TOPIC 3. CONDUCTION

Conduction is the transfer of heat energy in which kinetic energy is passed from one molecule to another by collisions. Thermal conductivity depends on the availability of free electrons drifting through intramolecular space, so metals, with an abundance of free electrons, are good conductors, and organic materials are generally poor conductors. Air has a low thermal conductivity, and air trapped between hairs in an animal's coat contributes significantly to the insulating properties of the hair coat.

Conduction is associated with temperature gradients as faster vibrating molecules, characteristic of higher heat energy, strike slower vibrating molecules and give up energy. Energy is dissipated from regions of higher temperature to regions of lower temperature regions. When the energy is equally distributed, molecular vibrations are on the average, uniform and energy exchange by conduction is equal in all directions.

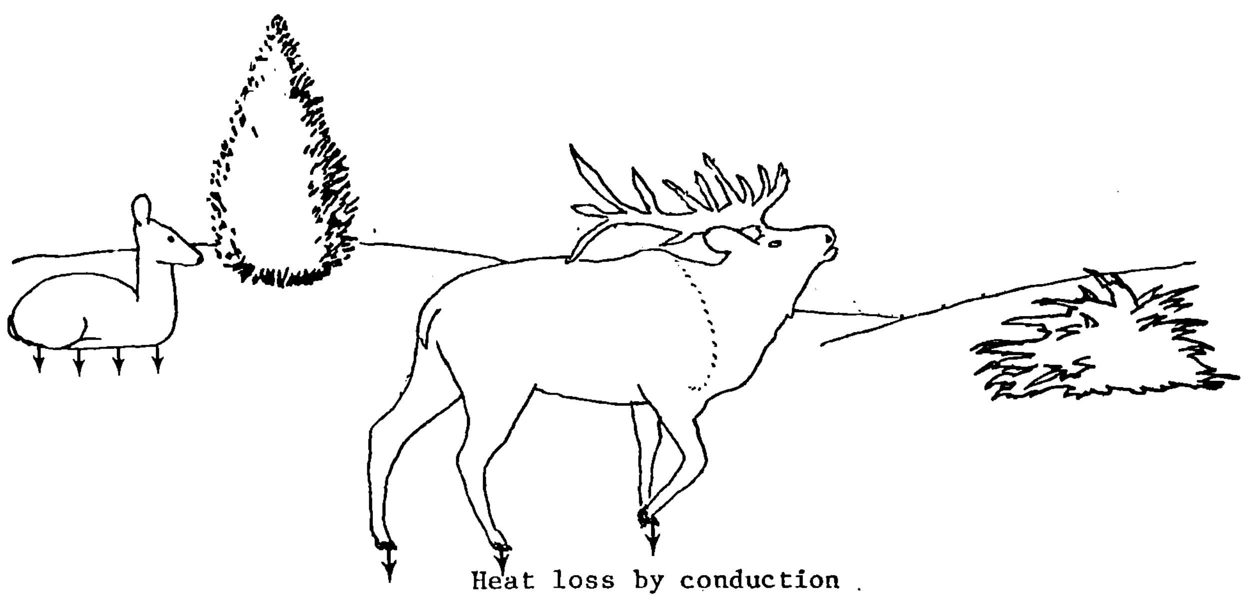
Ecologically, conduction is an important mode of heat transfer through the hair coats of animals to the soil and snow. An animal bedded in the snow, for example, has a subskin temperature that is higher than the snow. Heat energy passes through the skin and hair coat to the snow. The rate at which heat energy is conducted through the insulating hair is dependent on the depth of the insulating material, the temperature gradient between the skin and the snow, and the efficiency with which the hair conducts heat. The efficiency is expressed as a thermal conductivity coefficient, and is often represented by the symbol k. It is analagous to the convection coefficients discussed in the previous TOPIC.

The thermal conductivity coefficient may be defined as the rate at which heat passes through a given distance (one cm for example) of a substance when there is a temperature gradient of one degree. A good conductor has a higher thermal conductivity than a poor conductor. Hairy winter coats are expected to be poor conductors, of course.

The depth of the conducting material is an important variable in calculating conduction; the greater the depth of the conducting material, the less heat transfer by conduction. In other words, heat loss is inversely proportional to the depth of the hair coat.

The temperature difference across the hair coat is also important, of course; the greater the temperature difference, the more heat energy is transferred by conduction. Heat loss is directly proportional to the temperature difference across the hair coat. The actual depths and temperature differences act together, along with the thermal conductivity coefficient, in determining the actual amount of heat loss per unit area. Surface area and time are multipliers after the rates per unit time and area are determined.

Heat transfer by conduction is an important consideration for bedded animals since the loss of heat by conduction to the substrate is an important component of the total heat loss. This kind of conduction, with the conducting material (hair) enclosed between two barriers (skin and snow or soil) with no exposure to variable atmospheric conductions, is considered to be static conduction (UNIT 3.1). Hair exposed to the atmosphere has variable thermal conductivity coefficients as wind, moisture, and air temperature alter the thermal properties of the hair. No single thermal conductivity value is representative of the insulating qualities of porous materials such as hair under changing atmospheric conditions; this kind of conduction is called dynamic conduction (UNIT 3.2). Some important considerations pertaining to the use of static and dynamic conductivity coefficients are discussed in the next two UNITS.



Heat loss by conduction

UNIT 3.1: STATIC CONDUCTION

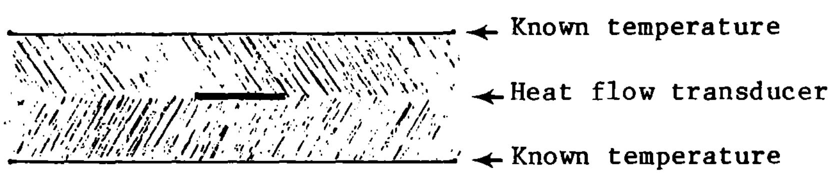
Static conduction occurs when the conducting material is enclosed between two solid barriers. The insulation between the walls of a home is enclosed between two solid barriers, the inside wall and outside wall, and hair in contact with the snow on the trunk of a bedded animal is enclosed between two solid barriers, the skin and the snow.

The quantity of heat conducted (QHCO) can be expressed with the formula:

$$\mathrm{QHCO = (TCCO)(SACD)(TIME)[(DLTA)/DPTH)]}$$

where QHCO = quantity of heat conducted,
TCCO = the thermal conductivity coefficient per cm of hair depth, which must be expressed in the units for QHCO (kcal per square meter per hour, for example),
SACD = surface area involved in conduction,
TIME = time,
DLTA = delta T = temperature difference, and
DPTH = depth of conducting material.

Thermal conductivity coefficients are determined by enclosing the insulating material to be tested between two surfaces with different temperatures at a known distance apart. This is the procedure used in determining thermal conductivity coefficients with the Thermal Conduction Apparatus at Cornell's Wildlife Ecology Laboratory (See Evans and Moen 1975). The design the the Thermal Conduction Apparatus is illustrated below.



The heat energy conducted through the material being tested is measured directly and the formula above rearranged to solve for TCCO. If SACD = 1 unit and TIME = 1 unit, these may be dropped from the formula, and the rearrangement completed as shown below.

$$\mathrm{QHCO = TCCO\ [(DLTA)/(DPTH)]}$$

which can be rearranged to:

$$\mathrm{TCCO = [QHCO][(DPTH)/(DLTA)]}$$

The published literature on conductivity coefficients is based on these kinds of measurements. Values of k determined in this way are applicable to the surfaces of the animal in contact with the substrate; the insulating hair is enclosed between two barriers: skin and snow. The results of such measurements of static conduction should not be used when calculating heat loss from the skin surface to the free atmosphere. Atmospheric effects on conduction are discussed in the next UNIT (3.2) on DYNAMIC CONDUCTION.

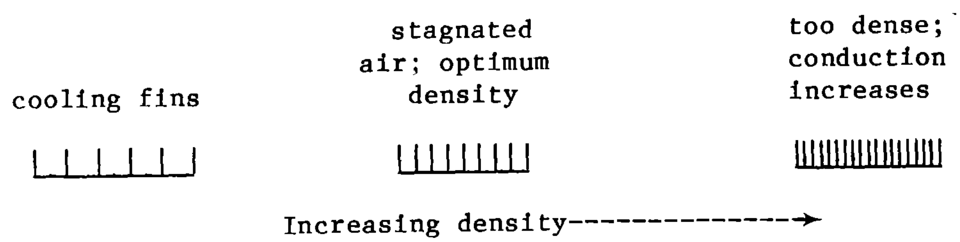
Measured conductivity coefficients of the coats of different species of wild ruminants tabulated below provide some indication of the amount of variation between species and between season. Since the depth of the insulating layer is part of the calculation, depth of the hair in cm (DHIC) must be known before TCCO can be applied. QHCO = quantity of heat (kcal m^{-2} hr^{-1}) conducted through the hair layer given, and is determined from TCCO/DHIC.

SPECIES	PELT CONDITION	DHIC	TCCO	QHCO	REFERENCE	
odvi	Early fall, fresh	1.70	3.32	1.95	Hammel	1953
			3.30	1.94		
			3.29	1.94		
			(3.30)	1.94		
odvi	winter	2.39	3.06	1.28	Moote	1955
rata	Fresh winter pelt	2.50	2.88	1.15	Hammel	1953
rata	parka	1.50	3.26	2.17	Hammel	1953
rata	winter	3.28	3.81	1.18	Moote	1955
rata	summer	1.19	3.13	2.66	Moote	1955
rata	thin summer	0.74	3.06	4.14	Moote	1955
			3.21 ± 0.30			

Division of these thermal conductivities for different kinds of hair coats by their depths results in expressions of conductivity coefficients on a per-unit-depth basis, and the different hair coats can be compared. Then, conductivity coefficients of different species are not greatly different; the mean $\pm$ SD is 3.21 ± 0.30. Maximum TCCO is 3.81 kcal m^{-2} hr^{-1} $^{o}C^{-1}$, which is 1.32 times minimum k of 2.98, both observed in caribou. Hair depths, however, varied from 0.74 cm to 3.28 cm, a ratio of 4.43. Thus it appears that differences in hair depths contribute more to differences in overall insulation of wild ruminants than differences in the characteristics of the hair coats of different species.

Stagnant air is a poor conductor of heat and thus is good insulation. In fact, the major role of fibrous insulation such as hair is its stagnation effect on the air between the fibers, and the insulating values of hair coats is most related to their ability to trap and stagnate air. If the hair is very dense, there is less air space and conductivity will actually increase if the hair shafts are better conductors than air. This was discussed by Hammel (1953) and demonstrated for cattle.

Interesting considerations can be raised concerning the function of the hair coat as a layer of insulation in relation to the role of individual hairs as cooling fins. Scattered individual hairs, projections from the skin, function as effective cooling fins as their small diameter keeps them closely coupled to the atmosphere. When their density increases and they tend to slow down and stagnate the air, then the hairs begin to function as a layer of insulation. The transition from the two functions--convection and conduction--is dependent on the density of the hairs. Optimum hair density as a layer of insulation occurs when the contribution of the stagnant air to the overall insulation of the hair-air interface is at maximum. Hair that is too dense results in an increase in conductivity.



Conductivity of air is temperature dependent, being greater at higher temperatures. It is 2.07 kcal per square meter per hour per cm depth at 0 C, so 2.07 is the intercept a in the equation below, and the change in conductivity for each degree (Celsius) change in air temperature is 0.00648. The linear regresion equation is (from Moen 1973; 98):

$$CCAI = 2.07 + 0.00648\ AITE$$

where CCAI = conductivity coefficient of air, per cm depth, in kcal per square meter per hour per °C, and
AITE = air temperature in °C.

This equation rather than a single value will be used in later calculations of the conductivity of air. Note that the conductivity of air at 0°C is only 64% of the average conductivity of deer and caribou hair (2.07/3.21 = 0.64). Air is better insulation than hair, which doesn't seem right until it is remembered that the air must be stagnant. The moving air in the atmosphere around an animal does not meet that condition. The properties of the hair coat which stagnate the air are most important in determining the overall insulation of the hair coat.

Compression effects. The compression of fibrous insulation such as hair maybe an important consideration in the rate of conductive heat loss. A bedded deer, for example, compresses the hair on its legs and trunk, and it is generally known that compression of insulation, reducing both its thickness and the amount of air space in it, reduces its effectiveness as insulation.

Effects of hair inclination. The inclination of the hair shafts can theoretically affect the rate of conduction through the hair, with the lowest rate of conduction when the fibers are parallel to the plane of the insulation and perpendicular to the plane of the insulation and parallel to the direction of heat flow (See Moen 1973). Hair in normal lie falls between these extremes. Piloerection decreases the insulation value of the fur per unit depth, but the increase in depth compensates for the change in hair inclination (Hammel 1953); the total insulation of erect fur was slightly greater than the total insulation of fur in normal position. While this consideration is of definite interest, data on different species are lacking because of the difficulty, if not impossibility of measuring heat flow in vivo on piloerected and normal-lie hair. Further, metabolic considerations which result from muscular contractions necessary to erect the hair also affect the thermal exchange through the hair surface. This is discussed by Moen (1973:282-283).

Effects of moisture. The amount of moisture in the coat has a marked effect on the rate of heat flow through the hair layer. This was indicated by the large increase in the metabolism of infant caribou when their coats were wet (see CHAPTER 16, UNIT 1.6), and by observations at the Wildlife Ecology Laboratory of deer bedded during sleet-like snow when the heart rate was 100% higher and breathing rate 23% higher than on another day two weeks earlier when snow was not falling (Moen and Jacobsen 1973:521). Moisture not only changes the conductivity per se, but adds the further consideration of heat loss by evaporation which, due to the large heat of vaporization, is potentially great. There are no data on conductivity coefficients of hair coats with different amounts of moisture, however.

The discussions in this UNIT have centered on the role of hair in static conduction, applicable only to an insulation enclosed between two barriers and not to hair coats exposed to the atmosphere. Considerations necessary when analyzing thermal conductivity characteristics of hair coats exposed to the atmosphere are discussed next, in UNIT 3.2: DYNAMIC CONDUCTIVITY.

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Moote, I. 1955. The thermal insulation of caribou pelts. Textile Res. J. 25(10):832-837.

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STATIC CONDUCTION

SERIALS

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odvi

CODEN VO-NU BEPA ENPA ANIM KEY WORDS----------------- AUTHORS---------- YEAR

odhe

CODEN VO-NU BEPA ENPA ANIM KEY WORDS----------------- AUTHORS---------- YEAR

ceel

CODEN VO-NU BEPA ENPA ANIM KEY WORDS----------------- AUTHORS---------- YEAR

alal

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
TRJOA	55-10	832	837	rata	thermal insulation of pelt	moote,i	1955

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
				anam			

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
				bibi			

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				oram			

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
PHZOA	30--2	93	105	many	melt pt anim fat cold clim	irving,l; schmid/	1957

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
AGMYA	18--5	387	400	dosh	conduction sheep to ground	gatenby,rm	1977
PHMBA	19--1	51	65	dosh	heat bal, therm resis, fle	cena,k; clark,ja	1974

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
ANYAA	53---	600	607	mamm	piliary sys, reln thrm env	herrington,lp	1951
BISNA	22-11	656	659	----	newtn's lw, ht los homeoth	tracy,cr	1972
CBCPA	21--2	405	414	----	therm con in brds and mamm	herreid,cf,ii;ke	1967
CJZOA	34...	53	57	----	season chngs in fur insula	hart,js	1956
PRLBA	188--	395	411	----	conducton, convectn, coats	cena,k; monteith,	1975

CHAPTER 15, WORKSHEET 3.1a

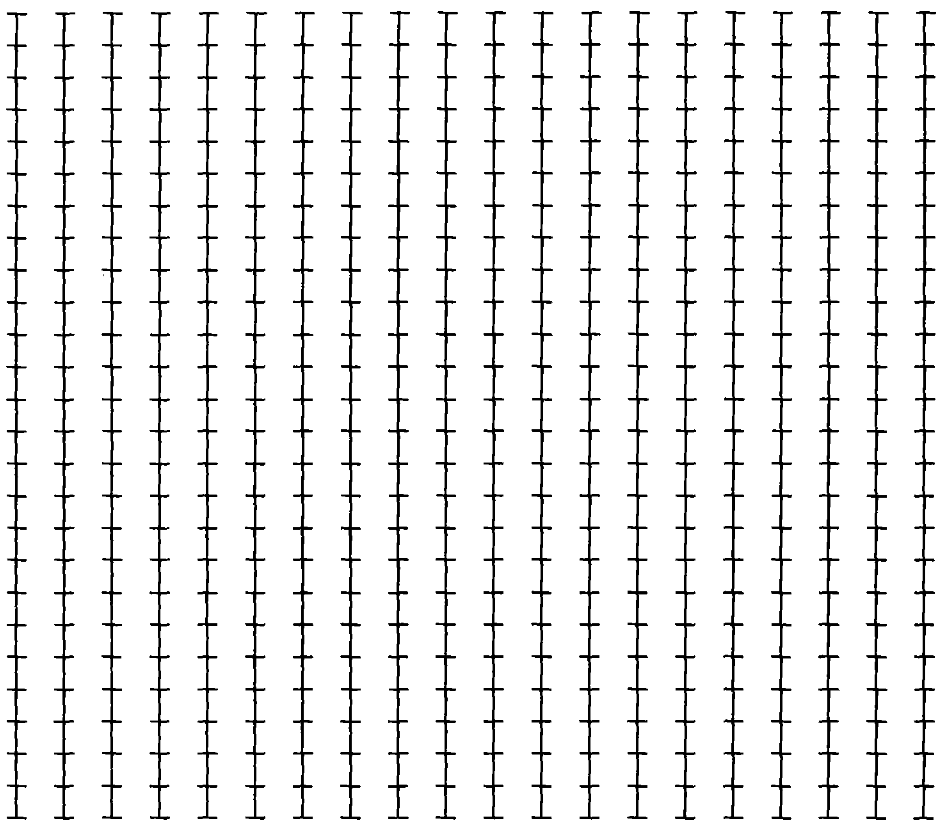
Conduction through the hair layer

Conduction through the hair layer with different conductivities per unit depth may be calculated with the following formula (See p. 37):

QHCO = TCCO [(DLTA)/(DPTH)]

Using data given on page 38 and other data available, plot conduction losses for different thermal conductivity coefficients and hair depths.

QHCO



TCCO or DHIC

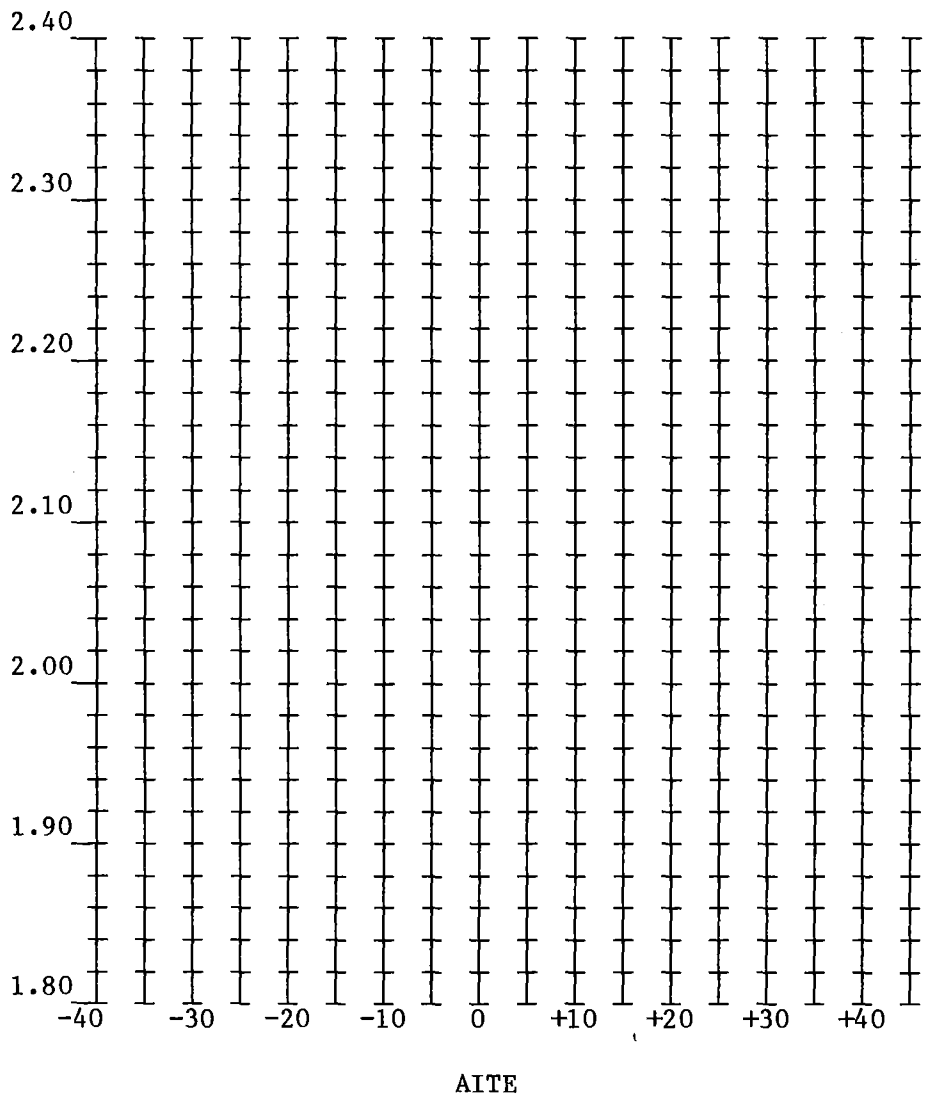
CHAPTER 15, WORKSHEET 3.1b

Conductivity of stagnant air in relation to air temperature

The conductivity coefficient of air, CCAI, in kcal per sq meter per hour per °C per cm depth may be calculated with the following equation, modified from Moen (1973):

$$CCAI = 2.07 + 0.00648\ AITE$$

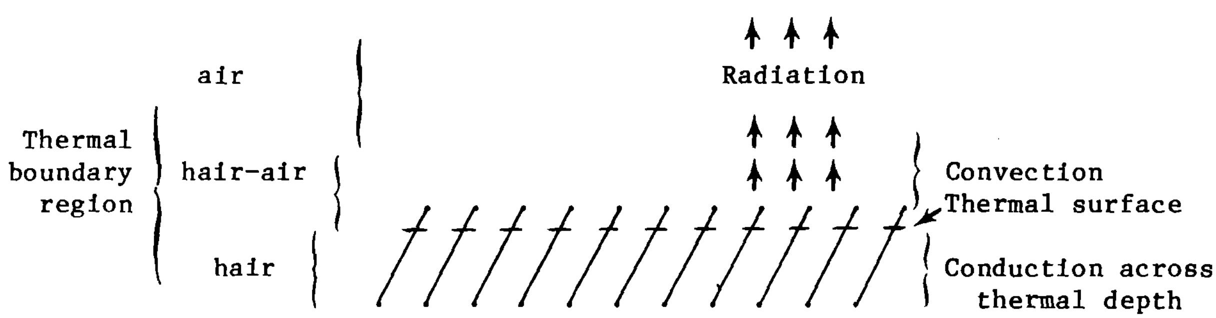
where AITE = air temperature in °C. Plot the results below.



UNIT 3.2: DYNAMIC CONDUCTION

The insulating value of fibrous hair coats when they are exposed to the atmosphere may be quite different from their insulating value when in direct contact with the soil or snow. Air penetrates the hair coat as a result of natural convection currents and wind, disturbing some of the air in the spaces between the hairs. The penetration of such fibrous insulation (hair) by wind alters its insulating value. The depth to which the wind penetrates is dependent on wind velocity and turbulence, with the velocity affecting the inertia of the wind as it strikes the coat and direction affecting the angle of attack by the wind.

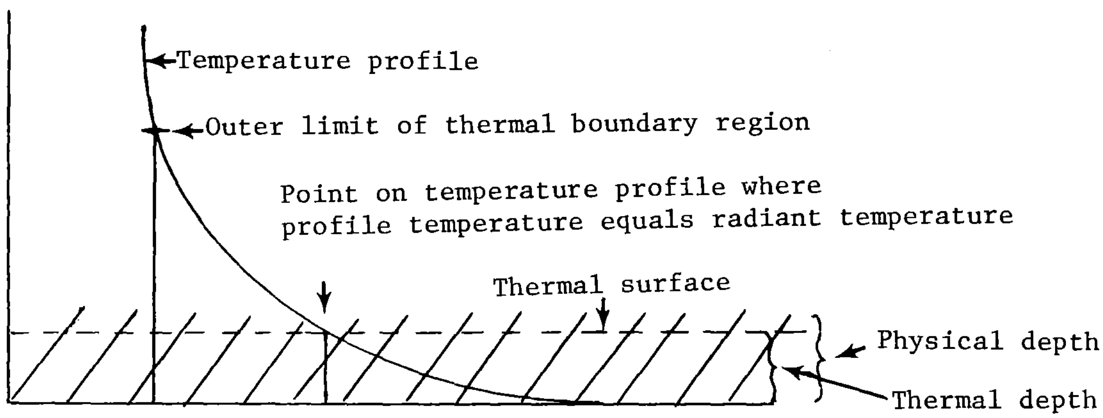
The depth of the hair (insulation) is a major factor determining the overall insulation of a hair coat. Disturbance of the air in the hair layer due to wind reduces the insulating value of the hair coat. If the disturbance were complete and there was no stagnant air present, conduction would no longer occur and heat transfer would be by convection and radiation only. This is not the case for wild ruminants, however, as their thick and rather long hair coats stagnate the air in the hair-air interface. Conduction is the dominant mode of heat transfer deep within the hair, and convection and radiation in the outer parts of the hair coat. This is illustrated below.



The heat loss by convection and radiation from the outer surfaces must equal the heat lost by conduction to the outer surfaces from the skin surface. As wind velocities and radiation flux change, conductivity changes due to changes in the temperature gradients and in the depth of the thermal boundary region. The conductivity of the entire physical depth of the hair coat must change as the air within the coat is disturbed; a single thermal conductivity coefficient cannot apply to a hair coat when atmospheric effects are considered. Several factors affecting these changes are discussed next.

THERMAL DEPTH

The dynamic, functional hair depth that is due to thermal characteristics of the pelage is called thermal depth (Moen 1973:261-262). It is determined by measuring the temperature profile from the skin out to the ambient atmosphere and the radiant temperature of the hair surface. Then, the point on the temperature profile where the radiant temperature equals profile temperature is determined, and the distance from that point to the skin is the thermal depth. The thermal depth can be measured on the plotted curves or determined mathematically after curve fitting the temperature profile. Thermal depth in relation to physical depth and the temeprature profile is illustrated below.



THERMAL SURFACE

The plane parallel with the skin at the outer limit of the thermal depth is the thermal surface. It is the location of the radiant temperature, integrated over the horizontal and vertical depth of the target viewed by the radiometer, on the temperature profile. Thermal depth and thermal surface are theoretical parameters which, after measuring temperature profiles and radiant surface temperatures over a wide range of temperatures and wind velocities, illustrate the effects of wind and radiation on the effective depth of the insulating hair. The thermal depth approach and the concept of dynamic conductivity should divert attention away from the use of measured static conductivities for hair exposed to the atmosphere. An alternate and fundamental concept of insulation around animals is introduced in the next UNIT.

REFERENCES, UNIT 3.2

DYNAMIC CONDUCTION

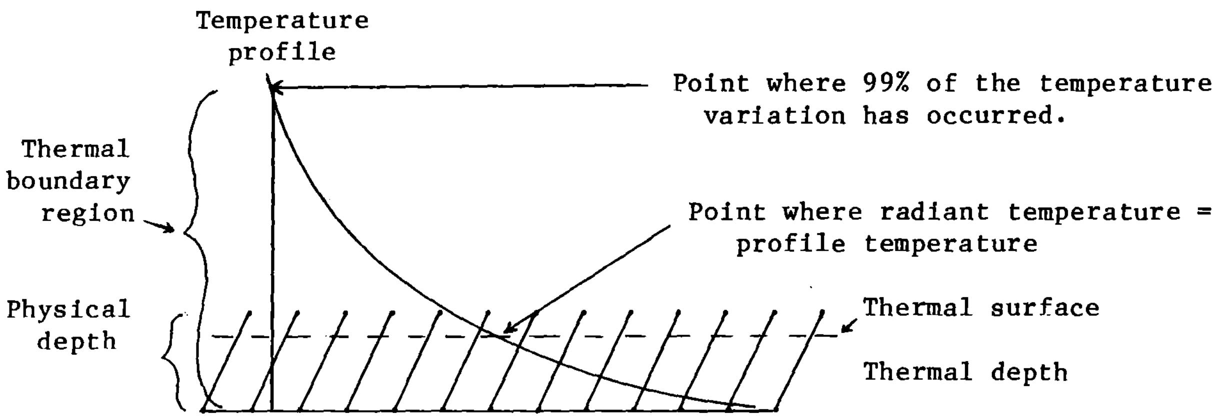
SERIALS

CODEN VO-NU BEPA ENPA ANIM KEY WORDS----------------- AUTHORS---------- YEAR

[No references on the concept of dynamic conduction have been found in the literature. Measurements of temperature profiles and heat transfer through pelts of animals have not been made.]

UNIT 3.3: THE THERMAL BOUNDARY REGION

The hair of an animal is usually thought of as its insulation, but that is a convenient rather than a correct conclusion. The hair coat of an animal is only part of the insulating medium surrounding the animal. The entire insulating medium is the thermal boundary region, and this is composed of the hair and the air surrounding the animal that is influenced by the animal and its coat of hair. Visualize an animal as being surrounded by a region of warmer air that can be delineated by a temperature profile through the hair-air interface as pictured below.



The outer limit of the thermal boundary region is defined as the point on the profile where 99% (a value commonly used in thermal engineering) of the variation in temperature from the skin to the free atmosphere has occurred. Since the outer part of the thermal boundary region is nothing but air with varying temperatures and densities, it is obviously very labile. The thermal boundary region has a greater depth in still air than in the wind, of course, since wind forcefully removes the warmed air next to the hair. A strong gust of wind just about completely destroys the thermal boundary region.

Identification of the thermal boundary region requires a series of temperature measurements from skin to ambient air. Such measurements must be made under controlled conditions, and have not been made for any of the wild ruminants except white-tailed deer. This species has been analyzed in the Thermal Environment Simulation Tunnel (See Moen 1973: Chapters 5,6, and 13) at the Wildlife Ecology Laboratory, Cornell University, where thermocouples were used at various distance intervals to measure temperatures through the entire thermal boundary region of different hair coats. The thermal boundary region may be divided into 3 layers: the hair layer, hair-air interface, and the air layer. Heat transfer occurs through each of these layers, at rates dependent on the thermal resistance of each layer. The overall resistance is equal to the sum of the resistances of each layer. Since the thermal boundary region is composed of both hair and air, convection and radiation exchange occur in addition to conduction. Thus an overall heat transfer coefficient is appropriate, describing the efficiency of heat transfer under different combinations of hair depths in relation to radiant energy, wind velocities, and air temperatures. Needless to say, no single overall heat transfer coefficient applies to a species, but there is rather a pattern of relationships between these thermal forces and the animal's hairy surface. Results of thermal boundary region measurements on white-tailed deer, analyses of data, and applications of this approach to thermal analyses are discussed in CHAPTER 16, TOPIC 2. Before going on to that, however, one more mode of heat transfer, evaporation, is considered here in CHAPTER 15.

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REFERENCES, UNIT 3.3

THE THERMAL BOUNDARY REGION

SERIALS

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