Title
A Derivation of the GAGGE 2-Node Model

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A DERIVATION OF THE GAGGE 2-NODE MODEL

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by

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Introduction

The Gagge 2-node model was introduced in 1970 (Gagge, Stolwijk, and Nishi, 1970). Gagge's model represents the human body as two concentric cylinders, a core cylinder and a thin skin cylinder surrounding it. Metabolic heat is generated in the core and lost to the environment via evaporation, convection, respiration, diffusion, and radiation. Clothing and sweat are assumed to be evenly distributed over the skin surface. At time "zero", the cylinder is exposed to a uniform environment, and the model produces a minute-by-minute simulation of the human thermoregulatory system. After the user-specifed time period is reached, the final surface temperature and surface skin wettedness of the cylinder are used to calculate standard comfort indices such as predicted thermal sensation (TSENS) and predicted thermal discomfort (DISC). In a project funded by the City of Toronto in 1991 (Bosselman et. al 1991), the author made modifications to the Gagge 2-Node model to allow consideration of outdoor meteorological data in predicting TSENS and other indices. More recently, the author has released a thermal comfort prediction tool for Microsoft Windows (TM) that includes a version of Gagge's model (Fountain and Huizenga 1995).

RWDI wishes to use the Gagge 2-Node model to predict TSENS for evaluating outdoor comfort. RWDI has a version of the model currently in place that is providing suspect results. RWDI wishes to verify that the equations used are correct and that previously used methods for incorporating outdoor meteorological data are followed. This paper contains a derivation of the 2-node model constructed from first principals. The result of the derivation is a differential equation that must be solved by numerical integration. The source code of a computer program (DOS) to perform this numerical integration is attached and is also given on disk. RWDI has already purchased a version of this software for Microsoft Windows (TM).

Conventions are: SI units unless otherwise noted and when an equation is presented, only newly introduced variables are defined.

Model Derivation

Objective

The objective is to arrive at predictions of skin temperature and core temperature for a human body based on measureable parameters of the surrounding environment, the clothing insulation, and metabolic heat generation. These temperatures can then be used to calculate comfort indices such as TSENS and DISC.

Basics

The independent environmental variables that govern heat exchange between the body and the environment are:

- Air temperature
- Mean radiant temperature
- Relative air velocity
- Barometric pressure
- Humidity

Personal variables are:

- Metabolic heat generation
- Clothing insulation

Mechanisms of heat exchange

The body exchanges heat with the environment via conduction, radiation, convection, evaporation, diffusion, and respiration. Conduction effects are negligible and are generally ignored.

Mechanisms of thermoregulatory control

- Shivering - increased contractive activity of skeletal muscles
- Vasodilation and vasoconstriction - dilation and constriction of peripheral blood vessels.
- Sweating - sweat secretion

These mechanisms are controlled by mean temperatures in the body core and skin surface.

Heat balance

All the metabolic heat production is generated in the core. External work done by muscles on surroundings and respiratory losses are also associated with the core. Core and skin compartments exchange heat through direct contact, and through blood flow. In the skin compartment, heat transported from the core is dissipated to the environment through sensible heat loss (convection and radiation) and insensible heat loss (evaporation, diffusion). These mechanisms are described by 2 coupled heat balance equations:

$$\mathrm{Scr}=\mathrm{RM}+\mathrm{Mshiv}-\mathrm{W}-\mathrm{Qres}-\mathrm{Qcs} \qquad (1)$$

$$\mathrm{Ssk}=\mathrm{Qcs}-\mathrm{Qc}-\mathrm{Qr}-\mathrm{Erws}-\mathrm{Ediff}. \qquad (2)$$

Where:

Scr = rate of energy storage in core
Ssk = rate of energy storage in skin
RM=metabolic rate (rate of energy released by oxidation processes in the body)
Mshiv= rate of energy released by shivering
W=rate of work done by body on surroundings
Qres=total rate of heat loss through respiration
Qcs=rate of energy transport from core to skin
Qc=rate convective heat loss
Qr=rate of radiative heat loss
Ersw=rate of heat loss from sweat evaporation
Ediff=rate of heat loss from diffusion of water vapor through the skin

Combining (1) and (2),

$$St=RM+Mshiv-W-Qres-Qc-Qr-Erws-Ediff \quad (3)$$

where:

St = total rate of heat storage

Each of these heat transfer processes can be expressed in terms of the seven environmental and personal parameters mentioned above. The next step is to explicitly define each component of equation 3.

Surface area

Surface area of the body is a variable that will be used throughout. Two expressions for surface area are required. One for the surface area of the nude body and one for the surface area of the clothed body.

Ad = .203(m^0.425)(L^0.725) (square meters) (ASHRAE 1993)
Acl = fcl(Ad) (square meters)

Where:

Ad = the Dubois surface area of the nude body (square meters)
Acl = the Dubois surface area of the clothed body (square meters)
m = mass of the body (kilograms)
L = length of the body (meters)
fcl = ratio of clothed body surface area to nude body surface area

Clothing resistance

All dry heat and water vapor passes through the clothing layer - represented in this model by a thermal resistance. In order to simplify

The thermal resistance of clothing ensemble is generally specified in “clo” units.

1 clo = 0.155 deg. C (m^2/W)

= 0.18 deg. C (m^2 hr/kcal)

Where:

M = meters

W = watts

hr = hours

kcal = kilocalories

Clothing thermal resistance is then:

$$Rcl = 0.155 Icl$$

Where:

Rcl = thermal resistance of ensemble (deg. C M^2/W)

Icl = thermal resistance of clothing (clo)

Values for Icl and corresponding fcl are generally drawn from tables such as those found in ASHRAE Standard 55 and ISO 7730. In 2-Node, fcl is estimated by:

$$fcl = 1+0.15Icl$$

Metabolic rate

The metabolic rate is proportional to the rate of oxygen consumed.

$$RM = 5.873\ (60\ V02)\ (0.23\ Rex + 0.77)$$

Where:

RM = rate of metabolic heat generation (watts)

V02 = rate of oxygen consumption (liters/minute)

Rex = respiratory exchange ratio

There are numerous tables that give RM per unit Dubois surface area (ASHRAE 55, ISO 7730). Similar to clothing insulation, metabolic rate has a special unit.

$$1 \text{ met} = 58.2 \text{ W/M}^2$$

Shivering

Shivering provides additional metabolic heat through muscle action and tension.

$$M_{shiv} = A_d\ 19.4\ (34 - T_{sk})\ (36.6 - T_{cr}) \quad \text{(Watts)}$$

where:

T_{sk} = skin temperature (deg. C)

T_{cr} = core temperature (deg. C)

Work

Work done on the surroundings is expressed in terms of thermal efficiency. For most stationary activities, external work is neglected.

$$W = \mu(RM)$$

Where:

μ = thermal efficiency

Respiration

The body loses both sensible and latent heat by convection and evaporation from the respiratory tract to the inhaled air. The latent heat loss depends on the difference in water content (while the dry heat loss depends on the difference in temperature) between inhaled and exhaled air. The total heat loss also depends on the pulmonary ventilation rate:

$$Q_{res} = V_{res}\ [(\lambda)\ (W_{ex} - W_a) + C_p(T_{ex} - T_a) \qquad \text{(Watts)}$$

Where:

Vres = pulmonary ventilation rate

λ = heat of vaporization of water

Wex = humidity ratio of exhaled air

Wa = humidity ratio of inhaled air

Cp = specific heat of dry air

Tex = temperature of exhaled air

Ta = temperature of inhaled air

Pulmonary ventilation rate can be expressed as a function of metabolic rate and the conditions of the exhaled air can be expressed in terms of the inhaled air. The examining the details of this relationship are beyond the scope of this derivation but Qres is generally (Fanger 1970) reduced to:

RM

$$Q_{res} = .0023\ RM\ (44 - P_a) + 0.0014\ (34 - T_a) \qquad \text{(watts)}$$

Where

Pa = the partial vapor pressure of water (mm Hg)

Convection

Convective heat transfer can be expressed in terms of the surface area of the clothed body, a convective heat transfer coefficient, and the difference in temperature between the outer surface of the clothed body and the ambient temperature:

$$Q_c = A_d\ f_{cl}\ H_c\ (T_{cl} - T_a) \qquad \text{(watts)}$$

Where:

Hc = the convective heat transfer coefficient (W/M^2 deg C)

Tcl = temperature of the outer surface of clothing (deg. C)

In general, the magnitude of Hc depends on whether the convection is predominantly natural or forced. The convention in comfort modeling has been to compute Hc for both types and use the larger value. Many expressions have been used for Hc based on experiments at different activities: We have used equations from (ASHRAE 1993) in Wincomf.

For forced convection:

$Hc = 8.6\ V^{.53}$ (W/M^2 deg C)

For free convection:

$Hc = 5.666\ (RM - 0.85)^{0.39}$ (W/M^2 deg C)

Where:

V = relative air velocity (meters per second)

Radiation

We express the radiative heat transfer in terms of a linearized radiative heat transfer coefficient:

$Qr = Ad\ fcl\ Feff\ \varepsilon\sigma\ (Tcl^4 - Tr^4) = Ad\ fcl\ Hr\ (Tcl - Tr)$ (watts)

Thus:

$Hr = Feff\ \varepsilon\sigma\ (Tcl^4 - Tr^4) / (Tcl - Tr)$ (W/M^2 deg C)

Where:

Feff = the effective radiation area factor, 0.72 (Fanger 1970)

ε = emmissivity of the surface of the clothed body

σ = the Stefan-Boltzmann constant

Hr = the radiative heat transfer coefficient

Numerically, Hr is between 4 and 6 and is typically set to a constant value in models (4.7 in Wincomf).

Maximum evaporative capacity

Maximum evaporative capacity (Emax) is the maximum evaporative heat loss from a totally wet surface to the environment.

$Emax = Ad\ Fcl\ He\ (P^*cl - Pa)$ (watts)

Where:

Emax = the maximum evaporative capacity

He = evaporative heat transfer coefficient

P*cl = saturated vapor pressure at the clothing temperature

However, He is usually defined in terms of Hc and the Lewis Relation

$$He = LR\ Hc \qquad \text{(ASHRAE 1993)}$$

Where:

LR = Lewis relation (2.2 at sea level)

Regulatory Sweating

Ersw represents the heat lost by vaporized sweat necessary for regulation of body temperature.

$$Ersw = Ad\ \lambda sw\ Sw\ Lcf$$

Where:

λsw = heat of vaporization of sweat (680 W/hr-kg)

Sw = sweat drive due to temperature stimuli (kg/hr-M^2)

Lcf = local control factor (non dimensional)

Now;

$$Sw = CSW\ (1-\alpha)\ (Tcr-36.6) + \alpha\ (Tsk - 34)$$

Where:

CSW = driving coefficient for regulatory sweating

α = the fractional skin mass

and:

$$Lcf = \exp[(Tsk-34)/10.7]$$

while:

$$\alpha = msk/m$$

where:

msk = the mass of the skin compartment

m = mass of the core compartment

α strictly depends on Vb (mass blood flow between core and skin) but is usually set to 0.1.

Vapor diffusion

At thermal neutrality, regulatory sweating is negligible but the skin is still damp due to vapor diffusion. For no sweating (Ersw = 0) this dampness has been found to be approximately 0.06 Emax. Diffusion can only occur through skin not covered by water and is then proportional to both the evaporative capcity of the environment and the area of skin not covered by water.

$$Ediff = (1 - wrsw)\ 0.06\ Emax$$

Where:

wrsw = fractional skin area covered by water

Total evaporative heat loss

Now we can combine expressions for regulatory sweating and vapor diffusion.

$$Esk = Ersw + Ediff$$

or

$$\begin{aligned} Esk &= wrsw\ Emax + (1-wrsw)\ 0.06\ Emax \\ &= (0.06 + 0.94\ wrsw)\ Emax \end{aligned}$$

Skin wettedness can now be defined as the ratio of skin surface covered by water to the total skin surface.

$$w = Esk/Emax = (0.06 + 0.94\ wrsw)$$

and thus:

$$Esk = Ad\ fcl\ LR\ Hc\ w\ (P^*cl - Pa)$$

Skin blood flow

The body moderates heat flow between core to skin compartments via vasodilation and vasoconstriction controlling blood flow to the skin. The vaso controls are triggered by differences in the temperature of core and skin from "neutral" or starting values. The starting values for skin and core respectively are Tn,sk = 34 deg. C and Tn,cr = 36.6 deg. C.

$$COLDS = (Tn,sk - Tsk)$$
$$WARMS = (Tcr - Tn,cr)$$

where:

COLDS = vasoconstriction signal
WARMS = vasodilation signal
Tn,sk = neutral value for Tsk
Tn,cr = neutral value for Tcr

These signals are combined with vasoconstriction and vasodilation coefficients and used to calculate skin blood flow.

$$Vb = [6.3 + CDIL\ (Tcr - 36.6)]/[1+CSTR(34-Tsk)]$$

Where:

Vb = mass blood flow between core and skin (kg/hr-M^2)
CDIL = coefficient for vasodilation
CSTR = coefficient for vasoconstriction

Core to skin heat flow

The combined thermal exchange between core and skin can now be written as:

$$Qcs = Ad\ (K + Cbl\ Vb)\ (Tcr - Tsk) \qquad \text{(watts)}$$

Where:

K = effective conductance between core and skin (W/M^2-deg C)

Cbl = specific heat of blood (W-hr/kg-deg. C)

Skin to Environment

We have now defined each component of equation 3. But we still have some expression in terms of the difference between skin temperature and core temperature and others in terms of the difference between clothing temperature and air temperature. We still need to connect the heat flow from the core to the skin and then to the environment through the clothing. This is done by expressing the heat and mass transfer through the clothing in terms of Tsk and 'clothing efficiency' factors.

Combining convection and radiation gives:

$$DRY = Qc + Qr = Ad\ fcl\ H\ Fcl\ (Tsk - Top) \qquad \text{(watts)}$$

where:

H = Hc + Hr

Fcl = thermal efficiency of clothing

= (Tcl - Top)/(Tsk-Top)

= 1/(1+0.155 h Icl fcl)

Top = operative temperature (deg. C)

= (Hc Ta + Hr Tr)/H

Tr = mean radiant temperature (deg. C)

We also need to rewrite equation 5 as:

$$Esk = Ad\ fcl\ LR\ Hc\ Fpcl\ w\ (P^*sk - Pa)$$

where:

Fpcl = moisture permeation of clothing

= (P*cl - Pa) / (P*sk -Pa)

$= 1 / (1 + 0.143\ Hc\ Icl\ fcl)$

P^*sk = saturated vapor pressure at the skin temperature

Rate of heat storage

The rate of heat storage in each compartment can be expressed as:

$$Ssk = \alpha\ m\ Cb\ dTsk/dt$$

$$Scr = (1-\alpha)\ m\ Cb\ dTcr/dt$$

Where:

Cb = specific heat of the body (0.97 W-hr/Kg-deg C)

t = time

Now we can rewrite equation 3 as:

$$m\ Cb\ [\alpha\ dTsk/dt + (1-\alpha) dTcr/dt)] = RM + Mshiv - W - Qres - Qc - Qr - Erws - Ediff$$

That's it - we know all the pieces of this differential equation so all we need to do to determine skin and core temperatures is integrate this equation over time. In practice, we do it numerically using the following process in a computer program.

1) initialize variables using "neutral sensation" values
2) compute all heat balance components based on initial values
3) compute heat flow for one time unit (typically a minute)
4) impose thermoregulatory controls
5) recompute all heat balance components based on new temperatures
6) recompute heat flows etc.

After the desired number of time steps has been reached, the final values for the compartment temperatures are used to calculate comfort indices. Appendix A presents a computer program for performing this computation.

Outdoor Comfort

The modification we need to make to the model to predict outdoor comfort is the conversion of solar radiation data to Tr or mean radiant temperature. Mean radiant temperature is an index that integrates radiation from various surfaces surrounding the body into a single temperature index.

To make this conversion we define:

ERF = Feff Hr (Tr - Ta) (Arens et al. 1986)

where:

ERF = effective radiant field (W/M^2)

We assume:

ERF is uniformly distributed.

Ad = 1.8 M^2

Solar elevation is 45 degrees

The projected area of a human exposed to direct beam sunlight is:

Ap/Ad = 0.23 Ap/AD (Fanger 1970)

so:

Ap = 0.41 M^2

We assume that diffuse sky and ground-reflected solar radiation are each uniformly distributed on half of the body. We can then write following equality for absorbed radiation from long-wave and short-wave sources.

ERF αlw = [Feff /2 (Id + Ir) + (Ap/Ad) In] αsw (Arens et al. 1986) (4)

where:

αlw = longwave absorptivity (0.95)

αsw = shortwave absorptivity (0.67 for white skin and average clothing)

In = direct beam solar radiation measured perpendicular to the beam
Id = diffuse irradiance of an upward facing horizontal surface
Ir = reflected irradiance of a downward facing horizontal surface
(values from Arens et al. 1986)

Now:

$$In = (Ith - Id)/ \sin \beta$$

where:

Ith = total solar irradiance of a horizontal surface
β = solar elevation

and using clear day values from Montieth 1973,

$$Ith = 4\ Id \quad \text{(approximately)}$$

We can now express equation 4 entirely in terms of ERF and Ith.

$$ERF = 0.29\ Ith \qquad \text{(Arens et al. 1986)}$$

Recall,

$$ERF = Feff\ Hr\ (Tr - Ta) \qquad \text{(Arens et al. 1986)}$$

then;

$$0.29\ Ith = Feff\ Hr\ (Tr - Ta)$$

assuming Hr = 6,

$$Tr = Ta + 0.6713\ Ith$$

We used this equation in the Toronto project to convert Ith from a weather tape to Tr to plug into the 2-Node model.

Other assumptions we made were:

1) averaging sitting and walking activities for a net 1.3 met.
2) Using 0.8 clo for spring and fall

3) Using 0.6 clo for summer

4) Using 1.5 clo and 2 met for winter

5) Ith reduced by 25% of its original value for points in the shade.

6) Exposure time = 20 minutes

7) Use DISC instead of TSENS (details provided in the next section).

8) For fall and winter, if air temperature was below 10 deg. C, we added 0.5 clo (representing the addition of an overcoat)

9) For summer, if air temperature was below 20 deg. C, we added 0.2 clo (representing the addition of a light sweater)

10) If DISC values were too hot but air temperature was below 20 deg. C, we assumed people would make themselves comfortable by reducing clothing

11) For spring, summer and fall seasons we assumed 8:00 am - 7:00 pm for daylight hours

12) For winter, we assumed 9:00 am - 5:00 pm for daylight hours

13) We assumed that $-0.25 < \mathrm{DISC} < 0.37$ was the comfort zone

RWDI calculation of ERF

For posterity, I'll show how your ERF equation (from RWDI e-mail 7-3-96) can be created from my equation 4

$$\mathrm{ERF}\ \alpha lw = [\mathrm{Feff}/2\ (Id + Ir) + (Ap/Ad)\ In]\ \alpha sw \tag{4}$$

$\mathrm{Feff} = 0.72$

$(0.9/1.8) = 2$

$Ap/Ad = 0.41/1.8$ Ap/Ae Ae/AD

So;

$$\mathrm{ERF} = \alpha sw/\ \alpha lw\ [0.72\ (0.9/1.8)\ (Id + Ir) + (0.41/1.8)\ In]$$

which is what RWDI is using.

Sensation Prediction

As one might imagine from the above derivation, the physiology of thermoregulation is well understood. Numerous laboratory studies confirm that models such as 2-Node are reasonably good at predicting the physiological response of humans. Predicting sensation is more difficult due to individual The following forms have been used by researchers for TSENS:

TSENS

Source	TSENS equations
Rohles and Nevins 1971	$TSENS=0.245*Ta+0.033Pdp-6.471$ and others
Rohles 1973	$TSENS = 0.245*Ta+0.248p-6.475$
Gagge 1986	$TSENS=4.7(Tb-Tb,c)/(Tb,h-Tb,c)$ if $Tb>Tb,c$ $TSENS=.68175(Tb-Tb,c)$ otherwise
Doherty 1988	$TSENS = 0.4685(Tb-Tb,c)$ if $Tb<Tb,c$ $TSENS = WCRIT(4.7)(Tb-Tb,c)/(Tb,h-Tb,c)$ if $Tb,c<Tb<Tb,h$ $TSENS = WCRIT(4.7)+.4685(Tb-Tb,h)$ if $Tb,h<Tb$
ASHRAE 1993	$TSENS = 0.4685(Tb-Tb,c)$ if $Tb<Tb,c$ $TSENS = 4.7Nev(Tb-Tb,c)$ if $Tb,c<Tb<Tb,h$ $TSENS = 4.7Nev+0.4685(Tb-Tb,h)$ if $Tb,h<Tb$
Berglund 1995	$TSENS=4.6(Tmb-Tmbs)$

where: Nev is the evaporative efficiency (=0.85)
WCRIT is the evaporative efficiency [$=.59*Vel^{(-.08)}$]

Tb (Tmb) is the mean body temperature

Tb,c is the mean body temperature cold setpoint and is a function of Met (define)

Tb,h is the mean body temperature hot setpoint and is a function of Met (define)

Tmbs is a mean body temperature setpoint (define)

The TSENS equation's used in the Toronto project and in Wincomf are from Doherty (1988)

Another index that RWDI might want to consider in warmer environments is DISC. DISC is numerically equal to TSENS in the cold but accounts for evaporative cooling effects of sweating in warm conditions. The following forms have been used by researchers for DISC.

DISC

Gagge 1986	DISC=5(ersw-ecomf)/(emax-ecomf-edif)
Berglund 1986	DISC=2.4W-.10 DISC=0.97W+0.216Tsk-6.79
Compiled DISC regressions derived from many different laboratory studies	DISC=5(W-0.06) DISC=3.71W+0.086 DISC=4.13Wuc+-.13 DISC=5.06Wuc+0.09 DISC=5.87Wuc+0.85Tskuc-28.6 DISC=3.6Wuc-0.25 DISC=3.02RHsk-0.37
Doherty 1988	DISC = 4.7*(ersw-ecomf)/(emax-ecomf-edif)

ASHRAE Fundamentals 1993	DISC=0.4685(Tb-Tb,c) ← if Tb<Tb,c DISC=4.7(ersw-ecomf)/(emax-ecomf-edif) ← if Tb,c <Tb ?

Where ersw is evaporative heat loss required for temperatur regulation
ecomf is evaporative heat loss during comfort
emax is maximum possible evaporative heat loss from the skin
edif is evaporative heat loss via diffusion
W is the skin wettedness
Tsk is the skin temperature
Wuc is the skin wettedness under clothing
Tskuc is the skin temperature under clothing
Rhsk is the skin relative humidity

The DISC equations used in the Toronto project and in Wincomf are from Doherty (1988).

Possible Improvements in the model

For the Toronto project we made a number of assumptions that could be improved upon if the data are available in your projects. These assumptions are listed below.

Ith = 4 Id

β = 45 degrees (sun is not always at 45 degrees)

αsw = 0.67 (not all people have white skin and average clothing)

Hr = 6

ERF is uniformly distributed

Sky and ground radiation are each distributed on half the body

all of the clothing and activity assumptions outlined above

Table of variables and constants used in derivation and/or in program

Symbol	Name	Value	Units

Acl	surface area of the clothed body	Ad + .15 clo	M^2
Ad	surface area of the nude body (Area Dubois)	1.8 (typical)	M^2
Eres	heat loss due to respiration	NA	Watts
fcl	ratio of the surface area of clothed body to the surface area of the nude body	1+.15 clo	NA
RM	metabolic rate	NA	Watts
Scr	rate of energy storage in the core	NA	Watts
Ta	air Temperature	NA	deg. C
Tr	mean Radiant Temperature	NA	deg. C
Tsk	skin temperature	NA	deg. C
Ssk	rate of energy storage in the skin	NA	Watts
St	total rate of energy storage	NA	Watts
Mshiv	rate of energy released by shivering	NA	Watts
W	rate of work done by the body on the surroundings	NA	Watts
Qres	Total rate of heat lost through respiration	NA	Watts
Qcs	rate of energy transport between core and skin	NA	Watts
Qc	rate of convective heat transfer	NA	Watts
Qr	rate of radiative heat transfer	NA	Watts
Ersw	rate of heat loss due to sweat evaporation	NA	Watts
Ediff	rate of heat loss due to diffusion of water vapor through the skin	NA	Watts
Rcl	thermal resistance of clothing ensemble	NA	(deg. C M^2)/W

Icl	thermal resistance of clothing	NA	clo
clo	clothing unit	NA	1 clo = 0.155 (M^2 deg. C)/W
VO2	rate of oxygen consumption	NA	liters/minute
Rex	respiratory exchange ratio	NA	NA
Met	metabolic heat loss per unit of body surface area	NA	1 met = 58.2 W/M^2
Tcr	core temperature	NA	deg. C
µ	thermal efficiency	NA	NA
Vres	pulmonary ventilation rate	NA	liters/sec
l	heat of vaporization of water	2340	Kjoules/Kg
Wex	humidity ratio of exhaled air	NA	g/Kg
Wa	humidity ratio of inhaled air	NA	g/Kg
Cp	specific heat of air		Kjoules/(Kg deg. K)
Tex	temperature of exhaled air	NA	deg. C
Ta	temperature of inhaled air	NA	deg. C
Pa	partial vapor pressure of water	NA	mm Hg
Hc	convective heat transfer coefficient	NA	W/(M^2 deg. C)
Tcl	clothing temperature	NA	deg. C
V	relative air velocity	NA	m/s
Hr	radiative heat transfer coefficient	NA	W/(M^2 deg. C)
Feff	effective radiation area factor	0.72	NA
ε	emmissivity of clothed surface	0.95	NA
σ	Stefan-Boltzmann constant	5.67 E-8	W/(M^2 deg. K^4)
Emax	maximum evaporative capacity	NA	Watts
He	evaporative heat transfer coefficient	NA	W/(M^2 deg. C)
P*cl	saturated vapor pressure at clothing temperature	NA	mm Hg

LR	Lewis relation	2.2 at sea level	deg C/mm Hg
λsw	heat of vaporization of sweat	680	W/(hrKg)
Sw	sweat drive		kg/(hr M^2)
Lcf	local control factor	NA	NA
α	fractional skin mass	usually 0.1	NA
msk	mass of skin	NA	Kg
m	mass of core	NA	Kg
wrsw	fractional skin area covered by water	NA	NA
Esk	Total evaporative heat loss	NA	watts
w	ratio of skin surface covered by water to total skin surface or skin wettedness	NA	NA
COLDS	vasoconstriction signal	NA	NA
WARMS	vasodilation signal	NA	NA
Tn,sk	neutral value for Tsk	33.7-34	deg C
Tn, cr	neutral value for Tcr	36.6 - 36.8	deg. C
Vb	mass blood flow between skin and core	NA	kg/(hr M^2)
CDIL	driving coefficient for vasodilation	50-240	NA
CSTR	driving coefficient for vasoconstriction	0.1 - 0.5	NA
K	effective conductance between core and skin	5.28	W/(M^2 deg. C)
Cbl	specific heat of blood	1.163	(W hr)/(Kg deg. C)
DRY	total sensible heat loss	NA	Watts
H	combined heat transfer coefficient	NA	W/(M^2 deg. C)

Fcl	thermal efficiency of clothing	NA	NA
Top	operative temperature	NA	deg. C
Fpcl	moisture permeation of clothing	NA	NA
P*sk	saturated vapor pressure at skin temperature	NA	mm Hg
Cb	specific heat of the body	0.97	(W hr)/(Kg deg. C)
M	total mass of the body	NA	Kg
ERF	effective radiant field	NA	W/M^2
Ap	projected area of a human exposed to direct beam sunlight	0.41	M^2
αlw	longwave absorptivity	0.95	NA
αsw	shortwave absorptivity	0.67	NA
In	direct beam solar radiation measured perpendicular to the beam	NA	W/M^2
Id	diffuse irradiance of an upward facing horizontal surface	NA	W/M^2
Ir	reflected irradiance of a downward facing horizontal surface	NA	W/M^2
Ith	total solar irradiance of a horizontal surface	NA	W/M^2
β	solar elevation	NA	degrees
WCRIT	evaporative efficiency	NA	NA
Nev	evaporative efficiency	NA	NA
Tb	mean body temperature	NA	deg. C
Tmb	mean body temperature	NA	deg. C
Tb,c	mean body temperature cold setpoint	NA	deg. C
Tb,h	mean body temperature hot	NA	deg. C

	setpoint		
Tmbs	mean body temperature setpoint	NA	deg. C
Ecomf	total evaporative heat loss during comfort	NA	watts
Wuc	skin wettedness under clothing	NA	NA
Tskuc	skin temperature under clothing	NA	deg. C
Rhsk	relative humidity in the boundary layer of the skin	NA	percent
CSW	driving coefficient for regulatory sweating	170	NA
RA	resistance of air layer to dry heat transfer	NA	(M^2 deg. C)/W
SKBF	mass blood flow between skin and core	NA	kg/(hr M^2)
SKBFN	neutral value for skin blood flow	6.3	kg/(hr M^2)
TBN	neutral setpoint for Tb	36.5	deg. C
ATM	atmospheric pressure	NA	torr
HFCS	rate of energy transport between core and skin	NA	Watts
SKSIG	thermoregulatory control signal from the skin	NA	deg. C
CRSIG	thermoregulatory control signal from the core	NA	deg. C
REA	evaporative resistance of air layer	NA	(M^2 mm Hg)/W
RECL	evaporative resistance of clothing	NA	(M^2 mm Hg)/W
PRSW	ratio of actual heat loss due to sweating to maximum heat loss due to sweating	NA	NA
PWET	skin wettedness	NA	NA
HSK	total heat loss from the skin	NA	watts

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APPENDIX A: COMPUTER CODE FOR 2-NODE

Below is a listing of the DOS version of this program written in BASIC. This listing shows the prediciton equations in a commonly understood format. The PMV code was obtained from ISO Standard 7730 and the 2-Node code was revised from a program written by Doherty (Doherty 1988).

```
5  Color 1,3:CLS:print
10 Print "  ASHRAE Thermal Comfort Model  (C) 1995 Environmental Analytics
":Print
15 Print "  Last Revised 5-25-95"
17 Print "  Note:  It is strongly recommended that you use the Windows(tm)
version"
18 Print "  of this program since the interface is much nicer.  The main purpose
of this"
19 Print "  DOS version is to show the source code of the prediction equations
in a"
22 Print "  commonly understood format.":Print
23
'****************************************************************************************************
***
24 Print " Program calculates: "
25 Print "      PMV - Predicted Mean Vote"
30 Print "      PPD - Predicted Percentage of Dissatisfied"
32 Print "      ET* - New Effective Temperature"
33 Print "      SET* - Standard Effective Temperature"
34 Print "      TSENS - Predicted Thermal Sensation  "
35 Print "      DISC - Predicted Discomfort"
36 Print "      PD - Predicted Percent Dissatisfied Due to Draft"
37 Print "      PS - Predicted Percent Satisfied With the Level of Air Movement"
38 Print "      Neutral Temperature based on long-term indoor temperature"
39 Print "    Neutral Temperature based on long-term indoor and outdoor
temperature"
40 Print:Print:Input"Would you like to run the program now:";R$:IF R$="n"then
goto3120
42  CLS:Color 1,3
43  CLS:
45  PRINT:Input "   Short (1) or Long (2) Data Entry?";D:Print
46  'Defaults
50  INPUT "   Air temperature (C),              [default = 25] "; TA:IF TA=0 then
TA=25
60 INPUT "  Mean radiant temperature (C),       [default = 25] "; TR:IF TR=0 then
TR=25
70  INPUT "   Air velocity (m/s),             [default = 0.1] "; VEL:IF VEL=0 then
VEL=.1
80  INPUT "   Relative Humidity (%),            [default = 50] "; RH:IF RH=0 then
RH=50
```

```
90  INPUT "   Clothing (clo),              [default = 0.8] "; CLO:IF CLO=0 then
CLO=0.8
100  INPUT "   Metabolic rate (met)       [default = 1.1] "; MET:IF MET=0 then
MET=1.1
110  IF D=1 then
WME=0:TU=40:TMMO=15:LTIME=60:PB=760:WT=70:SA=1.2:goto 120
111  INPUT "   External work (met),              [default = 0] "; WME
112  INPUT "   Turbulence intensity (%)         [default = 40] "; TU:IF TU=0 then
TU=40
113  INPUT "  Mean monthly outdoor temperature (C) [default = 15] "; TMMO:IF
TMMO=0 then TMMO=15
114  INPUT "  Exposure time (min), default = 60] "; LTIME:IF LTIME = 0 then
LTIME=60
115  INPUT "Barometric pressure (torr),       [default = 760] "; PB:IF PB=0 then
PB=760
116  INPUT "   Weight (Kg),                   [default = 70] "; WT:IF WT=0 then
WT=70
117  INPUT "   Surface Area (M^2)              [default = 1.2] "; SA:IF SA=0 then
SA=1.2
118  'PMV-PPD Calculation ****************************************************
120  ICL = .155 * CLO : M = MET * 58.2 : W = WME * 58.2
125  PWS=exp(18.6686-(4030.183/(TA+235))):PA=RH*PWS
130  EPS = .00015
140  MW = M - W
150  REM --- Compute the corresponding FCL value--------------------------
160  IF ICL < .078 THEN FCL = 1 + 1.29 * ICL ELSE FCL = 1.05 + .645 * ICL
170  FCIC = ICL * FCL
180  P2=FCIC*3.96
190  P3=FCIC*100
200  TRA=TR+273
210  TAA = TA + 273
220  P1 = FCIC * TAA
230  P4 = 308.7 - .028 * MW + P2 * (TRA/100)^4
240  REM --- First guess for surface temperature---------------------------
250  TCLA = TAA + (35.5-TA) / (3.5*(6.45*ICL+.1))
260  XN = TCLA / 100
270  XF = XN
280  HCF=12.1*SQR(VEL)
290  NOI=0
300  REM---COMPUTE SUFACE TEMPERATURE OF CLOTHING BY
ITERATIONS----
310  XF=(XF+XN)/2
320  HCN=2.38*ABS(100*XF-TAA)^.25
330  IF HCF>HCN THEN HC=HCF ELSE HC=HCN
340  XN=(P4+P1*HC-P2*XF^4)/(100+P3*HC)
350  NOI=NOI+1
360  IF NOI > 150 THEN GOTO 490
```

```
370  IF ABS(XN-XF)>EPS GOTO 310
380  TCL=100*XN-273
390  REM--- COMPUTE PMV--------------------------------------------
400  PM1=3.96*FCL*(XN^4-(TRA/100)^4)
410  PM2 = FCL * HC * (TCL-TA)
420  PM3 = .303 * EXP(-.036*M) + .028
430  IF MW > 58.15 THEN PM4 = .42 * (MW-58.15) ELSE PM4 = 0!
440  PM5 = 3.05*.001*(5733-6.99*MW-PA)
450  PM6 = 1.7 * .00001 * M * (5867-PA) + .0014 * M * (34-TA)
460  PMVF = PM3 * (MW-PM5-PM4-PM6-PM1-PM2)
470  TCLN = INT(TCL*100)/100
480  REM---Compute PPD-----------------------------------------------------
490  PPD=100-95*EXP(-.03353*PMVF^4-.2179*PMVF^2)
500
****************************************************************************************************
**
520 DEF FNSVP(T) = EXP(18.6686 - 4030.183 / (T + 235))
530 DEF FNP(X)=X*(-1)*(X>0)
540 DEF FNFAR(T)=9/5*T+32
550 DEF FNERRE(X)=HSK-HD*(TSK-X)-W*HE*(PSSK-.5*FNSVP(X))
560 DEF FNERRS(X)=HSK-HD.S*(TSK-X)-W*HE.S*(PSSK-.5*FNSVP(X))
570 SBC=5.67E-08 'Stephan-Boltzmann constant
580 'CONSTANTS, SETPOINTS AND CONTROL COEFFICIENTS
590 '
600 KCLO=.25
620 CSW=170   'driving coefficient for regulatory sweating
630 CDIL=200  'driving coefficient for vasodilation
640 CSTR=.5   'driving coefficient for vasoconstriction
650 '
660 TSKN=33.7  'setpoint (neutral) value for Tsk
670 TCRN=36.8  'setpoint value for Tcr
680 TBN = 36.49  'setpoint for Tb (.1*Tskn + .9*Tcrn)
690 SKBFN=6.3  'neutral value for SKBF
700 '
710 'INITIAL VALUES - start of 1st experiment
720 TSK = TSKN
730 TCR = TCRN
740 SKBF = SKBFN
750 MSHIV=0
760 ALFA=.1
770 ESK=.1*RM
780 '
800 'UNIT CONVERSIONS (from input variables)
810 ATM=PB/760
820 TIMEH=LTIME/60
830 RCL = .155*CLO
```

Gagge/Doherty 1988
Debate; should be 75?

```
840 FACL=1+.15*CLO  '% INCREASE IN BODY SURFACE AREA DUE TO CLOTHING
850 LR=2.2/ATM   'Lewis Relation is 2.2 at sea level
860 RM=MW:M=RM
865 PA=PA/100
870 '
880 IF CLO<=0 THEN WCRIT=.38*VEL^(-.29):ICL=1 ELSE WCRIT=.59*VEL^(-.08):ICL=.45
890 '
900 CHC=3*ATM^.53
910 IF RM/58.2 <.85 THEN CHCA=0: GOTO 930
920 CHCA=5.66*((RM/58.2-.85)*ATM)^.39
930 CHCV=8.600001*(VEL*ATM)^.53
940 IF CHC<=CHCA THEN CHC=CHCA
950 IF CHC<CHCV THEN CHC=CHCV
960 '
970 'initial estimate of Tcl
980   'IF PASS>1 THEN GOTO 1080
990   CHR = 4.7
1000   CTC = CHR + CHC
1010   RA = 1/(FACL*CTC) 'resistance of air layer to dry heat transfer
1020   TOP= (CHR * TR + CHC * TA) / CTC
1030   TCL = TOP+ (TSK - TOP)/(CTC*(RA + RCL))
1040  'REA = 1/(LR*FACL*CHC) 'evaporative resistance of air layer
1050  'RECL = RCL/(LR*ICL)  'evaporative resistance of clothing (icl=.45)
1060  'HE = 1/(REA + RECL)  'total evaporative heat exchange coeff.
1070  'TOP= (CHR * TR + CHC * TA) / CTC
1080 TIM=1
1090 '
1100 '=======================  BEGIN ITERATION
1110 '
1120 'Tcl and CHR are solved iteritively using: H(Tsk - To) = CTC(Tcl - To),
1130 '  where H = 1/(Ra + Rcl) and Ra = 1/Facl*CTC
1140 '
1150   TCL.OLD=TCL
1160   CHR = 4 * SBC * ((TCL + TR) / 2 + 273.15) ^ 3 * .72
1170   CTC = CHR + CHC
1180   RA = 1/(FACL*CTC) 'resistance of air layer to dry heat transfer
1190   TOP= (CHR * TR + CHC * TA) / CTC
1200   TCL = (RA*TSK + RCL*TOP)/(RA + RCL)
1210   IF ABS(TCL-TCL.OLD)>.01 THEN TCL.OLD=TCL: GOTO 1160
1220 '
1230   DRY = (TSK - TOP)/(RA + RCL)
1240   HFCS = (TCR - TSK) * (5.28 + 1.163 * SKBF)
1250   ERES = .0023 * M * (44 - PA)
1260   CRES = .0014 * M * (34 - TA)
1270   SCR = M - HFCS - ERES - CRES - WK
```

```
1280   SSK = HFCS - DRY - ESK
1290   TCSK = .97* ALFA * WT
1300   TCCR = .97* (1 - ALFA) * WT
1310   DTSK = (SSK * SA) / TCSK/60     'deg C per minute
1320   DTCR = SCR * SA / TCCR/60       'deg C per minute
1330   DTIM=1    'minutes
1340 ' U=ABS(DTSK): IF U>.1 THEN DTIM=.1/U
1350 ' U=ABS(DTCR): IF U>.1 AND .1/U<DTIM THEN DTIM=.1/U
1360   TSK = TSK + DTSK * DTIM
1370   TCR = TCR + DTCR * DTIM
1380   TB=ALFA*TSK+(1-ALFA)*TCR
1390   SKSIG = TSK - TSKN
1400   WARMS=FNP(SKSIG):COLDS=FNP(-SKSIG)
1410   CRSIG = (TCR - TCRN)
1420   WARMC=FNP(CRSIG):COLDC=FNP(-CRSIG)
1430   BDSIG= TB-TBN
1440   WARMB=FNP(BDSIG):COLDB=FNP(-BDSIG)
1450   SKBF = (SKBFN + CDIL*WARMC) / (1 + CSTR*COLDS)
1460     IF SKBF>90 THEN SKBF=90
1470     IF SKBF<.5 THEN SKBF=.5
1480   REGSW = CSW * WARMB * EXP(WARMS / 10.7)
1490     IF REGSW >500 THEN REGSW=500
1500   ERSW = .68 * REGSW
1510 ' LR = 2.02*(TSK+273.15)/273.15
1520   REA = 1/(LR*FACL*CHC) 'evaporative resistance of air layer
1530   RECL = RCL/(LR*ICL)  'evaporative resistance of clothing (icl=.45)
1540   EMAX = (FN SVP(TSK) - PA)/(REA + RECL)
1550   PRSW = ERSW / EMAX
1560   PWET = .06 + .94 * PRSW
1570   EDIF = PWET * EMAX - ERSW
1580 ESK=ERSW+EDIF
1590 IF PWET>WCRIT THEN PWET=WCRIT:PRSW=(WCRIT-
.06)/.94:ERSW=PRSW*EMAX:EDIF=.06*(1-PRSW)*EMAX: ESK=ERSW+EDIF
1600   IF EMAX<0 THEN EDIF=0: ERSW=0: PWET=WCRIT: PRSW=WCRIT:
ESK=EMAX
1610   ESK=ERSW+EDIF
1620   MSHIV=19.4*COLDS*COLDC: M=RM+MSHIV
1630   ALFA = .0417737 + .7451833/ (SKBF + .585417)
1640   'GOSUB 2680   'screen output
1650   'IF OUTOPT=1 THEN GOSUB 3900   'minute-by-minute Hcopy output
1660   TIM= TIM+DTIM: IF TIM<=LTIME THEN GOTO 1200
1670  'GOSUB 1790  'Calculate COMFORT Indices
1680  'GOSUB 3430  'display DISC and TSENS on screen scale
1690 'IF OUTOPT=1 THEN GOSUB 4200 'output minute-to-minute values
1700 'IF OUTOPT=2 THEN GOSUB 4300 'output s.s. values
1710 'IF OUTOPT=5 THEN GOSUB 7030  'ASHRAE project output
1720 'RETURN
```

```
1730 '
1740 '
==================================================================
1750 ' =============== CALCULATE COMFORT INDICES
==================
1760 '
==================================================================
1770 '
1780 'Define new heat flow terms, coeffs, and abbreviations
1790 STORE=M-WK-CRES-ERES-DRY-ESK  'rate of body heat storage
1800 HSK=DRY+ESK  'total heat loss from skin
1810 RN=M-WK      'net metabolic heat production
1820 ECOMF = .42*(RN - 58.2): IF ECOMF<0 THEN ECOMF=0  'from Fanger
1830 EREQ = RN - ERES - CRES - DRY
1840 EMAX =EMAX*WCRIT
1850 HD=1/(RA + RCL)
1860 HE= 1/(REA + RECL)
1870 W=PWET
1880 PSSK=FNSVP(TSK)
1890 '
1900 'Definition of ASHRAE standard environment... denoted "S"
1910 CHRS = CHR
1920 IF RM/58.2<.85 THEN CHCS=3: GOTO 1950
1930 CHCS=5.66*((RM/58.2-.85))^.39
1940 IF CHCS<3 THEN CHCS=3
1950 CTCS = CHCS+CHRS
1960 RCLOS=1.52/((RM-WK)/58.15+.6944)-.1835:  RCLS=.155*RCLOS
1970 FACLS=1+KCLO*RCLOS
1980 FCLS=1/(1+.155*FACLS*CTCS*RCLOS)
1990 IMS=.45
2000 ICLS=IMS*CHCS/CTCS*(1-FCLS)/(CHCS/CTCS-FCLS*IMS)
2010 RAS = 1/(FACLS*CTCS)
2020 REAS = 1/(LR*FACLS*CHCS)
2030 RECLS = RCLS/(LR*ICLS)
2040 HD.S= 1/(RAS + RCLS)
2050 HE.S= 1/(REAS + RECLS)
2060 '
2070 ' ET* (standardized humidity/ actual clo, Pb, and CHC)
2080 ' determined using Newton's iterative solution
2090 ' FNERR is defined in GENERAL SETUP section above
2100   DELTA = .0001
2110     X.OLD = TSK - HSK/HD   'lower bound for ET*
2120     ERR1 = FNERRE(X.OLD)
2130     ERR2 = FNERRE(X.OLD + DELTA)
2140     X = X.OLD - DELTA*ERR1/(ERR2 - ERR1)
2150     IF ABS (X-X.OLD)>.01 THEN X.OLD=X: GOTO 2120
2160   ET = X
```

```
2170  '
2180 ' SET* (standardized humidity, clo, Pb, and CHC)
2190 ' determined using Newton's iterative solution
2200 ' FNERRS is defined in the GENERAL SETUP section above
2210    X.OLD= TSK-HSK/HD.S    'lower bound for SET
2220    ERR1=FNERRS(X.OLD): ERR2=FNERRS(X.OLD + DELTA)
2230    X=X.OLD - DELTA*ERR1/(ERR2-ERR1)
2240    IF ABS(X-X.OLD)>.01 THEN X.OLD=X: GOTO 2220
2250  SET=X
2260 '
2270 'STO = standard operative temperature:
2280 ' defined by: (Tsk-STo)/(Ras+Rcls)=(Tsk-To)/(Ra + Rcl)
2290  STO = TSK - (RAS+RCLS)*(TSK-TOP)/(RA+RCL)
2300 '
2310 'SVPO = standard operative vapor pressure:
2320 ' defined by: (Psk - SVPO)/(Reas+Recls) = (Psk-Pa)/(Rea+Recl)
2330  SVPO = PSK - (REAS+RECLS)*(PSK-PA)/(REA+RECL)
2340 '
2350 'TSENS is a function of Tb
2360  TBML=(.194/58.15)*RN  + 36.301   'lower limit for evaporative regulation
2370  TBMH=(.347/58.15)*RN + 36.669    'upper limit for evaporative regulation
2380  IF TB<TBML THEN TSENS = .4685*(TB - TBML)
2390  IF TB>=TBML AND TB<TBMH THEN TSENS = WCRIT*4.7*(TB-
TBML)/(TBMH-TBML)
2400  IF TB>=TBMH THEN TSENS = WCRIT*4.7 + .4685*(TB-TBMH)
2410 '
2420 'DISC varies with relative thermoregulatory heat strain
2430 'Valid only when DISC>0. When DISC<0, DISC is numerically =TSENS.
2440   DISC = 4.7*(ERSW - ECOMF)/(EMAX-ECOMF-EDIF)
2450   IF DISC<0 THEN DISC=TSENS
2460 '
2470 'Calculate Gagge's version of Fanger's Predicted Mean Vote (PMV)
2480   PMVG=(.303* EXP(-.036*M) +.028)*(EREQ-ECOMF-EDIF)
2490 '
2500 'Gagge's PMV.SET is the same as Fanger's PMV except that DRY is
calculated
2510 'using SET* rather than Top
2520   DRY2 = HD.S*(TSK-SET)
2530   EREQ2 = RN-CRES-ERES-DRY2
2540   PMV2=(.303* EXP(-.036*M) +.028)*(EREQ2-ECOMF-EDIF)
2550
2560 '  Other models
2570 TUE=(34-TA)*(VEL-0.05)^0.6223
2580 PD=TUE*(3.143+0.3696*VEL*TU)
2590 PS=100*(1.13*(TOP^.5)-.24*TOP+2.7*(VEL^.5)-.99*VEL)
2600 TSR=0.245*TA+0.248*PA*.133-6.475
2610 TNA=9.22+0.48*TA+0.14*TMMO
```

Appendix B - other attachments

is the apparent fractional mass of the skin compartment. For example, in cold environments, blood flow to the skin lowers and the skin and fat become isolated from the core. The actual body mass approximated by t_{cr} is therefore smaller and α increases. The effect of blood flow on the relative masses of the skin and core compartments can be written as:

$$\alpha = 0.0418 + 0.745/(3600\,\dot{m}_{bl} + 0.585) \qquad (44)$$

During thermal equilibrium and while sedentary, $\alpha \cong 0.2$. With exercise or overheating, circulation to the extremities increases and the skin layer becomes more closely coupled to the core, producing a value of $\alpha \cong 0.1$. When the body is exposed to cold, circulation to the extremities decreases and the skin layer becomes less closely coupled to the core, resulting in a higher value of $\alpha \cong 0.33$. As indicated in Equation (42), $\dot{m}_{bl}$ and, consequently, α are both determined by the deviations of t_{cr} and t_{sk} from their neutral values.

Regulatory sweating. The activity of the sweat glands is activated by warm signals from both the core and the skin, and is expressed in terms of the warm signal from the weighted average body temperature, and a local control factor at the skin:

$$\dot{m}_{rsw} = 4.7 \times 10^{-5}\,\mathrm{WSIG}_b \exp(\mathrm{WSIG}_{sk}/10.7) \qquad (45)$$

The value of $\dot{m}_{rsw}$ [calculated in Equation (45)] is then used to determine E_{rsw} in Equation (15).

Shivering. Generating additional metabolic heat through shivering and muscle tension is a more effective mechanism for maintaining the body's heat balance in extremely cold weather than vasoconstriction of the blood vessels. Shivering can raise M as much as three times its normal sedentary value. Metabolic energy production due to shivering requires simultaneous cold signals from both the skin and core, and is related to the two signals by the expression:

$$M_{shiv} = 19.4\,\mathrm{CSIG}_{sk}\,\mathrm{CSIG}_{cr} \qquad (46)$$

The total metabolic energy M is then the sum of the shivering energy M_{shiv} and the metabolic heat generated due to activity M_{act}:

$$M = M_{act} + M_{shiv} \qquad (47)$$

The following section describes the estimation of M_{act} in more detail.

ENGINEERING DATA AND MEASUREMENTS

Applying the preceding basic equations to practical problems of the thermal environment requires quantitative estimates of the body's surface area, metabolic requirements for a given activity and the mechanical efficiency for the work accomplished, evaluation of the heat transfer coefficient h_r and h_c, and the general nature of the clothing insulation used. This section provides the necessary data and describes methods used to measure the parameters of the heat balance equation.

Body Surface Area

The terms in the heat balance equations previously presented have units of energy per unit area (W/m²) and refer to the surface area of the nude body. The most useful measure of nude body surface area, originally proposed by DuBois (1916), is described by:

$$A_D = 0.202\, m^{0.425}\, l^{0.725} \qquad (48)$$

where

A_D = DuBois surface area, m²
m = mass, kg
l = height, m

A correction factor $f_{cl} = A_{cl}/A_D$ must be applied to the heat transfer terms from the skin (C, R, and E_{sk}) to account for the actual surface area of the clothed body A_{cl}. This factor can be found in Table 7 for various clothing ensembles. For an average sized man, 1.73 m and 70 kg, A_D = 1.8 m². All terms in the basic heat balance equations are expressed per unit DuBois surface area.

Metabolic Rate and Mechanical Efficiency

Maximum energy capacity. In choosing optimal conditions for comfort and health, the energy expended during routine physical activities must be known, because metabolic energy production increases in proportion to exercise intensity. Metabolic rate varies over a wide range, depending on the activity, the person, and the conditions under which the activity is performed. Table 4 lists typical metabolic rates for an average adult (A_D = 1.8 m²) for activities performed continuously. The highest energy level a

Table 4 Typical Metabolic Heat Generation for Various Activities

	W/m²	met[a]
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relaxed	70	1.2
Walking (on the level)		
0.89 m/s	115	2.0
1.34 m/s	150	2.6
1.79 m/s	220	3.8
Office Activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7
Lifting/packing	120	2.1
Driving/Flying		
Car	60–115	1.0–2.0
Aircraft, routine	70	1.2
Aircraft, instrument landing	105	1.8
Aircraft, combat	140	2.4
Heavy vehicle	185	3.2
Miscellaneous Occupational Activities		
Cooking	95–115	1.6–2.0
House cleaning	115–200	2.0–3.4
Seated, heavy limb movement	130	2.2
Machine work		
sawing (table saw)	105	1.8
light (electrical industry)	115–140	2.0–2.4
heavy	235	4.0
Handling 50-kg bags	235	4.0
Pick and shovel work	235–280	4.0–4.8
Miscellaneous Leisure Activities		
Dancing, social	140–255	2.4–4.4
Calisthenics/exercise	175–235	3.0–4.0
Tennis, singles	210–270	3.6–4.0
Basketball	290–440	5.0–7.6
Wrestling, competitive	410–505	7.0–8.7

Compiled from various sources. For additional information, see Buskirk (1960), Passmore and Durnin (1967), and Webb (1964).

[a] 1 met = 58.2 W/m²

$$R = 0.155I \qquad (56)$$

or 1.0 clo is equivalent to 0.155 m²·K/W.

Since clothing insulation cannot be measured for most routine engineering applications, tables of measured values for various clothing ensembles can be used to select an ensemble comparable to the one(s) in question. Table 7 gives values for typical indoor clothing ensembles. More detailed tables are presented by McCullough and Jones (1984) and Olesen and Nielsen (1983). Accuracies for I_{cl} on the order of ±20% are typical if good matches between ensembles are found.

Often it is not possible to find an already measured clothing ensemble that matches the one in question. In this case, the ensemble insulation can be estimated from the insulation of individual garments. Table 8 gives a list of individual garments commonly worn. The insulation of an ensemble is estimated from the individual values using a summation formula (McCullough and Jones 1984):

$$I_{cl} = 0.835\,\Sigma_i I_{clu,i} + 0.161 \qquad (57)$$

where $I_{clu,i}$ is the effective insulation of garment i (clo), and I_{cl}, as before, is the insulation for the entire ensemble. A simpler and nearly as accurate summation formula is:

$$I_{cl} = \Sigma_i\, I_{clu,i} \qquad (58)$$

Either Equation (57) or (58) gives acceptable accuracy for typical indoor clothing. The main source of inaccuracy is in determining the appropriate values for individual garments. Overall accuracies are on the order of ±25% if the tables are used carefully. If it is important to include a specific garment that is not included in Table 8, its insulation can be estimated by (McCullough and Jones 1984):

$$I_{clu,i} = (0.534 + 0.135\,x_f)\,(A_G/A_D) - 0.0549 \qquad (59)$$

where

x_f = fabric thickness, mm
A_G = body surface area covered by garment, m²

Values in Table 7 may be adjusted by information in Table 8 an a summation formula. Using this method, values of $I_{clu,i}$ for th selected items in Table 8 are then added to or subtracted from th ensemble value of I_{cl} in Table 7.

Moisture permeability. Moisture permeability data for som clothing ensembles are presented in terms of i_{cl} and i_m in Table The values of i_m can be used to calculate $R_{e,t}$ using the relatior ships in Table 2. Ensembles worn indoors generally fall in the rang $0.3 < i_m < 0.5$ and assuming $i_m = 0.4$ is reasonably accurat (McCullough *et al.* 1989). This latter value may be used if a goo match to ensembles in Table 7 cannot be made. The value of i_m c $R_{e,t}$ may be substituted directly into equations for body heat los calculations (see Table 3). However, i_m for a given clothin ensemble is a function of the environment as well as the clothin properties. Unless i_m is evaluated at conditions very similar to th intended application, it is more rigorous to use i_{cl} to describe th moisture permeability of the clothing. The value of i_{cl} is not sensitive to environmental conditions; thus, given data are mo accurate over a wider range of air velocity and radiant and a temperature combinations for i_{cl} than for i_m. The relationships i Table 2 can be used to determine $R_{e,cl}$ from i_{cl}, and i_{cl} or R_{e} can then be used for body heat loss calculations (see Table 3 McCullough *et al.* (1989) found an average value of $i_{cl} = 0.34$ fc common indoor clothing; this value can be used when other dat are not available.

Measurements of i_m or i_{cl} may be necessary if unusual clothin (*e.g.*, impermeable or metalized) and/or extreme environmen (*e.g.*, high radiant temperatures or high air velocities) are to b addressed. There are three different methods for measuring th moisture permeability of clothing: the first uses a wet manikin t measure the effect of sweat evaporation on heat loss (McCulloug 1986); the second uses moisture permeability measurements o component fabrics as well as dry manikin measurements (Umbac 1980); the third uses measurements from sweating subjects (Nisl *et al.* 1975, Holmer 1984).

Table 8 Garment Insulation Values

Garment Description[a]	$I_{clu,i}$, clo[b]	Garment Description[a]	$I_{clu,i}$, clo[b]	Garment Description[a]	$I_{clu,i}$, cl
Underwear		Short-sleeve, knit sport shirt	0.17	Sleeveless vest (thick)	0.22
Men's briefs	0.04	Long-sleeve, sweat shirt	0.34	Long-sleeve (thin)	0.25
Panties	0.03			Long-sleeve (thick)	0.36
Bra	0.01	**Trousers and Coveralls**			
T-shirt	0.08	Short shorts	0.06	**Suit jackets and vests (lined)**	
Full slip	0.16	Walking shorts	0.08	Single-breasted (thin)	0.36
Half slip	0.14	Straight trousers (thin)	0.15	Single-breasted (thick)	0.44
Long underwear top	0.20	Straight trousers (thick)	0.24	Double-breasted (thin)	0.42
Long underwear bottoms	0.15	Sweatpants	0.28	Double-breasted (thick)	0.48
		Overalls	0.30	Sleeveless vest (thin)	0.10
Footwear		Coveralls	0.49	Sleeveless vest (thick)	0.17
Ankle-length athletic socks	0.02				
Calf-length socks	0.03	**Dresses and skirts**[c]		**Sleepwear and Robes**	
Knee socks (thick)	0.06	Skirt (thin)	0.14	Sleeveless, short gown (thin)	0.18
Panty hose	0.02	Skirt (thick)	0.23	Sleeveless, long gown (thin)	0.20
Sandals/thongs	0.02	Long-sleeve shirtdress (thin)	0.33	Short-sleeve hospital gown	0.31
Slippers (quilted, pile-lined)	0.03	Long-sleeve shirtdress (thick)	0.47	Long-sleeve, long gown (thick)	0.46
Boots	0.10	Short-sleeve shirtdress (thin)	0.29	Long-sleeve pajamas (thick)	0.57
		Sleeveless, scoop neck (thin)	0.23	Short-sleeve pajamas (thin)	0.42
Shirts and Blouses					
Sleeveless, scoop-neck blouse	0.12	Sleeveless, scoop neck (thick), *i.e.*, jumper	0.27	Long-sleeve, long wrap robe (thick)	0.69
Short-sleeve, dress shirt	0.19				
Long-sleeve, dress shirt	0.25	**Sweaters**		Long-sleeve, short wrap robe (thick)	0.48
Long-sleeve, flannel shirt	0.34	Sleeveless vest (thin)	0.13	Short-sleeve, short robe (thin)	0.34

[a] "Thin" garments are made of light, thin fabrics worn in the summer; "thick" garments are made of heavy, thick fabrics worn in the winter.

[b] 1 clo = 0.155 m²·K/W

[c] Knee-length

$$h_r = \epsilon\, 4.7\ \mathrm{W/(m^2 \cdot K)} \tag{51}$$

where ϵ represents the area-weighted average emissivity for the clothing/body surface.

Convective heat transfer coefficient. Heat transfer by convection is usually caused by air movement within the living space or by body movements. Equations for estimating h_c under various conditions are presented in Table 6. An additional relationship is presented in Equation (75). Where two conditions apply (*e.g.*, walking in moving air), a reasonable estimate can be obtained by taking the larger of the two values for h_c. Limits have been given for all equations. If no limits were given in the source, reasonable limits have been estimated. Care should be exercised in using these values for seated and reclining persons. The heat transfer coefficients may be accurate, but the effective heat transfer area may be substantially reduced due to body contact with a padded chair or bed.

Quantitative values of h_c are important, not only in estimating convection loss, but in evaluating (1) operative temperature t_o, (2) clothing parameters I_t and i_m, and (3) rational effective temperatures t_{oh} and ET*. All heat transfer coefficients in Table 6 were evaluated at or near 101.33 kPa. These coefficients should be corrected as follows for atmospheric pressure:

$$h_{cc} = h_c\,(p_t/101.33)^{0.55} \tag{52}$$

where

h_{cc} = corrected convective heat transfer coefficient, W/(m²·K)
p_t = atmospheric pressure, kPa

The combined coefficient h is the sum of h_r and h_c described in Equation (50) and Table 6, respectively. The coefficient h governs exchange by radiation and convection from the exposed body surface to the surrounding environment.

Evaporative heat transfer coefficient. The evaporative heat transfer coefficient h_e for the outer air layer of a nude or clothed person can be estimated from the convective heat transfer coefficient using the Lewis relationship given in Equation (27). If the atmospheric pressure is significantly different from standard (101.325 kPa), the correction to the value obtained from Equation (27) is:

$$h_{ec} = h_e\,(101.33/p_t)^{0.45} \tag{53}$$

Table 6 Equations for Convection Heat Transfer Coefficients

Equation	Limits	Condition	Remarks/Sources
$h_c = 8.3\,V^{0.6}$ $h_c = 3.1$	$0.2 < V < 4.0$ $0 < V < 0.2$	Seated with moving air	Mitchell (1974)
$= 2.7 + 8.7\,V^{0.67}$ $= 5.1$	$0.15 < V < 1.5$ $0 < V < 0.15$	Reclining with moving air	Colin and Houdas (1967)
$h_c = 8.6\,V^{0.53}$	$0.5 < V < 2.0$	Walking in still air	V is walking speed (Nishi and Gagge 1970)
$h_c = 5.7(M - 0.85)^{0.39}$	$1.1 < M < 3.0$	Active in still air	Gagge *et al.* (1976)
$h_c = 6.5\,V^{0.39}$	$0.5 < V < 2.0$	Walking on treadmill in still air	V is treadmill speed (Nishi and Gagge 1970)
$= 14.8\,V^{0.69}$ $h_c = 4.0$	$0.15 < V < 1.5$ $0 < V < 0.15$	Standing person in moving air	Developed from data presented by Seppenan *et al.* (1972)

Note: h_c in W/(m²·K), V in m/s, and M in met units, where 1 met = 58.2 W/m².

where h_{ec} is the corrected evaporative heat transfer coefficient, the W/(m²·kPa).

Clothing Insulation and Moisture Permeability

Thermal insulation. The most accurate methods for determining clothing insulation are: (1) measurements on heated manikins (McCullough and Jones 1984, Olesen and Nielsen 1983) and (2) measurements on active subjects (Nishi *et al.* 1975). For most routine engineering work, estimates based on tables and equations presented in this section are sufficient. Thermal manikins can measure the sensible heat loss from the "skin" ($C + R$) in a given environment. Equation (12) can then be used to evaluate R_{cl} if the environmental conditions are well defined and f_{cl} is measured. Evaluation of clothing insulation on subjects requires measurement of t_{sk}, t_{cl}, and t_o. The clothing thermal efficiency is calculated by:

$$F_{cl} = (t_{cl} - t_o)/(t_{sk} - t_o) \tag{54}$$

The intrinsic clothing insulation can be calculated from manikin measurements by the following relationship, provided f_{cl} is measured and conditions are sufficiently well-defined to make an accurate determination of h:

$$R_{cl} = (t_{sk} - t_o)/q - 1/(hf_{cl}) \tag{55}$$

where q = heat loss from the manikin, W/m².

It is traditional to express clothing insulation in terms of the clo unit. In order to avoid confusion, the symbol I is used with the clo unit instead of the symbol R. The relationship between the two is:

Table 7 Typical Insulation and Permeability Values for Clothing Ensembles[a]

Ensemble Description[b]	I_{cl} (clo)	I_t^c (clo)	f_{cl}	i_{cl}	i_m^c
Walking shorts, short-sleeve shirt	0.36	1.02	1.10	0.34	0.42
Trousers, short-sleeve shirt	0.57	1.20	1.15	0.36	0.43
Trousers, long-sleeve shirt	0.61	1.21	1.20	0.41	0.45
Same as above, plus suit jacket	0.96	1.54	1.23		
Same as above, plus vest and t-shirt	1.14	1.69	1.32	0.32	0.37
Trousers, long-sleeve shirt, long-sleeve sweater, t-shirt	1.01	1.56	1.28		
Same as above, plus suit jacket and long underwear bottoms	1.30	1.83	1.33		
Sweat pants, sweat shirt	0.74	1.35	1.19	0.41	0.45
Long-sleeve pajama top, long pajama trousers, short 3/4 sleeve robe, slippers, (no socks)	0.96	1.50	1.32	0.37	0.41
Knee-length skirt, short-sleeve shirt, panty hose, sandals	0.54	1.10	1.26		
Knee-length skirt, long-sleeve shirt, full slip, panty hose	0.67	1.22	1.29		
Knee-length skirt, long-sleeve shirt, half slip, panty hose, long-sleeve sweater	1.10	1.59	1.46		
Same as above, replace sweater with suit jacket	1.04	1.60	1.30	0.35	0.40
Ankle-length skirt, long-sleeve shirt, suit jacket, panty hose	1.10	1.59	1.46		
Long-sleeve coveralls, t-shirt	0.72	1.30	1.23		
Overalls, long-sleeve shirt, t-shirt	0.89	1.46	1.27	0.35	0.40
Insulated coveralls, long-sleeve thermal underwear, long underwear bottoms	1.37	1.94	1.26	0.35	0.39

[a] From McCullough and Jones (1984) and McCullough *et al.* (1989)
[b] All ensembles include shoes and briefs or panties. All ensembles except those with panty hose include socks unless otherwise noted.
[c] For $\bar{t}_r = t_a$ and air velocity less than 0.2 m/s (I_a = 0.72 clo and i_m = 0.48 when nude)