WIND-CHILL INDEX FOR SHEEP

by

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Chapter I

INTRODUCTION

It has been established that dry bulb temperature and wind velocity are the major variables which contribute to reduction of the effective temperature[1] during cold stress. Effective temperature is not similarly related to wind and cold separately but is affected by a combination of the two, commonly expressed as the wind-chill effect. The United States Weather Bureau has prepared and uses a wind-chill index for humans (bare-skinned animals); however, work by Insley and Ames (1970) indicates that the predicted cooling power of wind and cold by conventional wind-chill indices is invalid for animals with external insulation.

It was the goal of this study to present a prediction equation for the rate of heat loss in sheep during cold-wind combinations. Methods for predicting performance, maintenance requirements, and other facets of energy utilization are only valid under defined environmental conditions. If adjustments are available to compensate for the wind-chill effect on the prediction of energy retention, maintenance requirements, and severity of cold stress, it would be useful to sheepmen.

[1] Effective temperature is used to rate the cooling power of the physical environment in terms of dry bulb temperature.

Chapter II

LITERATURE REVIEW

Sheep exposed to ambient temperatures below the thermoneutral zone respond by increasing rate of heat production and minimizing rate of heat loss. Avenues of heat loss during cold are radiation, conduction, convection, and evaporation (Blaxter, 1962; Hafez, 1968; and Berry and Shanklin, 1961). Respiratory evaporation during cold is obligatory and cannot be effectively controlled (Brockway, McDonald, and Pullar, 1965); however, the remaining sensible avenues of heat exchange can be regulated or modified to a limited extent by either behavioral and/or physiological adjustments.

The rate of heat flow from animal to cold environment depends on thermal gradient and the presence of insulatory barriers. Total insulation in sheep is composed of three additive components:

1) Tissue insulation (I_t) is the thermal resistance to the flow of heat from the body core to the skin surface. Vasomotion, amount of subcutaneous fat, and skin characteristics determine insulatory value of the tissue (Sykes and Slee, 1968; Slee, 1971; and Esmay, 1969).

2) External insulation (I_E) is provided by the fleece. A linear relationship exists between fleece length and fall in ambient temperature. Density and grade of wool significantly affect external insulation (Hutchinson and Bennett, 1962).

3) Air interface insulation (I_A) is the thermal resistance of the flow of heat from the surface of the hair or wool to the environment. A thin layer of still air near the body surface irrespective

of the size or shape of the animal accounts for this insulatory component (Blaxter, 1962 and Hafez, 1968). Animal movement or air velocity over the surface will affect I_A (Kleiber, 1961). These three components are additive with destruction of any resulting in reduced total insulation.

Variables affecting the rate of sensible heat loss are temperature gradient, fluid velocity, radiation characteristics of surface, and thermal conductance (Hafez, 1968). Together, these variables should be combined to offer an effective temperature which reflects the cooling power of the environment. Environmental variables, wind and temperature, directly affect rate of sensible heat loss with the former reducing total insulation and the latter affecting thermal gradient. In combination these variables constitute what is termed "wind-chill effect" which alters effective temperature.

The effect of cold-wind combinations have been studied by the United States Army, who developed a wind-chill index for humans by observing the time necessary for a plastic bag filled with water to freeze when subjected to cold and wind combinations (United States Government Printing Office, 1964). Comparisons of rate of freezing at calm conditions with that observed with various wind velocities equivalent conditions were reported (Sipple and Passle, 1945).

Other methods for estimating the effect of wind-chill include the use of calorimeters, respiration chambers, and psychrometric rooms (Webester, Hicks, and Hays, 1969). Treager (1965) designed an experiment using pelts and skins of swine, horses, and rabbits. The effect of wind velocities of 0-18 miles per hour were examined. Winds were found to increase the rate of heat loss, but this was dependent upon the density of the hair involved.

Webester (1971) designed a model cow for determining heat losses from cattle exposed to cold outdoor environments. The unit, MOOCOW (Model Ox Observing Cold Outdoor Weather), was used to estimate heat loss and account for external insulation. The results indicate wind was related to heat loss in MOOCOW by the equation:

H = Kcal/m^2/24 hr.
T_A = ambient temperature
V = wind velocity (meters/minute)

$$H = \frac{39.0 - T_A}{18.56 - 0.44}$$

Webester's wind-chill index is usable, but a factor for the natural insulation must be presented before it can be used effectively.

Joyce, Blaxter, and Park (1966) found the I_A for sheep can be described using the following equation:

V = air velocity (miles per hour)

$$I_A = \frac{1}{0.115 + 0.099\ V^{\frac{1}{2}}}$$

Joyce and Blaxter (1964) found the air interface insulation and external insulation must be used together unless under still air conditions. Thus, $I_E + I_A$, (total external insulation), with values obtained at fleece lengths of zero are regarded as estimates of I_A.

The effect of cold-wind combination on domestic animals has also been determined by measuring performance. For example, research has shown that cold ambient temperature with wind resulted in increased maintenance requirements and less efficient gains. Blaxter and Wainman (1964) found winds as small as 0.4 - 1.6 miles per hour increased heat production in cattle 6 percent in freezing conditions. Griffith and Doney (1969) found sheep exposed to 12 miles per hour winds for 6 hours for 7 days showed increased heat loss due to reduction in insulation. It was observed under these conditions that the short dense Merino type fleece was less disturbed than the long open fleece of the Blackface. Blaxter, et al. (1958), observed insulation provided by unit thickness indicated no big difference up to a fleece length of 50 mm. Thus, both density and long staple fleeces were found to depress the critical temperature and minimize the effect of falls of environmental temperature below the critical level (Blaxter, Graham, and Wainman, 1959).

Ambient temperature alone had no statistically significant effect on external insulation, but wind reduced it markedly under experimental conditions. Webester, Hicks, and Hays (1969) found a constant cold environment could produce an increase in heat production which could be related to the intensity of cold stress to which the sheep were exposed. Sheep wintered for six months increased their heat production from 110 to 128 Kcal/Kg^{3}/4/day. Hidiroglou and Lessard (1970) reported steers exposed to natural extremes in weather (October through April) gained 25.2 Kg less per animal than those protected from the extremes. Williams and Bell (1964) has found protection from higher wind velocities will reduce maintenance costs. Hidiroglou and Lessard (1970) reported that daily nutrient requirements for 275-365 Kg wintering yearling steers proved to be nearly 50 percent greater than the National Research Council recommendations when animals were subjected to cold ambient temperatures.

Insley (1973) developed a wind-chill index by exposing hides from cattle and sheep to combinations of dry bulb temperature and a wide range of wind velocities. He found that rate of heat loss was not linearly proportional to increased wind velocity but was more accurately predicted by a cubic model which accounted for destruction of the external insulation during wind speeds greater than 25 miles per hour. As more knowledge is gained on the effect of cold and wind on insulatory breakdown of animal's natural covering, it could prove beneficial to develop a specific wind-chill index for sheep.

Chapter III

MATERIALS AND METHODS

Nine sheep, three per trial, were exposed to wind and temperature combinations. Each trial consisted of a Hampshire ewe, a Rambouillet wether, and a ½ Rambouillet x ½ Border Leicester ewe. All individuals were less than 12 months old. The weight of each individual was recorded before exposure periods. Average weights were 60, 55, 64 kg. in trials 1, 2, and 3 respectively. The depth of the staple was measured at five sites on the wool covered areas. Staple length refers to the mean of these measurements. All sheep were trained to experimental system for a one-week period before the sampling began. During the pre-exposure period each was fed a maintenance ration and housed in a room maintained at 17^{o}C.

Cold temperatures were generated in a Forma Scientific Walk-In Room (11'x15'x8') with temperature range of -17^{o}C. to 37^{o}C. and temperature sensitivity of $\pm$ .5^{o}C. Wind velocities were developed by a 72 cm x 72 cm squirrel cage fan with sensitivity of $\pm$ 5 miles per hour. A plastic plenum ensured uniform wind distribution. A cup anemometer (Weather Measure Corporation W103-DC) recorded the wind velocities by using voltage output recorded on desk model physiograph (Physiograph type DMP-4A). Influence of outside wind currents were eliminated by a plywood tunnel covering the trimming stand.

A ventilated mask technique was used to measure oxygen consumption and carbon dioxide production (figure 1). Each animal was restrained in a standing position and exposed to treatment for 65

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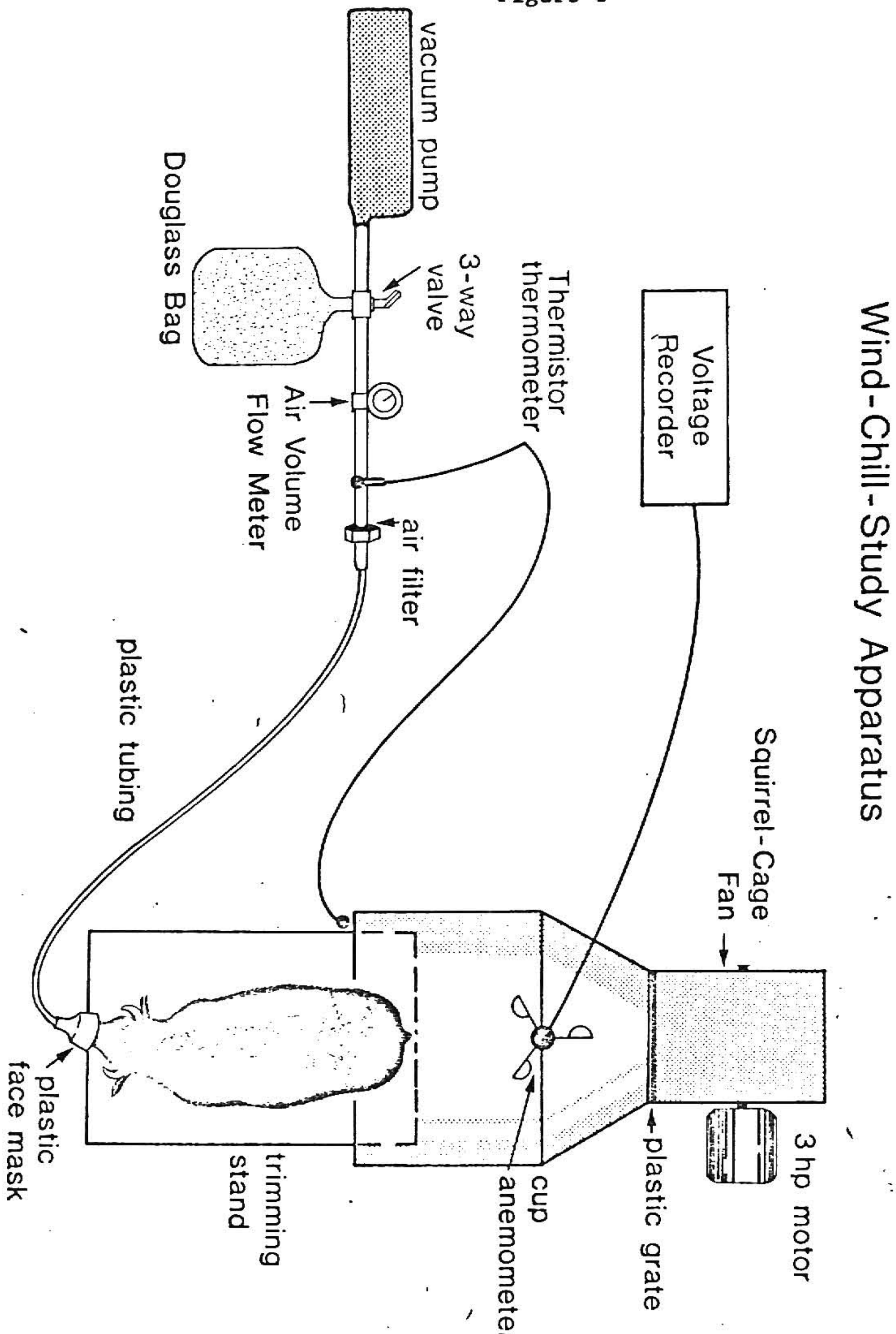
Figure 1


Wind-Chill-Study Apparatus
Voltage Recorder
Thermistor thermometer
3-way valve
vacuum pump
Douglass Bag
Air Volume Flow Meter
air filter
plastic tubing
Squirrel-Cage Fan
3 hp motor
plastic grate
cup anemometer
trimming stand
plastic face mask

minutes. After exposure for 60 minutes a five minute sample was collected and analyzed. A vacuum air pump pulled air through the system at a rate of 930 liters per hour. A dead air space assured no loss of expired air at air inlet. A temperature probe and volume flow meter adjusted air sample before collection in a Douglass bag. Samples of room air were analyzed before each exposure and animal air samples were analyzed from Douglass bag by paramagnetic oxygen analyzer (Servomex Oxygen Analyzer Type OA150). Heat loss was assumed to be equal to heat production. Heat production was calculated on Kcal/day basis using the formula:

$$Y = (0.047)\ (1440)\ (x)\ (y)$$

Y = Kcal/day
x = difference in oxygen percent in room and expired air
y = adjusted flow (liters/hr.)

Trial 1 (less than 1 cm wool), trial 2 (3 cm wool), and trial 3 (greater than 6 cm wool) involved ninety-two, sixty-eight, and seventy-two observations respectively. The same experimental procedure was observed in all trials.

Least square analysis of variance with unequal subclass was used to account for variation in heat loss (Kemp 1972). Linear wind, linear temperature, quadratic wind, and cubic wind were the power function variables included in the model. Weight, breed, quadratic temperature, and cubic temperature were dropped from the analysis after initial processing revealed a small F-ratio. Equations for each trial were developed from the analysis (table 1).

Chapter IV

RESULTS AND DISCUSSION

Rate of heat loss from body core to environment is a function of temperature gradient and total insulation ($I_A + I_E + I_T$). During cold stress (ambient temperature below the critical temperature), rate of heat loss increases resulting in increased energy requirement to maintain core temperature. Reduced efficiency at effective temperature below the critical temperature are expressed in feedlot trials (Hidiroglou and Lessard, 1970) and in maintenance requirements for breeding stock (Webester, 1970 and 1971). Development of optimum nutritional programs and management systems for sheep require an accurate description of the ambient environment. This requires establishment of "effective temperature" which accounts for environmental variables affecting rate of heat loss during cold stress.

Rate of heat loss from sheep exposed to cold is a linear function when related to dry bulb temperature (Blaxter, McC Graham, Wainman, and Armstrong, 1958). This is expected from the equation:

$I_T = \frac{T_1 - T_2}{Hp}$ where I_T is total insulation, T_1 is core temperature, T_2 is ambient temperature, and Hp is heat production. However, wind velocity affects rate of heat loss in a nonlinear fashion. This nonlinear relationship was observed in both shorn and medium fleeced animals. Rate of heat loss increased rapidly at low wind velocities (less than 10 miles per hour) and high wind velocities (greater than 25 miles per hour). A slower rate of heat loss was noted between 10

Figure 2

Schematic of Structural
breakdown of external insulation

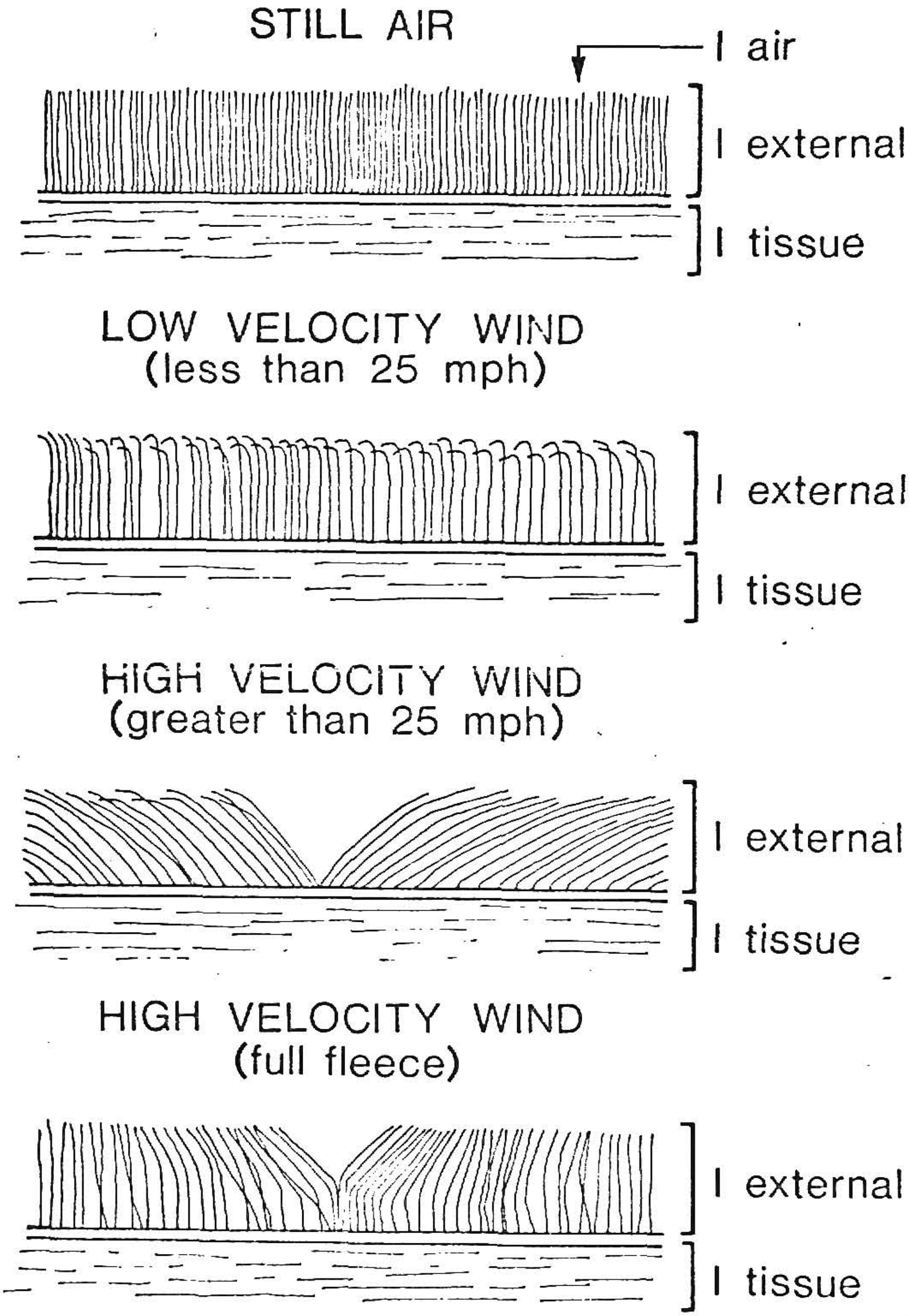


TABLE 1. ANALYSIS OF VARIANCE TABLES AND PREDICTION EQUATIONS FOR HEAT PRODUCTION

Trial I (less than 1 cm)

	D.F.	S.S.	MS	F ratio	Prob
Wind	1	269	269	.114	.736
Temp	1	327544	327544	138.682	.000
$Wind^2$	1	1813	1813	.768	.383
$Wind^3$	1	1706	1706	.723	.397
Residual	87	205479	2361		
Total	91	773360			

$Y = 226.2922 + 1.2077(x) - 2.9674(z) + .2194(x^2) - .0039(x^3)$

Trial II (1-6 cm)

	D.F.	S.S.	MS	F ratio	Prob
Wind	1	574	574	.548	.462
Temp	1	40599	40599	38.668	.000
$Wind^2$	1	141	141	.135	.714
$Wind^3$	1	298	298	.285	.595
Residual	63	66146	1049		
Total	67	142765			

$Y = 172.3561 + 1.9304(x) - 1.2509(z) - .0704(x^2) + .0019(x^3)$

Trial III (greater than 6 cm)

	D.F.	S.S.	MS	F ratio	Prob
Wind	1	0.500	0.500	.001	.979
Temp	1	35961	35961	44.821	.000
$Wind^2$	1	0.080	0.080	.000	.991
$Wind^3$	1	7	7	.010	.921
Residual	68	54558	802		
Total	72	94740			

$Y = 95.2638 + .0590(x) - 1.1248(z) + .0017(x^2) + .003(x^3)$

to 25 miles per hour. These results agree with the model equation presented by Insley (1973). In the full fleece the cubic response noted in shorter fleeces was absent and a quadratic response was exhibited as ambient temperature drops.

These results can be explained by the hypothesis of insulation breakdown and separation (figure 2). With still air the rate of heat loss is a function of: (1) tissue insulation, altered only during vasomotion and not directly affected by wind velocity; (2) external insulation, provided by the wool or hair coat; and (3) air interface insulation, present on all surfaces and the first insulation destroyed by air movement. Still air conditions do not exist since air currents and body movement will result in air flow. In shorn and medium fleece sheep the external insulation is broken down as wind velocity is increased. This separation or breakdown of the fibers renders sheep different to bare-skinned animals, and causes the wind-chill indices prepared for bare-skinned animals to be invalid for animals with wool or hair. Wind has a quadratic relationship with rate of heat loss from full fleece sheep (greater than 6 cm wool), but unlike indices for bare-skinned animals the full fleece provides external insulation that is not significantly reduced by 35 miles per hour wind velocities. The conventional measure of wind-chill is based on Sipple and Passel's formula:

$$H = 10.45 + 10\sqrt{v} - v$$

$H = \text{Kcal/m}^2\text{/hr}$
v = wind speed (mph)

This model is a parabola in terms of the square root of the velocity and assumes a quadratic relation (Steadman, 1970).

A cubic equation was found to best fit the heat loss data which is shown in appendix I. Temperature had a highly significant effect on heat loss in all three fleece lengths ($P<.01$). Wind variables had a nonsignificant influence in all fleece lengths, but regression coefficient differences were shown within the equations.

Shorn $Y = 226.2922 + 1.2077X - 2.9674z + .2194x^2 - .0039x^3$

Medium $Y = 172.3561 + 1.9304x - 1.2509z - .0704x^2 + .0019x^3$

Full $Y = 95.2638 + .0590x - 1.1248z + .0017x^2 + .0003x^3$

Y = Kcal/day
x = wind velocity (mph)
z = temperature (^{o}F)

Linear wind had the greatest effect upon the medium fleece. Quadratic wind and cubic wind had most effect upon shorn sheep. Full fleece animal's insulatory properties were not reduced by wind velocities of 0 to 35 miles per hour which is shown by the low F-ratio in the model analysis (table 1). Breed and weight differences were analyzed and found to not be significantly different within the scope of the experiment ($P<.01$).

Wind-chill tables for each fleece length are shown in table 2, 3, and 4. They were developed by plotting wind and temperature in prediction equation; effective temperatures were produced by solving the model equations. These equations are a valid means of evaluating the ambient environment, but any great deviations from the stated bounds may result in invalid conclusions.

TABLE 2. WIND-CHILL INDEX SHORN (TRIAL 1)

	-15	-10	-5	0	5	10	15	20
	Dry Bulb Thermometer Reading (°C)							
Wind Speed (mph)								
Calm	-15	-10	-5	0	5	10	15	20
5	-17	-12	-7	-2	3	8	13	18
10	-21	-15	-10	-6	1	4	9	14
15	-25	-20	-15	-10	-5	0	5	10
20	-30	-25	-20	-15	-10	-5	0	5
25	-35	-30	-25	-20	-15	-10	-5	0
30	-39	-34	-29	-24	-19	-14	-9	-4
35	-41	-36	-31	-26	-21	-17	-12	-7
40	-42	-37	-32	-28	-23	-18	-13	-8

TABLE 3. WIND-CHILL INDEX MEDIUM FLEECE (TRIAL 2)

	-15	-10	-5	0	5	10	15	20
	Dry Bulb Thermometer Reading (^{o}C)							
Wind Speed (mph)								
Calm	-15	-10	-5	0	5	10	15	20
5	-17	-13	-8	-3	2	7	12	17
10	-21	-16	-11	-6	-1	4	9	14
15	-24	-19	-14	-9	-4	1	6	11
20	-26	-21	-17	-12	-7	-2	3	8
25	-30	-25	-20	-15	-10	-5	0	5
30	-35	-30	-25	-20	-15	-10	-5	0
35	-43	-38	-33	-28	-23	-18	-13	-8
40	-53	-48	-43	-38	-33	-28	-23	-18

TABLE 4. WIND CHILL INDEX FULL (TRIAL 3)

	-15	-10	-5	0	5	10	15	20
	Dry Bulb Thermometer Reading (^{o}C)							
Wind Speed (mph)								
Calm	-15	-10	-5	0	5	10	15	20
5	-15	-10	-5	0	5	10	15	19
10	-15	-10	-5	0	4	9	14	19
15	-16	-11	-6	-1	4	9	14	19
20	-17	-12	-7	-2	3	8	13	18
25	-18	-13	-8	-3	2	6	12	17
30	-20	-15	-10	-6	-1	4	9	14
35	-23	-18	-13	-8	-3	2	7	12
40	-27	-22	-17	-12	-7	-2	3	8

Nutritional requirements, nutrient composition, and how feeds may be supplemented are affected by the environment. It has been shown that during cold growth rate decreases; therefore, requirement for protein may be lowered. Published nutrient requirements (National Research Council) have failed to account for these environmental effects. Thus, ration composition should be tailored to effective temperature, and nutrient requirements must be matched with the environment so that rations are as efficient as possible in terms of red meat produced per unit of cost. Profit in the sheep industry is based on a small margin. If the wind-chill index can be used to tailor rations to environment conditions, then improved efficiency and performance of sheep will result.

Chapter V

SUMMARY

Two-hundred and thirty-two observations with nine trained sheep indicated increases in the rate of heat loss upon exposure to combinations of cold (-10°C. to 20°C.) and windy (0 through 35 mph) environments. Oxygen consumption was determined by a ventilated mask technique, and heat production was assumed to be equal to heat loss. Heat production was calculated on Kcal/day basis, then a least square analysis of variance was computed.

Shorter fleece depths (less than 3 cm wool) produced a cubic model when rate of heat loss was plotted as a function of wind velocity. Fleece length greater than 6 cm (full fleece) assumed a quadratic model comparable to wind-chill index developed by the Weather Bureau (U.S. Government Printing Office, 1964). Increasing wind velocity accounted for destruction of the external insulation and air interface insulation in shorn and medium fleece, but this destruction was not observed with full fleece in the wind and temperature combinations tested.

The equivalent temperature for each fleece was generated from the predicted analysis equations. Temperature was the most important factor in the rate of heat loss. Wind variables exhibited most effect in shorn and medium fleece sheep. Breed and weight differences had no significant effect on the rate of heat loss ($P<.01$). Wind-chill tables produce a meaningful way of evaluating the ambient environment during wind and cold combinations.

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Appendix 1

Wind Speed (mph)	Temperature (^oC) -10	0	+10	+20	72-26 shorn
0	6501	5074	3820	2537	Kcal/day
5	---	4475	3638	2947	
10	5726	5497	4405	3621	
15	6889	6342	4154	3835	
20	7667	7103	5601	3933	
25	8380	7923	---	3728	
30	8613	---	7341	---	
35	8740	7080	7344	4062	

Appendix 2

Wind Speed (mph)	Temperature (^oC) -10	0	+10	+20	71-36 shorn
0	4014	3650	3356	3075	Kcal/day
5	4066	3408	3778	3024	
10	5377	5736	3238	3001	
20	8157	7224	5544	3852	
25	7922	3776	3165	4188	
30	8548	8187	1708	4575	
35	8725	8518	6389	5103	

Appendix 3

Wind Speed (mph)	Temperature (°C) -10	0	+10	+20	2 shorn
0	2450	3317	2202	2965	Kcal/day
5	4720	2727	2264	2481	
10	3594	4240	2895	2688	
15	5289	4228	3006	2750	
20	6144	4334	2892	2062	
25	8384	6383	4886	2526	
30	9297	6981	4125	2742	
35	8746	7062	4002	3650	

Appendix 4

Temperature (^oC)

Wind Speed (mph)	-10	0	+10	+20	71-36 medium fleece
0	2782	2590	2769	2688	Kcal/day
5	---	---	---	---	
10	3024	3103	---	2239	
15	2850	3580	3190	1821	
20	2818	2847	---	2097	
25	3212	2781	2651	---	
30	3920	3701	3656	1321	
35	5052	3303	3665	---	

Appendix 5

	Temperature (^{o}C)				
	-10	0	+10	+20	
Wind Speed (mph)					72-26 medium fleece
0	3539	2973	3303	2979	Kcal/day
5	---	---	---	---	
10	3360	3539	2654	2742	
15	3518	3986	---	---	
20	4886	3719	2931	---	
25	4718	4480	---	3217	
30	5180	4954	---	---	
35	4985	5571	2950	2990	

Appendix 6

Wind Speed (mph)	Temperature (°C) -10	0	+10	+20	2 medium fleece
0	2482	2359	2164	2806	Kcal/day
5	---	---	---	---	
10	3531	3303	2799	3120	
15	4019	4364	---	---	
20	4652	3781	2871	2688	
25	5122	4482	---	---	
30	4912	4128	2216	2819	
35	5662	4836	---	---	

Appendix 7

Wind Speed (mph)	Temperature (^oC) -10	0	+10	+20	30 full fleece
0	963	1321	1101	1810	Kcal/day
5	2128	1822	1070	1510	
10	---	---	---	---	
15	2016	1650	886	1597	
20	2306	1601	---	958	
25	2278	1441	1218	---	
30	2555	2179	1587	863	
35	2847	1651	1977	---	

Appendix 8

Wind Speed (mph)	Temperature (°C) -10	0	+10	+20	80 full fleece
0	4074	3728	1211	1651	
5	---	---	---	---	
10	3844	3920	---	1538	
15	4673	3652	763	1031	
20	3830	4046	1791	---	
25	4284	3877	1837	---	
30	4526	3998	1473	1392	
35	4670	4019	---	1356	

Appendix 9

	Temperature (°C)				
	-10	0	+10	+20	
Wind Speed (mph)					100 full fleece
0	1783	1965	1965	1619	
5	---	---	---	---	
10	1903	1008	1952	1181	
15	2041	1983	---	1538	
20	1983	1977	1750	---	
25	1902	1943	---	1778	
30	2111	2764	1677	1965	
35	1943	1867	1727	---	

WIND-CHILL INDEX FOR SHEEP

by

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ABSTRACT

WIND-CHILL INDEX FOR SHEEP

By Timothy A. Barnes

Two hundred and thirty-two observations with nine trained sheep indicated increases in rate of heat loss when exposed to combinations of cold (-10°C. to 20°C.) and wind (0 through 35 mph). Heat production was calculated by respiration calorimetry using a ventilated mask technique, and heat production was assumed to equal heat loss. Shorter fleece depths (less than 6 cm wool) produced a cubic model when rate of heat loss was plotted as a function of wind velocity. Fleece length greater than 6 cm (full fleece) assumed a quadratic model comparable to wind-chill index developed by the Weather Bureau (U.S. Government Printing Office, 1964). Increasing wind velocity accounted for destruction of the external insulation and air interface insulation in shorn and medium fleece, but this destruction was not observed with full fleece in the wind and temperature combinations tested. The equivalent temperature for each fleece was generated from a predicted analysis equations. Temperature was the most important factor in the rate of heat loss. Wind variables exhibited the most effect in shorn and medium fleeced sheep. Breed and weight differences had no significant effect on the rate of heat loss ($P<.01$). Wind-chill tables produce a meaningful way of evaluating the ambient environment during wind and cold combinations.