

Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles

by David P Wyon, PhD¹

WYON DP. Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles. *Scand J Work Environ Health* 1989;15(suppl 1):76–83. A thermal manikin with constant skin temperature and a wind-chill tunnel with constant air temperatures and wind speeds were used to measure whole-body heat loss for seven ensembles chosen to represent the full range of civilian outdoor clothing in use for everyday, nonsporting wear. Equations fitting the data with correlation coefficients exceeding 0.99 were derived for each ensemble, and diagrams were produced with these equations to interpolate and extend the range of conditions. The conditions studied were those resulting in total heat loss from 50 to 250 W · m⁻², so very little extrapolation was required. The wind-chill equivalent temperature (with reference to 2 m · s⁻¹), based on the average value for all seven ensembles, showed good agreement on this measure. The values predicted on the basis of whole-body heat loss through clothing were shown to be much lower than those predicted from the Siple wind-chill index for unprotected skin.

Key terms: clo, index thermal insulation, temperature, thermal manikin, wind speed.

Buildings can affect the microclimate in their immediate vicinity in a variety of ways. For example surface materials, textiles, and color affect radiation temperatures considerably if wind speeds are low; and building shapes, juxtapositions and heights, and their ancillary walls, fences and vegetation all affect local wind speeds. The resulting microclimate determines the heat balance of people wearing a wide range of clothing while engaged in a wide variety of activities.

As far as possible, building design should take account of these thermal requirements. For instance, the season for sitting outside or for using a playground or for going to the car and running local errands in indoor clothing may possibly be extended by several months. Waiting for a bus or to cross a road may be made less of an ordeal by the proper design of the microclimate.

However, necessary modifications to a built environment may be prohibitively expensive once a building complex has been completed, and it is therefore desirable to be able not only to predict the expected microclimate, in physical terms, but also its resulting effect on human heat balance and human activities. The physical effects on the microclimate may be studied by means of scale models in an appropriate wind tunnel and verified by means of field measurements (1, 2), but the effects on human heat balance have hitherto been very difficult to predict with any accuracy.

The conventional wind-chill index, derived by Siple & Passel (3) from studies of the rate of cooling of cans of water, is appropriate for exposed skin, but not for

the clothed body unless the outer layer of clothing is completely windproof and all extremities are equally well protected. It may be used for predicting the risk of frostbite on the face or unprotected hands and for military or survival purposes when clothing may be assumed to approximate the aforementioned conditions, but it is not useful for the civilian clothing, low wind speeds, and relatively mild temperatures of interest in the present discussion. Heat balance equations which take account of clothing assume that clothing insulation values are unaffected by wind and assume the characteristic square-root dependence of heat loss on air velocity that is appropriate for impervious cylinders. To the extent that civilian clothing is not impervious to wind and does not protect all parts of the body equally, these assumptions will be wrong and will lead to an underestimate of the effects of wind and of the potential benefits of microclimate modification.

The present study was undertaken to derive empirical equations predicting the combined effects of wind and temperature on total heat loss for a range of civilian clothing in everyday use, from shirt-sleeves to down-jackets. A wind-chill chamber was constructed for the purpose, and the measurements of whole-body heat loss were made with the 16-section thermal manikin SIBMAN, a full-size model of a standing man. Air-temperature and wind-speed combinations giving whole-body heat loss rates from 50 to 250 W · m⁻² (resting to heavy work) were used for each clothing ensemble. It appears to be the first time such measurements have been made.

Methods

Wind-chill tunnel

A well-insulated space, normally cooled to –20°C for heatflow studies of prototype window, outer wall and

¹ Human Criteria Laboratory, National Swedish Institute for Building Research, Gävle, Sweden.

Reprint requests to: Dr DP Wyon, Human Criteria Laboratory, National Swedish Institute for Building Research, Box 785, S–801 29 Gävle, Sweden.

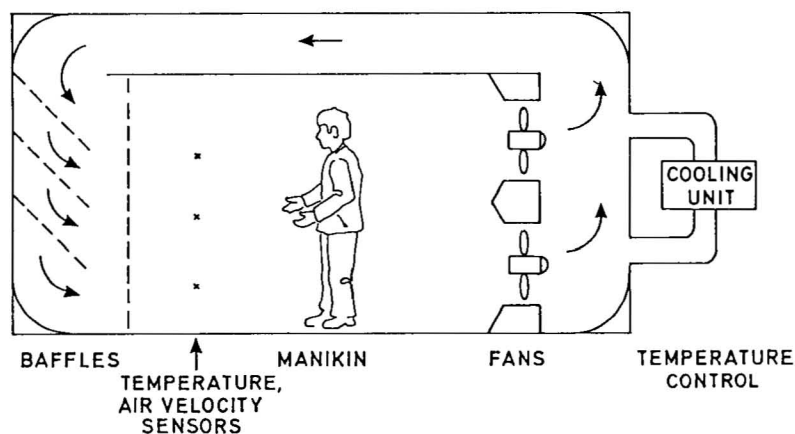


Figure 1. Wind-chill tunnel built for the experiment.

door constructions, was available. The floor was 6×1.20 m, the height 2.40 m. Two large frequency-controlled fans were installed as shown in figure 1. They drew air down the "tunnel" and returned it above a false ceiling at a height of 1.90 m. Baffles were installed as shown in the figure to reduce energy losses and to ensure an approximately even air speed at all heights above the floor. A variable amount of air was withdrawn from the tunnel after the fans; it was cooled and returned just downstream. The volume flow of this air was adjusted automatically by means of a proportional-integral regulator to maintain each preset air temperature, as measured upstream of the manikin. Fan speeds were set manually. The cooling system, with a maximum cooling effect of 10 kW, limited the maximum wind speed to about $4 \text{ m} \cdot \text{s}^{-1}$, as higher fan speeds led to a loss of temperature control. Wind speeds were measured upstream of the manikin with a hot-bead anemometer. As the manikin obstructed the airflow, some increase in air speed around the manikin, in excess of that taking place in the open, had to be assumed.

Thermal manikin

SIBMAN was the first thermal manikin built at the National Swedish Institute for Building Research, and it incorporated a number of disadvantages. A hollow plastic display manikin (Hindsgaul A/S) was fitted with joints at the elbow, shoulder, hip, and knee and divided into 16 sections. Heating wires with a resistance of 40Ω were distributed evenly over the inside surface of each section, the cables emerging from the back of the neck. Each section was filled with foam plastic to eliminate internal convection.

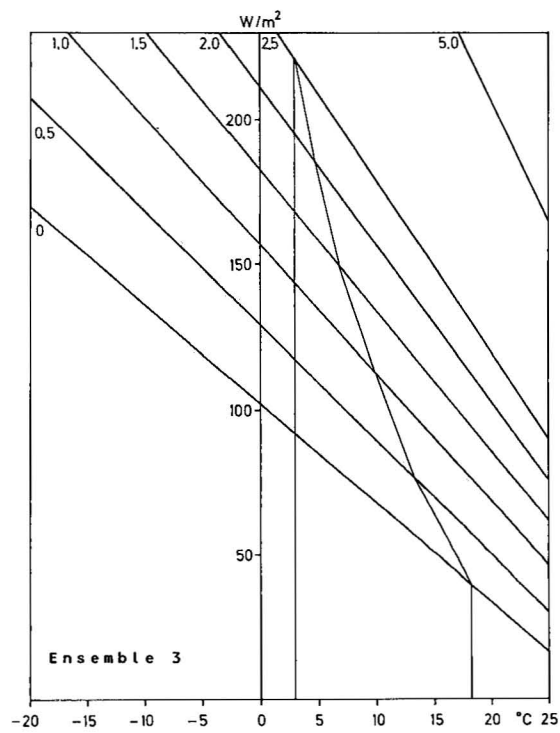
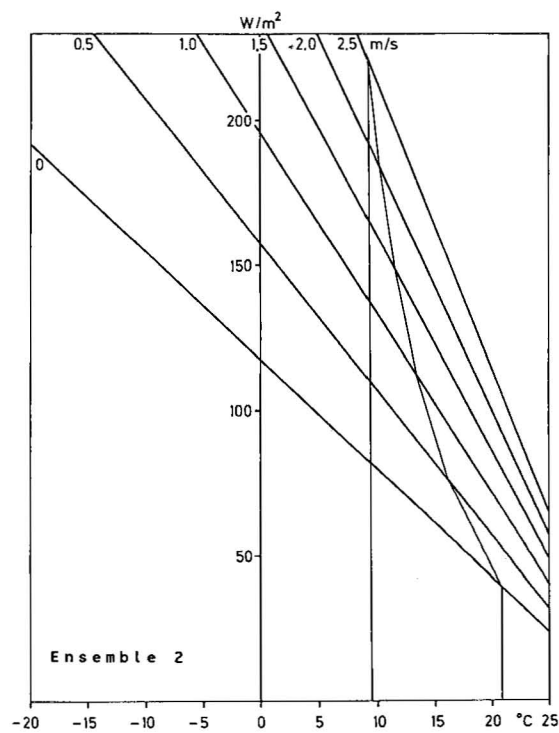
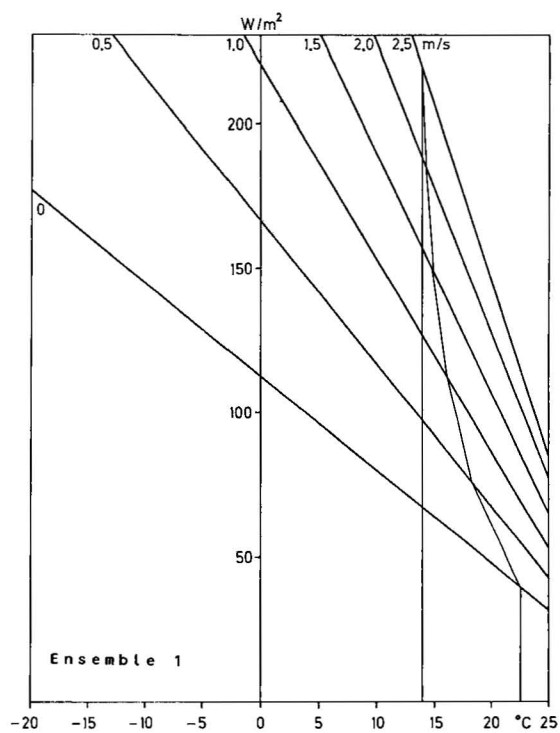
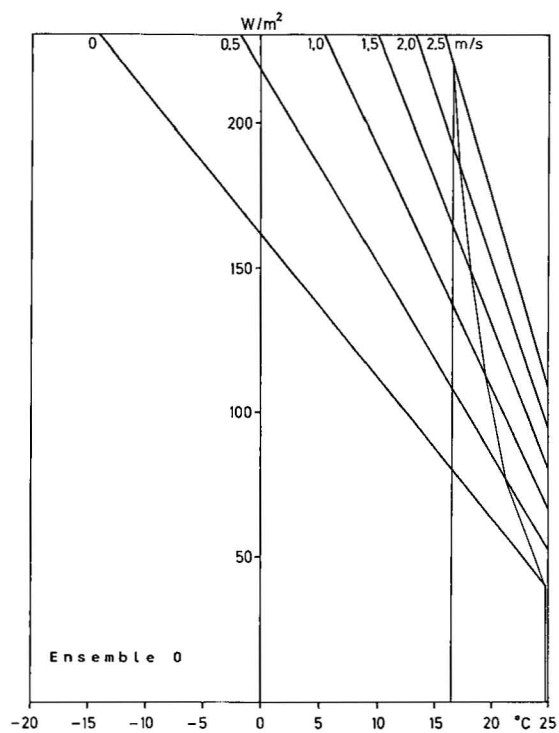
Section skin temperatures were estimated by affixing a copper-constantan foil sensor at "a representative point" determined empirically from extensive measurements of skin temperatures with the manikin heated but unclothed. The error introduced by this expedient varied, being lower the higher the clothing insulation value. Thermal manikins developed subsequently (VOLTMAN, TORE) have heating wires closer to

Table 1. Constants for each clothing ensemble in the equation $W \cdot \text{m}^{-2} = A - B \times T + C \times V - D \times V \times T$, where T is temperature ($^{\circ}\text{C}$) and V is air velocity ($\text{m} \cdot \text{s}^{-1}$).

Ensemble	A	B	C	D
0 Shirt-sleeves	161.26	4.87	113.08	3.41
1 Sweater	111.91	3.20	107.38	5.37
2 Windbreaker	118.02	3.72	76.75	2.40
3 Windbreaker, augmented ^a	101.62	3.39	54.32	0.99
4 Overcoat	86.59	2.18	118.21	4.19
5 Overcoat, augmented ^a	83.94	2.64	48.57	1.03
6 Down-jacket	75.58	2.25	57.42	2.49
Average	105.56	3.18	82.25	2.84

^a See the text for the components of the ensemble.

the surface, a metal heat-conducting layer outside the heating wires (to ensure even surface temperatures), and sensors distributed over the surface of each section. They are thus capable of simulating human heat balance in asymmetric environments, with large local variations and even shadow boundaries in direct sun. SIBMAN, though adequate for the present purpose, was found to be too sensitive to conditions at the point sensor, and it was in any case too slow in achieving equilibrium under changing conditions. The wind-chill tunnel could maintain conditions indefinitely, so time was not a limiting factor. The power supplied to each section, at a constant voltage of 55 volts direct current, was adjusted under computer control by means of pulse-length modulation, with a resolution of 1:1023 (Wessing, unpublished internal report of the National Swedish Institute for Building Research). Skin temperatures were measured by means of a conventional logger (Acurex 9) interfaced to the controlling computer (HP80). Skin temperatures could be maintained constant with an accuracy of 0.20°C ; heat flows were recorded to the nearest $1 \text{ W} \cdot \text{m}^{-2}$. The electrical measurements were made with a total accuracy of 0.2 % of full power. Section areas, measured by covering each section with masking tape, weighing the tape used to 0.01 g, and calibrating against a similarly measured cylinder of known area, were known with an accuracy of 1 %.



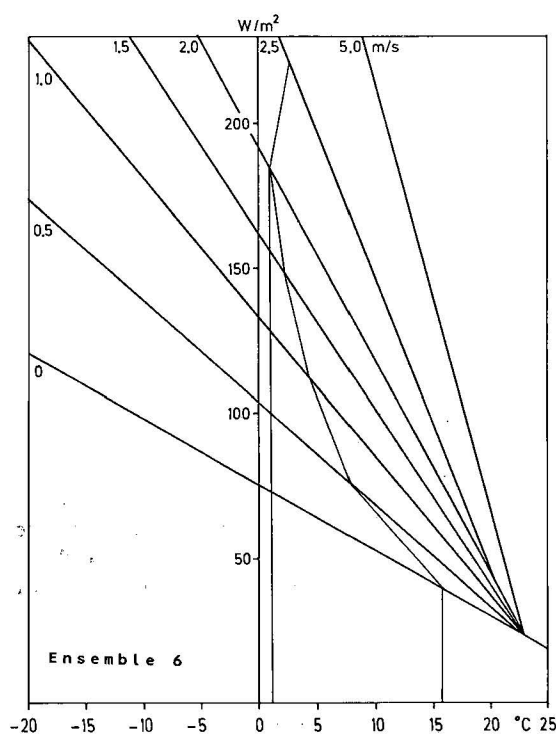
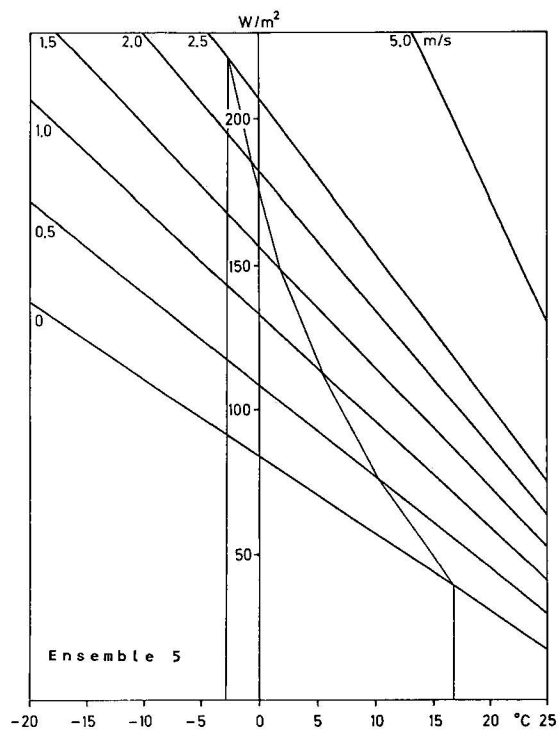
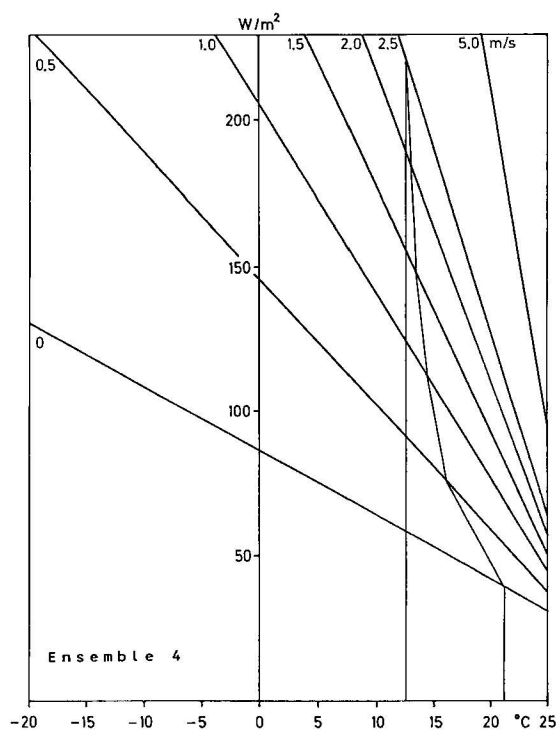


Figure 2. Predicted heat loss in watts per square meter for each ensemble. The curve in each figure is the locus of watts per square meter and meters per second for performing the activities listed in table 2. (For a description of the ensembles, see the text.)

Skin temperature distribution

Hands and feet were maintained at a temperature of 31°C, calves and lower arms at 32°C, thighs, upper arms and head at 33°C, and the trunk sections at 34°C. The area-weighted mean skin temperature was 32.8°C.

Clothing

The following seven different ensembles were measured:

Ensemble 0. Long-sleeved cotton shirt, wool trousers, cotton underpants, wool ankle socks, sturdy leather shoes with rubber soles, and nylon wig. This basic indoor ensemble was common to all of the ensembles, and only the additional items are listed in the descriptions of ensembles 1–6.

Ensemble 1. Loose-knitted sweater of thick acrylic fiber reaching to the trouser pockets, with long sleeves and a round neck.

Ensemble 2. Waist-length windbreaker with zipper, close-fitting at wrist.

Ensemble 3. Windbreaker as for ensemble 2, short leather gloves lined with cotton, knitted woolen hat covering hair and ears.

Ensemble 4. Wool overcoat extending to mid thigh, worn hanging open.

Ensemble 5. Wool overcoat as for ensemble 4, buttoned up and with woolen scarf tied to block lapel opening; also leather gloves and hat as for ensemble 3.

Ensemble 6. Zippered quilted down-jacket extending to the trouser pockets and close-fitting at the wrists; also leather gloves and woolen hat as for ensembles 3 and 5.

Estimates of the conventional insulation values for these ensembles are given in table 3 in the Results section.

Posture

The manikin faced the wind squarely with its legs slightly apart, knees straight, feet on the floor, and arms hanging at its sides. It was suspended from the ceiling on a hook so that its weight was not on its feet, but the manikin did not move.

Procedure

The conditions were maintained until all sections were in stable equilibrium. Frequent returns to the same conditions were made to confirm repeatability. Temperature increments were about 2°C, and air velocity increases were 0.5 m/s with a minimum of 0.2 m · s⁻¹ to maintain temperature control. Within the limits of the tunnel, combinations were measured which resulted in total heat losses between 50 and 250 W · m⁻².

Results

Equations

Total heat loss in watts per square meter as a function of temperature (T) in degrees centigrade and velocity (V) in meters per second was found to be adequately predicted by an equation of the form:

$$W = A - B \times T + C \times V - D \times V \times T,$$

where A, B, C, and D are constants with different values for each ensemble. The correlation coefficients between the values predicted by the empirical equation and the actual measurements were greater than 0.99 in all seven cases. The values for A, B, C, and D are given in table 1, and the results are depicted graphically for each ensemble in figure 2.

Activity

Table 2 gives values of heat production for various activities, taken from the literature, and relative velocities typical for each activity. They conform to the approximate equation $W = 40 + 72 \times V$. For each ensemble, there is a neutral temperature at which the relative velocity for a given activity will result in a total heat loss equal to the heat produced.

Evaporative heat losses were neglected in relation to this study as they were likely to be very small compared with the thermogenesis required to maintain body temperatures under the conditions studied. The locus of neutral temperatures, relative velocities, and heat losses predicted by this equation is shown for each ensemble in figure 2.

Clothing insulation

Table 3 gives conventional clo values for each ensemble, calculated with the use of each equation to predict total heat loss at 0.1 m · s⁻¹, at a temperature giving a total heat loss of 50–90 W · m⁻² in each case. The temperatures considered appropriate were 20, 10, and 0°C, as shown in table 3. The clo value of the surrounding air was taken to be 0.7 in each case (at 0.1 m · s⁻¹). Calculating clo values at inappropriate temperatures, with predicted total heat losses outside the range of 50–90 W · m⁻², gave remarkably stable values for ensembles 0 and 6. The values decreased with temperature for the more wind-tight ensembles, but increased at lower temperatures for the least wind-tight ensembles (ensembles 1 and 4). The best estimates of clo value (table 3) were rank-ordered as expected from 0.51 to 1.90 clo, with increments of about 0.23 clo.

Wind effects

Table 4 gives some values of wind speed in meters per second that may be useful for matching predicted total heat loss to the heat production expected in various activities (table 2). Unless a given activity involves continuous movement into the wind, there is no need to

Table 2. Heat produced and outdoor activities at relative velocities. [$W \cdot m^{-2} = 40 + 72 \times V$, where V is air velocity ($m \cdot s^{-1}$)].

Activity	Heat produced ($W \cdot m^{-2}$)	Air velocity	
		$m \cdot s^{-1}$	$km \cdot h^{-1}$
0 Sitting	55	0.20	—
1 Standing	65	0.35	—
2 Strolling	80	0.56	2
3 Walking	120	1.11	4
4 Walking fast	160	1.67	6
5 Forced march	180	1.94	7
6 Jogging	220	2.50	9

add relative velocity to wind speed. In most activities it should just as often be subtracted, as one tends to walk, or run, in circles. Relative velocities are perhaps useful corrections for activities to be performed in otherwise still air.

Wind chill

The concept of a wind-chill equivalent temperature has been widely adopted and is familiar to many people, as it is often used by broadcasters. Siple & Passel's equation (3) is used to calculate the still-air temperature that would give the same wind-chill index value as the forecast combination of air temperature and wind speed. When clothing is chosen for outdoors, however, it may be assumed that most people are familiar with the effect of their own relative velocity and would allow for it. An air velocity of $2 m \cdot s^{-1}$ would therefore seem to be a more appropriate reference condition, corresponding to a fast walk (table 2) or a light breeze (table 4).

The forecast outdoor air temperature should be corrected for wind chill. Figure 3 has been devised for this purpose, with the use of the average values of A, B, C, and D given in table 1. Wind-chill equivalent temperatures, expressed as air temperatures which would result in the same total heat loss at $2 m \cdot s^{-1}$, were found to be almost the same for all seven ensembles, particularly at lower temperatures. Separate diagrams for each ensemble would be necessary to equate warmer conditions accurately, but this information is perhaps not as necessary. Figure 4 shows wind-chill equivalent temperatures for unprotected skin, again relative to $2 m \cdot s^{-1}$, as calculated by the Siple wind-chill index. It may be seen that wind-chill equivalent temperatures based on heat loss through clothing are much lower, even though the Siple index is for the rate of cooling of an unrealistically high skin temperature of $33^{\circ}C$. The equation used was the version given by McIntyre (4):

$$WCI = (10 \times SQR(V) + 10.45 - V) \times (33 - T),$$

where $SQR(V)$ is the square root of V .

Table 3. Thermal insulation (clo) estimated from equations at $0.1 m \cdot s^{-1}$, at a given temperature ($^{\circ}C$) and under the assumption that the insulation of air = 0.7 clo at $0.1 m \cdot s^{-1}$ (1 clo = $0.155 m^2 \cdot ^{\circ}C \cdot W^{-1}$)

Ensemble	Temperature ($^{\circ}C$)	Heat produced ($W \cdot m^{-2}$)	Thermal insulation (clo)
0 Shirt-sleeves	20	68	0.51
1 Sweater	20	48	0.89
2 Windbreaker	10	86	1.01
3 Windbreaker, augmented	10	72	1.34
4 Overcoat	0	98	1.45
5 Overcoat, augmented	0	89	1.68
6 Down-jacket	0	81	1.90

Table 4. Wind conditions in meters per second and kilometers per hour.

Condition	$m \cdot s^{-1}$	$km \cdot h^{-1}$	Observations
Wind still	0.2	—	None
Barely moving	1	3.6	Felt on face
Gentle breeze	2	7.2	Felt on face
Light breeze	3	10.8	Felt on face
Breeze	4	14.4	Clothes flap
Strong breeze	5	18.0	Flags outstretched
Quite windy	6	21.6	Tree branches in motion
Definitely windy	7	25.2	Dust and paper whirl up

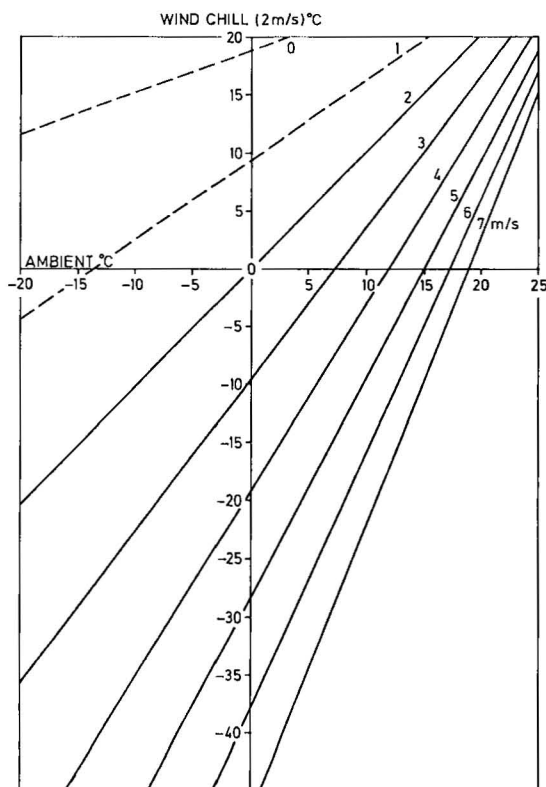


Figure 3. Wind-chill (equivalent heat loss) temperature (HLT) related to $2 m \cdot s^{-1}$, according to the average equation from table 1 [$HLT(2.0) = 18.6 - 9.28 \times V + (0.36 + 0.32 \times V) \times T$].

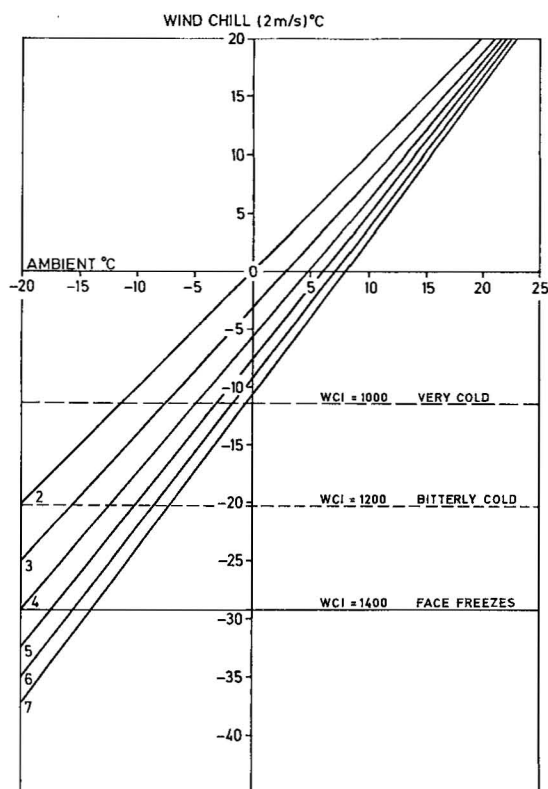


Figure 4. Wind-chill (equivalent index) temperature (WCT) related to $2 \text{ m} \cdot \text{s}^{-1}$, according to the Siple wind-chill index [WCT (2.0) = $33 + (T - 33) \times [0.44 \times \text{SQRT}(V) + 0.46 - 0.44 \times V]$].

Discussion

The increased heat losses through clothing because of wind or relative motion are so high that the activities considered appear to have neutral temperatures down to only -3°C in still air [figure 2, ensemble 5 (forced march)], yet the ensembles are in common use for outdoor activities at temperatures down to -20°C . It is worth considering how this is possible.

First, it is normal to wear a sweater under the outer garment when it is sufficiently cold. On the assumption that the thermal insulation of a sweater is equivalent to 0.4 clo , the neutral range would be extended downwards by 7.4°C during normal walking ($120 \text{ W} \cdot \text{m}^{-2}$), and by 11.2°C during a forced march ($180 \text{ W} \cdot \text{m}^{-2}$). Additional garments such as boots and long underclothes might have an equivalent effect. Second, some decrease in average skin temperature is acceptable, though probably not more than about 5°C without severe discomfort. The neutral range would be extended downwards by this amount. Third, Benzinger et al (5) have shown that the physiological mechanism of thermogenesis can double bodily heat production at a skin temperature of 28°C , as core temperature falls by only 0.2°C in response to cold. Thermogenesis begins at a higher core temperature the lower the skin temperature and can thus anticipate body cooling to a greater extent the faster it tends to

occur. It is the safety mechanism of thermogenesis that ensures that one not only survives when uncomfortably cold but also returns with a healthy appetite due to the extra energy consumed.

In planning the outdoor environment, as in selecting a clothing ensemble, it is prudent to regard these physiological responses to cold as constituting a margin of safety should conditions become worse than expected. They have no effect on the wind-chill equivalent temperatures shown in figure 3. Field observations of the wind-chill equivalent temperatures at which people abandon various activities will be necessary to determine absolute levels, and the diagram can then be used to equate other combinations of wind and temperature. It seems likely that an inability to maintain whole-body heat balance will be more critical than facial discomfort below a Siple index value of 1200, designated "bitterly cold," in figure 3.

It should be noted that one can convert ensemble 2 to ensemble 3 by putting on the gloves and hat that one has prudently taken along. Ensemble 4 can be converted to ensemble 5 by buttoning up the coat and similarly putting on accessories. The neutral range of ensemble 6 can be extended upwards by opening the zipper. These aspects of clothing design are important in that they permit adaptation to changing weather and a wider range of activity level without clothes being changed. The present results make it clear, however, that the main source of adaptation under really cold conditions is to be found in the body itself.

Concluding remarks

Total heat losses through seven typical civilian outdoor clothing ensembles can be predicted by means of the empirical equations derived to fit the experimental data. Once either the relative velocity produced by the activity itself or the wind speed is taken into account, they can be used to select appropriate clothing for a given activity and temperature. Though very different from each other, all seven ensembles lead to very similar values of "wind-chill equivalent temperature," expressed as the air temperature that, in combination with a wind speed of $2 \text{ m} \cdot \text{s}^{-1}$, would result in the same total heat loss as would occur in the actual combination of air temperature and wind speed. Wind-chill equivalent temperatures calculated in this way for heat loss through clothing are much lower than those calculated with the Siple wind-chill index for unprotected skin. The Siple index does not take account of the penetration of clothing insulation by wind, and it therefore underestimates the cooling effect of wind at low temperatures for typical civilian outdoor clothing.

References

1. Glaumann M. Wind environment in housing areas in Sweden. In: CIB. Proceedings of the symposium "Build-

- ing Climatology." Moscow: CIB, 1982:456—69.
2. Glaumann M, Taesler R. Klimastudier inför planering av energisnål bostadsbebyggelse in Södertuna, Södertälje. [Climate studies for energy efficient buildings to be built in Södertuna, Södertälje]. Stockholm: Swedish Council for Building Research, 1985. (Report R12:1985.)
3. Siple PA, Passel CF. Dry atmospheric cooling in subfreezing temperatures. Proc Am Philos Soc 1945;89:177.
4. McIntyre DA. Thermal climate. London: Applied Science, 1980.
5. Benzinger TH, Kitzinger C, Pratt AW. The human thermostat. In: Hardy JD, ed. Temperature: its measurement and control in science and industry; vol 3. New York, NY: Rheinhold Book Corporation, 1963:637.