RESEARCH BULLETIN 600 FEBRUARY, 1956

UNIVERSITY OF MISSOURI COLLEGE OF AGRICULTURE
AGRICULTURAL EXPERIMENT STATION
J. H. LONGWELL, *Director*

Environmental Physiology and Shelter Engineering

With Special Reference to Domestic Animals

XXXVII. Moisture Vaporization by Jersey and Holstein Cows During Diurnal Temperature Cycles as Measured with a Hygrometric Tent

R. G. YECK AND H. H. KIBLER

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

(Publication authorized February 1, 1956)

COLUMBIA, MISSOURI

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ACKNOWLEDGMENTS

This is a part of a cooperative investigation between the Departments of Agricultural Engineering and Dairy Husbandry of the Missouri Agricultural Experiment Station, University of Mo., and Agricultural Engineering Research Branch, Agricultural Research Service, United States Department of Agriculture. Assistance was also provided by the North Central Regional Project NC-23 in the development of the hygrometric tent. The bulletin reports on Department of Dairy Husbandry Research Project 125, "Climatic Factors." Acknowledgment is made to A. C. Ragsdale and Samuel Brody, Department of Dairy Husbandry for their cooperation and counsel in the dairy and physiological aspects, M. M. Jones, Department of Agricultural Engineering for cooperation and counsel in the engineering aspects and to H. J. Thompson of the United States Department of Agriculture who suggested the use of the hygrometric tent and assisted in the initial aspects of its design.

Environmental Physiology and Shelter Engineering

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XXXVII. MOISTURE VAPORIZATION BY JERSEY AND HOLSTEIN COWS DURING DIURNAL TEMPERATURE CYCLES AS MEASURED WITH A HYGROMETRIC TENT

R. G. YECK AND H. H. KIBLER

INTRODUCTION

Evaporative cooling is an important means of heat dissipation by cattle. With air and surface temperatures near or above the body temperatures, it becomes their primary means of heat dissipation. The resultant change in the total vaporization rate is a measure of the evaporative cooling ability of an animal. The changes in vaporization rate within and between some diurnal temperature cycles was the subject of this study.

The preceding total vaporization studies with cattle at the Missouri Agricultural Experiment Station were made by an insensible weight loss method[1] wherein insensible weight loss was measured with a very sensitive scale. Total vaporized moisture was then computed by subtracting metabolic weight loss (the difference in weight between the oxygen consumed and the weights of carbon dioxide and methane produced) from the insensible weight loss. The major difficulties with this system were: (1) sampling and analysis of exhaled air were required; (2) this assumed that all of the carbon dioxide and methane produced by the animals appeared in exhaled air; and (3) the weighing scale lacked mobility and required moving the animals from the test room into a corridor wherein control of environmental conditions was difficult.

This bulletin reports a unique method for direct determination of the total vaporization rate. No metabolic measurements were required and the apparatus was used inside one of the test rooms.

EXPERIMENTAL DESIGN

Three Holstein and three Jersey cows, midway in lactation, were stanchioned in Test Room I of the Psychroenergetic Laboratory at the Missouri Agricultural Experiment Station. Water and chopped alfalfa hay were available to the cows at all times. Two pounds of dried beet pulp were fed daily and grain was fed according to milk production. The Jerseys received

1 pound of grain per 3 pounds of milk and the Holsteins received 1 pound per 4 pounds of milk. Periods for grain feeding and milking were scheduled twice daily at about 5 a.m. and 3 p.m.

The stable temperatures were controlled by conditioning the air used in ventilation. Four diurnal temperature rhythms simulating some daily temperature cycles were used. In consecutive order they were: a 5-week low temperature range of 10 to 40° F; a 5-week medium range of 40 to 70° F; a 2¼-week extreme range of 60 to 110° F; and a 3-week high range of 70 to 100° F. Like outdoors, the maximum temperatures occurred in the early afternoon between 3 and 4 p.m. with the minimums in the early morning between 5 and 7 a.m. A plot of hourly average air and dew point temperatures for each week are shown along with vaporization rates in Figures 3, 4, 5, and 6.

Moisture vaporization measurements were made in Test Room II. This necessitated leading the cattle from one room to the other. The temperatures in both rooms as well as the alleyways were conditioned approximately alike. Other details of animal productivity and the laboratory are reported in a companion bulletin. [2, 3]

THE HYGROMETRIC TENT

The method devised for measuring the total vaporization rate of cattle was given the name of "a hygrometric tent for determining animal vaporization rates." Mr. H. J. Thompson, an agricultural engineer with the United States Department of Agriculture, suggested the use of this device and assisted with the initial aspects of its design. Basically, the device was a plastic canopy or tent of sufficient size to enclose a 1500 pound cow. A measured quantity of air was exhausted from the front of the tent near the cow's head and air was supplied through openings in the rear. The moisture content (pounds of water per pound of dry air) of both the supply and the exhaust air was measured. The difference between the moisture content of incoming and exhaust air was then multiplied by the flow rate of the exhaust air (pounds per hour).

Figure 1 is a schematic diagram of the device. Critical considerations were: (1) a vapor tight enclosure; (2) sufficient air exchange; (3) measurement of the rate of air exhange; and (4) vapor pressure measurement. Figure 2 is a photograph of the tent in use.

The vapor tight enclosure was provided by a polyethylene plastic canopy stretched over a frame of ½ in. electrical conduit and 2 in. x 4 in. welded wire fencing. The bottom edges of the plastic were taped to a 2 in. x 8 in. plank extending from the gutter to the manger and to varnished plywood sides around the manger. Caulking compound provided a vapor seal between the wood and concrete. The stall platform was varnished and covered

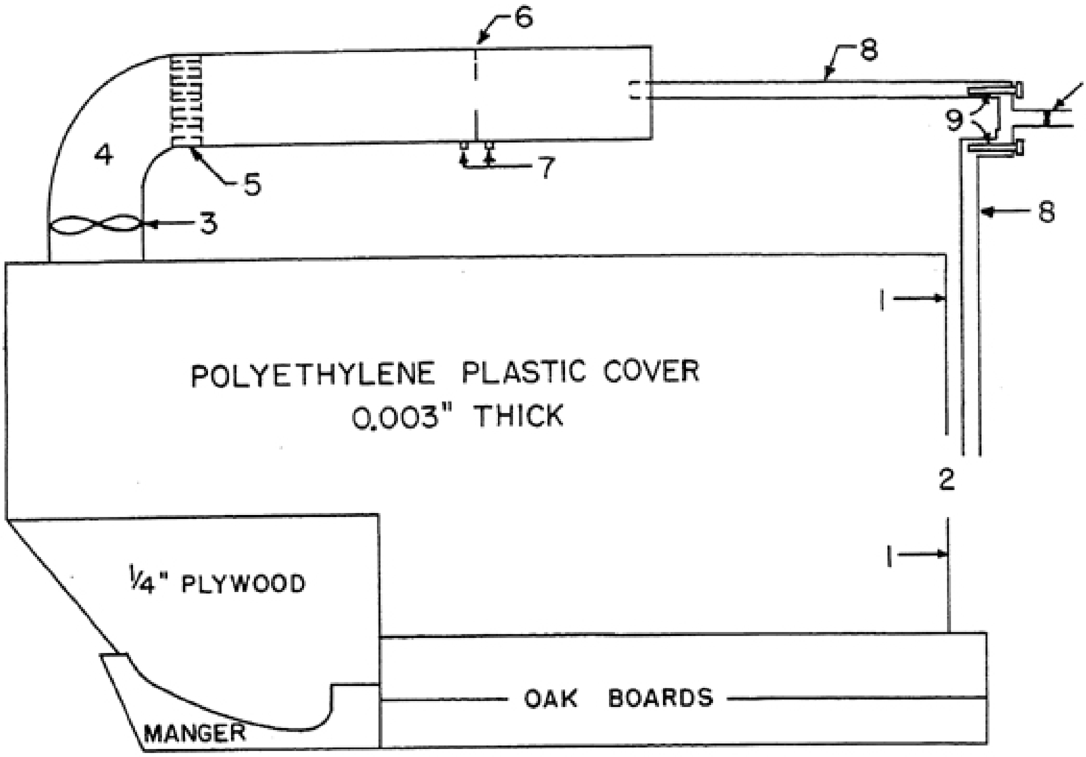

Figure 1.—Schematic diagram of the hygrometric tent as used in the 1954 diurnal tests. The polyethylene plastic cover was supported by a ½ in. frame of electrical conduit. The cow was admitted by lifting the rear flap (1). Air was drawn through a 200-square inch hole (2) centered in the back flap by a propeller type fan located in a 12 in. duct (4). Air turbulence in the duct was reduced by a 1 in. x 3 in. egg crate type straightener (5) and air volume was measured by measuring the pressure drop across a 6 in. orifice (6) with flange type taps (7). Samples of intake and exhaust air were continuously drawn through 2 in. flexible rubber hoses (8) over lithium chloride type hygrometer elements (9) by a small exhaust fan (10). The oak boards serve as a partition between stalls.

with a rubber mat. The 10 square feet of manger area was untreated and a source of some error due to moisture permeability.

Urine and feces were trapped in a bucket and immediately removed from the tent. Saliva produced during high temperatures was trapped under oil in a tank to retard vaporization.

A 12 in. propeller type fan powered by a 100 watt, 1725, r.p.m. motor was mounted in a 12¾ in. diameter duct to exhaust the air from the tent. Sufficient air exchange was provided so that no more than a 6° F. rise in dew point occurred within the bag. Although no change in dew point would be desirable from the standpoint of environmental change, a minimum change of 3° F. dew point was necessary in order to measure the gradient with less than 10 percent error. The capacity of the blower was also governed by the desired air velocities inside of the bag (about 50 feet per minute).

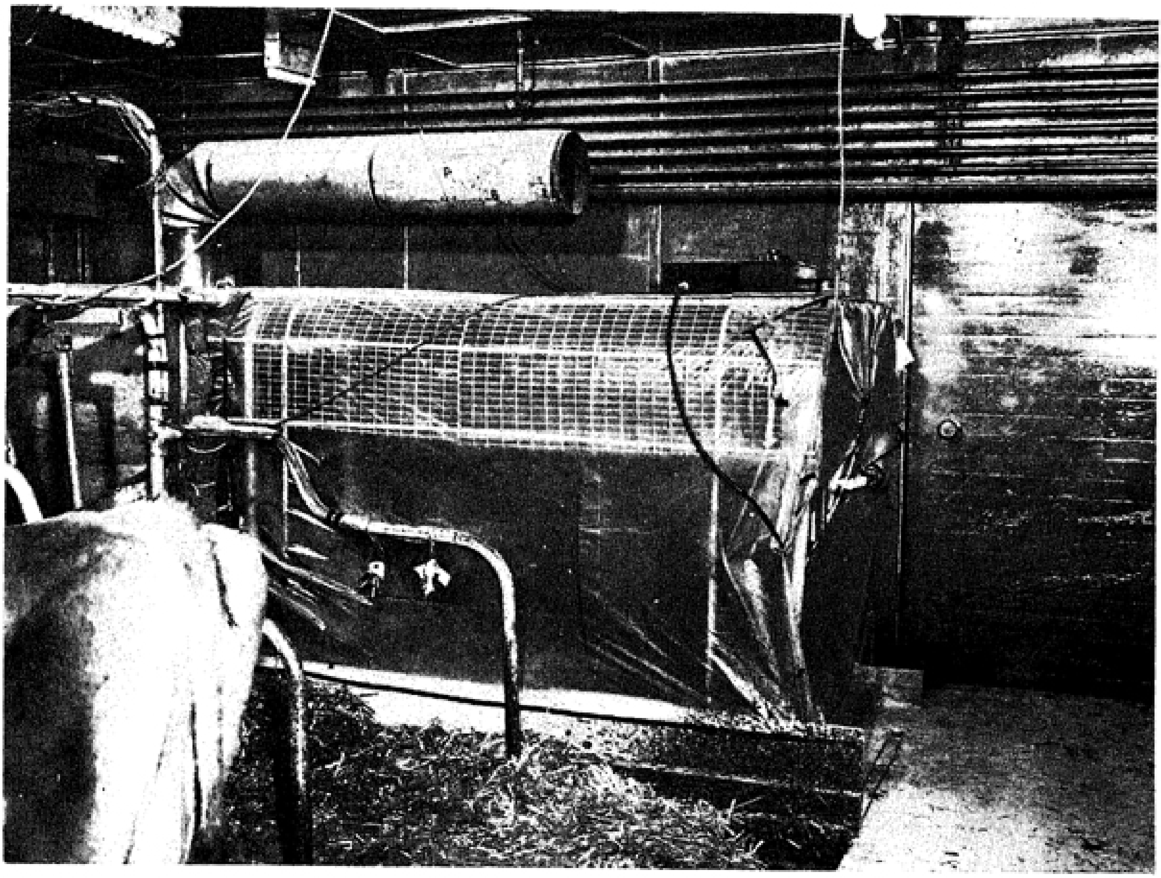

Figure 2.—Photograph of the hygrometric tent as initially used for the diurnal tests. The intake dewcel was at the rear intake opening of the tent (right side in picture). The exhaust dewcel was inside the bag immediately below the exhaust fan. Manual measurements were made with a resistance bridge shown atop the tent. This system was later modified for automatic recording and the air sampling system was changed to that shown in Figure 1.

The quantity of air was determined by measuring the pressure drop across a 6-inch diameter orifice. The pressure drop was measured with an inclined manometer connected to flange type taps on each side of the orifice. The pounds of dry air exhausted were then determined from a simplified equation for flow through orifices; $Q = C \sqrt{hd}$, where "Q" is the pounds of dry air, "h" the differential pressure across the orifice, and "d" the density of exhaust air. "C" is a combined constant based on the characteristics of the orifice as well as conversion and expansion factors.[4] The "C" value was empirically determined by calibration tests. Empirical rather than theoretical "C" values were used as economy of space and equipment resulted in (1) foreshortened duct lengths for proper laminar flow, (2) slightly irregular pipe surfaces, and (3) a mediocre orifice. Since the rate of air flow was nearly constant, calibration tests at various temperatures provided reliable "C" values.

The difference between the moisture content of the intake and exhaust air was measured with lithium chloride "dewcels" manufactured by The Foxboro Instrument Company. With this instrument the moisture in the air was determined in terms of the temperature at which the lithium chloride on the dewcel changed from a dry to a moist salt and became an electrical conductor. These dewcel temperatures were then correlated with the humidity ratio (pounds of water per pound of dry air) according to the manufacturer's conversion tables. Air was drawn over the "dewcels" through 2-inch rubber hoses. The exhaust air sampling hose drew its air from a point beyond the orifice near the end of the exhaust duct, and the intake air sampling hose drew its air at a point outside of the rear of the tent near the air intake hole. Extreme care was necessary in the placement of the exhaust air sampling hose. If too close to the orifice, the air volume measurements would be upset. If too near the end of the duct, some room air would be drawn into the sampling hose and the exhaust air moisture content would be erroneously evaluated.

CALIBRATION OF THE HYGROMETRIC TENT

Calibration of the hygrometric tent was initially accomplished by vaporizing a known amount of water from a 2000 ml beaker placed on a small hot plate. The vaporization rate (R) so determined was used with the formula $C = \dfrac{R}{(W_e - W_i)\ \sqrt{hd}}$ in order to determine the "C" value for the air flow equation. In this equation, "h" and "d" were, respectively, the pressure drop across the orifice and the density of the exhaust air. $(W_e - W_i)$ was the difference between the moisture content of the exhaust and intake air. A "C" value of 9396 was adopted for all tests. Under the initial constant temperature tests this "C" value provided results with less than 10 percent variation.

PRESENTATION OF DATA

Figures 3 through 6 show the diurnal changes in vaporization rate for each animal along with the accompanying environmental conditions. Air and dew point temperatures are shown for Test Room I and for the hygrometric tent. The tent air temperatures were measured in the tent exhaust air duct and included the heat added by the fan motor. The indicated tent temperatures should therefore be reduced about 2° F in order to show true tent air temperatures.

The total vaporization rate for each observation within the 70-100° F diurnal cycle is shown in Figure 3. Figures 4, 5, and 6 show the same information concerning the 10-40° F, 40-70° F, and 60-110° F diurnal cycles ex-

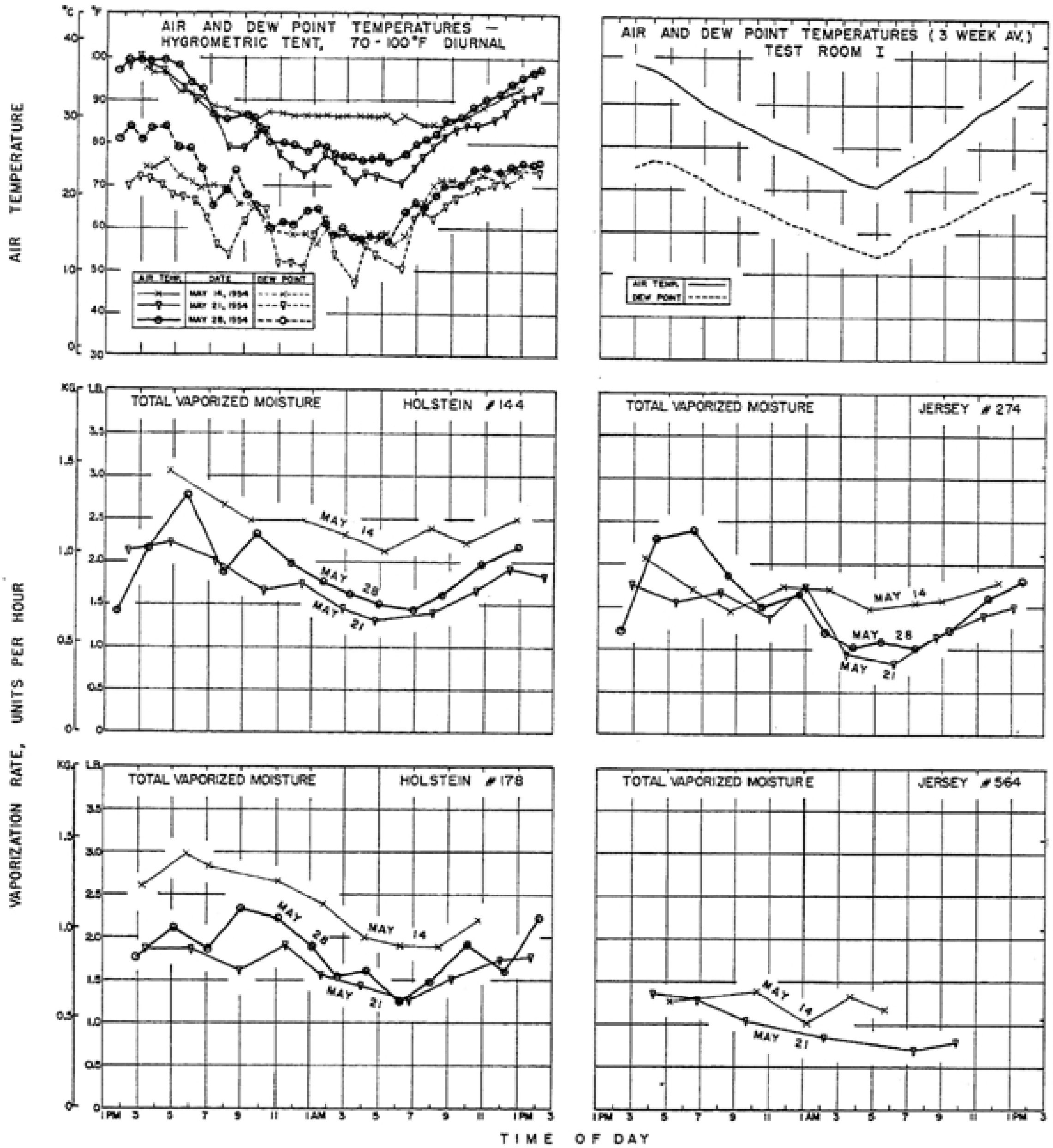

Figure 3.—Diurnal vaporization rates for each cow within the 70-100° F diurnal temperature cycle. The air and dew point temperatures for the test room are a three-week average of conditions within Test Room I. Those for the hygrometric tent exhaust air represent conditions inside of the tent except that the exhaust fan caused about a 2° F air temperature rise. Jersey 564 was removed from laboratory on May 24, 18 days after aborting a 5-month fetus.

cept that each observation is given in terms of the deviation of a given observation from the average daily loss for that given day and animal.

Several findings are shown by these data. First, in comparing one diurnal with the other, the average vaporization rate for each day increased with the average temperature of each diurnal. The 10-40° F cycle (24° F average

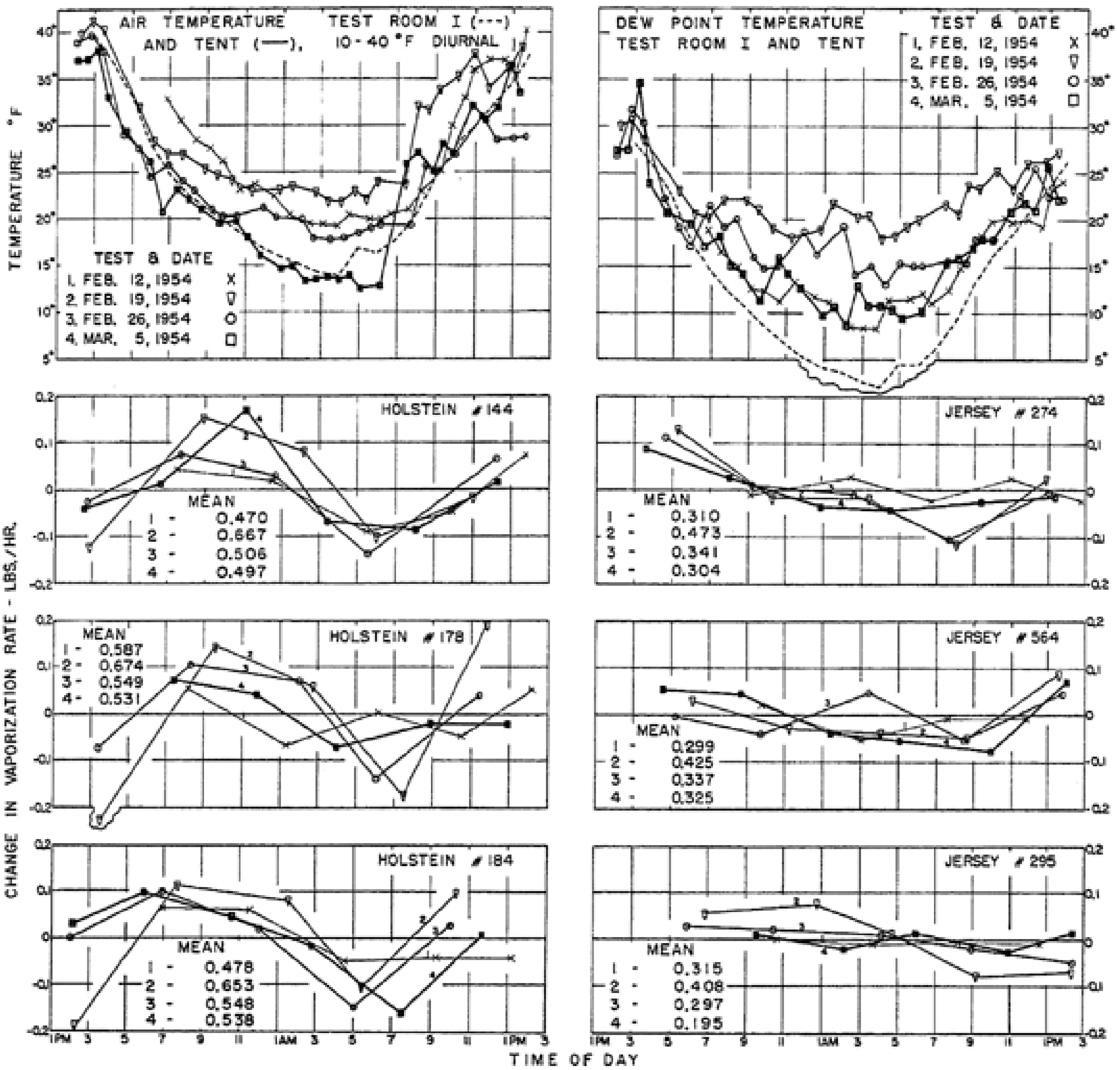

Figure 4.—The magnitude of the change in vaporization rates for each cow within the 10-40° F diurnal temperature cycle in terms of the deviation from the mean. Mean values are shown for each test. A plus value represents a vaporization rate greater than the mean for that day. As in Figure 3 the Test Room I environmental temperature represent an average for the entire test period and the hygrometric or vaporization tent air temperatures are actually about 2° F greater than those inside of the tent.

temperature) caused average losses of 0.55 lb./hr. in Holsteins and 0.35 lb./hr. in Jerseys. Within the 40-70° F cycle (55° F average temperature), the losses were 1.05 lb./hr. in the Holsteins and 0.50 lb./hr. in the Jerseys. Within the 60-110° F cycle (83° F average temperature), the losses were 1.77 lb. lb./hr. in the Holsteins and 1.32 lb./hr. in the Jerseys. Within the 70-100° F cycle (84° F average temperature), the losses were 1.94 lb./hr. for the Holsteins and 1.34 lb./hr. for the Jerseys.

Next, the data also show the Holsteins to have from 34 to 90 percent higher vaporization rates than the Jerseys. Much of this difference is due to

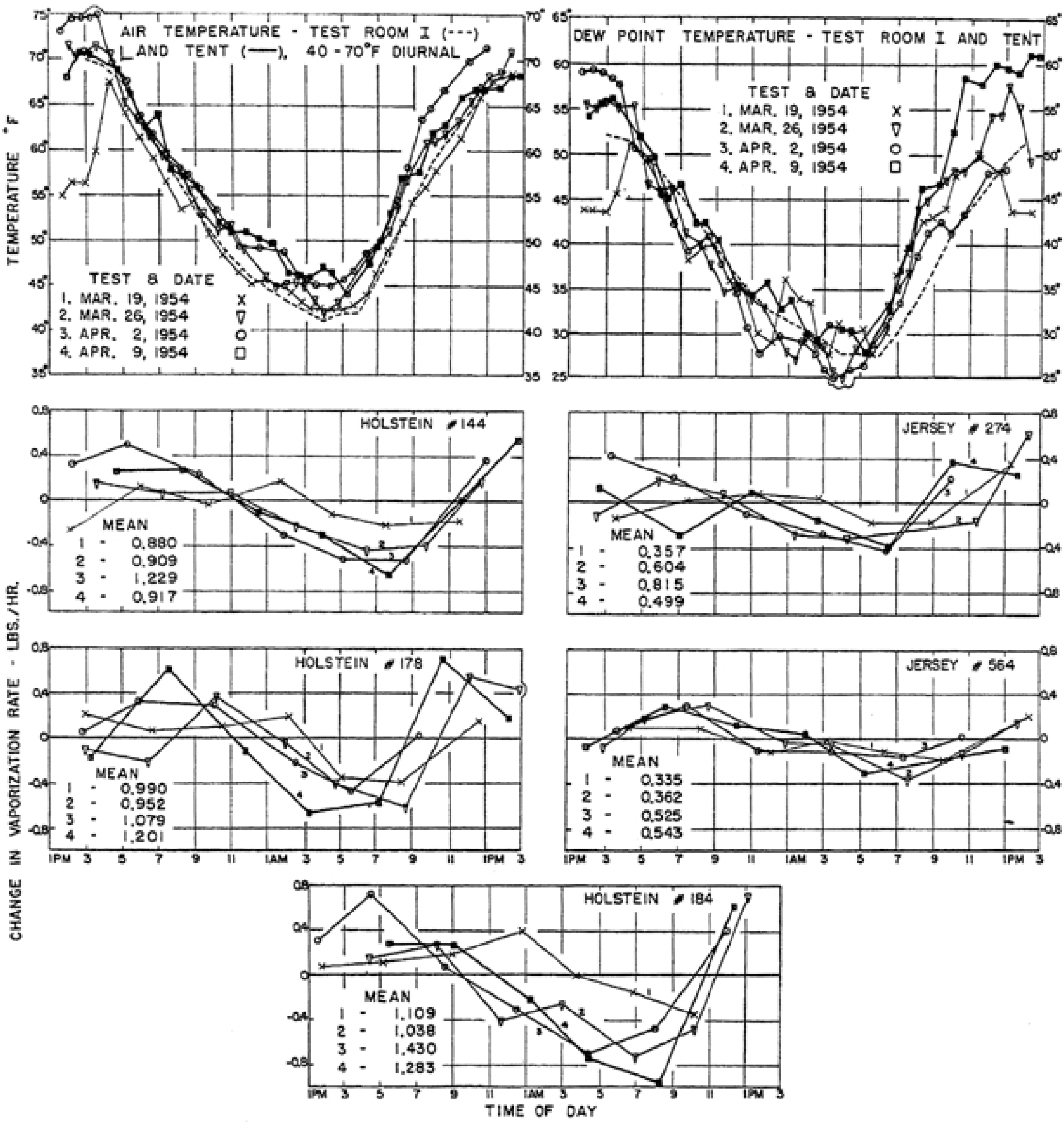

Figure 5.—The magnitude of the change in vaporization rates for each cow within the 40-70° F diurnal temperature cycle. Jersey 295 was taken from the laboratory on March 9 for removal of hardware in the rumen.

the difference in size. When losses were based on 1000-pound animal units the Holstein and Jersey losses were much more alike. Holstein and Jersey average losses (lbs./hr./1000-lb. of body weight) were respectively, 0.423 and 0.408 within 10-40° F cycle, 0.789 and 0.561 within the 40-70° F cycle, 1.327 and 1.483 within the 60-110° F cycle, and 1.453 and 1.546 within the 70-100° F cycle.

A third finding was a diurnal cycle in the vaporization rate that changed with the air and dew point temperature cycle. Highest vaporization rates

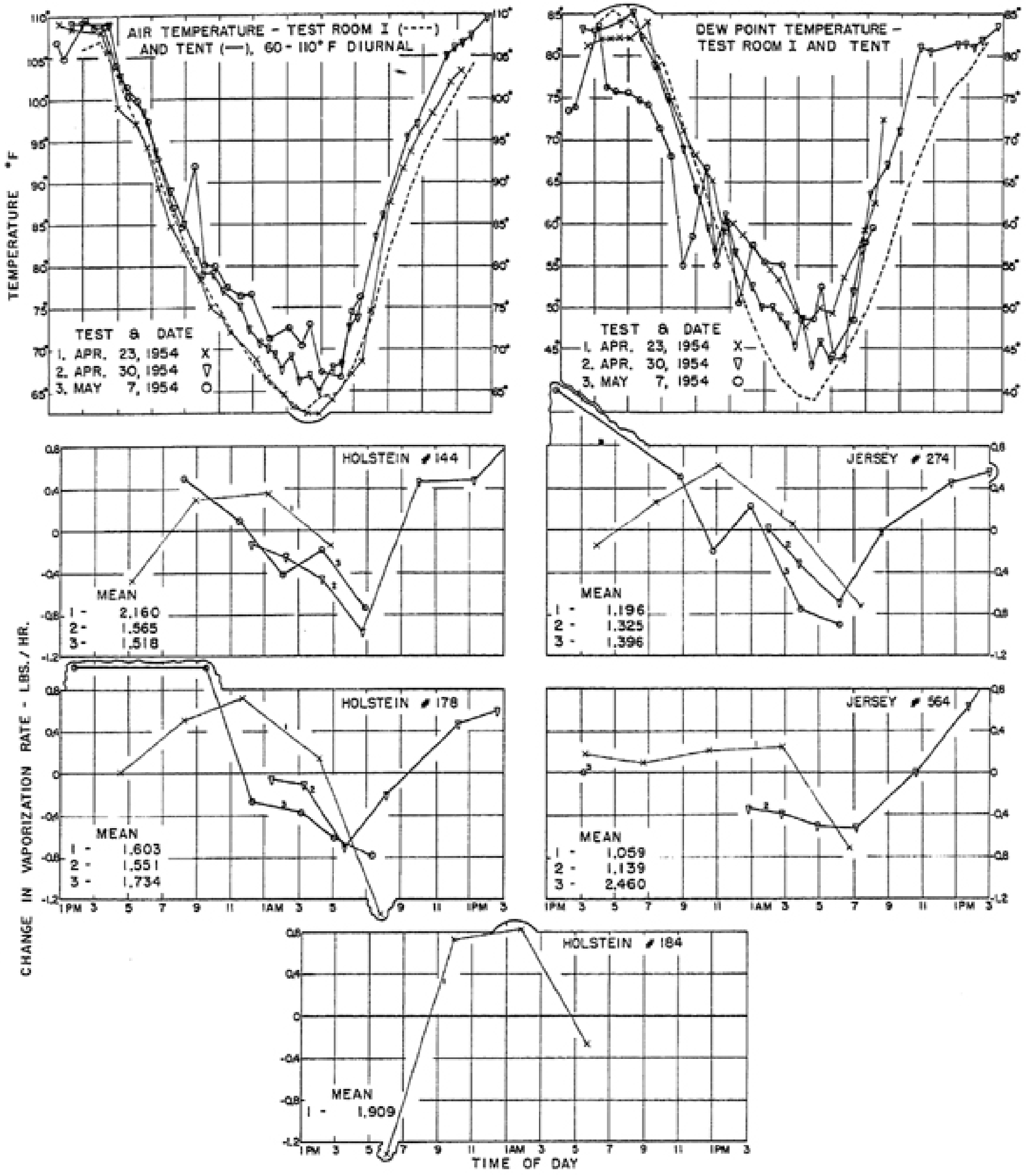

Figure 6.—The magnitude of the change in vaporization rates within the 60-110° F diurnal temperature cycle. Jersey 564 aborted a 5-month fetus shortly after the one test made on May 7. Holstein 184 suffered a heat stroke with paralysis of the left hind leg on the day after,the April 30, 1955, test. All cows were restless inside the tent during the test period and considerable experimental error is assumed.

occurred approximately two to four hours after the maximum temperatures and the lowest occurred approximately two to four hours after minimum temperatures. Whether the air temperature, dew point temperature, or a combination of both was the major contributing factor was not determined as both air and dew point temperature had the same pattern of variation.

A fourth finding was that the magnitude of the cycle (the total change in vaporization rate within each day) increased with the high temperature diurnal cycles. Within the 10-40° F cycle the magnitude of the cycle was about 0.2 lb./hr. for the Holsteins and about 0.1 lb./hr. for Jerseys. It increased to about 0.8 lb./hr. for Holsteins and to about 0.4 lb./hr. for Jerseys within the 40-70° F cycle. Within the 70-100° F it further increased to about 1.2 lb./hr. for Holsteins and 1.0 lb./hr. for Jerseys. The amplitude of the vaporization rate cycle within the 60-110° F temperature cycle appeared greater than within the 70-100° F cycle. This, of course, would be expected as the 50° F daily temperature change was being compared with a 30° F daily temperature cycle. The 60-110° F data were limited and erratic as the cows were difficult to handle. They driveled excessively, urinated frequently, and were generally restless.

Within the 10-40° F and 40-70° F cycles the cycle in vaporization rate was smallest for the first week of test. In the 10-40° F cycle this was attributed to orientation. It was the animals' initial entrance into the tent and they were quite restless. In the 40-70° F cycle the small first week's vaporization cycle was associated with a cooling equipment failure. On the first day of test the holding stable (Test Room I) had a narrow diurnal temperature cycle (56-70° F instead of 40-70° F).

Some vaporization rate measurements with the insensible weight loss method were also made. These measurements were taken randomly, generally during Saturday morning at the time of the hygrometric tent observations and as such represent a period of rising environmental temperature. Data within each diurnal cycle were averaged according to individual animals. Insensible weight losses as measured at the scale were reduced to vapor losses by subtracting metabolic weight losses as measured in the test room at other times. This is a recognized source of error and one reason for using the new hygrometric tent method of measurement. Another reason for using the new method is shown in the discrepancy between environmental conditions in the test room and at the scale. The average (using individual observations) difference between the test room and scale environment within each diurnal cycle was very great. At the scale during the 10-40° F cycle, the temperature averaged 5.3° F below and the relative humidity 10 percent above test room values. During the other diurnals, the corresponding values were: 3° F above and 5 percent above in the 10-40° F cycle; 7° F below and 14 percent above in the 70-100° F cycle; and 5° F below and 19 percent above the test room conditions.

EVALUATION OF HYGROMETRIC TENT TECHNIQUE

Comparative evaluation of the hygrometric tent results with the insensible weight loss measurements that were made during the diurnal tests and previous constant temperature tests is shown in Table 1. Within the diurnal temperature tests the two methods of measurement showed reasonable agreement, particularly when the discrepancy in time (the tent values are averages for the entire day and the weight loss values are averages for only part of a day) and the inherent errors in the scale method were considered. The comparison of tent values and previous constant temperature values[1] showed even more favorable agreement (less than 0.05 lb./hr. difference in the 10-40° F cycle and only about 0.1 lb./hr. difference in the 40-70° F diurnal). Greater differences occurred in the two high temperature diurnals but they were in a temperature range associated with rapidly increasing vaporization rates where there were great differences between individual animals even within breeds.

Also shown in Table 1 are comparable stable vaporization rates as determined through stable ventilation exchange measurements.[3] The stable rates include the moisture dissipated by the cows, their litter, drinking cups, and feed. The stable rates were sufficiently above the tent rates to provide reasonable values for the vaporization rate from sources other than the animal itself. The greater difference between stable and tent vaporization rates during the 60-110° F cycle than during the other cycles (a difference of .73 lb./cow/hr. for that diurnal as compared with a difference of about .35 lb./cow/hr. for the other three cycles) was attributed to excessive splashing of water from the drinking cups into the manger.

The comparisons made in Table 1 were sufficiently favorable to provide strong confidence in the hygrometric tent data.

TABLE 1 -- COMPARATIVE ANIMAL AND STABLE VAPORIZATION RATES FOR HOLSTEIN AND JERSEY COWS AT EACH DIURNAL WITH COMPARABLE VAPORIZATION RATES UNDER PREVIOUS CONSTANT TEMPERATURE CONDITIONS

	Vaporization Rates Lb/Hr/Cow							
Diurnal Cycle °F Test Room I	10-40		40-70		70-100		60-110	
Avg. Temperature of Diurnal °F	24		55		84		83	
Cattle*	H	J	H	J	H	J	H	J
As Measured With Tent	0.55	0.35	1.05	0.50	1.94	1.34	1.77	1.32
As Measured With I.L. Scale	0.66	0.48	1.16	0.75	1.55	1.16	2.00	1.60**
Previous Constant Temperature Data***	0.52	0.39	0.93	0.62	2.21	1.55	2.20	1.58
Total Stable Dissipation Rates****	0.79		1.11		1.99		2.27	

* H = Holsteins 144 and 178.
J = Jerseys 274 and 564
** Record available on Jersey 564 only.
*** Extrapolating from Table 8, reference (1).
**** From Figure 7, reference (3).

STATISTICAL ANALYSIS OF DATA

An analysis of variance with the hygrometric tent data was conducted using classifications as follows:

1. Between breeds.
2. Among diurnal temperature cycles.
3. Among temperatures within cycles.

In all cases the observed variance ratio, "F", was greater than that expected due to chance at the 1 percent point. This indicates that the difference between Holsteins and Jerseys was highly significant. It also shows that the variation among the diurnal cycles was very significant and that the variation within each cycle was significant.

DISCUSSION OF RESULTS

One of the more significant results of these studies was the rapidity and magnitude with which the vaporization rates changed with changing temperatures within each diurnal temperature cycle. This means that cattle can quickly adjust their evaporative heat dissipation rates to changing environmental temperatures. Since vaporization rates increased with rising environmental vapor pressures (or dew point temperatures) and decreased with decreasing vapor pressures we might add that the cattle were able to adjust their moisture dissipation rates against adverse vapor pressure conditions.

This consideration also shows that the increased vaporization rates must have arisen from some change in the skin rather than a lowered ambient air vapor pressure. It is evident that some homeothermic mechanism accelerated sweating or moisture diffusion processes. The greater part of the increase was from the skin. Respiratory vaporization accounted for not more than 35 percent of the total.[5]

The importance of the evaporative cooling process in the animal's heat tolerance (the ability of the animal to dissipate heat being used as a measure of heat tolerance) can be best understood by comparing the amount of heat lost by evaporative cooling to the heat production as measured by oxygen consumption.[5] Table 2 shows the average heat production as measured before and after each of the two feeding periods within each diurnal cycle. Also shown are the heat losses through evaporation as determined from the hygrometric tent vaporization rates for comparable periods. These values are further compared by presenting them as ratios of evaporative heat dissipation to heat production. The values initially represented the average of 3 Jerseys and 3 Holsteins in the 10-40° F diurnal but loss of cows occurred as follows: one Jersey at 40-70° F, one Holstein at 60-110° F, and one Jersey at 70-100° F.

TABLE 2 -- EVAPORATIVE HEAT DISSIPATION** AS COMPARED WITH TOTAL HEAT PRODUCTION

Diurnal Temp. Range °F	Time	Temp. °F		Average Heat Production Cal/Hr***		Av. Evaporative Heat Dissipation Cal/Hr		Ratio Evaporative Heat Loss to Heat Production	
		Air	Dew Pt.	Holsteins	Jerseys	Holsteins	Jerseys	Holsteins	Jerseys
10-40	2-5*AM	14.1	2.3	992	707	116	96	.12	.14
	7-9 AM	19.1	7.6	1092	817	113	81	.10	.10
	1-3*PM	36.0	24.8	1042	686	136	86	.13	.13
	4-7 PM	30.4	20.0	1151	829	144	127	.13	.15
40-70	2-5*AM	41.6	28.5	886	584	175	100	.20	.17
	7-9 AM	47.7	31.6	976	666	138	74	.14	.11
	1-3*PM	67.8	50.7	972	618	377	161	.39	.26
	4-7 PM	65.8	49.0	1061	758	325	212	.31	.28
70-100	2-5*AM	72.8	55.1	783	528	397	269	.51	.51
	7-9 AM	77.0	61.4	945	651	417	326	.44	.50
	12-3*PM	94.7	73.5	754	564	528	460	.70	.82
	5-7 PM	94.0	72.8	939	639	668	494	.71	.77
60-110	2-5*AM	63.5	39.3	801	576	393	209	.49	.36
	7-9 AM	71.1	52.4	831	561	213	197	.26	.35
	12-3*PM	102.5	80.0	769	544	610	593	.79	1.09
	5-7 PM	100.3	83.2	807	564	437	303	.54	.54

* Before feeding measurements.

** Using 263 Cal/lb. of evaporated moisture.

*** As measured by O_2 consumption and reported in Table 4 of reference (5).
To obtain Btu/hr. multiply by 3.968

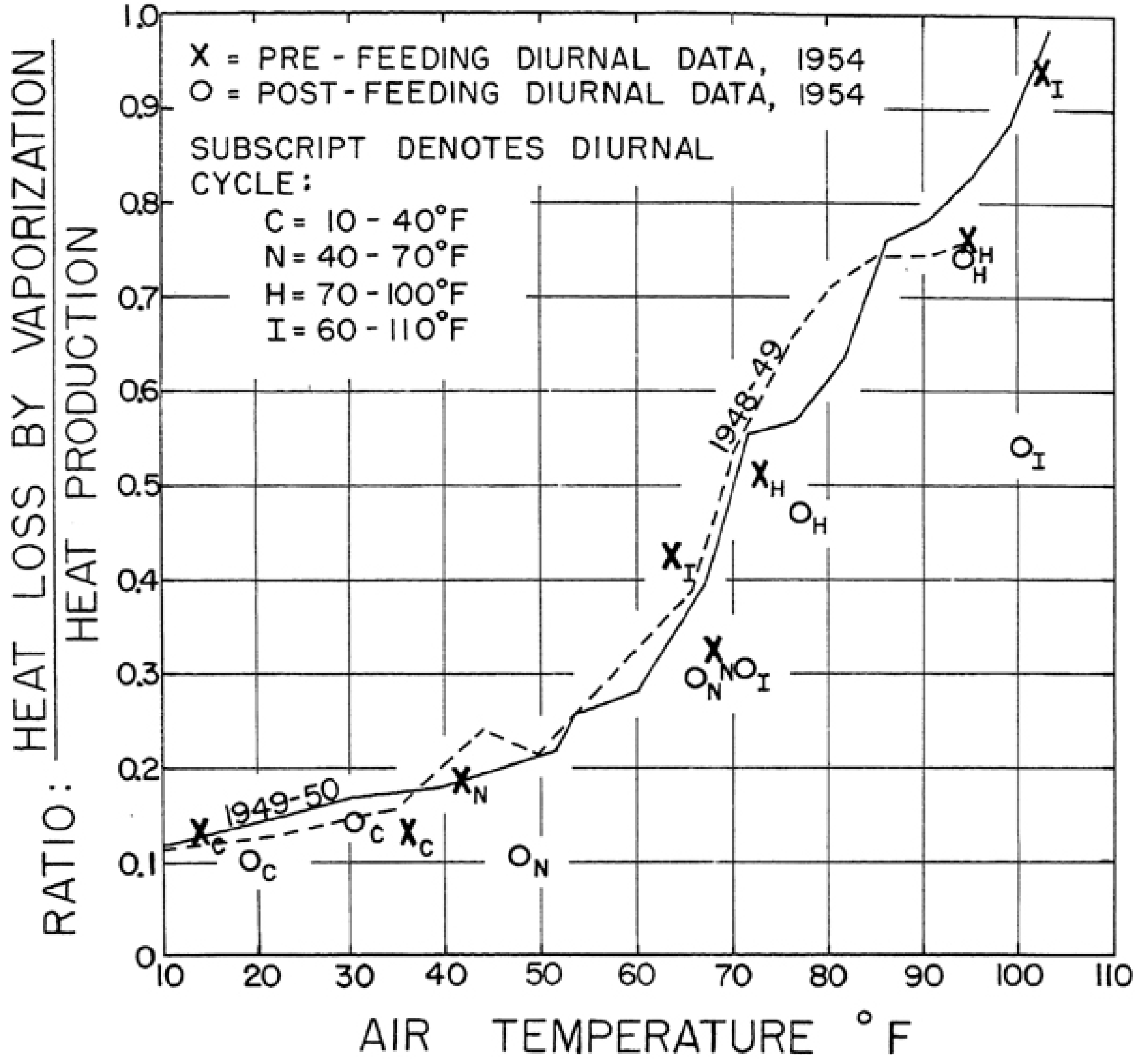

Figure 7.—Importance of evaporative cooling as related to total heat production at various stable temperatures. At 103° F almost 100 percent of the total heat production was dissipated through vaporization of water. The before feeding data from the diurnal experiments (X) compare favorably with the ratios of previous years which also represent before feeding measurements. The circle points (0) represent measurements made after feeding in the diurnal tests. The 1948-49 curve was taken from Tables 1 and 2 of Mo. Agr. Exp. Sta. Bulletin 451 [6] and the 1949-50 curves were taken from Tables 1 and 2 of Mo. Agr. Exp. Sta. Bulletin 479.[1]

As in previous work, [1, 6] the ratios were generally the same for both the Jersey and Holstein breeds at each condition. Figure 7 shows the relationship of these ratios (both breeds averaged together) to the environmental temperatures at the time the measurements were taken. The ratios are shown to increase from about 10 to 20 percent with a temperature increase of from about 10 to 50° F. However, from about 65 to 100° F they increase much more rapidly (from about 30 to near 100 percent). This emphasizes the importance of evaporative cooling at higher temperatures.

Shown also in Figure 7 are the ratios of evaporative to total heat from previous (1948-49 and 1949-50) investigations wherein exposure to each temperature was constant for a week or more and all measurements were made before feeding. Of importance in this comparison is the close agreement between these and the before feeding values from the diurnal studies. This comparison between the constant temperature and the diurnal ratios further substantiates the finding that the cattle adjust their evaporative cooling mechanism very rapidly to changing environment.

Mentioned in the presentation of data was the fact that vaporization rates for Holstein and Jersey cattle would be more nearly equal if adjusted for difference in size. A unit weight standard was suggested. However, since between 60 and 64 percent of the total vaporization loss was from the skin during the two high temperature diurnals (and between 44 and 54 percent at the two low temperature diurnals), the vapor loss per unit surface area might be a better basis for equalization. Table 3 shows a comparison of the two methods. This table shows that either method would be satisfactory for general comparisons for all except the 40-70° F diurnal temperature range. At the higher temperatures, the unit weight base shows greater losses for the Jerseys and the unit area shows greater losses for the Holsteins.

TABLE 3 -- AVERAGE DAILY VAPORIZATION RATES BY HOLSTEIN AND JERSEY COWS

Diurnal Temp. Range °F	Pounds per hour		Pounds per hour per 1000 pounds body weight		Pounds per hour per square meter of surface area*	
	Holstein	Jersey	Holstein	Jersey	Holstein	Jersey
10-40	0.55	0.35	0.42	0.41	0.10	0.08
40-70	1.05	0.50	0.79	0.56	0.19	0.12
70-100	1.94	1.34	1.45	1.55	0.36	0.32
60-110	1.77	1.32	1.33	1.48	0.33	0.31

*Based on the equation: Surface Area (sq. meters) = 0.15 (weight in Kg)$^{0.56}$ (See Brody, S., "Bioenergetics and Growth.")[7]