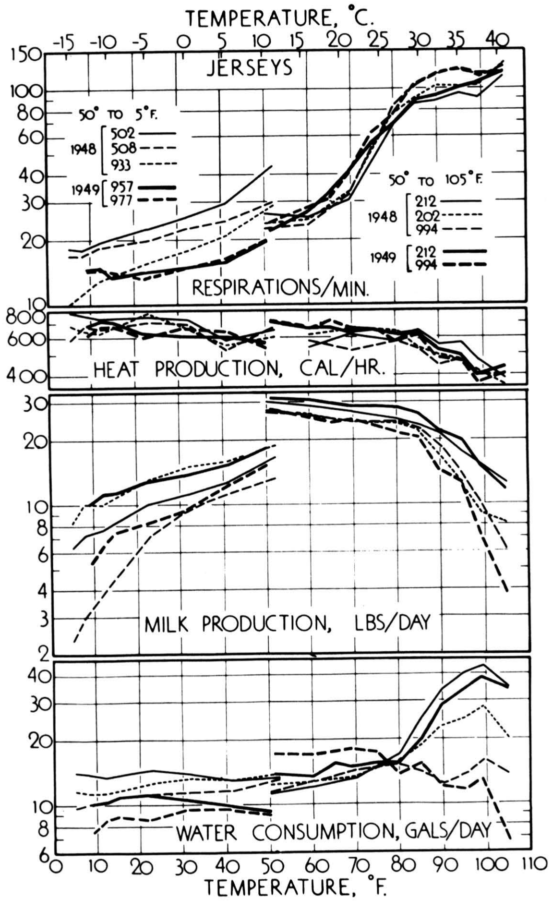

Fig. 11.—Individual differences in response to changing temperature in four lactating cows and one dry Holstein cow.

is associated with decline in milk yield and feed consumption. Lactating Jersey cow 212 paralleled the water consumption pattern of the dry (and slightly lactating) Brahman cows and heifers.

Breed and Age Comparison: Indian-evolved cattle are undoubtedly more heat tolerant than European cattle; the curves on feed consumption, milk production, and other physiological reactions in the Indian-evolved cows began to decline 15° later and the decline was less steep than in the European cows (Figs. 3 to 5). Although this greater heat tolerance is popularly attributed to a greater "sweating" rate of Indian cattle, our data do not substantiate this[5].

Three factors seem to contribute to the higher heat tolerance of Brahman cattle. First, they have 12 per cent more surface area (pendulous ears, dewlap, navel flap, hump) than European cattle of the same weight (Fig. 8). This enables them to dissipate more heat by convection and radiation as well as by vaporization.

Second, Brahman cattle produce very much less heat than European cows of the same weight (Fig. 8). The lower Brahman heat production may have resulted, in part, from a lower basal metabolism but mostly from a lower productivity rate (milk yield in this case). Occasionally there has been recorded for Indian cattle[6]—mostly in cooler localities—a yearly 10,000-lb. milk yield by a Sahiwal or a 7.000-lb. milk yield by a Sindhi, but nothing has been found comparable to the 26,000-lb. FCM (fat corrected milk to 4% fat) yield by the 700-lb. Jersey cow Stonehurst Patrician's Lily, or the 37,000-lb. FCM yield of the larger Holstein Carnation Ormsby Butter King Daisy in cool climates.

A third factor that may contribute to the greater heat tolerance of Brahmans is their low initial levels in the cardiorespiratory functions which give them a greater functional range or reserve for use under conditions of stress (Table 3). For instance, the normal respiration rate (Table 2) of the Brahmans is about 10 respirations per minute lower than in the European cows, and whereas the European cows have reached a maximum level at 85° or 90°F, the respiration in the Brahman indicates no decrease in the acceleration up to 105°F. Table 5 indicates that the *percentage increase* in respiration rate between 50°F and 105°F was over 200 per cent greater in the Brahman than in the European cows.

What was said about the heat tolerance of Brahmans tends to hold, within limits, for other breeds and ages. The smaller the animal the greater its

[5]Helge Ederstrom's unpublished observations on our European and Indian cattle indicate that neither "sweat" appreciably in the sense that man sweats. The outer surface moisture vaporization in cattle is apparently produced by physical processes, as by "osmosis".

[6]"Milk records of cattle in approved dairy farms in India", Vol. II, Misc. Bull. 36. The Imperial Council of Agricultural Research, New Delhi, 1941.

surface area per unit weight and, therefore, other conditions being equal, the more heat tolerant it tends to be and the less cold tolerant. Similarly, the lower the productive level, the lower the heat production that has to be dissipated and the more heat tolerant the animal.

But there are exceptions to the above generalizations. There seemed to be breed differences in heat tolerance between the Brown Swiss and Holstein cows although they were in the same body-weight and milk-production category. On increasing the environmental temperature from 50° to 105°F, the decline in milk production in the Holstein was 80 per cent and in the Brown Swiss only 60 per cent; the decline in feed consumption and rise in rectal temperature began at 80°F in the Brown Swiss and at 70°F in the Holsteins; the respiratory vaporization (as also the pulmonary ventilation) increased 150 per cent in the Brown Swiss and only 70 per cent in the Holsteins.

The Brown Swiss heifers were even more heat tolerant than the Brown Swiss cows; they showed greater cardiorespiratory reserve (greater percentage increase in the cardiorespiratory activities) and higher critical temperatures than the Brown Swiss cows, which is in accordance with the above generalization relating to the greater surface area per unit weight in the smaller animals.

Because of their smaller size the Jerseys are more heat tolerant than the Holsteins but apparently not more than the Brown Swiss in spite of the much greater size of the Brown Swiss. In some reactions the Jerseys showed a greater heat tolerance than the Brown Swiss while in others the Brown Swiss appeared superior to the Jerseys. However, the rectal temperature was higher in the Brown Swiss at 105° environmental temperature.

DISCUSSION

Cattle seem to react to low temperatures more like arctic species in contrast to man who reacts more like tropical species. Our animals seemed to be entirely comfortable at near 0°F, and it is known that beef cattle do not seem to be injured wintering outdoors in our mountain states with temperatures down to –40°F (difference of 140°F between rectal and outdoor temperature) whereas upon exposure to temperature of 75°F the rectal temperature begins to rise.

This *high cold tolerance* in cattle is associated with several heat conserving mechanisms: 1) reduction of respiration rate with consequent reduction of heat loss by vaporization and convection from the respiratory tract; 2) heat conservation by seeking shelter and by huddling; 3) seasonal adjustments to cold by growing warmer fur; 4) diurnal and other short-swing adjustments to falling temperature by erecting or fluffing the hair by pilomotor reflexes; 5) reduction of the conductivity of the peripheral tissue and the temperature of the skin by vasoconstriction (the skin temperature may be reduced at a certain critical temperature to just above freezing and is maintained there by delicate vasomotor control on further decline in environmental temperature thus preventing freezing); 6) high "basal metabolism" and overall heat production per unit surface area[7].

The *low heat tolerance* of cattle appears to be associated with their relatively high heat production[7] and low moisture vaporization[5] at higher temperatures. European cattle show a sudden vaporization acceleration at the relatively low temperature above 60°F (16°C) in contrast to vaporization acceleration ("breaking out in sweat") in man at the relatively high temperature 80° to 85°F (27° to 29°C). In cattle the vaporization acceleration declines above 75°F (24°C) with resulting rise in rectal temperature to the near lethal 109°F (42°C) at 105°F (41°C) environmental temperature, in contrast to man whose evaporative cooling by sweating increases in compound-interest fashion with rising temperature so that his rectal temperature is entirely normal at 105°F environmental temperature.

The surprising difference between the rectal temperature of cow and man at 105°F is also indicated by the differences in the ratio of heat dissipation by vaporization to heat production. This ratio at 105°F environmental temperature is about 200 per cent in man and only about 100 per cent in cattle; there appears to be no substantial differences between Brahman and European cattle in this ratio (Fig. 3a).

This ratio of heat dissipation by vaporization to heat production in cows tends to follow a linear course on the semi-logarithmic grid. When the entire group (with the exception of the dry Brahman cows) is considered, this ratio is increased exponentially, at a constant percentage rate of 2.7 per cent per 1°F rise (or 4.9 per 1°C rise) from 5° to 105°F, according to the equation $Y = ae^{kt}$ in which Y in the ratio and k is the instantaneous percentage rate at which Y increases per degree rise in temperature, t. However, when the curves are considered separately for each breed as in Fig. 3b, the percentage increase in this ratio is not always constant. While the curves for the heifers (lower segments) show constant percentage increases from 50° to 105°F, the curves for the European mature cows show changes in slopes following 65° or 70°F and in the lactating Brahman cows following 85°F. The upper segments indicates that for man the value of k following 80°F is 3 to 6 times greater than for cows—the value of k in man is 15 to 20 per cent for each 1°C rise and for cattle 3 to 5 per cent.

The inability of cattle to sweat increases steadily their surface temperature which meets the environmental temperature (Fig. 2) at about 105°F (41°C), when the rectal temperature attains 106° to 109°F (41°C to 43°C)

[7]The basal metabolism of a 30-40 year woman is 37 Cal/sq.m/hr.; the "basal metabolism" of a 765-lb. Guernsey cow, 48 hours after feeding, was 62 Cal/sq.m/hr., and when normally fed, 125 Cal/sq.m/hr. The ratio of "*basal metabolism*" of cow to basal metabolism of man is thus 62/37 = 1.7 fold; and the ratio of *lactating metabolism* of cow to basal metabolism of man is 125/37 = 5 fold.

and the animals are on the verge of collapse. This contrasts to the profusely sweating skin temperature of man which does not rise above about 92°F (33°C) on increasing the environmental temperature to 105°F. In man the blood is brought—by vasodilation—to the cool skin surface for cooling, this reduces the blood volume in the body interior and therefore increases the pulse rate. The opposite seems to occur in cattle with the increasing skin temperature and decreasing pulse rate with rising environmental temperature.

While the "comfort zone" in cattle was estimated to be between about freezing and 60°F (0° to 16°C), no data were obtained on the zone of thermoneutrality. This zone of thermoneutrality is the temperature range which does not affect the heat production in animals under conditions of "basal metabolism". The determination of the zone of thermoneutrality, and of heat production in post-absorptive conditions at the various temperatures outside the zone of thermoneutrality, is of the greatest physiological importance, and this, it is hoped, will eventually be worked out.

Since heat dissipation by non-evaporative methods decreases rapidly with increasing environmental temperature (decreasing temperature gradient, Fig. 2) and since productive processes are associated with high heat increments, it is obvious that there is a basic incompatibility between high productivity and high environmental temperature, especially in the larger non-sweating species.

This incompatibility of high production and high temperature challenges the shelter engineer for developing practicable cooling systems. Many years ago we used sponge blankets with built-in water sacks which, by moisture vaporization, kept the animals comfortably cool when exposed to a hot summer sun (shade temperature over 100°F). Sprinkling devices activated by the animals by means of an "electric eye" should also be useful[8]. Appropriate shade is particularly useful in reducing the summer solar-heat load.[9] Selection of animals for hair and skin color which best reflect solar radiation should be helpful. Bonsma[10] stressed the importance of selecting short, smooth light hair for hot regions.

Mention was made of cow 212 distinguished by great increase in coolwater consumption with increasing temperature. This increased her ability to withstand higher temperatures. This is presumably a hereditary characteristic. What is more important, just as there is a small percentage of nonsweating humans, so is there, apparently, a small percentage of sweating

[8]Kelly, C. F., and Ittner, N. R., Artificial shades for livestock in hot climates. Agric. Engineer. *29*, 239-242, 250, 1948.

[9]Kelly, C. F., Bond, T. E., and Ittner, N. R., Thermal design of livestock shades. Agric. Engineer, *31*, 601-606, 1950. Ittner, N. R., and Kelly, C. F., Cattle Shades, J. Animal Science, *10*, 184-194, 1951.

[10]Bonsma, J. C., Breeding cattle for increased adaptability to tropical and subtropical environments. J. Agric. Sc., *39*, part 2, 204-221 1949. See also Stewart, R. E., Absorption of Solar Radiation by the Hair of Cattle. Agric. Engineering, *34*:235-238, 1953.

cattle[11] which are, therefore, highly heat tolerant. This characteristic is presumably also hereditary. It should be possible, with the aid of a mobile climatic laboratory and systematic search for such heat tolerant individuals, to locate and by selective breeding to develop strains of profusely sweating and/or water-drinking, or otherwise heat tolerant, cattle.

SUMMARY AND ABSTRACT

This report presents an interpretive integration of the effects of gradually rising dry-bulb temperature 50° to 105°F (10° to 41°C) and declining temperature 50° to near 0°F (10° to –18°C) on many physiological reactions of European and Indian-evolved mature and yearling cattle. This integration is illustrated by 14 arithlog charts and summarized in 8 tables.

The "comfort zone" (maintenance of normal body temperature without serious aid from physical or chemical homeothermic mechanisms) was between about freezing and 60°F. The precise range of this comfort zone depends on the productive level—the higher the productive level and the larger the individual the greater the cold tolerance and the lower the heat tolerance.

Declining temperature to near 0°F (–18°C) had no appreciable effect on the heat production of the high-producing, large, Holstein cows; but it increased greatly the heat production and feed consumption in the low-producing, small, Brahman cows, and to a less extent in the well-producing Jersey cows (of approximately the same weight but of 12 per cent lower surface area than the Brahmans). The declining temperature gradually reduced the rates of respiration, pulmonary ventilation, and moisture vaporization in the European cows. No other changes were observed. The animals—even the Brahman—appeared to have been comfortable under our laboratory conditions at 8° (–12°C), and experience in wintering beef cattle outdoors in our mountain states indicates that they can withstand temperatures of –40°F without harm.

Rising temperature, however, affected the European animals profoundly above the (to man) cool temperature level of 60°F (16°C) when the respiration and moisture vaporization rates were suddenly accelerated, reaching a maximum at about 85°F (29°C). The rectal temperature began to rise in high-producing European cattle at about 70°F (21°C) followed by depression of feed consumption, milk production, heat production, pulse rate, blood CO_2-combining power and ascorbic acid and increase in blood creatinine. The low heat tolerance of cattle appears to be associated with their low moisture vaporization (for heat dissipation) and high heat production per unit surface area. Neither European nor Indian cattle "sweat" in the sense that man sweats.

[11]J. F. Findlay of the Hannah Dairy Research Institute, Ayr, Scotland, is reported by C. W. Turner, to have recently found a profusely sweating Ayrshire heifer.

The Brahman (Indian) cows lagged behind the European by about 15°F in their rise in rectal temperature and other physiological reactions, due to their 12 per cent greater surface per unit weight, lower heat production, mostly because of lower productivity and possibly lower basal metabolism; also to low initial levels of the physiological functions providing a greater range for increase under stress. But, as the environmental temperature approached 105°F (41°C), the distress in the Indian cows approached that of European cows.

While our Brown Swiss and Holsteins were in the same body-weight and milk yield category, the Brown Swiss appeared to be much more heat tolerant than the Holsteins, and were approximately equal to that of the smaller Jerseys.

The ratio of evaporative cooling to heat production at 105°F is about 200 per cent in man and only 100 per cent in cattle; above 80°F this ratio increases 15 to 20 per cent per 1°C in man and 3 to 5 per cent per 1°C in cattle.

There seems to be much more urgent need for developing methods for protecting cattle against rising temperature above 80°F (27°C) than against declining temperature below freezing and zero.

APPENDIX

Research Bulletins in the "Environmental Physiology" Series

Mo. Agr. Exp. Sta. Res. Bul. No.	Series No.	Title and Authors
423	I.	Physiological Backgrounds. Samuel Brody.
425	II.	Influence of Temperature, 50° to 105°F, on Milk Production and Feed Consumption in Dairy Cattle. A. C. Ragsdale, Samuel Brody, H. J. Thompson, and D. M. Worstell.
433	III.	Influence of Ambient Temperature, 50° to 100°F, on the Blood Composition of Jersey and Holstein Cows. Samuel Brody, Gloria Burge, Clifton Blincoe, Jay Barton, Robert Tary, and Wesley Platner.
435	IV.	Influence of Temperature, 50° to 105°F, on Heat Production and Cardiorespiratory Activities in Dairy Cattle. H. H. Kibler, Samuel Brody, and D. M. Worstell.
436	V.	Influence of Temperature, 50° to 105°F, on Water Consumption in Dairy Cattle. H. J. Thompson, D. M. Worstell, and Samuel Brody.
449	VI.	Influence of Temperature, 50° to 0°F and 50° to 95°F, on Milk Production, Feed and Water Consumption and Body Weight in Jersey and Holstein Cows. A. C. Ragsdale, D. M. Worstell, H. J. Thompson, and Samuel Brody.
450	VII.	Influence of Temperature, 50° to 5°F and 50° to 95°F, on Heat Production and Cardiorespiratory Activities of Dairy Cattle. H. H. Kibler and Samuel Brody.

Research Bulletins in the "Environmental Physiology" Series (*Contd.*)

Mo. Agr. Exp. Sta. Res. Bul. No.	Series No.	Title and Authors
451	VIII.	Influence of Ambient Temperature, 0° to 105°F, on Insensible Weight Loss and Moisture Vaporization in Holstein and Jersey Cattle. H. J. Thompson, R. M. McCroskey, and Samuel Brody.
460	IX.	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. A. C. Ragsdale, H, J. Thompson, D. M. Worstell, and Samuel Brody.
461	X.	Influence of Temperature, 5° to 95°F, on Evaporative Cooling from the Respiratory and Exterior Body Surfaces in Jersey and Holstein Cows. H. H. Kibler and Samuel Brody.
464	XI.	Effects of Temperature, 50° to 105°F and 50° to 9°F, on Heat Production and Cardiorespiratory Activities in Brahman, Jersey and Holstein Cows. H. H. Kibler and Samuel Brody.
471	XII.	Influence of Increasing Temperature, 40° to 105°F, on Milk Production in Brown Swiss Cows, and on Feed and Water Consumption and Body Weight In Brown Swiss and Brahman Cows and Heifers. A. C. Ragsdale, H. J. Thompson, D. M. Worstell and Samuel Brody.
473	XIII.	Influence of Increasing Temperature, 40° to 105°F, on Heat Production and Cardiorespiratory Activities in Brown Swiss and Brahman Cows and Heifers. H. H. Kibler and Samuel Brody.
479	XIV.	Influence of Temperature on Insensible Weight Loss and Moisture Vaporization in Brahman, Brown Swiss, Holstein, and Jersey Cattle. H. J. Thompson, R. M. McCroskey, and Samuel Brody.
481	XV.	Influence of Environmental Temperature, 0° to 105°F, on Hair and Skin Temperatures and on the Partition of Heat Dissipation Between Evaporative and Non-Evaporative Cooling in Jersey and Holstein Cattle. H. J. Thompson, D. M. Worstell, and Samuel Brody.
484	XVI.	Effect of Increasing Temperature, 65° to 95°F, on the Reflection of Visible Radiation from the Hair of Brown Swiss and Brahman Cows. R. E. Stewart, E. E. Pickett, and Samuel Brody.
488	XVII.	The Influence of Temperature on the Blood Composition of Cattle. Clifton Blincoe and Samuel Brody in collaboration with Gloria Burge, H. Grieg Turner, Dorothy Worstell, and J. R. Elliott.
489	XVIII.	Influence of Environmental Temperature, 0° to 105°F, on Hair and Skin Temperature of Holstein, Jersey, Brown Swiss, and Brahman Cattle with Notes on the Thermal Properties of Hair and Skin. H. J. Thompson, D. M. Worstell, and Samuel Brody.
497	XIX.	Relative Efficiency of Surface Evaporative, Respiratory Evaporative, and Non-evaporative Cooling in Relation to Heat Production in Jersey, Holstein, Brown Swiss, and Brahman Cattle, 5° to 105°F. H. H. Kibler and Samuel Brody.

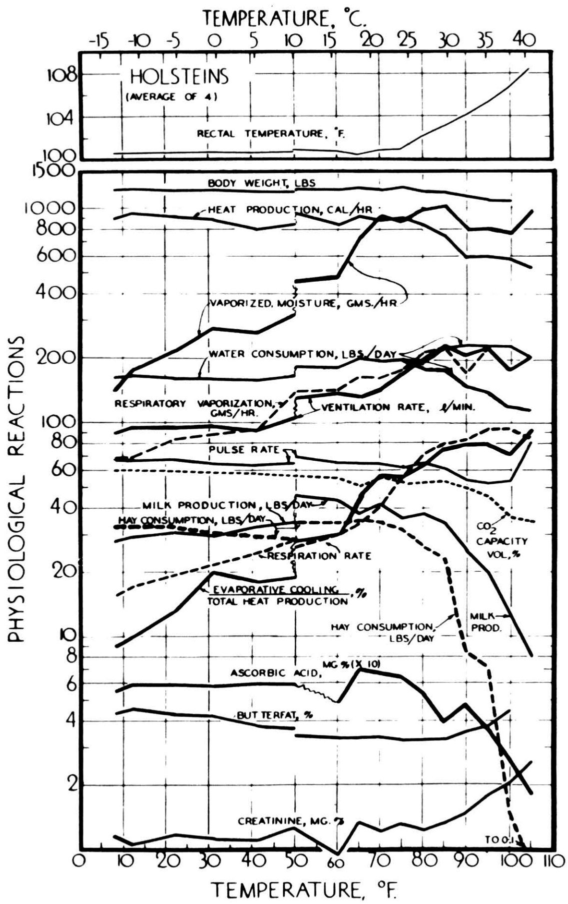

Fig. 12.—The average of the various physiological reactions on four lactating Holstein cows (2 during the summer 1948 period averaged with 2 during the summer 1949 period, and 2 during the winter 1948 period averaged with 2 during the winter 1949 period) plotted on semi-logarithmic paper to show the relative changes between them. Rectal temperature (upper section) is plotted on coordinate paper. Above 75°F, the water consumption data were separated into two averages—one for cows showing increase in consumption and the other for those showing a decrease. The curves for hay consumption do not include the 1948 data (because the refused hay was not dried). The curves for total vaporized moisture, respiratory moisture, pulmonary ventilation rate, ratio of vaporized moisture to heat production also represent 1949 data only. Since H-7 was removed from the chamber after a day at 100° (rectal temperature of 107.0°F) temperature, the average for the 105°F temperature period represents one cow on the curves mentioned previously.

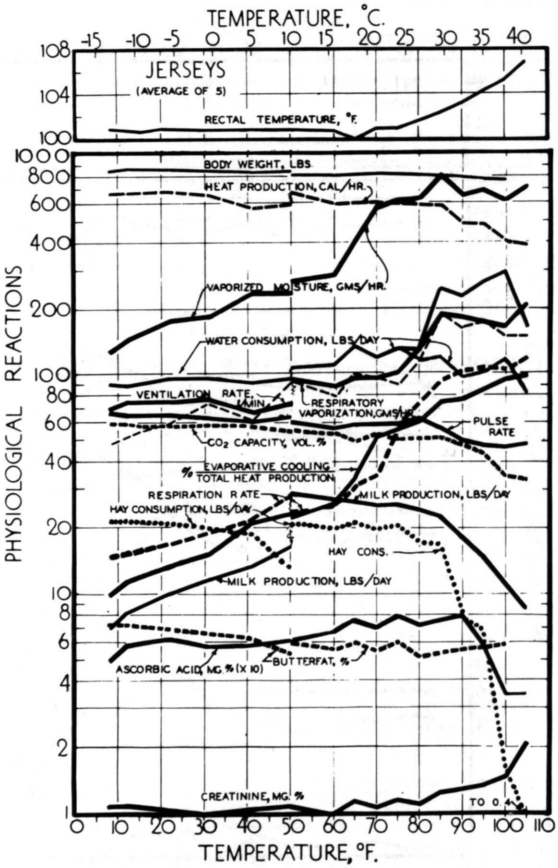

Fig. 13.—Similar to Fig. 12 but for lactating Jersey cows (average of 5, except for those reactions as listed in the text).

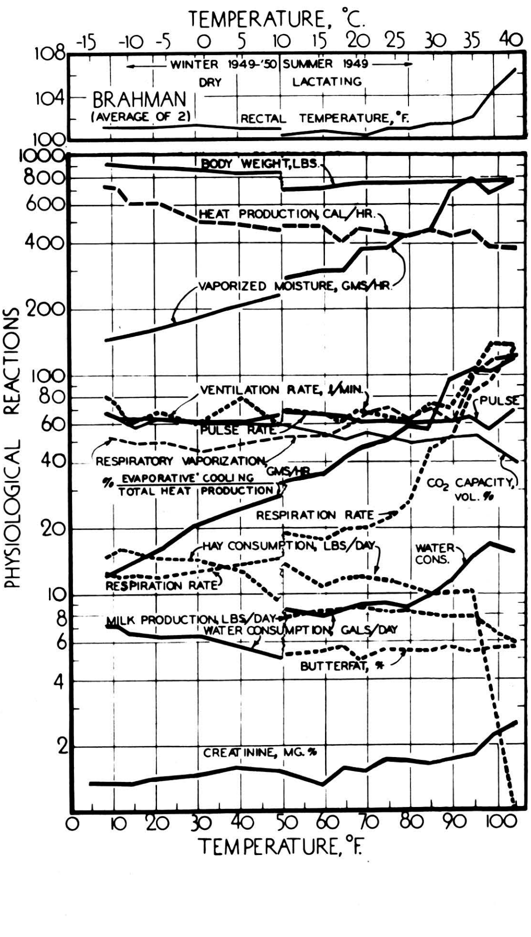

Fig. 14.—The average of the various physiological reactions on two lactating Brahman cows (50° to 105°F) and two dry Brahman cows (50° to 5°F) plotted on semi-logarithmic paper to show the relative changes between the various reactions. Rectal temperature (upper section) is plotted on coordinate paper.

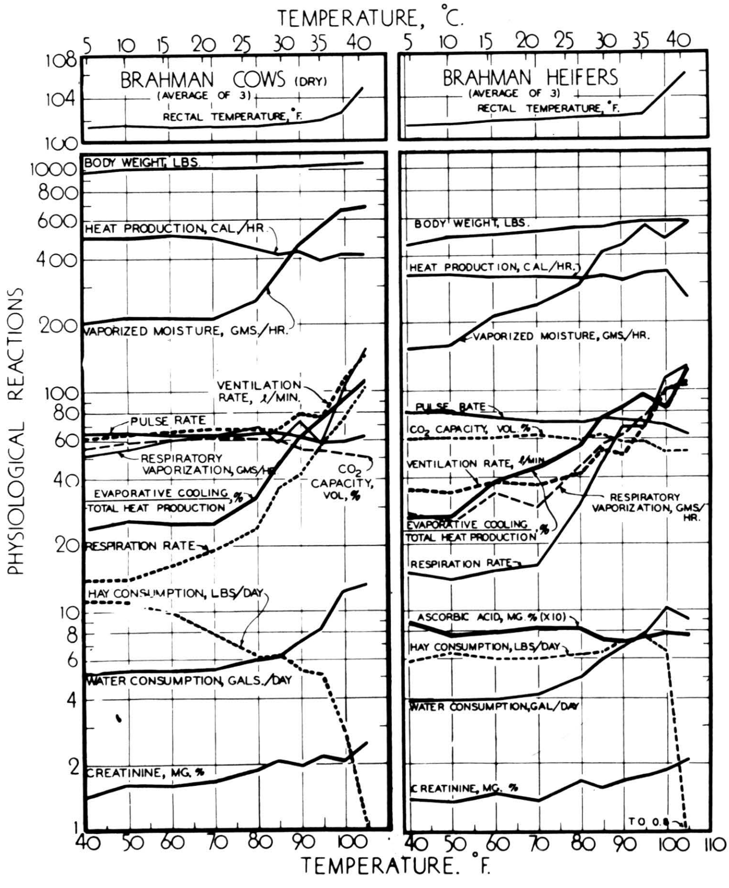

Fig. 15.—A semi-logarithmic analysis of the various physiological reactions on the average of three Brahman cows (left section) and the average of three Brahman heifers (right section). Rectal temperature is plotted on coordinate paper (upper section).

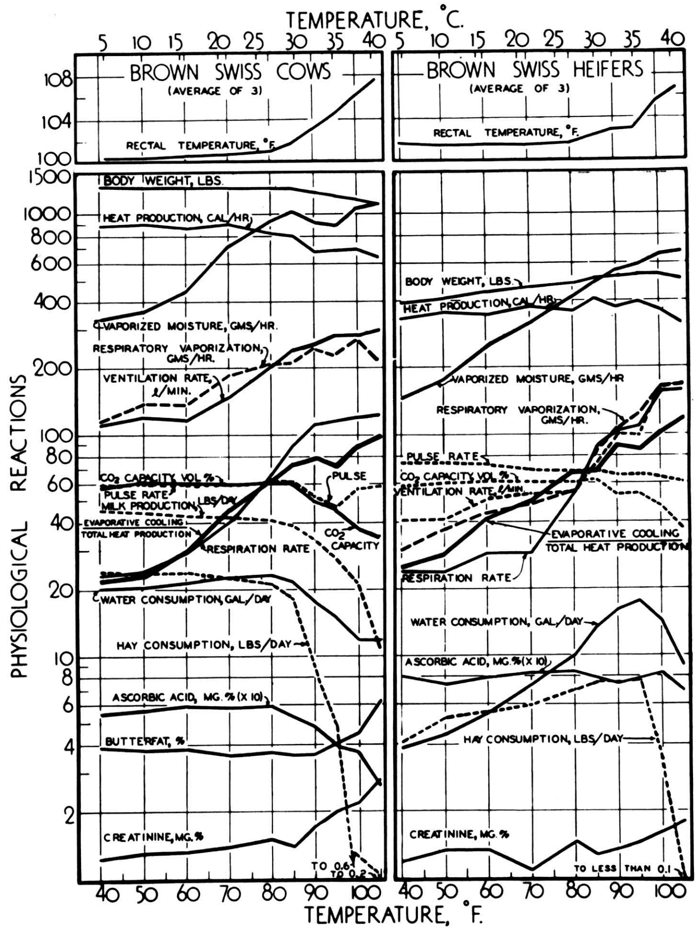

Fig. 16—The same as Fig. 15 but for Brown Swiss cows and heifers.

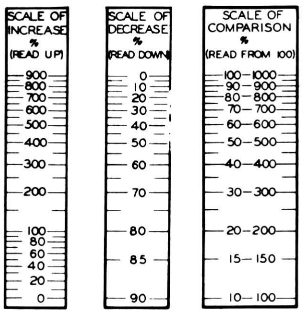

Fig. 17.—On a logarithmic grid the distance from 1 to 10 is equal to the distance of 10 to 100, or 100 to 1000. Therefore, it is possible to construct scales like this useful for determining the percentage change between two points on a curve direct from the chart. A "scale of increase" was prepared for determining the percentage rise for rising slopes; a "scale of decrease" for determining the percentage decline for declining slopes; and a "scale of comparison" for determining the percentage relation of one curve to another, or for determining for a given reaction the per cent relation at two temperature levels—for declining reactions, the scale is 10 to 100, and for rising reactions the scale is 100 to 1000.

These scales may be clipped from the page and used as a ruler for reading off the various percentage relations; or they may be used for measuring the vertical distance between two points on the chart curve, laying this distance off on the scale and reading from the scale the per cent relations.

To illustrate, suppose we wish to determine the percentage increase in respiration rate between 50° and 100°F in Holstein Cow 109 (Fig. 9). This is done by measuring the vertical distance on the curve between 50° and 100°F; laying off this distance on the left-hand scale of Fig. 17; and reading from "O" up, a value of 350 is obtained. Hence, the increase in respiration for H-109 from 50° to 100°F was 350 per cent. Likewise if it is desired to determine the percentage decrease in milk production from 50° to 105°F, begin from the top and read down the measured distance on the center scale and read a decrease of 80 per cent.

Suppose, it is desired to find the percentage relation between the milk production decreases on increasing the temperature to 105°F in Holstein and Brown Swiss cows (Fig. 4, upper section). By measuring the distance between the two curves at 105°F (the initial level is approximately the same in both) a value of 45 is obtained by reading from 100 down on the right-hand scale. Therefore, at 105°F, the milk production of the Holstein cows was 45 per cent that of the Brown Swiss cows. Or from Fig. 9, by using the comparison scale (starting at 100), measure the distance the milk production curve has declined from 50° to 105°F, and obtain a value of 20, meaning that the milk production of H-109 at 105°F was 20 per cent of that at 50°F. Similarly, the scale may be applied to the curve for respiration rate; by using the scale for values above 100, the respiration rate at 105°F was 400 per cent the value at 50°F.