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Environmental Physiology and Shelter Engineering

With Special Reference to Domestic Animals

LXIV. Physical Factors Affecting Thermal Insulation of Livestock Hair Coats

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

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SUMMARY

Insulation values of livestock hair coats were determined by calculation and direct measurement. Physical hair characteristics which might affect the transfer of heat through animal hair coats were measured and were correlated with the measured insulation values.

Preliminary calculations and correlations indicated that the total hair-coat insulation of dairy calves was linearly related to the hair weight per unit area of body surface.

Further work, with more complete measurements of physical hair characteristics, indicated that hair orientation, as estimated by the depth-over-length ratio, had more influence than the other measured variables on hair-coat conductivity. Increasing depth-over-length ratios increased the transfer of heat through a unit thickness of hair coat, but the change in hair depth associated with increasing depth-over-length ratios for hair of a constant length resulted in a decline in the amount of heat transferred through the entire depth of hair coat.

Increasing numbers of hairs per unit area increased the total heat transferred, indicating that the heat transfer along the hairs and hair contacts was a major portion of the total.

Hair diameter was related to the factors of depth over length, number of hairs per unit area, and hair depth, and may have exerted indirect influence on conductivity or insulation through such relations.

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INTRODUCTION

The failure of certain breeds of livestock to adapt to hot weather has been attributed to their limited ability to dissipate body heat to the surroundings. A thermal barrier on the body surface, in the form of a hair coat, would appear to be an important factor in heat dissipation processes. Knowledge of the thermal properties of hair coats is necessary before their influence upon heat dissipation from the body can be determined.

The purposes of this investigation were (1) to determine hair weight, hair length, hair depth, and other characteristics that might influence the transfer of heat through cattle hair; (2) to devise a method of quantitatively measuring heat flow through cattle hair coats; and (3) to compute hair-coat conductance values or insulation values and relate them to other hair-coat characteristics, with an evaluation of the relative influence of each characteristic.

DEFINITION OF TERMS

Heat Transfer or heat flow. The movement of heat from one location to another. Units of measurement will be expressed as Btu/hr or gm-cal/sec.*

Insulation. Insulation generally refers to a material used in reducing the movement of heat, sound, and electrical charge. Within this bulletin, insulation refers to the effectiveness of a material or object in reducing heat transfer.

Total Insulation. Total insulation refers to the total resistance of an object or plane barrier to the transfer of heat from one surface to another. Within this bulletin, the resisting object considered is usually an animal's hair coat. Units of measurement will be expressed as °F-ft²-hr/Btu or °C-M²-sec/gm-cal.**

Insulation per unit depth. Insulation per unit depth refers to the thermal resistance of a layer of material one dimensional unit thick. Units of measurement will be expressed as °F-ft²-hr/Btu-in. or °C-M²-sec/gm-cal-M.***

*One gm-cal/sec equals 14.27 Btu/hr.

**One °C-M²-sec/gm-cal equals 1.355°F-hr-ft²/Btu.

***One °C-M²-sec/gm-cal-M equals .03442°F-hr-ft²/Btu-in.

Conductance. Conductance refers to the ability of a plane barrier to conduct heat from one surface to another. Conductance is equal to the reciprocal of total insulation. Units of measurement will be expressed as Btu/°F-ft^2-hr or gm-cal/°C-M^2-sec.

Conductivity. Conductivity refers to the ability of a layer of material, one dimensional unit thick, to transfer heat from one surface to another. Thermal conductivity is dependent on the material within an object, rather than the dimensions of the object. Units of measurement will be expressed as Btu-in./°F-ft^2-hr or gm-cal-M/°C-M^2-sec.

Heat-flow meter. Heat-flow meter refers to a devise which produces an electrical signal proportional to the rate of heat transfer through itself. The electrical signal may be voltage.

REVIEW OF LITERATURE

Comparisons between European and tropically evolved breeds of livestock have indicated that hair characteristics may be related to the heat tolerance of livestock. Bonsma and Pretorius found that the summer coats of Shorthorn heifers were about ten times as heavy as those of Afrikander heifers exposed to the same summer temperatures in South Africa.[1] The Shorthorn heifers which shed their hair earlier in the spring than other heifers of the same breed, were significantly heavier at one and one and one-half years of age. Bonsma indicated that hair-coat thickness and color were related to weight gain, body temperature, pulse rate, and respiratory rate during hot summer months.[2]

Dowling indicated that the percentage of medullated hairs, followed by hair diameter, hair length, and the weight of hair per unit skin area exerted the most influence on body temperature during the summer months.[3] Schleger and Turner found that the hair depth, the hair diameter, and the number of hairs were more closely related to growth than was the weight of hair per unit area.[4, 5]

The relations between physical hair characteristics, body temperature, and growth indicated by the above references could be a result of two other phenomena: (1) the influence of hair characteristics on solar radiation absorption and (2) the influence of hair characteristics on the transfer of heat from the skin to the outer hair surface.

The absorption of solar radiation by hair coats was shown to vary directly with hair color.[6, 7] Hair orientation seemed to have relatively little influence on radiation absorption. Both hair color and absorption coefficients varied with environmental temperature.[8]

The influence of hair characteristics on the transfer of heat from the skin to the outer hair surface has not been thoroughly investigated, possibly because of the difficulty of measuring the heat flow per unit surface area on a live animal. Various investigators have estimated the insulation values of fur on pelts from furred mammals, assuming such values would apply to fur on live animals.

Scholander and others found that the apparent insulation of fur from 32 arctic and tropical mammals was about 0.774 °C-m²-sec/gm-cal per centimeter depth[9] (about 2.664 °F-ft²-hr/Btu per inch of hair depth). Hammel estimated the apparent insulation of the fur of certain northern mammals to be about 1.072 ° C-m²-sec/gm-cal per centimeter depth of hair.[10] Convection appeared to account for 25 to 50 percent of the total transfer of heat through the hair.

Thompson and others computed the heat flow per unit surface area of Jersey, Holstein, Brown Swiss, and Brahman cattle with total heat production, total moisture vaporization, respiratory vaporization, and surface area measurements.[11] The heat transfer was equated with skin and hair temperatures to obtain total hair-coat insulation values ranging from 0.014 ° C-m²-sec/gm-cal to 0.40 ° C-m²-sec/gm-cal.

Textile researchers have developed empirical formulas relating heat flow through fabrics to the thickness and density of the fabric. For a summary of research relating to fabric insulation see Reference 12.

Heat transfer through fibrous materials may consist of the following:

(a) conduction along and between fibers
(b) conduction through entrapped air and vapor
(c) convection through entrapped air and vapor
(d) radiation

Verschoor and Greebler found that gas conduction was the most important mechanism of heat transfer through glass fiber insulations of densities ranging from 0.5 to 8.4 pounds per cubic foot.[13] The proportions of heat carried through a glass fiber insulation by the mechanisms of heat transfer at varying bulk densities are presented in Figure 1. Finck estimated that fiber conduction in several fibrous materials was responsible for about 30 to 50 percent of the total heat transferred at bulk densities of about 15 pounds per cubic foot.[14] Heat conductivity increased with increasing bulk density at densities above about 10 pounds per cubic foot, indicating that fiber conduction was responsible for more heat transfer at the greater densities. Finck found that fiber orientation had considerable influence on heat transfer, with maximum conductivity being obtained when the fibers were parallel to the direction of heat flow.

Hair and skin temperatures are important in the investigation of the thermal properties of hair coats because they determine the thermal gradient through the hair. Instruments and techniques for determining hair and skin temperatures are discussed in References 11, 15, 16, and 17.

Hair characteristics which may pertain to hair-coat insulation include hair weight, color, depth, length, diameter, orientation, bulk density, numerical density, and resistance to separation. Quantitative measurements of such characteristics may be difficult to make, and inaccurate, particularly when measurement without disturbing the thermal characteristics of the hair is desired. A summary of techniques used in measuring various hair qualities is presented by D. H. K. Lee.[18] Radioisotopes have been used to determine the weight of hair per unit area.[19]

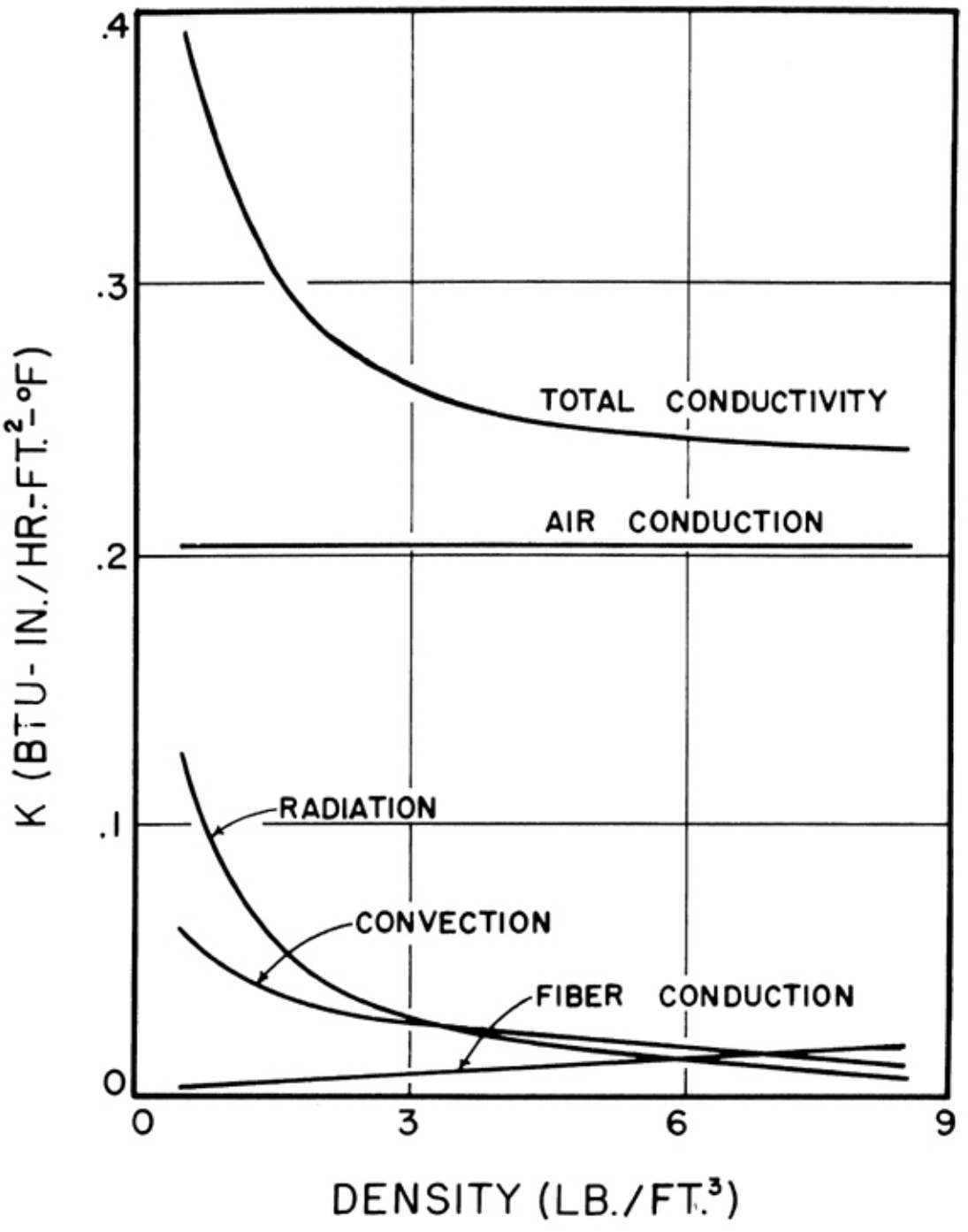

Figure 1—Contribution of each component of the total conductivity of fiber glass insulation versus insulation density at 150° F mean temperature and atmospheric pressure. (J. D. Verschoor and Paul Greebler.)[13]

Samples of hair can be obtained with modified side-cutter pliers without greatly changing the hair coat.[20] A method of describing the hair-coat characteristics by a subjective coat score is presented by Turner and Schleger.[5]

MATERIALS AND METHODS

The investigation consisted of two parts, a preliminary study with dairy calves and a later, more complete study with Guernsey cows. The methods and procedures used in the separate portions are reported together, although they were not always the same. The first part of the investigation is referred to as the preliminary study and the later part, as the major study.

Animals and Facilities

All measurements were taken in the Psychroenergetic Laboratory at the University of Missouri. Tests were conducted in two test rooms with air temperatures ranging from 50° to 90° F. The preliminary study was made with growing Jersey, Brown Swiss, and Holstein calves held at constant temperatures of 50° and 80° F for approximately 12 months. The experimental design and details concerning the experimental design are presented in References 21 and 26.

The major study was made with non-lactating Guernsey cows held at a constant 90° F for six weeks and 65° F for the seventh week. The experimental design is reported by Bedwell.[22]

Air velocities around the animals were about 50 feet per minute. The walls, ceiling, and floor were about the same temperature as the air. Six 200-watt incandescent bulbs lighted each room during the day and one 25-watt bulb in each room was left on continuously.

Measurement of Hair Characteristics

The preliminary measurements of hair weight per unit area were made with a "beta-gauge" with the Promethium isotope, Pm^{147}, mounted in a stainless steel probe.[17] The probe was rigidly fixed about two inches from a Geiger-Muller tube used with an integrating count-rate meter. The reduction of the count rate, after insertion of the probe under the hair, could be converted directly into weight per unit area by means of a calibration curve obtained by taking readings on known thicknesses of aluminum and paper.

The measurements of hair weight per unit area taken during the major study were taken with linemen's "side-cutter" pliers, modified to pull hair from a specific area of animal skin.[20] The pliers appeared to give more accurate results than the beta gauge and several different measurements could be made on the samples obtained by the pliers. Ten hair samples were taken for each determination of hair-coat insulation. The samples were weighed to an accuracy of 0.1 milligram and were saved for further measurements.

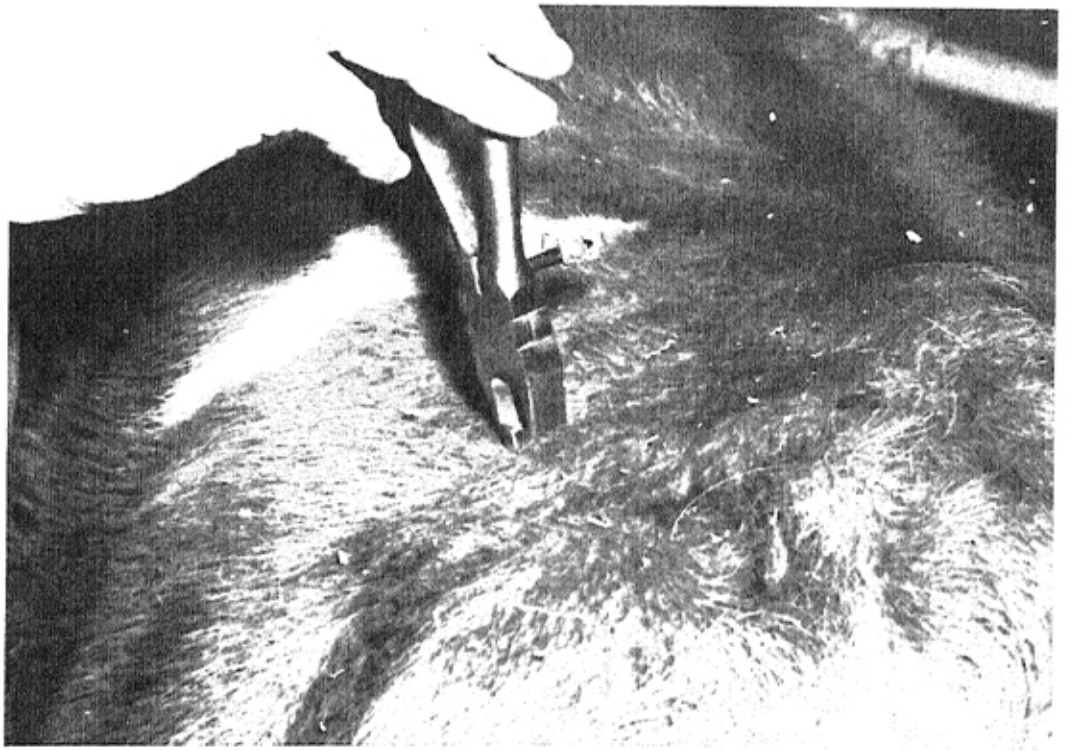

Figure 2—Hair sampler being inserted into the hair coat. After the sampler was in place, the small spacer (A) was removed, allowing the hair contained within the jaws to be gripped.

Figure 3—Hair sampler and sample. The samples were placed in small cans for later counting and weighing.

The depth of the hair coat was measured on the animal with a small metal scale. The scale was inserted into the hair unil it touched the skin. The reading was taken by sighting across the hair surface. Readings were estimated to the nearest sixteenth of an inch and five depth readings were averaged for each corresponding measurement of insulation.

The hair length was estimated while on the animal by the metal scale used in determining hair depth. Five readings of hair length were averaged for each measurement of hair-coat insulation.

Hair diameter was measured with a microscope having a filar eye-piece. A sample of more than 20 hairs was placed on a slide and covered with a glass cover plate. Twenty readings on 20 different hairs were averaged for each measurement of hair insulation. The filar eyepiece and microscope were accurate to the nearest 0.1 micron.

The number of hairs per unit area of skin surface was determined by counting the number of hairs in one of the 10 samples taken for each insulation reading. Hair orientation was estimated by dividing the hair depth by the hair length to obtain the sine of the angle between the hair and the skin surface. The bulk density of the hair was estimated by dividing the hair per unit area by the hair depth.

Measurement of Heat Flow and Temperature Gradients

Both the skin and hair temperatures were obtained with a 24 A.W.G. copper-constantan touch thermocouple. The butt-welded thermocouple was mounted on and held taut by two brass arms, which were in turn mounted in a wood handle.

Skin temperatures were taken by inserting the thermocouple parallel to the hair growth and moving it lengthwise until skin contact was made and maintained. The hair surface temperatures were taken by slowly brushing the thermocouple over the hair-coat surface in the direction of hair growth. The difference between the skin and the hair temperatures was assumed equal to the temperature gradient, ΔT.

The thermocouples were used with a Brown electronic potentiometer with a calibrated accuracy of 0.5 percent of scale range, a sensitivity of less than 0.1° C, and a scale range of 0° to 50° C.

Heat flow per unit surface area for the preliminary study was indirectly determined from measurements of total heat production, animal vaporization rates, and surface area. These measurements were taken by other investigators and are presented in References 23, 24, and 25.

The heat flow per unit area was calculated by dividing the difference of total heat and latent heat by surface area. This method of determining heat flow per unit area was disadvantageous because the several measurements were taken at different times during the period of a week, thus allowing day-to-day variation to introduce errors in the final values.

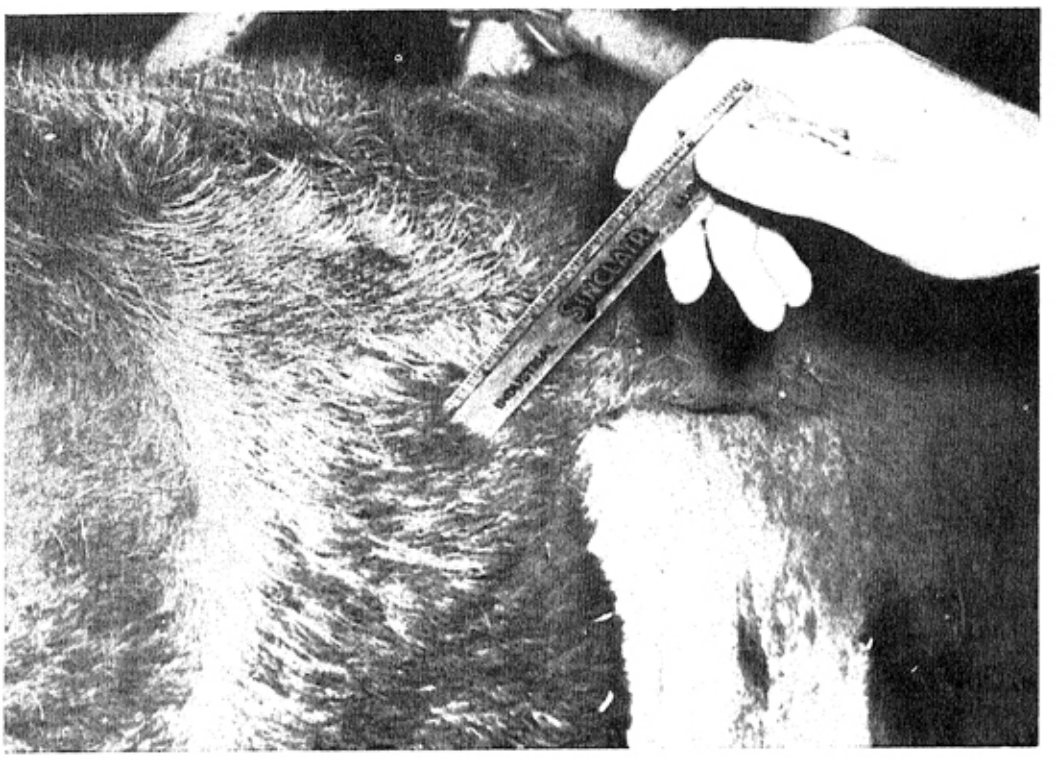

Figure 4—A scale used in estimating the hair-coat depth and the hair length.

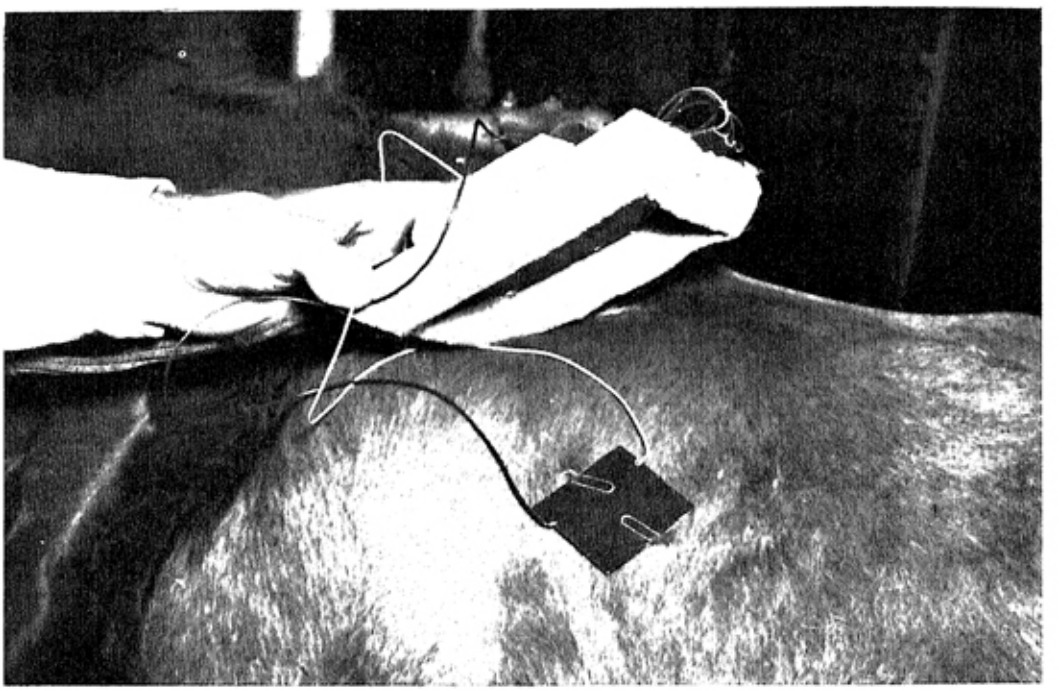

Figure 5—The two heat-flow meters used to determine the sensible heat flow per unit area of hair-coat surface. The larger meter is visible between the edges of the foam rubber "gasket."

Direct heat flow measurements were made during the major study with two Gier and Dunkle heat flow meters. These meters produced an electromotive force proportional to the heat flow through them. The larger meter had a sheet metal frame around its periphery which held a foam rubber seal designed to hold the heat from an area of about 24.0 square inches for transfer through the meter. The seal held the meter about one-half inch above the hair surface. Both meters were painted black. The electromotive forces of the meters were recorded on a Leeds and Northrup Speed-O-Max millivolt recorder. The recorder had a calibrated accuracy of 0.7 percent on the 0 to 1 millivolt scale and 0.3 percent accuracy on the 0 to 10 millivolt scale.

The small meter was first placed on the hair surface and was held by wire clips. After the heat flow through the small meter reached equilibrium, a reading was taken and the hair and skin temperatures were taken in the area adjacent to the meter without touching or moving it. The large meter was then placed over the small meter and held in place until the readings of both meters became constant and were recorded.

Hair length and depth were measured and hair samples were pulled immediately after each measurement of heat flow.

Computations

The flow of heat across a hair coat was assumed to follow Fourier's law for heat conduction in the steady state:

$$Q_1 = A\ K\ \Delta T_1, \tag{1}$$

where

Q_1 = rate of heat flow across a hair coat before the large heat-flow meter was in place,

A = area of hair coat covered by the large heat-flow meter,

K = conductance of the hair coat, and

ΔT_1 = thermal gradient across a hair coat before the large heat-flow meter was in place.

After the large heat-flow meter was in place and equilibrium was reached, the following equation was assumed applicable:

$$Q_2 = A\ K\ \Delta T_2, \tag{2}$$

where the subscript, 2, indicates values obtained after the large heat-flow meter was in place. Equations (1) and (2) may be combined to obtain

$$Q_1 = Q_2 \frac{\Delta T_1}{\Delta T_2}. \tag{3}$$

The heat flow across the small plate meter was assumed proportional to the thermal gradient, both before and after the large heat-flow meter was in place; therefore,

$$q_1 = C\ \Delta T_1, \tag{4}$$

and

$$q_2 = C\ \Delta T_2, \tag{5}$$

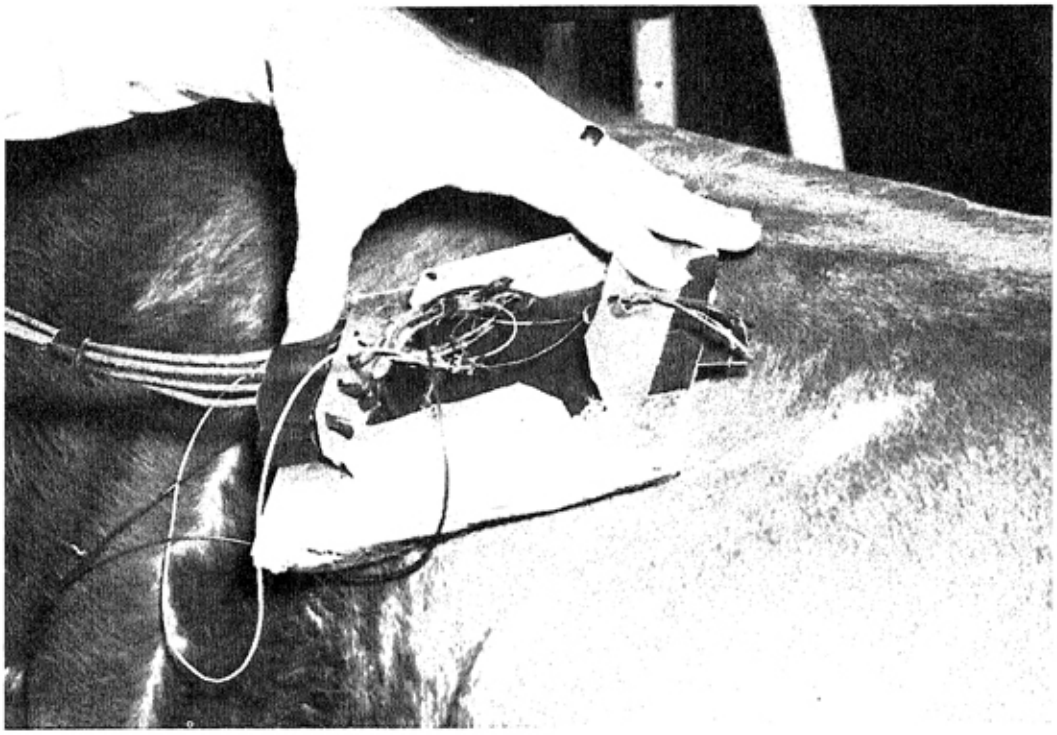

Figure 6—View of the large heat-flow meter. Surface temperatures have been taken and the meter has been placed over the area to be measured.

where

q = measured heat flow per unit area across the small heat-flow meter, with the subscripts having same meaning as previously indicated, and

C = proportionality constant.

Equations (3), (4), and (5) may be combined to obtain

$$Q_1 = Q_2 \frac{q_1}{q_2}, \tag{6}$$

where Q_1 is the heat flow from the area covered by the large heat-flow meter before it was in place. Equation (6) may be corrected for the reduction in heat flow caused by the small meter:

$$Q_1 = \frac{Q_2 \frac{q_1}{q_2} - q_1 a}{1 - \frac{a}{A}}, \tag{7}$$

where

a = area of small heat-flow meter.

The value of heat flow obtained from equation (7) was then used for solution of Fourier's equation for K, the thermal conductance. This conductance was used to determine the total insulation, insulation per unit depth, and conductivity of the hair coat.

Analysis of data

The random nature of the measurements and the number of variables considered in this investigation required the use of linear multiple regression and correlation procedures to evaluate the relative effects of each variable. The problem of evaluating each variable and its relation to other variables was confounded by the existence of four related variables which might be considered as dependent variables. In an effort to evaluate more completely the effects of the variables despite their inter-related nature, several linear regression equations were fitted to the data taken during this investigation. Statistical parameters obtained from the analyses were simple and partial correlation coefficients and partial and standard partial regression coefficients.

DATA AND DISCUSSION

Hair-Coat Insulation

The original data from both the preliminary study and the major study are in the Appendix. All values which were used in the statistical analyses may be computed from these data. The values that are considered to be variables are listed in Table 1, together with their symbolic notation, averages, and standard deviations.

TABLE 1-AVERAGES AND STANDARD DEVIATIONS OF VARIABLES

Variable	Units	Symbol	Average	Standard Deviation
Preliminary study				
Conductance	Btu/^{o} F-hr-ft^2	C	3.654	1.8354
Total insulation	^{o} F-hr-ft^2/Btu	R	0.359	0.2053
Areal density	lb/ft^2	D_a	.0200	.00488
Major study				
Conductance	Btu/^{o} F-hr-ft^2	C	3.622	1.650
Total insulation	^{o} F-hr-ft^2/Btu	R	0.352	0.1928
Insulation/depth	^{o} F-hr-ft^2/Btu-in.	r	0.962	0.6164
Conductivity	Btu-in./^{o} F-hr-ft^2	k	1.440	0.7621
Depth	inches	D	0.407	0.1782
Length	inches	L	0.883	0.2177
Depth/length	percent	S	46.72	13.953
Diameter	microns	d	48.23	7.502
Number of hairs/area	1000 hairs/in.^{2}	N	13.55	6.027
Areal density	lb/ft^2	D_a	0.188	.0931
Bulk density	lb/ft^3	D_b	5.206	1.364

Figures 7, 8, and 9 show the relations of total insulation to hair length, hair depth, and the number of hairs per unit area. Data in Figures 7, 8, and 9 were collected during the major part of the investigation and show the variation of individual readings. The insulation values indicate the influence of a factor

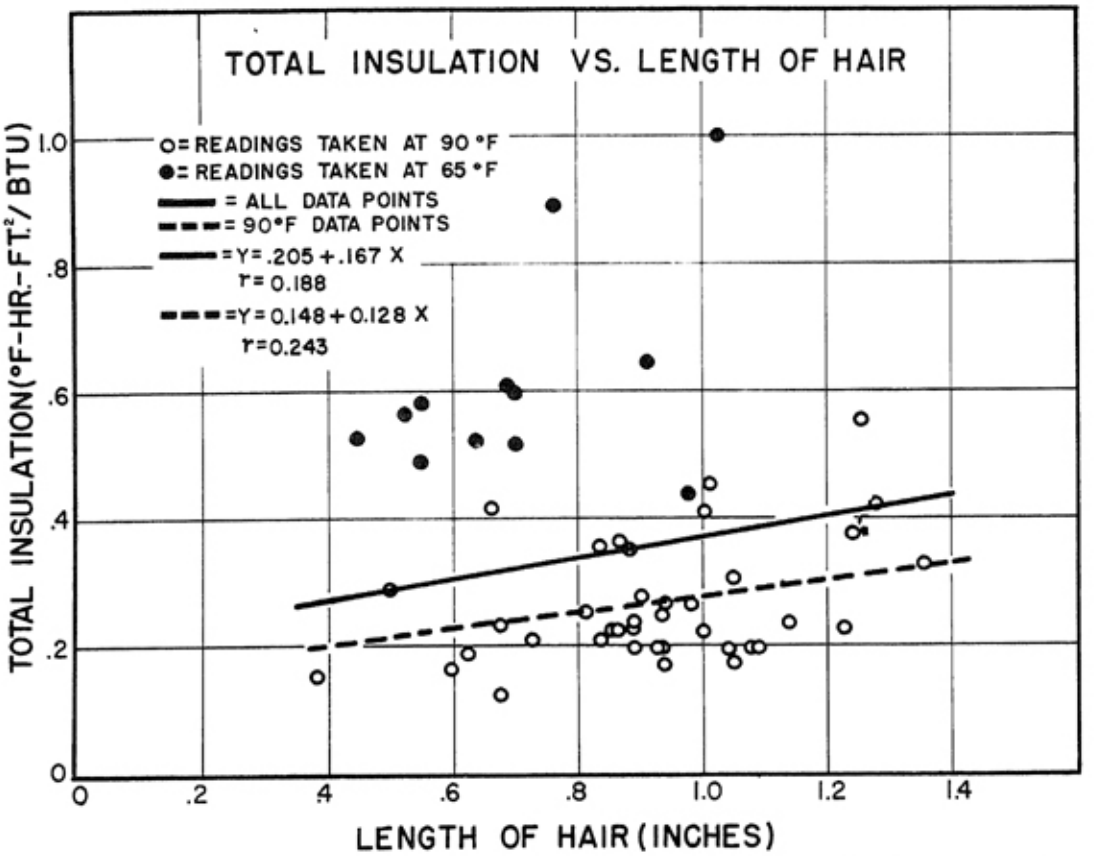

Figure 7—Relation of total hair-coat insulation to hair length. The regression lines were computed with the data in the Appendix.

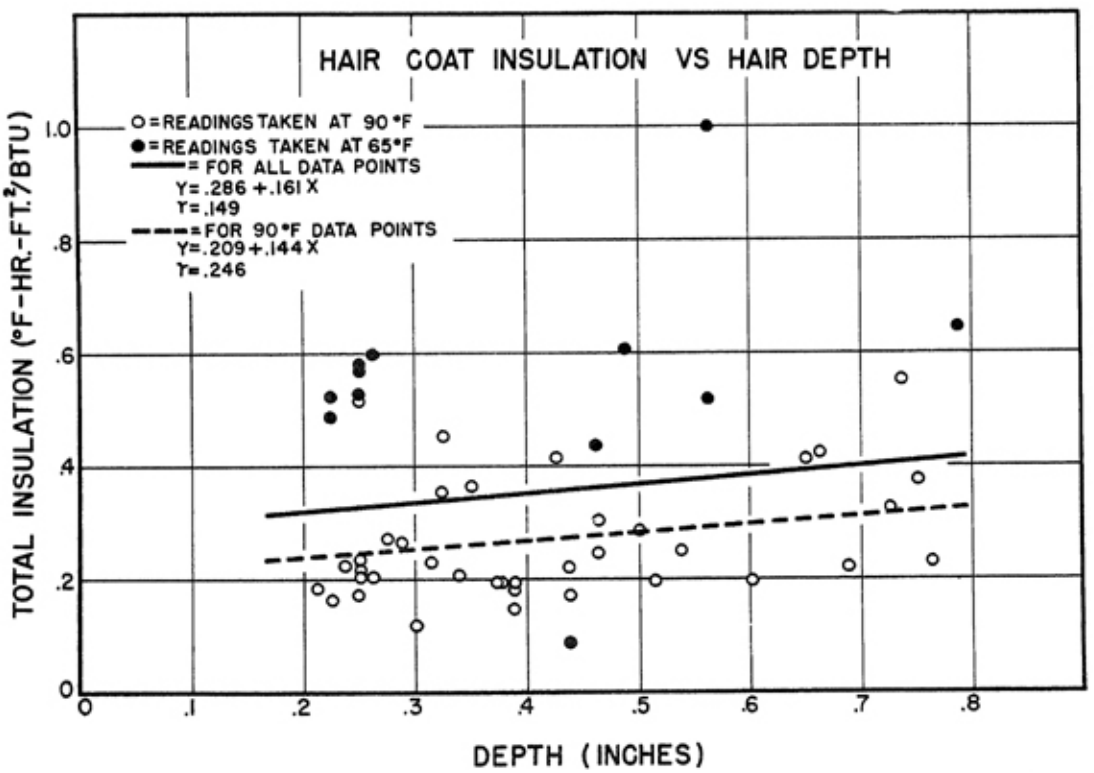

Figure 8—Relation of total hair-coat insulation to hair depth. The regression lines were determined by simple correlation and do not consider the effects of other variables.

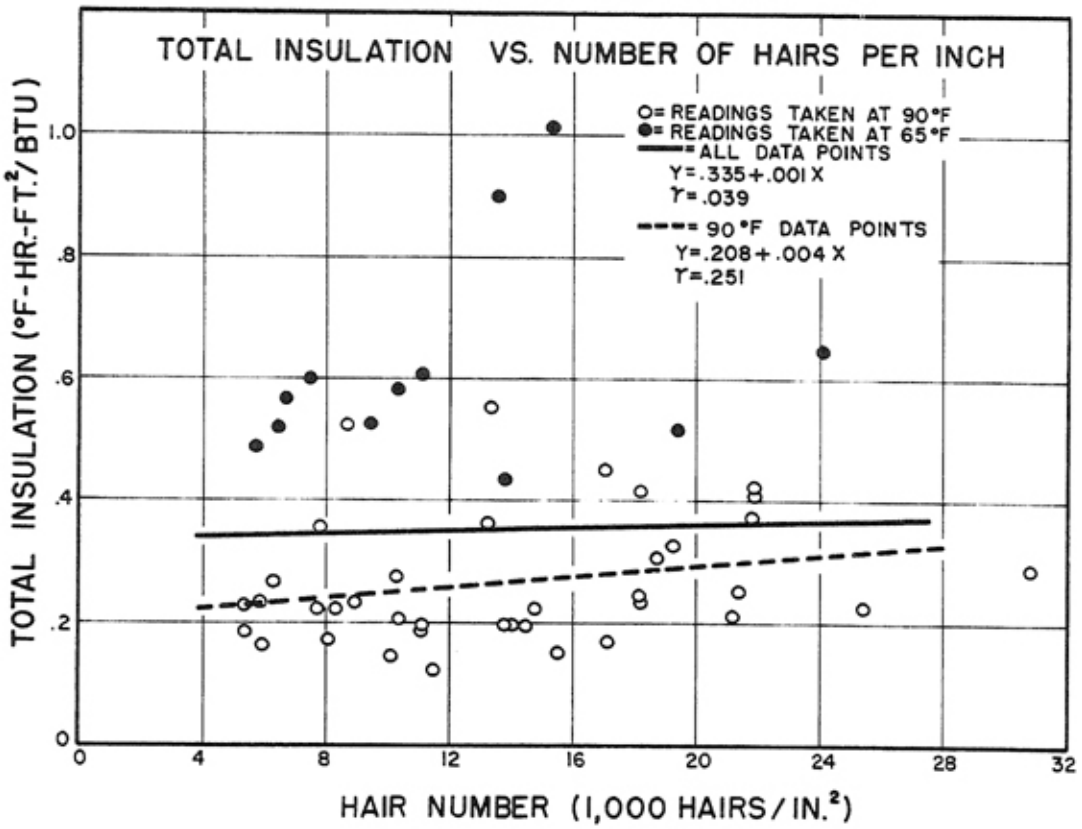

Figure 9—Relation of total hair-coat insulation to the number of hairs per unit area. The regression lines were determined by simple correlation.

which was ignored during the major study. The average of the total insulation values obtained at an air temperature of 65° F was 0.6155 ° F-hr-ft²/Btu, compared to an average of 0.2682 ° F-hr-ft²/Btu obtained at the 90° F air temperature. As air temperature was assumed to affect hair insulation only through its influence on the physical hair-coat characteristics, the difference in insulation shown in Figures 7, 8, and 9 indicates that temperature influenced either the measuring technique or some physical characteristic of the hair coat which was not measured. Because of the apparent temperature influence, further correlations were made with only the data taken at a constant 90° F air temperature.

Complete results of the statistical analyses are in the Appendix. More significant and consistent results were obtained with the regression analyses when hair conductivity or insulation per unit depth, rather than total insulation or conductance, were treated as dependent variables. Depth was not included as an independent variable when conductivity and insulation per unit depth were dependent variables because it was used in the computation of the dependent variables. The increased significance of the correlation coefficients when conductivity was the dependent variable tended to verify the assumption that total insulation was proportional to depth when factors influencing conductivity were held constant.

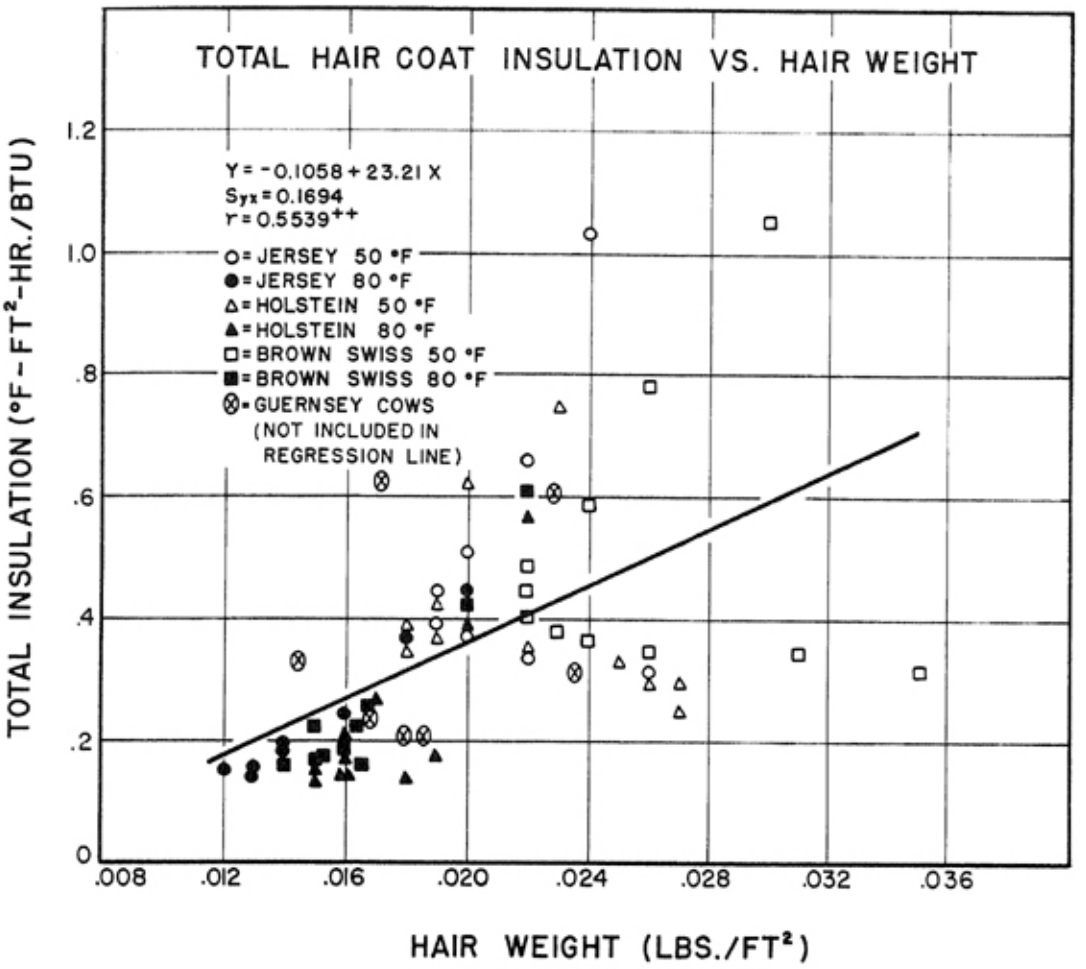

Figure 10—Relation of total hair-coat insulation to hair weight per unit area. The regression line was computed with the data in the Appendix.

Relation of Hair-Coat Weight per Unit Area to Total Insulation

Total insulation and conductance are related to hair-coat weight per unit area in Figures 10 and 11. Total insulation appeared to vary linearly with hair weight. The straight line shown in Figure 10 reduced the sum of squared errors significantly at the 0.01 probability level, as shown by the two asterisks on the correlation coefficient, (r).

The relation of hair conductance to hair weight was assumed to be non-linear. If total insulation were related to hair weight in a linear fashion, then the conductance (the reciprocal of total insulation) would be related to hair weight in the form of a hyperbola. Figure 11 shows the conductance values plotted against hair weight per unit area. The hyperbola shown in Figure 11 was determined by using the reciprocal of the expression fitted to the data in Figure 10, rather than by using the least squares method.

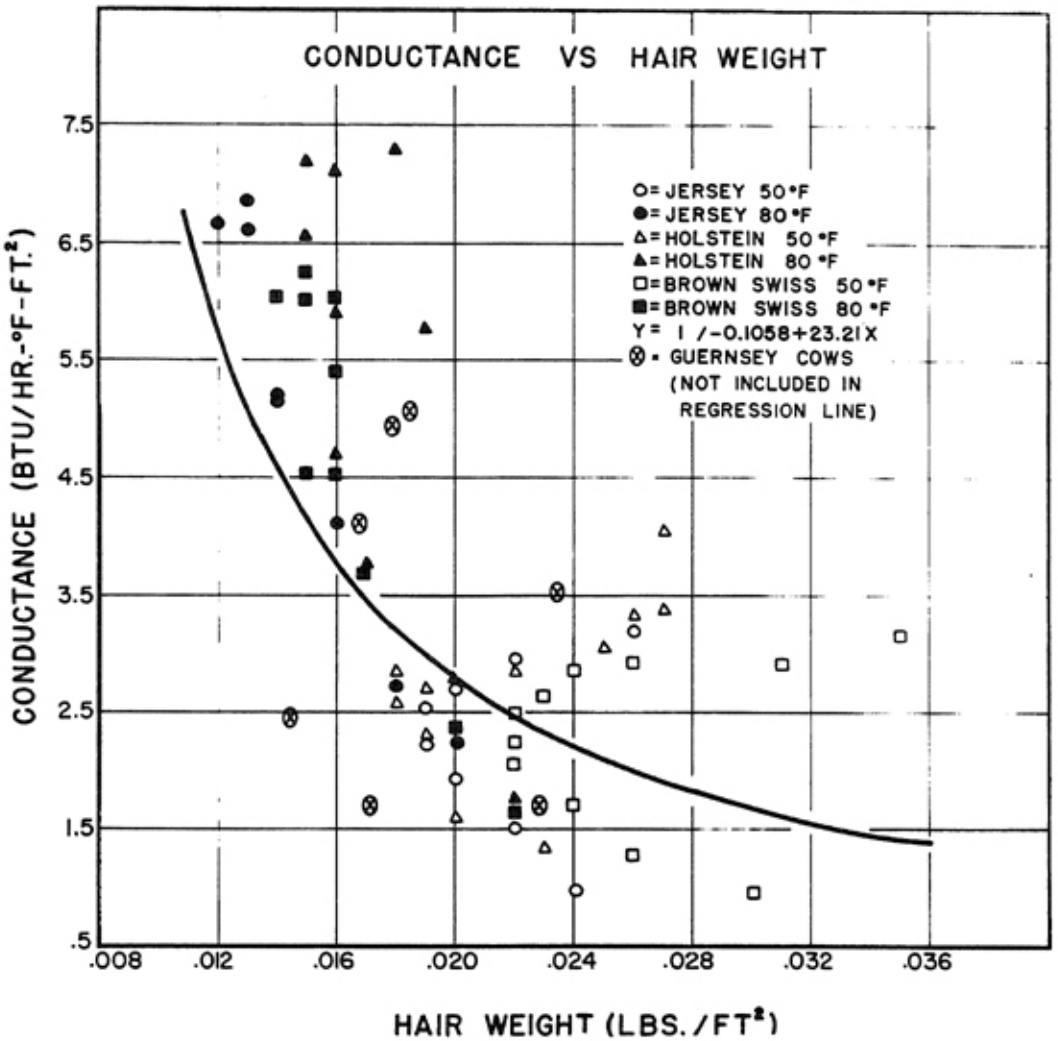

Figure 11—Relation of hair-coat conductance to hair weight per unit area. The conductance values are the reciprocals of the total insulation values in Figure 10.

The nature of the relations shown in Figures 10 and 11 indicate that the net effect of increasing hair weight per unit area on total insulation is the same as that caused by increasing hair depth, when the hair conductivity is held constant. As hair depth was not measured during the preliminary study, the actual influence of depth cannot be determined with the preliminary data shown in Figures 10 and 11.

The preliminary data in Figure 10 indicate the difference in hair weight and the resulting difference in hair insulation due to the difference in temperatures at which the dairy calves were grown. Both the total insulation and the hair weight per unit area were approximately twice as great at 50° F as at 80° F.

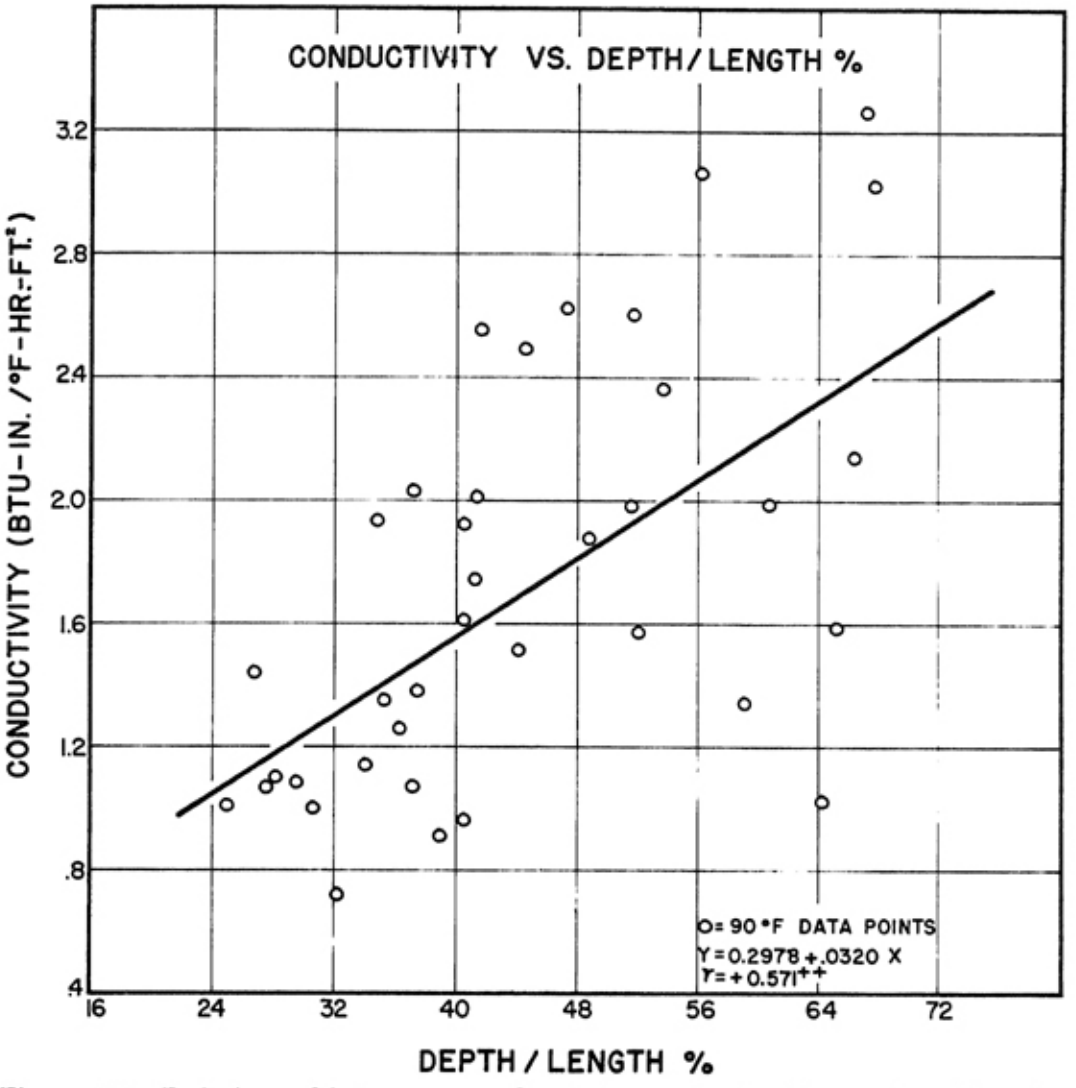

Figure 12—Relation of hair-coat conductivity to the depth-over-length ratio. The regression line was determined by simple correlation of data from Appendix.

Relation of Hair-Coat Conductivity to Hair Orientation

Hair orientation was determined by computing the ratio of hair depth to hair length in percent, a quantity equivalent to 100 times the sine of the angle between the hair and the skin surface. The regression analyses of the data from the major study indicated that hair orientation had more influence on hair conductivity than other factors measured during the major study. The conductivity values taken at 90° F air temperature are plotted against the depth-over-length ratios in Figure 12. The simple regression line fitted to the data reduced the error term by a highly significant amount as shown by the two asterisks on the correlation coefficient, (r), in Figure 12.

Hair conductivity was positively related to the orientation factor in both simple and multiple regression analyses. When the depth-over-length ratio was correlated with insulation per unit depth of hair, the correlation was negative and was not significant, indicating that the measure of orientation affected conductivity in a more linear fashion than insulation.

The significance of the depth-over-length ratio is more apparent when considered in relation to the hair depth. The data in Figure 12 indicate that thermal conductivity was increased as the depth-over-length ratio was increased and the hairs became more nearly parallel with the direction of heat flow. However, for hair of a particular length, an increase in the depth-over-length ratio would increase the hair depth, tending to reduce the over-all conductance of the hair. Consideration of these relations indicates that, for a particular hair coat, a change in the depth and the depth-over-length ratio would result in two reactions of opposite effect, with the net effect on conductance being much less than that of only one reaction. The net effect of such a change in a hair coat may be shown by an examination of the correlation between total insulation and the depth-over-length ratio. This correlation was positive in sign, indicating that an increase in the depth-over-length ratio would increase the total insulation, but would decrease the insulation per unit depth of hair.

Relation of Hair-Coat Conductivity to the Number of Hairs per Unit Area

The regression analyses indicated that the number of hairs per unit area was the second most influential factor affecting the hair conductivity. Increasing numbers of hairs tended to increase the conductivity of the hair, as shown in Figure 13.

Changing numbers of hairs per unit area might affect thermal properties of the hair coat in several ways. An increase in the number of hairs might increase the conduction along and between the hairs, thus increasing the total heat transferred. A larger number of hairs might result in a larger number of still air spaces and surfaces between the air and hair, tending to reduce the amount of heat transferred. An increase in the number of hairs would reduce the size of the air spaces, with an undetermined effect on heat transfer.

The relations indicated by the statistical analyses show that heat transfer was increased by increasing numbers of hairs. In consideration of this observation, it might be assumed that heat flow along the fibers and fiber contacts was a major portion of the total heat transferred and increasing numbers of fibers and fiber contacts resulted in increases in conductivity.

Effects of Hair Diameter and Bulk Density on Hair Conductivity

Results of the statistical analyses were not highly significant or consistent when the variables of hair diameter and bulk density were considered. Hair diameter was significant at the 0.05 probability level when related to conductivity by simple correlation, but the relation appeared to be practically non-existent

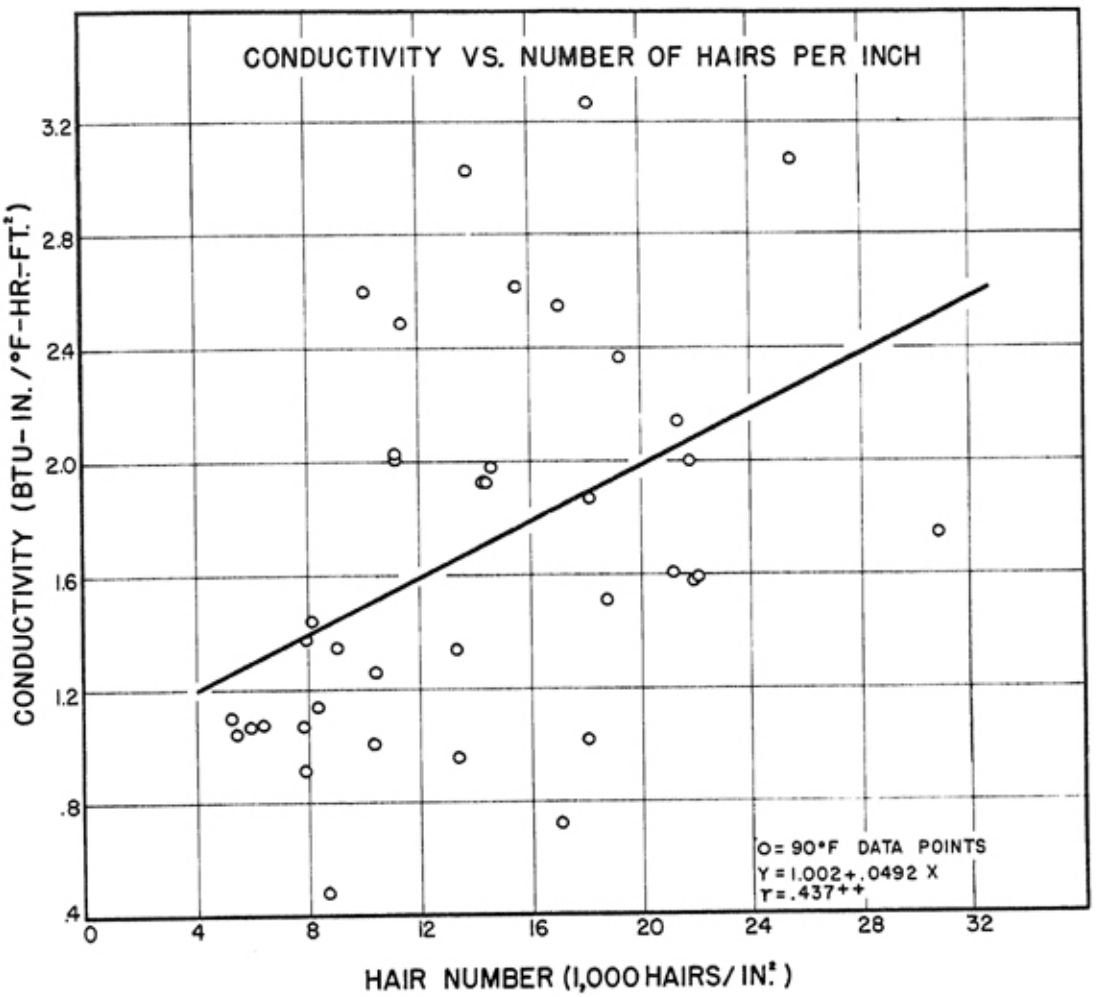

Figure 13—Relation of hair-coat conductivity to the number of hairs per unit area. The regression line was computed by simple correlation of data in the Appendix.

when the combined effect of the other independent variables was considered in the multiple regression analysis.

The factor of bulk density may be directly related to hair diameter and the number of hairs because an increase of these factors for a unit volume would tend to increase the weight of the volume. Inspection of the simple correlation coefficients between the three variables revealed that neither hair diameter nor the number of hairs appeared to be closely related to bulk density. However, the simple correlation between hair diameter and the number of hairs indicated a significant inverse relationship. If bulk density was actually directly related to hair diameter and the number of hairs, the inverse relationship of hair diameter and number of hairs would tend to have opposite effects on bulk density, with a consequent reduction of the variation in bulk density due to these factors.

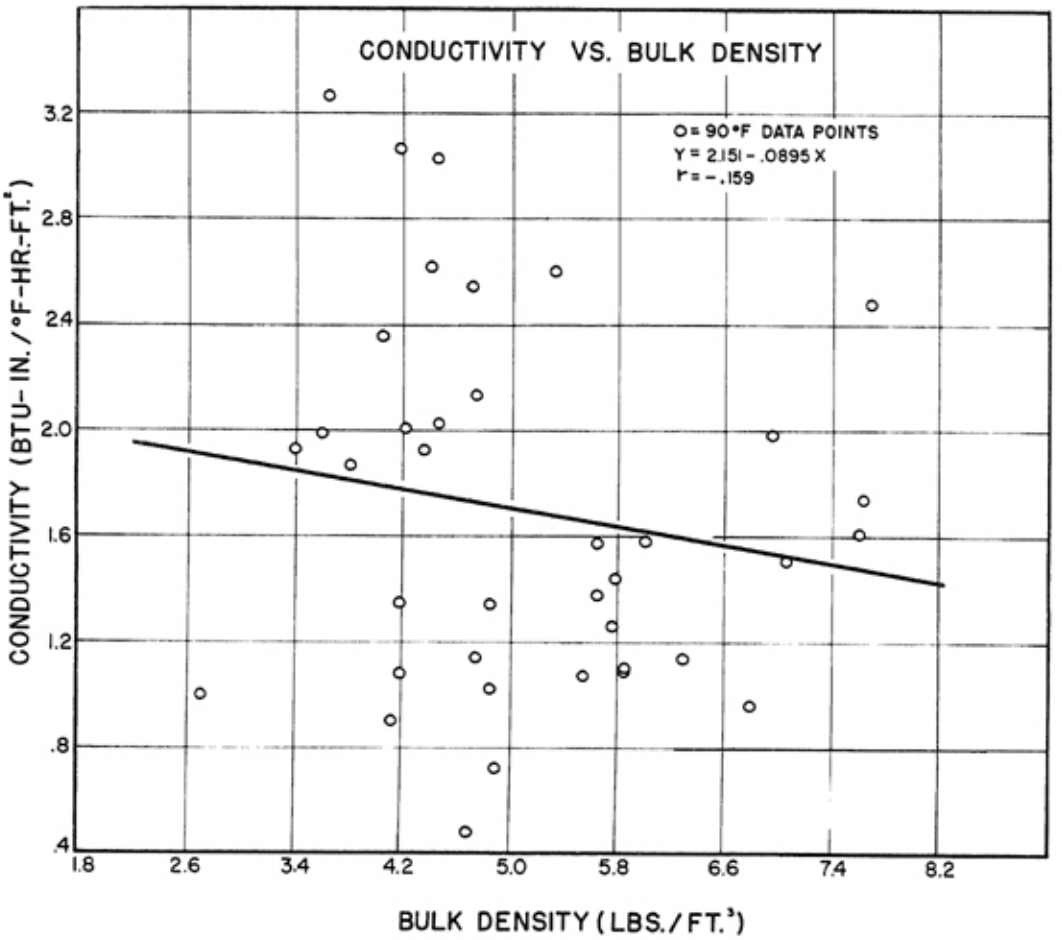

Figure 14—Relation of hair-coat conductivity to the bulk density of hair. The regression line was determined by simple correlation of data from the Appendix.

These observed relations and the possibility of their effect on bulk density indicated that further study of the interrelations was necessary. Partial correlation indexes of the first order were computed and are shown in Table 2, along with the simple correlation indexes. Neither the simple nor the partial correlation indexes indicated any relation of bulk density to the factors of hair diameter and hair numbers, even though hair diameter and the number of hairs per unit area were significantly related. The absence of any observed relation of bulk density to hair diameter, number of hairs, or thermal conductivity indicates that the relation previously shown to exist between conductivity and the number of hairs was probably due to the direct influence of the number of hairs, rather than an indirect influence of a change in bulk density.

Relations Among the Physical Hair Characteristics

Several of the simple correlations between the independent variables were significant at the 0.01 and 0.05 probability levels. Although some of these relations did not appear to be directly related to the thermal properties, certain indirect influences were indicated.

Hair depth appeared to vary directly with hair length. Increasing hair length would tend to reduce the depth-over-length ratio, which was previously shown to vary directly with hair conductivity. These relations indicated that the change in hair depth and length produced the same effects upon the heat transfer, rather than opposing effects.

The depth-over-length ratio varied directly with the number of hairs. Previous discussions have indicated that increases in either of these factors tend to increase heat transfer. Length was shown to vary directly with the number of hairs. As increasing length would reduce the depth-over-length ratio, the net effect of an increase in both of these factors would be a reduced change in heat transfer.

Hair diameter appeared to vary inversely with all three factors of hairs per unit area, depth over length, and hair depth. These factors were previously shown to have opposite effects on heat transfer through hair coats, perhaps partially explaining the limited influence of hair diameter on heat transfer.

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APPENDIX

TABLE 2-SIMPLE AND FIRST-ORDER PARTIAL CORRELATION INDEXES OF THE RELATIONS BETWEEN BULK DENSITY, NUMBER OF HAIRS, AND HAIR DIAMETER

Variables	Bulk Density	Hair Diameter
Hair Number		
Simple	+.1122	-.4556**
Partial	+.1485	-.4639**
Hair Diameter		
Simple	+.0436	
Partial	+.1071	

** Indicates significance at probability level of 0.01.

TABLE 3-HAIR-COAT INSULATION AND CONDUCTANCE AND THEIR RELATION TO HAIR-COAT WEIGHT FOR JERSEY, HOLSTEIN, AND BROWN SWISS CALVES

Breed and Temperature		Age (Weeks)	Hair Weight (lbs/ft^2)	Conductance (Btu/$^\circ$F-ft^2-hr)	Total Insulation ($^\circ$F-ft^2-hr/Btu)
Jersey	50°F	10.4	.024	0.97	1.033
		13.0	.022	1.50	.667
		17.8	.020	1.93	.518
		22.1	.019	2.23	.448
		28.6	.019	2.55	.392
		33.8	.020	2.70	.370
		39.4	.022	2.96	.338
		45.9	.026	3.19	.313
Jersey	80°F	11.3	.020	2.24	.446
		13.9	.018	2.72	.368
		18.6	.016	4.11	.243
		23.0	.014	5.15	.194
		29.5	.013	6.86	.146
		35.5	.012	6.66	.150
		42.5	.013	6.61	.151
		49.0	.014	5.20	.192
Holstein	50°F	9.5	.023	1.34	.746
		12.6	.020	1.61	.621
		16.0	.019	2.28	.438
		19.5	.018	2.86	.350
		22.1	.018	2.58	.388
		24.7	.019	2.71	.369
		29.0	.022	2.88	.347

TABLE 3- (continued)

Breed and Temperature		Age (Weeks)	Hair Weight (lbs/ft^2)	Conductance (Btu/$^\circ$F-ft^2-hr)	Total Insulation ($^\circ$F-ft^2-hr/Btu)
		32.9	.025	3.05	.328
		37.3	.026	3.32	.301
		41.6	.027	3.38	.296
		45.9	.027	4.06	.246
Holstein	80°F	10.4	.022	1.77	.565
		13.9	.020	2.57	.389
		18.2	.017	3.75	.266
		21.2	.016	4.68	.214
		24.7	.016	5.90	.169
		28.6	.015	6.56	.152
		32.5	.015	7.19	.139
		37.3	.016	7.10	.141
		42.5	.018	7.28	.137
		48.1	.019	5.77	.173
Brown Swiss	50°F	10.0	.030	.95	1.050
		14.3	.026	1.28	.781
		18.6	.024	1.71	.585
		21.2	.022	2.06	.485
		24.7	.022	2.25	.444
		27.7	.022	2.49	.402
		31.6	.023	2.64	.379
		35.5	.024	2.75	.364
Brown Swiss	50°F (cont.)	39.4	.026	2.91	.343
		43.3	.031	2.93	.342
		47.7	.035	3.15	.317
Brown Swiss	80°F	11.7	.022	1.65	.606
		15.2	.020	2.37	.422
		19.1	.017	3.74	.267
		22.5	.016	4.54	.220
		25.6	.016	5.41	.185
		29.5	.016	6.04	.166
		33.8	.015	6.26	.160
		37.7	.015	6.02	.166
		42.0	.014	6.05	.165
		46.8	.015	4.53	.221

TABLE 4-HAIR-COAT CONDUCTANCE AND ASSOCIATED PHYSICAL CHARACTERISTICS FOR NON-LACTATING GUERNSEY COWS

Date	Cow Number	Conductance (Btu/^{o}F-ft^{2}-hr)	Depth (inches)	Length (inches)	Diameter (microns)	Numerical Density (1000 hairs/in^{2})	Areal Density (lb/ft)
12/19/60	339	4.29	.762	1.14	40.7	18.1	.232
"	260	5.25	.387	1.04	55.9	11.1	.142
"	334	2.37	.662	1.28	45.8	21.8	.311
"	235	4.48	.238	0.86	56.3	7.8	.115
"	282	2.21	.325	1.01	47.3	17.0	.132
12/20/60	300	4.31	.312	0.89	38.3	9.0	.109
"	339	4.05	.462	0.94	40.4	18.1	.147
"	260	5.19	.388	0.94	46.1	11.1	.136
"	334	2.66	.750	1.24	39.5	21.7	.225
"	282	5.83	.438	1.05	45.5	17.0	.172
"	235	4.78	.262	0.72	49.4	10.3	.126
12/27/60	339	4.47	.688	1.22	38.3	25.4	.240
"	300	6.13	.225	0.60	39.7	7.9	.105
"	260	8.32	.300	0.68	56.7	11.4	.192
"	334	3.47	.500	1.21	43.3	30.7	.316
"	282	4.78	.338	0.84	46.3	21.1	.213
"	235	4.54	.250	1.00	63.0	8.3	.131
12/28/60	339	5.09	.512	1.09	42.9	15.5	.188
"	300	5.36	.212	0.62	52.2	5.4	.084
"	260	5.13	.375	0.92	52.1	14.1	.136
"	334	3.06	.725	1.35	46.8	19.2	.243
"	282	4.53	.438	0.85	44.1	14.6	.250
"	235	5.79	.250	0.94	62.6	8.1	.121
1/3/61	339	3.27	.462	1.05	46.9	18.7	.271
"	300	5.16	.375	1.08	48.1	14.4	.106
"	260	3.65	.275	0.90	76.7	10.3	.202
"	334	1.82	.738	1.25	57.3	13.3	.298

TABLE 4- (continued)

Date	Cow Number	Conductance (Btu/^{o}F-ft^{2}-hr)	Depth (inches)	Length (inches)	Diameter (microns)	Numerical Density (1000 hairs/in^{2})	Areal Density (lb/ft)
1/7/61	282	3.99	.538	0.81	50.8	21.3	.320
"	235	4.41	.250	0.89	55.2	5.2	.121
"	339	2.43	.650	1.00	34.9	21.9	.323
1/10/61	339	5.06	.600	0.89	41.3	13.8	.330
"	260	3.75	.288	0.98	47.9	6.3	.100
"	282	6.73	.388	0.75	50.0	10.1	.171
"	235	4.30	.250	0.67	51.4	5.9	.115
1/17/61	300	2.81	.325	0.84	46.0	7.8	.112
"	260	2.74	.350	0.86	55.5	13.3	.196
"	282	2.40	.425	0.66	51.3	18.0	.171
"*	235	1.90	.250	0.59	45.9	8.7	.098
1/31/61	339	1.12	.438	0.76	49.2	13.5	.211
"	300	1.91	.225	0.45	45.8	9.4	.080
2/1/61	334	1.55	.788	0.91	42.0	24.0	.531
"	282	1.94	.562	0.70	46.0	19.4	.266
"	260	1.77	.250	0.52	44.0	6.7	.177
"	235	2.05	.225	0.55	51.8	5.7	.104
2/7/61	339	2.30	.462	0.98	54.1	13.7	.168
2/8/61	282	1.65	.487	0.69	43.0	11.1	.236
"	235	1.72	.250	0.55	48.1	10.3	.087
"	300	1.92	.250	0.64	40.8	6.4	.044
"	260	1.67	.262	0.70	52.9	7.5	.129
"	334	0.98	.562	1.02	39.9	15.3	.367

* Readings through January 17, 1961, were determined with an air temperature of 90° F. Later readings were determined at 65° F. air temperature.

TABLE 5-PARAMETERS OBTAINED BY MULTIPLE LINEAR REGRESSION AND CORRELATION OF TOTAL INSULATION WITH DEPTH-OVER-LENGTH RATIO, BULK DENSITY, HAIR DIAMETER, NUMBER OF HAIRS PER UNIT AREA, HAIR LENGTH, AND HAIR DEPTH

Averages and Standard Deviations[1]

Variable	Symbol	Average	Standard Deviation
Total Insulation	R	0.3517	0.1928
Depth/Length (%)	S	46.722	13.953
Bulk Density	Db	5.206	1.364
Hair Diameter (microns)	d	48.226	7.502
Number of Hairs (1000/in.^{2})	N	13.552	6.027
Hair Length (Inches)	L	0.8826	0.2177
Hair Depth (Inches)	D	0.4074	0.1782

[1]Dimensional units are those presented in Table 1.

Variables		Regression and Correlation Coefficients Correlations		Regressions		
Dependent	Independent	Simple	Partial	Simple	Partial	Standard Partial
R	S	+.399*	+.219	+.0055*	+.0068	+.4888
R	Db	+.153	+.144	+.0216	+.0194	+.1370
R	d	-.184	-.039	-.0047	-.0011	-.0416
R	N	+.039	-.155	+.0012	-.0081	-.2520
R	L	-.188	-.037	-.1667	-.0790	-.0891
R	D	+.149	+.016	+.1608	+.0463	+.0428
S	Db	+.082				
S	d	-.472**				
S	N	+.568**				
S	L	+.075				
S	D	+.677**				
Db	d	-.013				
Db	N	+.144				
Db	L	-.141				
Db	D	-.029				
d	N	-.398*				
d	L	-.085				
d	D	-.414*				
N	L	+.596**				
N	D	+.699**				
L	D	+.700**				

* Significance at .05 probability
** Significance at .01 probability

TABLE 6-PARAMETERS OBTAINED BY MULTIPLE LINEAR REGRESSION AND CORRELATION OF CONDUCTIVITY AND INSULATION PER UNIT DEPTH WITH THE DEPTH-OVER-LENGTH RATIO, NUMBER OF HAIRS PER UNIT AREA, BULK DENSITY AND HAIR DIAMETER

Averages and Standard Deviations[1]

Variable	Symbol	Average	Standard Deviation
Conductivity	k	1.693	0.6916
Insulation/Unit depth	r	0.708	0.3428
Depth/Length (%)	S	44.166	12.343
Number of Hairs (1000/in.^{2})	N	14.066	6.135
Bulk Density	Db	5.112	1.2316
Hair Diameter (Microns)	d	48.782	8.159

[1]Dimensional units are those presented in Table I.

Variables		Regression and Correlation Coefficients Correlations		Regressions		
Dependent	Independent	Simple	Partial	Simple	Partial	Standard Partial
k	S	+.571**	+.355	+.0320**	+.0232*	+.4133
k	N	+.437**	+.148	+.0492**	+.0179	+.1590
k	Db	-.159	-.134	-.0895	-.0634	-.1130
k	d	-.374*	-.097	-.0317*	-.0078	-.0924
r	S	-.416**	-.212	-.0116**	-.0072	-.2611
r	N	-.406*	-.202	-.0227*	-.0136	-.2428
r	Db	+.020	+.010	+.0057	+.0025	+.0088
r	d	+.256	+.016	+.0108	+.0007	+.0163
S	N	+.601**				
S	Db	-.146				
S	d	-.494**				
N	Db	+.112				
N	d	-.456**				
Db	d	+.044				

* Significance at .05 probability

** Significance at .01 probability