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A SIMPLIFIED MODELING APPROACH FOR ESTIMATING HEAT LOSS DURING COLD EXPOSURE

by

W.R. Santee

June, 1996

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DISCLAIMER

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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EXECUTIVE SUMMARY

Equations to predict heat debt (D) and survival time (ST) were derived from a simple rational model (Burton and Edholm, 1955) that predicted the clothing insulation (I_T). The methodology is analogous to a more complex approach derived by Holmér (1984) to calculate required insulation (IREQ) and survival times. The derived equations parallel simple models developed by other investigators (Tikuisis and Frim, 1995), but are explained in sufficient detail to allow other users to fully understand the methods and to develop variations of the basic model. The derived equations are used to calculate values for comparison to both theoretical and experimental results. The equation development process demonstrates both basic heat transfer principles and the derivation of a simple model. Other equation modifications are suggested to provide insight into how basic models may be used in conjunction with experimental data to develop more sophisticated models. The equations may be used to generate predictions that may be used as simple alternative hypotheses for cold exposure modeling validation studies.

INTRODUCTION

GENERAL

The materials presented in this note were initially generated in response to a relatively simple question: how much heat is lost to the environment by a passive soldier wearing the Extended Cold Weather Clothing System (ECWCS) at -51°C (-60°F)? The basis for this question was to determine how much power would be required to electrically heat clothing to offset heat lost to the environment that could not be replaced by metabolic heat production. The process of answering that question presented an opportunity to review the basic principles of cold protection and to demonstrate the process of deriving a relatively simple model from the existing literature. The basic equation which was independently derived is virtually identical to an equation derived by Tikuisis and Frim (1995) from NATO (1992) materials to predict heat loss. The disappointment in replicating other recent work is offset, to some extent, by recognizing that if the results are equivalent, then the processes and logical basis for deriving the model were also consistent with other investigators. The agreement between results therefore validates both the logic behind the derivation and the work of the previous investigators.

During extreme cold exposure, metabolic heat production, even supplemented by shivering thermogenesis, is insufficient to establish thermal equilibrium. The difference between heat production and heat loss has been termed the heat debt (D). A net loss of energy to the environment reduces body heat storage (S), which is indicated by a decrease in body temperature (T_b). However, prior to a significant decline in T_b, the thermoregulatory response is to reduce heat transfer from the body core to the extremities by vasoconstriction. By reducing blood flow to the extremities, heat loss is reduced, but local temperatures also decline.

The bottom line is that when heat production is insufficient to offset the heat debt, body heat storage will be depleted until either a lower thermal equilibrium is reached or, at critical threshold, basic physiological processes are significantly impaired. The ultimate result may be tissue damage, severe body dysfunction and death. The options to offset heat debt are to increase body heat production by shivering or greater activity, alter the clothing or shelter parameters, termination of the cold exposure or supplementing internal heat production by auxiliary heating.

Clothing insulation is passive heat conservation which can slow or moderate the rate of heat loss. Providing improved clothing insulation is an adequate solution to cold exposure in many situations, but there are practical limits to the bulk and weight of clothing (Appendix A).

AUXILIARY OR SUPPLEMENTAL HEATING

Goldman (1964) indicates that when insulation can only delay the onset of cold strain, the alternative to passive heat conservation is external or auxiliary heat production. As noted, the origin of the calculations in this note was a simple request for an estimate of the heating power required to offset the heat debt and extend the tolerance or exposure time of soldiers in cold environments.

The technology of supplemental heat production is at least as old as human use of fire. Body warming around a campfire is a form of auxiliary heating which is relatively inefficient. Non-electronic sources include heated rocks, bed-pan heaters, hot water bottles, hot potatoes and heated bags of sand or salt used as hand-warmers, and catalytic handwarmers. Electronic systems, which have been used since WWI, include electrically heated handwear, socks or foot inserts, vests and heated underwear.

Electrically heated clothing, including gloves, socks and entire clothing ensembles, is one form of auxiliary heating. Efforts include heat socks and gloves sold through sporting goods companies and the use of electrically heated clothing by the military. American aviators used French electrically heated gloves as early as WWI (Sweeting, 1984). An important and successful application was the use of heated clothing by aviators during high altitude, non-pressurized flights in WWII (Link and Coleman, 1955; Sweeting, 1984). Aircraft electrical capacity was sufficient to supply power requirements for auxiliary heating, but an adequate electrical power supply can be a major limitation for ground personnel in forward areas. Consequently, one factor in both the design of an electrically heated clothing system and identifying the practical applications for the system in the field is to determine power requirements.

METHODS

BACKGROUND

The primary emphasis in the popular weather media is Wind-chill Index (WCI) and equivalent wind-chill temperatures (Siple and Passel, 1945; Osczevski, 1995). The WCI has been incorporated into military doctrine and reported, sometimes to the exclusion of actual temperatures and wind speeds, on civilian weather broadcasts. An important criticism of WCI is that it does not indicate how much clothing insulation an individual will need to wear (Holmér, 1984; Osczevski, 1995).

Burton (Belding, 1949; Burton and Edholm, 1955) developed an equation that did predict the required clothing from environmental parameters. Holmér (1984, 1994) refined these predictions into minimal neutral insulation required ($IREQ_{min}$) and thermoneutral $IREQ_{neutral}$, which are presented as in ISO TR 11079 (1993). Holmér's approach incorporates a calculation of (R+C) and T_{cl} which may be adapted from Gagge and Nishi (1977).

For both civilian and military user, one critical need is to translate physiological data, equations and research models into useable materials, such as executable computer models or survival tables. Holmér presents the code for a computer program. The Tikuisis (1995) model incorporates shivering, which is a difficult task. Both Holmér and Tikuisis generate predictions of survival time.

By returning to Burton's original equation, a much simpler set of predictions may be derived for the heat loss and survival time. The value of such an exercise is partially to generate simple alternative equations for hypothesis testing and partially to independently review the principles of heat transfer and modeling assumptions.

For discussion purposes the following basic energy balance equation (1,2) may be modified (equation 3) by assuming that both the conductance (K) and work (W) terms are zero. During cold exposure, the basic transfer equation may be further modified by combining the remaining dry heat transfer terms (C + R) into a single heat loss term (H). Burton and Edholm (1955) go one step further by assuming that the storage term (S) is always a net loss or heat debt (D) to the environment, and they rewrite the cold energy balance (equation 4).

Finally, in an equilibrium state, S or D is zero, and the equation simplifies to indicate that at equilibrium metabolism (M_e) equals the sum of wet (E) and dry (H) heat loss.

(1) $\dot{S} = \dot{M} - (\pm\dot{W}_k) \pm \dot{E} \pm \dot{R} \pm \dot{C} \pm \dot{K}$ [W]

(2) $S = M \pm K \pm C \pm R \pm E \pm W$ [$W \cdot m^{-2}$]

(3) $S = M \pm C \pm R \pm E$ [$W \cdot m^{-2}$]

(4) $M - D = H + E$ [$W \cdot m^{-2}$]

(5) $M_e = H + E$ [$W \cdot m^{-2}$]

ORIGINAL EQUATION

The original Burton equation is presented in Belding (1949) as:

(6) $I = 3.09 (\bar{T}_{sk} - T_a) \div (0.75 M)$ [clo]

Units for the variables are:

T_a °F
M $kcal \cdot m^{-2} \cdot h^{-1}$

The equation incorporates evaporative heat loss (E) as 25% of M by using 0.75 M rather than M and assumes a "comfortable" $\bar{T}_{sk}$ of 92°F. A slightly refined version of the same equation is presented in Burton and Edholm (1955):

(7) $I = 0.082 (91.4 - T_a) \div M$ [clo]

The changes are a $\bar{T}_{sk}$ of 91.4°F, and M is now calculated in MET units. The equation can be rewritten to calculate the metabolic rate (M) required to maintain a comfortable equilibrium for a given combination of clothing insulation (I) and air temperature (T_a). The calculated metabolic rate is actually the equilibrium metabolic rate (M_e).

(8) $M_e = 0.082 (91.4 - T_a) \div I$ [MET]

The equation assumes an equilibrium, so that the total heat loss to the environment (H) equals M_e. In this equilibrium state, the heat debt (D) is 0. For a non-equilibrium situation where metabolic heat production cannot offset the total heat loss, the heat debt (D) may be calculated from:

(9) $D = M_b - M_e$ [MET]

(10) $D' = -D = M_e - M_b$ [MET]

The heat debt is the difference between the metabolic rate required to maintain equilibrium (M_e) and the actual metabolic rate (M_b). Where M_b is the metabolic cost of a specific activity, for sitting, without shivering, the metabolic cost is 1 MET:

(11) $D = 1 - M_e$

Support for this approach is found in another Burton and Edholm (1955) equation:

(12) $M - D = H + E$

(13) $D = M - (H + E)$

To find D in a non-equilibrium state, M_e is substituted for H+E, and M equals M_b:

(14) $D = M_b - M_e$

AUXILIARY HEATING REQUIREMENTS

The answer to the initial question regarding the electrical power required to maintain thermal equilibrium is the heat debt (D). Table 1 presents estimates of the heat debt (D) derived from the original Burton and Edholm (1955) conditions for a comfortable $\bar{T}_{sk}$ of 33°C, an M_b of 1 MET and a standard man with an A_{DU} of 1.8 m^2. Based on the original parameters, a seated soldier in the standard ECWCS (3.6 clo) would remain comfortable at -60°F with an auxiliary heat source of 256 W.

Table 1. Estimated heat debt (D) based on sweating condition, with $\bar{T}_{sk}$ = 33°C, M_b = 1 MET

T_a	I_T	D	I_T	D	I_T	D	I_T	D	I_T	D
°F	clo	W	clo	W	clo	W	clo	W	clo	W
40	3.0	42	3.5	21	4.0	6	4.5	___	5.0	___
30	3.0	71	3.5	46	4.0	27	4.5	12	5.0	1
20	3.0	100	3.5	70	4.0	49	4.5	32	5.0	18
10	3.0	128	3.5	95	4.0	70	4.5	51	5.0	35
0	3.0	157	3.5	119	4.0	91	4.5	70	5.0	52
-10	3.0	185	3.5	144	4.0	113	4.5	89	5.0	69
-20	3.0	214	3.5	169	4.0	134	4.5	108	5.0	87
-30	3.0	243	3.5	193	4.0	156	4.5	127	5.0	104
-40	3.0	271	3.5	218	4.0	177	4.5	146	5.0	121
-50	3.0	300	3.5	242	4.0	199	4.5	165	5.0	138
-60	3.0	328	3.5	267	4.0	220	4.5	184	5.0	155

EQUATION MODIFICATIONS

The preceding equations are based on several assumptions, which are not necessarily valid for extreme environments. The first assumption for equation 8 was the assumption of an equilibrium. Another assumption is that evaporative heat loss (E), including respiratory losses, is 25% of M. While respiratory water loss may increase in extreme cold, thermoregulatory sweating and evaporative heat loss to the environment may decline. Some sweat may evaporate from the relatively cool skin surface, but that evaporative heat may be retained within the clothing if the water vapor recondenses within the clothing, a process referred to as "regain." The slope of the metabolic curve may be modified to eliminate the adjustment for sweating by multiplying the constant 0.082 by 0.75 and substituting the new values (0.062) into the equations.

The comfortable skin temperature for the equations is 33°C, but in fact a $\bar{T}_{sk}$ of 91.4°F (33°C) is high for a cold exposed individual. If a lower $\bar{T}_{sk}$, such as the 28°C (82.4°F) comfort limit suggested by Webb, et. al. (1991) and used by Holmér (1984), is substituted for 91.4°F

(33°C), the gradient between the individual and the environment is reduced, thereby reducing the driving force for convective heat loss. Both a lower $\bar{T}_{sk}$ and smaller E term would reduce the total heat loss to the environment.

Incorporating both the assumption of no thermoregulatory sweating and a lower $\bar{T}_{sk}$ of 28°C (82.4°F), the new basic equation for the equilibrium metabolic rate is:

(15) $M_e = [0.062\ (82.4 - T_a)] \div I_T$ [MET]

Table 2 presents the estimated heat debt for the non-sweating condition with a lower $\bar{T}_{sk}$ of 28°C. For a seated soldier in an ECWCS uniform with an I_T of 3.6 clo, the auxiliary heating requirement at -60°F would be 152 W. For a complete ECWCS uniform with an I_T of 4.8 clo, under the same conditions, the auxiliary heating requirement would be 88 W.

Table 2. Estimated heat debt (D) based on non-sweating condition, with $\bar{T}_{sk}$ = 28°C, M_b = 1 MET

T_a	I_T	D	I_T	D	I_T	D	I_T	D	I_T	D
°F	clo	W	clo	W	clo	W	clo	W	clo	W
40	3.0	___	3.5	___	4.0	___	4.5	___	5.0	___
30	3.0	9	3.5	___	4.0	___	4.5	___	5.0	___
20	3.0	30	3.5	11	4.0	___	4.5	___	5.0	___
10	3.0	52	3.5	30	4.0	13	4.5	0	5.0	___
0	3.0	74	3.5	48	4.0	29	4.5	14	5.0	2
-10	3.0	95	3.5	67	4.0	45	4.5	29	5.0	15
-20	3.0	117	3.5	85	4.0	61	4.5	43	5.0	28
-30	3.0	138	3.5	104	4.0	78	4.5	57	5.0	41
-40	3.0	160	3.5	122	4.0	94	4.5	72	5.0	54
-50	3.0	182	3.5	141	4.0	110	4.5	86	5.0	67
-60	3.0	203	3.5	159	4.0	126	4.5	101	5.0	80

OPTIONAL MODIFICATIONS

Respiratory Heat Loss

The evaporative water loss term usually includes a value for respiratory water loss (E_{res}), which may actually increase due to the low water vapor pressure of cold air. A correction for respiratory water loss may be treated as either a constant that is added to the heat debt, or a new slope for the basic equation may be calculated that assumes a value intermediate between the no sweating and the original 25% evaporative loss value.

$$E_{rw} = 400\ g \cdot day^{-1}:$$

$$= 0.0046\ g \cdot s^{-1}$$

The latent heat of vaporization equals 0.576 $kcal \cdot g^{-1}$ or 2.41 $kJ \cdot g^{-1}$. For 400 $g \cdot day^{-1}$, E_{res} = 11 W, and for 1000 $g \cdot day^{-1}$, E_{res} = 28 W.

Adjustments for Wind Effects

Burton and Edholm (1955) presented other equations to adjust clothing insulation levels (I_T) for the increase in convective heat loss at wind speeds. The adjusted I_T values could then be substituted into the basic equation to obtain new values for the equilibrium metabolic rate and/or heat debt.

SURVIVAL TABLES

The preceding equations provide an estimate of the net change in storage or heat debt. As noted elsewhere, when exposed to extreme cold, an individual has several behavioral thermoregulatory options. Retreating to a safer, less exposed environment is probably the best option. Three situations may preclude the pursuit of a rational thermoregulatory strategy. The first situation is accident or catastrophe, such as equipment failures, a fall or an extreme weather event, that eliminate the ability to reach a safe thermal refugium. Injury or incapacitation, the second situation, often occurs in conjunction with a catastrophic event. The third factor is voluntary or enforced altruism, as typified by Search and Rescue teams, emergency workers and the military. Survival tables become important when any of these three situations occur in conjunction with extreme weather conditions.

Chronological Measurements

For operational military personnel the critical concern may be represented as a endurance, tolerance or exposure time. The terminology for these time categories is not standardized nor wholly discrete. The basic concepts may be related to three levels: comfort, function and survival. Tolerance time may be most appropriately used in reference to a specific threshold, such as discomfort, pain, or a surface temperature related to those responses with some assumption of a voluntarily element in the termination criterion. Endurance time is often expressed in operational terms of the length or period of an activity or task such as dexterity or tactile sensitivity, but the actual termination criteria, usually a surface temperature, may be the same threshold as tolerance. Exposure time is more closely related to the general medical terminology that implies an actual cold injury. Hypothermia, non-freezing cold injury (NFCI) and frostbite are the results of cumulative exposure. The problem with the use of the term "exposure" is that it is often used essentially as a measurement of cold "dosage" in the context of a level or length of cold stress. In medical circles exposure is used to describe the combined effects of environmental stress and "cold exposure" is virtually synonymous with hypothermia.

The last category of a chronological measurement is survival time. Survival time is not really as useful a term if it refers to actual death. The limits or measurements that predict the thresholds for more moderate cold strain are more useful because those limits allow time for reaction and correction. The point of death marks the point at which there is no longer any time left for correction or treatment. In the context of death, survival time is the point at which search and rescue efforts should be terminated. In that context, survival times need to be extremely conservative. Circumstances vary greatly, and the human limits for actual survival are amazing. Another consideration is that survival time is always an estimate; there can be no ethical experimental human protocol to validate the threshold of death.

A more useful definition of survival time is the exposure time required to reach the threshold for irreversible injury; as defined by either frostbite (WCI and WCT) or hypothermia. At the threshold, the soldier becomes non-functional, and <u>requires</u> removal from the field and/or medical treatment or the soldier will not survive. The term "irreversible injury" is used to indicate that without removal and/or treatment continued exposure will result in permanent injury and/or death. Survival time is determined by the rate of heat loss, heat storage, metabolic heat production (basal, activity and shivering), insulation, posture and environmental conditions (air and/or surface temperatures, wind speed, radiation and, to a lesser extent, relative humidity). In this paper, survival time will be defined at the threshold of clinical hypothermia, a body temperature of 35°C.

Construction of Survival Tables

The basic assumptions to calculate survival time (ST) are a drop in core temperature of 2°C, a "standard" body mass (m) of 70 kg and the specific heat (c_p) of body tissue (3.48 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$). The first step is to calculate the change in body heat storage ($\Delta S'$):

(16) $\Delta S' = c_p \cdot m \cdot \Delta T_b$ [kJ]

$c_p = 3.48\ kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$

$m = 70$ kg

$\Delta T_b = 2°C$

$\Delta S' = 487$ kJ

Calculating ST is relatively simple. The critical threshold $\Delta S'$ (kJ) is divided by the rate of heat loss. $\Delta S'$ is in kJ, and D is in W ($J \cdot s^{-1}$). Constants are used to obtain the desired unit balance and ST in minutes.

(17) $ST_m = (1000 \cdot \Delta S') \cdot (D \cdot 60)^{-1}$ [min]

An alternative method to calculate the survival time is to use an "intolerable" heat debt of 630 kJ (ASHRAE, 1993) as the tolerance threshold. This corresponds to a 2.6°C decrease in $\bar{T}_b$. The alternative equation for survival time simply substitutes 630 kJ for $\Delta S'$.

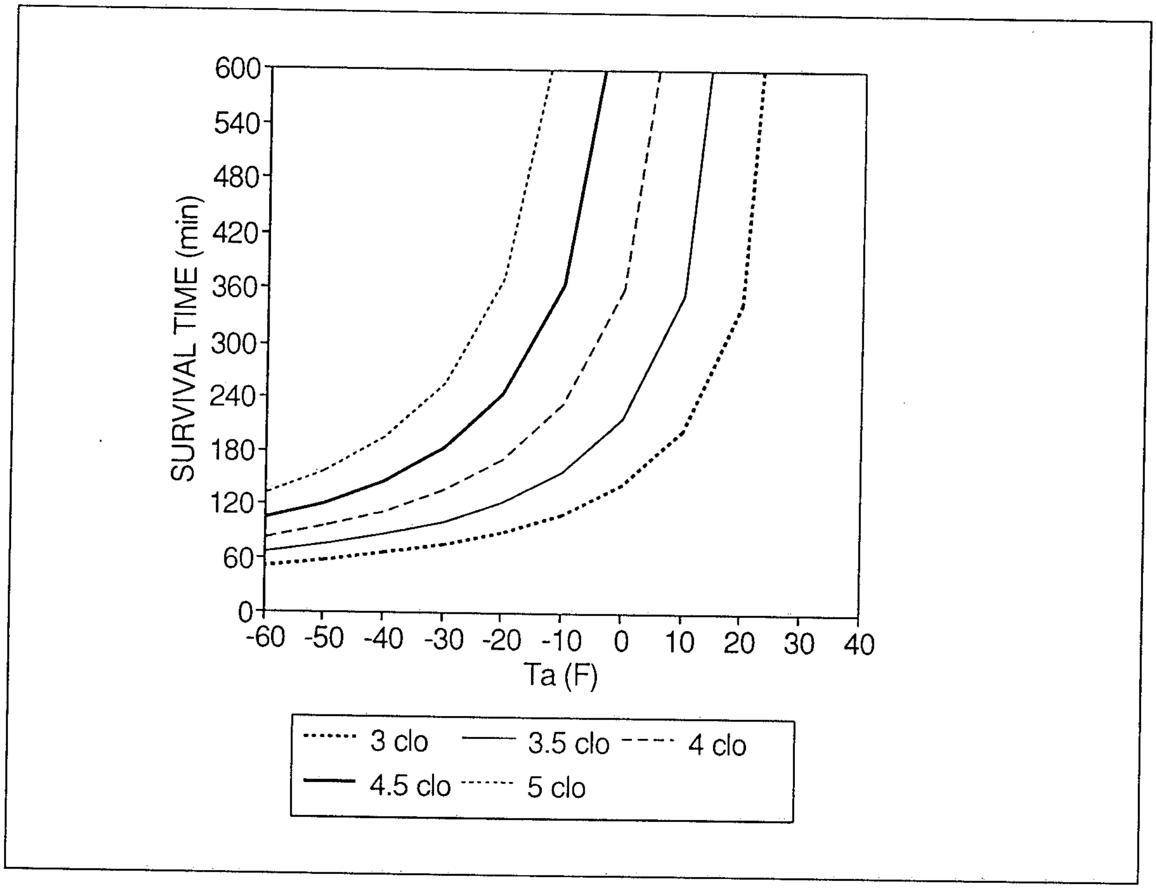
Tables

The following table and figure (1) were calculated for an alert, resting individual of standard mass. The baseline metabolic rate (M_b) was 1 MET (58.15 $W \cdot m^{-1}$) and the survival/tolerance limit was 630 kJ. Table 3 shows a non-sweating condition of either an injured or extreme cold-stressed individual who would be unlikely to sweat excessively. A relatively low $\bar{T}_{sk}$ of 28°C was also utilized, and there was no correction for respiratory heat loss (E_{res}).

Table 3. Estimated survival time (ST) based on sweating condition, with $\bar{T}_{sk}$ = 28°C and a 630 kJ threshold

T_a	I_T	ST	I_T	ST	I_T	ST	I_T	ST	I_T	ST
°F	clo	min	clo	min	clo	min	clo	min	clo	min
40	3.0	NL	3.5	NL	4.0	NL	4.5	NL	5.0	NL
30	3.0	>6 h	3.5	NL	4.0	NL	4.5	NL	5.0	NL
20	3.0	346	3.5	>6 h	4.0	NL	4.5	NL	5.0	NL
10	3.0	202	3.5	355	4.0	>6 h	4.5	NL	5.0	NL
0	3.0	143	3.5	218	4.0	362	4.5	>6 h	5.0	>6 h
-10	3.0	110	3.5	158	4.0	232	4.5	367	5.0	>6 h
-20	3.0	90	3.5	123	4.0	171	4.5	244	5.0	372
-30	3.0	76	3.5	101	4.0	135	4.5	183	5.0	255
-40	3.0	66	3.5	86	4.0	112	4.5	146	5.0	194
-50	3.0	58	3.5	75	4.0	95	4.5	122	5.0	156
-60	3.0	52	3.5	66	4.0	83	4.5	104	5.0	131

Figure 1. Survival times for different levels of clothing insulation (I_T)



VALIDATION

CALCULATED DRY HEAT LOSS

One approach to validation is to use an equation from Gagge and Nishi (1977) to calculate the dry heat loss (ΔH).

$$(18) \quad \Delta H = R + C = (h_c + h_r)\,(F_{cl})\,(A_{DU})\,(\bar{T}_{sk} - T_o) \quad [W]$$

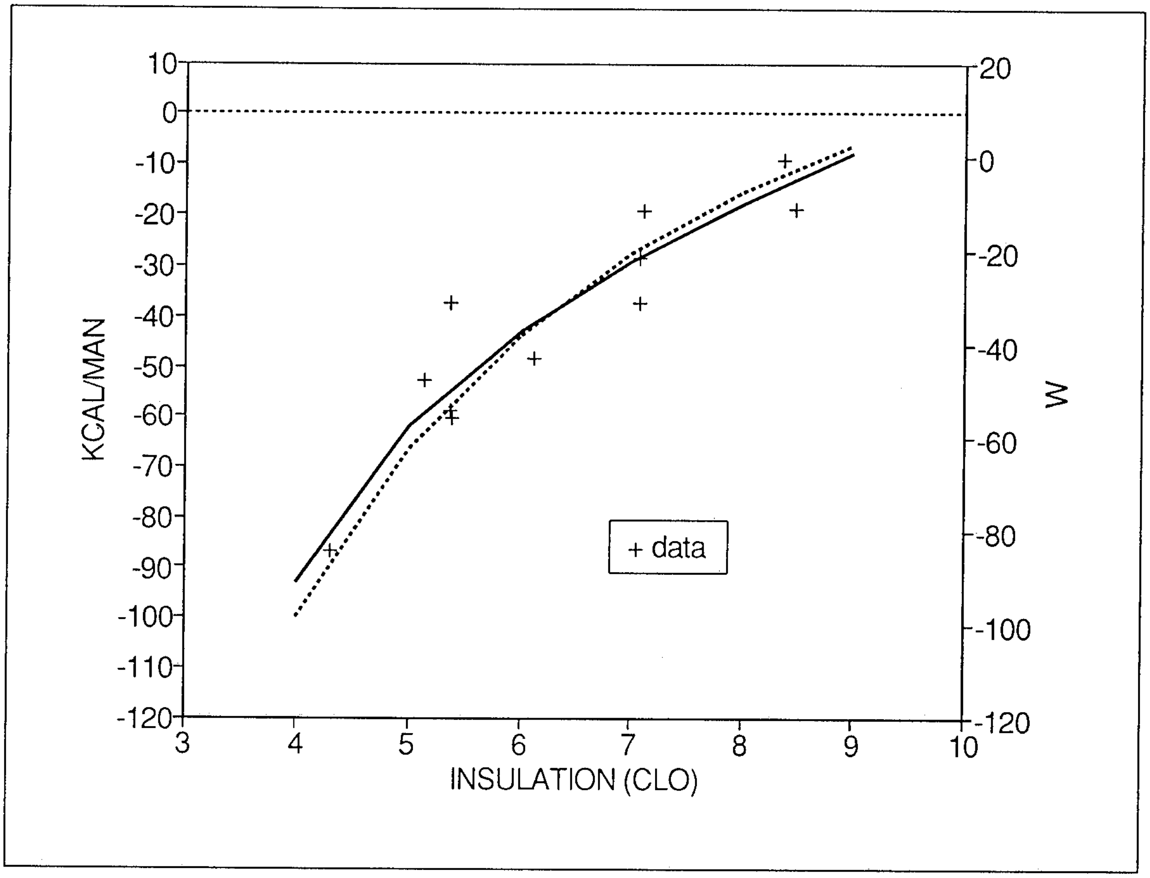
For a cold-wet uniform ensemble, their input parameters are $h_c + h_r = 8.70$; $F_{cl} = 0.27$, $A_{DU} = 1.8$ and $\bar{T}_{sk} = 28°C$. For T_o, the assumption is made that $T_a = T_o$. At a T_a of -51°C (-60°F), ΔH equals 334 W. Further assuming that $\Delta H = D + M_b$, for an M_b of 1 MET, D = 229 W. Using equation 15 for a uniform with 2.0 clo, D equals 357 W. Gagge and Nishi (1977) state the insulation of the cold-wet uniform as 2.0 clo, whereas a differing USARIEM value of 2.9 clo may include the insulated clothing liners. Using the higher USARIEM value, D would be 214 W. Using the data as supplied by Gagge and Nishi (1977), equation 15 overpredicts the heat debt.

HUMAN TESTING

Sleeping Bag Study

Goldman (1988) present data from USARIEM sleeping bag studies to plot the heat debt for 3 h during supine, resting activity (M_b = 0.8 MET). The heat debt (D) was calculated from $\bar{T}_{sk}$ and T_{re} values and expressed as $kcal \cdot man^{-1}$ on a plot. Goldman (1988) apparently used the Burton and Edholm (1955) equation with a comfortable $\bar{T}_{sk}$ of 32°C (89.6 °F) to estimate the required sleeping bag insulation. Data from Gonzalez, et al. (1989) indicates that the estimated heat losses are too low. An alternative explanation, in the absence of the test data, is an error in calculating the units. The resting M_b of 0.8 MET is presented as 40 $kcal \cdot m^{-2}$ or 57 $W \cdot m^{-2}$, whereas the correct values or units would be 40 $kcal \cdot h^{-1} \cdot m^{-2}$ or 47 $W \cdot m^{-2}$. Although neither of these values were used to calculate the heat debt, the errors indicate the possibility of some confusion in the unit balance. Figure 2 compares values derived from Goldman (1988) in $kcal \cdot man^{-1}$ versus values calculated for an M_b of 0.8 MET using equation 15 for the rate of whole body heat loss in W.

Figure 2. Calculated versus observed* heat debt for sleeping bags at -34°C (-30°F).



*Goldman (1988)

Handwear Study

Current USARIEM protocol guidelines allow testing down to a rectal temperature (T_{re}) of 35°C and/or a skin surface temperature (T_{sk}) of 4.5°C. It would be feasible to test the predicted values for survival time and heat debt. However, given the rather simple assumptions involved in these calculations, it is preferable to use data (Gonzalez, et al., 1989) from an existing study where surface temperatures were allowed to drop to 5°C and the subjects had the option of withdrawing due to discomfort or pain. Hence, the experimental times are more accurately described as tolerance times. Data for $\bar{T}_b$, $\bar{T}_{sk}$, T_{re}, chamber exposure time and subject parameters (m, A_{DU}) were available in the data set.

Data from this report were replicated for three exposures (2 at -30°C) for subjects wearing the same uniform: the ECWCS with an I_T of 0.56 $m^2 \cdot K \cdot W^{-1}$ (3.6 clo) with three different types of handwear. The measured baseline metabolic rate (M_b) for sitting was approximately 1.1 MET or 65 $W \cdot m^{-2}$, which was higher than the 1 MET value used in the original equations. It is possible that the increase in the M_b term is due to shivering. Values for the mean heat debt at 0°C, -20°C and -30°C were presented in the paper (Gonzalez, et al., 1989) in kJ. Using the chamber exposure times, the mean heat debt for each exposure was recalculated as a rate of heat loss (W).

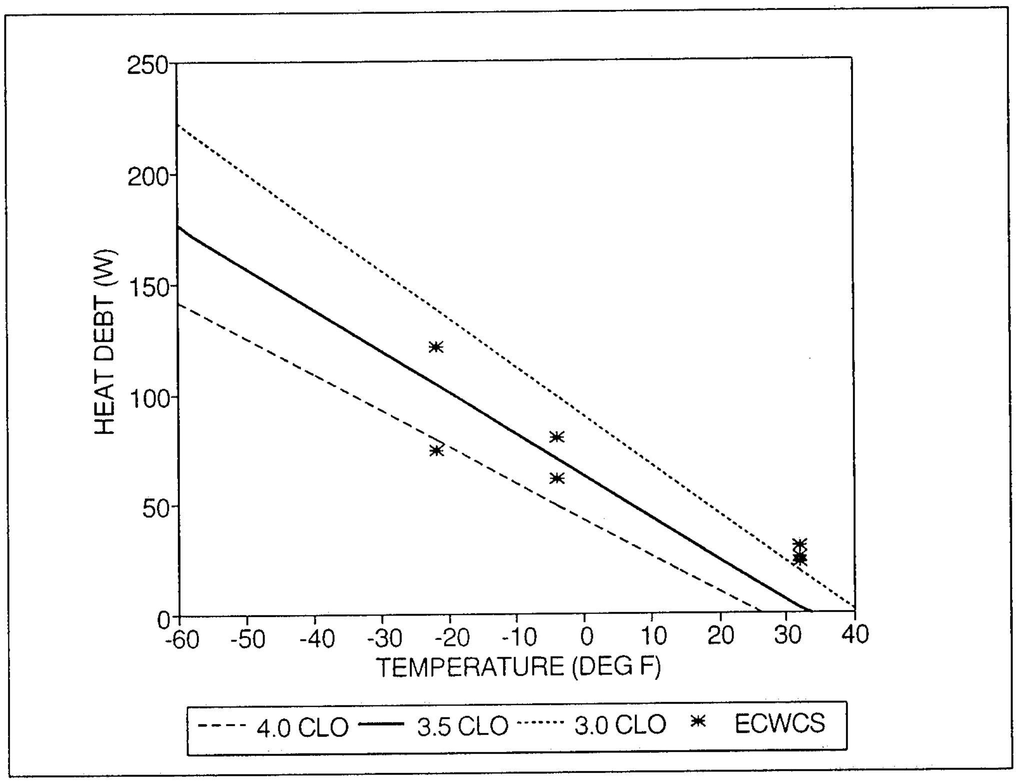
Based on data from the handwear study, several adjustments to equation 15 were considered. The correct $\bar{T}_{sk}$ for the model is neither 33°C nor 28°C. Based on data from USARIEM studies (Gonzalez, et al., 1989; Santee, et al., 1990a), the correct range is between 29° and 30°C. For the handwear data, an offset of 11 to 14 W for evaporative (respiratory) heat loss appears warranted. To improve fit, modified equations using different combinations of skin temperature (33°, 30°, 29.5°, 28°C), sweating and non-sweating coefficients (0.082, 0.062) and corrections for E_{res} (11, 28 W) were explored. The equation selected used a $\bar{T}_{sk}$ of 30°C, an M_b of 65 $W \cdot m^{-2}$, a non-sweating coefficient of 0.062 and an constant correction for E_{res} of 11 W.

Figure 3 presents the relationship between the predicted observed values. Values for 3.0 and 4.0 clo level of clothing insulation were also plotted. A higher wind speed would reduce the clothing insulation, so the line drawn for 3.0 clo is an upper bound for the predicted heat debt.

What is most noticeable about Figure 3 is that the actual data appear to have a lower slope of about 1.3 $W \cdot °F^{-1}$ (-2.38 for $W \cdot °C^{-1}$), whereas using the non-sweating co-efficient, the slope for the predicted values is 1.9 $W \cdot °F^{-1}$ (-3.36 for $W \cdot °C^{-1}$), and using the sweating coefficient, the slope would be even higher, 2.5 $W \cdot °F^{-1}$ (-4.48 $W \cdot °C^{-1}$).

However, if the slope for the observed data is calculated for only the mean change between -20° and -30°C (-4° and -22°F), the slope is 1.7 $W \cdot °F^{-1}$ (3.02 $W \cdot °C^{-1}$). Using the later slope and ignoring the data at 0°C would result in an estimated equilibrium (D = 0) at 3°C (37°F) in the heavily insulated ECWCS uniform, whereas using the empirical equation derived using all three environmental sets would calculate the equilibrium point at 11°C (51°F).

Figure 3. Observed and calculated values for heat loss from seated soldiers during cold exposure in ECWCS uniforms



Derivation of an Empirical Model

The simplest method for developing a "model" would be to simply plot the best fit for the data using the most prominent independent parameter, T_a, to predict total heat loss. A more complex empirical model could be developed by adjusting the coefficients for clothing insulation (I_T). The slope of -1.3 multiplied by an I_T of 3.5 clo yields a slope of -4.6. Baseline or activity metabolic rate (M_b) and respiratory heat loss (E_{res}) could be accommodated by a constant offset. Equation 19 illustrates an empirical equation that fits the handwear data from Gonzalez, et al. (1989).

(19) $D = [(-4.6\ T_a) \div I_T] + 65$ [W]

COMPARISON TO OTHER MODELS

The equations presented thus far were derived directly from Burton and Edholm (1955), but as noted previously, the approach outlined in this report are not unique. Tikuisis and Frim (1995) present a simple model based on an equation presented in NATO ACCP-1 (1992) for calculating heat loss in the cold in an appendix to their model. Their simple model is based on the same assumptions that are detailed in this report. They also indicated that a 33°C $\bar{T}_{sk}$ was too high under thermoneutral conditions, as would the data from USARIEM handwear and boot studies. The original equation from NATO ACCP-1 (1992) which yields on estimate of dry heat loss from resting, non-sweating individuals is:

(20) $H_{(R+C)} = (A/R_c)(T_s - T_a)$ [W]

Equation 20 is a reconfiguration of equation 18. The temperatures are in °C, R_c is the clothing resistance in $m^2 \cdot K \cdot W^{-1}$, A equals A_{DU} and I_T equals "clo." The conversion factor is commonly cited as 6.45, but 6.46 is correct.

(21) $R_c = 6.46 \div clo$

(22) $H_{(R+C)} = 6.45 \cdot (A/clo)\ (T_s - T_a)$ [W]

Tikuisis and Frim reordered the equation as:

(23) $H_{(R+C)} = 6.45\ (T_s - T_a) \cdot A_{DU} \div I$ [W]

In their text, Tikuisis and Frim identify the units for equation 22 as $W \cdot m^{-2}$, but in their example, they present the results in W. This is equivalent to equation 15, with the temperatures in °F multiplied by A_{DU} and the conversion constant from MET to $W \cdot m^{-2}$.

(24) $H_F = [0.062\ (\bar{T}_{sk} - T_a) \div I_T] \cdot (A_{DU} \cdot 58.2)$ [W]

The derivation of the 6.45 constant is based on a conversion from clo to SI resistance units, but it may also be derived by multiplying the coefficient for non-sweating heat transfer in equation (0.062) by the conversion from °F to °C (1.8) and the conversion from MET units to $W \cdot m^{-2}$. Rounding errors prevent an exact conversion. If adjusted for body surface area and conversions in units from MET to $W \cdot m^{-2}$ and from °F to °C, equation 15 is identical to the NATO equation. The Tikuisis and Frim simplified model also estimates heat loss as the difference between dry heat loss and metabolic heat production, and survival time as a change in heat storage divided by the heat debt. Their model differs in the assumption of a much lower T_b (30°C), and they present a more elaborate equation for calculating $\bar{T}_{sk}$ based on both tissue and clothing insulation. For their sample calculation, they calculated an equilibrium $\bar{T}_{sk}$ of 16°C at -40°C, assumed an I_T of 3.2 clo ($I_T = I_{clo} + I_a$) and a simplified metabolic rate (M_b), with shivering, of 150 W. For 1 MET, M_b would be 105 W for a standard man. Using the higher 65 $W \cdot m^{-2}$ value from Gonzalez, et al. (1989), M_b would be 117 W.

The main difference between the ST predictions for the different models is due to different assumptions regarding the ΔS' required to reach the survival point. For a constant rate of heat loss, the greater the ΔS' value, the longer the estimated survival time (ST). The Tikuisis model is a true catastrophic survival model, whereas the survival limit in this report is an estimated lower functional limit. The ST tables presented in this report were based on the simple assumption of a $\Delta\bar{T}_b$ of 2°C (Table 2) or the ASHRAE (1993) "intolerable" ΔS' of 630 kJ. Using the Burton and Edholm (1955) equation for $\bar{T}_b$, which weights T_{re} two-thirds and $\bar{T}_{sk}$ one-third, a decline from a pre-exposure comfortable state (37°C T_{re}, 33°C $\bar{T}_{sk}$) to state of discomfort at the upper boundary of hypothermia (35°C T_{re}, 28°C $\bar{T}_{sk}$) would result in calculated $\bar{T}_b$ of 35.7°C and 32.7°C. The change in body temperature ($\Delta\bar{T}_b$) increases to 3°C, which represents a proportional change in body heat loss (ΔS') required to reach the designated survival threshold. Thus for a 70 kg individual, ΔS' would increase from 487 kJ to 731 kJ. The ASHRAE (1993) "intolerable" threshold of 630 kJ in between those two estimates. For a constant rate of heat loss, the greater the ΔS' value, the longer the estimated survival time (ST). If the rate of heat loss was 50 W, the ST estimate would change from 162 min to 243 min. Table 2 could be recalculated to accommodate a different ΔS' value, or the ST values could be multiplied by 1.5.

The other difference between the two models is that their model has an equation to estimate $\bar{T}_s$ rather than using a constant. A change in $\bar{T}_s$ will alter the heat debt (D) term. A smaller D term indicates a slower rate of heat loss to the environment, thereby increasing ST.

The Tikuisis model proposes a survival limit at a T_{re} of 30°C, and for a T_a of -40°C, an $\bar{T}_s$ of 16°C is calculated, so that the calculated $\bar{T}_b$ is 25.4. The ΔS' term to reach that survival limit from a warm, comfortable state is 2,510 kJ versus a functionally defined ΔS' of either 731 or 487 kJ. For the same conditions, an I_T of 3.2 and a T_a of -40°C, the difference in ST between the two "simple models" would range from 62 or 93 min to 8 h. The heat debt (D) calculated using a $\bar{T}_{sk}$ of 28°C would be 131 W, whereas using a $\bar{T}_{sk}$ estimate of 16°C reduces D to 87 W. Applying all of the Tikuisis assumptions, ST would be 12.8 h.

Ignoring any direct data, in the author's opinion, based on both winter outdoor experiences in the northern United States and 7 USARIEM chamber studies conducted between 0 and -30°C (Santee, et al., 1988; Gonzalez, et al., 1989; Santee, et al., 1990a; Santee, et al 1990b; Endrusick, et al., 1990; Endrusick, et al., 1992; Santee, 1994; Endrusick, et al., 1994), a seated, sedentary individual at a T_a of -40°C, would have numb extremities and be shivering violently within the 62 to 93 min functional ST limits. The Tikuisis model predicts that an individual would be near death somewhere between 8 and 13 h unless shivering significantly increased M_b. Using the more sophisticated model from Tikuisis and Frim (1995), their predicted survival time would be closer to 24 h. As noted elsewhere, there is no way to ethically validate a lethal prediction.

Given the high individual variability and the observation that under real conditions, behavior is rarely constant, even the best model is only a well educated guess. For both civilian activities and military operations, functional ST values are important. For Search and Rescue (SAR) operations, unless SAR personnel were forced to withdraw due to extreme danger, the search would probably continue past 24 h.

DISCUSSION

The original Burton equation (Belding, 1949; Burton and Edholm, 1955) was derived from first principles of heat and mass transfer theory and experimental studies. An advantage of the original model was that it used basic parameters (T_a, I_T and M) that were readily available to the military. The equations require only basic mathematics and values can be readily calculated in the field. The most difficult parameter to obtain is an I_T value for the clothing. Also, as noted, Burton and Edholm used another relationship to adjust I_T for the effects of wind speed on clothing insulation. As demonstrated by its adaptation by both Holmér (1984) and Goldman (1988), the basic model is still considered credible.

Tikuisis and Frim (1995) contrasted the results from a simple models to the more sophisticated projections derived from a multi-node thermoregulatory model. What is most interesting about all of the models is the number of different factors and range of variability for each of the potentially confounding variables. It is the nature of a catastrophic event that no one is taking precise notes or making exact measurements. Hence, there is generally no way to completely validate lethal predictions. In an actual emergency, the status of the individual parameters will be inexactly known. Therefore it will be important to understand how each factor may impact the final result. It is much easier to manipulate a simple model to determine the direction and potential impact of each variable on the overall prediction.

PRINCIPLES OF HEAT TRANSFER

The terms from the basic energy or heat balance equation (1) are represented in the Burton equation in the following manner:

- The driving force for dry convective heat transfer is the temperature difference between the body surface and the environment, as represented by the relationship $\Delta T = \bar{T}_{sk} - T_a$.

- In these equations radiation (R) is combined with convective heat loss (C) as a net loss. In common with the WCI, the basic Burton equation ignores solar radiation gains.

- Clothing insulation, which is a resistance to heat transfer, is inversely related to the combined convective and radiative heat transfer coefficient. The appropriate input I_T^{-1} should be converted from clo to $W \cdot m^{-2} \cdot K^{-1}$ with an appropriate constant.

- Metabolism (M) is the only significant source of heat production. A subcategory of metabolism, shivering, is an important factor in the cold. However, prediction of shivering could only be approximated in a simple model by modifying the M_b term.

- Evaporative heat loss is treated either as a constant function of M, or it may be considered of reduced importance in the absence of thermoregulatory sweating.

- Thresholds for negative impact on physiological functions (hypothermia) are tied to body temperatures, and changes in core body temperature are related to energy balance and net change in heat storage (ΔS or $\Delta S'$).

RATIONAL VS. EMPIRICAL MODELING

The strong point of a rational model derived from first principles is the universal application of the model. The limitation of such a universal model is that the fit to any specific data set does not inspire confidence. The section did demonstrate how a data set could be used to modify or improve the fit, but the model must then be tested against a third data set. The simple empirical model derived in the validation section provides a good fit to the handwear data set, but is dependent on the quality of the specific data. A model that is empirically derived entirely from a data set provides no clear guidance regarding applications beyond the data set for additional factors such as different uniforms or metabolic rates. An empirically derived model is seldom an adequate basis for expansion into a more universal model.

QUALITY OF COLD DATA

One problem with the validation of any cold model is the quality of the experimental data base. Cold test results are often contradictory or demonstrate such great variation that it is difficult to use an existing data base to validate a specific model. The model presented here assumes a constant rate of heat loss, but using experimental short-term chamber data to derive a rate of heat loss may be difficult. Values for heat debts derived from experimental data are cumulative. Subjects enter the cold chambers from a comfortable 20°-23°C environment. Characteristically, they have high skin temperatures; they are generally vasodilated, and due to the heavily insulated clothing in a warm pre-chamber environment, they are often sweating. There may be significant heat storage in garments. The initial effects due to vasodilation, heat storage in clothing and sweating may be partially compensated by allowing for an initial baseline stabilization period prior to selecting the initial condition. The initial rate of heat loss is high, yet vasoconstriction and declining skin temperatures may be effective enough to conserve a relatively high core temperature. These conditions may be significantly different than those experienced by soldiers that sleep and dress in cold tents.

The final conclusion regarding the effort to "validate" the equations is that the variability of the observed data is too great to justify broad conclusions. A relatively simple, modified Burton model which makes broad assumptions concerning respiratory heat loss, shivering and $\bar{T}_{sk}$ would probably fit the experimental data just as well as a more sophisticated model. The data often fit a span of models from the simplistic model derived in this demonstration to more elaborate models.

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APPENDIX A. CLOTHING

One of the basic tenets of clothing research has been the assumption that there is a practical upper limit to clothing insulation. Insulation is generally equated with material thickness and as thickness increases, the ratio of the outer surface area of the clothing relative to the skin surface area also increases. This ratio is incorporated into clothing factors, (F_{cl} or f_{cl}), which are used as clothing correction factors to adjust for the combined convective and radiative heat loss. Van Dilla (1949) generated a widely copied illustration that illustrates the increasing bulk of insulation required to prevent a significant decrease in hand temperature at -20°F. Van Dilla (1949) indicated that the maximum practical mitten (2.9 clo) would allow a resting individual to maintain a comfortable hand temperature of 29°C (84°F) for 2-3 hr at -29°C (-20°F). Gonzalez (1995) has indicated that the "hobbling effect" of increasing clothing weight and bulk also limits the practicality of increasing insulation.

Insulation is a passive approach which slows the rate of heat loss to the environment to conserve body heat. In an extreme environment where heat loss exceeds the internal capacity for heat production, a heat debt (D) is incurred. The heat debt is balanced by the loss of heat stored in the body, but as heat is lost to the environment, body temperature also decreases. The total body heat storage (S) may be calculated from body mass (m), body temperature and the heat capacity of body tissue ($3.5\ kJ \cdot kg^{-1} \cdot °C^{-1}$). Actual thermoregulation incorporates such factors as decreasing $\bar{T}_{sk}$ and vasoconstriction to conserve heat and maintain core body temperature at a functional level. The simplified approach incorporated into this exercise assumes a fixed $\bar{T}_{sk}$ of either 33°C or 28°C. The higher temperature represents a "comfortable" $\bar{T}_{sk}$, and the lower 28°C was used by Holmér (1984) and others to represent a stressed or minimum acceptable $\bar{T}_{sk}$. Webb, et al. (1991) also cites 28°C as the threshold between tolerable and uncomfortable skin temperatures, whereas Van Dilla suggested 84°F (29°C).

APPENDIX B. OBSERVED VS. ESTIMATED VALUES

Unpublished data from Santee, et al. (1990a) was used to obtain values for $\Delta\bar{T}_b$, average $\bar{T}_{sk}$, individual weights to calculate and compare values for heat debt and endurance time (ET). To reduce any error due to the rapid loss of an excessive heat load upon initial entry into the chambers, all values are calculated after an initial 10 min baseline. As a consequence, elapsed times differ by 10 min from total chamber exposure time (ET). The requisite or threshold ΔS' was calculated from the actual change in heat storage so the Δt values may be compared to the actual elapsed time (Δt_o) value. There is some concern that the process has a circular element. Data is presented for three different days of testing. The only difference between the three sets of test conditions was that a different glove was worn each day.

CALCULATIONS

The dry heat loss [$H_{(C+R)}$ ($W \cdot m^{-2}$)] was calculated from observed $\Delta\bar{T}_b$ and individual body weights divided by elapsed time (t_o) using equation 16. The heat debt calculation - based on the individual subject parameters [D_o (W)] - used the average observed $\bar{T}_{sk}$ as $\bar{T}_s$, T_a, the non-sweating coefficient from equation 15 (0.062), and an I_T of 2.9 clo. D28 (W) was calculated using a $\bar{T}_s$ of 28°C and D29.4 (W) was calculated using a $\bar{T}_s$ of 29.4°C, which is the average of all three test sets. Δt_{co} was calculated using ΔS' and D_o in equation 17. Δt28 and Δt29.4 (min) were calculated using D28 and D29.4 respectively. M_b (W) was calculated using 65 $W \cdot m^{-2}$ and individual A_{DU} ΔS'(kJ) calculated from $\Delta\bar{T}_b$ and body mass using equation 16.

RESULTS

The results are listed in Table A-C for the three test sets. All calculated mean values for D and Δt are within one standard deviation of the mean values for $H_{(C+R)}$ or Δt_o. This may be a reflection of the basic utility of the various modified equation or it may simply prove that with a large enough variability, almost any model can fit the data. Only data for the -6.7°C chamber exposure are presented. Results for the estimate of Δt in the 0°C chamber environment were not comparable.

Table A. T_a = -6.7 °C, Data from Santee, et al. (1990)

Subject	$\Delta\bar{T}_b$ (°C)	m (kg)	$\bar{T}_s$ (°C)	$H_{(C+R)}$ ($W \cdot m^{-2}$)	D_o (W)	D28 (W)	D29.4 (W)	Δt_o (min)	Δt_{co} (min)	Δt28 (min)	Δt29.4 (min)
1	0.60	75	27.98	24	24	24	30	111	110	109	87
2	0.41	79	29.99	26	34	25	31	72	56	76	60
3	0.27	76	30.42	35	34	24	30	34	34	49	39
4	0.44	63	29.75	47	29	22	27	34	56	73	58
5	0.51	66	30.36	27	31	22	28	74	63	89	71
$\bar{x}$	0.45	72	29.70	32	30	23	29	65	64	79	63
sd	0.12	7	1.00	10	4	1	2	32	28	22	18

Table B. T_a = -6.7 °C, Data from Santee, et al. (1990)

Subject	$\Delta\bar{T}_b$ (°C)	m (kg)	$\bar{T}_s$ (°C)	$H_{(C+R)}$ ($W \cdot m^{-2}$)	D_o (W)	D28 (W)	D29.4 (W)	Δt_o (min)	Δt_{co} (min)	Δt28 (min)	Δt29.4 (min)
1	0.31	75	27.96	15	24	24	30	88	57	56	45
2	0.39	79	29.39	31	31	25	31	59	58	72	57
3	0.50	76	29.75	33	32	24	30	67	69	91	72
4	0.28	63	28.48	20	24	22	27	51	43	47	37
5	0.31	66	29.95	24	30	22	28	49	40	54	43
$\bar{x}$	0.36	72	29.10	25	28	23	29	63	53	64	51
sd	0.09	7	0.85	7	4	1	2	16	12	18	14

Table C. T_a = -6.7 °C, Data from Santee, et al. (1990)

Subject	$\Delta\bar{T}_b$ (°C)	m (kg)	$\bar{T}_s$ (°C)	$H_{(C+R)}$ ($W \cdot m^{-2}$)	D_o (W)	D28 (W)	D29.4 (W)	Δt_o (min)	Δt_{co} (min)	Δt28 (min)	Δt29.4 (min)
1	0.42	75	27.80	32	23	24	30	58	79	76	61
2	0.41	79	30.33	25	35	25	31	75	54	76	60
3	0.76	76	29.70	38	31	24	30	89	106	138	110
4	0.36	63	28.89	24	25	22	27	54	52	60	48
5	0.38	66	31.02	21	34	22	28	70	43	66	53
$\bar{x}$	0.47	72	29.55	28	30	23	29	69	67	83	66
sd	0.17	7	1.25	6	5	1	2	14	26	31	25