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Environmental Physiology and Shelter Engineering

With Special Reference to Domestic Animals

XLIII. ENERGY METABOLISM AND CARDIORESPIRATORY ACTIVITIES IN SHORTHORN, SANTA GERTRUDIS, AND BRAHMAN HEIFERS DURING GROWTH AT 50 AND 80° F TEMPERATURES

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University of Missouri Agricultural Experiment Station and the United States Department of Agriculture, Cooperating

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SUMMARY AND CONCLUSIONS

Brahman, Santa Gertrudis, and Shorthorn female calves were raised in three groups at 50° F, 80° F, and outdoor temperatures. Measurements were made from 2 to 16 months of age on three animals of each breed in each temperature group. The measurements reported in this bulletin include energy metabolism, pulmonary ventilation rate, respiration rate, pulse rate, rectal temperature, oxygen consumption, carbon dioxide production, and methane production.

Age changes in the group exposed to outdoor temperatures were masked by seasonal temperature effects. In the groups raised at 50 and 80° F, however, age effects were evident in pulse rate and energy metabolism. Increases from initially low values in young calves to maximum values occurred in pulse rate at 4 to 5 months of age, and in energy metabolism per unit surface area at about 6 months of age. Thereafter they decreased. Rectal temperature also decreased slightly with age.

The Brahman and Santa Gertrudis breeds proved to be quite tolerant to all three experimental temperatures as indicated by their rectal temperatures and respiration rates. The Shorthorns grown at 50° F and at outdoor temperatures did well, but those raised at 80° F experienced constant physical strain (rectal temperature about 104° F and respiration rate about 90).

Breed differences in heat tolerance were found to be inversely related to heat production per unit surface area and per unit weight. The Brahmans, which had the lowest rate of heat production (or energy metabolism), were most heat tolerant. The Shorthorns, which had the highest rate of heat production, were least heat tolerant. The Santa Gertrudis were intermediate in both respects. Basal metabolism measurements at 65° F temperature further confirmed the inverse relationship between heat production and heat tolerance. Measurement of rectal temperature during short exposures to temperatures of 90 to 110° F likewise indicated the order of heat tolerance to be: Brahman, Santa Gertrudis, Shorthorn.

A considerable body of basic data useful in studies of cattle nutrition and ventilation requirements were accumulated. Equations were fitted to these data and the results expressed in useable prediction tables which show breed and temperature differences.

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XLIII. ENERGY METABOLISM AND CARDIORESPIRATORY ACTIVITIES IN SHORTHORN, SANTA GERTRUDIS, AND BRAHMAN HEIFERS DURING GROWTH AT 50 AND 80° F TEMPERATURES

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INTRODUCTION

Studies of heat tolerance in cattle have been concerned mainly with factors which affect heat dissipation, such as insulating qualities of hair, number of sweat glands, and related measures. Thermal balance, however, may also be affected by the rate of energy metabolism or heat production. Since an animal has a limited surface area for heat dissipation the rate of heat production per unit surface area is an important consideration.

Attention has been called to the possible importance of the rate of heat production as a factor in heat tolerance in preceding bulletins in this series. Heat production per unit surface area was shown to be 20 to 30 percent higher in lactating Jersey and Holstein cows than in lactating Brahman Cows[1], and up to 70 percent higher in high producing Brown Swiss cows than in non-lactating Brahman cows[2]. Differences of about 25 percent were reported between growing Brown Swiss and Brahman calves [2]. Unfortunately, these breed comparisons were complicated by differences in the productive levels of the cows, and by differences in the ages of the calves.

This experiment with growing calves provides more definite and straightforward breed comparisons. Experimental groups comprised of three animals of each breed were raised at constant 50 and 80° F temperatures and a control group was raised at variable outdoor temperatures. Measurements of energy metabolism were made from the second to sixteenth month of age. These data on normally fed animals were supplementd by basal metabolism measurements at a common 65° F temperature. Indices of thermal balance including rectal temperature, respiratory rate, and pulse rate were measured at the 50 and 80° F temperatures, and also during short-term stress tests at 80 to 110° F temperatures following the growth study. These and related data on pulmonary ventilation, oxygen consumption, and carbon dioxide and methane production are presented in charts and prediction tables.

Other measurements were made during this experiment with growing calves by other members of this project. Two companion bulletins give the data on stable heat and moisture dissipation[3], and on dimensional and weight changes[4]. Other reports will present data on feed and water consumption, vaporization rates, blood volume and total extra-cellular body water, thyroid *in vivo* counts, surface temperature and area, hair growth and density, and ovarian and physical activity.

METHODS

Animals and Environment

The Shorthorn, Brahman, and Santa Gertrudis calves used in this experiment were brought to Columbia, Mo., by truck from southern states. Their ages ranged from one to three months. They were divided into three groups matched as closely as possible for age and weight. Two of the groups were placed in pens at the Climatic Laboratory. One of these groups consisting of three animals of each breed was raised at 50° F (10° C) temperature, 62 percent relative humidity, 5.5 mm. Hg. vapor pressure. The other, similar group was raised at 80° F (26.7° C) temperature, 54 percent relative humidity, 13.5 mm. Hg. vapor pressure. An air velocity of about ½ mile per hour was produced in both rooms by the air-conditioning system[3]. A third group was raised in an unheated shed with access to an outdoor lot. Temperatures inside the shed were similar to, but usually less extreme than outside temperatures. The three groups were raised under these different climatic conditions until all animals were approximately 16 months of age. Beyond that age the laboratory groups were tested at several temperatures from 65 to 110° F. The feeding and management[4] were similar for all three groups.

Measurements and Apparatus

Measurements were made on the animals listed in Table 1. The respiratory exchange measurements, including pulmonary ventilation rate, were made with the open-circuit metabolism apparatus shown in Figure 1a. Some adjustments in the sizes of masks and hose were necessary as the animals grew larger. Analyses of samples of exhaled air collected in the metabolism apparatus were made by chemical and electronic analyzers[5] to determine the rates of oxygen consumption, carbon dioxide production, and methane production. Simultaneous measurements of respiratory vaporization rate (an important means of evaporative heat loss) were also made with the open-circuit apparatus but will be reported in a later bulletin.[6]

Respiration rate was counted from flank movements when the animal was not wearing the mask. Pulse rate was counted with the aid of a stethoscope. Rectal temperature was determined with a veterinary thermometer.

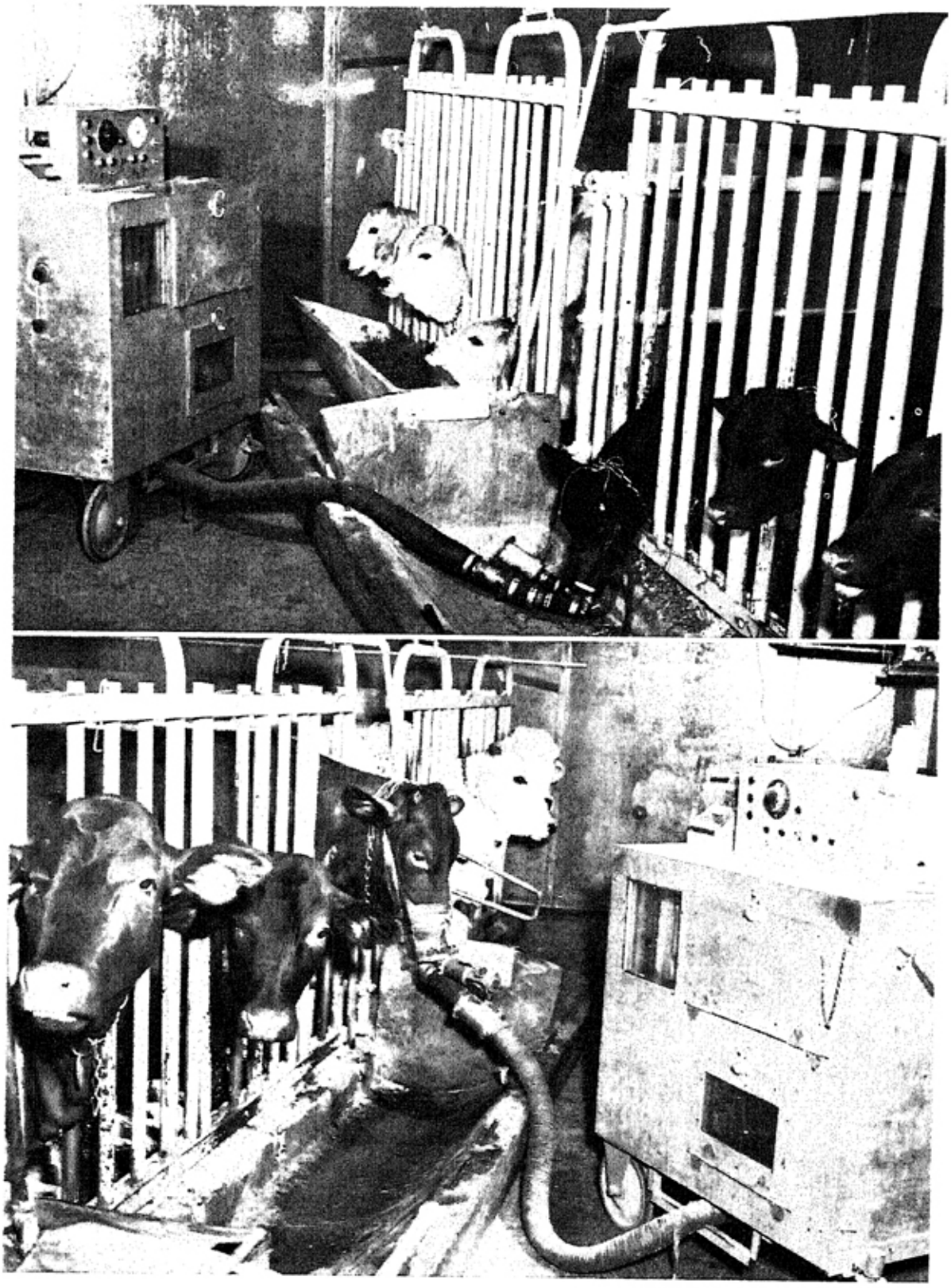

Fig. 1a—Views of metabolism measurements with the open-circuit apparatus when the calves were about 3 and 17 months of age. During the measurements, room air was inspired through a check valve and mask and expired through a hose and check valve into a large rubber bag within the apparatus case. The exhaled air was drawn from the rubber bag and through a gas meter by a motor-driven blower. It was then discharged back into the room. A small portion of the exhaled air was drawn through a collecting tube by means of a vacuum pump to provide a sample for gas analysis. The water vapor in the room air and exhaled air was measured with dewpoint indicators.

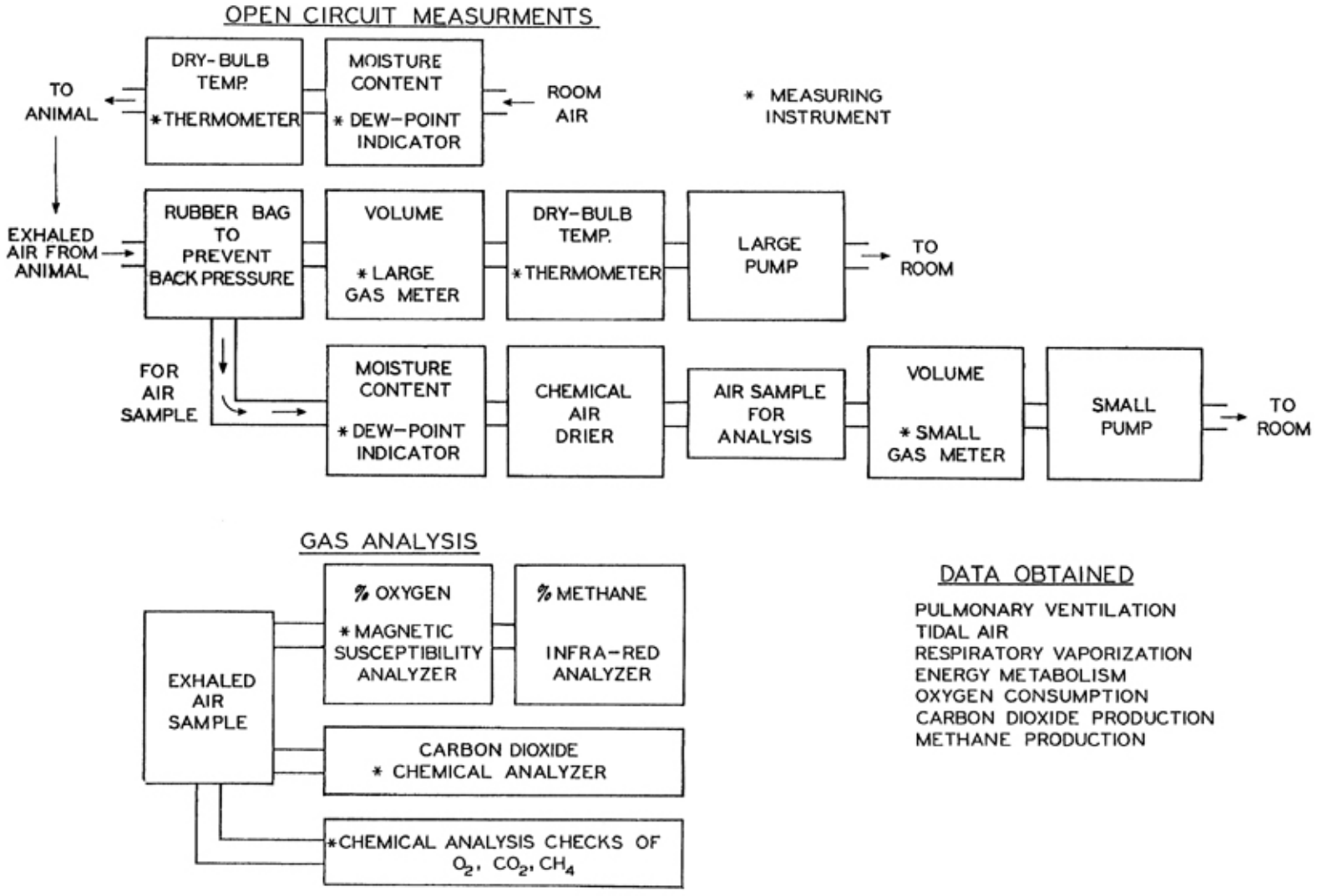

Fig. 1b—Block diagram of measurements and data obtained by use of the open-circuit metabolism apparatus shown in Fig. 1a. The interior of the cabinet is maintained at a temperature of 100° F by means of a 300-watt heating unit, fan, and thermostat. Tests are timed by an electric clock readable to 0.01 of a minute. The gas analyzers are not part of the apparatus shown in Fig. 1a, but they are an essential part of the open-circuit measurement system.

TABLE 1. SCHEDULE OF TESTS AND EXPERIMENTAL CONDITIONS AND NUMBER OF OBSERVATIONS OF REPORTED MEASUREMENTS

		50° Group	80° Group	Shed Group
Animal Numbers	Brahman	301,309,319	302,315,321	313,361,362
	Santa Gert.	366,368,387	384,393,396	371,379,385
	Shorthorn	332,342,349	338,354,355	*329,334,344
Period: Nov. 13, 1954 - Dec. 28, 1955				
Avg. Temperature, °F		50	80	Seasonal**
Avg. Relative Humidity, %		62	54	Seasonal
Number of Observations per Group				
Respiratory Exchange†		432	432	--
Respiration Rate		2250	2235	2343
Pulse Rate		2250	2235	2343
Rectal Temperature		2250	2235	2343
30 - hour fasts		27‡	27‡	---
Period: Jan. 3 - Mar. 27, 1956				
Temperature		65 to 100°F	65 to 110°F	None
Humidity		See Fig. 6	See Fig. 6	
Number of Observations per Group				
Respiratory Exchange†		177	147	
Respiration Rate		468	471	
Pulse Rate		468	471	
Rectal Temperature		468	471	
30-hour fasts at 65°F		27‡	27‡	

* No. 329 Shorthorn was placed in the 80°F room part of the time to observe the effects of clipping.
† This includes measurements of oxygen, carbon dioxide, methane, ventilation rate, and tidal air.
‡ Each type of measurement was made on each animal during each of three fasts.
**The average December, 1954, outdoor temperature was 30.9°F. Inside the shed the average was 36°F. The average July, 1955, outdoor temperature was 81.4°F; the maximum was 100°F.

DATA AND DISCUSSION

The data are presented in Tables 2 to 8 and Figures 2 to 9, arranged to permit comparisons of (1) sequence of changes with age, (2) breed difference during growth at constant environmental temperatures, and (3) relative effects of 50 and 80° F temperatures on each of the three breeds. Tests of significance were made by analyses of variance and covariance.

The values given in Tables 2, 4, and 8 are breed averages which were computed from equations fitted to the individual data. These data were plotted against body weight on a logarithmic grid and the method of least squares was used in fitting the relative growth equation

$$Y = aX^b. \quad (1)$$

Y represents the dependent variable such as energy metabolism and X represents body weight. The relative or percentage change in Y for a small percentage change in X is given by b. Two equation segments were usually required to fit the data over the whole growth period as b was greater during early growth than during later growth. The values of b and other statistical constants for the different sets of data are given in Tables 3 and 7.

Figure 2 summarizes approximately 20,000 individual observations of rectal temperature, respiration rate, and pulse rate. The data were averaged by two-week age periods for each animal, and later classified and averaged by breed and experimental condition. Each plotted mean was computed from 12 to 24 individual measurements. The occasional non-systematic variations in the data at constant 50 and 80° F temperatures reflect temporary changes in the condition of the animals. Where possible, abnormal data obtained after dehorning, vaccination, and other known disturbing events were omitted from the averages.

The separation of age and seasonal effects in the outdoor group was difficult. Averaging by age combined data obtained on different dates and at different environmental temperatures. Averaging by dates combined data for animals of different age. Both types of means were plotted in Figure 2 for the outdoor group. The curves show that age effects were obscured more by season than seasonal effects were obscured by age.

Body Temperature

Circulatory and respiratory activities are, of course, involved in the transport of oxygen and removal of carbon dioxide in metabolic processes. They also are involved in the transport of heat away from the central part of the body, the major site of heat production in the resting animal. Changes in pulse rate, respiratory rate, pulmonary ventilation rate, and rectal temperature, therefore, may reflect variations both in heat production and in heat transport and dissipation. Under constant temperature conditions, the rectal temperatures of the 50 and 80° F groups were highest at 3 to 5 months of age and thereafter declined a fraction

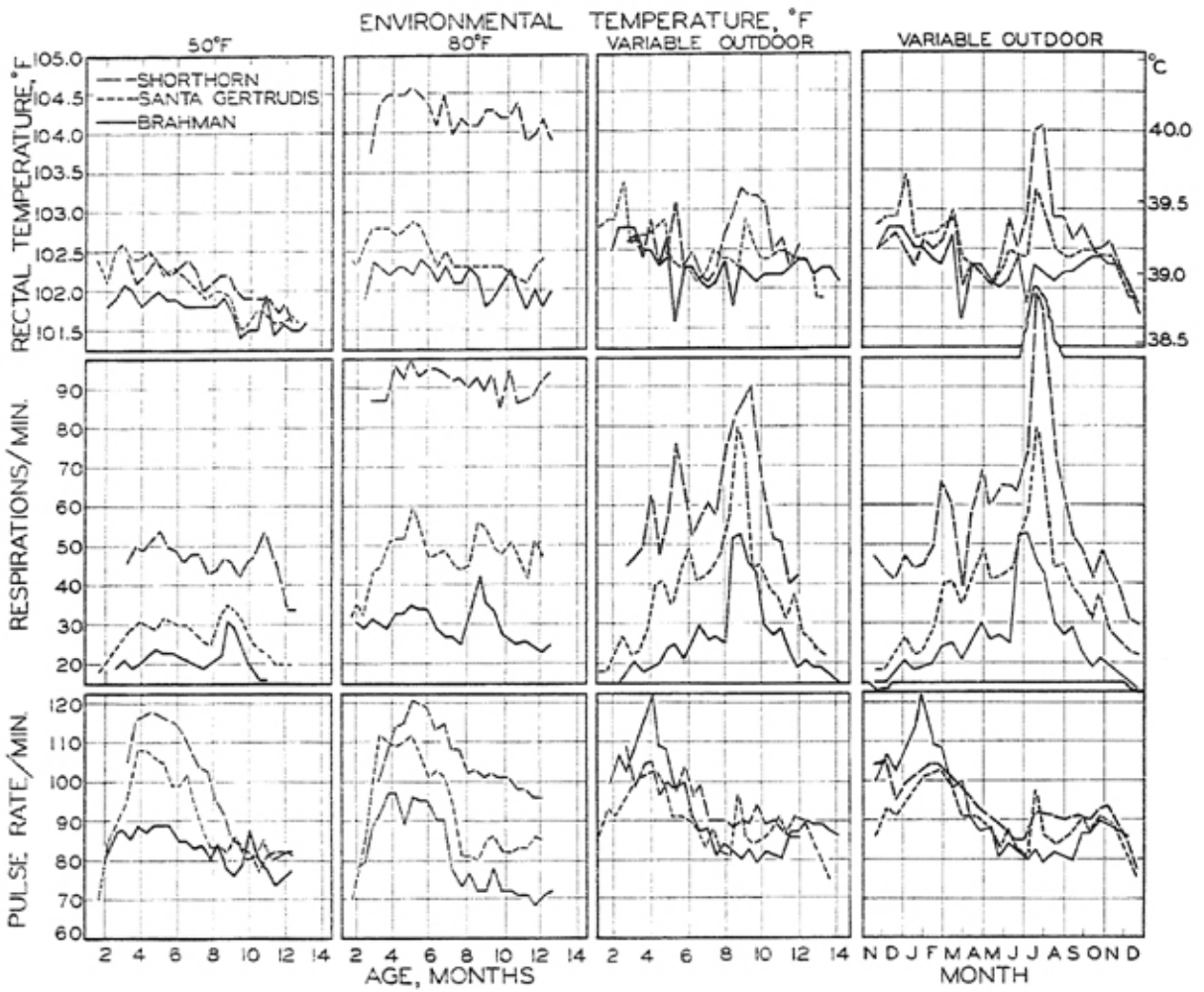

Fig. 2—Changes in the cardiorespiratory activities with age in Brahman, Santa Gertrudis, and Shorthorn calves raised at constant 50° and 80° F and variable outdoor or shed temperatures. As discussed in the text, the data for the group raised in the shed were plotted both by age and date of measurement. Each line connects points which represent 14-day averages of all data for the breed represented.

of a degree. Age changes in body temperature of the outdoor group were obscured by seasonal temperature effects.

Breed differences in body temperature were minor in the 50° F group. In the 80° F group, however, the levels for the Shorthorns were about 2° F higher throughout the experiment than for the other breeds. Under all three conditions, the Brahmans tended to have slightly lower values than either of the other breeds. As will be shown later, the Brahmans also had lower rates of heat production per unit surface area. The Shorthorns tended to have higher body temperatures than the other breeds but the difference was pronounced only in the 80° F group and in the outdoor group during the hottest weather. Nighttime cooling was a factor in holding down body temperature in the outdoor group.

Since the data were averaged from daily measurements over a two-week period, extreme daily variations tended to be averaged out.

Respiratory Rate

Changes in respiratory rate occurred with changes in temperature but not with changes in age. High temperatures naturally imposed a greater load on the heat dissipating functions. Increased respiration aided heat dissipation by increasing the volume of air passing over warm moist respiratory surfaces; thus increasing the sensible and evaporative cooling.

The respiratory rates were higher at 80° F than at 50° F in all breeds, and seasonal variations due to changes in temperature were reflected in the group exposed to outdoor temperatures.

In all groups, the respiratory rates were highest in the Shorthorns, lowest in the Brahmans, and intermediate in the Santa Gertrudis. At 80° F, for example, the mean rates per minute were about 90 in the Shorthorns, 50 in the Santa Gertrudis, and 30 in the Brahmans. At 50° F the corresponding rates were approximately 50, 28, and 22. Thus the respiratory rate of the Shorthorns at 50° F was equal to that of the Santa Gertrudis at 80° F and higher than that of the Brahmans at 80° F.

Pulse Rate

Pulse rate showed definite age effects. Maximum levels were reached at 4 to 6 months of age, followed by a rapid decrease between 6 and 8 months of age and slower decreases thereafter. Grad[7], working with rats, attributed similar decreases with age in pulse rate (also in oxygen consumption per unit size) to diminished responsiveness to thyroxine.

At 50° F, maximum mean pulse rates were 118 in Shorthorns, 108 in Santa Gertrudis, and 89 in Brahmans. At 80° F the corresponding rates were 120, 110, and 95. At 10 to 12 months of age these breed differences had largely disappeared in the 50° F group (all were about 80) but were quite pronounced in the 80° F group, ranging from 96 in the Shorthorns to 85 in the Santa Gertrudis and down to 70 in the Brahmans.

Pulmonary Ventilation Rate

The bovine species, unlike man, increases its ventilation rate (volume of air exhaled per unit time) with increasing temperature. By increasing their respiratory activity to a maximum, cattle may dissipate up to 40 percent of their body heat in the exhaled air. At low temperatures, a part of the respiratory heat loss occurs by convection (warming of the inspired air). At 80° F and higher temperatures, the greater part of this heat loss occurs by evaporation. It appears that increases in ventilation rate at higher temperatures occur primarily to increase

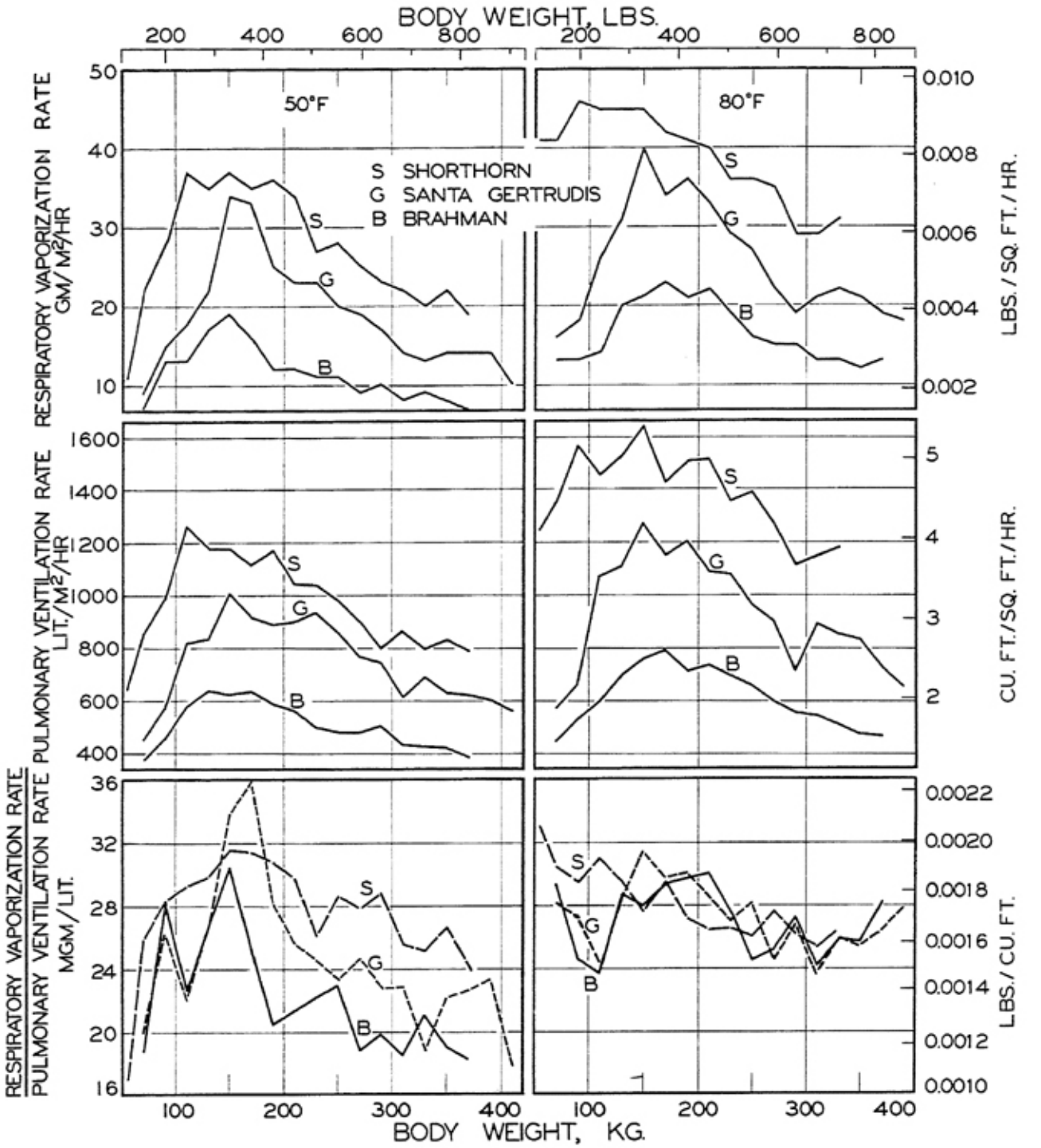

Fig. 3—Pulmonary ventilation rate and vaporization rate for the respiratory tract relative to body weight. Each line connects monthly averages of all data for the breed represented. Both metric and customary scales are provided.

vaporization from the respiratory tract.

The similarity of the curves for ventilation rate and respiratory vaporization rate during growth is shown in the two upper sections of Figure 3. The bottom section shows the ratios of the two measures. Changes in these ratios during growth were similar in shape but of less amplitude than the changes in the mea-

sures themselves. At the 50° F temperature, the mgm of water evaporated per liter of exhaled air varied from 16 to 36. At the 80° F temperature, the variation was only from 24 to 32. Maximum ventilation rates during growth were about one-third higher at 80 than at 50° F.

It is quite striking that in the 50° F room the Brahmans, which had the lowest ventilation rate, also vaporized the least water per unit volume of exhaled air. Similarly the Shorthorns, which had the highest ventilation rate, vaporized the most water per unit volume of exhaled air. One might expect that a low rate of movement of air over a surface would increase vaporization per unit volume of air. The data, however, indicate otherwise. The explanation may not be simple. Undoubtedly changes occur in the circulation of blood to the exposed surfaces. Changes in the turbulence of the air stream may be a factor. The amount of surface exposed varies with depth and frequency of respiration. Bligh's[8] comparisons of the temperature of the blood in the pulmonary artery and in the bicarotid trunk indicated that most of the evaporation in panting calves occurred in the respiratory passages rather than at the alveolar level. As indicated in a preceding bulletin[9], respiratory vaporization in cattle cannot be computed on the assumption that exhaled air is 90 to 100 percent saturated. Also it cannot be assumed that the temperaure of the exhaled air is equal to the temperature of the body.

Predicted ventilation rates for the three breeds for different ages and body weights are given in Table 2. The equations from which these values were calculated are given in Table 3.

Energy Metabolism Per Animal

The energy metabolism per animal was computed from the volume and composition of the respired air, and the caloric equivalent of the oxygen consumed. The individual measurements of the nine calves raised at 50° F and of the nine calves raised at 80° F are shown in Figure 4. The equation $Y = aX^b$ was fitted to the data for each breed by the methods discussed at the beginning of the section. Two equations were required for each set of data as the metabolism increased more rapidly relative to body weight in the early stage than in the later stage of growth. The correlations were all highly significant. Figure 4 visualizes the variability in the data. Standard errors of estimate, coefficients of correlation, and equation constants are given in Table 3. Prediction Table 4, which gives the values of energy metabolism for the different breeds during growth, was computed from the fitted equations in Table 3. As a result of these measurements, basic data were accumulated on the rates of oxygen consumption, carbon dioxide production, and methane production. As the changes in the volumes of these gases with age and temperature may be of value in ventilation and rumen studies, these data are presented in the Appendix.

TABLE 2. PREDICTION VALUES* FOR PULMONARY VENTILATION RATE AND RATIO OF OXYGEN CONSUMPTION TO VENTILATION RATE IN BRAHMAN (B), SANTA GERTRUDIS (G), AND SHORTHORN (S) CATTLE DURING GROWTH AT 50° AND 80°F CONSTANT TEMPERATURES

Approximate Age, Months			Body Weight		Ventilation Rate liters/minute			% Oxygen Consumption / Ventilation Rate		
B	G	S	kg.	lb.	B	G	S	B	G	S
				Environmental Temperature 50°F (10°C)						
1.1	0.8	2.0	50	110	5.6	5.2	12.9	5.95	7.05	4.13
1.7	1.4	2.7	60	132	7.5	7.7	16.8	5.33	5.85	3.67
2.7	2.5	3.6	80	176	11.8	14.5	25.6	4.38	4.25	3.07
3.6	3.2	4.3	100	221	16.8	23.7	35.4	3.87	3.30	2.63
4.5	4.0	5.0	125	276	22.5	32.2	39.5	3.63	3.10	2.83
5.3	4.7	5.7	150	330	23.8	33.9	41.0	4.13	3.58	3.17
6.3	5.5	6.6	175	386	25.1	35.4	42.4	3.98	3.53	3.07
7.2	6.3	7.4	200	441	26.2	36.8	43.6	4.07	3.67	3.10
8.4	7.1	8.5	225	496	27.2	38.1	44.7	4.10	3.72	3.13
10.1	7.9	9.5	250	551	28.2	39.3	45.8	4.13	3.73	3.13
11.2	8.8	10.8	275	606	29.1	40.3	46.7	4.18	3.77	3.18
12.9	10.1	12.2	300	661	29.9	41.4	47.6	4.18	3.78	3.18
14.9	11.3	13.5	325	716	30.7	42.3	48.4	4.23	3.78	3.20
16.1	12.4	15.2	350	772	31.5	43.2	49.1	4.23	3.82	3.22
	13.6	16.4	375	827		44.1	49.8		3.85	3.25
	14.9	17.7	400	882		44.9	50.5		3.87	3.27
	15.3	19.4	425	937		45.7	51.2		3.87	3.25
				Environmental Temperature 80°F (26.7°C)						
1.0	0.8	2.3	50	110	7.9	6.6	31.4	4.43	5.30	1.60
1.9	1.5	3.0	60	132	10.0	9.6	34.4	4.17	4.52	1.70
2.6	2.6	4.5	80	176	14.4	17.4	39.8	3.82	3.45	1.80
3.4	3.5	6.0	100	221	19.1	27.4	44.5	3.58	2.80	1.95
4.3	4.2	7.1	125	276	27.1	39.0	49.8	3.13	2.52	2.07
5.1	5.0	8.3	150	330	28.8	41.6	54.5	3.58	2.88	2.17
5.9	5.9	10.2	175	386	30.3	43.9	58.9	3.52	2.82	1.90
6.5	6.7	11.3	200	441	31.6	46.0	63.0	3.53	2.75	1.88
7.4	7.6	12.9	225	496	32.8	47.9	66.8	3.55	2.72	1.87
8.7	8.8	14.4	250	551	34.0	49.7	70.4	3.58	2.65	1.85
10.1	10.1	15.4	275	606	35.0	51.4	73.9	3.57	2.63	1.85
12.0	11.5	16.4	300	661	36.0	53.0	77.2	3.62	2.62	1.83
13.5	12.6	17.9	325	716	37.0	54.5	80.4	3.60	2.57	1.82

TABLE 2 -- (continued)

Approximate Age, Months			Body Weight		Ventilation Rate liters/minute			% Oxygen Consumption / Ventilation Rate		
B	G	S	kg.	lb.	B	G	S	B	G	S
15.1	14.1	19.2	350	772	37.9	55.9	83.4	3.60	2.53	1.80
16.6	16.0		375	827	38.8	57.2		3.60	2.50	
17.7	17.0		400	882	39.6	58.6		3.62	2.50	

* From weekly respiratory exchange measurements made between 1:00 and 3:00 p.m. on normally fed animals standing quietly in stanchions. The tabular values were computed from the equations given in Table 3. All volumes are given as dry gas at 760 mm Hg. pressure and O°C temperature.

Conversion Factor: lit./min. x 0.035315 = cu. ft. /min.

TABLE 3. CONSTANTS OF EQUATION $Y = aX^b$ USED IN COMPUTING PREDICTION TABLES FOR THREE BREEDS OF CATTLE DURING GROWTH AT CONSTANT TEMPERATURES OF 50° AND 80°
(X is body weight, kg; Y indicates measure shown below)

Growth Period	Number of Observations 50°	Number of Observations 80°	Breed	Equation Constants a 50°	Equation Constants a 80°	Equation Constants b 50°	Equation Constants b 80°	Correlation Coefficient 50°	Correlation Coefficient 80°	Standard Error of Estimate % + 50°	Standard Error of Estimate % + 80°	Standard Error of Estimate % - 50°	Standard Error of Estimate % - 80°
				Y = Energy Metabolism, Cal/hr.									
Early	38	37	Brahman	1.76	1.99	1.02	1.01	0.884	0.900	13.0	14.2	11.5	12.4
	40	39	Santa Gertrudis	1.49	1.16	1.10	1.15	0.936	0.889	12.1	17.5	10.8	14.9
	39	49	Shorthorn	6.86	6.18	0.81	0.81	0.921	0.853	10.1	12.6	9.2	11.2
Later	103	100	Brahman	34.6	50.4	0.42	0.36	0.721	0.624	10.9	10.6	9.8	9.6
	99	103	Santa Gertrudis	62.9	128.3	0.35	0.21	0.732	0.415	9.7	11.2	8.8	10.1
	97	85	Shorthorn	68.8	41.0	0.33	0.41	0.775	0.718	8.2	10.6	7.6	9.6
				Y = Pulmonary Ventilation Rate, liters/minute (S.T.P.)									
Early	34	24	Brahman	0.0115	0.0553	1.583	1.269	0.917	0.840	15.1	20.0	13.1	16.7
	23	22	Santa Gertrudis	0.0010	0.0022	2.187	2.048	0.888	0.880	21.4	23.8	17.6	19.2
	20	132*	Shorthorn	0.0426	4.407	1.460	0.502	0.760	0.847	22.3	16.4	18.2	14.1
Later	111	113	Brahman	4.611	5.682	0.328	0.324	0.618	0.713	12.4	9.6	11.0	8.8
	116	117	Santa Gertrudis	8.002	7.234	0.288	0.349	0.749	0.661	9.8	12.3	8.9	11.0
	121	**	Shorthorn	14.19		0.212		0.508		17.8		15.1	

* For entire period from 2 to 16 months of age.
** See * above.

TABLE 4. PREDICTION VALUES FOR ENERGY METABOLISM OR HEAT PRODUCTION* IN BRAHMAN (B), SANTA GERTRUDIS (G), AND SHORTHORN (S) CATTLE DURING GROWTH AT 50° AND 80° F CONSTANT TEMPERATURES

Approximate Age Months			Body Weight		Heat Production, Cal/hr.									†
					Per Animal			Per sq. meter**			Per kilogram			
B	G	S	kg.	lb.	B	G	S	B	G	S	B	G	S	
					Environmental Temperature, 50°F (10°C)									
1.1	0.8	2.0	50	110	95	110	163	68	80	122	1.90	2.20	3.26	
1.7	1.4	2.7	60	132	115	135	189	75	90	130	1.92	2.25	3.15	
2.7	2.5	3.6	80	176	154	185	239	85	107	141	1.92	2.31	2.99	
3.6	3.2	4.3	100	221	193	236	286	96	123	155	1.93	2.36	2.86	
4.5	4.0	5.0	125	276	242	302	343	111	144	174	1.94	2.42	2.74	
5.3	4.7	5.7	150	330	284	369	366‡	120	164	174	1.89	2.46	2.44	
6.3	5.5	6.6	175	386	303	383	378	119	160	168	1.73	2.19	2.16	
7.2	6.3	7.4	200	441	320	402	395	118	160	164	1.60	2.01	1.98	
8.4	7.1	8.5	225	496	337	419	411	115	158	159	1.50	1.86	1.83	
10.1	7.9	9.5	250	551	352	434	426	110	154	153	1.41	1.74	1.70	
11.2	8.8	10.8	275	606	366	449	439	102	148	146	1.33	1.63	1.60	
12.9	10.1	12.2	300	661	380	463	452	93	139	137	1.27	1.54	1.51	
14.9	11.3	13.5	325	716	393	476	464	89	131	127	1.21	1.46	1.43	
16.1	12.4	15.2	350	772	405	488	476	88	122	119	1.16	1.39	1.36	
	13.6	16.4	375	827		500	486		114	112		1.33	1.30	
	14.9	17.7	400	882		512	497		111	107		1.28	1.24	
	15.3	19.4	425	937		523			109			1.23		

TABLE 4 -- (continued)

Approximate Age Months			Body Weight		Heat Production, Cal/hr.									†
					Per Animal			Per sq. meter**			Per kilogram			
B	G	S	kg.	lb.	B	G	S	B	G	S	B	G	S	
					Environmental Temperature, 80°F (26.7°C)									
1.0	0.8	2.3	50	110	104	104	147	74	73	106	2.08	2.08	2.94	
1.9	1.5	3.0	60	132	125	129	170	83	81	115	2.08	2.15	2.83	
2.6	2.6	4.5	80	176	166	179	215	93	103	128	2.08	2.24	2.69	
3.4	3.5	6.0	100	221	208	231	258	104	122	140	2.08	2.31	2.58	
4.3	4.2	7.1	125	276	261	291	309	119	139	155	2.09	2.33	2.47	
5.1	5.0	8.3	150	330	314	369	320	135	168	152	2.09	2.46	2.13	
5.9	5.9	10.2	175	386	323	379	341	130	169	152	1.85	2.16	2.95	
6.5	6.7	11.3	200	441	339	389	360	128	166	146	1.70	1.94	1.80	
7.4	7.6	12.9	225	496	354	397	378	125	153	132	1.57	1.76	1.68	
8.7	8.8	14.4	250	551	368	408	394	118	135	118	1.47	1.63	1.58	
10.1	10.1	15.4	275	606	381	416	410	109	122	111	1.38	1.51	1.49	
12.0	11.5	16.4	300	661	393	424	425	99	114	104	1.31	1.41	1.42	
13.5	12.6	17.9	325	716	404	431	439	91	108	102	1.24	1.33	1.35	
15.1	14.1	19.2	350	772	416	438	453	86	100	102	1.19	1.25	1.29	
16.6	16.0		375	827	426	444		84	95		1.14	1.18		
17.7	17.0		400	882		445			93			1.11		

* Computed from equations relating energy metabolism to body weight fitted by the least squares method to weekly data measured between 1:00 and 3:00 PM on normally fed animals standing quietly in stanchions. Equations and statistical constants are given in Table 3.

** The surface area values used in these ratios were derived from unpublished data by E. B. O'Bannon, P. R. Cornelison, D. A. Hartman, A. C. Ragsdale, and S. Brody.

† For body weights used in these ratios see Table 5, Ref. 4.

‡ Average of two intersecting equations.

Conversion Factor: Cal./hr. x 3.968 = B.t.u./hr.

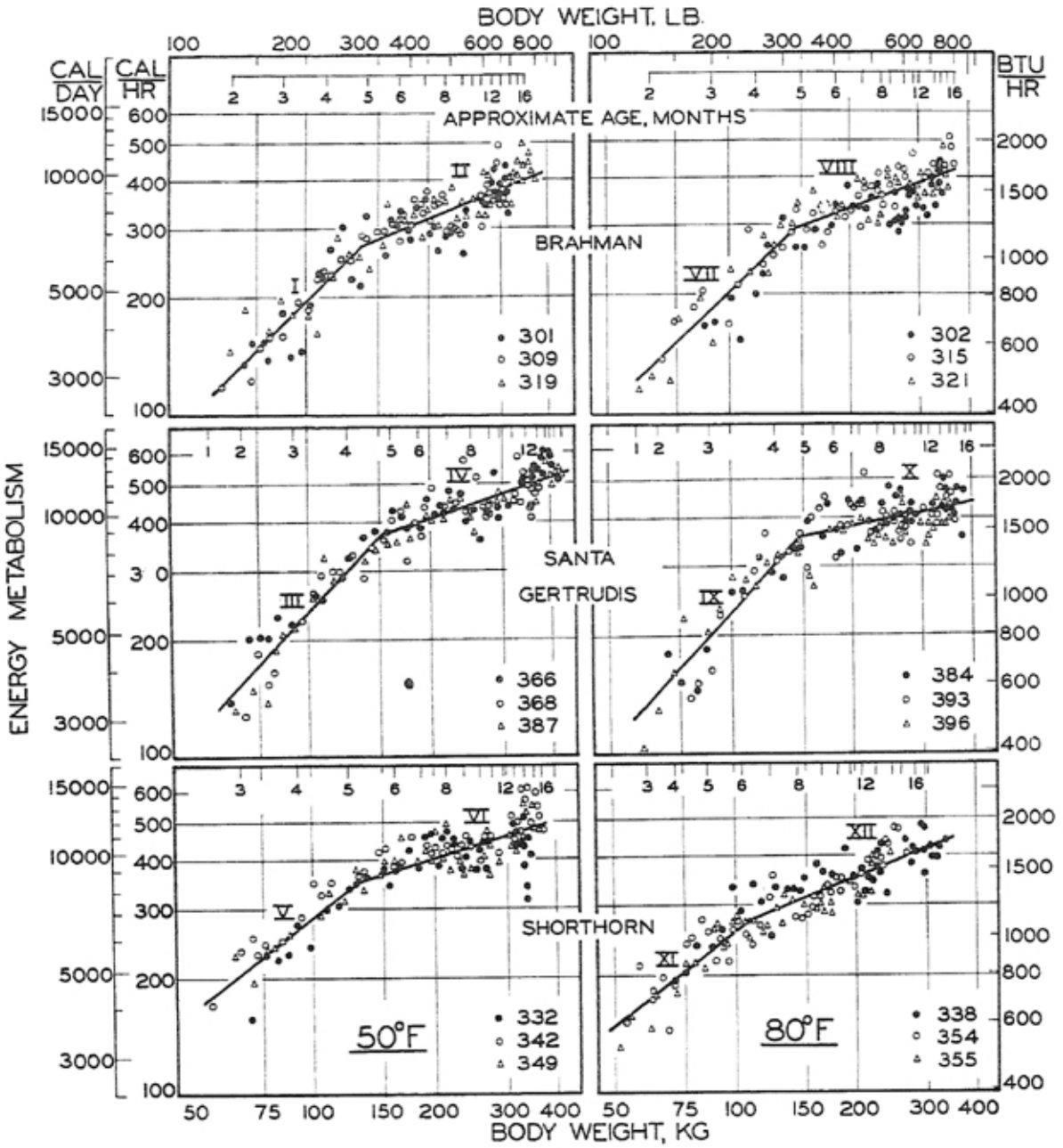

Fig. 4—Energy metabolism expressed as Cal/hr or Btu/hr plotted against body weight. The lines represent the equation $Y = aX^b$ fitted to the data for each breed and temperature group by the method of least squares. Each point represents a single measurement. The scatter of the data about the lines gives a visual estimate of the variability of the individual measurements. The equation constants and statistical measure of variability are given in Table 3.

Energy Metabolism per Unit Surface Area

Heat production per unit of outer surface area is one of the most logical means of expressing the metabolic heat load of the animal. All the body heat must be dissipated through respiratory or outer surfaces, and the greater part is dissipated through the outer surface.

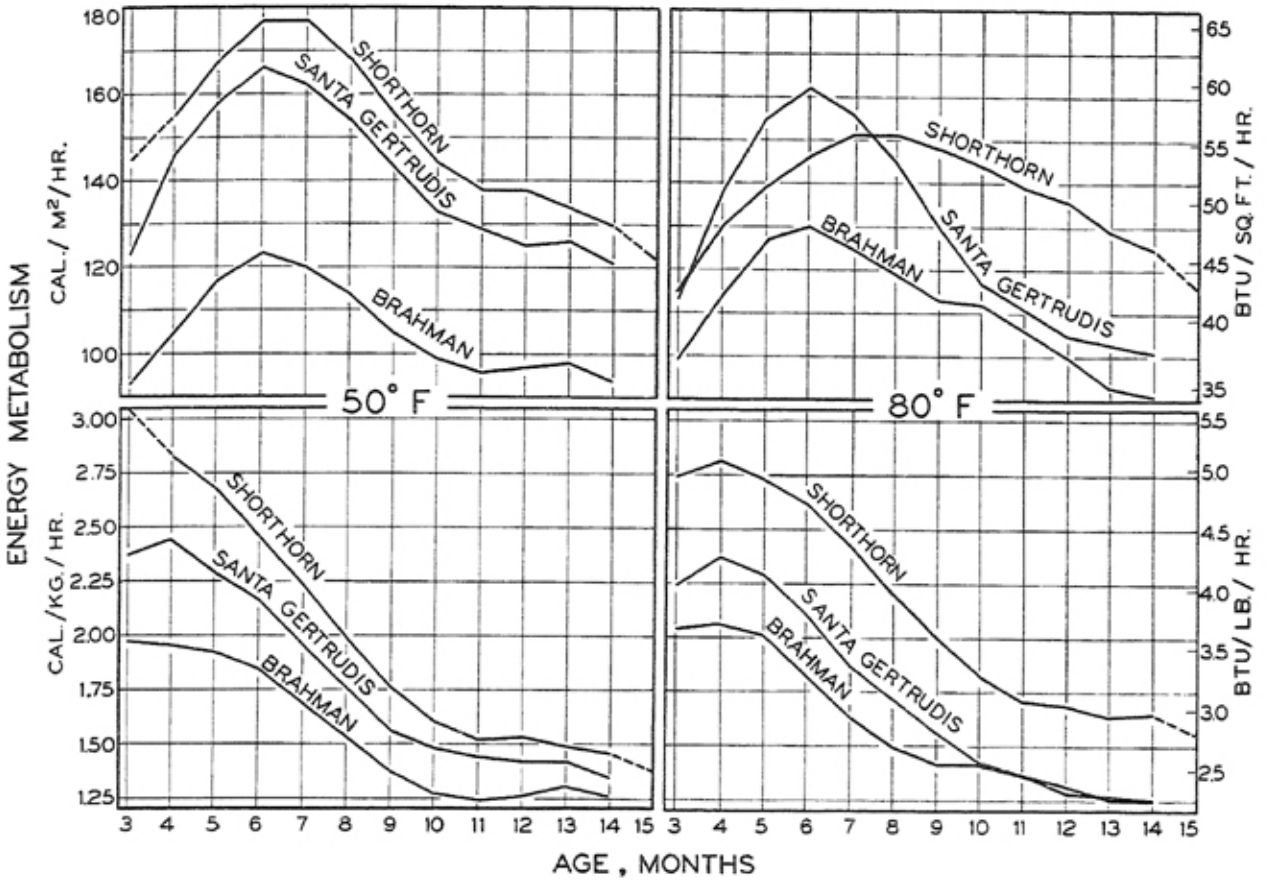

Fig. 5—Energy metabolism or heat production per unit surface area and per unit weight plotted against age. The smooth curves represent, three-point moving averages of monthly breed averages. The scatter of individual measurements about the smooth curves are shown in Figures 8 and 9. As discussed in the text, the heat tolerance of the three breeds proved to be in inverse relation to their heat production rates.

Thermal balance, then, may be said to depend on two factors: the heat load per unit surface area and the heat dissipation per unit surface area. If the heat production per unit area remains constant, heat tolerance will vary directly with the rate of heat dissipation per unit area. Conversely, if the rate of heat dissipation per unit area is constant, heat tolerance will vary inversely with the rate of heat production per unit area.

During growth, the heat production per unit surface was not constant but rose to maximum levels at about 6 months of age, at body weights from 350 to 450 pounds, as shown in the upper part of Figure 5. In the Shorthorns raised at 80° F, maximum levels were reached at similar body weight but at eight months of age. This slower rise in heat production seemed to be related to their slower gain in weight. These differences and the variability of the individual measurements are shown more clearly in Figures 8 and 9 in the Appendix. By 14 to 16 months of age, the heat production per unit area had decreased in all breeds to about the level reached at three months of age. In the Brahman heifers, the value was about 100 Cal/m^2/hr or approximately the same as reported for mature Brahman cows in a preceding experiment[2]. This decrease in heat production per

unit area at ages greater than six months may explain why cows have been found[10,11] to be more heat tolerant than calves.

Since the maximum levels of heat production per unit area generally occurred at about six months of age, one might expect the heat tolerance to be lowest at this age, unless the heat dissipation per unit area likewise increased at the same time. The upper sections of Figure 3 show that respiratory evaporation was maximum at this time, and a later bulletin[6] will show that total evaporative cooling was likewise high. High heat production at six months of age was evidently compensated by increased evaporative cooling, as rectal temperature did not increase at that time. The heat production of the Shorthorns raised at 80° F was depressed below that of those raised at 50° F but, even so, was never satisfactorily dissipated as rectal temperature was always about 2° F above normal in this group. More striking than the age changes in heat production are the breed differences in Cal./m^2/hr. shown in Figure 5. In the 50° F room, the average Shorthorn level was 8 percent above that of the Santa Gertrudis, and 44 percent above that of the Brahman. Differences in surface area among breeds only partly accounted for the differences in the curves; differences in heat production were largely responsible.

An analysis of the breed differences in the 80° F room was complicated by the fact that the three breeds were not in comparable condition. The Shorthorns had abnormally high body temperatures whereas the other breeds had normal temperatures. The curves of Figure 5 show that the Brahman calves had the lowest heat production. From 3½ to 7½ months of age, the heat production per unit surface area was higher in the Santa Gertrudis than the Shorthorns. This difference was probably correlated with their greater growth rate during this four-month period. The daily rate of gain in weight[4] reached its peak in the Santa Gertrudis between 4 and 5 months but not until 7½ months in the Shorthorns. After 7½ months of age, the rate of gain was not greatly different in the two breeds but the heat production per unit area was higher in the Shorthorns.

These breed differences in heat production per unit surface apparently were not compensated by corresponding differences in heat dissipation. The low heat producing Brahmans were found to be most heat tolerant in further high temperature tests which will be discussed in a later section. The high heat producing Shorthorns were found to be least heat tolerant. The Santa Gertrudis were found to be intermediate both in regard to heat production and heat tolerance.

Energy Metabolism per Unit Weight

Heat production per unit weight is not as meaningful from the physiological viewpoint as heat production per unit surface area but this measure has practical merit. It is easier to weigh an animal than to measure its surface area. Also,

when heat production per unit weight is plotted against age, both age and weight factors are taken into account. This dual factor allowance is especially applicable to the data for the slow growing Shorthorns raised at 80° F. When allowance was made for both weight and age by this method, heat tolerance varied inversely with heat production at both the 50 and 80° F temperatures, as shown in Figure 5.

Fasting Metabolism

Arrangements were made for several 30-hour fasts for the groups in the 50 and 80° F rooms at ages between 13 and 17 months. Fasting was avoided while the calves were young to avoid complicating the measurements of growth rate, feed and water consumption, and other factors. Table 5 gives the metabolism

TABLE 5. ENERGY METABOLISM IN BRAHMAN, SANTA GERTRUDIS, AND SHORTHORN HEIFERS BEFORE AND AFTER 30-HOUR FASTS. (EACH BREED AVERAGE WAS COMPUTED FROM NINE OBSERVATIONS; OR THREE MEASUREMENTS ON EACH OF THREE ANIMALS.)

	Brahman		S. Gertrudis		Shorthorn	
	Heifers grown at 50° F. (10°C)					
Room Temperature, °F.	50	65	50	65	50	65
Age, months	13.6	15.6	13.5	15.5	14.6	16.6
Body Weight (lb.	685	752	826	917	751	838
(kg.	310	341	374	416	340	380
Cal/hour per animal						
Normal	389	365	505	512	467	484
Fasted	355	226	344	317	330	292
% Reduction	9	38	32	38	29	40
Cal/m^2/hr.						
Normal	90	81	115	109	122	110
Fasted	82	50	78	67	86	66
Cal/kg/hr.						
Normal	1.25	1.07	1.35	1.23	1.37	1.27
Fasted	1.15	.67	.92	.76	.97	.77
	Heifers grown at 80°F. (26.7°C)					
Room Temperature, °F.	80	65	80	65	80	65
Age, months	14.0	16.0	14.0	16.0	14.7	16.7
Body Weight (lb.	729	802	764	849	570	664
(kg.	330	364	346	385	258	301
Cal/hour per animal						
Normal	420	420	429	415	418	484
Fasted	268	264	323	267	287	292
% Reduction	36	37	25	36	31	40
Cal/m^2/hr.						
Normal	93	85	100	88	125	119
Fasted	59	53	75	57	86	72
Cal/kg/hr.						
Normal	1.29	1.15	1.24	1.08	1.62	1.61
Fasted	.81	.72	.73	.69	1.11	.98

Conversion Factors: Cal/hr. X 3.968 = B.T.U./hr.
Cal/m^2/hr. X 0.3686 = B.T.U./sq. ft./hr.
Cal/kg./hr. X 1.7999 = B.T.U./lb./hr.
Cal/kg./hr. X 0.0018 = B.T.U./1000 lb./hr.

data on these groups at their respective 50 and 80° F temperatures and at a subsequent common 65° F temperature.

Fasting at the 50 and 80° F temperature levels lowered the metabolic level about equally in all breeds except the Brahmans in the 50° F room. These Brahmans, apparently in order to maintain thermal balance, increased their heat production by greater activity or other means sufficiently to offset the loss of heat production associated with normal feeding. The net reduction in metabolic level in the Brahmans due to fasting was only 9 percent in the 50° F group compared to 36 percent in the 80° F group.

The fasts at the 65° F temperature gave less variable results than those at the 50 and 80° F temperatures. The fasted animals of all breeds were apparently able to maintain thermal balance at the 65° F temperature with only minimal or basal heat production. Table 5 shows that the drop in metabolic level due to fasting at the 65° F temperature was never less than 36 nor more than 40 percent in any breed or temperature group.

Breed differences in the heat production, Cal/m^2/hr shown in Table 5, were highly significant for the 65° F fasts. Like the data for normal feeding shown in Figure 5, the 65° F fasting values were, relatively, quite low in the Brahmans of the 50° F group and quite high in the Shorthorns of the 80° F group. As these measurements were made at about 16 months of age they do not reflect the large breed differences shown for younger ages in the curves of Figure 5.

Heat Tolerance Tests

A series of high temperature tests were made when the heifers were about 18 months of age. Table 6 shows the changes that occurred in six measures during simultaneous exposure of the different breeds to the same environmental conditions. Figure 6 presents graphic comparisons of the more striking changes.

Several of the above measures have been used as indices of heat tolerance. Recent experiments by different investigators have contributed to our knowledge of their relative utility for this purpose. Beakley and Findlay[12] concluded from experiments with Ayrshire bull calves that heart rate was an unreliable index of heat tolerance. McDowell, Lee, Fohrman, and Anderson[13] questioned the value of respiratory frequency as an index of heat tolerance. They noted that heat tolerant Sindhi X Jersey crosses showed a greater reduction in tidal volume than Jerseys on exposure to high temperatures. Findlay[14] observed that as temperature increased his more heat tolerant Ayrshire bull calves showed large increases in respiratory frequency, large decreases in tidal volume, little change in minute volume. His less heat tolerant calves showed large increases in respiratory frequency, little change in tidal volume, large increases in minute volume. General acceptance is given to rectal temperature as an index of heat tolerance.

As discussed above, the heat production per unit area or per unit weight seems to be an important index of heat tolerance in unstressed animals. At high

TABLE 6. EFFECTS OF HIGH TEMPERATURES ON SEVERAL PHYSIOLOGICAL ACTIVITIES OF CATTLE RAISED AT CONSTANT TEMPERATURES OF 50° AND 80°F

	Experimental Conditions*													
Temperature °F	65	80	90	100	105		106	110	65	80	90	105		106	110
Relative Humidity %	70	42	31	23	25	52	26	23	70	42	31	25	52	26	23
	Animals Raised at 50°F								Animals Raised at 80°F						
	BRAHMAN														
Rectal Temperature °F	101.7	101.8	101.8	101.8	102.0	103.0	102.5	102.3	101.7	101.6	102.0	102.3	104.4		
Respirations/min.	17	24	39	43	64	129	67	66	17	24	33	56	133		
Pulse Rate/min.	71	72	74	74	81		83	81	73	75	73	70			
Ventilation Rate 1./min.†	34	38	39	43	63	112	63	73	36	41	45	62	101		
Tidal Air, liters †	2.2	2.0	1.8	1.7	1.6	1.4	1.9	1.8	2.3	2.3	2.2	1.6	1.3		
Heat Production, Cal/m^2/hr	86	89	77	79	82	93	84	100	85	88	92	96	110		
	SANTA GERTRUDIS														
Rectal Temperature °F	101.8	101.8	101.9	102.4			104.7	104.0	101.8	101.7	102.2			104.5	103.6
Respirations/min.	27	39	59	77			97	111	29	37	50			89	86
Pulse Rate/min.	78	76	79	78			73	75	79	79	79			81	81
Ventilation Rate 1./min. †	49	62	78	92			117	140	47	57	68			116	117
Tidal Air, liters †	2.2	2.0	1.8	1.7			1.7	1.8	2.0	1.9	1.7			1.8	1.8
Heat Production, Cal/m^2/hr	107	111	107	91			96	115	90	97	99			87	99
	SHORTHORN														
Rectal Temperature °F	102.1	102.3	103.6	104.4					102.7	103.	104.4				
Respirations/min.	46	64	91	114					69	70	93				
Pulse Rate/min.	80	79	80	79					98	89	85				
Ventilation Rate 1./min. †	66	77	98	91					64	83	90				
Tidal Air, liters †	1.8	1.7	1.5	1.2					1.4	1.5	1.3				
Heat Production, Cal/m^2/hr	105	105	104	92					113	110	108				

* See text

† All volumes are reported at standard conditions: dry, 0°C, 760 mm.

Conversion Factors: liters x 0.035315 = cu. ft.
Cal/m^2/hr x 0.3686 = Btu/sq. ft./hr

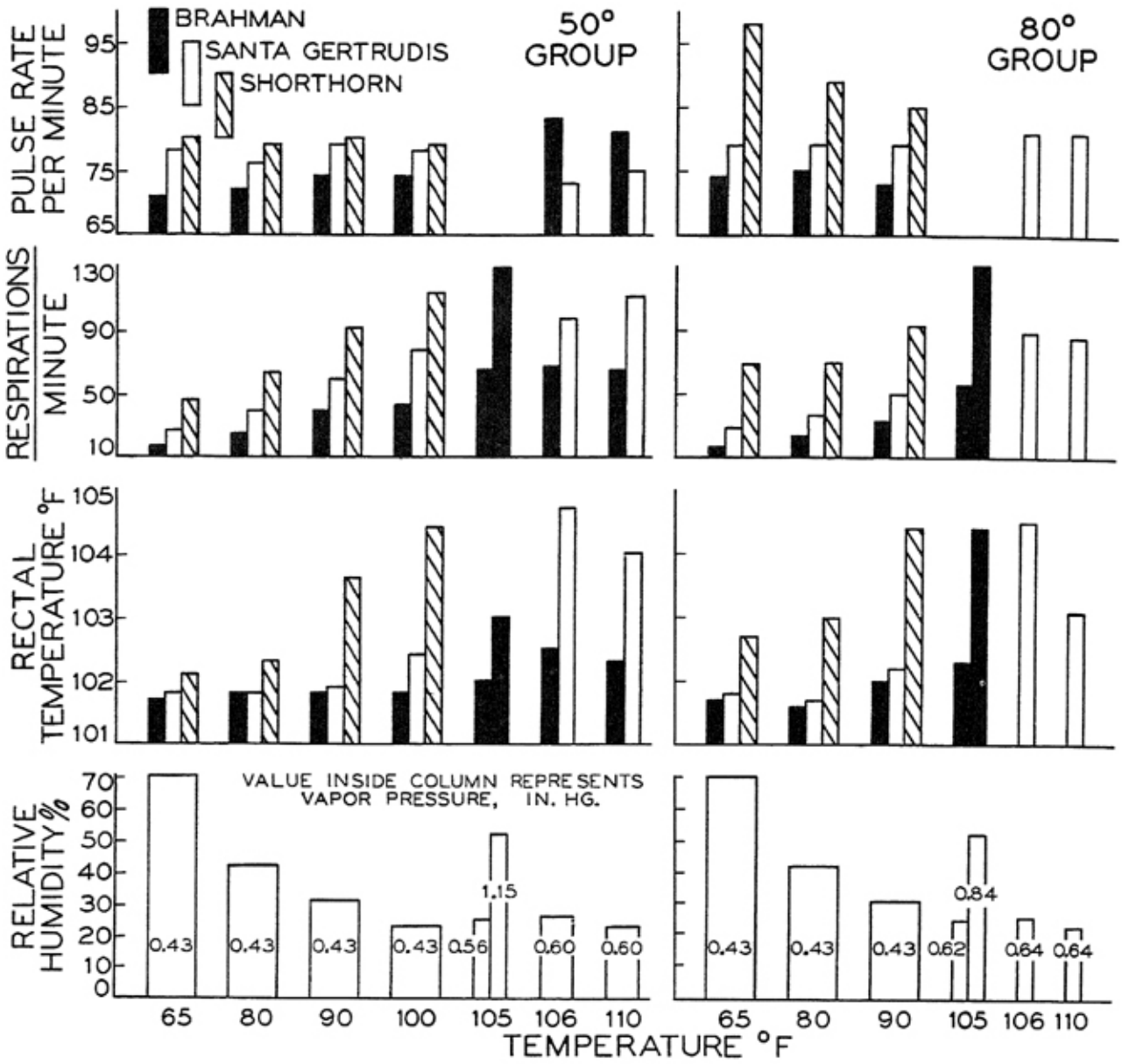

Fig. 6—Cardiorespiratory activities in two groups of Brahman, Santa Gertrudis, and Shorthorn heifers relative to environmental temperature and humidity. Differences in heat tolerances are shown by the differences in rectal temperature during simultaneous exposures to the given conditions.

environmental temperatures, however, changes in heat production are difficult to interpret. Reduced heat production resulting from reduced feed consumption tends to be offset by increased heat production resulting from elevated body temperature and high respiratory activity.

During our recent tests, the exposures to the 65, 80, and 90° F temperatures were for 5, 3, and 2 weeks, respectively. At 100, 105, 106, and 110° F, the exposures were limited to 2 to 4 days with nighttime cooling to 5 or 10° F lower values. The responses of the heifers to the different conditions were dependent on the duration of exposure and the reduction in temperature at night as well as on the experimental daytime temperatures.

Differences in heat tolerance appeared as two to three of the breeds were ex-

posed at the same time to each of the various high temperatures. Reference to Table 6 shows that the levels of response of rectal temperature, respiratory frequency, pulse rate, and tidal air were not equal in the different breeds at any one environmental temperature. They were about equal, however, for exposures to the following different environmental temperatures: Brahmans to 110° F, Santa Gertrudis to 100° F, Shorthorns to 80° F. For pulmonary ventilation rate, the corresponding comparative temperatures were 110, 90, and 80° F. Contrary to the results reported by others, as cited above, tidal air reached lowest levels in the least heat tolerant breed.

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APPENDIX

Table 7 presents statistical data for equations fitted to the data on oxygen consumption, carbon dioxide production, and methane production. Figure 7 shows these equation lines arranged for convenient comparisons of differences due to breed and environmental temperature.

Breed differences in oxygen consumption rate were found to be highly significant at both the 50 and 80° F temperatures. For animals of the same weight, the oxygen consumption rate was highest in the Shorthorns, lowest in the Brahmans, and intermediate in the Santa Gertrudis. Depression of the oxygen consumption rate at 80° F below that at 50° F was significant in the Shorthorns at all stages of growth; it was slight but significant during the later stages of growth in the Santa Gertrudis and was not significant in the Brahmans.

Most of the carbon dioxide in the exhaled air was produced by the metabolic processes of the body but some was produced by fermentative processes in the rumen. As these two fractions were not separated, it is difficult to interpret these data. In general, the rate of carbon dioxide production tended to parallel the rate of oxygen consumption.

The methane found in the exhaled air was all produced in the rumen. Some was absorbed through the walls of the rumen and carried to the lungs by the blood. The remainder presumably was eructed irregularly through the esophagus[15]. The irregularity of the eructation process coupled with short collection periods probably accounted for the considerable variability in the methane data.

The equations given in Table 7 and the equation lines drawn in Figure 7 show that methane production increased rapidly with increasing body weights up to 300 pounds. During this period of early growth breed differences were highly significant in the 50° F room but not in the 80° F room. Methane production during this period was significantly depressed in the Shorthorns raised at 80° F compared to those raised at 50° F.

At body weights greater than 300 pounds, methane production was not significantly correlated with body weight. The data for this later growth period are therefore shown as averages instead of equations. The variability of the individual observations was quite large as shown by the standard deviations in Table 7. However, the means for the different breeds and temperature conditions were stable within 5 to 10 percent as shown by the standard errors of the mean.

Table 8 gives predicted values of oxygen consumption, carbon dioxide production, and methane production during growth at the 50 and 80° F temperatures.

Figure 8 shows the variability of the individual measurements of energy metabolism per unit surface area about the moving average lines shown in Figure 6. Figure 9 shows the same data plotted against body weight instead of age.

TABLE 7. CONSTANTS OF EQUATION $Y = aX^b$ USED IN COMPUTING PREDICTION TABLE 8, IN THREE BREEDS OF CATTLE DURING GROWTH AT CONSTANT TEMPERATURES OF 50° AND 80° F

(X is body weight, kg.; Y indicates measure shown below)

Growth Period	Number of Observations 50°	Number of Observations 80°	Breed	Equation Constants a 50°	Equation Constants a 80°	Equation Constants b 50°	Equation Constants b 80°	Correlation Coefficient 50°	Correlation Coefficient 80°	Standard Errors of Estimate % + 50°	Standard Errors of Estimate % + 80°	Standard Errors of Estimate % - 50°	Standard Errors of Estimate % - 80°
			Y = Oxygen Consumption Per Animal, lit/hr.										
Early	38	37	Brahman	0.40	0.45	0.997	0.980	.874	.898	13.3	14.0	11.7	12.3
	40	39	Santa Gertrudis	0.34	0.26	1.075	1.124	.934	.890	12.0	17.0	10.6	14.5
	39	49	Shorthorn	1.40	1.33	0.802	0.795	.917	.839	10.4	13.1	9.4	11.6
Later	103	100	Brahman	7.13	9.82	0.414	0.363	.714	.629	11.0	10.5	9.9	9.5
	99	100	Santa Gertrudis	12.08	24.88	0.359	0.210	.727	.412	10.0	11.6	9.1	10.4
	97	85	Shorthorn	17.81	7.36	0.286	0.428	.674	.745	9.6	10.3	8.8	9.3
			Y = Carbon Dioxide Production Per Animal, lit/hr.										
Early	38	37	Brahman	0.16	0.19	1.191	1.155	.890	.900	14.7	16.5	12.8	14.2
	31	39	Santa Gertrudis	0.07	0.11	1.419	1.320	.926	.873	13.9	22.7	12.2	18.5
	34	48	Shorthorn	0.72	1.03	0.960	0.848	.903	.838	12.4	13.8	11.0	12.1
Later	103	100	Brahman	6.20	10.80	0.442	0.350	.651	.565	14.5	12.0	12.7	10.7
	108	100	Santa Gertrudis	15.23	23.96	0.326	0.226	.679	.269	12.0	20.9	10.7	17.3
	102	85	Shorthorn	29.12	4.01	0.202	0.548	.338	.769	16.2	12.3	13.9	11.0
			Y = Methane Production Per Animal, lit/hr.										
Early	38	37	Brahman	0.0041	0.0026	1.39	1.47	.469	.460	100	108	50	52
	31	38	Santa Gertrudis	0.00064	0.000088	1.84	2.24	0.56	.695	85	86	46	46
	34	48	Shorthorn	0.0035	0.0028	1.53	1.45	.623	.448	64	96	39	49

Statistical Constants for Mean Values Shown in Prediction Table __

Growth Period	Number of Observations 50°	Number of Observations 80°	Breed	Average Methane liters/hr. * 50°	Average Methane liters/hr. * 80°	Standard Deviation, % 50° +	Standard Deviation, % 50° -	Standard Deviation, % 80° +	Standard Deviation, % 80° -	Standard Error of Mean, % 50° +	Standard Error of Mean, % 50° -	Standard Error of Mean, % 80° +	Standard Error of Mean, % 80° -
Later	103	100	Brahman	4.9	5.0	94.6	48.6	76.2	43.2	6.8	6.4	5.8	5.5
	108	99	Santa Gertrudis	7.1	5.6	71.4	41.7	89.2	47.1	5.3	5.0	7.0	6.5
	102	84	Shorthorn	5.2	3.8	104.0	50.9	154.0	61.0	7.3	6.8	10.7	9.7

* Geometric mean to correspond to logarithmic equation used for early growth.

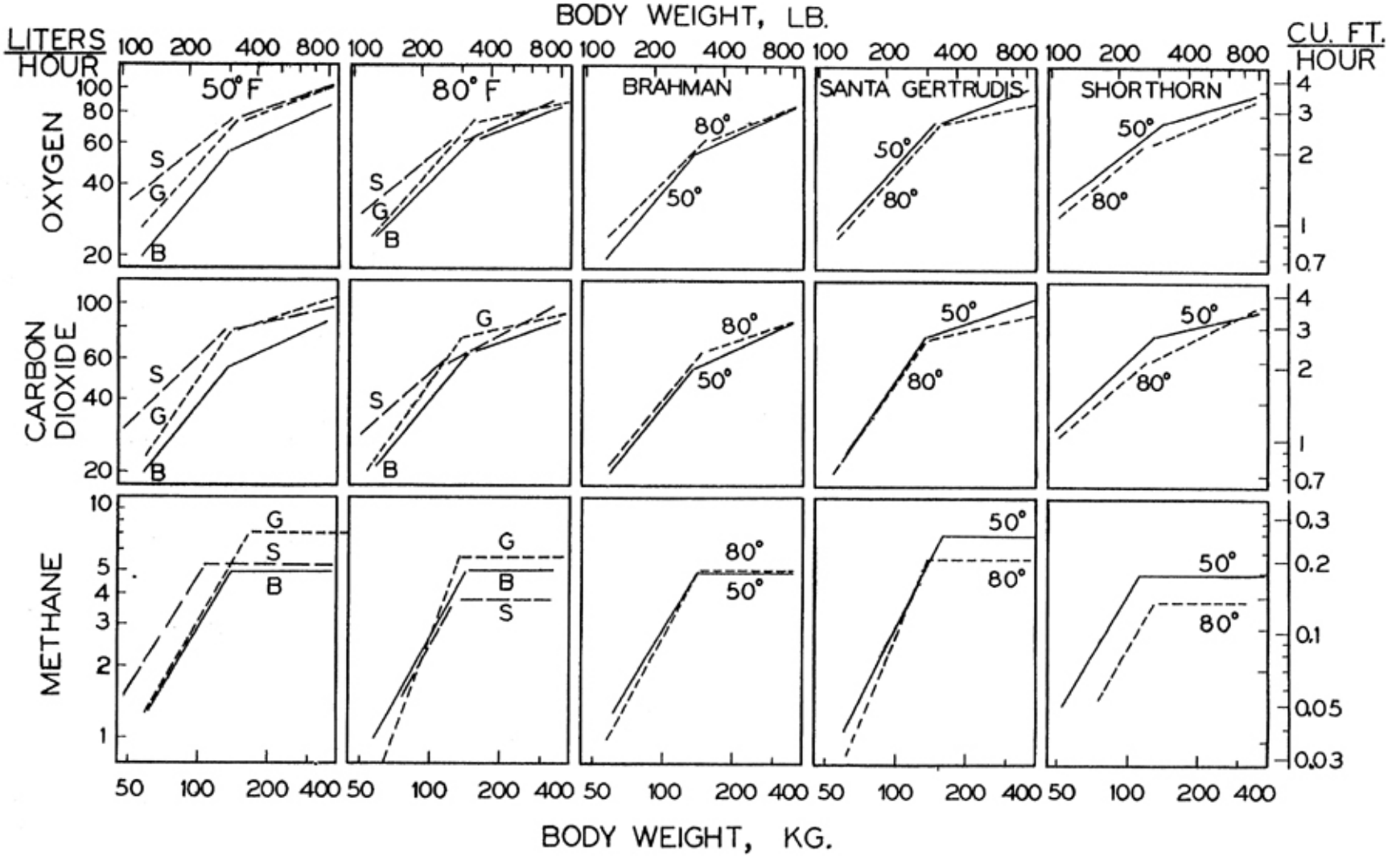

Fig. 7—Oxygen consumption and carbon dioxide and methane production relative to body weight. For clarity only the equation lines are shown. These were fitted to the individual measurement data. The two sections on the left show breed comparisons at two temperatures. The three sections on the right show the effects of temperature on each breed. The equations and statistical constants are given in Table 7.

TABLE 8. PREDICTION VALUES* FOR OXYGEN CONSUMPTION, CARBON DIOXIDE, AND METHANE PRODUCTION IN BRAHMAN (B), SANTA GERTRUDIS (G), AND SHORTHORN (S) CATTLE DURING GROWTH AT 50° AND 80° F CONSTANT TEMPERATURES

Approximate Months			Body Weight		Oxygen Consumption liters/hr			Carbon Dioxide Production liters/hr			Methane Production liters/hr		
B	G	S	kg.	lb.	B	G	S	B	G	S	B	G	S
					Environmental Temperature, 50° F (10°C)								
1.1	0.8	2.0	50	110	20	22	32	17	18	31	0.9	0.8	1.4
1.7	1.4	2.7	60	132	24	27	37	21	23	37	1.2	1.2	1.9
2.7	2.5	3.6	80	176	31	37	47	29	35	48	1.6	2.0	2.9
3.6	3.2	4.3	100	221	39	47	56	38	48	60	2.6	3.0	4.1
4.5	4.0	5.0	125	276	49	60	67	50	66	74	3.6	4.5	
5.3	4.7	5.7	150	330	59	73	78	62	86	89	4.5	6.3	
6.3	5.5	6.6	175	386	60	75	78	61	82	83			
7.2	6.3	7.4	200	441	64	81	81	65	86	85			
8.4	7.1	8.5	225	496	67	85	84	68	89	87			
10.1	7.9	9.5	250	551	70	88	86	71	92	89			
11.2	8.8	10.8	275	606	73	91	89	74	95	91	4.9**		5.2**
12.9	10.1	12.2	300	661	75	94	91	77	98	92		7.1**	
14.9	11.3	13.5	325	716	78	96	93	80	101	94			
16.1	12.4	15.2	350	772	80	99	95	83	103	95			
	13.6	16.4	375	827		102	97		106	96			
	14.9	17.7	400	882		104	99		108	98			
	15.3	19.4	425	937		106	100		110	99			

TABLE 8 -- (continued)

Approximate Months			Body Weight		Oxygen Consumption liters/hr			Carbon Dioxide Production liters/hr			Methane Production liters/hr		
B	G	S	kg.	lb.	B	G	S	B	G	S	B	G	S
					Environmental Temperature, 80°F (26.7°C)								
1.0	0.8	2.3	50	110	21	21	30	18	19	28	0.8	0.6	0.8
1.9	1.5	3.0	60	132	25	26	35	22	24	33	1.1	0.9	1.0
2.6	2.6	4.5	80	176	33	36	43	31	35	42	1.7	1.6	1.5
3.4	3.5	6.0	100	221	41	46	52	40	47	51	2.4	2.7	2.1
4.3	4.2	7.1	125	276	51	59	62	51	62	61	3.3	4.4	3.0
5.1	5.0	8.3	150	330	62	72	71	63	79	72	4.3		3.8
5.9	5.9	10.2	175	386	64	74	67	66	77	68			
6.5	6.7	11.3	200	441	67	76	71	69	79	73			
7.4	7.6	12.9	225	496	70	78	75	72	81	78			
8.7	8.8	14.4	250	551	73	79	78	75	83	83			
10.1	10.1	15.4	275	606	75	81	82	77	85	87			3.8**
12.0	11.5	16.4	300	661	78	83	85	80	87	91	5.0**	5.6**	
13.5	12.6	17.9	325	716	80	84	88	82	88	96			
15.1	14.1	19.2	350	772	82	85	90	84	90	100			
16.6	16.0		375	827	84	86		86	91				
17.7	17.0		400	882	86	88		88	93				

* From weekly respiratory exchange measurements made between 1:00 and 3:00 p.m. on normally-fed animals standing quietly in stanchions. The tabular values were computed from the equations given in Table 7 except as noted. All volumes are given as dry gas at 760 mm pressure and 0°C temperature.

** Average values are given since methane production was not significantly correlated with body weight over this range.

Conversion Factor: lit./hr. x 0.035315 = cu. ft./hr.

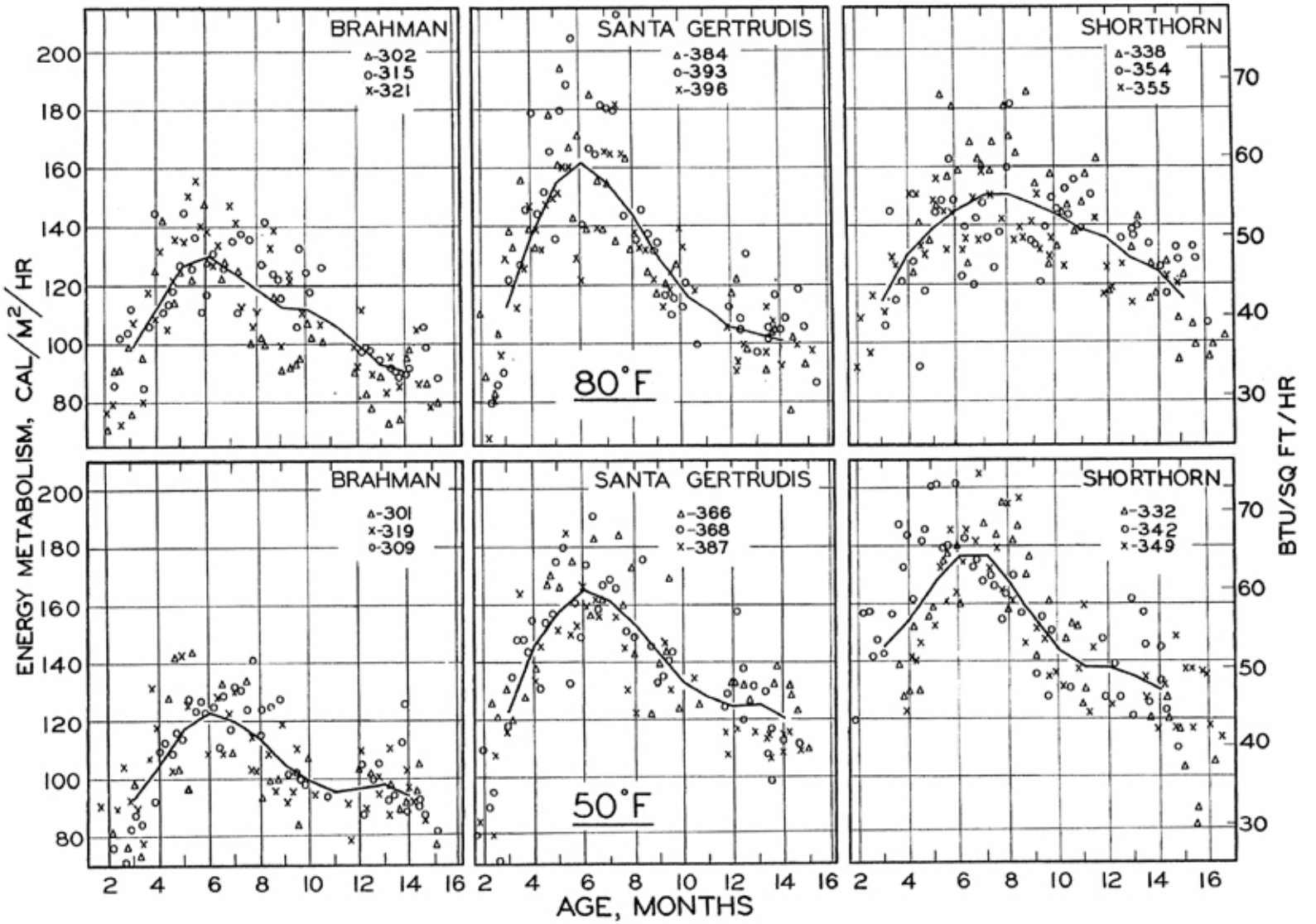

Fig. 8—Energy metabolism per unit surface area plotted against age. The average lines were computed by making a three-point moving average of the monthly breed averages. The individual data for each animal were plotted to show the variability about the moving average lines.

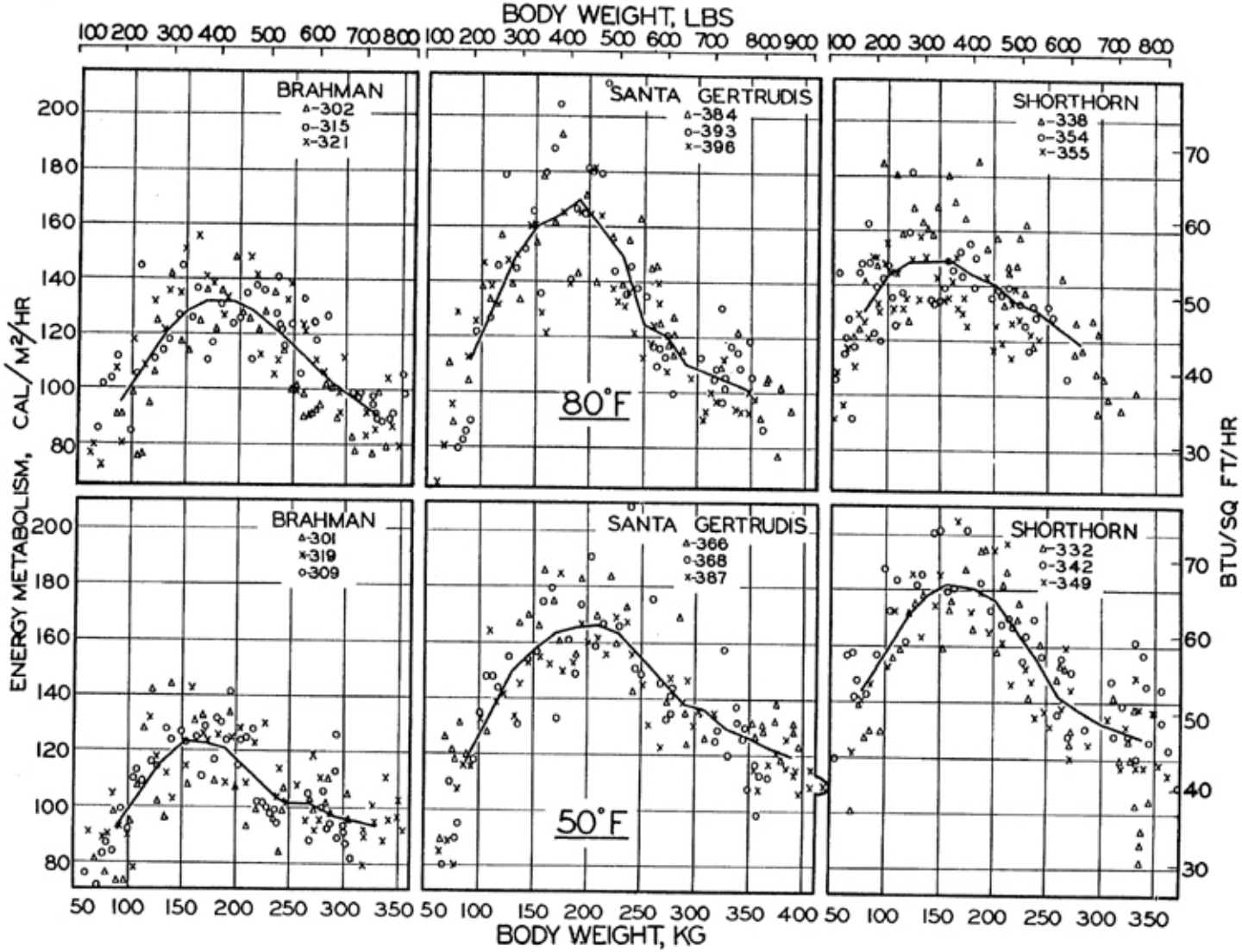

Fig. 9—Individul measurements of energy metabolism per unit surface area plotted against body weight. These data were averaged by 20 kg. body weight intervals for each breed and a three-point moving average of these values was computed.