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Environmental Physiology

With Special Reference to Domestic Animals

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

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ORIENTATION

Objectives.—From the present viewpoint, dairy cattle may be considered as converters of feed into milk. The energetic efficiency of the conversion of the digestible nutrients into milk in good dairy cattle is of the order of 25 per cent; most of the remaining 75 per cent of the nutrient energy is eventually given off as waste heat which must be promptly dissipated if the body temperature is to remain normal.

Heat is dissipated by two general methods: non-evaporative (convection, radiation, conduction) and evaporative (moisture vaporization). In cold weather heat dissipation is mostly by non-evaporative cooling; in hot weather mostly by evaporative cooling. When the environmental temperature equals, or exceeds, the body surface temperature, then barring the warming of ingested cool water and food, the body heat can be dissipated by vaporization alone and the ability to withstand high temperatures is proportional to the ability to produce surface moisture for vaporization—in which there are great species differences. At high temperatures the skin functions as a waste-heat excretory organ analogous in importance to the kidney as a soluble-waste excretory organ. Moisture vaporization is an efficient method of cooling because of its high latent heat of vaporization—over 580 kg-calories per kilogram or 1044 Btu per pound of moisture vaporized[1]—and, as will be presently shown, fairly high producing dairy cows standing quietly (in the shade) at 80° to 90°F vaporize near two pounds moisture per hour. This moisture, like the heat which it dissipates, must also be promptly dissipated in order to maintain good moisture-absorbing qualities of the air, building, and bedding materials.

[1]The latent heat of vaporization ranges from about 580 Cal/kg at 22°C (72°F) to 640 Cal/kg at 33°C (92°F)—see J. D. Hardy, p. 103, in R. H. Newburgh, "Physiology of Heat Regulation and the Science of Clothing", Saunders, 1949. The 580 Calorie conversion factor is used conventionally in the physiological literature and so also in this bulletin.

Hence, the need of the building industry for quantitative data on moisture vaporization, or evaporative cooling, as well as on heat production of animals, under various environmental conditions for use in designing ventilating systems in cold weather and air-conditioning systems in hot weather. Since the ability to tolerate high environmental temperature is dependent on the ability to sweat (or equivalent methods of moisture production), dairymen need such data for selecting and developing animals to different climatic regions. Comparative physiologists are interested in such data because of the insights they furnish into temperature-regulating mechanisms evolved in different species under different climatic conditions. A major objective of this research in general and of this bulletin in particular is to furnish quantitative data on moisture vaporization under various environmental temperatures in cattle of different body weight and conformation, age and productivity, and to compare and interpret them from the viewpoints of the engineer, dairyman, and physiologist that collaborate in this project.

Principles and Methods.—These, previously explained[2], are here briefly recalled for orientation.

Moisture vaporization from the animal is computed from two measureable quantities: insensible (or invisible) weight loss and metabolic weight loss. The *insensible weight loss* is a composite of two losses: a) *vaporized moisture;* b) *metabolic weight loss,* which is the difference in weight between the oxygen consumed and the sum of the weights of carbon dioxide and methane produced. The insensible weight loss is given by the equation:

$$\text{Insensible Loss} = H_2O + [(CO_2 + CH_4) - O_2] \quad \ldots\ldots \quad (1)$$

The weight of vaporized moisture (H_2O) is then computed from the equation:

$$H_2O = \text{Insensible Loss} - [(CO_2 + CH_4) - O_2] \quad \ldots\ldots \quad (2)$$

in which the expression $[(CO_2 + CH_4) - O_2]$ is the *metabolic weight loss,* as above defined, the data for which have been previously reported.[3]

The significance of the metabolic weight loss varies with the species. In man and other species with simple stomach and little fermentation-gas production the moisture vaporization is virtually identical with the insensible weight loss. In species, such as cattle, that produce huge amounts of methane in the rumen the moisture vaporization ranges from about 60 per cent of the insensible weight loss when the animals are on full feed in very cold weather to 100 per cent at 100°-105°F when under the constant temperature conditions of our laboratory the animals refuse hay and so produce virtually no methane

[2]Thompson, H. J., McCroskey, R. M., and Brody, S., Influence of ambient temperature, 0° to 105°F, on insensible weight loss and moisture vaporization in Holstein and Jersey cattle, Univ. Missouri Agric. Exp. Sta. Res. Bul. 451, 1949.

[3]Kibler, H. H., and Brody, S., Effect of temperature, 50° to 105°F and 50° to 9°F, on heat production and cardiorespiratory activities in Brahman, Jersey, and Holstein cows. Univ. Missouri Agric. Exp. Sta. Res. Bul. 464, 1950; Influence of increasing temperature, 40° to 105°F, on heat production and cardiorespiratory activities in Brown Swiss and Brahman cows and heifers. Id., Res. Bul. 473, 1951.

and the respiratory quotient is near 0.73 (when the weight of carbon dioxide produced equals the weight of oxygen consumed).

The insensible (or invisible) weight loss was measured by simply placing the animal on the platform of a sensitive scale (sensitized with an electronic relay[2] to give a weighing precision of about half an ounce for a 1500-lb. animal) and recording the weight losses at frequent intervals for about an hour or until consistent values were obtained. Since the feces, urine, and saliva are "sensible" losses, they did not enter into the insensible loss computations. They were collected in appropriate receptacles (the saliva under oil) mounted on the scale platform.

The psychrometric conditions in the weighing room were maintained as near as possible to those in the adjoining chamber where the animals were actually stabled. All temperatures here reported were those taken at the time and place of the insensible loss measurements (unless otherwise noted).

These data on insensible loss and moisture vaporization, like all physiological data, contain unavoidable errors from various sources. For instance, while the *insensible weight loss* was measured in the morning (9 to 12 a.m.), the *metabolic weight loss* was measured in the afternoon (1 to 3 p.m.); and since the metabolic weight loss tends to decline with the time after feeding, this factor may have been somewhat low with possibly higher apparent vaporization values. Then, while the *metabolic weight loss* was measured with the animals in their regular chamber stanchions, the *insensible weight loss* was measured in the adjoining room where at times the temperature, humidity, and air movement differed slightly from the stanchion rooms, with a consequent possible error due to these differences.

Animals.—The data on insensible weight loss and moisture vaporization here presented are extensions of those previously reported[2] on Holstein and Jersey cows. The extension includes Indian-evolved (but Texas bred) dry and lightly-milking Brahman cows and yearling heifers; and Missouri-bred heavily-milking Brown Swiss cows and yearling heifers. Special interest was attached to the Brown Swiss cattle because they are said by some observers to be more tolerant to high temperatures than most other European breeds; they are also said to be related in evolution to Brahman or Zebu cattle. At any rate, the wide range in evolutionary history, body weight and conformation, age and milk yield of these cattle is broad enough to satisfy the interests of the cooperators—engineers, dairymen, and comparative physiologists. It is generally believed that, in the long run, the deepest as well as the broadest and practically most useful insights are obtained most economically by comparative studies as here made[4].

The breed characteristics and other information about these animals, including their ages, weights, feed and water consumption, milk production, as

[4]In fact, there might be value in making these studies still broader by including other species, ruminant and non-ruminant, sweating and non-sweating, to furnish a base for broader practical deductions and theoretical generalizations.

well as the temperature and humidity calendars of the chambers, have been reported in preceding bulletins[5]. Data on heat production and cardiorespiratory activities of these animals have also been reported[3].

DATA AND DISCUSSION

Tables 1 to 7 present the observed data for the following three experimental periods:

May 23 to August 15, 1949: Lactating Jersey, Holstein, and Brahman cows during increasing temperature, 50° to 105°F.

October 4, 1949, to February 1, 1950: Lactating Jersey, Holstein, and dry Brahman[6] cows during decreasing temperature, 50° to 0°F.

February 6 to June 9, 1950: Heavily lactating Brown Swiss cows, dry Brahman cows[6], and Brown Swiss and Brahman yearling heifers during increasing temperatures, 40° to 105°F.

Table 8 is a summary, by temperature levels, of the average moisture losses of the above data combined with those on Holsteins and Jerseys previously reported[2] (Tables 1 and 2, Res. Bul. 451).

The data are also presented graphically. Fig. 1 presents the time and temperature trends of insensible weight losses of individual animals. Its upper left segment brings out the effect of declining temperature from 50°F (in October) to near 0°F (in December). The insensible loss was greater in the Holstein (large cows) than in the Jerseys and Brahman (small cows) but the relation between their curves remained constant.

The lower left segment in Fig. 1 brings out the effect of rising temperature from 50° (in June) to 105°F (in August). Here the change in temperature definitely changed the relations between the curves. Between 60° and 85°F, the rise in insensible loss was greatest in the Holsteins, less in the Jerseys, and least in the Brahmans. Beginning with 85°F the insensible loss decreased in the Holsteins and Jerseys and increased in the Brahmans. Between 90° and 105°F the curves for the three breeds criss-crossed each other without definite temperature trend. Because of the three involved variables—body size, productive level, breed—explanations of the differences in behavior between the three groups are hazardous. However, the curves in the lower right segment may throw some light on the problem.

The lower right segment in Fig. 1 compares the insensible loss curves of the heavily-milking Brown Swiss and dry Brahmans. At the beginning

[5]Ragsdale, A. C., Thompson, H. J., Worstell, D. M., and Brody, S., 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. Univ. Missouri Agric. Exp. Sta. Res. Bul. 460, 1950; 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. Id., Res. Bul. 471, 1951.

[6]The same Brahman cows were used in all three experiments. During the first period (summer, 1949) they were lactating but during the following two periods were dry. For the other breeds different cows for each test were obtained.

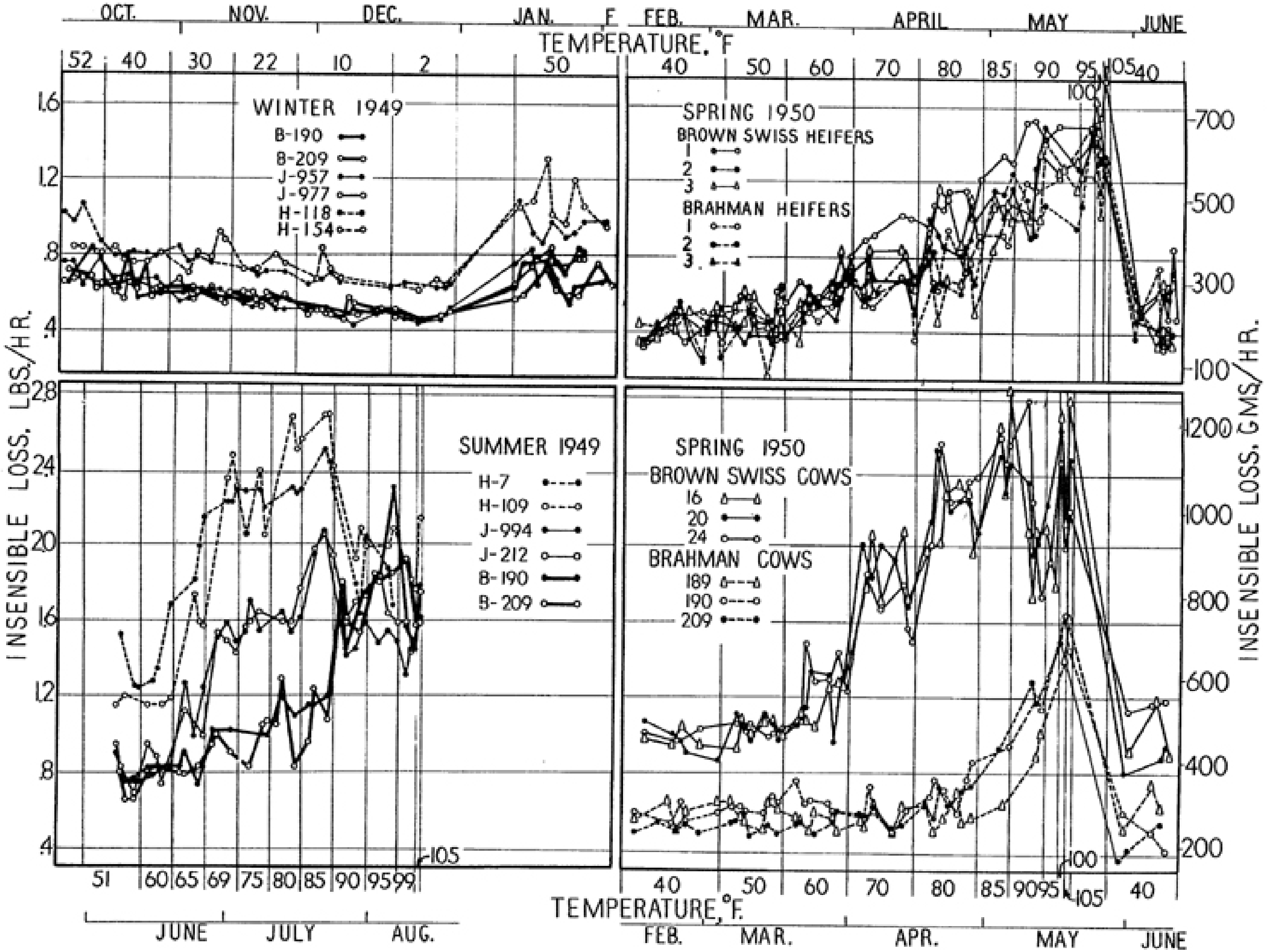

Fig. 1.—Individual insensible loss curves as function of time and temperature. The symbols "H", "J", and "B" represent, respectively, Holstein, Jersey, and Brahman cattle. The upper left segment represents declining temperature, 50° to 2°F; the other segments represent the effect of rising temperatures. The upper right segment represents the Brahman and Brown Swiss yearling heifers, the lower right, Brown Swiss and Brahman cows.

TABLE 1.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN JERSEY CATTLE, 0° to 105°F.

Temperature °F.		Relative Humidity	Number of Obser-	Body Weight	Insensible Loss grams	Vaporized Moisture*		Vaporized Moisture
Dry Bulb	Wet Bulb	%	vations	Kg.	per hour	grams per hr.	gms/sq.m. per hr.	% Total Heat Production*
			Jersey 994 (May 23 to August 15, 1949)					
53.5	47.5	66	3	360	368	277	68	23
59.5	54.0	70	3	359	377	286	71	25
67.0	59.0	62	3	363	531	440	108	36
71.5	62.5	60	3	364	696	605	148	52
76.0	66.5	60	3	359	727	636	157	56
81.0	72.5	66	3	358	729	638	158	64
86.5	77.0	65	2	355	920	829	206	78
90.5	79.5	63	3	344	676	636	161	77
95.0	80.5	54	3	326	690	681	178	85
99.0	85.0	58	2	313	632	613	164	96
103.0	91.0	62	1	310	738	736	198	105
			Jersey 212 (May 23 to August 15, 1949)					
53.5	48.0	66	3	445	369	272	60	23
59.5	54.0	69	3	445	390	293	64	26
67.0	58.5	60	2	447	482	385	84	33
71.0	62.0	60	3	449	677	580	126	53
77.0	66.5	59	3	441	731	634	140	57
81.5	73.5	67	3	445	752	655	144	61
86.0	76.5	66	3	446	910	813	178	74
90.5	79.5	61	3	431	767	706	158	78
94.5	80.5	54	3	423	771	718	162	87
99.0	86.0	59	2	426	692	671	151	97
104.0	90.5	60	1	424	725	727	164	96
			Jersey 977 (October 4, 1949, to February 1, 1950)					
51.0	47.5	76	4	422	296	225	51	24
39.0	35.0	69	5	423	271	200	45	18
30.5	27.5	65	5	431	269	198	44	17
21.0	18.5	64	5	430	254	183	41	18
11.0	9.0	65	6	433	220	149	33	13
2.0	1.0	70	4	443	210	139	30	13
50.0†	43.5	58	8	446	341	270	59	27
			Jersey 957 (October 4, 1949, to February 1, 1950)					
52.0	48.5	78	4	376	327	250	60	25
39.5	36.0	70	5	375	298	221	53	21
30.5	27.5	68	5	388	260	183	43	17
21.5	19.0	63	5	391	234	157	37	14
11.0	9.5	64	6	394	215	138	32	11
1.5	0.5	69	4	397	206	129	30	11
51.0†	44.5	58	8	384	345	268	64	26

* Metabolic weight losses from Table 8; heat production from open-circuit method, Tables 2 and 4, Missouri Research Bulletin 464; surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360).

† At end of Experiment.

(40°F) the Brown Swiss curves are above but parallel with the Brahman curves and both follow a horizontal course up to 60°F; the Brown Swiss show a steep rise from 60° to 85°F and the Brahmans from 85° to 105°F. The sharp decline following 100-105°F is, of course, due to the sharp decline in temperature from 105° to 40°F. It is hazardous to comment on the breed differences as such with regards to the temperatures at which the sudden insensible loss rise occurred, or to the shape of the curves, because the two breeds were under greatly different metabolic conditions—the Brown Swiss were heavy milkers and feed consumers while the Brahmans were not. The relation between these two sets of curves would, undoubtedly, be different if the Brown Swiss were dry like the Brahmans; or if the Brahmans were heavy milkers like the Brown

TABLE 2.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN HOLSTEIN CATTLE, 0° to 105°F.

Temperature °F.		Relative Humidity	Number of Obser-	Body Weight	Insensible Loss	Vaporized Moisture*		Vaporized Moisture
Dry Bulb	Wet Bulb	%	vations	Kg.	grams per hour	grams per hr.	gms/sq.m. per hr.	% Total Heat Production*
			Holstein 109	(May 23 to August 15, 1949)				
54.0	48.0	64	2	602	536	427	79	25
60.0	54.0	67	3	595	528	419	78	28
67.0	59.0	62	3	598	744	653	118	42
72.0	63.0	62	3	608	1081	972	179	62
77.0	66.0	56	3	591	988	879	164	57
81.5	73.0	66	3	614	1168	1059	194	69
85.5	77.0	67	3	603	1178	1069	198	76
90.0	79.5	63	3	561	910	861	166	84
95.0	81.5	56	2	543	951	886	174	81
100.0	86.5	59	2	521	816	785	157	72
103.0	91.0	62	1	492	975	991	205	93
			Holstein 7	(May 23 to August 15, 1949)				
52.0	47.0	69	3	592	612	502	94	31
60.5	55.0	69	3	586	654	544	102	33
66.5	58.5	63	3	600	902	792	147	48
71.5	63.0	62	3	606	1021	911	168	54
76.5	66.0	57	3	600	1023	913	169	57
82.0	73.0	65	3	592	1040	930	174	59
85.5	77.5	70	3	576	1100	990	188	76
90.0	79.5	63	3	543	834	792	155	74
95.5	82.5	58	2	536	812	767	151	78
			Holstein 118	(October 4, 1949, to February 1, 1950)				
51.5	48.0	76	4	548	435	324	63	22
40.0	36.5	70	5	549	354	243	47	16
29.0	26.0	65	4	557	350	239	46	18
21.0	18.5	65	4	543	313	202	40	14
10.0	8.0	61	5	544	295	184	36	12
2.0	1.0	70	3	547	283	172	34	12
50.5†	44.0	59	8	534	427	316	63	25
			Holstein 154	(October 4, 1949, to February 1, 1950)				
51.5	46.5	70	4	547	369	238	46	16
40.0	36.5	71	5	552	352	221	43	16
30.5	27.5	68	5	573	367	236	45	15
22.0	19.5	63	4	561	336	205	40	12
10.5	9.0	64	4	558	325	194	38	11
2.5	1.5	70	3	562	288	157	30	10
52.5†	45.5	57	8	549	484	353	69	22

* Metabolic weight losses from Table 8; heat production from open-circuit method, Tables 2 and 4, Missouri Research Bulletin 464; surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360).

† At end of Experiment.

Swiss. It is unfortunate that conditions prevented pairing animals of different breeds in closely similar productive states.

The curves in the upper right segment of Fig. 1 represent Brahman and Brown Swiss yearling heifers. This time the animals are comparable as they were virtually of the same age, weight (about 500 lbs.), and productivity (growing). Yet, they showed some breed difference (the Brown Swiss were slightly above the Brahmans) in level and course with increasing temperature.

As indicated by equation (1), the insensible weight loss trends in Fig. 1 represent composites of two variables, moisture loss and metabolic weight loss. Fig. 2 shows the relations between the two in the form of ratios of moisture loss to total insensible loss of the individuals. At the high temperatures, 100° to 105°F, when the animals virtually stop eating, the moisture vaporization is virtually identical with insensible weight loss; at the low temperature, about

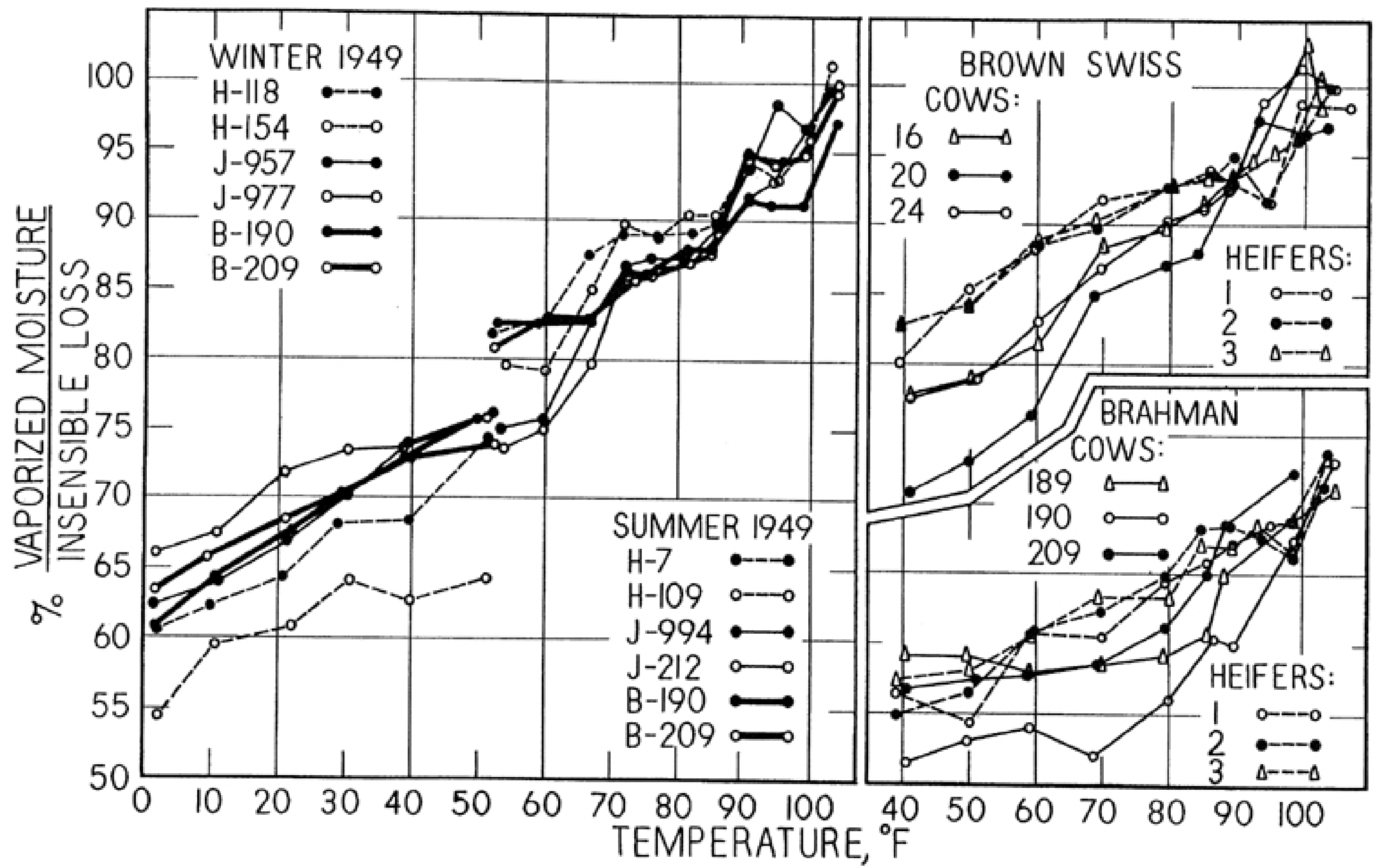

Fig. 2.—Ratios of vaporized moisture to insensible loss as function of temperature. The symbols "H", "J", and "B" represent, respectively, Holstein, Jersey, and Brahman cattle.

0°F, on the other hand, the ratio of vaporized moisture loss to total insensible loss is between 60 and 65 per cent. Approximate values between these two extremes are: 70 per cent at 30°F, 75 per cent at 50°F, 88 per cent at 80F°, and 90 per cent at 90°F. Each temperature, body weight, and productive level is not only associated with different heat production, evaporative cooling, and insensible weight loss, but also with a different ratio of moisture vaporization to insensible weight loss.

Fig. 3, representing the ratio of latent heat to total heat (that is, the ratio of evaporative cooling to total heat production), brings out three significant facts: 1) Within the limits of overall errors, this ratio is nearly the same in all cattle regardless of age, weight, milk production (and therefore, feed con-

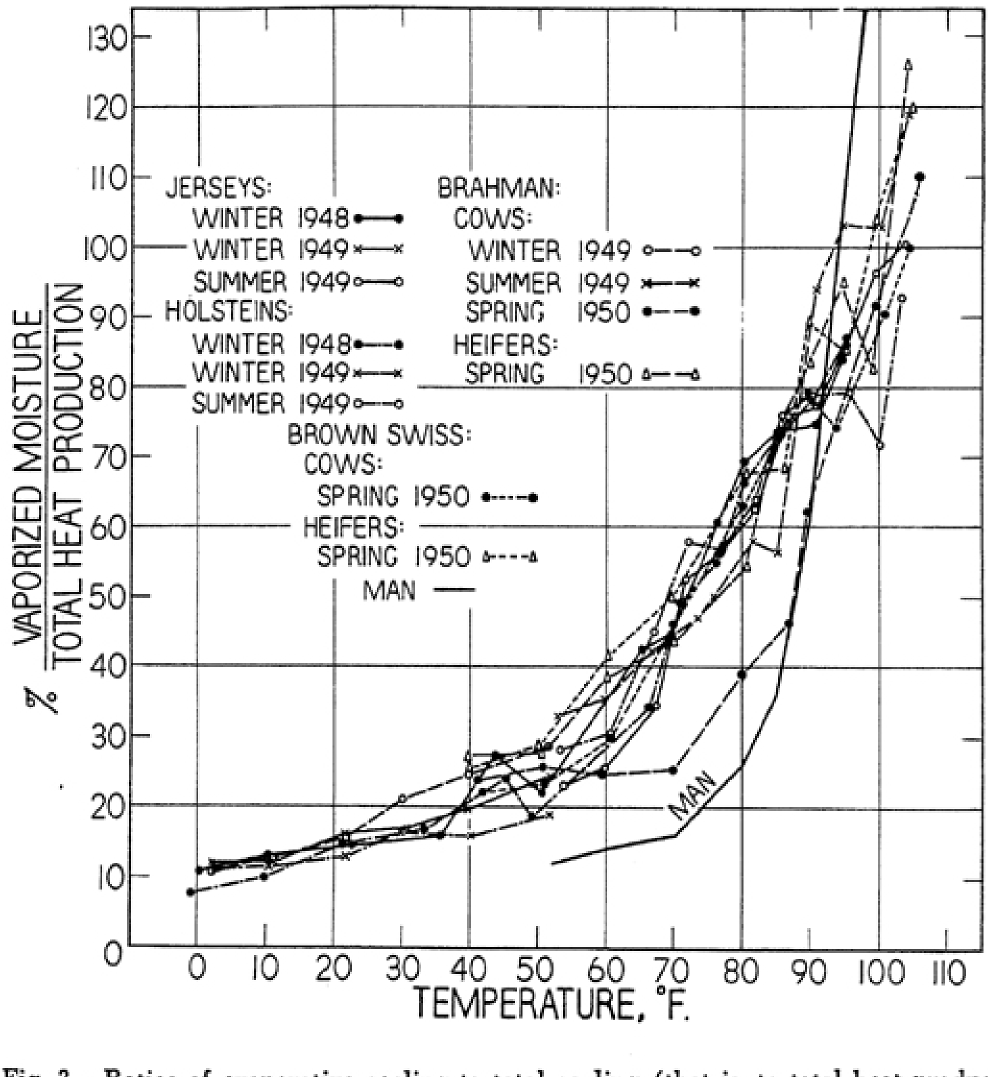

Fig. 3.—Ratios of evaporative cooling to total cooling (that is, to total heat production) as function of temperature in cattle and, for comparison, man (chart on man plotted from data by Gagge, Winslow, and Herrington as given on page 30, Missouri Res. Bul. 423, 1948). Data for total heat production from the open-circuit method previously reported in Missouri Res. Buls. 450, 464, and 473.

sumption), or breed. Only one curve, representing the average of three dry Brahman cows in their third experimental period in the chamber, deviates from the average between temperatures 60° to 90°F. 2) This ratio rises in virtually exponential manner with rising temperature from about 60° to 80°F. 3) The rise of this ratio is rather different in man (a profusely sweating species) than in cattle (a slightly sweating species). In resting man this ratio curve is below that for cattle prior to 80°F; following 80°F, when man "breaks out in sweat", the ratio curve for man gathers speed, crosses the curve for cattle at about 90°F, and continues its exponential rise, much more steeply than in cattle, with increasing environmental temperature[7]. The result of man's profuse sweating is that while his body temperature (rectal and skin) remains

TABLE 3.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN BRAHMAN CATTLE, 0° to 105°F.

Temperature °F.		Relative Humidity	Number of Obser-	Body Weight	Insensible Loss	Vaporized Moisture*		Vaporized Moisture
Dry Bulb	Wet Bulb	%	vations	Kg.	grams per hour	grams per hr.	gms/sq.m. per hr.	% Total Heat Production*
			Brahman 209 (May 23 to August 15, 1949)					
52.5	47.0	67	3	343	321	260	59	32
60.0	54.5	69	2	342	369	308	70	36
66.5	58.0	60	3	353	360	299	67	40
73.5	63.0	55	3	343	431	370	84	43
76.0	65.0	55	3	353	446	385	86	49
81.0	72.5	65	3	348	479	418	94	55
85.0	75.5	65	3	352	498	437	98	53
90.5	80.0	64	3	363	750	714	157	100
94.5	80.5	55	3	362	838	791	174	105
99.0	86.0	59	2	351	797	758	169	108
104.0	89.0	56	1	358	800	796	176	115
			Brahman 190 (May 23 to August 15, 1949)					
53.0	47.5	66	3	352	363	300	67	34
59.0	53.0	67	2	355	362	299	66	35
66.5	58.5	61	3	356	373	310	69	45
72.5	62.5	56	2	366	463	400	87	51
75.0	64.0	56	2	366	453	390	85	51
81.5	73.0	66	2	366	525	462	101	61
85.0	76.0	66	3	365	533	470	103	60
90.5	80.5	65	3	365	757	696	152	88
94.0	80.5	56	3	375	904	825	178	102
99.0	85.5	58	2	367	688	628	137	98
104.0	91.5	62	1	358	813	791	175	123
			Brahman 209 (October 4, 1949, to February 1, 1950)					
52.5	49.0	79	3	372	296	219	47	28
40.0	36.5	72	5	391	285	208	44	22
29.5	26.5	66	4	399	261	184	38	21
21.0	18.5	62	4	408	246	169	35	14
9.5	8.0	65	5	416	226	149	30	12
2.0	1.0	70	3	422	211	134	27	11
51.5†	44.0	56	8	432	284	207	41	24
			Brahman 190 (October 4, 1949, to February 1, 1950)					
50.0	46.5	76	3	393	323	245	51	29
39.0	36.0	73	5	403	289	211	44	27
30.0	27.0	67	5	417	263	185	38	21
22.0	19.5	64	4	423	242	164	33	17
11.0	9.0	59	5	437	219	141	28	13
1.5	0.5	69	3	448	200	122	24	10
52.0†	45.0	57	8	451	297	219	42	22

* Metabolic weight losses from Table 8; heat production from open-circuit method, Tables 2 and 4, Missouri Research Bulletin 464. Surface area of Brahman cows assumed to be 12 per cent greater than for Jersey or Holstein cows (see page 14 of Missouri Research Bulletin 464).

† At end of experiment.

[7]See charts on pp. 277-79 in S. Brody's "Bioenergetics and Growth," Reinhold Pub. Corp., 1945.

TABLE 4.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN BROWN SWISS COWS, 40° to 105°F. (February 6 to June 9, 1950)

Temperature °F.		Relative Humidity	Number of Obser-	Body Weight	Insensible Loss	Vaporized Moisture*		Vaporized Moisture % Total Heat
Dry Bulb	Wet Bulb	%	vations	Kg.	grams per hour	grams per hr.	gms/sq.m. per hr.	Production*
				Brown Swiss 20				
41.5	37.0	66	5	579	444	314	59	19
50.5	44.0	59	6	582	482	352	66	21
59.5	54.0	71	6	585	548	418	79	27
69.0	62.0	66	5	587	869	739	139	48
80.0	72.5	69	6	590	1022	892	167	60
84.5	76.0	68	3	578	1094	964	182	67
89.0	81.5	73	3	556	967	895	173	80
93.5	84.5	68	1	531	1013	989	196	71
100.5	85.0	52	2	517	1104	1067	215	98
104.0	90.0	58	1	491	1125	1094	227	93
40.5†	37.0	71	3	564	409	293	56	18
				Brown Swiss 16				
41.5	37.0	64	4	615	452	352	64	23
50.5	44.0	59	6	614	471	371	68	24
60.5	55.0	69	6	611	538	438	80	30
70.0	61.5	61	5	607	859	759	140	49
80.0	71.5	66	6	600	975	875	162	64
85.5	76.0	65	3	585	1175	1075	202	77
89.5	82.5	74	3	556	900	841	163	64
93.0	84.5	70	2	532	894	846	168	77
101.0	88.5	61	2	510	1100	1131	230	81
103.0	92.0	66	1	482	1269	1248	262	119
38.5†	35.5	72	3	582	463	322	61	19
				Brown Swiss 24				
41.5	37.0	66	4	650	450	349	62	24
51.0	44.5	58	6	652	477	376	67	24
60.5	54.5	69	6	653	596	495	88	33
70.0	61.5	61	5	659	769	668	118	41
79.5	72.0	68	6	659	1048	947	167	66
85.5	77.0	68	3	652	1148	1047	185	77
89.5	82.5	73	3	616	1084	1040	190	94
94.0	86.0	72	2	591	840	830	155	75
100.0	87.0	60	2	569	1022	1036	198	93
105.0	91.5	60	1	549	1000	998	194	88
39.0†	35.5	70	3	627	538	429	78	27

* Metabolic weight losses from Table 6; heat production from open-circuit method, Table 3, Missouri Research Bulletin 473. Surface area of Brown Swiss cattle is assumed to be the same as that of Jersey and Holstein cows, i.e., surface area in square meters equals 0.15 (weight in Kg.)$^{0.56}$.

† At end of experiment.

constant that of cattle rises sharply beginning with 80°F, so that at 105°F environmental temperature, the body temperature (rectal and skin) also attains 105°F both in Indian and European cattle. (The body temperature in cattle is normally 101°F but at 105°F environmental temperatures increases to 105° to 108.5°F, depending on body size and productive level.)

It is this inability of cattle to increase the sweat (or equivalent moisture) production in proportion to the body's evaporative cooling needs with rising environmental temperature that limits their feed consumption, and therefore milk production, in hot weather and, consequently, limits the dairy industry in tropical regions. Appetite and hunger in such cases act as temperature-regulating mechanisms[8]. The tropically-evolved Brahman or Zebu cattle compensate partially for the sweating deficiency by increasing the surface area (dewlap, navel flap, large ears, hump). This delays by 10° to 15°F the onset of their

[8]Brobeck, J. R., Regulation of energy exchange. Ann. Rev. Physiol., *10*, 315, 1948.

"critical temperature" (rise in rectal temperature, etc.) but does not help much at environmental temperature 105°F when environmental and surface temperatures meet. Reduced productivity appears to be the major adaptation of cattle to tropical climate; there may be an inherent incompatability between high milk production and high temperature because of the difficulty of dissipating the heat associated with the productive process.

TABLE 5.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN BRAHMAN COWS, 40° to 105°F. (February 6 to June 9, 1950)

Temperature °F. Dry Bulb	Temperature °F. Wet Bulb	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gms/sq.m. per hr.	Vaporized Moisture % Total Heat Production*
				Brahman 209				
41.0	36.5	65	5	440	235	192	38	24
51.0	44.5	58	6	458	245	202	39	24
59.0	53.5	71	6	463	249	206	39	23
69.5	61.5	64	5	470	263	220	42	26
79.5	72.0	68	6	474	311	268	51	34
86.0	76.5	65	1	473	431	388	73	51
89.0	81.0	72	2	476	569	531	100	71
99.0	89.0	68	1	478	688	670	126	95
39.5†	36.0	71	3	484	204	162	30	14
				Brahman 190				
41.0	37.0	67	5	468	270	206	39	24
50.0	43.0	58	6	477	291	227	43	24
59.0	53.5	70	6	485	303	239	45	25
69.0	61.5	66	5	487	278	214	40	22
80.0	72.0	66	6	498	338	274	50	33
87.0	81.0	77	1	492	438	374	69	51
90.0	79.5	63	2	506	540	459	84	55
99.0	85.5	58	1	510	763	706	128	95
105.0	91.0	59	1	494	669	657	121	87
40.5†	37.0	74	3	512	233	173	31	12
				Brahman 189				
40.5	36.5	66	5	440	270	227	45	24
50.0	43.0	58	6	452	271	228	44	30
59.0	54.0	71	6	456	252	209	40	27
70.0	62.0	62	5	461	260	217	42	27
79.5	71.0	66	6	462	271	228	44	33
86.0	77.5	68	1	462	300	257	49	37
88.5	81.0	72	2	465	447	402	77	60
99.0	88.5	66	1	467	650	611	116	86
105.0	92.0	60	1	467	744	716	136	133
41.0†	38.0	76	3	476	290	252	48	20

* Metabolic weight losses from Table 6; heat production from open-circuit method, Table 3, Missouri Research Bulletin 473. Surface area of Brahmans assumed to be 12 per cent greater than for Jersey or Holstein cows (see page 14 of Missouri Research Bulletin 464).

† At end of experiment.

Fig. 4 represents moisture vaporization per unit surface area plotted against environmental temperature. The striking features of the curves in the left segment in Fig. 4 are: 1) Lower vaporization rate per unit surface area in the Brahmans, particularly between 70° and 85°F. This may be associated with: a) greater surface area (by about 12 per cent) per unit weight in the Brahmans; b) lower heat production[3] associated with lower feed consumption[4] and milk production, as well as with apparently lower basal metabolism[3], with consequent less heat for dissipation. 2) Decline in moisture vaporization from the 85°F peak in the European cattle; this is, perhaps, in part

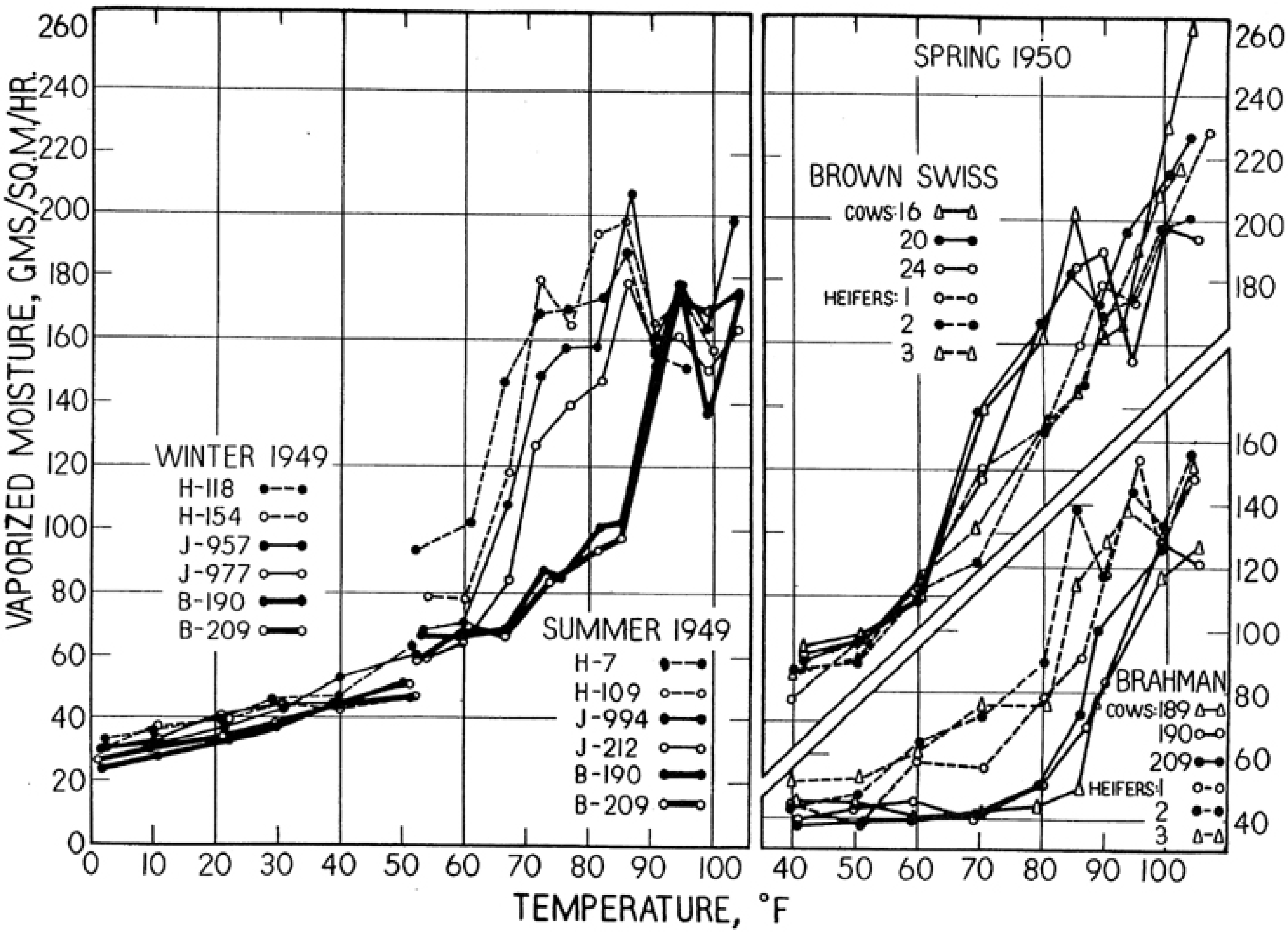

Fig. 4.—Vaporized moisture per unit surface area for individual animals as function of temperature. Formulas for computing surface area, as well as the numerical data, are given in Tables 1 to 7. The symbols "H", "J", and "B" represent, respectively, Holstein, Jersey, and Brahman cattle.

associated with declines in feed consumption, milk production, and heat production—approaching the level of the light milking Brahmans; it may, perhaps, reflect an exhaustion of the sweat glands or similar moisture-secreting mechanisms. 3) Slow linear rise in vaporization rate of cows from about 0°F to 60° or 65°F. 4) The right segment of Fig. 4 shows a greater rise in

TABLE 6.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN BROWN SWISS HEIFERS, 40° to 105°F. (February 6 to June 9, 1950)

Temperature °F. Dry Bulb	Temperature °F. Wet Bulb	Relative Humidity %	Number of Observations	Body Weight Kg.	Insensible Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gms/sq.m. per hr.	Vaporized Moisture % Total Heat Production*
				Brown Swiss 1				
39.5	35.5	67	6	206	176	141	48	21
50.0	45.0	67	6	221	239	204	66	31
59.5	54.5	72	6	234	299	264	83	40
70.0	64.5	74	4	247	432	397	121	50
80.0	72.5	69	7	261	489	454	134	66
86.0	77.5	70	2	275	593	558	160	71
89.5	81.0	70	4	278	675	629	179	91
95.0	81.0	55	1	286	675	619	174	81
99.5	85.0	55	1	280	700	692	197	92
107.0	90.5	53	1	271	800	789	228	132
40.5†	36.5	65	5	293	268	216	60	25
				Brown Swiss 2				
40.0	36.0	67	7	160	176	146	57	30
50.0	45.5	71	7	174	190	160	59	28
60.5	55.0	70	6	186	261	231	83	38
69.0	64.0	76	4	196	294	264	92	42
80.0	72.0	68	7	208	424	394	132	62
86.5	80.0	74	2	218	482	452	148	62
89.5	81.0	68	4	224	556	528	170	85
94.5	82.0	58	2	230	600	551	175	86
99.0	86.0	58	2	222	632	608	197	100
104.0	88.0	53	1	209	600	600	201	107
40.5†	36.5	66	5	232	251	213	67	30
				Brown Swiss 3				
39.5	35.5	67	6	181	187	155	56	27
50.0	45.5	69	6	192	203	171	60	27
60.0	55.0	70	6	201	285	253	87	47
69.0	63.5	74	5	208	336	304	102	58
80.5	72.5	68	7	220	450	418	136	76
85.5	79.0	75	1	229	488	456	145	72
89.5	80.5	68	4	230	555	518	164	94
95.5	77.5	44	1	236	638	608	190	90
99.0	87.0	62	2	228	678	653	208	121
102.5	88.5	57	1	219	600	604	197	122
42.0†	37.5	65	5	243	273	229	70	28

* Metabolic weight losses from Table 6; heat production from open-circuit method, Table 3, Missouri Research Bulletin 473. Surface area of Brown Swiss cattle is assumed to be the same as that of Jersey and Holstein cows, i.e., surface area in square meters equal 0.15 (weight in Kg.)$^{0.56}$.

† At end of experiment.

vaporization rate per unit surface in the Brahman heifers over the *dry* cows but lesser vaporization in the Brown Swiss heifers than in the *lactating* cows, especially between 60° and 85°F.

Fig. 5 represents the vaporization values for the "Control cows"—the effects of advancing gestation, lactation, age, and chamber housing under constant environmental conditions (50°F and 65 per cent relative humidity). It shows that during the Summer and Winter test periods approximate values of moisture vaporization in grams per square meter per hour were, respectively,

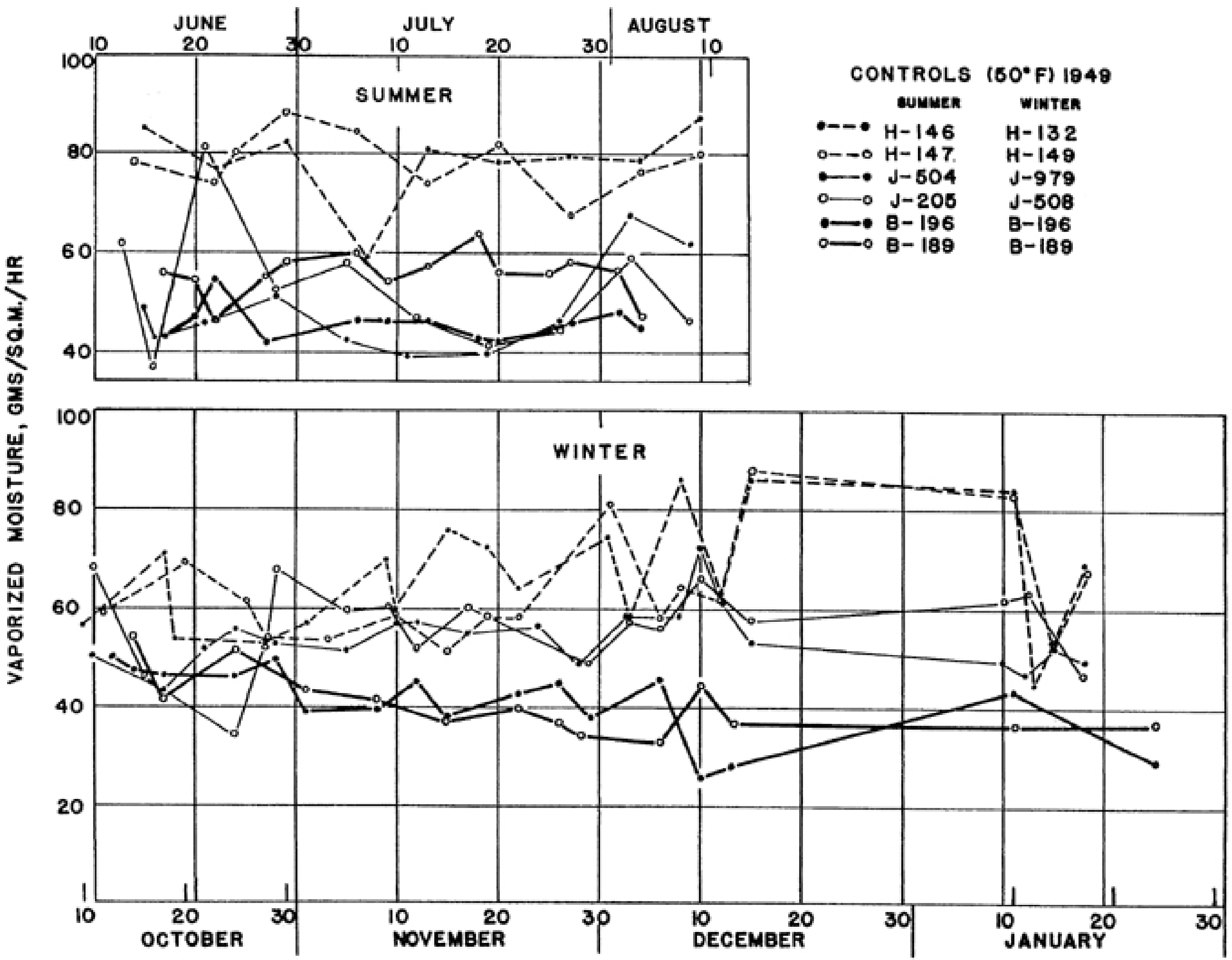

Fig. 5.—Moisture vaporization in the Control cows maintained at about 50°F and 65 per cent relative humidity throughout the test periods. The symbols "H", "J", and "B" represent, respectively, Holstein, Jersey, and Brahman cattle.

50 and 40 in the Brahmans (same individuals during Summer and Winter); 80 and 65 in the Holsteins (different individuals Summer and Winter); 50 and 55 in the Jerseys (different individuals). The charts show the order of variability of the data and the absence of significant time trends.

Fig. 6 is a vaporization prediction curve for Holstein and Jersey cows, weights 600 to 1600 pounds, constructed on the assumption that surface area

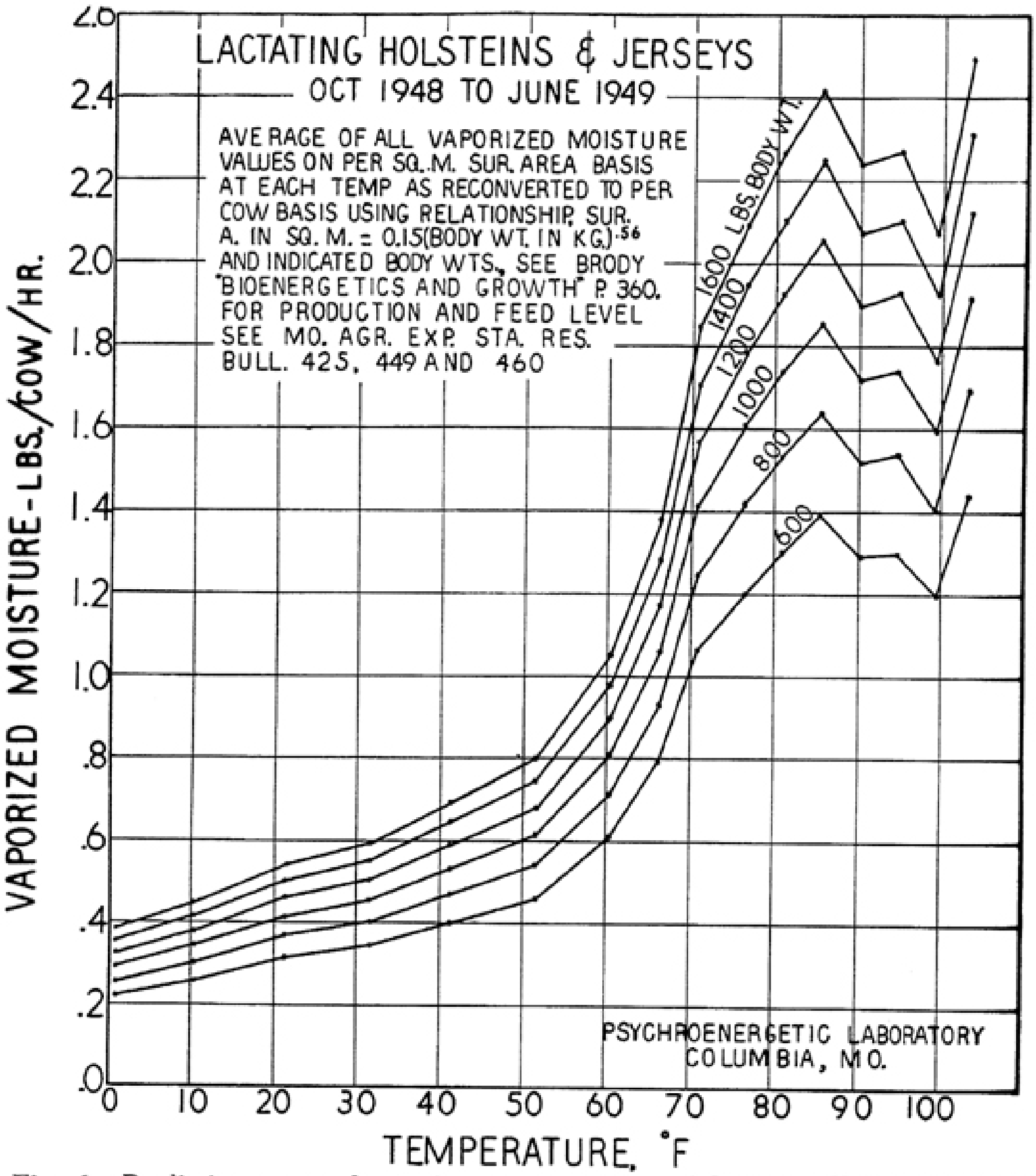

Fig. 6.—Prediction curves for moisture vaporization of lactating Holstein and Jersey cows of different body weights as function of temperature, 0° to 105°F, based on data from column 4, Table 8 (upper section).

is a good reference base for moisture vaporization and that there is no breed difference between Jerseys and Holsteins either in the relation of surface area to body weight or in vaporization rate to surface area (as shown[2] by the agreements between the two breeds on page 15, upper left segment, Res. Bul. 451).

Fig. 7 is a summary chart of the vaporization rates in all seven groups: lactating Brahman, Brown Swiss, Holstein, and Jersey cows; dry Brahman cows; Brahman and Brown Swiss heifers. This chart is rather confusing because, unlike the summary chart in the preceding report[2] (especially upper left segment, Fig. 4, Res. Bul. 451), the curves in Fig. 6 do not coincide.

To get a clearer picture of the situation, the cow and heifer data were plotted separately since the two are not comparable—the changing reactions of the heifers reflected not only changing environmental temperature but also increasing body weight and age—they were growing rapidly.

Fig. 8 is a comparison of the vaporization data of the heifers in terms of four different reference bases: surface area; 500 lbs. body weight (the average weight of the animals); individual animals; and ratio of evaporative

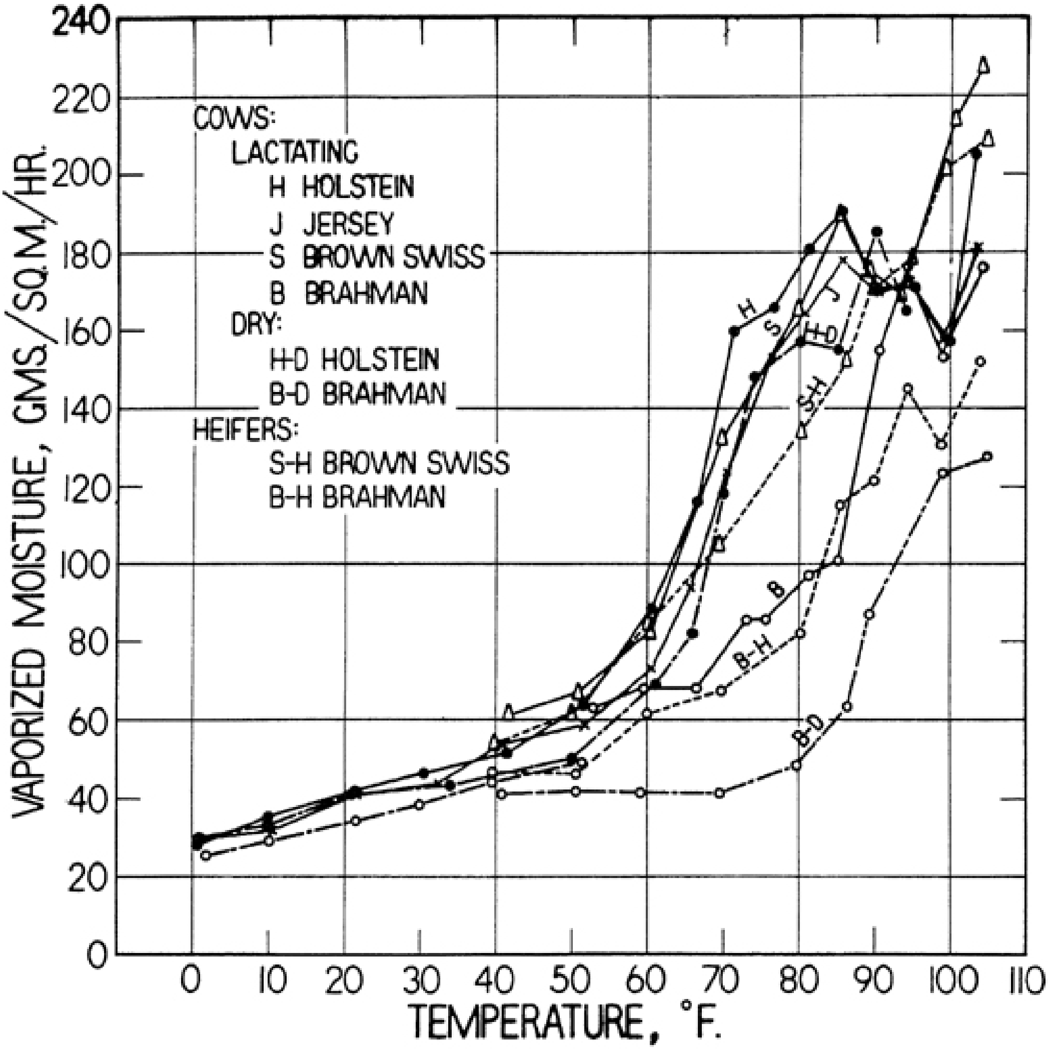

Fig. 7.—Summary chart of moisture vaporization per unit surface area for the mean values of the seven groups of cattle. The slopes of the heifer curves differ from the curves on cows because of their relatively greater change in weight.

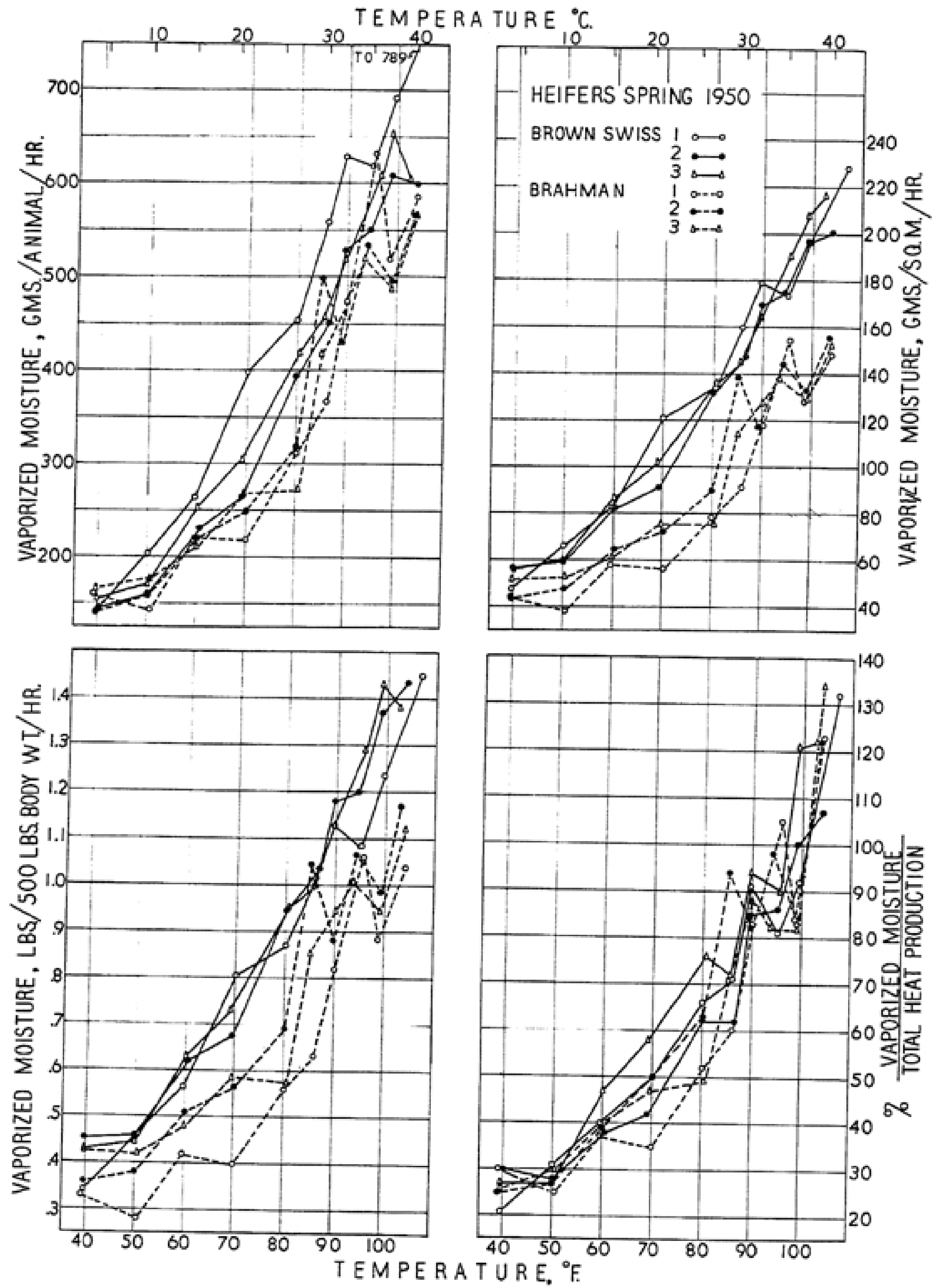

Fig. 8.—Comparison of moisture vaporization of the Brown Swiss and Brahman heifers in terms of different reference bases: individual animals, surface area, 500-lb. body weight, ratio of evaporative cooling to total heat production.

cooling to total heat production. While the weights of the Brahman and Brown Swiss heifers were virtually the same, the moisture vaporization in the Brahmans was less regardless of the reference base employed. This suggests that under the given conditions the Brahmans had a lower heat production with consequent lower need for evaporative cooling per unit body size. This idea

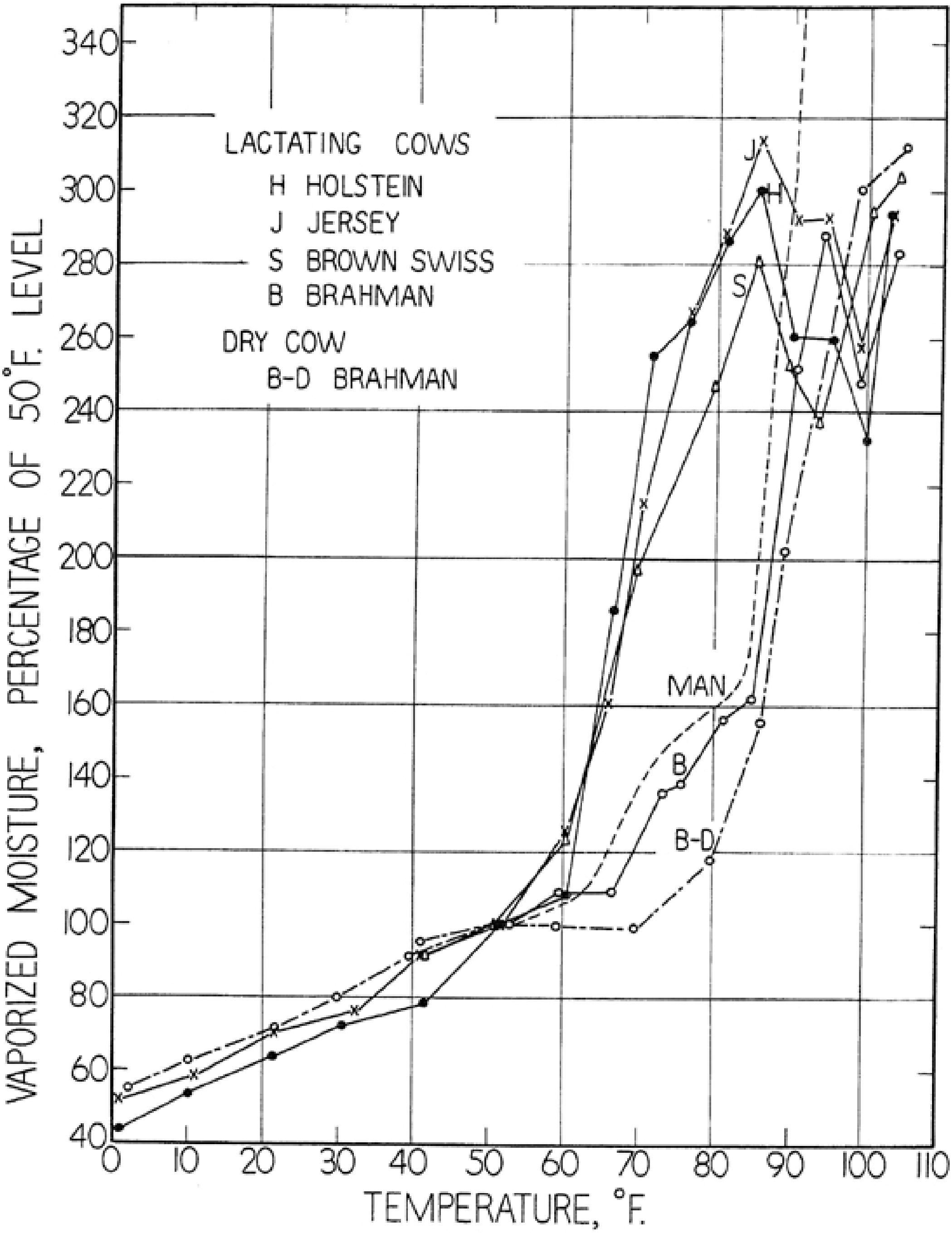

Fig. 9.—Comparison of the evaporative cooling of European- and Indian-evolved cows, and also of man, in relation to environmental temperature presented in terms of percentages of their vaporization levels at 50°F. The curve on man was recomputed for this chart from absolute values given by Gagge, Winslow, and Herrington, Am. J. Physiol., *124*, 34, 1938.

is substantiated by the way the ratio charts of latent heat to total heat coincide (lower right segment, Fig. 8).

Finally, Fig. 9 compares the evaporative cooling reactions of the cows in terms of percentages of their vaporization levels at 50°F as reference base; it shows that the vaporization data fall into two fairly distinct patterns, one for the European-evolved animals (Brown Swiss, Holstein, and Jersey) and the other for the Indian-evolved (Brahman or Zebu). The European cows are seen to reach the maximal vaporization rates at 80°F; most Brahman individuals reach the vaporization peak at 95°F. The curves of the European and Indian cows meet and/or cross at about 90°F. Prior to 90°F the vaporization rates in the Indian cows are considerably below those of the European, presumably, because, as previously noted, the low-producing Indian cows produce

TABLE 7.--INSENSIBLE LOSS AND EVAPORATIVE LOSS IN BRAHMAN HEIFERS, 40° to 105°F. (February 6 to June 9, 1950)

Temperature °F.		Relative Humidity	Number of Obser-	Body Weight	Insensible Loss	Vaporized Moisture*		Vaporized Moisture
Dry Bulb	Wet Bulb	%	vations	Kg.	grams per hour	grams per hr.	gms/sq.m. per hr.	% Total Heat Production*
				Brahman 1				
39.0	35.5	68	6	244	198	161	44	30
50.5	45.0	65	6	255	180	143	38	25
59.5	54.0	71	6	263	258	221	58	37
70.0	64.0	71	5	272	255	218	56	35
80.0	72.0	68	6	278	349	312	80	52
86.0	78.0	71	2	288	404	367	92	60
90.0	81.0	68	4	290	515	475	118	83
95.5	80.5	52	1	298	675	632	155	105
98.5	86.5	62	2	294	553	519	128	84
104.0	89.0	56	1	282	594	586	148	123
41.5†	37.0	64	5	308	219	176	42	21
				Brahman 2				
39.5	35.5	66	8	197	178	142	44	25
50.0	45.0	67	6	208	195	159	46	27
60.0	55.0	71	6	216	256	220	65	39
70.0	63.5	69	4	222	286	250	72	50
80.0	72.0	69	7	231	355	319	90	63
85.0	79.0	75	2	238	534	498	139	94
89.5	80.0	65	4	245	460	430	118	82
94.0	81.0	57	2	251	578	535	144	98
99.0	85.0	56	2	252	544	496	134	83
103.5	89.0	57	1	242	588	566	156	122
40.5†	36.0	65	5	255	176	137	37	18
				Brahman 3				
39.5	36.0	70	6	195	202	166	52	26
50.5	45.5	68	6	212	213	177	53	30
60.0	54.0	69	6	222	248	212	61	40
69.5	64.0	72	5	230	304	268	76	47
80.5	72.5	68	7	238	309	273	76	49
85.0	78.0	72	2	244	454	418	115	71
90.0	81.0	67	4	251	516	475	128	88
93.5	79.5	54	1	258	556	520	138	82
99.0	87.0	61	2	258	534	489	130	82
104.0	88.0	53	1	252	575	566	152	134
41.5†	37.0	64	5	259	183	138	37	18

* Metabolic weight losses from Table 6; heat production from open-circuit method, Table 3, Missouri Research Bulletin 473. Surface area of Brahmans assumed to be 12 per cent greater than for Jersey or Holstein cows (see page 14 of Missouri Research Bulletin 464).

† At end of experiment.

less heat than the high-producing European cows, with correspondingly lower need for evaporative cooling.

The variation in the evaporative peaks of the three European cattle (from 280 per cent for the Brown Swiss, 300 per cent for the Jerseys, and 310 per cent for the Holsteins) in Fig. 9 are within the limits of the overall experimental errors and biological variability of the material. One of the Brahman peaks was 290 per cent (below those of the Jersey and Holstein); another Brahman peak rose to 310 per cent at 105°F. One cannot be sure of the significance of these differences, if any. The experimental errors in all operations, and also individual variations, tend to increase at the high temperatures.

TABLE 8.--AVERAGE VAPORIZED MOISTURE LOSS PER HOUR
(October 1948 to June 1950)

Approx. Temperature °F.	COWS							HEIFERS		
	Lactating					Dry	Total No. of Observ.	Brown Swiss	Brahman	Total No. of Observ.
	Jersey*	Holstein*	Jersey & Holstein*	Brown Swiss	Brahman	Brahman				
			Grams per Sq. Meter					Grams per Sq. Meter		
0	29	28	29			26	30			
10	32	35	34			29	41			
20	41	42	41			34	36			
30	44	46	45			38	36			
40	54	51	53	62		42	68	54	46	39
50	58	64	61	67	63	44	85	62	46	37
60	73	87	80	82	68	41	58	84	61	36
65	93	116	104	---	68	---	27	---	---	0
70	123	160	140	132	85	41	57	105	68	27
75	153	166	159	---	86	---	27	---	---	0
80	164	180	171	165	97	48	63	134	82	41
85	178	190	183	190	100	64	37	152	115	11
90	169	170	170	175	154	87	42	171	121	24
95	173	171	172	168	176	---	29	178	145	8
100	158	157	157	214	153	123	19	201	131	11
105	181	205	189	228	176	128	10	209	152	6
			lbs. per 1000 lbs. Body Weight					lbs. per 500 lbs. Body Weight		
0	0.31	0.26	0.29			0.30				
10	.36	.33	.34			.34				
20	.43	.38	.41			.40				
30	.47	.42	.45			.45				
40	.59	.48	.52	0.55		.49		0.41	0.37	
50	.62	.59	.61	.59	0.80	.50		.46	.36	
60	.78	.80	.79	.73	.87	.46		.60	.47	
65	1.00	1.06	1.03	----	.86	----		----	----	
70	1.31	1.43	1.37	1.17	1.08	.46		.74	.51	
75	1.62	1.49	1.56	----	1.08	----		----	----	
80	1.73	1.62	1.68	1.47	1.22	.53		.92	.61	
85	1.88	1.72	1.80	1.71	1.26	.71		1.02	.84	
90	1.81	1.58	1.71	1.60	1.94	.96		1.14	.88	
95	1.88	1.60	1.78	1.57	2.19	----		1.20	1.05	
100	1.77	1.51	1.68	2.03	1.93	1.36		1.36	0.94	
105	2.04	2.01	2.03	2.21	2.22	1.43		1.42	1.11	

* Includes data from Tables 1 and 2, Missouri Research Bulletin 451.

On lowering the temperature from 50° down to 0°F, however, the Brahman curves in Fig. 9 are seen to be slightly above those of the Jersey and Holsteins. This is, perhaps, without significance because the reference base value at 50°F may have been, fortuitously, slightly low or high, giving one or the other curve an apparent—not real—advantage.

The difference between the two Brahman curves in Fig. 9—lightly lactating (about 7 lb. FCM per day) and dry—may have been caused by any one or more of several influencing factors, including milk yield with higher heat production and consequently higher evaporative cooling in the lactating group, weight difference, different sequence in measuring insensible loss and metabolic weight, and/or difference in hair coatings between tests.

It was thought interesting to trace in for comparative purposes an evaporative cooling curve for man in the same units—percentage of vaporization at 50°F. The data[9] are for clothed subjects. Prior to about 85°F, the curve for man parallels roughly the curves for the cows, particularly the Brahman cows. Between 85° and 90°F when the vaporization curves of the cows, at any rate of the European breeds, seem to decline that of man rises very steeply, and by 90°F leaves the cattle curves far behind. It is this rapid increase in vaporization rate in man above 80°F that enables him to withstand so much higher temperatures.

SUMMARY AND CONCLUSIONS

This bulletin reports data on the effect of environmental temperature from near 0°F to 105°F (and about 65 per cent relative humidity) on insensible weight loss and moisture vaporization in heavily-lactating Brown Swiss, Holstein, and Jersey cows; lightly-lactating and dry Brahman cows; Brown Swiss and Brahman yearling heifers. The following were among the more important observations and conclusions:

(1) At 100° to 105°F, when the feed consumption and milk production declined to near zero, the insensible weight loss was virtually identical with the weight of moisture vaporized; but near 0°F the weight of moisture vaporized was 60 to 65 per cent of the total insensible loss. The change in the ratio of moisture vaporization to total insensible loss increased linearly from near 60 per cent at 0°F to near 100 per cent at 105°F. The above statement seems to hold true for all the animals here reported.

(2) Another generalization that seems to hold for all animals is that the ratios of evaporative cooling to total heat production increase almost exponentially with increasing environmental temperature up to 85°F regardless of breed, weight, and productive level. Incidentally, this ratio for man was lower than for cattle below 80°F; but above 80°F the slope for man increased steeply, crossed the curve for cattle at 90°F, and left the cattle curve far behind at 100-105°F.

(3) The vaporization rate per unit surface area as function of environmental temperature was almost the same in the Brown Swiss, Holstein, and Jersey lactating cows and is characterized by: a) a slow linear rise from 0° to 50°F (with a vaporization rate of 50°F of about 60 grams per square meter

[9]By Gagge, A. P., Winslow, C. E. A., and Herrington, L. P., The influence of clothing on the physiological reactions of the human body to varying environmental temperatures. Am. J. Physiol., *124*, 34, 1938. Recomputed for this chart from absolute values given by these authors.

per hour); b) a sharp sigmoid rise from 50° to 85°F (with a vaporization rate at 85°F of about 180 to 200 grams per square meter per hour); c) uncertain oscillations from 85° to 105°F.

(4) Prior to 95°F the rise in vaporization rate per unit surface area with increasing temperature of the Brahman cows was below that of the European-evolved cows. This vaporization difference per unit surface area in the two categories of cattle seems to be associated with: a) 12 per cent greater surface area in the Brahmans; b) lower heat production in the Brahmans (because of their lower feed consumption, milk production, and heat production, and, perhaps, lower basal metabolic rate).

(5) When the vaporization rates of the several groups of European and Brahman cows are represented in terms of their respective vaporization at 50°F and plotted against environmental temperatures, the resulting curves are distributed into two sharply different categories—European and Indian—with the Brahmans having strikingly lower vaporization rates at all temperatures prior to 90°-95°F, where the curves of the Brahman and European-evolved cattle meet. The lag in the Indian cows seems to be associated with their greater heat-dissipating surface and lower productivity. By this method of plotting, the vaporization curve of man almost coincides with that of Brahman cattle up to about 95°F at which time the slope of the curve for man is accelerated beyond that of the cattle.

(6) While the Indian- and European-evolved *cows* here under investigation are not comparable on the basis of breed alone because of their differences in milk yield and, therefore, in feed consumption and heat production, the Brahman and Brown Swiss *heifers* are comparable because of their virtually identical body weights, ages, and productivity. The vaporization rates of the Brahman heifers—regardless of the reference base employed—were lower than the Brown Swiss heifers.

(7) It, therefore, appears, as a general conclusion, that *under the given conditions*, the Brahmans did not sweat more than the European cattle. Their ability to tolerate 10° to 15°F higher shade temperature seems to be associated rather with their 12 per cent greater surface area and their lower productive rates with consequently lower heat production. It would be edifying to obtain similarly quantitative data under the same conditions on heavily-milking Brahmans, or crosses of European and Indian cattle now being developed. We shall probably not have a real insight into the breed differences in heat tolerance (in the shade) until equally productive individuals of these categories of cattle have been measured quantitatively under the same conditions for their vaporization rates, as well as for their heat production.

ABSTRACT

Data are reported on the effect of temperature, 0°F to 105°F, on insensible loss and moisture vaporization in heavily-lactating Brown Swiss, Holstein, and Jersey cows; lightly lactating and dry Brahman cows; Brown Swiss and Brahman yearling heifers. The ratio of vaporized moisture to insensible loss increased linearly from near 60 per cent at 0°F to near 100 per cent at 100°-105°F environmental temperature. The ratio of evaporative cooling to heat production increased approximately exponentially from about 10 per cent at 0°F to about 100 per cent at 100°F. Prior to 80°F the level and slope of this ratio was lower in man than in cattle; above 80°F the slope of man increased sharply, and by 90°F overtook that of cattle. The vaporization rate per unit surface area at various temperatures was virtually the same in lactating Holstein, Jersey, and Brown Swiss cows and higher than for Brahmans prior to 90°-95°F, when the curves of the two criss-crossed, with vaporization rates of 180 to 200 grams per square meter per hour or 1.8 to 2.0 pounds per 1000-pounds body weight per hour. However, the ratio of evaporative cooling to heat production was approximately the same in Brahman and European cattle. The vaporization rates of Brahman heifers, regardless of the reference base used, were below those of very similar Brown Swiss heifers.