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Environmental Physiology And Shelter Engineering

With Special Reference to Dairy Cattle

XXVI. The Effect of Wind on Evaporative Cooling and Surface Temperature in Dairy Cattle

H. J. THOMPSON, R. G. Yeck, D. M. WORSTELL, S. BRODY

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

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Environmental Physiology

With Special Reference to Dairy Cattle

XXVI. The Effect of Wind on Evaporative Cooling and Surface Temperature in Dairy Cattle

H. J. THOMPSON, R. G. YECK, D. M. WORSTELL and S. BRODY

ORIENTATION

Of the four methods of heat dissipation by animals (radiation, convection, vaporization, conduction) only two, evaporative and convective cooling, are affected directly by wind. Of these two, evaporative cooling, because of the high latent heat of vaporization, is by far the more important if the outer surface (hair and skin) is moist, and, if the animal is exposed to cold rain and wind, loss of body heat by vaporization may become critical.

If, however, the outer surface has little moisture to vaporize, the increased heat-dissipating effect of increasing wind is due largely to convective cooling. If, in addition to having a dry outer surface, the animal has a highly insulating hair covering and thick layer of subcutaneous fat, it can resist considerable wind in cold weather as observed on arctic animals[1] where temperatures drop to -60° F with howling winds. The great importance of hair or feather covering on heat conservation is demonstrated by laboratory experiments on animals before and after removing these coverings,[2] and by the generally-known seasonal fur and subcutaneous fat accumulations, homeothermically adjusted to the seasonal temperature rhythms. It was observed[3] at the Wisconsin Experiment Station that cattle preferred to be outside during the day in dry zero weather rather than in barns or open sheds, although they preferred to sleep on the bedded area. The open lot

[1]Scholander, P. F., Hock, R., Walters, V., Johnson, F., and Irving L., Biol. Bul. 99:225, 237, and 259, 1950.

[2]See, among others, Landauer, W., Biol. Symposia 6:127, 1942. Benedict, F. G., Landauer, W., and Fox, E. L., Storrs Agric. Exp. Sta. Bul. 177, 1932; Morgulis, S., Am. J. Physiol. 71:49, 1924; Mitchell, H. H., and Hamilton, T. S., J. Agr. Res. 52:837, 1936.

[3]Witzel, S. A., Heizer, E. E., *et. al.*, Wis. Agr. Exp. Sta. Bul. 503, 1953; J. Dairy Sci. 36, 28, 1953, and Agr. Eng. 33, 635, 1952. See also Brown, D., Wyoming Roundup, Summer, 1953, p. 121.

used in this Wisconsin experiment had a southern exposure and was protected from the prevailing north and west winds.

One possible reason for the apparently low increase in cooling effect with increase in air velocity is that convective, unlike evaporative, cooling does not increase linearly with the increase in air velocity but approximately with its square root as indicated by the equation

$$Q_c = CA\sqrt{V}\,(t_1 - t_2) \qquad (1)$$

in which Q_c is total convective loss, A surface area, V air velocity, and $(t_1 - t_2)$ the temperature difference between body surface and environment; C is the convective constant. This is essentially the generalized convective cooling equation formulated for *man* by Gagge and associates.[4] This equation, of course, may or may not be applicable to cattle but is useful as a first approximation for explaining the non-linear effect of wind velocity on vaporization rate and surface temperature.

That wind affects but slightly the overall reaction of cattle in the laboratory has been indicated in the preceding report[5] on the effect of wind on milk production, feed and water consumption, and body weight.

Milk production, feed consumption and body weight, reported on in the preceding bulletin,[5] reflected the condition of the animals *as a whole*. This bulletin reports data on the effect of wind on two *specific* reactions, total evaporative cooling and surface temperature. A description of the animals and detailed schedule were given in the preceding bulletin.[5]

EVAPORATIVE COOLING

Method: The insensible weight loss was measured by placing the animal on the platform of a sensitive scale (sensitized with an electronic relay to give a weighing precision of about half an ounce for a 1500-lb. animal) and recording the weight loss. The details are essentially the same as those previously reported[6] except that a recording device with automatic weight loss compensation was added to the electronic balance indicator as illustrated in Figure 1.

Vaporized moisture was computed by deducting from the insensible weight loss the metabolic weight loss (the difference in weight between the oxygen consumed and the sum of the weights of carbon dioxide and methane produced).[7]

[4]Gagge, A. P., Herrington, L. P., and Winslow, C. E. A., Am. J. Hygiene, 26: 97, 1937.

[5]Univ. Mo. Agric. Exp. Sta. Res. Bul. 545, 1954.

[6]Univ. Mo. Agric. Exp. Sta. Res. Buls. 451 and 479.

[7]To be reported in Univ. Mo. Agric. Exp. Sta. Res. Bul. 552 (XXVII).

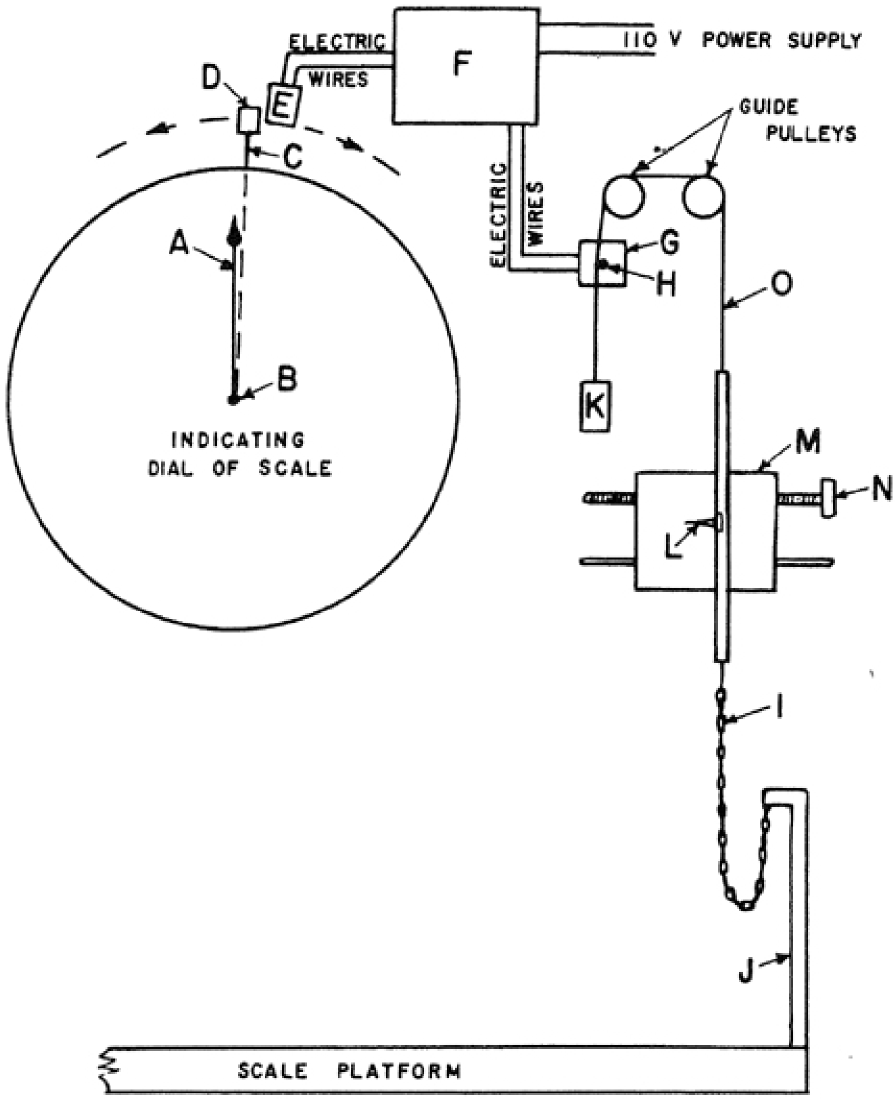

Figure 1 — Schematic diagram of mechanism used for recording insensible weight loss. A null or constant balance point of the scale indicator (A) was maintained by replacing any weight loss by links of chain (I) through a post (J). The chain was raised or lowered by a reversible motor (G) acting through its shaft (H) and a line (O) with line tension provided by a counterweight (K). The motor was actuated through an electronic relay (F) and a pick-up coil (E). In operation the indicating shaft (B) working through a balanced arm (C) causes the aluminum flag (D) to move, without contact, between the pick-up coils. Initial adjustment of the scale counter poise weights was necessary to bring the flag to the point where it changed the energy in the electronic circuit, as indicated by the reversal of the motor when the flag was between the coils. The movement of the chain was recorded by a pen (L) on a chart (M) which in turn was driven by a chart drive mechanism (N). Each inch of vertical travel represented 50 grams and each inch of horizontal travel represented ten minutes.

Means by which air velocity was controlled and measured in the chambers will be discussed in detail in a later publication. Briefly, the air velocities in the chambers (test rooms) were provided through the use of large propeller-type fans placed above every other stall partition and enclosed so that the air was directed downward between two cows. Part of the air would circulate beneath each cow and upward along the side of the cow that was opposite the fan.

As in previous experiments,[6] the insensible weight loss measurements were made outside the chambers, in the adjacent workrooms. Environmental conditions in the workroom were maintained as near like those in the chamber as possible.

The low air velocity (0.4 to 0.5 mph) used here was essentially the normal rate of air movement without use of fans employed in all the preceding experiments.[6] High and medium air velocities at the scales in the workroom were obtained by placing a 36-inch propeller-type fan in a vertical position so that it blew toward the cow along a horizontal plane. High air velocity (8 to 9 mph) measurements were made with the fans placed approximately 2 feet directly behind the cow. For medium velocity (4 to 6 mph) measurements the fan was placed 4.5 feet behind the cow in one workroom and in the other about 6 feet away from the cow's right front shoulder, so the wind blew approximately at a 30° angle. The average air velocities in the workrooms were thus made to approximate the average chamber velocities.

The measurements were generally made from 6 to 9 p.m.

Data and Interpretation: The results for individual animals are given in Tables 1 to 6 and for breed averages in Figures 2 to 5. The graphs bring out the following general features on the effect of air velocity on insensible weight loss (Figure 2) and total vaporized moisture (Figures 3, 4, and 5).

1. The effect of wind on vaporization is dependent on environmental temperature. At 18° F there was no noticeable effect of in-increased air velocity on vaporization rate (which paralleled insensible weight loss); at 50° F the effect of air velocity was uncertain; at 60° F and 80° F (and also at 95° F in the Jersey and Brahman) increasing air velocity reduced the vaporization rate. At 95° F there was a crossing of the vaporization curves for low and high air velocity in the Holstein and Brown Swiss cows. This crossing at 95° F resulted from an increase in the vaporization rate at high air velocity but not at low air velocity. The vaporization curve at low velocity had reached its maximum, while the corresponding curve for high velocity continued to

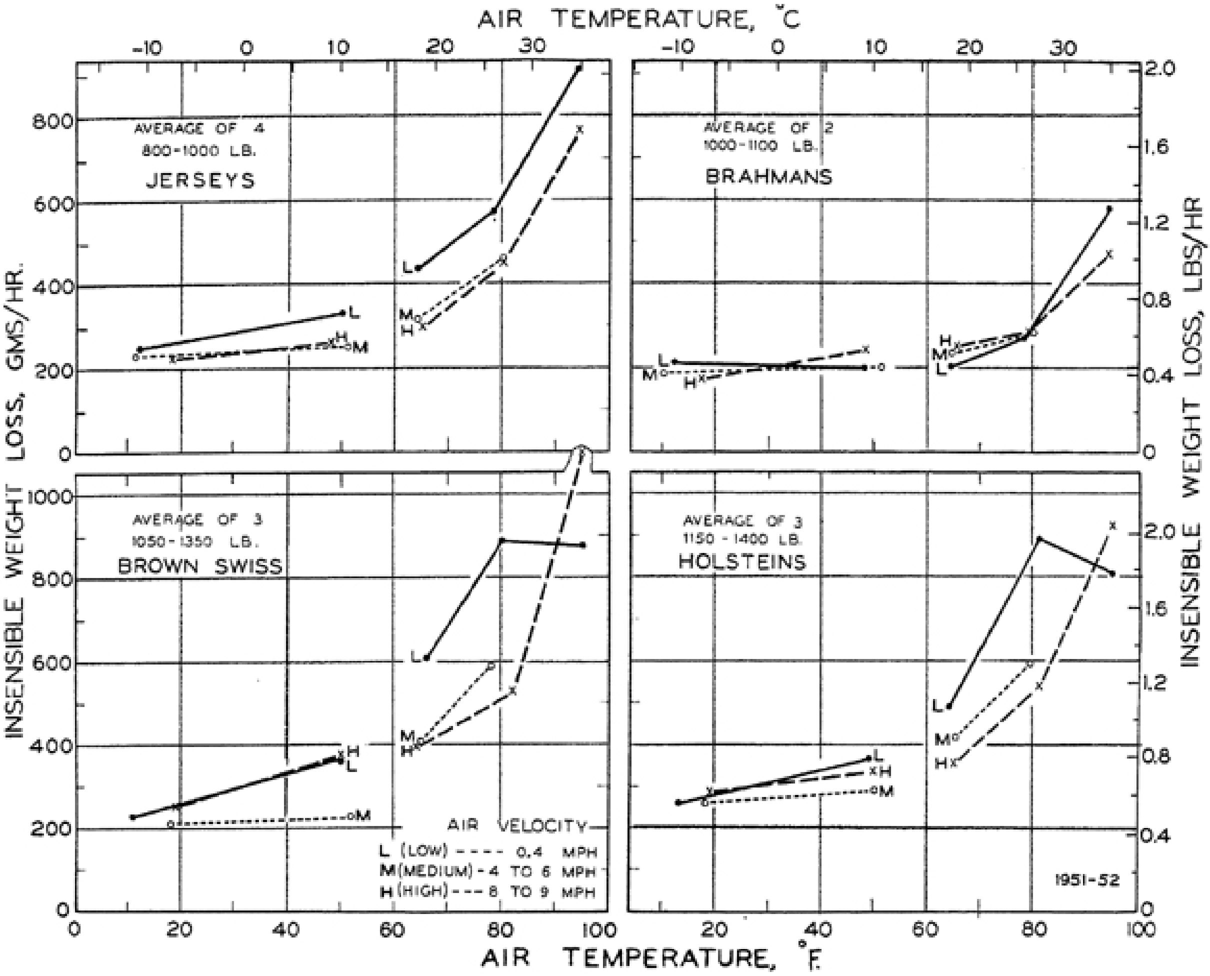

Figure 2 — Breed averages of insensible weight losses at low, medium, and high air velocities plotted against environmental temperatures. Lactating and dry Jerseys were combined as they showed no difference in their reactions. Note the higher weight losses at the lower air velocities.

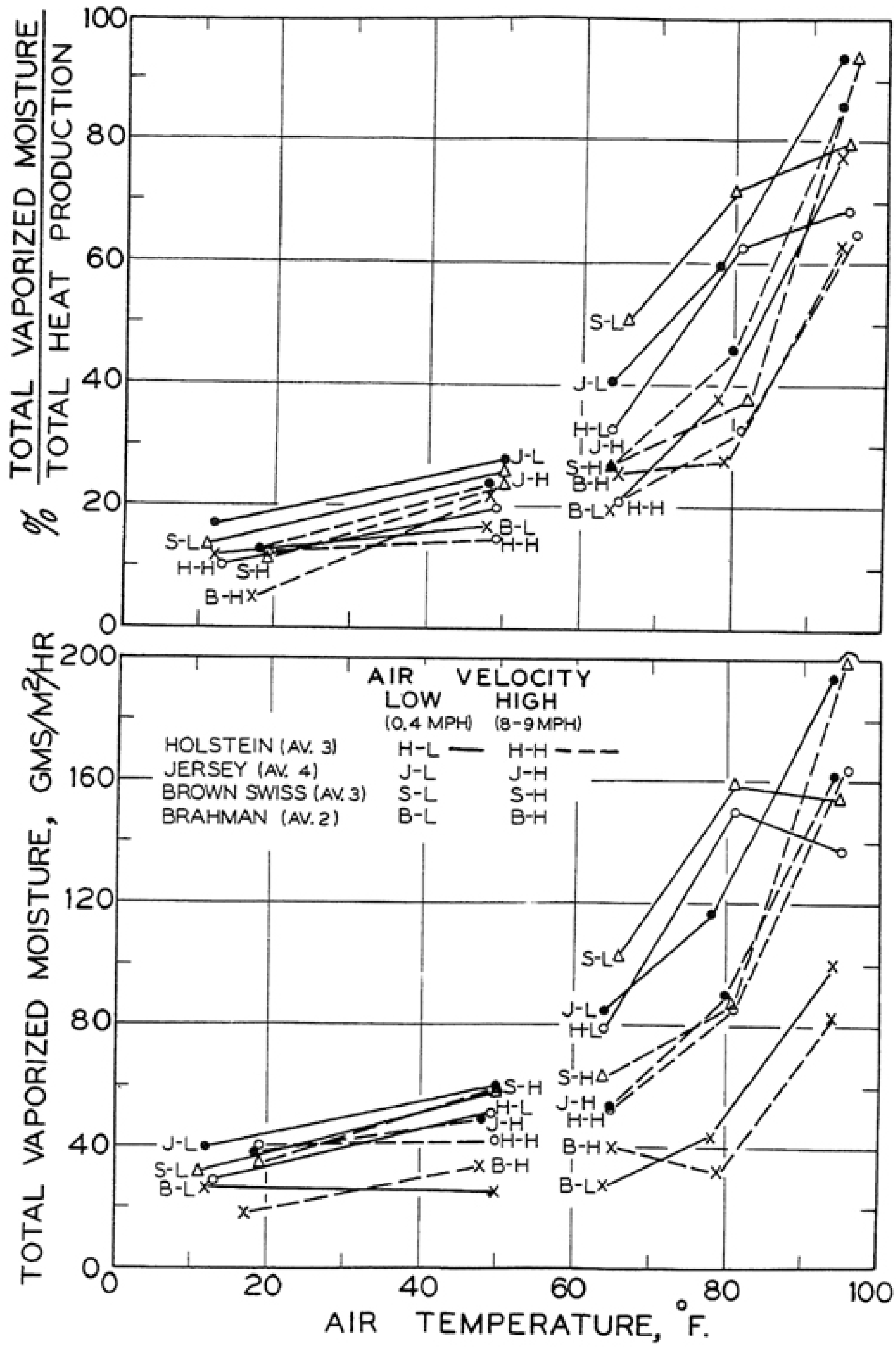

Figure 3 — Breed comparisons for vaporized moisture per unit surface area at low (L, continuous curves) and high (H, broken curves) wind plotted against environmental temperature (lower section). As in Figure 2, low air velocities are associated with greater vaporization. The vaporization curves are lowest for the Brahman and highest for the Jersey. Holstein, and Swiss. Vaporized moisture was converted to Calories by multiplying grams of moisture by 0.58 to obtain the ratios shown in the upper section. They have essentially the same distribution as the curves in the lower section.

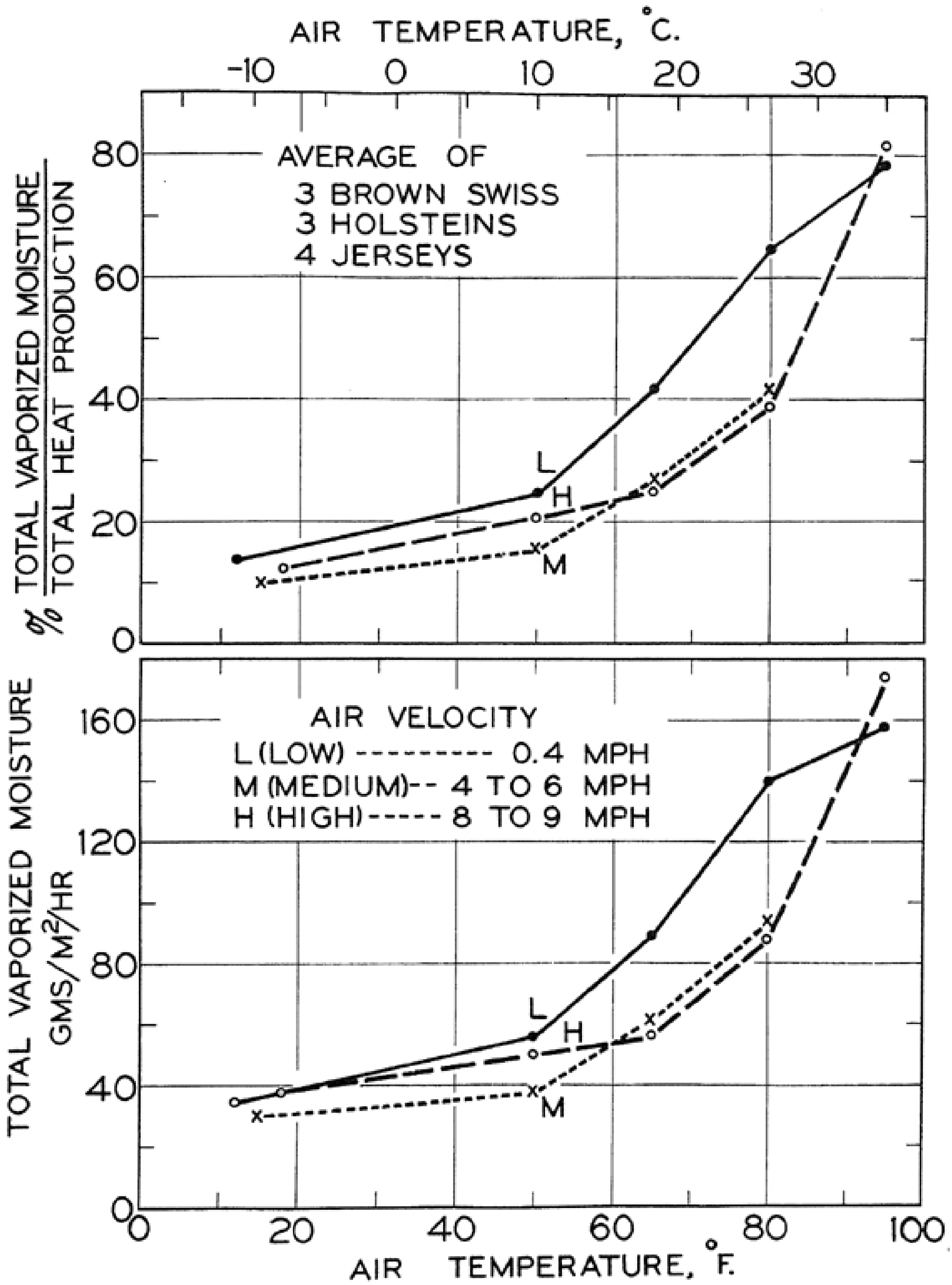

Figure 4 — A summary chart showing average values at each of the air velocities for the three European-evolved (Jersey, Holstein, and Brown Swiss) breeds.

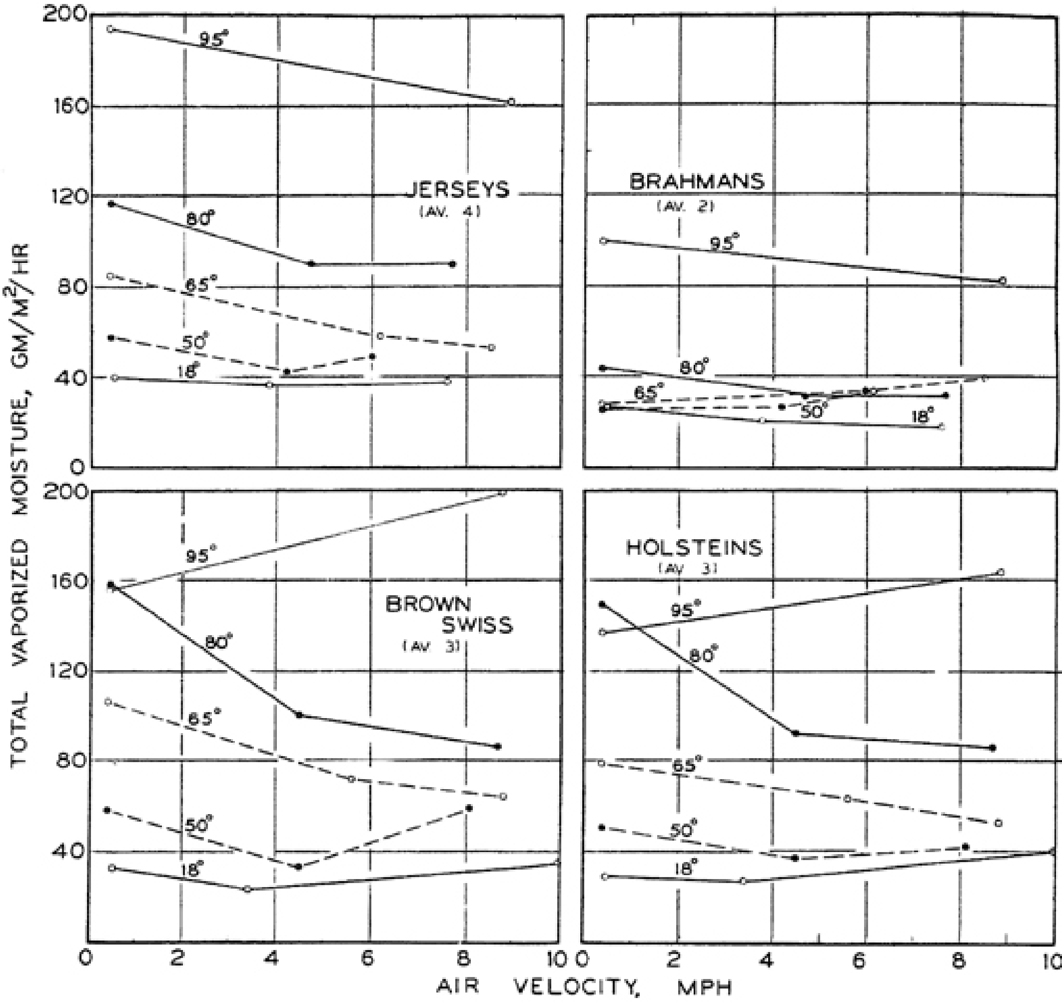

Figure 5 — Vaporized moisture per unit surface area plotted as function of air velocity at each of the several temperatures. Note the greater steepness in the curves from low to medium than from medium to high velocity.

rise. In brief, evaporative cooling operates at a higher temperature range at high than at low air velocity.

2. Little difference in insensible weight loss occurred between medium and high air velocity (Figure 2). When vaporization was plotted against air velocity as in Figure 5, the resulting curves were non-linear (see equation 1).

3. The ratios of vaporized moisture to heat production plotted against temperature have the same form as those for total vaporized moisture (see upper section of Figure 3).

4. The vaporization rate of the Brahmans was less affected by increased air velocity than that of the European cows.

These general features are complicated by detailed peculiarities, as, for example, the difference in vaporization of the Brown Swiss and Holstein on one hand and the Jerseys on the other. The inconsistencies between the 95° F curves of different breeds (Figure 5) may be due to breed differences in range of thermoneutrality, or comfort zone. This is undoubtedly true for the difference between the Brahman and European-evolved cows. It is doubtful, however, whether this explanation holds for the differences between the Holstein and Brown Swiss on one hand and the Jersey curves on the other. We are inclined to minimize the significance of the few data points at 95° F for low air velocity in the Jerseys,[8] because they are not only out of line with the corresponding values for the Swiss and Holsteins in this report but also with the values for the Jerseys in the preceding reports[4] for low air velocity. (The data for the Swiss and Holstein in this report compare favorably with those in the preceding reports.[4])

Figure 3, which shows breed average values, is somewhat confusing due to its many curves. Figure 4 was prepared to simplify and summarize the results on the effect of increased air velocity on vaporization rate in the form of averages of the three European-evolved breeds. Figure 4 indicates that increased velocity has shifted the vaporization curve to the right; it extended maximum vaporization to a higher temperature level. What might be the meaning of the decrease in vaporization with increasing air velocity at 60° and 80° F? It could mean that increasing air velocity increased convective cooling to such an extent that it decreased the skin temperature, as shown in the following section, and thus reduced its vapor pressure and,

[8]The 95°F data at low velocity were meager for the Jerseys. As only two velocity levels were measured, an error in one would give an entirely different curve in Fig. 5. Of the four Jerseys only two were measured at low velocity. The vaporization values were the same at high and low velocity levels for one cow (J-205); in the other (J-548) a much higher value was obtained at low than at high velocity (see Tables 3 and 4). Thus, the value shown at 95°F for low velocity may not be representative of the Jerseys.

therefore, reduced vaporization rate. It could also mean that the increased convective cooling by increasing air velocity reduced the homeothermic need for heat dissipation by evaporative cooling. At 95° F, on the other hand, convective cooling is decreased due to the decline in temperature gradient between body and environment. This decrease in convective cooling tends to be compensated by increase in evaporative cooling.

This situation is analagous to evaporative cooling by sweating in man, with and without a fan at, say, 85° F. Resting man sweats at 85° F but on increased velocity by fanning, convective cooling is increased; therefore, sweating does not begin until perhaps 90° F — the sweating curve is shifted and becomes operative at higher temperature levels.

SURFACE TEMPERATURE

The hair temperature was measured by Hardy radiometer and the skin temperature by touch thermocouple. Both methods have been described in previous reports.[9] The Hardy element was modified for temperatures 65° F and above by placing a calcium fluoride window over the radiometer opening to protect the exposed black body thermopile junction from air currents.

The data on surface temperature are given in Tables 7 and 8 and Figures 6 to 10.

Figure 6 shows that the lower the environmental temperature the greater the depression of surface temperature on increasing wind velocity. At 18° F, an increase in air velocity from 0.4 to 9 mph lowered the hair surface temperature 28° F and the skin temperature 14° F; at 95° F this increase in air velocity lowered the surface temperature only 1° to 2° F. This difference in effect of wind is not surprising because convective cooling depends on the temperature gradient between body surface and environment, and this temperature gradient declined with increasing environmental temperature, causing a corresponding decline in convective cooling.

The temperature gradients between body surface and environment (not shown) are considerably less at the high than at the low air velocity. For example, at 18° F the hair-less-air temperature difference is, roughly, 40° F for low and 10° F for high velocity. As the temperature increases the difference between surface and environmental temperature becomes less and less until at 95° F the difference between hair and air temperature is 4° for low and 1.8° F for high air velocity. Similar results were obtained on the skin-less-air differences; at air temperature 18° F the skin-less-air gradient was 62° F for low and 46° F for high velocity; at 95° F, it was 4.8° F for low and 3.5° F for high velocity.

[9]Univ. Mo. Agric. Exp. Sta. Res. Buls. 481 and 489.

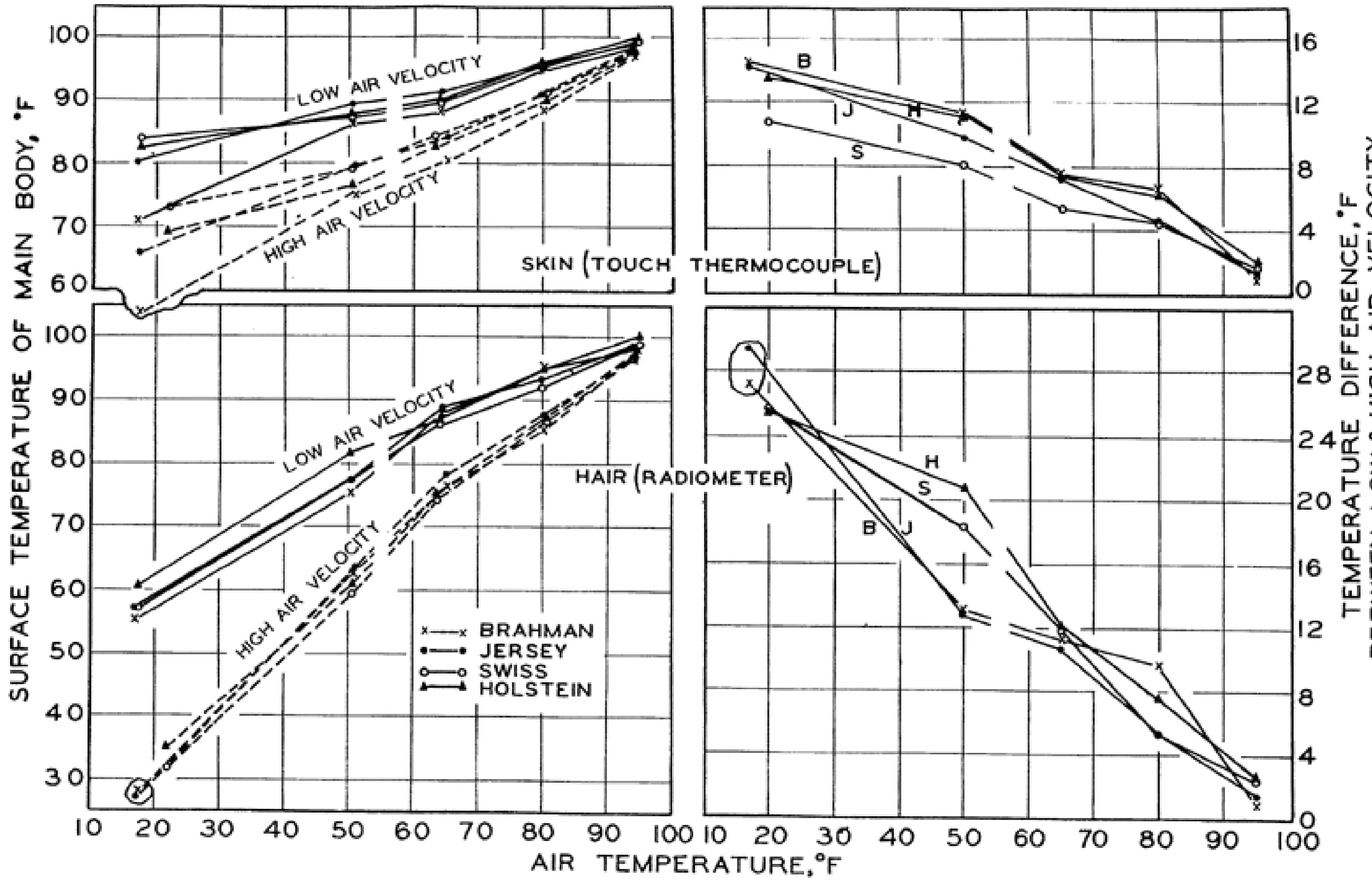

Figure 6 — Breed comparison of skin and hair temperatures at low (continuous curves) and high temperature difference between the two air velocities, plotted against environmental temperature. The (broken curves) air velocities of the main body (average of back, sides, neck, belly, and rear) and the encircled data points were taken with the thermocouple (which gives a somewhat lower reading) rather than with the radiometer.

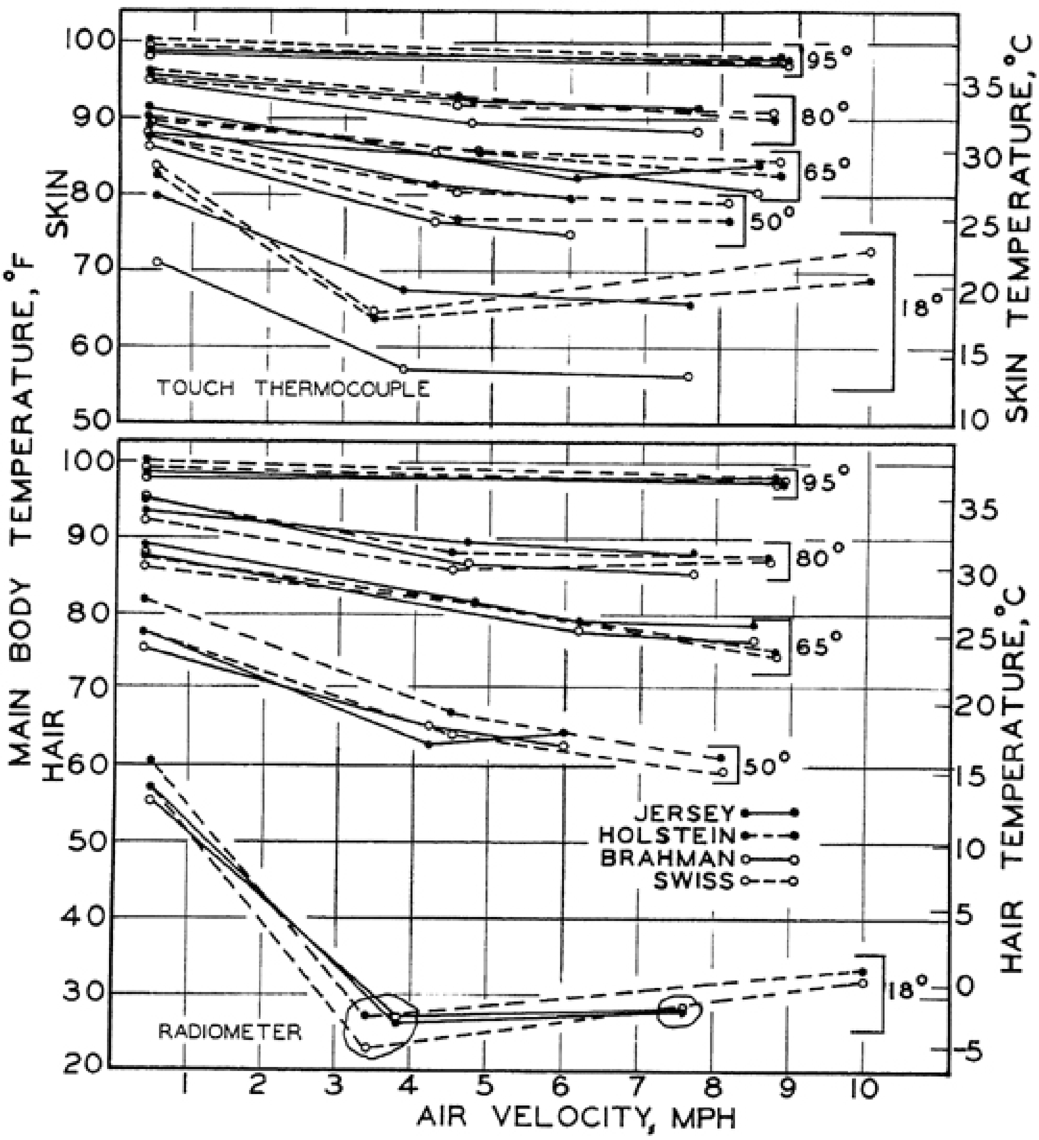

Figure 7 — The same data as the left-hand section of Figure 6, plus data for medium velocity, but plotted as function of air velocity. Note the greater steepness of curves from 0.5 to 5 mph than from 5 to 9 mph. The circled data points were taken with the thermocouple (which gives a somewhat lower reading) rather than with the radiometer.

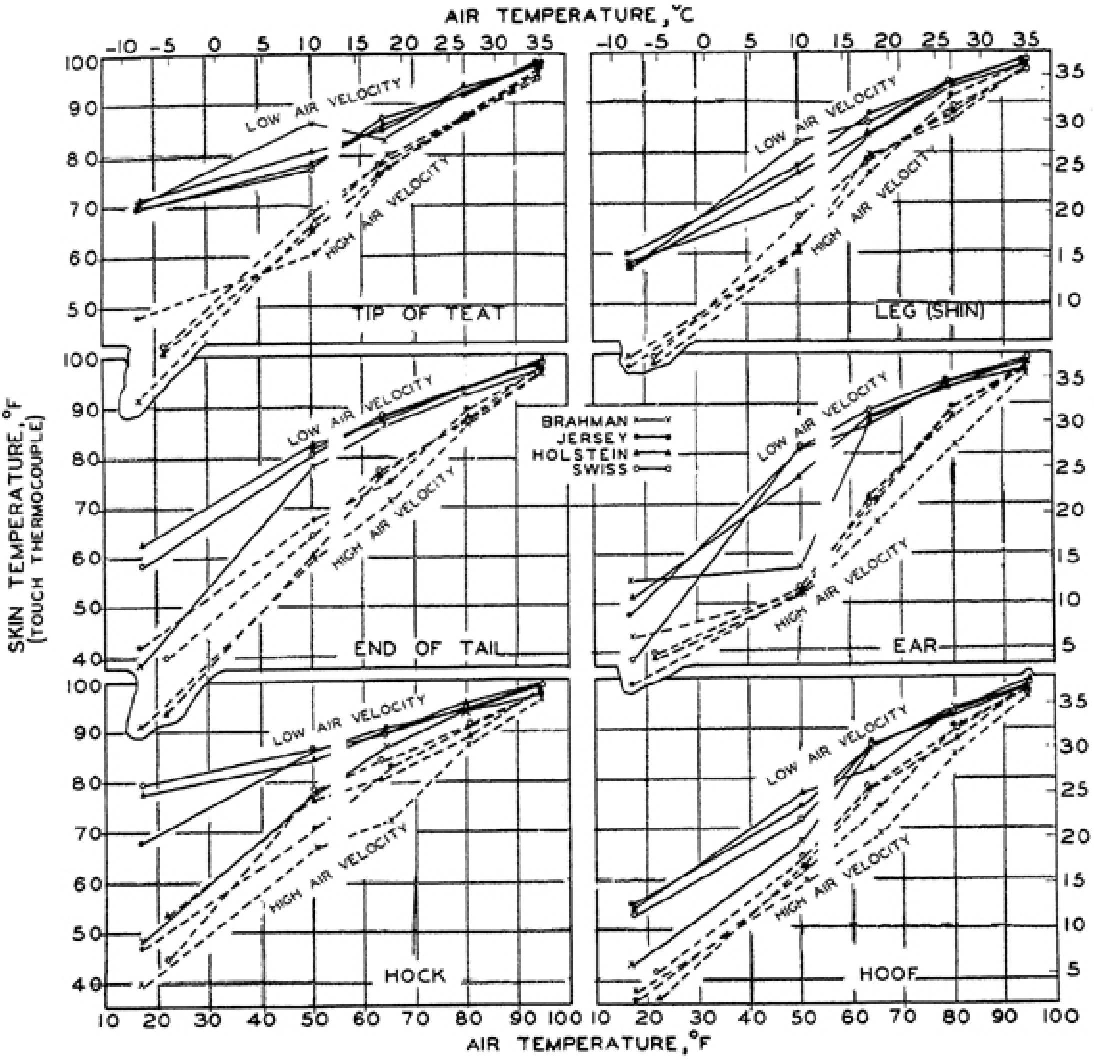

Figure 8 — Skin temperatures of different parts of the body for high and low air velocity for the 4 breeds.

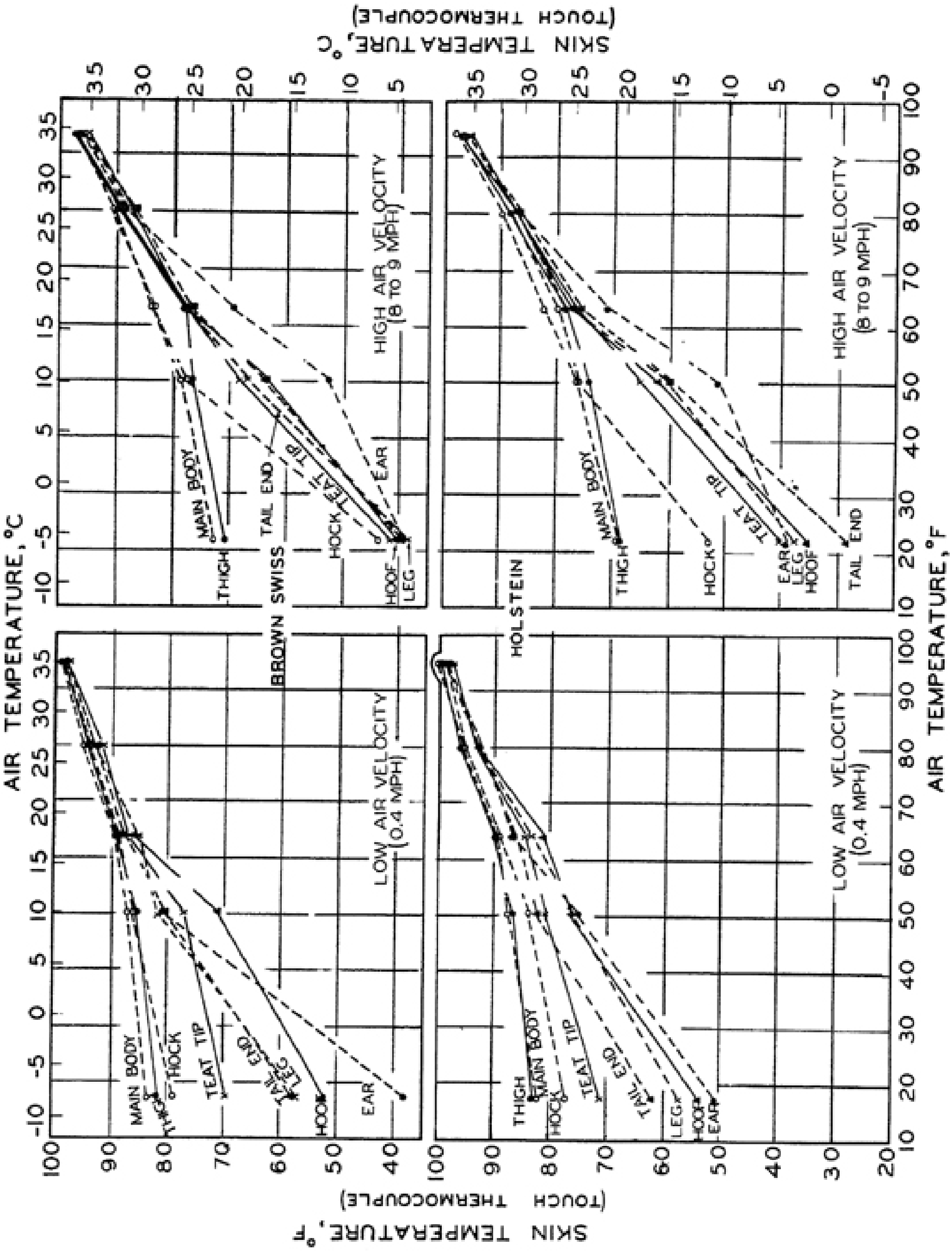

Figure 9.—Comparison of the effects of air velocity on rise of skin temperature of several parts of the body with rising environmental temperature in Brown Swiss (upper half) and Holstein (lower half).

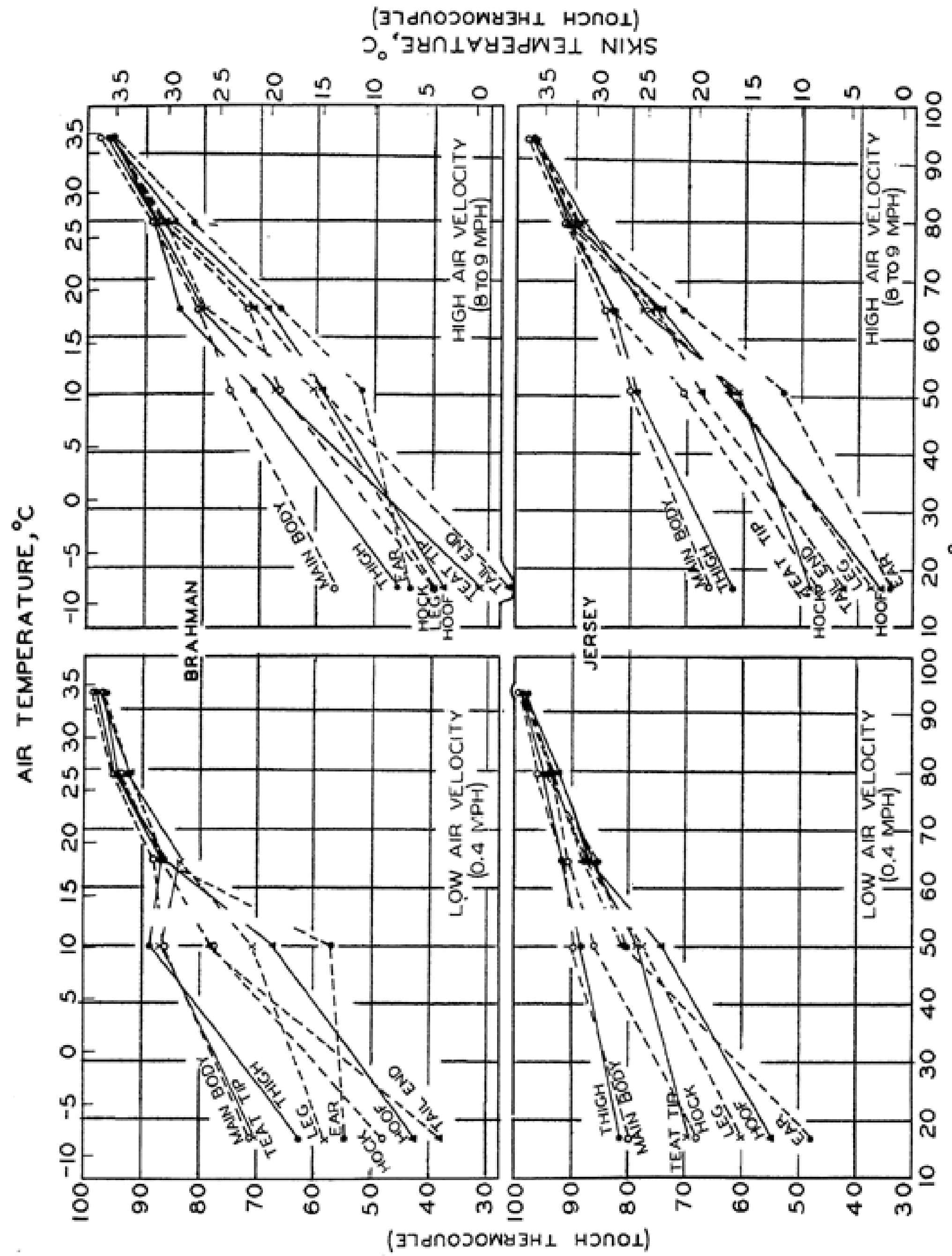

Figure 10 — Same as Figure 9 but for Brahman and Jersey.

Figure 7 shows hair and skin temperatures plotted against air velocity instead of against air temperature. The effect of wind is greater between 0.4 and 4 mph than between 4 and 9 mph, and the lower the air temperature the greater the slope of the curves. The rise in the slopes of the curves at 18° F on increasing wind from medium to high velocity probably reflects the difference in temperature conditions rather than increase of wind. The air temperature was about 5° F (for Jerseys and Brahmans) to 10° F (for Holstein and Swiss) lower at medium than at high air velocity (Tables 7 and 8).

The effects of high and low air velocities at various air temperatures on the surface temperatures of the main body (average of six measurements) are shown in Figure 6; similar effects on the skin temperature of other parts of the body are given in Figure 8. An interesting feature of Figure 8 is that the skin temperature, especially of the hock and hoof, is considerably lower in the Brahmans than in the other breeds. Similar differences are shown in Figure 6 for the main body temperature.

Comparisons of the skin temperatures of the main body with the skin temperature of the terminal parts are given in Figure 9 for Swiss and Holstein and in Figure 10 for Brahman and Jersey cows. While there is considerable divergence of the curves between 40° and 80° F air temperature, the curves for all parts converge at 95° F.

The ear temperatures for the Brahmans indicate irregularities and differences from those of European-evolved cows that cannot be explained, perhaps, because of differences in ear size, shape, and behaviorial conditions. The temperature of the Brahman ear is equal to, or lower than, the temperature of the ears of the other breeds at all temperatures except 18° F. At this temperature it is considerably higher (Figure 8). Likewise, in comparison to the skin temperature of other parts of the body, the ear temperature of the Brahman is conspicuously lower, especially at high air velocity, at all temperatures except 18° F. The Brahmans' objections to being touched around the ears, especially at the cold temperatures, undoubtedly introduced errors in the measurements that are reflected in the irregularities of the curves. One author feels that near 20° F the homeothermic mechanisms involved must have failed because the ear tips of one Brahman were slightly frozen. This condition was not observed by the veterinarian, herdsman or other authors. As expected, because of the large surface area, low blood supply, and difficulties in making the measurements, the lowest and also the most erratic surface temperatures were observed at the tip of the teat and end of tail, particularly on the Brahman (Tables 7 and 8).

SUMMARY

Data in tabular and graphic forms are presented on the effects of low, medium, and high air velocities (0.4, 4 to 6, and 8 to 9 mph) at 18,° 50,° 65,° 80,° and 95° F on total evaporative cooling (and insensible weight loss) and on surface temperature (hair and skin) of lactating Brown Swiss, Holstein, Jersey, and non-lactating Jersey and Brahman cows.

When plotted against environmental temperature, vaporization at low air velocity gradually increases with increasing temperature from 18° to 65,° then more rapidly to 80° F when maximum vaporization is reached. But when vaporization at high velocity is similarly plotted the rapid increase in vaporization begins nearer 80° F and continues up to 95° F. In other words, increasing air velocity shifts the vaporization curve to the right, extending the range of physiologically tolerable temperature to a higher environmental temperature.

Increasing air velocity reduced the skin and hair temperature roughly in proportion to the decline in environmental temperature. The lowering of the surface temperature with increasing air velocity was due to increased convective (rather than evaporative) cooling since increased air velocity did not increase the vaporization rate except at 95° F.

The effect of increasing velocity on evaporative cooling and surface temperature was non-linear, greater on increasing the wind from 0.4 to 5 than from 5 to 9 mph.

TABLES

TABLE 1 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION IN LACTATING HOLSTEIN CATTLE
February 23 to May 29, 1952 (arranged by time sequence)

Dry Bulb Temp. °F	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible weight loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. Total Heat Production*, Cal.
				Holstein 144				
66	Low (Beginning)	61	4	597	625	527	98	39
64	High	72	4	574	435	365	69	27
65	Medium	69	4	562	365	288	55	24
63	Low	70	1	573	375	341	65	31
79	Medium	56	3	571	435	331	63	27
81	High	50	4	568	399	342	65	26
81	Low	57	3	569	973	899	172	78
96	High	45	2	550	980	889	170	65
95	Low	64	2	533	935	844	167	74
				Holstein 154				
65	Low (Beginning)	61	4	635	711	680	122	40
65	High	69	3	615	383	305	56	24
65	Medium	70	3	616	480	402	73	28
65	Low	70	1	617	650	540	99	39
79	Medium	55	3	617	813	692	126	49
81	High	50	4	623	725	620	113	42
81	Low	56	3	627	953	828	150	50
96	High	46	2	598	1050	987	183	78
95	Low	64	2	570	775	637	122	74
				Holstein 118				
66	Low (Beginning)	48	3	602	543	459	85	31
65	High	75	3	581	263	180	34	13
65	Medium	73	3	576	407	298	57	21
65	Low	72	1	584	450	381	72	29
78	Medium	56	3	577	545	460	87	34
82	High	49	3	570	497	419	80	30
80	Low	55	2	555	750	662	128	62
95	High	51	2	524	765	699	140	52
94	Low	61	2	520	725	603	121	59

*Metabolic weight loss and heat production from Missouri Research Bulletin 552; surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 2 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION IN LACTATING BROWN SWISS CATTLE
February 23 to May 29, 1952 (arranged by time sequence)

Dry Bulb Temp. °F	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Weight Loss Grams per hour	Vaporized Moisture* Grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. / Total Heat Production*, Cal.
				Brown Swiss 47				
67	Low (Beginning)	57	2	485	560	496	104	47
64	High	69	2	482	325	265	56	25
65	Medium	68	3	486	385	312	65	30
66	Low	72	1	494	490	423	87	39
78	Medium	55	3	505	383	326	66	31
82	High	51	2	491	398	344	71	32
80	Low	55	2	489	690	635	132	57
95	High	51	2	496	775	718	148	75
94	Low	61	2	471	750	677	144	76
				Brown Swiss 22				
65	Low (Beginning)	61	4	600	699	610	113	47
65	High	73	3	583	390	311	59	28
66	Medium	71	1	589	400	350	66	30
66	Low	70	2	590	670	621	116	62
79	Medium	55	3	580	621	542	102	42
81	High	48	4	583	520	426	80	35
81	Low	58	3	583	933	881	116	82
96	High	45	2	577	1280	1180	224	102
96	Low	63	2	569	955	811	155	84
				Brown Swiss 23				
66	Low (Beginning)	59	3	648	687	661	117	45
64	High	85	2	613	475	420	77	27
64	Medium	74	3	591	432	361	68	26
65	Low	70	1	598	660	615	114	53
78	Medium	55	3	588	760	697	131	48
82	High	47	3	588	663	593	111	47
80	Low	55	2	600	1040	970	180	78
96	High	46	2	585	1250	1192	224	105
95	Low	64	2	547	920	862	168	--

*Metabolic weight loss and heat production from Missouri Research Bulletin 552; surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 3 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION IN DRY JERSEY CATTLE
February 23 to May 29, 1952 (arranged by time sequence)

Dry Bulb Temp. °F	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Weight Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. / Total Heat Production*, Cal.
				Jersey 548				
66	Low (Beginning)	64	4	405	540	470	109	54
64	Medium	73	4	412	354	278	64	33
63	Low	74	2	419	445	393	89	41
65	High	71	4	422	338	289	65	36
79	High	51	3	423	392	352	79	42
80	Medium	50	4	434	435	383	85	50
77	Low	62	3	427	623	586	132	73
92	Low	41	2	444	965	897	197	105
94	High	46	2	430	578	532	119	78
				Jersey 549				
66	Low (Beginning)	65	3	408	490	421	97	48
64	Medium	73	4	412	365	308	70	36
64	Low	74	2	422	420	357	81	34
64	High	73	2	426	298	239	54	32
80	High	50	3	439	543	490	108	64
80	Medium	53	4	444	531	464	102	58
77	Low	72	2	448	525	456	100	55
95	Low	--	-	---	---	---	---	--
95	High	50	2	452	875	821	178	100

*Metabolic weight loss and heat production from Missouri Research Bulletin 552; surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 4 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION IN LACTATING JERSEY CATTLE
February 23 to May 29, 1952 (arranged by time sequence)

Dry Bulb Temp. °F	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Weight Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. / Total Heat Production*, Cal.
				Jersey 205				
65	Low (Beginning)	64	3	458	610	547	118	78
64	Medium	75	4	437	290	233	52	21
64	Low	74	2	439	545	469	104	63
65	High	74	3	427	320	232	52	23
80	High	51	3	434	443	370	82	37
79	Medium	53	3	441	487	419	92	45
78	Low	69	2	435	610	537	119	53
96	Low	34	1	415	870	833	190	83
94	High	51	2	431	895	842	188	95
				Jersey 994				
67	Low (Beginning)	74	3	378	375	323	78	33
64	Medium	78	3	372	260	192	47	20
63	Low	74	2	369	335	268	65	26
65	High	74	3	375	227	174	42	17
77	High	53	2	365	445	367	90	39
80	Medium	50	4	373	400	336	81	38
77	Low	69	2	366	535	473	116	61
95	Low	--	-	---	---	---	---	--
94	High	48	2	359	725	653	161	70

*Metabolic weight loss and heat production from Missouri Research Bulletin 552; surface area in square meters equal 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 5 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION IN BRAHMAN CATTLE
February 23 to May 29, 1952 (arranged by time sequence)

Dry Bulb Temp. °F	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Weight Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. Total Heat Production*, Cal.
				Brahman 209				
68	Low (Beginning)	55	2	499	298	246	45	25
64	Medium	77	4	497	250	197	36	25
64	Low	74	2	496	233	165	30	21
65	High	73	4	501	267	223	41	22
78	High	51	4	459	164	162	31	28
80	Medium	50	4	438	120	104	23	20
78	Low	67	2	481	255	217	41	32
92	Low	41	2	484	495	448	84	65
94	High	46	2	482	470	437	82	60
				Brahman 189				
64	Low (Beginning)	77	2	464	275	234	45	34
64	Medium	74	3	480	220	171	32	22
64	Low	74	2	484	173	133	25	20
65	High	73	3	483	240	201	38	30
80	High	50	3	482	210	177	33	28
80	Medium	54	2	477	250	215	40	39
78	Low	61	2	487	290	258	48	44
97	Low	36	1	494	670	633	117	90
95	High	50	2	491	480	451	84	66

*Metabolic weight loss and heat production from Missouri Research Bulletin 552. Surface area of Brahman cows assumed to be 12 percent greater than for Jersey or Holstein cows (see pape 14 of Missouri Research Bulletin 464). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 6 -- INSENSIBLE WEIGHT LOSS AND TOTAL MOISTURE VAPORIZATION FOR 50° AND 18° F. TEMPERATURES
October 25, 1951, to February 14, 1952 (arranged by time sequence)

Dry Bulb Temp. °F.	Air Velocity	Relative Humidity %	Number of Obser-vations	Body Weight Kg.	Insensible Weight Loss grams per hour	Vaporized Moisture* grams per hr.	Vaporized Moisture* gm./sq.m. per hr.	Vaporized % Moisture, Cal. Total Heat Production*, Cal.
			Holstein (Average of 3)					
51	Low (Beginning)	65	4	565	350	232	44	18
50	Medium	65	7	563	289	194	37	14
49	Low	67	7	558	364	265	51	20
50	High	58	11	555	338	220	42	15
18	Medium	58	8	557	261	143	27	9
13	Low	59	6	566	258	152	29	10
19	High	56	10	556	287	207	40	12
			Brown Swiss (Average of 3)					
50	Low (Beginning)	67	3	498	252	160	33	15
52	Medium	65	6	514	224	163	33	14
50	Low	66	7	513	358	288	58	26
50	High	61	8	510	375	289	59	24
18	Medium	60	7	509	206	111	23	8
11	Low	57	5	504	226	156	32	14
19	High	57	9	509	246	173	35	12
			Jersey (Average of 4)					
48	Low (Beginning)	63	3	396	252	168	40	18
51	Medium	63	10	393	252	181	43	19
48	High	66	5	383	266	205	49	24
50	Low	63	12	402	330	254	59	28
11	Medium	61	7	413	232	163	37	13
18	High	54	7	414	228	165	38	13
12	Low	59	12	420	250	177	40	17
			Brahman (Average of 2)					
46	Low (Beginning)	64	1	461	220	183	35	27
51	Medium	62	7	478	201	144	27	16
48	High	67	4	487	246	186	34	22
48	Low	66	4	488	199	140	26	17
10	Medium	63	4	488	184	114	21	7
17	High	58	4	482	174	98	18	5
12	Low	62	6	479	212	142	27	12

*Metabolic weight loss and heat production from Missouri Research Bulletin 552. For European breeds, surface area in square meters equals 0.15 x (weight in Kg.)$^{0.56}$ (see S. Brody, "Bioenergetics and Growth," Reinhold, 1945, page 360); for Brahman cows the surface area is assumed to be 12 percent greater than for Jersey or Holstein cows (see page 14 of Missouri Research Bulletin 464). Vaporized moisture was converted to calories by multiplying grams of moisture by 0.58.

TABLE 7 -- EFFECT OF AIR VELOCITY ON THE SKIN AND HAIR TEMPERATURE OF JERSEY AND BRAHMAN COWS
(Each value consists of an average of one measurement for each cow)

Air Velocity mph	Air Temp. °F	Date of Measurement	Radiometer Chamber Surface	Main Body Temperature* Radiometer Hair	Main Body Temperature* Thermocouple Hair	Main Body Temperature* Thermocouple Skin	Skin Thermocouple Measurements Thigh	Hock	Hoof	End of Tail	Tip of Teat	Tip of Ear	Leg (shin)	Hair Temp. Radiometer Leg
						Jersey (Av. of 4)								
0.5	16.9	Feb. 4	20.5	57.1	----	80.0	81.5	67.8	54.8	----	69.5	47.5	60.0	----
3.8	13.5	Jan. 10	----	----	26.3	67.5	64.7	42.2	28.0	32.6	55.5	45.8	30.4	----
7.6	17.4	Jan. 23	----	----	27.6	65.8	61.4	46.4	35.4	42.0	47.8	33.8	37.6	----
0.4	50.4	Dec. 13	51.3	77.4	----	89.5	88.4	86.0	74.1	81.2	78.4	80.6	77.4	70.8
4.2	51.1	Nov. 16	51.4	62.9	----	81.3	81.3	68.3	53.7	68.4	67.9	59.2	60.7	46.4
6.0	51.2	Nov. 27	52.0	64.6	----	79.8	78.6	70.3	61.8	67.1	60.6	52.4	61.4	54.8
0.4	64.6	Mar. 25	65.9	89.1	----	91.5	91.6	90.5	86.9	87.8	86.2	85.4	87.4	84.8
6.2	63.7	Mar. 10	65.2	79.0	----	82.5	84.4	81.6	75.9	78.5	76.8	76.5	75.9	74.0
8.5	65.4	May 31	65.6	78.4	72.4	84.3	82.8	82.6	74.2	74.8	77.5	70.4	75.9	69.2
0.4	79.9	May 14	80.4	93.4	93.2	95.8	94.8	93.6	92.2	93.2	92.2	94.0	93.6	90.1
4.7	79.5	Apr. 30	----	89.4	87.5	92.4	92.2	91.8	88.5	89.4	89.5	84.6	89.4	86.4
7.7	80.3	Apr. 24	----	88.1	85.5	91.2	91.0	90.4	90.2	89.4	88.1	89.0	91.0	88.6
0.4	94.0	May 19	93.1	98.7	98.2	99.3	98.8	98.8	98.0	98.1	98.4	97.9	98.1	97.5
8.9	94.5	May 26	94.7	97.3	96.2	98.0	97.5	97.2	97.6	97.0	97.0	96.8	97.1	96.6
						Brahman (Av. of 2)								
0.5	16.9	Feb. 4	21.7	55.3	----	71.1	62.5	48.0	42.5	38.0	70.5	54.5	58.0	----
3.8	13.5	Jan. 10	----	----	27.0	57.5	51.1	38.4	34.4	30.3	45.0	37.4	33.4	----
7.6	17.4	Jan. 23	----	----	28.0	56.6	45.8	39.4	37.4	26.0	31.3	43.6	39.4	----
0.4	50.4	Dec. 13	50.8	75.4	----	86.3	88.6	77.6	66.9	77.8	86.6	57.0	70.5	63.6
4.2	51.1	Nov. 16	51.7	65.2	----	76.4	75.9	64.3	52.8	52.3	78.3	52.4	56.2	56.6
6.0	51.2	Nov. 27	51.5	62.4	----	75.1	71.1	66.5	59.0	59.2	67.0	51.9	60.4	54.4
0.4	64.6	Mar. 25	65.2	87.8	----	88.0	86.5	86.8	86.0	86.0	83.2	86.8	83.5	82.8
6.2	63.7	Mar. 10	64.7	77.6	----	85.4	79.2	78.5	69.8	75.5	83.0	76.5	75.8	73.5
8.5	65.4	Mar. 31	65.4	76.5	----	80.6	84.0	72.0	68.5	70.8	80.0	66.2	79.5	67.5
0.4	79.9	May 14	80.2	95.0	93.5	95.0	94.8	93.8	94.0	92.0	92.5	93.5	92.8	91.0
4.7	79.5	Apr. 30	-----	86.6	84.7	89.6	89.0	86.5	83.8	83.0	89.5	85.2	86.2	83.8
7.7	80.3	Apr. 23	----	85.3	83.2	88.4	88.0	87.0	84.5	86.2	87.5	81.5	86.2	82.8
0.4	94.0	May 19	92.5	98.2	97.5	98.4	98.2	97.2	96.8	96.8	97.8	96.5	97.0	96.2
8.9	94.5	May 26	94.4	97.5	96.4	97.5	96.8	96.2	96.2	96.2	96.0	95.5	96.8	96.2

*Average of six spot measurements: back, belly, right and left sides of body, neck and rump.

TABLE 8 -- EFFECT OF AIR VELOCITY ON THE SKIN AND HAIR TEMPERATURE OF HOLSTEIN AND BROWN SWISS COWS
(Each value consists of an average of one measurement for each cow)

Air Velocity mph	Air Temp. °F	Date of Measurement	Radiometer Chamber Surface	Main Body Temperature* Radiometer Hair	Main Body Temperature* Thermocouple Hair	Main Body Temperature* Thermocouple Skin	Skin Thermocouple Measurements Thigh	Hock	Hoof	End of Tail	Tip of Teat	Tip of Ear	Leg (shin)	Hair Temp. Radiometer Leg
						Holstein (Av. of 3)								
0.5	17.6	Jan. 21	22.6	60.5	----	82.5	83.2	77.6	54.0	62.1	71.3	51.1	57.5	----
3.4	11.5	Jan. 9	----	----	27.0	63.7	60.1	50.8	31.3	33.2	45.9	40.9	28.9	----
10.0	22.1	Feb. 5	20.5	35.0	33.3	69.0	69.0	53.0	35.7	28.7	40.7	38.9	38.0	27.8
0.4	50.4	Nov. 30	53.2	81.7	----	87.8	87.2	84.0	76.8	82.5	80.9	75.1	76.1	71.3
4.5	50.6	Nov. 20	51.8	67.1	----	77.1	80.1	71.9	54.1	55.9	57.3	53.4	56.5	55.3
8.1	50.6	Dec. 10	53.6	61.0	----	76.7	74.6	76.3	62.0	60.1	65.2	51.5	60.6	55.8
0.4	64.2	Apr. 4	65.5	87.4	84.9	90.1	90.5	89.5	81.7	86.7	85.0	87.2	83.5	79.7
4.8	64.9	Apr. 3	65.2	81.1	75.5	85.7	82.0	82.5	70.2	79.6	81.3	74.8	74.8	72.0
8.8	63.6	Mar. 11	64.1	75.3	----	82.7	78.7	80.3	77.7	76.0	76.7	71.3	78.8	73.0
0.4	80.2	May 13	80.3	95.0	94.1	96.3	96.5	95.5	93.5	93.3	93.8	93.0	93.5	90.0
4.5	80.0	Apr. 15	----	88.1	86.9	93.1	91.8	90.5	86.7	89.3	88.5	87.8	89.5	84.8
8.7	80.7	Apr. 29	----	87.5	85.3	90.1	88.7	88.8	87.8	87.0	87.5	87.2	87.7	85.2
0.4	95.0	May 28	94.0	100.2	99.0	100.2	100.2	99.3	99.8	99.2	97.8	98.3	98.7	98.5
8.8	94.2	May 21	94.6	97.7	96.2	98.2	97.7	97.8	98.0	96.8	95.7	96.8	96.8	96.8
						Brown Swiss (Av. of 3)								
0.5	17.6	Jan. 21	21.8	57.2	----	83.9	82.1	79.2	52.6	58.0	39.9	38.5	57.5	----
3.4	11.5	Jan. 9	----	----	22.7	64.7	61.3	55.1	39.3	31.0	35.7	33.2	44.4	----
10.0	22.1	Feb. 5	19.7	31.6	31.8	73.2	71.3	44.3	41.0	39.7	42.0	39.7	39.3	23.5
0.4	50.4	Nov. 30	52.8	77.6	----	87.4	85.7	86.3	71.3	80.4	77.3	81.0	82.1	74.6
4.5	50.6	Nov. 20	51.6	64.2	----	80.6	78.0	71.8	60.5	70.9	69.8	53.2	64.8	56.9
8.1	50.6	Dec. 10	52.6	59.2	----	79.3	77.2	78.1	63.7	64.0	68.9	53.1	67.5	55.8
0.4	64.2	Apr. 4	64.9	86.3	83.6	89.8	89.7	89.2	86.5	88.0	87.5	88.5	85.7	84.2
4.8	64.9	Apr. 3	65.1	81.1	74.3	86.0	81.2	81.8	77.2	81.3	80.7	77.5	80.3	77.2
8.8	63.6	Mar. 11	64.1	74.4	----	84.4	78.2	83.8	77.7	76.8	78.0	69.8	78.0	73.3
0.4	80.2	May 13	79.9	92.3	92.9	95.6	94.7	94.5	93.2	93.3	92.2	94.3	93.7	89.7
4.5	80.0	Apr. 15	----	85.9	85.6	92.0	91.3	91.8	89.2	90.5	88.7	89.2	89.7	84.0
8.7	80.7	Apr. 29	----	87.0	84.7	91.2	89.8	91.2	89.7	86.7	87.8	89.0	88.8	85.7
0.4	95.0	May 28	94.0	99.2	98.9	99.6	99.3	99.0	98.8	98.2	98.2	98.5	98.3	98.3
8.8	94.2	May 21	94.6	96.9	95.6	97.9	98.0	97.2	97.5	96.7	95.5	96.8	96.3	96.2

*Average of six spot measurements: back, belly, right and left sides of body, neck and rump.