N69-12440

THERMAL ENVIRONMENT

Heat is exchanged between man and the environment through four enues. (1) Exchanges of radiation may occur with surfaces having higher lower temperatures than that of the skin or radiation may be absorbed by skin from high temperature sources such as the sun. (2) The body may change heat by convection and this is an important source of heat loss pecially if the velocity of currents around the body is high and their temperature, low. (3) Heat may be exchanged by conduction with objects in direct ysical contact. (4) Heat may be lost by vaporization from the lungs through spiration and the skin by sweating. Heat may be lost in urine and feces. ie body also stores heat in the tissues and body fluids. This stored heat is e currency with which body heat balance is purchased. The various mani- stations and ramifications of these basic interactions encompass the field thermal biophysics.

Because the field of thermal biophysics draws upon many different iences the problem of consistent units is always present. The following iits are those found in the majority of cases but the policy of checking units, ien using an equation for the first time, should always be followed (21).

Table 6-1

Nomenclature

ymbol	Definition	BE Units	Metric Units
	area	ft^2	m^2
$_b$	surface area of body	ft^2	m^2
$_g$	surface area of garmented body	ft^2	m^2
$_r$	radiating area of body	ft^2	m^2
$_w$	wetted area of body	ft^2	m^2
$_f$	film thickness	in	cm
	E_r/E_m		
ΔC	concentration difference	lb/ft^3	gm/cm^3
$_p$	unit heat capacity at constant pressure	Btu/lb^oF	$kcal/Kg^oC$
$_v$	unit heat capacity at constant volume	$Btu/ft^{3o}F$	$kcal/m^3/^oC$
D	diameter or significant dimension	ft	m
D_v	vapor diffusivity -	ft^2/hr	cm^2/sec

Symbol	Definition	BE Units	Metric Units
D_{v0}	diffusivity of water vapor in air at standard pressure	f^2/hr	cm^2/sec
E	energy in general	Btu	kcal
E_r	evaporative water loss	lbs/ft^2/hr	gm/m^2/hr
E_m	evaporative water loss (maximum)	lbs/ft^2/hr	gm/m^2/hr
F_{ae}	shape-emissivity factor	dimensionless	
F_{12}	shape factor	dimensionless	
f_r	radiation area factor	dimensionless	
g	fraction of earth gravity		
G	mass velocity	lb/ft^{2}hr	Kg/m^{2}hr
h	overall heat transfer conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_c	convective conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_g	clothing conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_o	operative conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_r	radiant conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_{rb}	radiant conductance (black body)	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h_{sr}	solar radiant conductance	Btu/ft^{2}hr°F	kcal/m^{2}hr°C
h'	overall evaporative conductance	Btu/ft^{2}hr in Hg	kcal/m^{2}hr mm
h'_c	external, environmental evaporative conductance	Btu/ft^{2}hr in Hg	kcal/m^{2}hr mm
h_D	mass transfer coefficient	ft/hr	m/hr
k	thermal conductivity	Btu/ft hr°F	kcal/m hr°C
L	thickness	ft	cm
M	molecular weight	lbs/mole	gm/mole
P	barometric pressure	in Hg	mmHg
Pr	Prandtl number $(C_p\ \mu/k)$	dimensionless	
P_o	standard barometric pressure	in Hg	mmHg
p_a	water vapor pressure (absolute humidity)	in Hg	mmHg
p_s	water vapor pressure at the skin	in Hg	mmHg
p_s^*	saturated water vapor pressure at t_s	in Hg	mmHg
q_c	convective heat transfer	Btu/ft^{2}hr	kcal/m^{2}hr

ymbol	Definition	BE Units	Metric Units
$_e$	evaporative heat transfer	Btu/ft^{2}hr	kcal/m^{2}hr
$_m$	metabolism	Btu/ft^2 hr	kcal/m^{2}hr
$_r$	radiant heat transfer	Btu/ft^{2}hr	kcal/m^{2}hr
$_s$	storage rate	Btu/ft^{2}hr	kcal/m^{2}hr
$_{sr}$	solar heat transfer to man	Btu/ft^{2}hr	kcal/m^{2}hr
$_k$	conductive heat transfer	Btu/ft^{2}hr	kcal/m^{2}hr
$_v$	respiratory heat transfer	Btu/ft^{2}hr	kcal/m^{2}hr
$_w$	energy of work	Btu/ft^{2}hr	kcal/m^{2}hr
	total heat transfer	Btu/hr	kcal/hr
	radius	in	cm
$=1/h$	thermal resistance in general	$\frac{ft^2 hr\,^oF}{Btu}$	$\frac{m^2 hr\,^oC}{Kcal}$
e	Reynolds number		
$_g = 1/h_g$	thermal resistance of clothing	$\frac{ft^2 hr\,^oF}{Btu}$	$\frac{m^2 hr\,^oC}{Kcal}$
$_o = \frac{1}{h_o}$	thermal resistance of the environment	$\frac{ft^2 hr\,^oF}{Btu}$	$\frac{m^2 hr\,^oC}{Kcal}$
$'$	vapor resistance in terms of the equivalent thickness of still air	ft still air	cm still air
R'_g	clothing vapor resistance	ft still air	cm still air
R'_e	environment vapor resistance	ft still air	cm still air
	temperature	^oF	^oC
t_a	air temperature	^oF	^oC
t_b	weighted mean body temperature	^oF	^oC
t_{bm}	midpoint body temperature during exposure	^oF	^oC
t_E	effective temperature	^oF	^oC
t_{env}	environmental temperature	^oF	^oC
t_g	garment surface temperature	^oF	^oC
t_o	operative temperature	^oF	^oC
t_{or}	reference operative temperature	^oF	^oC
t_r	rectal temperature	^oF	^oC
t_{rm}	midpoint rectal temperature during exposure	^oF	^oC
t_s	weighted body skin temperature	^oF	^oC

Symbol	Definition	BE Units	Metric Units
t_{sm}	midpoint skin temperature during exposure	^oF	^oC
t_{sr}	temperature of the sun	^oF	^oC
Δt_{osr}	solar operative temperature increment	^oF	^oC
t_w	average wall temperature	^oF	^oC
T	absolute temperature	^oR	^oK
$T_g; T_w$	absolute temperature of garment, wall	^oR	^oK
T_O	reference or standard temperature	^oR	^oK
T_f	film temperature	^oR	^oK
u	internal energy per unit mass	Btu/lb	kcal/kg
U	internal energy	Btu	kcal
$\bar{V}$	velocity	ft/hr	km/hr
$\dot{V}$	respiration rate	lbs/hr	liters/min
v	volume per unit mass	ft^3/lb	cm^3/gm
w	work per unit mass	$ft\text{-}lb_f/lb$	$m\text{-}Kg_f/Kg$
W_e	work	$ft\text{-}lb_f$	$m\text{-}Kg_f$
W	weight	lb_f	Kg_f
W_p	perspiration rate	lb/ft^2hr	gm/m^2hr

GREEK SYMBOLS

α	Solar absorptivity of skin or garments		
β	coefficient thermal expansion (vol.)		
ϵ	emissivity	dimensionless	
ϵ_g	emissivity of garments	dimensionless	
θ	time of exposure	min or hrs	
θ_m	midpoint time	min or hrs	
θ_t	tolerance time	min or hrs	
λ_e	heat transfer due to evaporation	Btu/lb	kcal/kg
μ	viscosity	lb/ft hr	Kg/m hr
ρ	density	lb/ft^3	Kg/m^3

Symbol	Definition	BE Units	Metric Units
σ	Stefan-Boltzman constant	$Btu/ft^2 hr^o R^4$	$kcal/m^2 hr^o K^4$
τ	Transmission factor for transparent surfaces		
ω	wetted fraction of surface	dimensionless	

DIMENSIONLESS GROUPS OR NUMBERS

$Nu = \frac{h_c D}{k}$	Nusselt number
$Pr = \frac{C_p \mu}{k}$	Prandtl number
$Re = \frac{DV\rho}{\mu}$	Reynold's number

(After Blockley et al., (27))

THE BIOTHERMAL EQUATION

The conditions for thermal equilibrium between the human body and the environment can be examined in terms of the biothermal equation. This equation attempts to balance the normal heat gains and losses and is usually expressed as follows (27):

$$q_{sr} + q_m = q_s \pm q_r \pm q_c + q_v \pm q_k + q_e + q_w \qquad (1)$$

Table 6-2 gives the functions or criteria affecting these terms and their effect upon the biothermal equation.

For a state of thermal equilibrium, the heat storage rate is zero ($q_s = 0$). The conductive heat transfer mode is usually quite small and can be assumed, in most instances, to be included in the radiant and/or convective heat transfer terms ($q_k = 0$). Finally, if external heat fluxes are accounted for in terms of induced, environmental parameters, such as internal air and wall temperatures, the term (q_{sr}) can be omitted from the expression.

With comfort as the reference state ($q_s = 0$), the biothermal equation can be expressed as:

$$q_m = \pm q_r \pm q_c + q_e + q_v + q_w \qquad (2)$$

and the system can be examined qualitatively in the light of these terms after they have been adequately defined.

Table 6-2

Components of the Biothermal Equation

Term	Function	Effect on System
Metabolism, q_m	f (activity level, body temp.)	Gain at all times
Solar radiation, q_{sr}	f (h_{sr}, t)	Gain when present
Infrared radiation, q_r	f (h_r, t)	Gain: $t_w > t_g$; Loss: $t_w < t_g$
Convection, q_c	f (h_c, t)	Gain: $t_a > t_g$; Loss: $t_a < t_g$
Evaporation, q_e	f (D_v, ΔC. P, t)	Loss in all usual conditions
Resp. heat exch., q_v	f (Resp. mass flow, P, t)	Small gain or loss
Storage, q_s	f (W, C_p, A_b, $dt_b/d\theta$)	Gain: $dt_b/d\theta > 0$; Loss: $dt_b/d\theta < 0$
Work, q_w	nature of activity	Gain: Work done on body; Loss: Work done by body

Heat of metabolism (q_m) is considered to be the sum of the basal metabolic rate (energy required to maintain the body in good health and at equilibrium temperature while at rest) plus an incremental increase in heat energy due to activity and/or stress.

Radiant heat exchange (q_r) is a measure of the heat lost (or gained) as a result of the temperature difference between the skin of the human body and the walls of the surroundings.

Convective heat exchange (q_c) is a measure of the heat lost (or gained) as a result of the temperature difference between the skin and the immediate atmosphere.

Evaporative heat exchange (q_e) is the heat exchange resulting from the vaporization of moisture at the surface of the skin.

Respiratory heat exchange (q_v) is a measure of the heat lost (including vaporization of water) from the lungs due to respiration.

In any environment, all of the above modes of heat transfer may be present. In general, the ambient dry bulb temperature, humidity, air velocity, and ambient pressure determine the partition of mechanisms actually used by the body. Several computer programs using mathematical models of human thermoregulation have been proposed (37, 38, 188, 194). At the current stage of development, these should be used in close connection with empirical studies in evaluating the effects of unusual thermal environments.

Figure 6-3 represents the changing partition of heat loss mechanisms at rest with increasing dry bulb temperature at a constant relative humidity of 45% and constant gas velocity. The regions of primarily metabolic, vasomotor and evaporative regulation are noted. High metabolic rate at low temperature is a result of shivering; at temperatures above 90°F metabolic rate may increase due to restlessness and Q_{10} factors.

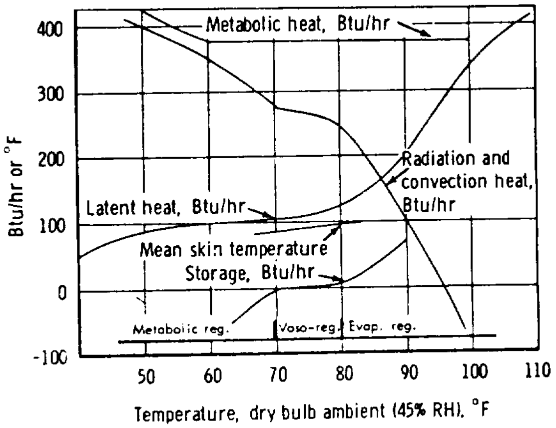


Figure 6-3

Typical Relation Between Human Heat Balance and Temperatures for Lightly Clothed, Resting Subjects in Still Air at Sea Level

(Adapted by Johnson(114) from(81, 102, 225, 226) and others)

Determination of the human body's thermal status in space operations requires analysis of a large number of variables. Many of these variables do not lend themselves to an exact mathematical solution but must be arrived at statistically from experimental data. Even then, the results must be treated with caution when applied to the small population represented by a flight crew. Individual metabolic rates, health variations, tolerances, and motivation can cause wide deviations from predicted states and performances. Diurnal cycles are especially significant.

In general, the variables of interest can be collected under three major classifications. These are environment, body state and clothing. Most of the variables are listed under these major classifications in Table 6-4.

As many of the variables are interdependent, solution of the complete biothermal equation becomes largely a reiterative process modified by heavy reliance on reasonable assumptions and experimental results. As a rule, equipment provided to satisfy a primary functional requirement for biothermal protection and control is integral to the environmental control systems and to the garment assemblies worn by the crew. Maintenance of thermal balance requires the regulation of environmental parameters to maintain man in a state of thermal equilibrium (or compensable quasi-equilibrium) at all anticipated levels of activity to ensure adequate performance and preclude irreversible physiological effects.

Engineering for thermal balance includes the specification of thermal design criteria for all equipment being provided to satisfy, as a primary functional requirement, biothermal protection and control. In addition, it includes identification, quantitatively if possible, of all factors related to

Table 6-4

Conditions for Prediction of Body Thermal Status

(After Bottomley(32))

Environment			
External (Natural)	Internal (Induced)	Body State	Clothing
Solar radiation (q_{sr})	Wall temperature (t_w)	Metabolic rate (q_m)	Thermal resistance (R_g)
Earth radiation (q_{er})	Atmospheric temperature (t_a)	Weight (W)	Vapor resistance (R'_g)
Lunar radiation (q_{lr})	Atmospheric pressure (P)	Posture	Wind permeability
Shadow cones (day/night)	Atmospheric velocity (V)	Area of body (A_b)	Weight
Atmospheric composition	Atmospheric composition	Skin temperature (t_s)	Color (emissivity absorptivity)
Vehicle velocity (if > C/7) (C = vel. of light)	Absolute humidity (p_a)	Rectal temperature (t_r)	Wicking efficiency
	Diffusivity (D_v)	Mean body temperature (t_b)	Effective clothing absorbtance
Vehicle attitude or orientation	Specific heats (C_p, C_v)	Respiration rate ($\dot{V}$)	
Vehicle altitude	Surface Area (surroundings) A	Insensible water loss	
	Shape emissivity factor F_{ae}	Sweat rate (sensible (W_ϵ) water loss)	
	Crew operating mode	Wetted area (ω)	
		Activity/work efficiency	
	Stress Factors	Physical condition	
	System failure	Degree of heat stress resistance (acclimatization)	
	G-loads (weightlessness)	Water/electrolyte balance	
	Toxicity (CO_2 etc.) effects	Radiation area factor (fr)	
	Radiation effects	Radiating area of body (A_r)	
	Decompression (emergency)	Area of body irradiated	
	Hypoxia	Effective skin absorbtance	
	Psychological (morale, anxiety)		
	Vibration		

biothermal control which must be considered in specifications and trade-off studies applicable to other systems and to mission operations, profiles, and constraints. All phases of the mission, including survival on Earth in case of aberrant landing site, must be considered. Data are available on the thermal and related environments to be assumed in the manned lunar surface program (105).

The primary environmental parameters affecting heat exchange between man and his surroundings are:

1. Convective sources or sinks
    a. Atmospheres (relevant factors include composition, pressure, temperature, absolute humidity, and ventilation rates)
2. Conductive sources or sinks
    a. Solids (relevant factors include temperature, contact pressure and thermal conductivity)
    b. Liquids (relevant factors include temperature, film coefficients, flow rates and thermal conductivity)

3. Radiant sources or sinks
   a. External - e.g., solar and planetary radiation, deep space (relevant factors include the solar constant, planetary surface and albedo, mean radiant temperatures, and deep space temperature)
   b. Internal - e.g., wall and equipment surfaces (relevant factors include temperatures and reflectivity, emissivity and absorptivity coefficients)

Once the analysis has entertained all pertinent variables, and a comfort region for thermal equilibrium has been determined, there still remains the establishment of an index which clearly defines the bounds of the region and is translatable into terms which are meaningful to the design engineer.

ENVIRONMENTAL COMFORT AND STRESS INDICES

Comfort zones have been defined in the literature in terms of skin temperature, sweat rates and various indices which relate environmental parameters to subjective impressions of comfort or measured values of selected physiological variables.

For the same conditions and individuals the established boundaries for thermal comfort, performance and tolerance as described by the various design indices may be completely consistent. However, variations in activity, wearing apparel, individual health and acclimatization, and thermal exposure immediately prior to making a determination of comfort will operate to shift the zones and introduce inconsistencies in results (76).

Examples of comfort indices established in the past are the British Comfort Index (67), ASHRAE Effective Temperature (7), and Operative Temperature (212). All but Operative Temperature are psychophysiological determinations which, having been established subjectively, are not as adaptive to quantitative treatment in design and analysis.

For these reasons Operative Temperature is probably the most useful as the primary comfort index for use in biothermal systems design. However, information relating to other indices in general use is provided to permit comparison of new data with old in those cases where an index other than Operative Temperature has been used as a reference. Recent reviews of thermal stress assessment from heat balance data are available (139, 183, 228).

Operative Temperature (t_o)

"Operative Temperature" was first introduced to establish "a generalized environmental temperature scale, that combines as a single measurement certain of the thermal effects of the physical environment, aqueous or atmospheric, and in the latter case for any combination of radiant temperature, ambient air temperature and air movement" (80). They cover only sea level conditions.

(Metric) $$t_o = 0.18\, t_w + 0.19 \left(\sqrt{\overline{V}}\; t_a - (\sqrt{\overline{V}} - 1)\, t_s\right) \tag{3}$$

when t_a, t_w, t_s = °C

$\overline{V}$ = atmospheric velocity in cm/sec

(English) $$t_o = 0.18\, t_w + 0.135 \left(\sqrt{\overline{V}}\; t_a - (\sqrt{\overline{V}} - 1.40)\, t_s\right) \tag{4}$$

when t = °F

$\overline{V}$ = ft/min

Without sacrificing the validity or accuracy of the original definition, operative temperature has been redefined (225) in the following form:

$$t_o = \frac{h_r\, t_w + h_c\, t_a}{h_r + h_c} = t_a + \frac{h_r\,(t_w - t_a)}{h_r + h_c} \tag{5}$$

where

t_w = wall temperature - °F. (°C.)

t_a = atmospheric temperature - °F. (°C.)

h_r = radiant conductance-Btu/ft^2 hr °F. (kcal/m^2 hr °C.)

h_c = convective conductance-Btu/ft^2 hr °F. (kcal/m^2 hr °C.)

The term $h_r(t_w - t_a)$ has been recently called the effective radiant field (ERF) and used as an energy term in calculating total body heat load (77 , 78 , 79).

Operative temperature is simply the weighted mean of air and wall temperatures and may be determined by use of the nomograph (Figure 6-5) or the values of h_r and h_c for specific atmospheres as computed in accordance with derivations to be covered below. For known values of air and wall temperature, Figure 6-5 may be used.

While operative temperature is derived from the environmental and physiological parameters which determine heat transfer from or to the body in terms of radiation and convection, the design objectives that body storage shall be zero, evaporative heat losses shall be limited to insensible evaporation of moisture produced only by diffusion through the skin without the activity of sweat glands, and that body and skin temperatures shall be maintained near nominal while reflecting the effects of environmental parameters (including humidity, atmospheric pressure) and insensible water loss should be sufficient to bound the design area for thermal control.

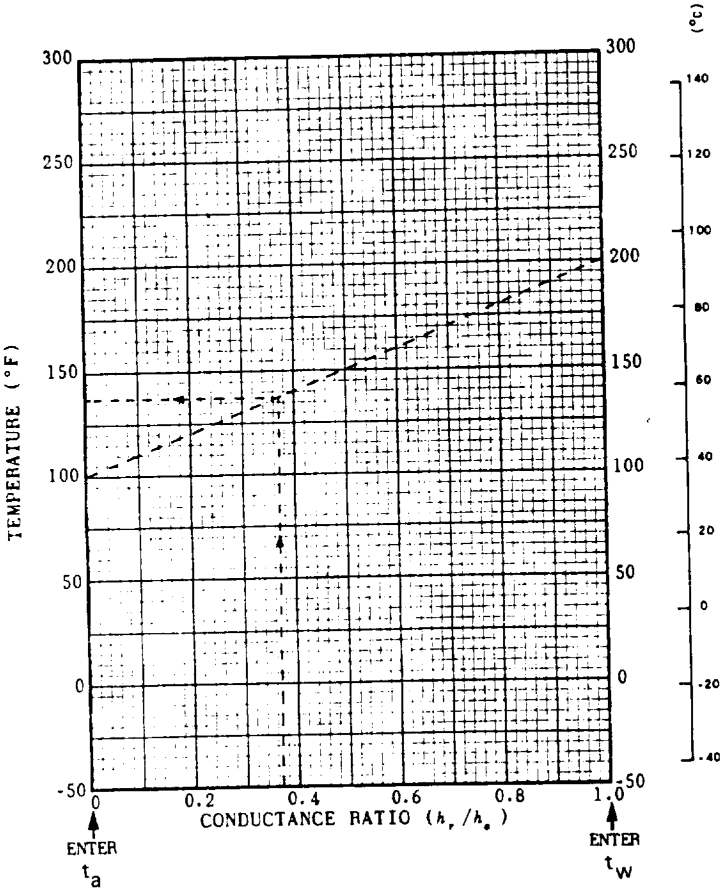


Figure 6-5

Operative Temperature Nomograph

Procedure for graphical solution of:

$$t_o = \frac{t_w h_r + t_a h_c}{h_o}$$

Enter t_a and t_w on indicated ordinates; connect the two points with a straight edge; read t_o at the intersection with the appropriate value of the conductance ratio.

(After Blockley et al(27))

Environmental Temperature ($t_{env.}$)

Environmental temperature is used as a design index when direct solar radiation to the man is a significant heat load not adequately accounted for in terms of induced environmental parameters; otherwise $t_{env} = t_o$ (27).

$$\text{Then } t_{env} = t_o + \Delta t_{o(sr)} \qquad (6)$$

$$\text{And } \quad \Delta t_{o(sr)} = \frac{q_{sr}}{h_r + h_c + h_{sr}} \qquad (7)$$

$$\text{or } \quad \Delta t_{o(sr)} = \frac{G_t \, \tau \, \alpha_1 \, (A_{sr}/A_b)}{h_r + h_c} \qquad (8)$$

where G_t = Total Solar radiation Btu/ft^2 hr (kcal/m^2 hr)

τ = Transmission factors for transparent surfaces

α_1 = Solar absorptivity of skin (or clothing)

A_{sr}/A_b = Ratio of area of body directly irradiated by the sun to total area of body

h_r & h_c are as previously defined for t_o

Effective Temperature (t_E) (or E. T.)

The effective temperature index integrates the effects of atmospheric temperature, humidity and ventilation rates based on subjectively reported sensations of warmth, comfort and cold (107, 127 , 151). It is acceptable for use when radiant heat exchange is relatively insignificant in comparison with other modes.

Figure 6-6 shows effective temperature indices (i.e., lines of constant thermal sensation in air at sea level) for ventilation flow rates of 15 to 25 feet per minute in air at sea level with effects of seasonal acclimatization.

Figure 6-7 is somewhat more appropriate to spacecraft conditions where confined spaces and high ventilation flow rates are likely to be encountered, but covers only air at sea level. It may be of value in consideration of post-landing conditions. Comfort criteria for gaseous variables in sealed cabins will be discussed below.

Comfort bands are of value in defining design conditions for office or field laboratory conditions in different climates. In view of the many variables outlined above, the delineation of comfort bands is most difficult. Tables 6-8 and 6-9 present the available data for air at sea level with some

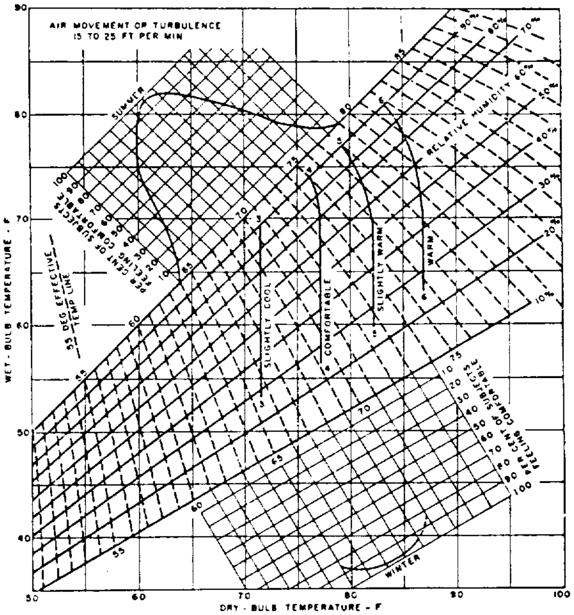
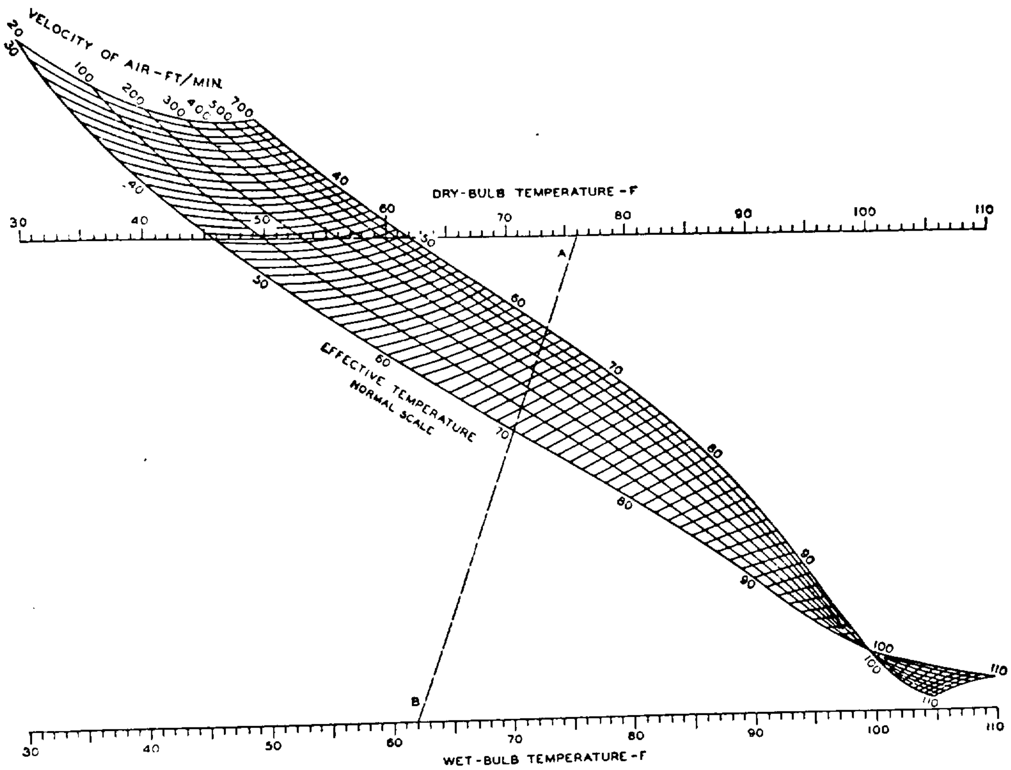


Figure 6-6

Comfort Zones in Summer and Winter.

(After ASHRAE Guide[7])



Example of the use of the chart: Given dry bulb temperature of 76°F, wet bulb temperature of 62°F, velocity of air 100 fpm; determine: 1) effective temperature (ET) of the condition, 2) ET with still air, 3) cooling produced by the movement of the air, 4) velocity necessary to produce the condition of 66°ET.

Solution: 1) Draw line A-B through given dry and wet bulb temperatures. Its intersection with the 100-fpm curve gives 69° for the ET of the condition. 2) Follow line A-B to the right to its intersection with the 20-fpm velocity line, and read 70.4° for the ET for this velocity or so-called still air. 3) The cooling produced by the movement of the air is 70.4 - 69.0 = 1.4°ET. 4) Follow line A-B to the left until it crosses the 66° ET line. Interpolate velocity value of 340 fpm to which the movement of the air must be increased for maximum comfort.

Figure 6-7

Thermometric Chart Showing Normal Scale of Effective Temperature. Applicable to Inhabitants of the United States Under the Following Conditions: 1) Clothing: Customary Indoor Clothing; 2) Activity: Sedentary or Light Muscular Work; 3) Heating Methods: Convection Type.

(After ASHRAE Guide[7])

Table 6-8

Comparison of Comfort Ranges with Zone of Thermal Neutrality

(After ASHRAE Guide(7))

Investigators	*Effective Temperature*		*Operative Temp Range*	*Remarks*
	Optimum Line	*Range*		
		Comfort Zone		
Houghten and Yaglou	66	63–71	...	Winter nonbasal; at rest, normally clothed. Men and women.
Yaglou and Drinker (237)	71	66–75	...	Summer nonbasal; at rest and normally clothed. Men.
Yaglou (236)	72.5	66–82	...	Entire year; nonbasal; at rest and stripped to waist. Men.
Keeton et al	75	74–76	...	Entire year; basal, nude. Steady state (9 hr exposure). Men and women.
		Zone of Thermal Neutrality		
DuBois and Hardy	75	73.2–76.9	...	Basal; nude; men.
	71.8	64.8–76.0	...	Basal; clothed; men.
Winslow, Herrington, and Gagge (226)	...	...	84.0–87.8	Nonbasal; at rest; nude; men.
	...	...	74 –84	Nonbasal; at rest; clothed; men.

Table 6-9

Comfort Bands at Rest in Air at Sea Level

	Physiological Parameter (1)		Environmental Parameter	
Comfort Level	t_s	$E_r/E_m \times 100$	t_a	t_E
Hot	>95°F	70-100%	>87°F	>87°F
Tolerable	93-94°F	25-70%	79-86°F	82°F
Comfortable	90-92°F	10-25%	68-78°F	70-75°F
Cold	<89°F	0-10%	67°F	<65°F

Relative humidity 30-70%; air velocity 15-40 ft/min.

ysiological correlates. Many field studies have been made to determine the
:imum indoor effective temperature for both winter and summer in several
:tropolitan districts of the United States and Canada, in cooperation with
: managements of offices employing large numbers of workers (8).
rsons serving in all of these studies were representative of office workers
essed for air-conditioned spaces in the summer season, and engaged in
: customary office activity. Some of the results of these studies for the
mmer season are shown in Figure 6-10. In the warmer areas of the country

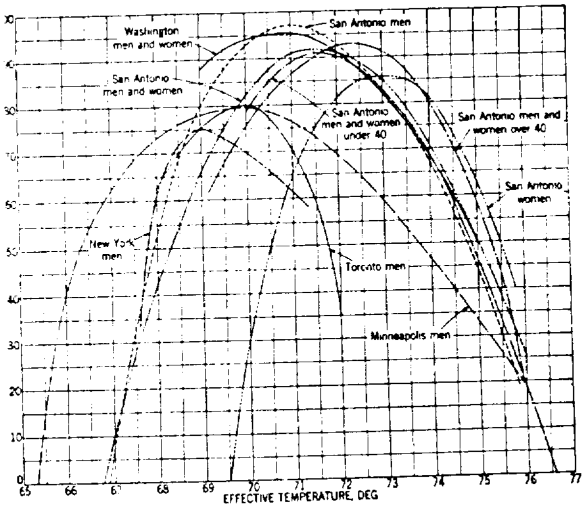


Figure 6-10

Relation Between Effective Temperature and Percentage Observations Indicating Comfort of Office Workers in the Summer Season.

(After ASHRAE Guide[7])

ıe optimum effective temperature for summer cooling is approximately
degrees higher than in the northern cities. Variations in sensation of comɔrt among individuals may be greater for any given location than variations
ue to a difference in geographical location. Available information indicates
ıat changes in weather conditions over a period of a few days do not alter
ptimum indoor temperature. On the whole, women of all age groups studied
refer an effective temperature for comfort 1.0 degree higher than men.
\ll men and women over 40 years of age prefer a temperature 1 deg ET
igher than that desired by persons below this age.

In addition to defining environmental zones of comfort, one must con,ider indices of graded environmental stress. Indicators of stress may be
;tated in terms of environmental or physiological variables. In this section,
he environmental indices of stress will be covered. Physiological indicaors are covered in specific sections on heat and cold stress.

Reference Operative Temperature (t_{or})

Reference Operative Temperature was introduced to permit consideratio of the humidity effect as a specific design parameter in assessing the biothermal state under stressful conditions (27). Skin temperature is independent of humidity between zero and about 20 mm Hg vapor pressure. The data in the current literature supports the view that absolute humidity in the range from 0.20 to 0.59 in Hg (5 to 15 mm Hg) is not a significant consideration for biothermal regulation under moderate ambient conditions. For warm humid environments leading to time-limited biothermal states, Reference Operative Temperature can be used as a design index. To determine the equivalent Reference Operative Temperature, Figure 6-11 is entered with values of Operative Temperature and absolute humidity.

"Oxford" or W/D Index

The "Oxford" or W/D Index, is a simple weighting of wet bulb temperature (85%) and dry bulb (air) temperature (15%). It is based on the observation that in non-compensable heat exposures the time to incipient collapse correlated well with this parameter and is used primarily in this context. The presumption is that W/D value is directly related to rate of heat storage, or the imbalance of surface heat exchange. A related index for outdoor use is the wet bulb-globe temperature (WBGT) index. Figure 6-12 can be used for calculation of the Oxford Index. Figure 6-80 presents tolerance times as related to this index.

The following indices of stress are more closely tied to specific physiological endpoint and will be covered in greater detail in the section on heat and cold stress.

The Belding-Hatch Stress Index

This index predicts the ratio for evaporation required for thermal balance in a given environment and compares it to the maximum rate safely attainable for prolonged periods of time. Equation 46 and Figure 6-74 and 6-75 cover this index.

The P4SR Index (Predicted Four Hour Sweat Rate)

The rate of sweating for men in hot environments can be predicted and related to degree of stress. Figure 6-76 presents a nomogram for calculation of the P4SR.

The Body Storage Index

The rate of body heat gain can be correlated with physiological and psychological measurements of heat stress. Tolerance and performance times can be predicted using this index (See Figures 6-77 and 6-78).

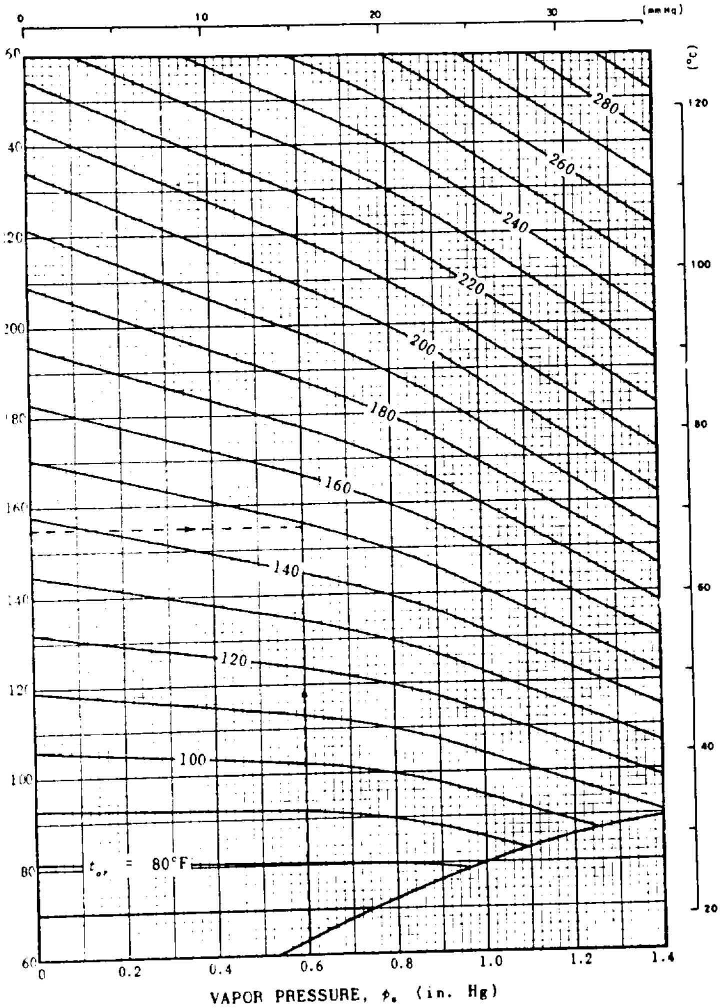


Figure 6-11

Reference Operative Temperature

Display of temperature-humidity equivalences in air according to human thermal effect. Reference operative temperature, t_{or}, is defined as the operative temperature at 0.79 in. Hg vapor pressure.

Procedure: Enter with p_a and t_o; read t_{or} by interpolation in parametric scale.

(After Blockley et al.,(27))

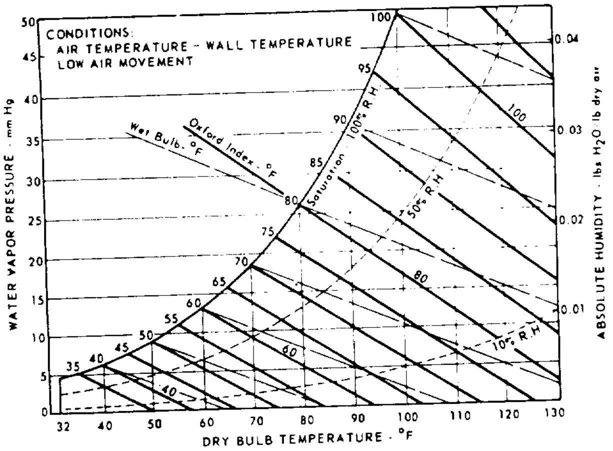


Figure 6-12

The Oxford or W/D Index

(After Blockley(30) Adapted from Data of Provins, Hellon et al(162) and Leithead and Lind(127))

Windchill Index

In severely cold environments, the Windchill Index may be used as a rough measure of cold stress. This is covered in Figure 6-99.

BIOTHERMAL PROPERTIES AND COMFORT ZONES IN SPACE CABIN ATMOSPHERES

The determination of human thermal constants in atmospheres other than air is a difficult task (21, 100, 121, 131, 155, 165). Extrapolation of comfort zones to these unusual gaseous environments is also fraught with several uncertainties (174).

The thermal constants of gases and of candidate atmospheres other than air are seen in Table 6-13 representing the properties of the individual gases at 1 atmosphere and Table 6-14, the properties of the mixtures as recommended for space cabins (174). Psychrometric charts are also available for these atmospheres (90, 174, 175).

Table 6-13

Thermal Properties of Component Gases at 80°F (540°R) and Atmospheric Pressures

(After Breeze(36))

Gas	Molecular Weight M	Specific Gas Constant R Ft-Lb/Lb-°R	Density Lb/Ft^3	Specific Heat C_p Btu/lb-°F	Dynamic Viscosity X 10^6 μ Lb/Sec-Ft	Thermal Conductivity k Btu/Hr-Ft^2-°F/Ft	Prandtl Number N_{P_r}
Air	29.0	53.3	0.0735	0.240	12.4	0.0152	0.708
CO_2	44.010	35.1	0.1122	0.208	10.1	0.00958	0.770
H_e	4.002	386	0.0105	1.242	13.5	0.0861	0.740
N_e	20.183	76.6	0.0512	0.246	21.2	0.0280	0.668
N_2	28.016	55.1	0.0713	0.249	12.0	0.0151	0.713
O_2	32.000	48.25	0.0812	0.220	13.9	0.0155	0.709
Water Vapor	18.016	85.81	0.0373	0.445	6.6	0.0103	1.03

Table 6-14

Properties of Candidate Systems for Space-Cabin Atmospheres 80°F (540°R)

(After Johnson(114))

Atmosphere	Molecular weight, m	k, Btu/ft-hr-°R	ρ, lb/ft³	C_p, Btu/lb-°R	μ, lb/ft-hr	d, ft²/sec (steam) $\times 10^{-3}$	α, ft²/sec $\times 10^{-3}$	N_{Le}, α/d	N_{Pr}, $C_p\mu/k$
14.7-psia air	29	0.0151	0.076	0.24	0.0421	0.264	0.238	0.902	0.67
5-psia O_2	32	.0154	.0283	.222	.0500	.756	.707	.935	.72
5-psia O_2-N_2	31	.0153	.0268	.23	.0465	.756	.707	.935	.70
5-psia O_2-He	24	.0267	.0198	.278	.0520	.862	1.355	1.572	.54
7-psia O_2-N_2	30	.0152	.0362	.23	.0470	.540	.500	.926	.71
7-psia O_2-He	18	.0304	.023	.33	.0512	.705	1.512	2.15	.496

In the determination of comfort zones, heat exchange via conduction ill be considered negligible and provided for in heat exchange via convection nd/or radiation. Conductive heat exchange, however, is significant in deermining garment temperature; assessing the impact of heat shorts and hot r cold surfaces coming in contact with the bare skin; and in analyzing the ffectiveness of conduction concepts for thermal regulation. Accordingly, ata and equations for calculating conductive heat exchange are included elow (Equations 39, 40, 41, Figure 6-56, Tables 6-58, 6-64 and 6-65).

In the comfort state, a man at rest will have a mean skin temperature f 91.4 ± 1.8°F (33 ± 1°C) and a rectal temperature of 98.6 ± 0.9°F 37 ± 0.5°C). There will be no visible sweating and the blood vessels near he surface of the skin will be slightly dilated (36). Any subsequent variation n metabolism or environmental conditions will initiate a change in peripheral lood flow (vascular regulation) of the body (See Figure 6-3).

At nominal ambient temperatures, with light work loads, rectal temperaure will be maintained constant at some level above resting value determined y metabolic rate; while skin temperature, respiration rate and, in certain nstances, perspiration rate will be varied by regulatory systems of the body o attain thermal balance under the new conditions. Raising the temperature f the environment or increasing metabolic rate by activity or ingestion of food will result in vasodilatation to increase the heat exchange between the core and skin (See Figure 6-3). Sweating or shivering usually occur before the limits of vascular regulation are reached and, in so doing, serve to reduce the load on the vascular system. Experiments indicate that at the limits of vasoregulation, the vasomotor system is capable of exerting a stabilizing effect on rectal and skin temperatures for a finite period (226). The period of stabilization is reduced as the severity of thermal stress is increased.

Radiant Heat Exchange

The analysis of net radiant heat exchange between an astronaut and his surroundings is complicated by the following factors:

a. Ability of the crew to move around and change position.

b. Arrangement and surface temperature of the various equipment enclosures.

c. Localized differences in temperature of the cabin walls due to structural anomalies resulting from variations in thickness, feed-through equipment (e.g., sextant, antennas, etc.) exposed to the space environment, and size and location of windows.

The net radiant exchange of energy between two ideal radiators is

$$q_r = f_r \sigma (T_w^4 - T_s^4) \qquad (9)$$

(Stefan-Boltzman) constant)

σ = 0.173×10^{-8} BTU/ft^2 hr $^\circ$R

σ = 4.92×10^{-8} kcal/m^2 hr $^\circ$K

f_r = radiation area factor

T_w, T_s = mean black-body temperature of walls, and body surface, respectively.

Radiant conductance h_r can be determined directly from Figure 6-15 when the black body temperature of the walls is known. The black body temperature of the skin can be assumed as 92.5°F or 32.5°C. In order to account for variable emissivities and geometric considerations of the human body and environment - a shape-emissivity factor (F_{ae}) and radiation area factor (f_r) must be introduced.

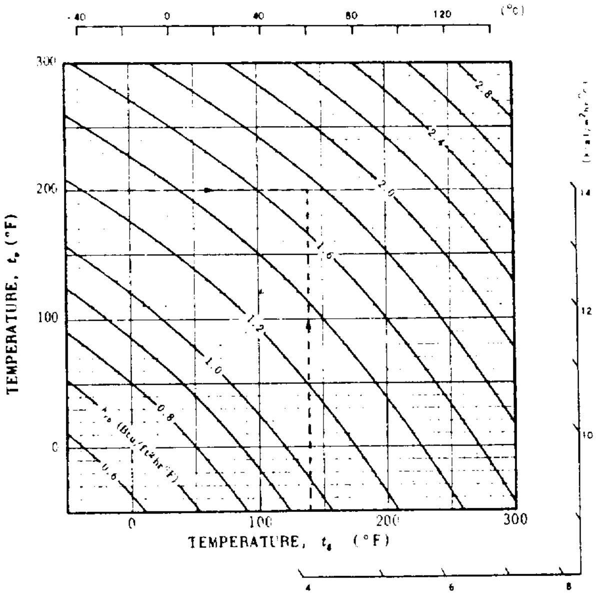


Figure 6-15

Unit Black Body Radiant Conductance

The radiant conduction between black body surfaces of temperature t_w and t_s, is displayed according to the equation:

$$h_{rb} = \sigma(T_w^2 + T_s^2)(T_w + T_s)$$

The average black body temperature of the skin is approximately 92.5°F or 32.5°C.

(After Blockley et al$^{(27)}$)

Assuming that source and sink are gray bodies, the following equation which includes the effect of geometric configuration, can be used.

$$F_{ae} = \frac{1}{\frac{1}{F_{12}} + (\frac{1}{\epsilon_1} - 1) + \frac{A_b}{A_s}(\frac{1}{\epsilon_2} - 1)} \qquad (10)$$

where F_{12} = shape modulus or configuration factor

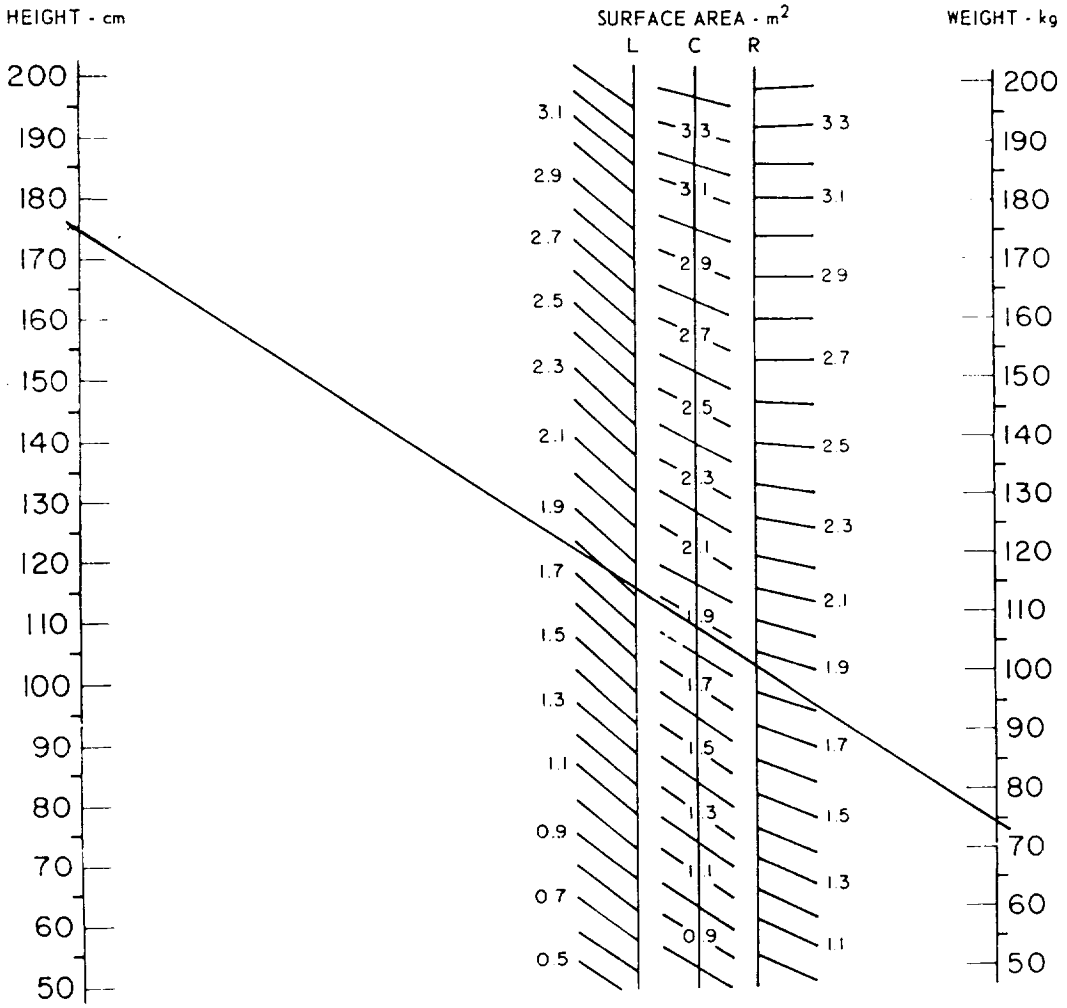
ϵ_1 = emissivity of clothing and skin of astronaut's body

ϵ_2 = emissivity of surroundings (walls, equipment, other astronauts)

A_b = surface area of body - $ft^2 (m^2)$ (Refer Figure 6-16)

A_s = surface area of surroundings - $ft^2 (m^2)$

The shape modulus (F_{12}) is 1 for the case of radiation exchange between a completely enclosed body and its enclosure.



Example: To find the surface area of a U.S. Air Force male of mean height and weight (175.5 cm, 74.4 kg), a straight line is drawn between the two appropriate points on the H and W scales. The slope of the line most nearly approximates the slope of the C-scale bar. The surface area of such an individual is approximately 1.9 m^2.

Figure 6-16

A Nomograph for the Determination of Human Body Surface from Height and Weight, Based on Data from 252 Subjects.

(Adapted from Sendroy and Collison(180) by Webb(212))

The emissivity of human skin in the infrared range is approximately 0.99. The emissivity of clothing and skin (ϵ_1) at body temperature if not known is assumed to be the generally used value, 0.95.

The emissivity of surroundings (ϵ_2) will depend on the proportion of high and low emission surfaces subtended by the body. The range of emissivities will vary from 0.2 (for oxidized aluminum) through 0.9 (for transparent plastics and oil painted surfaces) to 0.95 for an adjacent crew member - also in shirt sleeves.

The radiation area factor (f_r) is required to account for radiation exchange between portions of body.

$$f_r = \frac{A_r}{A_b} \quad (= 0.75 \text{ for sitting man in an average-sized cockpit}) \qquad (11)$$

where A_r = equivalent radiating area of the human body (Figures 6-17 and 6-18)

A_b = total surface area of the body (Figure 6-16)

Then: $$q_r = F_{ae} f_r \sigma \; (T_w^4 - T_s^4) \qquad (12)$$

In terms of unit thermal conductances:

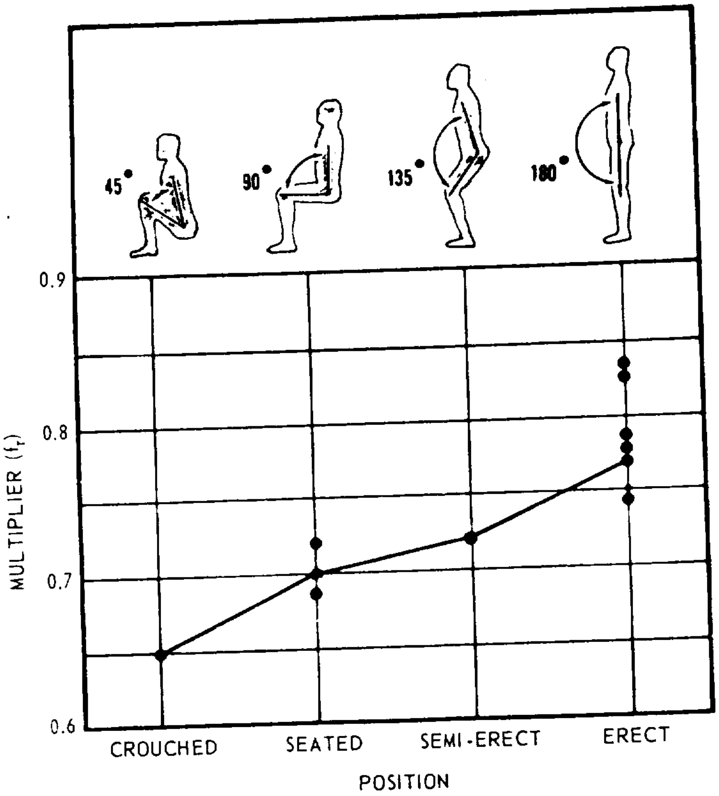
$$q_r = h_r (t_w - t_s) \qquad \text{BTU/ft}^2 \text{ hr (kcal/m}^2 \text{ hr)} \qquad (13)$$

and $$h_r = \frac{\sigma F_{ae} f_r (T_w^4 - T_s^4)}{t_w - t_s} \qquad \text{BTU/ft}^2 \text{ hr } ^\circ\text{F (kcal/m}^2 \text{ hr } ^\circ\text{C)} \qquad (14)$$

In addition to determining the mean radiant temperature of the surroundings, it is important to locate the external sources and sinks of radiation exchange. A man located between warm and cold surfaces at a neutral atmospheric temperature and apparently comfortable may experience pain and stiffness in the muscles exposed to the cold surface after a prolonged period of time, especially after sleep.

Absorption of radiant energy by the gaseous atmosphere need not be considered in the heat exchange analysis for the following reasons:

1. Gases with symmetrical molecules (e.g., oxygen, nitrogen) do not show absorption or emission bands in the infrared region at the temperatures of interest.



Since the total radiation area of the body varies with position, the diagram shows what multiplier (f_r) to use with total body surface area for each of four common positions. For the nude body the following steps are involved:

(1) Find the total surface area (S. A.) by:

$$\text{S. A. (in ft}^2\text{)} = 0.108\, W^{0.425} \times H^{0.725}$$

where W is weight in pounds and H is height in inches; or

$$\text{S. A. (in m}^2\text{)} = 0.007184\, W^{0.425} \times H^{0.725}$$

where W is weight in kg and H is height in cm

(or use the nomogram, Figure 6-16)

(2) Then, to find the total radiation area (A_r) for a given position,

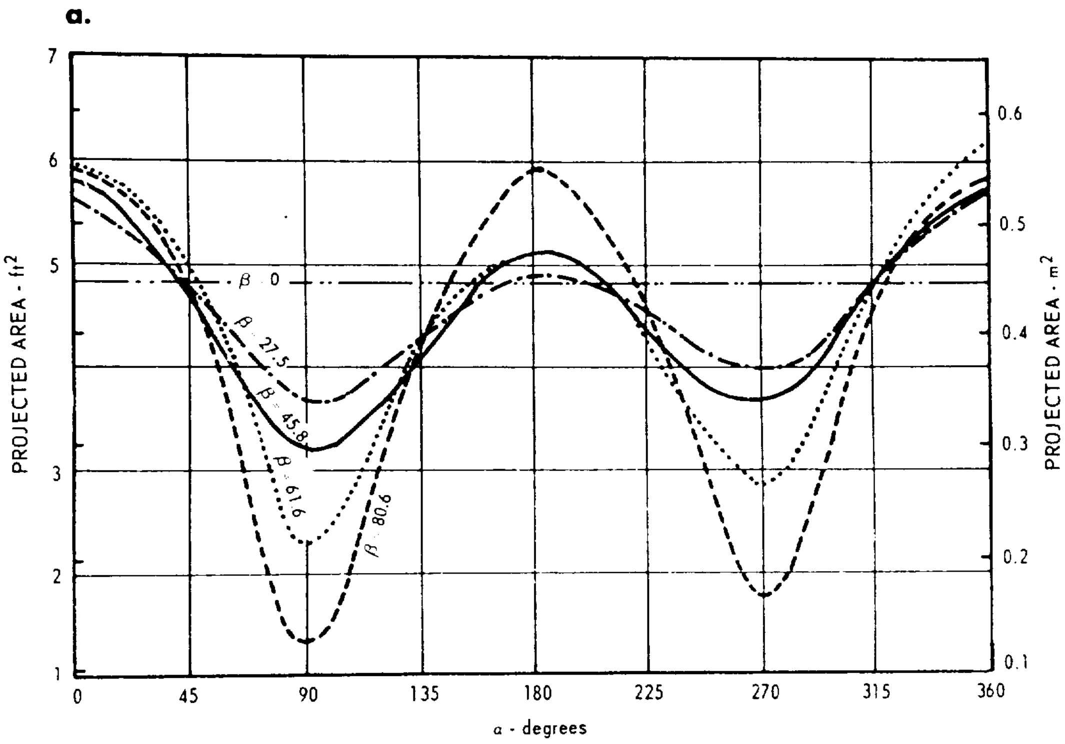
$$A_r = \text{S. A.} \times f_r.$$

A_r is increased by clothing, but each assembly will add its own increment. A standard set of light street clothing increases A_r by 1.14

Figure 6-17

Total Radiation Area

(Adapted from Guibert and Taylor(92))



Projected areas of the body varying with the angle of view, as shown in the figure at the right. Note that the projected areas apply only to the one position of the body shown. The subject shown is medium-sized (67.8", 159 lb), and lightly clothed in loose-fitting shirt, trousers, socks and low shoes.

Examples of projected surface areas read from the chart:

Given α = 202.5° and β = 45.8°, the projected surface area is 5.00 ft2;

Given α = 90° and β = 80.6°, the projected surface area is 1.33 ft^2.

Similar data are presented (Figure 6-17) for a nude figure in the erect, semi-erect, seated and crouched positions.

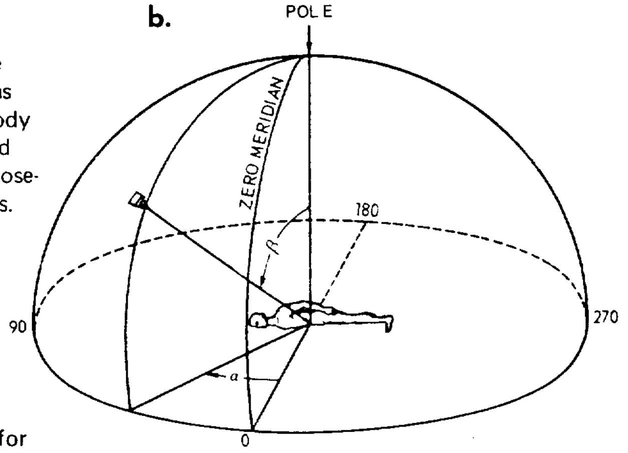


Figure 6-18

Projected Surface Areas

(Adapted from Guibert and Taylor(92))

2. The heteropolar gases (such as sulfur dioxide, carbon monoxide, carbon dioxide and water vapor) while having absorption bands in the area of interest will not normally exist in sufficient concentrations in the cabin atmosphere to affect the radiation exchange.

Solar radiation (q_{sr}) and all other external heat fluxes, and all internal heat fluxes from internal equipment and other astronauts are considered to be completely described by wall temperature (t_w).

By assuming a small crewman of 15.6 sq ft body surface area with a uniform clothing surface temperature and an enclosure of greater than 100 sq ft per man, i.e., f_{gs} = area factor of garment = ϵ_g, a simplified radiation cooling equation can be written:

$$q_r = 2.65 \times 10^{-8} \; \epsilon_g \; (T_g^{\;4} - T_w^{\;4}) \qquad (15)$$

A sample graph, assuming $\epsilon_g = 0.9$ is seen in Figure 6-19 where the radiation heat loss to any given environmental temperature is given for several clothing surface temperatures (155). Figure 6-20a represents the radiation heat transfer coefficients (h_r) for different combinations of environmental and clothing temperature desired from the simplified form of equation (15). Figure 6-20b gives h_r for a more severe radiative environment which may be encountered in emergency conditions.

Forced Convective Heat Transfer

The correlation between convective heat transfer processes and mass transfer processes has been used by many investigators to develop analytic models for forced convection heat exchange in man. In the recent analysis of Berenson (19), the following assumptions were made:

1. All sensible heat passes through the clothing by conduction and the clothing heat transfer area is equal to the skin surface area. Since sensible heat loss occurs from non-clothed skin and since the clothing surface may be up to 40% greater than skin surface, these assumptions are conservative. It must be remembered, however, that even though the area increases, the air pockets which are formed act as thermal and mass transfer resistances. Zero gravity will tend to increase resistance by eliminating convection currents in the pockets.

2. The relationship between garment surface temperature (t_g) and skin temperature (t_s) can be determined by the equation:

$$t_g = t_s - \frac{L}{k}\left(\frac{q_c + q_r}{A}\right) \qquad (16)$$

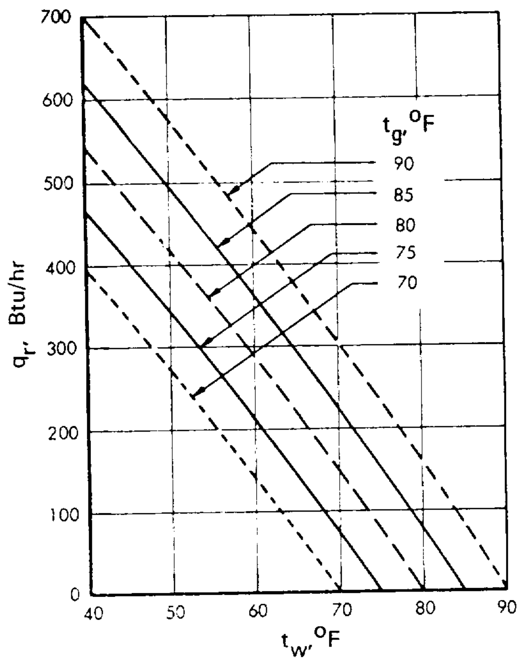


Figure 6-19

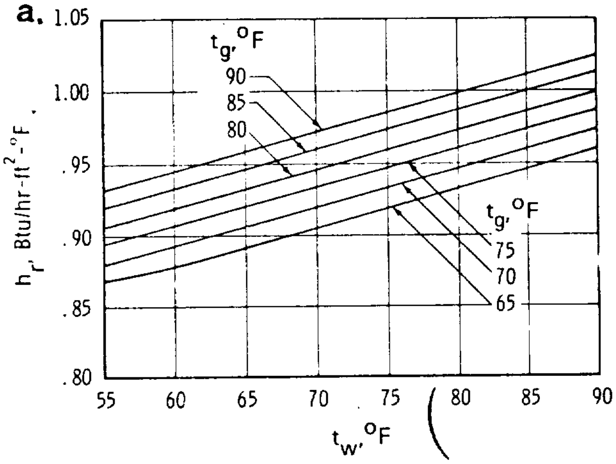
Radiative Heat Loss from Man to His Surroundings

(After Parker et al[155])

Figure 6-20

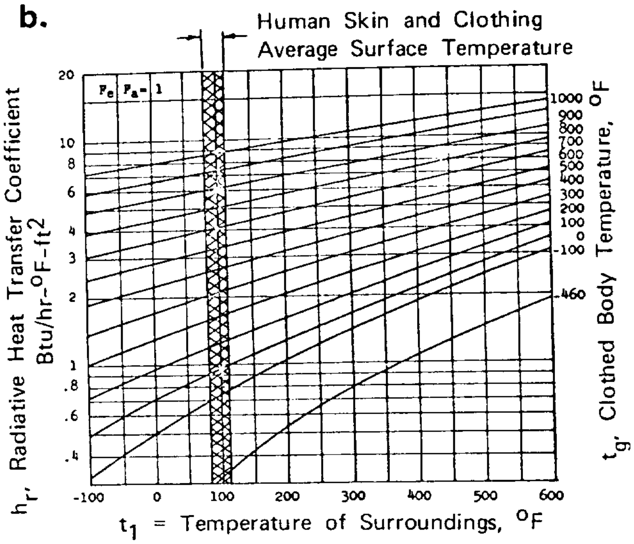
Radiative Heat Transfer Coefficients

Figure a. represents a narrow band of temperatures in Figure b.



Notes:

1. $h_r = \epsilon\sigma\left(\frac{T_g^4 - T_w^4}{T_g - T_w}\right)$
2. $\epsilon = 0.9$
3. T_g = Clothing Temperature
4. T_w = Environment Temperature



(After Parker et al[155])

(After Breeze[36])

The value of L/k is the useful function of clothing heat transfer resistance, Clo, where 1 Clo = .88°F - ft^2 - hr/BTU.(See Tables 6-46 and 6-64).

The rate of heat transfer by convection can be written:

$$q_c = h_c A \; (t_g - t_a) \qquad (17)$$

The convective-heat-transfer coefficient is actually a complicated function of fluid flow, thermal properties of the fluid, and the geometry of the body. The value of h_c for convective exchange about the whole human body is a critical coefficient quite sensitive to second-order conditions such as fluid-flow patterns, posture, etc. Unfortunately, there has been some variance between the values used by several different groups in relating the h_c of man to the atmospheric gas velocity. Selection of the appropriate film coefficient or actual heat transfer coefficient is a difficult problem (122). A discussion of the implication of different coefficients used in analysis of forced convection about the human body has been recently published (115).

The early data suggest that for clothed humans sitting in a turbulent air flow the following equation may be used (232):

$$h_c = .153 \; \overline{V}^{\,0.5} \left(\frac{\rho}{\rho \mathrm{STD}} \right)^{0.5} \qquad (18)$$

This equation is not too different from that derived for rough flat plates (154).

$$h_c = 1.03 \; k \left(\frac{\rho \overline{V}}{\mu} \right)^{0.5} \qquad (18a)$$

Figure 6-21 represents a summary of several approaches to forced convective heat transfer coefficients (convective film coefficients) for man in an environment containing air at 1/2 atmosphere. The first three curves represent the h_c values obtained from data on empirical studies of humans (94, 149, 224). These are compared with four theoretical curves: (1) a cylinder in longitudinal flow, (2) a cylinder ten inches in diameter in cross-flow, (3) a flat plate with flow perpendicular to it, (4) a cylindrical model of man in cross-flow (Figure 6-22). The value of h_c for the cylindrical model of man corresponds closely with those obtained by Nelson (149) and are equivalent to h_c for cross-flow about cylinders five inches in diameter. The specific equation used for the flat plate model in this graph was not stated but appears to differ from the flat plate equation noted above (154) which gives results closer to those of the equation of Winslow et al (224).

For the human body in a semi-reclining position and one atmosphere pressure, loss by convection is proportional to the square root of air velocity for velocities up to 250 cm/sec (493 ft/min).

Figures 6-23 and 6-24 can be used to determine from mass flow rates the unit convective conductance for air (27). Dimensional analysis indicates that pure oxygen at the same absolute pressure as air provides about 0.9 the convective cooling.

Figure 6-25 shows the effect of gas velocity on the convective heat transfer coefficient based on the cylindrical model of man for various helium-oxygen and nitrogen-oxygen atmospheres. The partial pressure of oxygen at 170 mm Hg is near the sea level equivalent and is held constant with the diluent gas ranging from 0 to 400 mm Hg. These curves were generated by taking the heat transfer coefficient as proportional to the various fluid properties as follows:

$$h_c \sim k\,(Pr)^{0.33}\,(Re)^{0.5} \sim k\,(Pr)^{0.33}\left(\frac{\rho \overline{V}}{\mu}\right)^{0.5} \qquad (19)$$

The values for neon mixtures will lie between those for helium and nitrogen. It is clear from comparing physical properties of the gases that for different mixtures of oxygen-nitrogen there is little sensitivity of h_c to percent composition of gas (Table 6-13).

The following equation, derived from the heat mass-transfer analog (70) for Prandtl numbers of 0.6 to 15 and Reynolds numbers of 10 to 10^5, approximates the forced convection cooling rate for all gas mixtures (18, 21).

$$q_c = 0.407\,k_c\,\sqrt{P\overline{V}}\,(t_g - t_a) \qquad (20)$$

where P = psia, $\overline{V}$ = ft/min, and t_g, t_a = °F and

k_c = a factor that depends on the transport properties of the gas mixture. For dry air, $k_c = 1$. For $O_2 - N_2$ mixtures $k_c = 1$; for other gases,

$$k_c = \frac{k_{mix}}{k_{air}}\left(\frac{M_{mix}}{M_{air}} \times \frac{\mu_{air}}{\mu_{mix}}\right)^{0.5}\left(\frac{Pr_{mix}}{Pr_{air}}\right)^{0.33} \qquad (21)$$

For the 70-percent oxygen atmosphere in helium at 5 psia,

$$k_c = \frac{7.37}{4.14}\left(\frac{23.6}{29.0} \times \frac{12.10}{13.49}\right)^{0.5}\left(\frac{0.503}{0.710}\right)^{0.33} = 1.356$$

For the 50-percent oxygen atmosphere in helium at 7 psia,

$$k_c = \frac{10.38}{4.14}\left(\frac{18}{29} \times \frac{12.10}{13.47}\right)^{0.5}\left(\frac{0.437}{0.170}\right)^{0.33} = 1.594$$

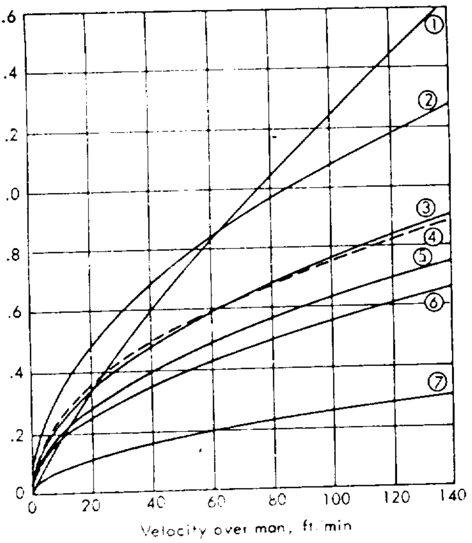


Figure 6-21

Comparison of Forced Convection Film Coefficients for Standing Man at 1/2 Atmosphere of Air.

(1) Hall(94)

(2) Winslow, Gagge and Herrington(224)

(3) Nelson et al(149)

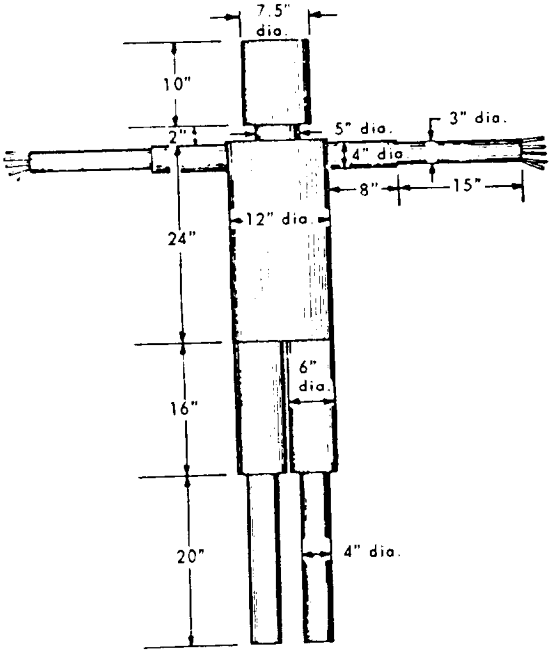
(4) Cylindrical Model of Man in Cross-Flow (Analytical)

(5) Flat Plate (Hamilton Standard Curve)

(6) 10" Dia. Cylinder in Cross-Flow

(7) Longitudinal Flow

(After Parker et al(155))



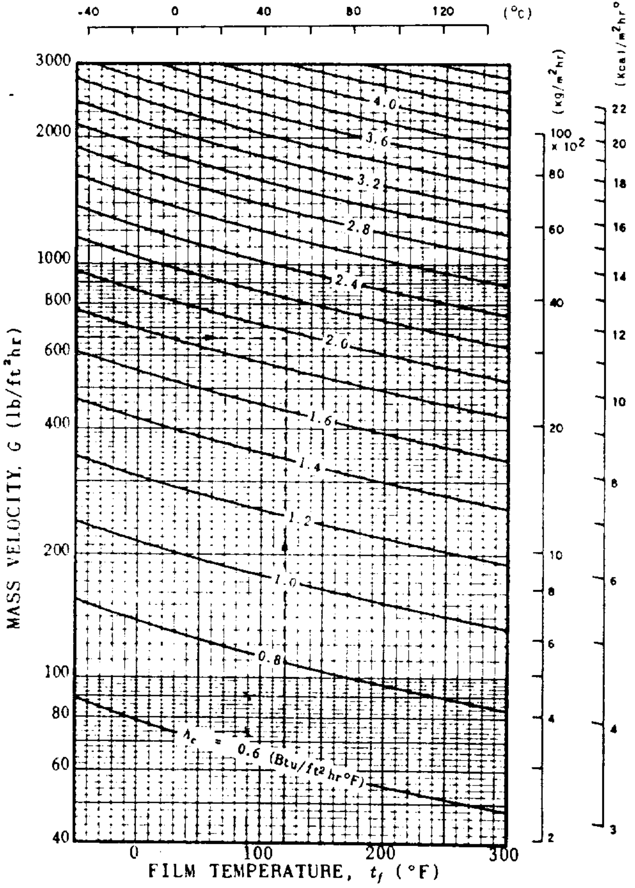
Part	Area, ft² (a)
Head	1.95
Neck	.22
Trunk	6.18
Upper legs	4.19
Lower legs	3.49
Upper arms	1.40
Lower arms	1.96
Fingers	b .67
Total	20.06

[a] 19.5 ft² used to include some factor of safety.
[b] Each finger: 3½ inch long by ⅞ inch diameter.

Figure 6-22

Cylindrical Model of Man

(After Parker et al(155))



The convective conductance is given in terms of mass velocity and average film temperature according to the equation:

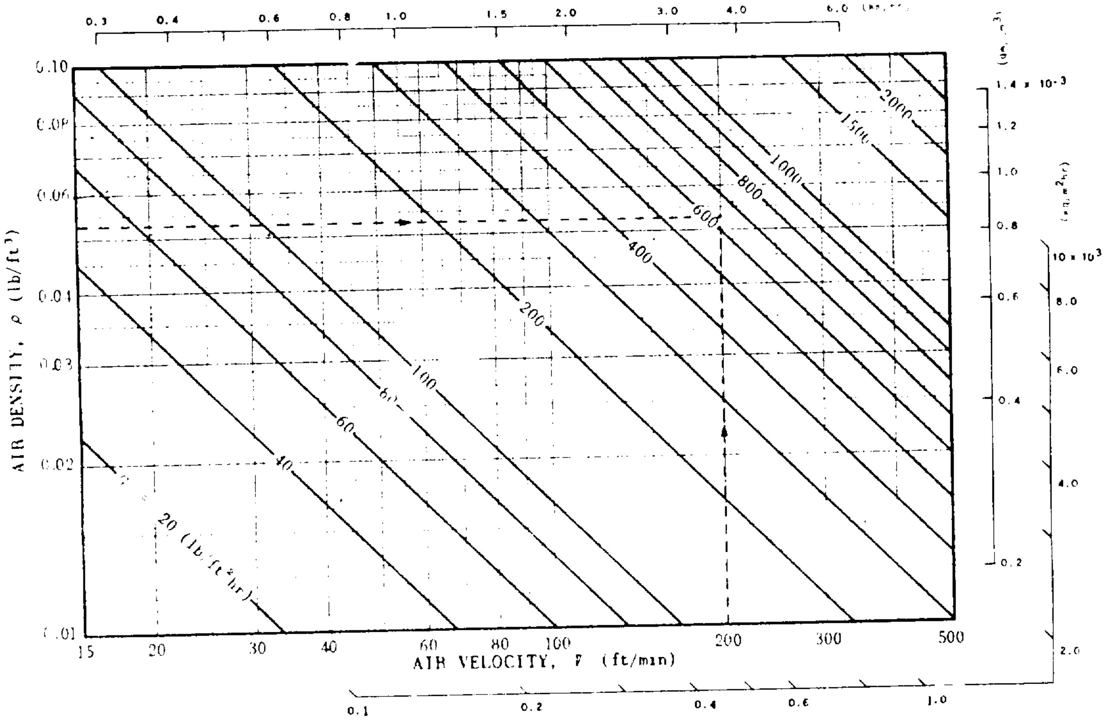
$$h_c = 0.0735\,(T_f/T_o)^{.5}\,G^{.5}$$

where: $T_o = 536^{\circ}R$ and $T_f = \dfrac{T_g + T_a}{2}$

Figure 6-23

Unit Convective Conductance in Air

(After Blockley et al(27))



The mass velocity is shown as a function of air density and air velocity according to the equation: G = 607 p.

Figure 6-24

Mass Velocity

(After Blockley et al$^{(27)}$)

Figure 6-25

Heat Transfer Coefficients of Man Standing in O_2-He and O_2-N_2 at Different Gas Velocities

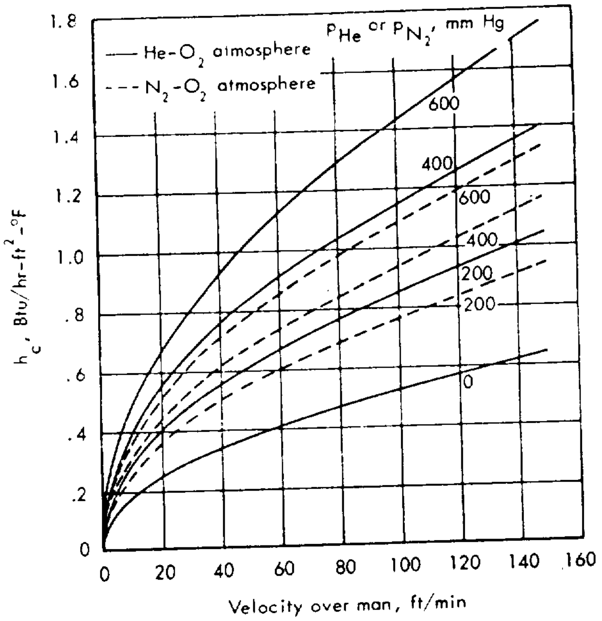
(1) 170 mm Hg of O_2

(2) pHe = Partial Pressure (mm Hg) of He in Atmosphere.

(3) pN_2 = Partial Pressure (mm Hg) of N_2 in Atmosphere.

(4) Based on Cylindrical Model of Man

(After Parker et al$^{(155)}$)



Free Convective Heat Transfer

In the presence of a gravitational field such as on the Earth, planetary surfaces or rotating space stations, free convection is possible and is the preferred mode of cooling because no additional energy need be expended. One can combine the general free-convection equations with the assumptions regarding clothing effects to yield an equation for free-convective cooling of all nitrogen-oxygen mixtures (19, 20).

$$q_c = 1.17 \left[P^2 g (t_g - t_a)\right]^{0.25} (t_g - t_a)^{1.25} \qquad (22)$$

where P = psia, t_g, t_a = °F

The handling of mixed free and forced convection environments can be simplified by the McAdams rule, i.e., both the free and forced convective heat transfer coefficients are calculated and the higher of the two values is used (132). The critical crossover point of the forced convection velocity (V_{crit}) where the forced convection heat transfer coefficient is equal to the free convection coefficient can be calculated for oxygen-nitrogen mixtures by equating equations 20 and 22 and solving for $\overline{V}$.

Evaporative Heat Transfer (q_e)

The evaporative heat exchange mode (q_e) is limited in this section to sensible and insensible perspiration from the surface of the body. Water loss via respiration is covered under Respiratory Heat Loss.

Low mixing efficiency of ventilating gas and forced convection (i.e., lack of free convection in the weightless state) requires consideration of perspiration rates, sweating thresholds and the order of recruitment of various regions of the body. Stagnant pockets or low ventilations rates in areas of the crew compartment and/or space suits may reduce the effectiveness of evaporative cooling by a significant amount. Because the sweat rate is regulated by the cooling needs of the body, failure to provide sufficient evaporative cooling after initial recruitment of certain regional areas will necessitate recruitment of additional areas in order to bring the biothermal system into equilibrium. Mixing efficiencies not greater than 60% have been realized in gas-cooled space suit assemblies.

Insensible water loss is a continuing non-adaptive process and results in loss of body heat under virtually all environmental conditions of interest in space flight. The irreducible insensible water loss from skin and lungs is 0.6 g/kg (body weight)/hr. The lower limit for insensible water loss from the skin alone at one atmosphere and low temperature, t_a = 68°F (20°C), is approximately 10 gms/m^{2}hr. At air temperatures above 68°F the rate of insensible water loss increases linearly to a value of about 25 gms/m^{2}hr at t_a = 78.8°F (26°C). Below the sweating threshold about 40% of the moisture loss is from the palm, sole of the foot, and head (about 13% of the total body rface). At an operative temperature of 87.8°F (31°C) with air temperatures tween 79-93°F (26-34°C), there is a curvilinear increase in water loss as gional areas of the body begin to sweat. The progression of recruitment generally from the extremities toward the central regions of the body and adward and is subject to effects of training. In this temperature range at st the onset of sweating for all regions of the body appears at rates of -60 gm/m^2hr. Above an air temperature of 93°F (34°C) the increment in eat rate is again linear-increasing at the rate of 18-24 gm/m^2hr °C in ell trained subjects at rest. With full sweating the trunk and lower limbs ovide 70-80% of the total moisture perspired (104).

Tables 6-26, 6-27, and 6-28 summarize the order of recruitment, mean gional evaporative rates, and regional fractions of total evaporation spectively in a still air environment with subject at rest.

Figure 6-29 is a diagrammatic summation of insensible and sensible ater loss from regional areas of the body at rest in air at sea level with oling requirements (16, 116, 154).

The maximum attainable perspiration rate of the human body is in the rea of 1.8 liters/hr at rest and 3.9 liters per hour during exercise which ould provide an evaporative cooling rate of 572 $kcal/m^2/hr$ to 1530 kcal/ ^{2}/hr respectively. At these rates, however, even with adequate consump- on of water and electrolytes, the sweating mechanism "fatigues" in 6-8 ours and perspiration rates decrease significantly. This fatigue is a func- on of skin wetness. The maximum effective perspiration rate which can be ustained is extremely variable depending on the individual and his degree of cclimatization.

Evaporative heat loss is a function of volume flow rate, absolute umidity, temperature, and pressure of the atmosphere.

The expression for evaporative heat loss is:

$$q_e = W_e \lambda_e \quad \text{BTU/ft}^2\text{ hr kcal/m}^2\text{ hr)} \qquad (23)$$

where W_e = weight of water evaporated (gms/lb)

λ_e = latent heat of vaporization - 1800 BTU/lb (.582 kcal/gm)

nder standard conditions. The weight of water evaporated (W_e) is a function f vapor diffusivity, the vapor concentration difference between the body (skin) surface and the atmosphere, and the thickness of the boundary layer

$$W_e = \frac{D_v \Delta C}{R_t'} \qquad (24)$$

Table 6-26
Recruitment of Sweating
(After Randall and Hertzman[164])

AREA	USUAL (BUT NOT INVARIABLE) ORDER OF RECRUITMENT
Dorsum foot	1
Lateral calf	2
Medial calf	3
Lateral thigh	4
Medial thigh	5
Abdomen	6
Dorsum hand	7 or 8
Chest	8 or 7
Ulnar forearm	9
Radial forearm	10
Medial arm	11
Lateral arm	12

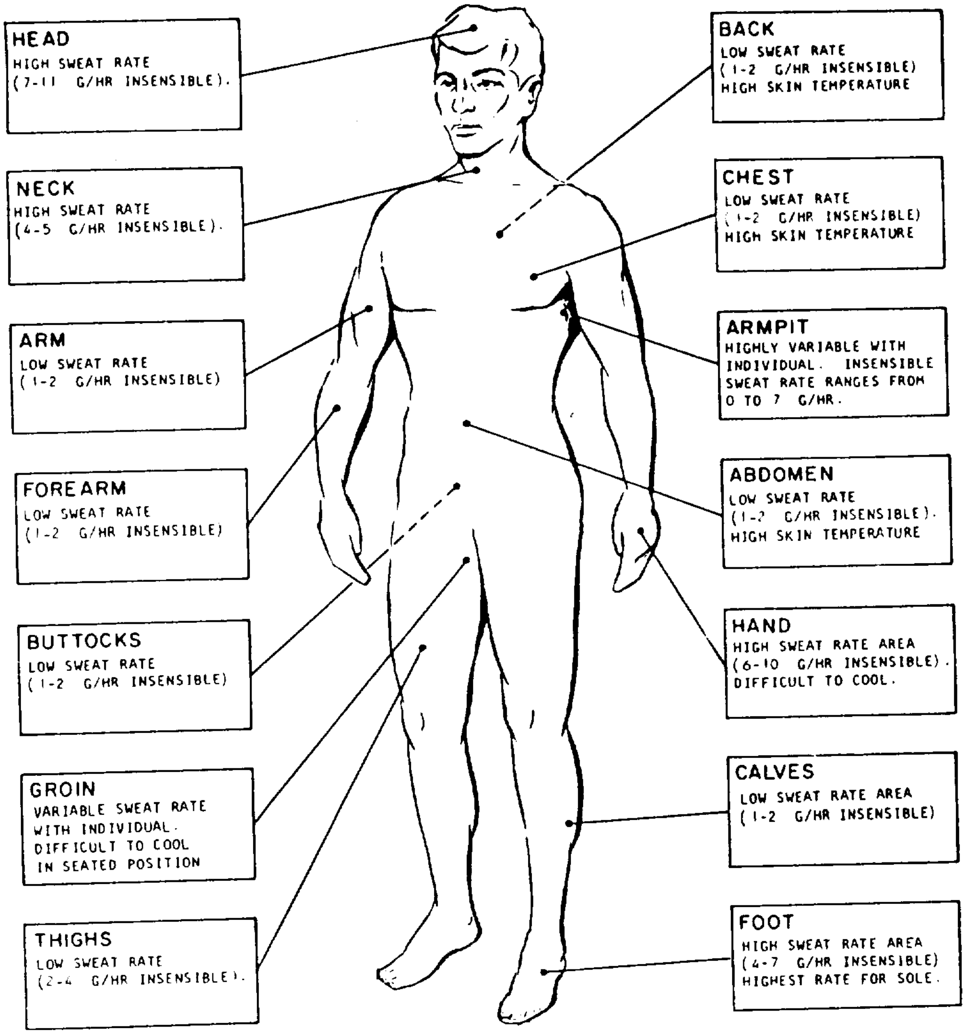
Table 6-27
Increments in Mean Regional Evaporative Rates with Rise in Environmental Temperature

REGION	EVAPORATIVE RATE			INCREMENT IN EVAPORATIVE RATE	
	T_A 29°C.	34°C.	38°C.	29-34°C.	34-38°C.
	gm/m^2/hr.			gm/m^2/hr/°C.	
Calf	18.0	86.5	169.0	13.7	20.4
Thigh	14.4	58.7	144.0	8.0	21.3
Abdomen	12.0	60.0	156.0	9.6	24.0
Chest	9.6	37.2	120.0	5.5	20.7
Forearm	12.0	21.6	96.0	1.9	18.6
Arm	10.8	14.4	65.0	0.7	13.0
Cheek	24.0	36.0	108.0	2.4	18.0
Forehead	24.0	60.0	240.0	7.2	45.0

Table 6-28
Regional Fractions of Total Cutaneous Evaporation Expressed as Percentage of Total

REGION	AIR TEMPERATURE							
	24°C.	26°C.	28°C.	30°C.	32°C.	34°C.	36°C.	37°C.
Head	11.8	12.1	11.9	9.7	8.0	7.0	8.5	8.4
Arm	4.6	4.4	4.2	3.4	2.6	2.2	3.1	3.3
Forearm	8.2	7.2	6.0	4.3	3.2	3.1	4.4	4.3
Trunk	22.8	23.0	22.2	22.2	30.0	33.0	43.0	38.2
Thigh	13.6	13.1	17.1	20.2	22.6	23.8	25.5	22.3
Calf	8.5	9.0	11.9	16.0	20.3	22.8	24.1	19.8
Palm	15.6	15.3	13.1	9.6	6.8	4.6	3.5	2.5
Sole	14.7	15.1	13.5	9.9	6.4	3.7	2.3	1.5

(Tables 6-27 and 6-28 After Hertzman et al[104])



Region	Preferred temperature (°F)	Heat loss Btu/hr	Area Ft^2	Skin conductance $Btu/ft^2/hr/°F$
Head	94.4	15.9	2.15	1.61
Chest	94.4	32.6	1.83	3.87
Abdomen	94.4	17.9	1.29	3.02
Back	94.4	49.3	2.48	4.31
Buttocks	94.4	33.0	1.94	3.70
Thighs	91.4	47.7	3.55	1.76
Calves	87.5	58.0	2.15	2.35
Feet	83.5	39.7	1.29	1.98
Arms	91.4	33.4	1.07	4.10
Forearms	87.5	34.2	0.86	3.45
Hands	83.5	63.5	0.75	5.45

Figure 6-29

Regional Cooling Requirements of the Human Body in Air at Sea Level at Rest

(After Berenson(21) from the Data of Kerslake(116)) where D_v = vapor diffusivity - ft^2/hr (cm^2/sec)

ΔC = concentration difference - lb/ft^3 (gm/cm^3)

R_t' = thickness of still air layer ft (cm)

The nature of clothing will determine the R_t' factor. This is covered in greater detail in the section on space suits and clothing (see Equation 37 and Tables 6-44 and 6-45).

For air and water vapor under standard conditions (refer to Figure 6-30),

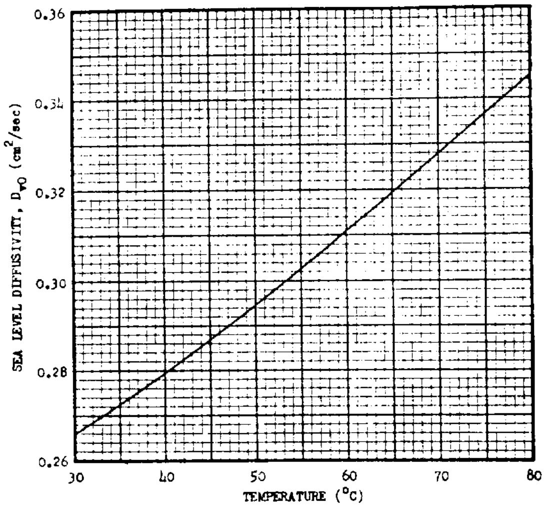


Figure 6-30

Diffusivity of Water Vapor in Air for Standard Sea Level Pressure.

(After Blockley et al(27))

diffusivity,
$$D_v = 0.85\left(\frac{T}{T}\right)^{1.75} \frac{P_o}{P}\ ft^2/hr. \qquad (25)$$

$$D_v = 0.220\left(\frac{T}{T_o}\right)^{1.75} \frac{P_o}{P}\ cm^2/sec \qquad (26)$$

where 0.85 = diffusivity of air and water vapor at standard conditions ft^2/hr (cm^2/sec)

T_o, T = temperature in °R for standard and ambient conditions respectively = 536°R (273°K)

P_o, P = pressure in lbs/ft^2 for standard and ambient conditions respectively.

The diffusivity of oxygen and water vapor under standard conditions is:

$$D_v = 0.81\left(\frac{T}{T}\right)^{1.75} \frac{P_o}{P}\ ft^2/hr \qquad (27)$$

where the terms have the same definitions as covered above.

The concentration difference is related to the amount of water vapor contained in the atmosphere and at the boundary of the skin (153). It is expressed: (Refer to Figures 6-31 and 6-32).

$$\Delta C = 0.825\left(\frac{P_1}{T_1} - \frac{P_2}{T_2}\right) \text{lb/ft}^3 \qquad (28)$$

$$\Delta C = 2.89 \times 10^{-4}\left(\frac{P_1}{T_1} - \frac{P_2}{T_2}\right) \text{gm/cc} \qquad (29)$$

where P_1, P_2 = represent partial pressures of water at the two boundaries respectively in Hg (mm Hg)

T_1, T_2 = temperatures at the two boundaries ^{o}R (^{o}K).

To determine the diffusivity of other air atmospheres the following expression can be used:

$$D_{v_1} = D_{v_2} \frac{\rho_2}{\rho_1} \qquad (30)$$

where D_{v_1}, D_{v_2} = diffusivity of the respective atmospheres ft^2/hr (cm^2/sec)

ρ_1, ρ_2 = density of the respective atmospheres lb/ft^3 (kg/m^3)

The concentration difference (ΔC) is:

$\Delta C = C_1 - C_2$

where $C = \frac{1}{V}$ and V = specific volume ft^3/lb (cc/gm)

$$C = \frac{T_o}{P_o V_o} \cdot \frac{P}{T} \qquad (31)$$

where T_o, T = are temperature in ^{o}R (^{o}K) at standard and ambient conditions respectively

P_o, P = are pressure in Hg (mm Hg) at standard and ambient conditions respectively

V_o = volume in ft^3/lb (cc/gm) at standard conditions

The necessity for specifying (and controlling) absolute humidity rather than relative humidity for biothermal control is carefully spelled out (85, 215).

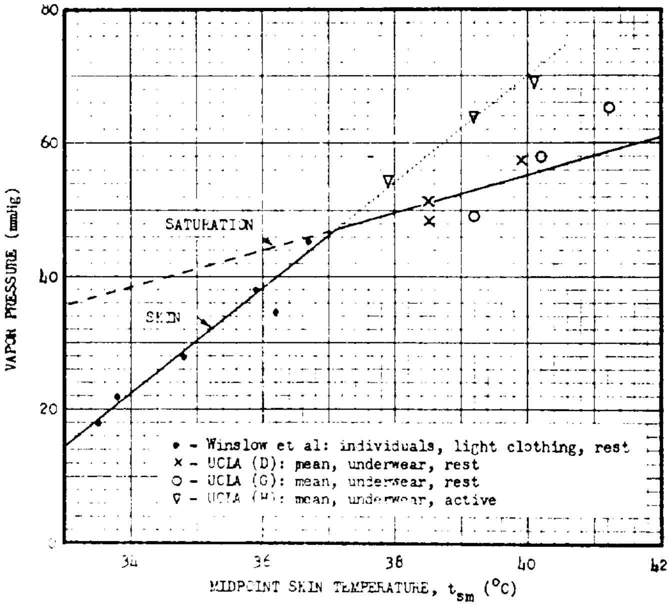


Figure 6-31

Skin Vapor Pressure Prediction Chart for Reference Conditions (P_a = 20 mmHg).

The solid line is recommended for general prediction purposes. Note that this line follows the saturation curve beyond 37°C, ignoring the possible beneficial effects of wicking associated with activity. The dotted line of relationship is probably valid only in special lightly-clothed conditions where evaporation takes place at the surface of wet clothing.

(After Blockley et al[27])

Figure 6-32

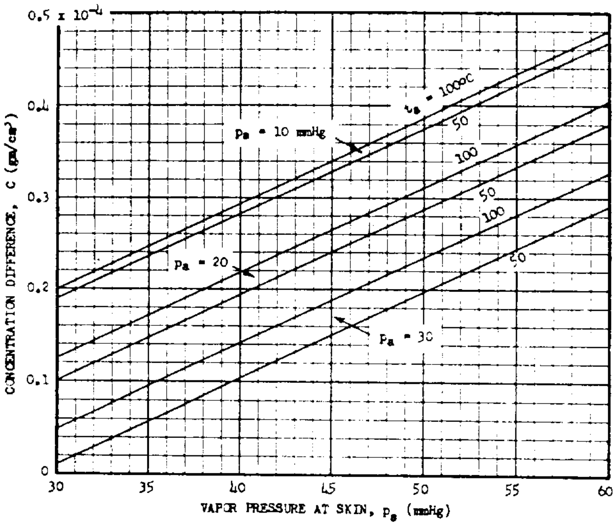
Vapor Concentration Difference for Various Ambient Temperatures and Humidities.

The basic equation is:

$$\Delta C = 2.89 \times 10^{-4} \left(\frac{P_s}{t_s} - \frac{P_a}{t_a} \right);$$

A constant value of 37.5°C has been assumed for t_s in this chart making it applicable only for heat stress situations.

(After Blockley et al[27])



The absolute humidity is dependent on the molecular constitution of the gas and this factor must be accounted for in evaporative heat exchange (174). A recent review of water vapor control in space conditions is available (159).

When thermoregulation is completely successful, humidity, as a parameter in evaporative thermal control, is a significant determinant in the fractional area of the skin over which sweating occurs. The wettedness area (ω) varies from 0.1 for comfort conditions (essentially insensible water loss only) to 1.0 for full sweating. Table 6-33 represents the expected comfort level relative to the percent of maximum capacity being used. This concept is quite simplified and may not hold for all values of total sweat output work and atmospheric conditions (27, 115, 183, 215).

It is likely that the body does not become fully wetted with sweat until the sweat rate is about twice the maximum evaporative capacity. Loss of sweat by dripping probably begins when the sweat rate is about 1/3 of the maximum evaporative capacity (115). These figures refer to linear winds only. In turbulent air movements, dripping would be expected to start at relatively higher sweat rates and full wetness be reached at relatively lower ones. It can be assumed that a skin temperature of 36°C marks the onset of the wet skin condition where the zone of evaporative cooling terminates.

Table 6-33

Percent of Maximum Evaporative Capacity	Comfort Level
0 - 10	Cold
10 - 25	Comfortable
25 - 70	Tolerable
70 - 100	Hot
Over 100	Dangerous

The first 10% or so of maximum capability represents basal insensible loss from respiration and diffusion. These losses are, of course, a function of the metabolic output and respiratory rate (vide infra).

The water loss from the nude skin under different atmospheric conditions can be expressed (196):

$$E_r = K_e W \ (P_s^* - P_a) \qquad (32)$$

where E_r = evaporative water loss ($gm/m^2 hr$)

K_e = vapor conductance from skin to air ($gm/m^2 hr$ mm Hg)

P_s^* = saturated water vapor pressure at t_s (mm Hg)

P_a = absolute humidity or water vapor pressure (mm Hg)

W = wetted fraction of skin surface

The value of vapor conductance of body skin in air for the erect man is a function of the convective air movement and pressure by the equation (57, 149, 196, 224):

$$K_e = C\overline{V}^n \ (P_o/P)^n \qquad (32a)$$

where C and n are empirical constants of 0.45 and 0.63 respectively

$\overline{V}$ = air velocity in km/hr

P, P_o = barometric pressure at altitude and standard sea level (mm Hg)

The perturbing effect of body position and geometry on the constants of these equations cannot be overemphasized. The effect of clothing is also an important factor in determining evaporation rates (27). The vapor conductance from skin to air (R_e) must be modified to include vapor resistance of clothing. This factor is covered in the Section on space suits and clothing. (See Equation 24, 37 and Tables 6-45a and 6-45b.)

Respiratory Heat Loss

Heat loss via respiration varies directly with metabolic rate and is influenced by atmospheric composition (including carbon dioxide and water vapor content) and pressure. Because the respiratory tract is a very efficient saturator of inspired air, heat gain to the body via respiration will not occur until atmospheric temperature approximates 185°F (85°C) (136).

Heat loss via respiration, and insensible water loss from the skin, has been grossly estimated to be equivalent to 25% of the metabolic rate (123). Heat loss from the lungs approximates 10% of the metabolic rate (7-8 kcal/hr) in the neutral zone (97). Definitive data for determining respiratory heat loss for the atmospheric compositions and pressures of interest in space flight environments, especially those of the space suit, are available (39, 136, 214, 215, 232). (See also Figure 6-69.)

After determining the pulmonary ventilation rates corresponding to a specific activity level and stress factors such as hypoxia, hypercapnia, anxiety, etc., the heat loss via respiration can be calculated by determining the sensible heat required to raise the inspired atmosphere to expiration temperature and adding the heat of vaporization increment for the moisture lost to the inspired air from the respiratory tract.

One expression for calculating Respiratory Heat Loss is (232):

$$q_v = V \rho C_p (t_e - t_i) + 0.58 (W_e - W_i) \text{ (Cal/hr)} \qquad (33)$$

where V = volume of atmosphere breathed per hour (liters/hr)

ρ = density of the atmosphere (gms/liter)

C_p = specific heat of atmosphere (kcal/Kg °C)

t_e = temperature-expired atmosphere (°C)

t_i = temperature-inspired atmosphere (°C)

0.58 = heat of vaporization H_2O (kcal/gm)

W_e = weight of water in expired atmosphere (gms)

W_i = weight of water in inspired atmosphere (gms)

A more simplified approach is also available (136).

First-Order Estimate of Evaporative Heat Loss in Space Cabins

For the purpose of determining comfort zones and performing tradeoff analyses of space-cabin atmospheres and thermal control systems, a first-order estimate of evaporative heat loss is often required. Many of the concepts presented in Equations 6-23 to 6-33 can be lumped together as a first approximation of evaporative heat loss. The subject and the cabin must therefore be idealized with such factors as body position and clothing neglected. In view of the very light and loose garment assemblies proposed for shirt sleeve operation (Clo values of 0.25 (163), the total intrinsic vapor resistance will probably be low enough to be neglected for this first-order approximation.

The metabolic rate can be estimated for any given level of activity and the difference between the metabolic and sensible heat loss is the required evaporative cooling rate. A simplified equation for latent or evaporative cooling rates neglecting clothing factors (vide supra) can be derived from the heat-mass transfer analogy of Eckert (70) and Equation 19.

A mass-transfer coefficient (h_D) can be defined as

$$\left(\frac{dm}{dt}\right)_{H_2O} = - DA\left(\frac{\partial p}{\partial x}\right)_s = h_D\, A(p_s - p_a)_{H_2O} \qquad (34a)$$

Evaporative heat loss,

$$q_e = h_D\, \lambda_e\, AC'\left(\frac{p_s - p_a}{Rt_s}\right) \qquad (34b)$$

where h_D = mass transfer coefficient (ft/hr) and $C' = \frac{E_r}{E_m}$

R = gas constant (ft lbs/lb ^{o}R)

x = path length

Since the heat-transfer properties of nitrogen-oxygen mixtures are independent of the fraction of each component, the above equation can be reduced for all oxygen-nitrogen mixtures in a forced convection environment to yield (21).

$$q_e = 2.46\ C't_a\left(\frac{\overline{V}}{P}\right)^{0.5}(p_s - p_a) \qquad (35)$$

It should be pointed out that this equation assumes the exponent of $\overline{V}$ to be 0.5. It can be seen from Equation (32a) that an exponent of 0.63 would probably be a more realistic value for this exponent (57). In view of the other assumptions made regarding clothing and body position, the error introduced by this simplification does not present too great an error. In fact, the values of evaporative loss under conditions of C' = 1 give predicted results only 10% higher than actually measured (57, 174, 215). Since the rate of evaporation and the diffusion coefficient for water vapor are inversely proportional to pressure, it is clear that the latent cooling will increase with decreased (total) pressure (196). Curves illustrating the general magnitude of the predicted pressure, dewpoint, and gas-stream velocity effects at $t_a = 80^\circ F$ and $t_s = 95^\circ F$ are seen in Figure 6-34. These calculated maximum q_e values may be slightly high (174, 215). In the temperature range under consideration for space cabins, the temperature and the dewpoint have relatively little effect as compared to gas stream velocity and ambient pressure.

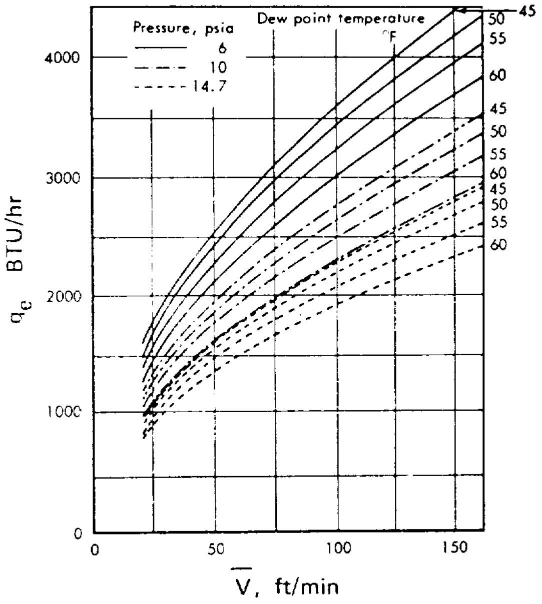


Figure 6-34

Maximum Evaporation Rate at Rest in Oxygen-Nitrogen Mixtures

$$q_e = 2.46\, t_a \sqrt{\bar{V}/P}\, (p_s - p_a)\, H_2O$$

$t_s = 95^\circ F$; $t_a = 80^\circ F$.

(After Berenson[19])

For first-order estimates assuming free convection in nitrogen-oxygen mixtures, thermal equations have been developed by combining equations for free convection, transport properties of air, and evaporative cooling to yield (19):

$$q_e = 25.7 \frac{C't_a}{P} (p_s - p_a) \left\{ Pg \left(.005\, P (t_g - t_a) + 1.02 (p_s - p_a) \right) \right\}^{0.25} \qquad (36)$$

Under forced convection, the following equation holds for nitrogen-oxygen: (18, 20)

$$q_e = 1.98\, C't_a^{\;1.036}\, k_e \left(\frac{\bar{V}}{P}\right) (p_s - p_a)_{H_2O} \qquad (36a)$$

where k_e = a factor that depends upon the diffusivity of water vapor in the gas mixture and on the transport properties of the gas mixture itself. For dry air, $k_e = 1$. For other gases,

$$k_e = (k_D)^{0.67} \left(\frac{M_{mix}}{M_{air}} \times \frac{\mu_{air}}{\mu_{mix}} \right)^{0.17} \qquad (36b)$$

The diffusion coefficient for water in helium is 3.5 times that for water in air (166). For the case where the water is diffusing into a mixture of helium and oxygen, diffusivity relative to air is found from

$$k_D = \frac{1}{\frac{\text{MOL FRACT. He}}{3.5} + \frac{\text{MOL FRACT. } O_2}{1}} \qquad (36c)$$

For the 70-percent oxygen atmosphere in helium at 5 psia,

$$k_D = \frac{1}{\frac{0.298}{3.5} + \frac{0.702}{1}} = 1.271$$

For the 50-percent oxygen atmosphere in helium at 7 psia,

$$k_D = 1.554$$

Therefore, the k_e values can be calculated for the oxygen-helium atmosphere containing 70-percent oxygen,

$$k_e = (1.271)^{0.67} \left(\frac{23.6}{29.0} \times \frac{12.10}{13.49} \right)^{0.17} = 1.113$$

and for the oxygen-helium atmosphere containing 50-percent oxygen,

$$k_e = (1.554)^{0.67} \left(\frac{18}{29} \times \frac{12.10}{13.47} \right)^{0.17} = 1.219$$

Again, it should be emphasized that Equations 34 to 36 are only first-order estimates of the evaporative heat loss.

Comfort Zone Predictions in Unusual Gaseous Environments

In view of the dearth of empirical data on comfort zones in the mixed gas environments, several attempts have been made to predict these values. Figures 6-35, 36 and 37 represent sample predictions of one approach, combining the Equations 15, 20, 22, and 36, to estimate the comfort zone in oxygen-nitrogen mixtures under several different assumptions regarding forced vs. free convection, Clo values, etc. (21). Comfort was estimated from the ratio of predicted to maximum evaporative capacity, C' using the criteria of Table 6-33. For subjects at rest with little clothing, this comfort criterion may not be too fanciful (121, 224). Recent unpublished data from

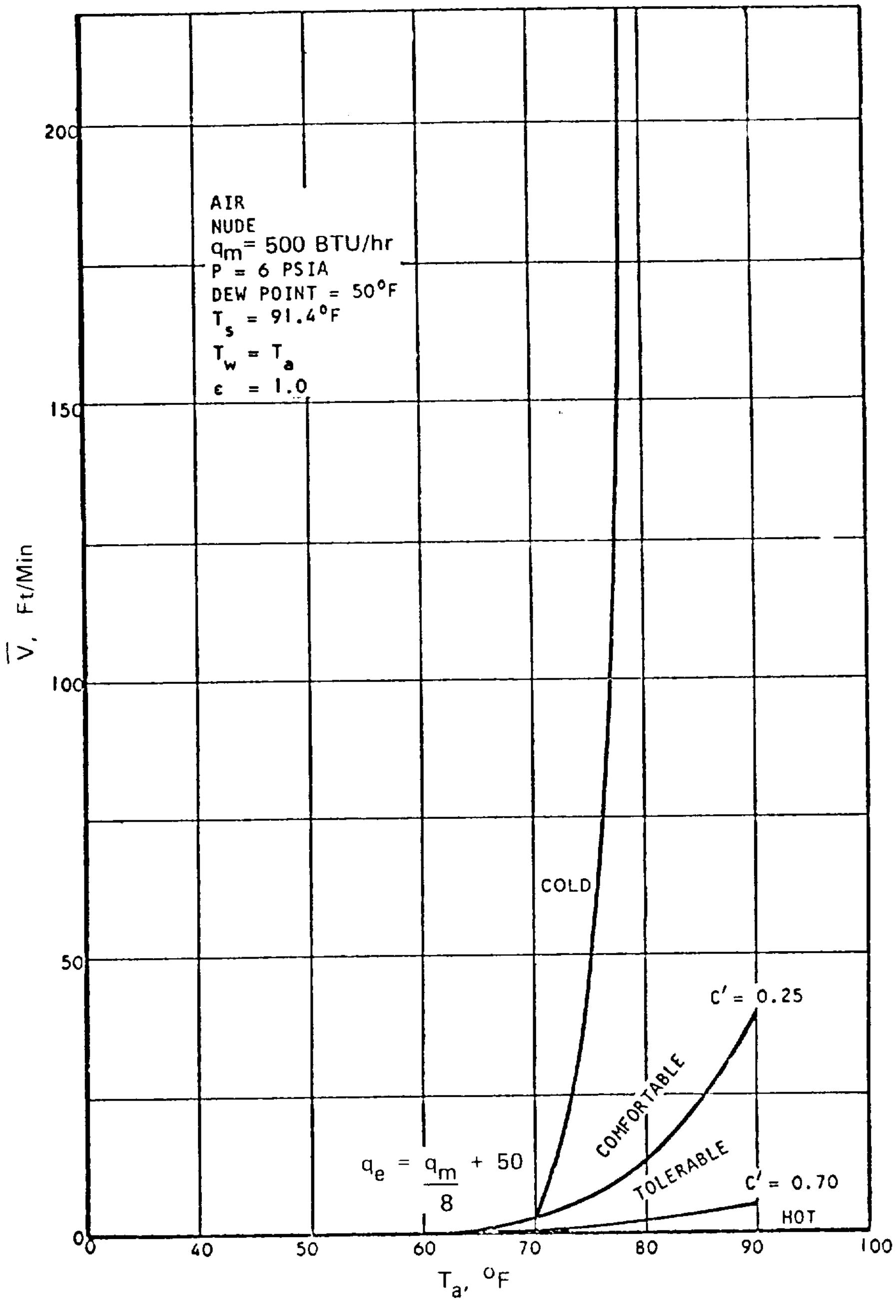


Figure 6-35

Forced-Convection Comfort Zones During Mild Exercise with 1/2 Clo. (Modified from Berenson(21))

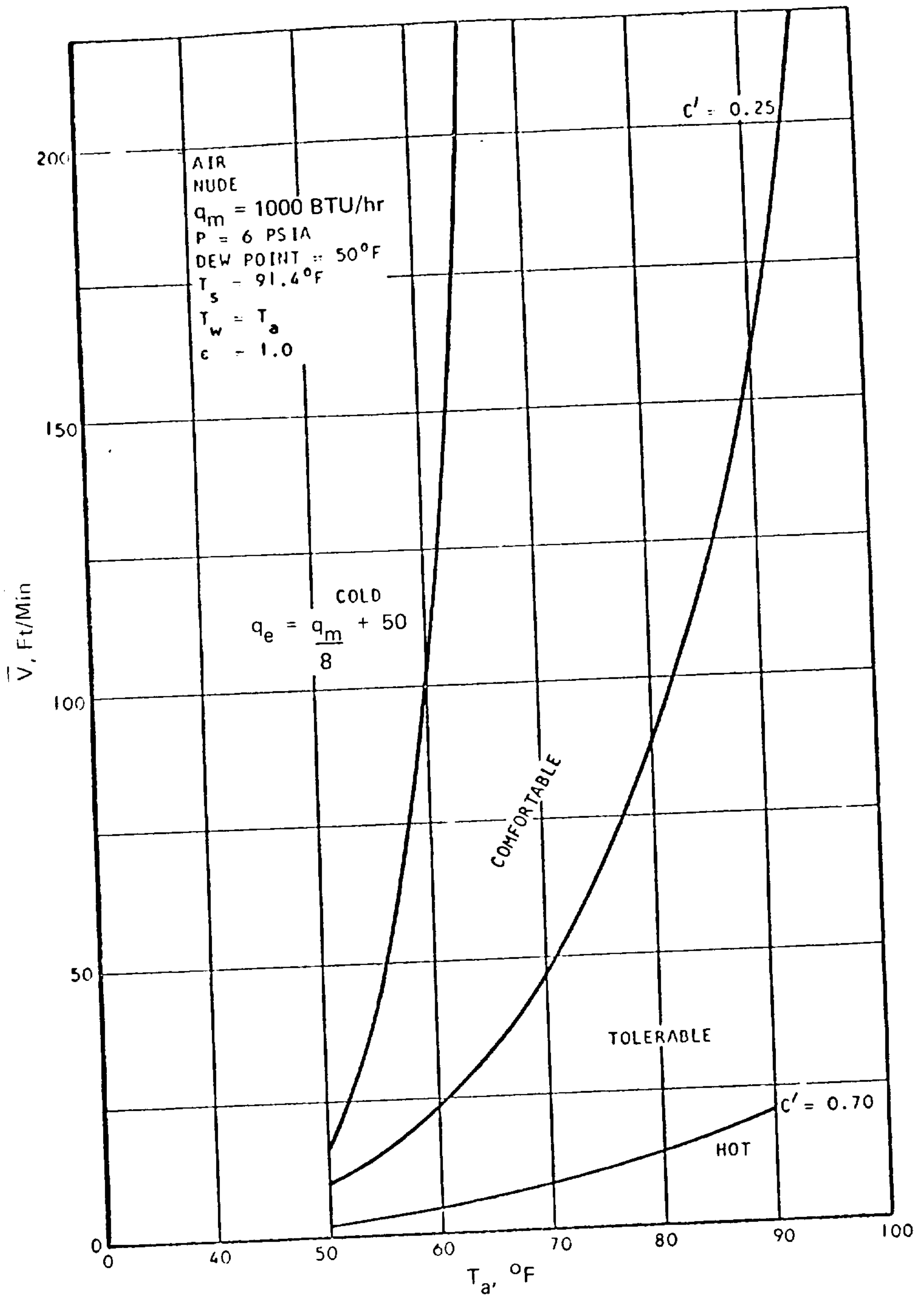


Figure 6-36

Forced-Convection Comfort Zones at Moderate Exercise in the Nude (Modified from Berenson[21])

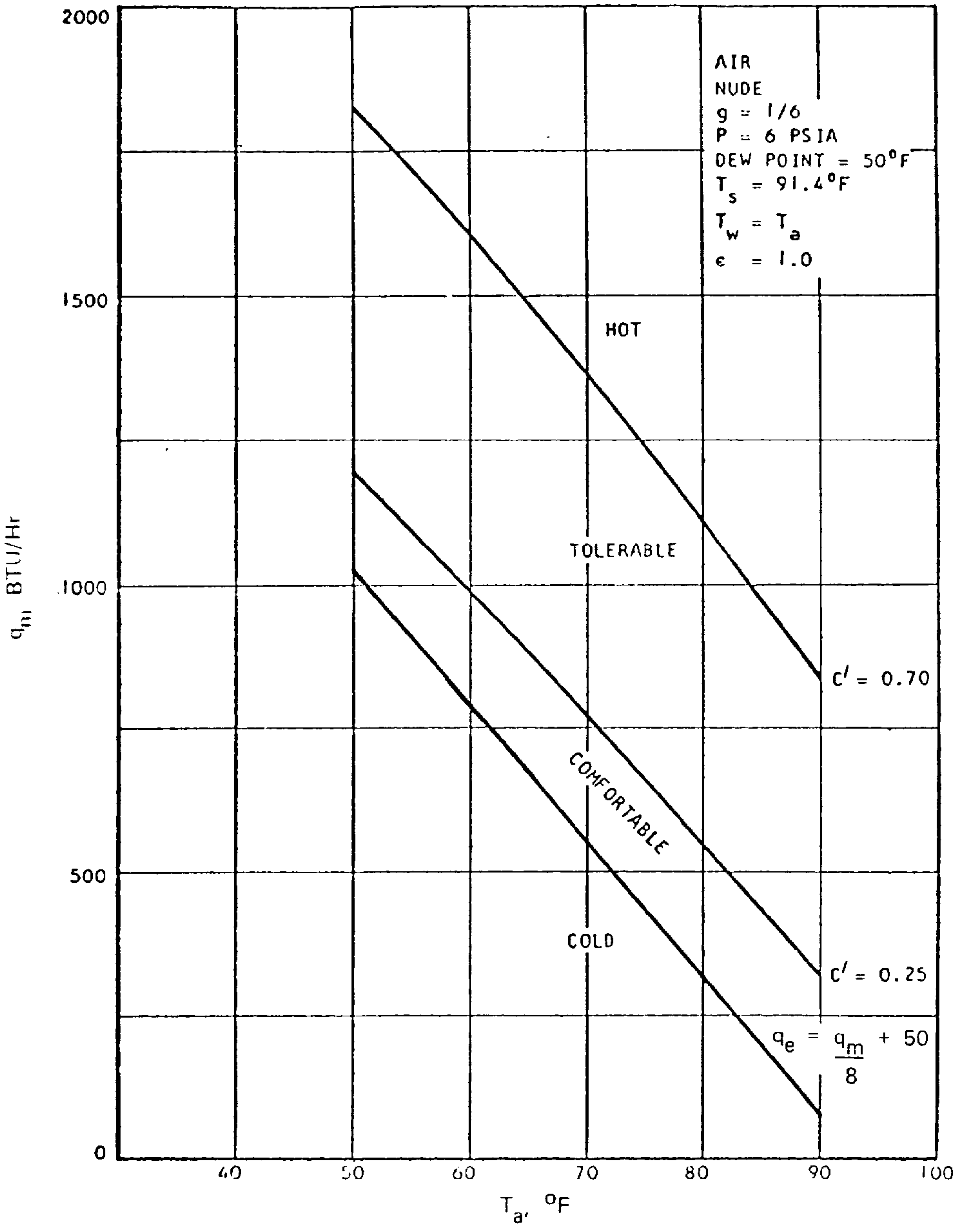


Figure 6-37

Lunar Free-Convection Comfort Zones as Related to Exercise Rate in the Nude (Modified from Berenson(21)) e NASA Manned Spacecraft Center, Houston, suggest that the minimum tent heat loss by evaporation, $q_{e\ min}$ is given by the following equation:

$$q_{e\ min} = 0.125\ q_m + 50\ (\mathrm{BTU/hr})$$

his fact alters previous approaches to setting the cold-comfort boundary sing C' = 0.1 as a criterion (19). The 6 psia pressure is a midpoint of the -7 psia range under consideration in the U. S. Space Program (174).

The assumption of a constant skin temperature of 91.4°F and a nude ondition represent the most significant errors in these predictive curves. skin temperature of 90°F should probably be used to evaluate the lower oundary of the comfortable zone, while values of 93° and 95°F should be sed to evaluate the boundaries at 25 and 70 percent of maximum evaporative apacity, respectively. This would have the effect of broadening both the omfortable and tolerable zones. Until it has been shown that using a uniform kin temperature leads to a significant error in the results, there is little istification for analyzing the body as a number of separate regions for these redictive curves (20).

The assumption that the mean radiation temperature of the walls and quipment is approximately equal to the atmospheric gas temperature is very seful for general parametric studies, but may be in error. It is necessary n many cases to perform a more rigorous radiation heat-transfer analysis fter the enclosure geometry and temperature distribution have been estab-ished in some detail (18). The effect of clothing was greatly simplified; the eat-transfer resistance of the clothing was assumed to be uniform over the ntire body, and the heat-transfer area and the evaporative-cooling capacity vas assumed to be unaffected by the presence of clothing. It is difficult to mprove on these assumptions, because of the lack of detailed information ertaining to clothing heat-transfer resistance and area. These assumptions, nherent in Equations 15, 20, 22, and 36 and in Figures 6-35, 6-36, and -37, will be modified in future calculations of this type (18). Unfortunately, here are few empirical data to substantiate these curves. Preliminary studies tend to corroborate some of these predictions for different O_2 - N_2 environments (31, 179, 219).

Comfort zone predictions for an oxygen environment at 5 psia with clothing assemblies varying in thermal resistance from 1/4 to 1 Clo have been established by the U.S. Air Force as shown in Figure 6-38 (114). However, the equations and assumptions used in the generation of this figure have not yet been published. The predictions of Figures 6-35 to 6-38 cannot be used for systems other than pure oxygen or oxygen-nitrogen.

For cabins with oxygen-helium mixtures, other heat flow constants must be used to determine comfort zones. (See Equations 21, 36b and 36c.) In order to avoid the movement of papers at one atmosphere in 1-G environments in air, a velocity of 50-60 fpm is stated as the tolerable upper limit of velocity above the 40-50 fpm draft threshold. Since the force of a gas stream is proportional to ρV^2, a table of constant force thresholds equivalent

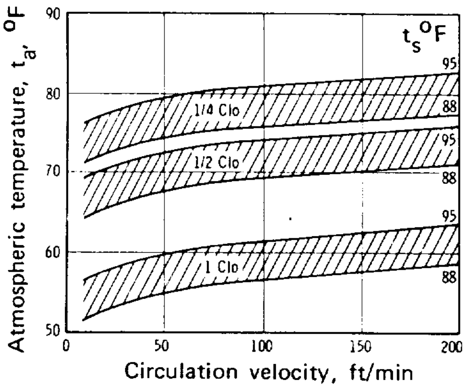


Figure 6-38

Human Comfort Chart at Rest
5.0 psia O_2 (Theoretical)

p_{O_2} = 243 mm Hg
p_{H_2O} = 10 mm Hg
p_{CO_2} = 5 mm Hg

(After Johnson(114))

to 50-60 fpm in air can be calculated. Table 6-39 represents this maximum-force velocity along with the corresponding ambient temperature t_a (°F) required for maintenance of thermal comfort as measured by average skin temperatures t_s, at 91° and 94°F (116). Fig. 6-40 was used for t_a values.

Predictions of thermal comfort zones of Figure 6-40 a to d for different gas velocities of varied mixtures of oxygen-helium and oxygen-nitrogen in zero g have been made assuming the following conditions:

1. $t_a = t_w$ (Air Temperature = Environment Temperature = Wall Temperature
2. No body heat storage
3. P_{O_2} = 170 mm Hg, in all cases and P_{N_2} or P_{He} increasing from 200 up to 600 mm Hg
4. Zero gravity environment
5. Evaporative heat loss is the same as it is at 1 atmosphere and 1 "g"

Table 6-39

Maximum Velocity over Man

(After Parker et al(155))

p_{He} mm Hg	p_{N_2} mm Hg	Maximum velocity over man, ft/min	t_a, °F, required for –	
			t_s = 91° F	t_s = 94° F
0	0	100 to 120	56.5 to 58.5	66 to 67.5
200	0	94 to 113	65 to 66.5	72 to 73
400	0	88 to 106	68 to 69	74.4 to 75.5
600	0	84 to 100	70 to 71	76.5 to 77.5
0	200	71 to 86	61.5 to 63	69 to 70
0	400	57 to 69	63.5 to 65	70 to 71.5
0	600	50 to 60	64.5 to 65.5	71 to 72

Note: p_{O_2} = 170 mm Hg ; maximum velocity for avoiding movement of papers in 1-G; 1 Clo at rest.

6. Convective heat loss is for cylindrical model of man with $A_g = 19.5$ ft^2 in cross-flow (as in Figure 6-22)

7. Metabolic heat generation is for a man seated at rest (400 BTU/hr at 70°F).

8. t_s = skin temperature in the 91°F range

9. Clo = 1, $\varepsilon_2 = 0.9$

10. $A_r = 15.6$ ft and $A_r/A_g = 0.8$

11. Partition of heat loss is similar to that seen in Figure 6-3.

12. The clothing temperature, t_g, is related to atmospheric temperature, t_a, by the relation

$$t_g = t_a + \frac{1.137\ (t_s - t_a)}{(0.8\ h_r + h_o)\mathrm{Clo} + 1.137}$$

13. The relation of h_r to t_g is the same as that noted in Figure 6-20: $t_w = t_a$

Equations 34, 35, and 36 predict that the rate of evaporation is inversely elated to the ambient pressure. However, evaporation probably accounts or less than one-third of the total heat loss at the temperatures in question. The assumption (Figure 6-8) of 1 atmosphere pressure does not present too great an error. In the presence of adequate forced convection, the gravitaional factor in Equation 35 would play a minimal role in evaporative heat oss and can be neglected in the solution of comfort zone temperatures. The /4th power factor in this equation would in itself reduce the overall weighting of gravity effect.

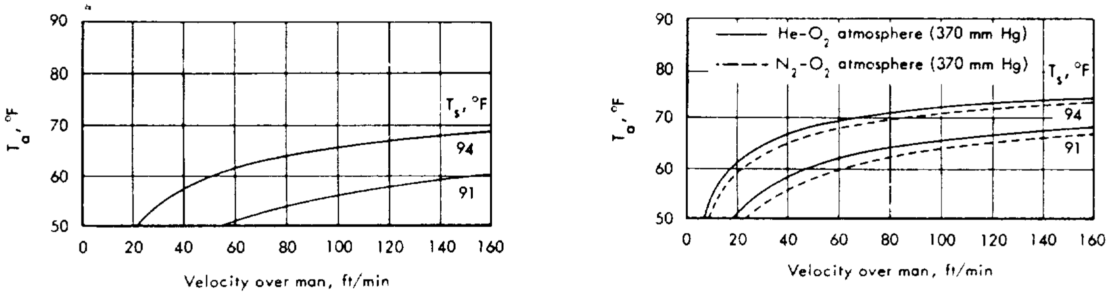
In Figures 6-40a, b, c, and d representing the results of these calculaions, the helium-oxygen mixtures show a narrower zone of comfort occurring at higher temperatures especially at lower flow rates than do the nitrogen-oxygen mixtures. This is more marked in the cases of higher fractional content of inert gas (6-40c and d). The temperature values in Table 6-39 indicate the zone of comfort for the maximum gas velocities calculated for each mixture with rustling of papers in 1G as an endpoint.

It should be noted that in these predictions, the one Clo value is as high as one would probably expect to find in a shirt sleeve environment. More typical values would be .25 Clo for the Gemini underwear (163). The effect of helium in reduction of the Clo values of different garments has not been studied. Preliminary studies confirm that Clo values tend to vary inversely with the thermal conductivity of the atmosphere. (See Figure 44b.) The Clo value in 7 psia 50% O_2-50% He would therefore probably be 0.015/0.027 or about 0.56 that of sea level air (174). The expected effect of Clo on the helium-oxygen comfort chart is predicted in Figure 6-41. The 1 Clo prediction is closely parallel to that in Figure 6-40a.

Figure 6-40

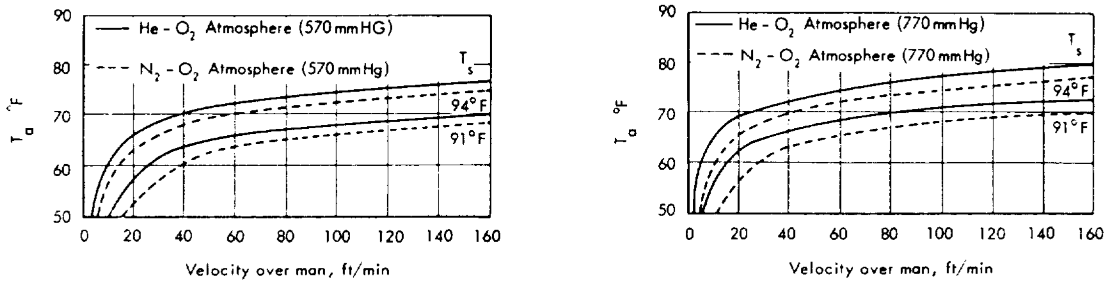
Comfort Lines for Man Seated at Rest

(After Parker et al[155])



a. With p_{O_2} = 170 mm Hg at 1 Clo

b. With p_{O_2} = 170 mm Hg and He or p_{N_2} = 200 mm Hg at 1 Clo



c. With p_{O_2} = 170 mm Hg and p_{He} or p_{N_2} = 400 mm Hg at 1 Clo

d. With p_{O_2} = 170 mm Hg and p_{He} or p_{N_2} = 600 mm Hg at 1 Clo

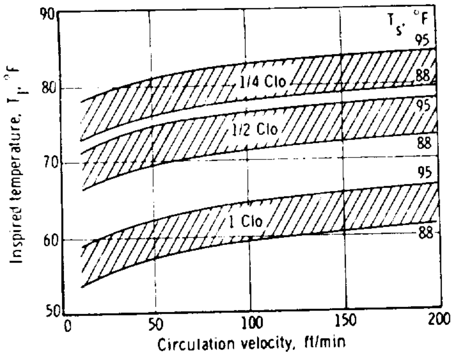


Figure 6-41

Human Comfort Chart
5 psia O_2 - He (Theoretical)

P_{O_2} = 173 mm Hg
P_{He} = 75 mm Hg
P_{H_2O} = 10 mm Hg
P_{CO_2} = 5 mm Hg

(After Johnson[(114)])

Empirical comfort temperatures in different gas mixtures have not been ystematically obtained. Comfort temperatures have been recorded only as e average cabin temperature set over periods of several weeks by subjects ho had control over the thermostat within the cabins (219). These temperare settings can be seen in Table 6-42 for subjects in surgical clothes which ould have about 0.5 Clo in air. These data include varied numbers of diferent subjects being studied under each gas mixture. No wind speed easurements were made during these studies, however, papers were not ustling and no complaints of wind chill were recorded. No measurements f average skin temperatures were made. The prediction in Figure 6-41 for /4 to 1/2 Clo is borne out in these data. Other studies have found comfort emperatures in He-O_2 at higher levels (31, 179). In these studies, the verage temperature settings during a varied work-rest cycle with 0.7 Clo vere 78°F for nitrogen-oxygen at 7 psia and 85°F for helium-oxygen at 5 psia. igure 6-41 may therefore have to be altered when more complete data become vailable. Zero gravity will tend to lower the comfort temperature (31).

Work is in progress to extend the predictive charts of Figures 6-35, -36, and 6-37 to He-O_2 mixtures of different composition and pressures and different values of Clo, exercise rate and skin comfort temperatures (18, 20).

During exercise, the partition of heat loss would be expected to vary vith different atmospheres. Figure 6-43 represents the relative modes of eat loss calculated during exercise at 100 watts for 1 hr in ground level air (G. L. air) at 745 mm Hg; ground level He - O_2 (159 mm Hg of O_2 and 579 m Hg of He) and altitude helium (alt. He-O_2) of 380 mm Hg with 165 mm Hg f O_2 and 206 mm Hg of He. The similarity between G. L. air and alt. He - O_2

Table 6-42

Temperatures Selected by Subjects in Space Cabin Simulators

(After Welch[(219)])

	3.7 psia O_2-100%	5 psia O_2-100%	5 psia P_{O_2}-175 mm Hg pHe - 74 mm Hg	7.3 psia P_{O_2}-150 mm Hg pHe-230 mm Hg	7.3 psia P_{O_2}-165 mm Hg P_{N_2}-206 mm Hg
Selected Temp °F	69.3	70.9	74.7	75.4	72.7

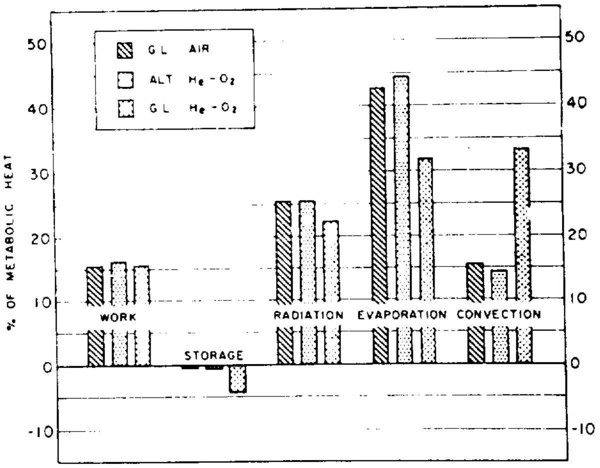


Figure 6-43

Avenues of Heat Exchange as Percentages of Total Metabolic Heat for a 150-Minute Test Period with 1 Hour of Exercise at 26°C.

Dewpoints are:

G.L. Air = 7.4°C

Alt. He - O_2 = 5.0°C

G.L. He - O_2 = 4.0°C

Alt. He - O_2 = O_2 - 165 mm Hg
He - 206 mm Hg

(After Epperson et al[73])

is striking as is the difference in convective and evaporative losses produced by the high pHe environment during this exercise load.

SPACE SUITS AND CLOTHING

The thermal physiology of clothing and space suits incorporates many of the principles already covered but requires knowledge of several other factors (27, 30, 48, 151, 173). Clothing must be considered for the shirt-sleeve environment within the cabin, for extravehicular operations in space or on the lunar surface and for survival conditions in remote parts of the Earth.

Radiant Insulation

Radiant input to the astronaut during EVA and on the lunar surface is a major factor in the design of external insulation for space suits. Detailed analyses of radiant input to multicylindrical and hemispherical models of man on the lunar surface (158) and to man in orbit (167, 168) are currently under study.

Surface control of the radiant input can be obtained by varying the α / ϵ ratio of the surface materials of the outer coveralls of space suits (167). In noon orbit where the astronaut is out of the umbra and receiving solar input over one-half of his suit, it has been calculated that equilibrium, external temperatures of less than 50°F cannot be maintained by α_o / ϵ_o surface coatings ($\alpha_o / \epsilon_o > 0.2$) when internal heat generation rates are in excess of about 1800 Btu/hr. For an α_o / ϵ_o of 0.2 (the approximate lower limit of α_o / ϵ_o for available space suit coating materials), the range of insulation conductance required for external wall temperatures of 75°F extends from 0.3 Btu/sq ft hr °F at 1000 Btu/hr to 20 Btu/sq ft hr °F at about 2300 Btu/hr. The minimum conductance actually approaches infinity for internal heat generations in excess of 2300 Btu/hr, indicating that the external surface α_o / ϵ_o limits the heat flow.

The α_o/ϵ_o of surface coatings required to maintain the internal wall temperature at 75°F when the insulation conductance is 20 Btu/sq ft hr °F decreases from 0.9 at 1000 Btu/hr to zero for 2500 Btu/hr internal heat generation. Such a range of external surface α_o/ϵ_o ratios is outside the capability of present day spacecraft coating technology. It is concluded that for typical materials ($\epsilon_o = 0.85$ and $\alpha_o/\epsilon_o \geq 0.2$) comfortable skin temperatures cannot be achieved by insulation alone for the highest internal heat generation rate of 2500 Btu/hr. For the lowest internal heat generation rate, 1000 Btu/hr, control is possible by varying α_o/ϵ_o, by varying the insulation conductance or by varying both. Similar calculations have been made for less severe orbital conditions (167). Data are available on the physical properties of various textiles, plastics, and metalized surfaces in current use for thermal control of flexible structures (227) and suits (22, 167, 168). Degradation of the surface with use must be anticipated.

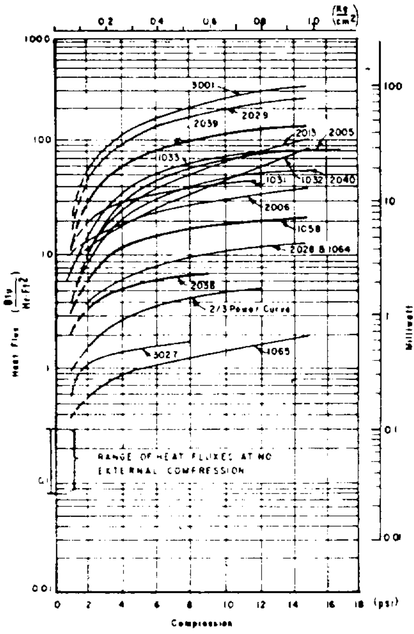
Insulation design for space suits has made use of the newer, multilayer and vacuum insulations (24, 86, 167, 220). The primary requirement for a radiation shield is that it exhibit a low emittance. Silver, aluminum, and gold are low-emittance materials that can be used either as coatings for radiation shields or to form thin foils. Aluminum and aluminum-coated plastic films are most frequently selected for the radiation shields because the emissivity of aluminum is only slightly higher than that of clean silver, whereas silver tarnishes in air, aluminum forms a very thin layer of aluminum oxide which prevents further degradation of the surface. Aluminum is also inexpensive and readily available in various thicknesses of foil and as a coating on a variety of metallic and nonmetallic surfaces. Aluminum vaporizes at a lower temperature than gold, making the aluminum deposition process easier to control. Plastic films with an aluminum deposit have been used for decorative purposes in industry for many years. As a result, aluminum-coated films are less expensive and of a better average quality than gold- or silver-coated films. Data are available on many different metalized film and foam systems for radiant shielding (86).

The performance of any given insulation will be greatly affected by the following variables: applied compressive load, number of shields used in the sample, kind of gas filling the insulation and its pressure, size and number of perforations in the insulation to permit outgassing, and temperatures of the warm and cold boundaries. Compressive loads by mechanical contact, by atmospheric pressure when a flexible outer skin is used to contain the insulation and permit evacuation, or those developed during application of multilayer insulations, reduce overall insulating effectiveness (86, 167). Even if the compression by the weight of the upper layers on the lower layers is disregarded, external forces (e.g., tension applied during wrapping of a multilayer insulation around a cylindrical object, thermal expansion or contraction of the insulation components with respect to the object, and localized loads in the vicinity of support points can compress the insulation. These compressive loads may be in the range from 0.01 to 1 psi (0.0048 to 0.48 g/cm^2). Figure 6-44a shows the effects of compression on the heat flux through 16 different multilayer insulations used for cryogenic insulation. When compression up to 2 psi (0.96 g/cm^2) is applied, the heat flux for the majority of the insulations is about 200 times greater than at the no-load condition. Plots of the heat flux in BTU/hr - ft^2 (characteristic also of the

Figure 6-44

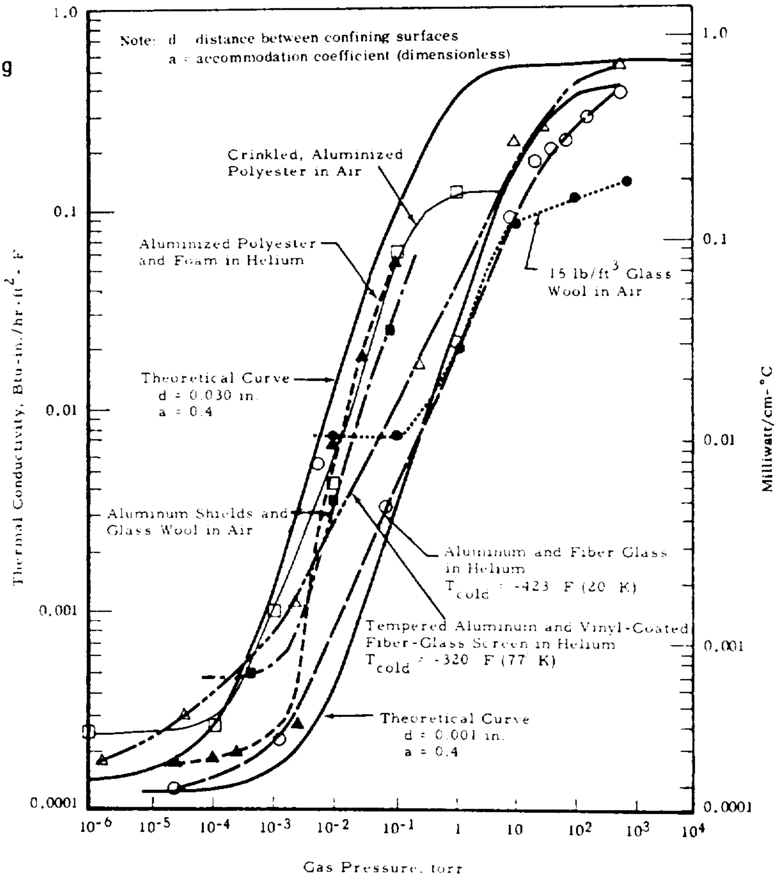
Insulation Values for Typical Radiant Shielding

(After Glaser, Black et al(86))



Sample No.	*T_{cold}, °F*	*Number of layers*	*Description*
1031	−320	20	Aluminized polyester film
		11	Fiber-glass mesh
1032	−423	10	Tempered aluminum
		11	Perforated fiber-glass mat
1033	−423	10	Aluminized polyester film
		11	Perforated fiber-glass mat
1058	−423	10	Tempered aluminum
		11	CT-449 (0.020 in.)
1064	−423	10	Aluminized polyester film
		11	Polyurethane foam
1065	−423	10	Aluminized polyester film
		11	Polyurethane foam (11 percent support)
2005	−320	60	Aluminized polyester film
		61	Fiber-glass cloth
2006	−423	20	Soft aluminum
		21	Polyester film
2013	−423	10	Tempered aluminum
		10	0.003-inch glass-fiber paper
2028	−423	10	Waffled aluminum
		11	Fiber-glass mat
2029	−423	10	Waffled aluminum
		11	Three-layer fiber-glass cloth
2038	−423	10	Tempered aluminum
		11	CT-449 (11 percent support area, 0.020 in.)
2039	−423	10	Double aluminized polyester film (both sides)
		11	Nylon netting (0.007 in.)
2040	−423	10	Tempered aluminum
		11	Nylon net
3001	−320	60	Crinkled, aluminized polyester film
3027	−320	6	Aluminized polyester film
		7	CT-449 (11 percent support area, 0.080 in.)

a. (top) Effect of Mechanical Loading on the Heat Flux Through Multilayer Insulation.



b. (right) Effect of Gas Pressure on Thermal Conductivity.

apparent thermal conductivity) versus compressive load in psia on a logarithmic scale fall on straight lines with a slope between 0.5 and 0.67.

In theory, the heat flux passing through an uncompressed sample of the multilayer insulation is inversely proportional to the sample thickness (i.e., number of shields), and, therefore, its thermal conductivity can be evaluated. Experimentally, under 1 g conditions, heat-flux data for a sample with 40 shields are somewhat higher than predicted from the 5-shield sample data (86). This discrepancy may be explained by the compression exerted by the weight of the upper layers on the lower layers of the sample, which may cause the lower layers to perform less efficiently than the upper layers. If an accurate estimate of the heat flux is required, a correction factor for the effect of compression must be applied.

The effects of a gas and its pressure on the performance of insulations have been studied by many investigators (86). The presence of residual gas inside fibrous and powder insulations decreases the thermal performance of a system. Gases of high thermal conductivity (e.g., helium or hydrogen) cause more rapid performance deterioration than gases with low conductivity (e.g., nitrogen or air). These effects are even more pronounced for a multilayer insulation. The effect of gas pressure on the thermal conductivity of several multilayer insulations is shown in Figure 6-44b. For comparison purposes, data for one fibrous insulation (glass wool in air) are plotted in the same figure. The thermal conductivity relates to gas pressure by an S-shaped curve. However, the effect of pressure on performance of multilayer insulations is 2 magnitudes larger than the effect of pressure on powder or fibers (i.e., the performance of a multilayer insulation is 100 times higher than that of a powder, but a pressure 100 times lower is required to reach it). At pressures below 10^{-5} torr, the heat transferred by a gas is directly proportional to the gas pressure. However, the heat conducted by a gas at that pressure is only a small portion of the total heat transferred through the insulation; therefore, the apparent thermal conductivity of the multilayer insulation decreases only slowly at pressures below 10^{-5} torr. At pressures of 10^{-5} to 10^{-4} torr, the mean free path of the gas molecules approaches the distance between the solid particles of the insulation. Beginning at these pressures, the apparent thermal conductivity of the insulation rapidly increases. For this reason the multilayer insulation must be maintained at a pressure below 10^{-4} torr or it will not provide the desired insulation effectiveness. When the gas pressure reaches atmospheric pressure, the heat conducted by the gas becomes the dominant mode of heat transfer. For a warm boundary at room temperature, the radiation component becomes small in comparison to the gas conduction component. Therefore, the apparent thermal conductivity of a multilayer insulation approaches the conductivity of the interstitial gas. After atmospheric pressure has been reached, the conductivity of the gas remains nearly constant and independent of the pressure, as does the apparent thermal conductivity of a multilayer insulation.

Perforations through insulation decrease the efficiency by local compression effects. Perforations have a smaller effect on an insulation with crinkled, aluminized polyester shields than on one with aluminum shields, presumably because the crinkles introduce a more random distribution of holes and improve outgassing (86).

Temperature of the warm and cold boundary layers controls the apparent conductivity of the multilayered insulations (86). For large temperature differentials, heat flux is directly proportional to the fourth power of the warm-boundary temperature through 10 tempered aluminum shields spaced with 11 vinyl-coated fiber-glass-screen spacers. For multilayer insulation with crinkled, aluminized polyester film radiation shields, apparent thermal conductivity is approximately proportional to the third power of the warm-boundary temperature. When the warm-boundary temperature is held constant, a higher thermal conductivity results from increasing the cold-boundary temperature. Data are available on the adequacy of the surface temperature control systems of current Apollo EVA Systems in many different operational conditions (89). Design and effectiveness of the Gemini System are covered under zero gravity of Acceleration, (No. 7), and Pressure, (No. 12).

Insulation of "Shirtsleeve" Garments

In the design of garments for wear within the space cabin it should be recognized that addition of clothing to the body surface reduces the quantity of heat that can be lost by evaporation because of the increased resistance to water vapor diffusion. At the same time, garments reduce the quantity of heat gained or lost by the body through radiation and convection. The addition of clothing may be detrimental, beneficial, or ineffective, depending on the amount of clothing, operative temperature, barometric pressure, and type of fabric used. Two properties of clothing must be evaluated to determine the effect of clothing on thermal balance. These are thermal resistance (R_g), and vapor resistance (R'_g).

Thermal resistance is the resistance of a particular clothing assembly to flow of heat. It is generally expressed in "Clo" units. It is directly proportional to the sum of the thickness of fabrics plus the thickness and the composition of the gas layers between fabrics (See Equation 16).

The thermal resistance of garments expressed in Clo units is:

$$1 \text{ Clo} = 0.88^{\circ}\text{F ft}^2 \text{ hr/BTU} = 0.18^{\circ}\text{C m}^2 \text{ hr/kCal}$$

Clo values of garment resistance vary from zero (for the nude man) through approximately 5 for pressure garment assemblies to values of 6-7 Clo for fox fur. Insulation values for typical Air Force clothing are recorded (27). The Gemini underwear has an insulation value of 0.25 Clo in sea level air (163).

The total insulation value of a clothing assembly to the man must include the insulation of gas trapped between clothing layers. The best value for still-air insulation at sea level as determined empirically is 0.19 C/kcal-m^2-hr (97). The rate of heat transfer across air space reaches a constant value for thicknesses exceeding 0.3 inches (0.75 cm) at sea level (27). Experimental Clo values for helium-oxygen and nitrogen-oxygen mixtures in fabrics are not yet available. Calculation of the total insulation value of newly designed garments and fabrics requires the knowledge of the thickness of the still air layer (R'_t) which is equal to the sum of the clothing vapor resistance (R'_g) as a still air equivalent and film resistance of the still air layer, (R'_e):

$$R'_t = R'_g + R'_e \qquad (37)$$

where R'_e = 0.24 in (0.6 cm) for air.

Values for R'_g for standard fabrics are shown in Table 6-45a. If fabric thickness is known the relationship

$$\frac{R'_g}{L} = \frac{\text{equivalent air thickness}}{\text{fabric thickness}} \text{ can be used}^{(27)}.$$

If thermal resistance in Clo units is known, the relationship

$$\frac{R'_g}{R_g} = \frac{\text{vapor resistance (inches of air)}}{\text{thermal resistance (Clo units)}} = 0.5 \frac{\text{inches}}{\text{Clo}} \text{ of air or } \frac{1.2 \text{ cm of air}}{\text{Clo}}$$

can be used. If the air layer thickness exceeds 0.3 in (0.75 cm) then these latter values should be used for R'_t (27). Techniques are available for measuring insulation values of clothing on working subjects (228).

Vapor Resistance

Vapor resistance (R'_g) depends on vapor diffusion of evaporated water, weave and thickness of the fabric material, the thickness of the air layers between the garments, and the nature of the gaseous environment. While the rate of vapor transfer across near-isothermal air layers is directly proportional to thickness, bellows action and resulting convection suggest use of the same maximum effective thickness for vapor transfer as for heat transfer, i.e., 0.3 inches (0.75 cm). The values of R'/L in Table 6-45a are a convenient estimate of resistance of similar fabrics, even though a more exact relationship of $R' = a(L)^{+b}$ probably is more true to reality (27).

If the resistances to vapor of all the fabrics making up a clothing assembly are known and the thickness of each air layer between successive garments is measured, the total resistance of the assembly can be easily determined (27). The air layer thicknesses can be determined in the following manner (128). Girths are measured first on the nude body at 6 locations (i.e., at two levels on arm, trunk, and leg), and again after each garment is donned. Assuming the body parts to be cylinders, successive radii are computed from the measured girths. The air layer thickness is obtained by subtracting the known garment thickness from the increment in radius produced by each garment.

Strictly speaking, a correction should be applied to the total resistance value obtained by successive addition for each of the three body parts, since the curvature effect reduces the actual resistance below that which would obtain for plane surfaces. However, there is insufficient knowledge at present to permit such a correction, and indeed, the limited accuracy of estimating individual fabric resistances probably does not warrant this

Table 6-45a

Vapor Resistance of Fabrics

(After Blockley et al[27])

Fabric	Weight (oz/yd^2)	Thickness (L) (cm.)	Resistance (R') (cm air)	R'/L	Ref.
COTTONS					
cotton net	4.4	0.100	0.12	1.2	95
3 x 1 cotton twill	8.2	.097	.19	1.9	94
5 x 1 cotton twill	8.8	.112	.24	2.1	94
2 x 1 cotton twill	4.4	.069	.15	2.2	94
cotton poplin	5.8	.039	.09	2.3	95
cotton oxford	6.7	.081	.19	2.4	94
cotton balloon cloth	2.2	.015	.04	2.6	95
cotton "jungle cloth" (bedford cord)	13.6	.107	.30	2.9	95
heavy cotton	13.5	.076	.28	3.7	95
close-weave cotton (Shirley L-30)	9.8	.051	.23	4.5	95
WOOLS					
double-face wool pile	22.	1.1	1.1	1.	95
2 x 2 wool twill	10.	.173	.26	1.5	94
worsted serge	6.1	.056	.12	2.1	95
wool serge	10.7	.130	.31	2.4	94
NYLONS					
spun-nylon fabric	4.9	.046	.18	3.9	95
nylon poncho cloth	1.5	.018	.07	3.9	94
5-end nylon sateen	2.3	.016	.08	5.0	94
filament nylon fabric	2.0	.013	.09	6.9	95
plain weave nylon	2.6	.020	.19	9.5	94
RAYONS					
viscose rayon 2 x 2 twill (fil.)	3.6	.025	.13	5.2	94
acetate rayon satin (fil.)	2.7	.018	.14	7.8	94
GLASS					
glass fabric	3.3	.013	.12	9.2	95
plain weave glass fabric	6.6	.030	.32	10.5	94

refinement. Disregard of the curvature effect is a conservative procedure, and may be justified on this basis.

In combining the data for the three areas into an overall resistance value for the body as a whole, some weighting factors for local evaporation rates must be employed. It is appropriate to use as weighting factors the relative proportion of body surface area for the part concerned. In the case of evaporative resistance, however, cognizance should also be taken of the variation in sweat production of these parts (Figure 6-29 and Table 6-45b). Proportionality factors must be used which include both relative surface area and sweat production, measured as evaporation, for various levels of thermal stress (103). Taking data for the upper portion of the environmental range (air temperature 36-37°C), and lumping values for adjacent parts, the relative proportion of trunk, leg, and arm sweat can be obtained (Table 6-45b).

Table 6-45b

Proportions of Evaporative Loss

(After Hertzman et al(103))

	Proportion of Total Body Surface Sweat	Relative Proportion of Trunk, Leg, Arm Sweat
Arms (forearm & arm)	.07	.08
Legs (calf & thigh)	.42	.48
Trunk	.38	.44
Totals	.87	1.00

The remaining 13% of the body average sweat per unit area is contributed by hands, feet, and head, which are not included in the clothing evaluation under discussion (See Tables 6-26 to 6-28). In a more exact analysis, the gloves, footgear and headgear could be separately evaluated, and their resistances weighted 0.03, 0.02, and 0.08 respectively (103). In a gaseous environment other than air, at sea level, appropriate corrections must be made for R'_g using the factors illustrated by Equations 6-24 to 6-31.

To aid in the first approximation of garment temperature t_g, since both h_c and h_r are functions thereof, Table 6-46 has been prepared for the standard clothing assemblies, showing t_g as a function of $(t_w + t_a)/2$, and the thermal insulation (Clo) value of the garment. Other tables must be prepared for gas mixtures other than air at sea level using Table 6-45a and Equations 17 and 18. For very high radiative temperatures, Figure 6-20b may be used to calculate h_r values.

The relationship between clothing surface temperature (t_g) and skin temperature (t_s) is seen in Equation 16.

When thermal resistance and vapor resistance of the garment assembly have been determined, the boundary for heat exchange with the environment may be shifted from the skin of the body to the surface of the clothing. With clothing as the boundary, t_g is substituted for t_s in all expressions for heat

Table 6-46

Approximate Garment Temperatures

(After Blockley et al[27])

$(t_w + t_a)/2$		1 Clo		2.5 Clo		4 Clo	
°F	°R	°F	°R	°F	°R	°F	°R
100	560	100	560	100	560	100	560
150	610	139	599	145	605	147	607
200	660	178	638	190	650	194	654
250	710	217	677	235	695	241	701
300	760	255	715	280	740	287	747

exchange. The effect of "shirt sleeve" clothing can be considered to increase the effective surface area of the body by a factor of 1.14.

Recent analyses of passive mass transfer of water in space suits are available (159, 167, 168, 182, 209).

Ventilated Suits

Typical air ventilated garments remove heat convectively (q_v) at a rate shown in Figure 6-47. The graph shows the rate of convective suit cooling which must be supplied a seated man at rest wearing typical aviation clothing to maintain a comfortable skin temperature of 90°F (32°C) for a range of hot conditions given as operative temperatures (See also Figure 6-5). Suit

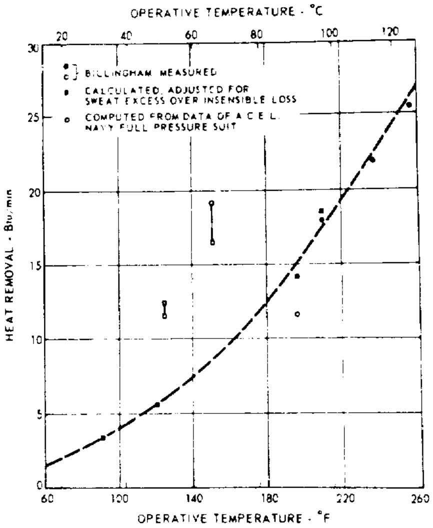
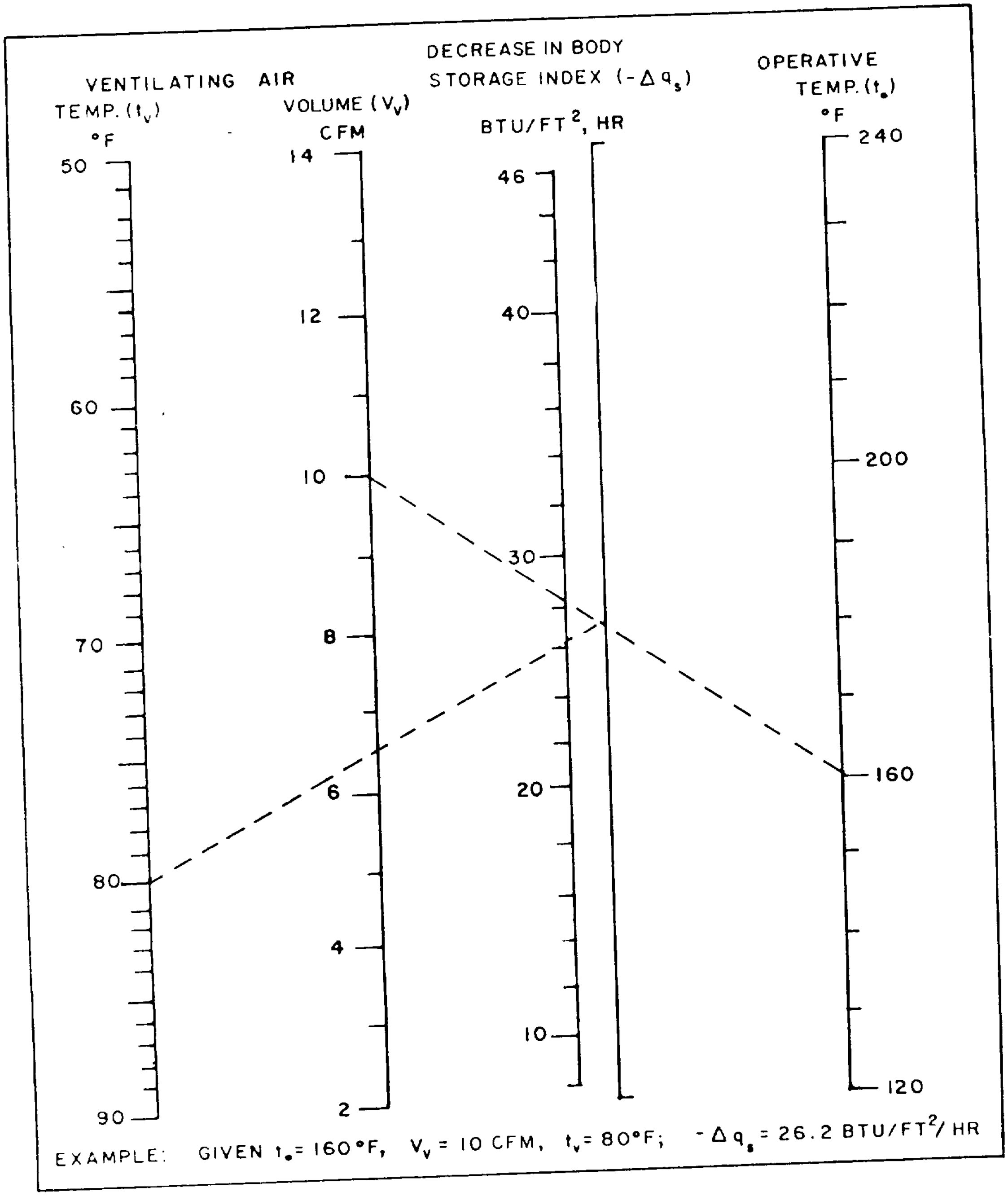


Figure 6-47

Cooling by Ventilated Clothing

The Data Points Marked with Hollow Squares, which are Farthest from the Curve Drawn Through the Other Points, are from Experiments Where There Was Moderate Sweating and Some Heat Storage, Although the Subjects Judged Themselves to be Comfortable. The Adjustments and Corrections for These Cases Could only be approximate.

(After Blockley et al[27] Adapted from Data of Billingham and Hughes[23], Greider and Santa Maria[91] and Mauch et al[141])



EXAMPLE: GIVEN $t_o = 160°F$, $V_v = 10$ CFM, $t_v = 80°F$; $-\Delta q_s = 26.2$ BTU/FT^2/HR

Figure 6-48

Nomograph for Computing Cooling Power of Ventilating Garment (After McCutchan and Isherwood[135]) convective heat removal is computed from the mass flow of ventilating air and the difference between inlet air temperature and the desired surface temperatures (30):

$$q_v = 0.24\,(90 - t_v)\,W_v$$

where q_v = suit convective heat removal in BTU/min

t_v = temperature of ventilating air in °F, and

W_v = mass flow of ventilating air in lbs/min.

When a ventilating garment is worn, the effective body heat storage index ($q_{s\ eff}$) is found by the following equation:

$$q_{s\ eff} = q_s - \Delta q_s$$

where

q_s = heat storage index (BTU/ft^2 hr)

Δq_s = decrease in heat storage index

Figure 6-48 presents a nomograph for computing the cooling power of a typical ventilating garment ($-\Delta q_s$) from the ventilating air temperature (t_V), the volume flow (V_V), and operative temperature (t_O) (135). Each garment will present somewhat different parameters. Figure 6-48 should therefore be used only as a general example for first-order engineering estimates.

The cooling capacity of Apollo prototype ventilated suits as a function of gas flow at several internal suit pressures is seen in Figure 6-49. The partition of cooling into sensible and latent loads is shown. Figure 6-53 compares the efficacy of ventilated and liquid cooled suits under different metabolic loads.

The capacity of Apollo prototype ventilated suits to handle different metabolic loads is seen in Figure 6-50.

Liquid Cooled Suits

The inadequacy of ventilated suits in handling large metabolic loads is clear in Figure 6-50 (45, 173). For work loads above 600 BTU/hr, liquid cooling must be added. The dotted line in Figure 6-49 represents projected capacity for liquid-cooling cascade addition to ventilated suits (44).

Total liquid loop suits have been used to extract heat in a warm environment and heat the body in a cool environment (49, 113, 119, 125). The thermodynamics of suit performance for current designs have been studied (45, 49, 51, 113, 119, 125). Analytic studies of skin to liquid loop conduction for other liquid-cooled systems are also available (9, 60, 168).

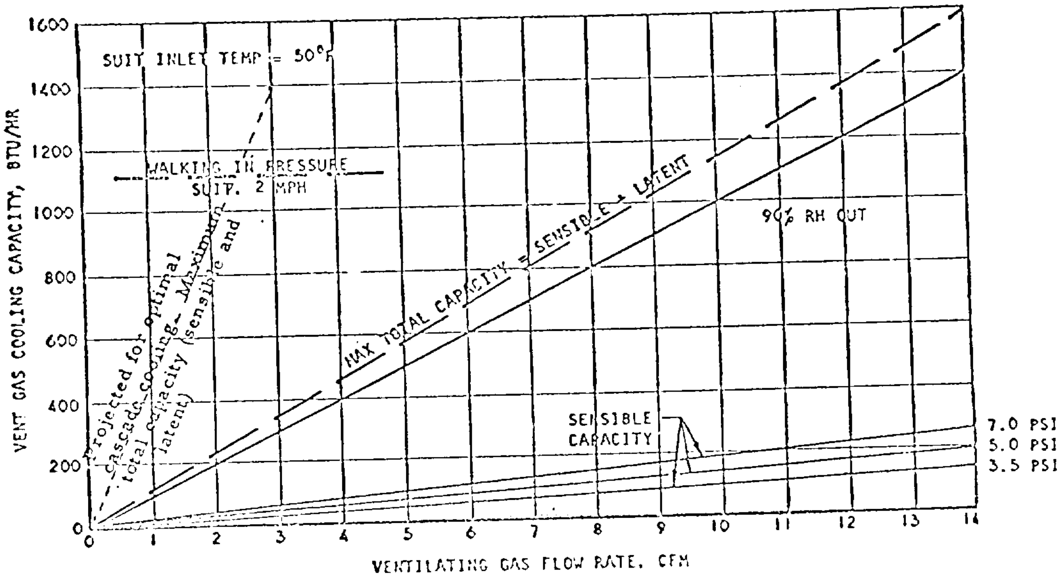


Figure 6-49

Pressure Suit Ventilating Gas Cooling

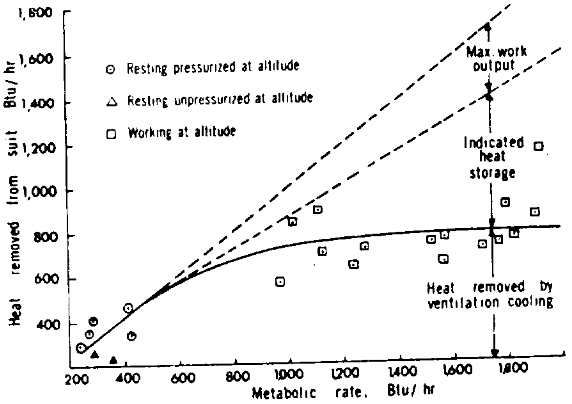
The dashed line represents the addition to cooling capacity of the ventilating suit theoretically possible by optimum function of a cascade cooling system proposed for the Apollo system.

(Adapted from Burris et al(44))

Figure 6-50

Heat Removed from an International Latex Prototype Apollo Suit Pressurized at 3.5 psia Above Ambient with Air Flow at 15 ft^3/min.

(After Roth(173)) Adapted from Air Research Corp.(6))



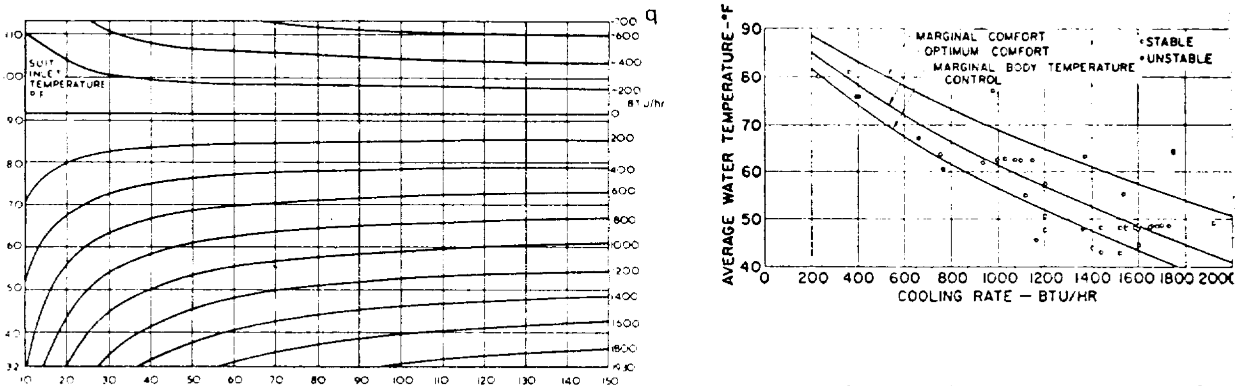
For an early prototype suit system, Figure 6-51a plots the suit performance equation as suit mass flow rate vs inlet temperature according to the equation

$$t_{in} = 91.5 - q/\dot{m}\, C_p \left[1 - \exp\left(-AU/\dot{m}\, C_p\right)\right] \qquad (38)$$

where $\dot{m}$ = total mass flow of air in suit (lb/hr)
q = the cooling requirement (BTU/hr)
AU = the thermal conductance of the clothing and its associated air film (BTU/hr °F)
t_{in} = temperature of inlet fluid (°F)
91.5 = the assumed mean skin temperature of a comfortable subject (°F)
C_p = specific heat of liquid at constant pressure (BTU/lb °C)

Figure 6-51

Effect of Water Temperature on the Performance of Prototype Liquid-Cooled Suits



a. Suit Performance for an Early Prototype Liquid-Cooled Suit.

(After Burton(50))

b. Cooling Garment Operating Limitations of Average Water Temperature and Cooling Rate for Several Prototype Apollo Suits.

(After Jennings(113))

If the cooling requirement for a given thermal situation is accurately known, the appropriate line on Figure 6-51a gives a family of suitable inlet temperature and flow combinations to meet the requirement. The inlet temperature coordinate has a lower limit of 32°F because for all practical purposes pure water can only exist in liquid form above this temperature and because of the possibility of causing local frostbite. The upper limit of inlet temperature has been set at 113°F because it has been found that temperatures above this are liable to burn the skin. Mass flow coordinates extend up to 150 lb/hr because this is about the maximum flow of which this specific suit is capable. It is seen that the suit should be capable of absolute maximum cooling rates of 1930 BTU/hr, and heating rates up to 700 BTU/hr at a flow of 150 lb/hr. The heat transfer range is not very much reduced if the flow is cut by half to 75 lb/hr because of the compensating increase of effectiveness. If the oling requirement is accurately known the performance equation of gure 6-51a should specify inlet temperatures to about 2°C (σ = 1.81°C) 32°F. The optimum mass flow will be determined not only by metabolic ctors but also by tradeoffs on battery vs. cooling sublimator weight (125).

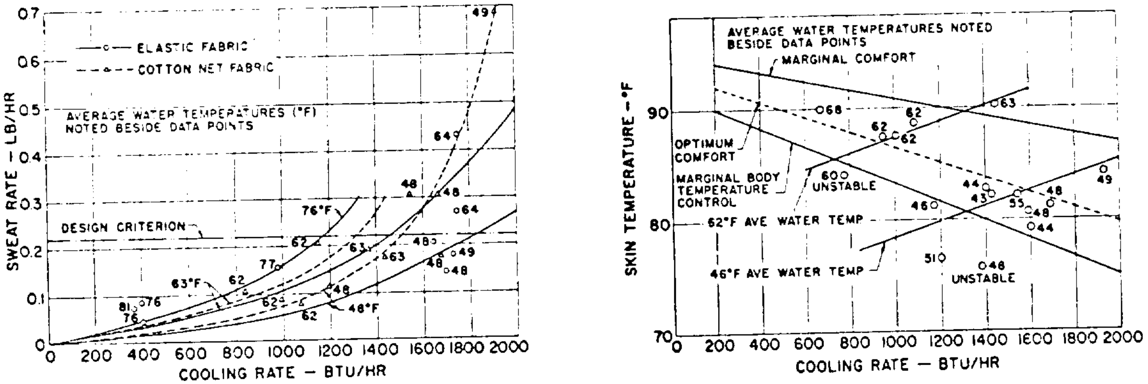
Figure 6-51b gives the average water temperature vs. cooling rate for l test runs of several Apollo prototype suits (113). The boundary envelope llows approximately the limits of comfort, since tests were not run beyond e edge of serious discomfort. The points marked unstable were those runs which the rectal temperature did not approach a constant value for some ason, usually because of excessive cooling.

Other methods of evaluating suit function are the sweat rate, skin temrature and rectal temperature responses. Figure 6-52a shows that sweat

Figure 6-52

Physiological Response to Several Apollo Prototype Liquid-Cooled Garments

(After Jennings(113))



a. Sweat Rate as a Function of Cooling Rate at Constant Average Water Temperature.

b. Skin Temperature as a Function of Cooling Rate at Constant Average Water Temperature. Subjective Comfort Zone Boundaries are Superimposed.

rates for the Apollo prototype elastic fabric garments (solid curves, CG7, CG6, CG10) are lower than for the cotton net fabric garments (dashed curves, CG3, CG3A) because of better skin contact with the former. Subjective reaction to elastic garments was that the apparent temperature distribution was more uniform. The horizontal line at 0.22 lb/hr sweat rate represents a design objective. Water inlet temperatures were recorded at 45°, 60° and 75°F for the elastic garments, and at 45° and 60°F for the cotton net.

Measurements of skin temperatures at 6 to 9 positions on the body were weighted according to local body areas and averaged. Figure 6-52b depicts mean skin temperature vs cooling rate for 46 and 62°F average water temperatures. Two additional solid curves define approximate boundaries at which various test subjects complained of excessive cold or warmth. An estimated optimum comfort line (dashed) starts from a skin temperature of 92°F and 200 Btu/hr cooling rate corresponding to 400 Btu/hr metabolic.

Figure 6-53 compares the equilibrium rectal temperatures attainable for different suit systems at various metabolic rates.

The recommended distribution of tubing in a typical water-conditioned suit (for use at rest) required to give no local overcooling is seen in Figure 6-54a (51). Unfortunately, requirements brought about by severe exercise conditions may alter this distribution (113, 213). Distributions used in the early prototype Apollo suits are shown in Figure 6-54b. The rationale for this approach was as follows: "Cooling tubes were connected to supply and return manifolds. By designing for low water velocity, the system losses were mainly from wall friction (losses at bends, entrances, and exits were small). The use of equal manifold-to-manifold tube lengths insured uniformity of flow distribution throughout the garment. Local tube length distribution of Table 6-54b was made proportional to body mass distribution, on the assumption that regional heat generation during work would be nearly proportional to the regional mass of muscle tissue. Coolant was supplied at the garment extremities and returned from the waist in accordance with observed conditions of comfort at rest, in which extremities are maintained cooler than the mid-region of the body. Water temperature rise along the cooling tubes was intended to be limited to comfortable ranges by control of the water flow rate, and by the layout of the tube patterns on the garment, includin on the torso where necessary reversals of direction were kept small. The tubes were not extended over the hands, feet, or head. Internal cooling by means of blood circulation was relied upon for the cooling of these parts, which, fortunately, do not generate large quantities of heat as do the massively muscled parts of the body.

Open mesh fabric was used as the garment structure to which the tubes were attached. This choice was made to permit compatible operation in a pressurized space suit supplied with ventilation gas but no circulating water by a cabin life support system. Body cooling by evaporation of sweat would be enhanced by gas circulation through the mesh. The stretch characteristic of the net fabric further afforded snugness of fit. The tubes generally were laid out in patterns following the 45° slope of the net strands, or in meandering paths between parallel boundaries, so that the garment's two-way stretch with body displacement was not impaired. The later garment, CG7, of one-way stretch elastic fabric, had tubes laid out in straight lines along the grain of the material.

The tube wall thicknesses were selected to reduce the likelihood of collapse from external loads or sharp bends. Transparent 0.063-in. i.d. x 0.031-in. wall polyvinylchloride (PVC) tubing was chosen for its flexibility and durability and to permit visual inspection of joint bonds and gas bubbles; supply and return tubes (0.188-in. i.d. x 0.063-in. wall) were of stiffer PVC to increase wall support.

Tubing was fastened to the garment by stitching while the garment was distended over a flat form having dimensions corresponding to body semi-circumferences. Tack stitches were taken through mesh cross strands on each side of tube with the thread crossing over the tube. The tube thereby followed the strand centerline and had no noticeable effect upon garment flexibility. For CG1, each cooling tube was 74 in. long, and ten started at

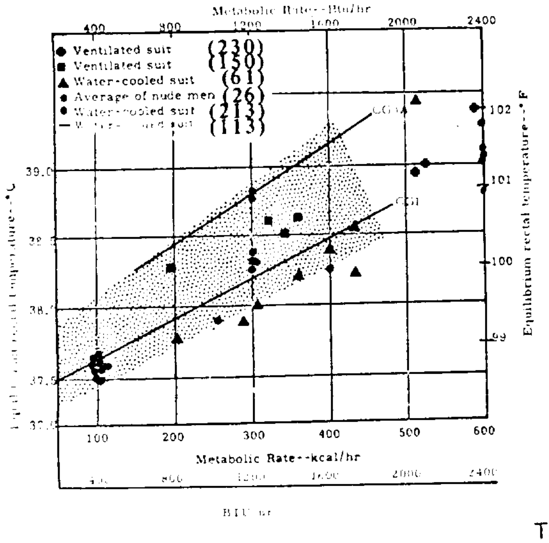


Figure 6-53

A Plot of Rectal Temperatures at Equilibrium (thermal balance) Versus Work Level, Incorporating Data from Many Sources. The shaded area is an envelope of data from 5 sources (212). The solid lines represent the range of prototype Apollo suit systems, CGI and CG3A (113).

(Adapted from Webb and Annis(213) and Jennings(113)).

Table 6-54

Distribution of Tubing and Cooling in Liquid-Cooled Suits

a. Recommended Distribution of Tubing in Water-Conditioned Suit at Rest.

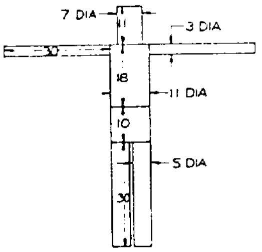
Region	Percentage of Tubing
1/2 Head	0
Hand	0
Foot	0
Forearm	9.3
Arm	16.9
1/2 Back	10.0
1/2 Chest	8.8
Calf	18.1
Thigh	25.6
Buttock	4.5
1/2 Abdomen	6.8

(After Burton and Collier(51))

b. Tube Distribution Calculation Based on Body Mass Distribution Used in Apollo Prototype Liquid-Cooled Garments (CG1)

							Distributed volume and area[b]			
	Vol., in.³	Wt., lb	Area, ft²	Vol. fraction	Area fraction	Height, in.	Vol. fraction	Area fraction	Tube length, in.	Tube Length fraction
Arm, each	212	7.6	1.96	0.045	0.104		0.049	0.114	15.4	0.052
Upper torso[a]	855	30.8	2.16	0.182	0.115	18	0.201	0.126	58.6	0.198
Lower torso[a]	475	17.1	1.20	0.102	0.064	10	0.111	0.070	33.4	0.113
Leg, each	589	21.2	3.27	0.126	0.173	30	0.139	0.190	40.6	0.137
Total	4685	168.8	18.85	1.000	1.000	69	. . .	. . .	. . .	. . .

[a] Left or right half each.
[b] Includes distributed portion for head.



(After Jennings(113))

each wrist and ankle. Other suits had 232 ft of tubing in contact with the skin. Of the total 247 ft of tubing, 232 ft made contact with the skin. Tubes were attached to a two-piece, medium-size, net fabric undergarment of about 7/16-in. mesh. Supply and return tubes followed zigzag patterns from waist to ankles and elbows for flexibility. They were attached to the cooling tubes by cementing to molded PVC connectors." In addition to the liquid cooling, heat transfer by conduction through gas at the surface of tubes and adjacent skin is available in these garments. For example, for a 0.12-in. heat-transfer distance through O_2 at 3.5 psia and 85°F and adjacent surfaces 0.12 in. wide on the skin and the tube at each side, the heat transfer over 300 ft of tubing with 50°F water will be 334 Btu/hr, or about 19% of the 1800 Btu/hr desired.

Other reviews of the efficacy of liquid-loop suit designs are available (61, 125, 177, 207, 210, 213, 231). Data on the latency of cooling after exercise loads have recently been gathered and are most useful for design of thermal regulators for liquid-cooled suits (213).

Liquid cooled suits create the unusual condition of sweating with a cool skin (12, 16). The effect of skin cooling on expected sweating response to high body core temperatures may be seen in Figure 6-70. Figures 6-52b and 6-55 give shivering and sweating thresholds for subjects in Apollo prototype liquid-cooled suits. Extravehicular suits for lunar operations must be designed to remove at least 2000 BTU/hr (500 kcal/hr) of heat and remain within these thresholds of sweating and shivering (125, 173). Automatic temperature control for liquid-cooled suits is now under study (142, 213).

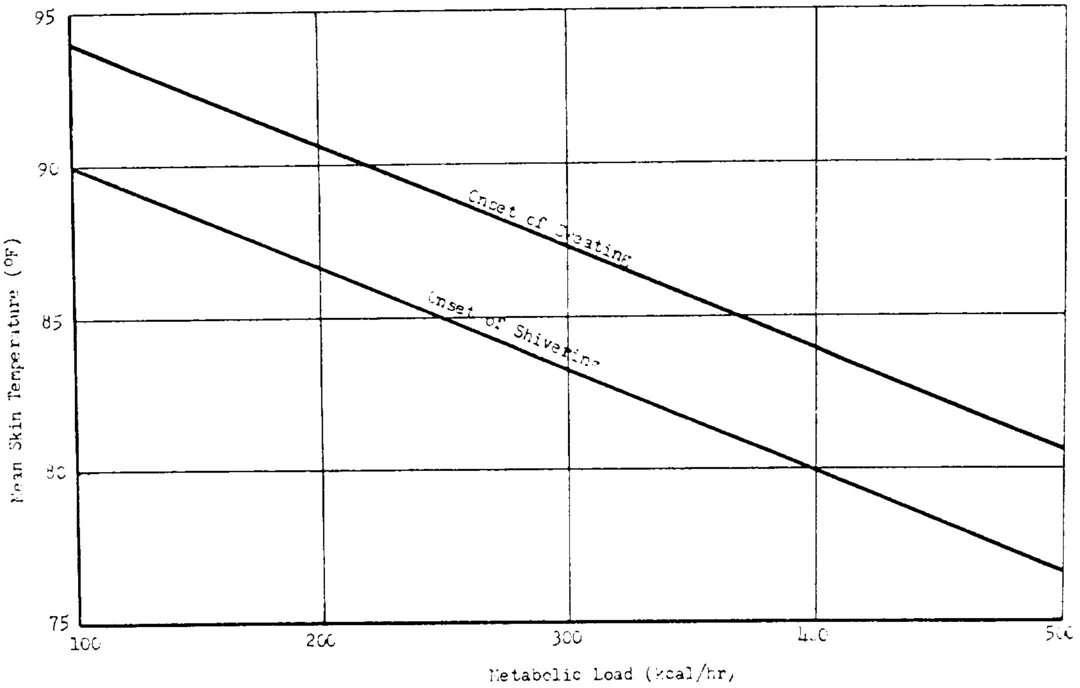


Figure 6-55

Comfort Thresholds of Sweating and Shivering in a Prototype Liquid-Cooled Apollo Suit (After Lang and Syversen(125))

Another approach to the cooling of space suits is the passive control system. Concepts including passive heat sinks, semi-permeable membranes, and wicking systems involving the pressure-retaining structures of the suits are being considered (159, 167, 168, 181, 182, 209).

Conductive Heat Exchange (q_k)

In the thermal analysis of man in an open environment, conductive heat exchange can, in many instances, be assumed to be included in the computations for radiation and convective heat exchange. This is justified, for the latter cannot exist if conduction is occurring over a given area. In addition, body heat lost by conduction will usually be transferred to the environment by radiation or convection modes. Liquid cooling garments, require that physiological constraints to conductive cooling modes be quantifiably identified. These constraints include sensitivity to thermal and pressure gradients on the skin surface, tube-to-skin contact resistance, skin resistance, temperature ranges (for comfort) of the body parts, and the effects of hair and perspiration on conductive exchange.

Unfortunately, the liquid-cooled space suit is worn under exercise conditions where skin comfort temperatures, thermal conductances to deeper subcutaneous structures, and similar factors are quite different from the resting condition (113, 213). The characteristics of the skin in thermal comfort as represented by Figure 6-29 and Tables 6-57, 6-58, 6-64, and 6-65 cannot be used under the unusual environmental condition of exercise in a liquid-cooled suit. Specific data are needed on the determinants of skin comfort under such conditions (113). Figure 6-55 is a good example of the type of data needed.

In the determination of heat conduction in the steady state, the following equation may be used for conditions other than space suits (39).

$$q_k = h_k (t_1 - t_2) \tag{39}$$

and

$$h_k = \frac{k}{L}$$

where q_k = conductive heat transfer - BTU/ft^2 hr (kcal/m^2 hr)

h_k = thermal conductance - $\frac{\text{BTU-inch}}{\text{ft}^2\text{-hr-}^\circ\text{F}}$ $\frac{\text{kcal-cm}}{\text{m}^2\text{-hr}^\circ\text{C}}$

t_1, t_2 = temperature of surfaces - °F (°C)

k = thermal conductivity BTU/in sec °F (kcal/cm sec °C)

L = thickness of the conducting medium inches (cm)

In the resting condition, the thermal conductivity constant, k, for conducting heat from the interior of the body to the skin (tissue conductance only) is:

$$k = 1.5 \pm 0.3 \times 10^{-3} \text{ kcal/cm sec}^\circ\text{C (at 23-25}^\circ\text{C ambient)}$$

At full vasoconstriction, when tissue conductance is 9-10 kcal/m^2/hr/°C the value for conductance corresponds to a tissue layer 1.8-2.2 cm thick. At the limit of vasodilation, thermal conductance is increased to values of 28-30 kcal/ m^2 hr °C. Values above and below these limits have been reported in the literature. However, many of the subjects may have become acclimated by the tests and accordingly, their values of conductance would exceed the norm. As a rule of thumb, a change from full vasoconstriction to full vasodilation lowers thermal resistance of the body approximately 1 Clo unit.

Figure 6-29 represents typical local skin conductances of local body areas at rest in still air at sea level. Tables 6-58, 6-64, and 6-65 present thermal conductivity and inertia data of body parts which may be of value in evaluating conductive heat loss and discomfort thresholds at rest. Equivalent thermal conductance between adjacent radial layers of head, trunk, and extremities has recently been suggested. Assuming the specific conductivity of tissue of 36 kcal cm/m^2 hr °C (194) physiologically effective masses and heat capacitance of different body compartments have also been calculated. Measure of the effectiveness of vascular convective heat transport can be made quantitatively by deriving values of thermal conductance for the peripheral tissues of the body (194). Cardiovascular changes such as shunting during exercise considerably complicate such calculations and are, unfortunately, key factors in operational situations where such data are sorely needed (168).

The commonly used expression for conductance is:

$$K = \frac{q_m - q_s - q_v}{t_r - t_s} \text{ BTU/hr ft}^2\ {}^\circ\text{F (kcal/hr m}^2\ {}^\circ\text{C)} \qquad (40)$$

where the terms on the right side of the equation are as previously defined.

Values of thermal conductance as a function of operative temperature are shown in Figure 6-56 (80).

The large difference in the two cases between the rate of rise in peripheral circulation with increasing operative temperature indicates the relative economy in vascular effort provided by the process of evaporation in air. An expression for nude human conductance, h_o, in air is:

$$h_o = 7.0 \left(0.48 + 0.52 \sqrt{\frac{\bar{V}}{7.6}}\right) \text{ kcal/m}^2 \text{ hr }^\circ\text{C} \qquad (41)$$

$\bar{V}$ = atmospheric velocity in cm/sec

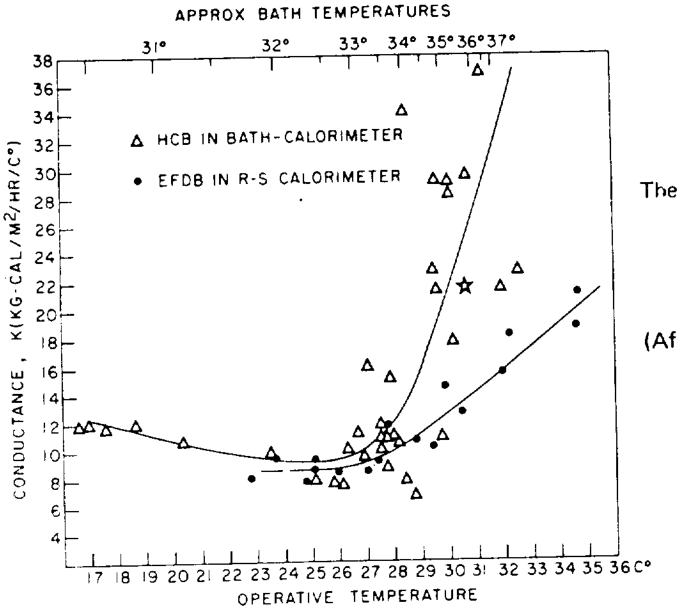


Figure 6-56

The Relation Between Conductance (A Measure of of Peripheral Blood Flow) and Operative Temperature for a Subject (EFDB) in the Dubois-Hardy Calorimeter, and Another (HCB) in the Burton-Bazett Water Bath Calorimeter.

(After Gagge[80])

HEAT STRESS AND TOLERANCE

To establish indices of thermal stress and tolerance in space operations, data are required beyond those for basic comfort limits such as presented in Section 2. Such variables as body temperature, sweating response to thermal loads, pain and discomfort thresholds for heat and cold, body stress indices, and performance under thermal stress must be evaluated. The role of dehydration in thermal tolerance has been covered in Water (No. 15).

Body Temperature

The body temperatures of interest in biothermal analyses are mean body temperature (t_b), rectal temperature (t_r), and skin temperature (t_s).

Mean Body Temperature (t_b)

Mean body temperature is the weighted average of rectal and skin temperature. The weighting varies with ambient temperature (194). In accordance with the Burton expression, (for $t_a < 30^oC$):

$$t_b = 0.67\ t_r + 0.33\ t_s \quad {}^oF\ ({}^oC) \qquad (42)$$

In the heat ($t_a > 30^oC$), the weighting is 1:9 for t_r:t_s. Mean body temperature is used primarily as a parameter in determing heat storage as seen in Equation 47.

Table 6-57

Mean Surface Temperature at Various Stations on a Supine Human Subject at Rest in Still Air at Sea Level

(After Iberall and Cardon[111])

Mean Ambient Temperature (°C) of:

	1			2		3	
Station No. & Name	21.0±.2	20.0±.1	20.5±.3	29.0±.2	29.0±.1	35.0±.3	34.0±.2
1 Forehead	33.8±.4	32.4±.3	---	35.2±.2	35.7±.3	35.5±.3	36.1±.6
2 Left Shoulder	31.8±.3	30.1±.7	32.7±1.6	34.2±.1	35.8±.5	35.6±.4	36.7±.4
3 Left Bicep	31.0±.2	30.5±.4	34.0±.4	33.9±.1	35.7±.1	36.2±.2	36.7±.2
4 Left Forearm	30.1±.3	28.9±.5	31.2±1.1	33.5±.2	36.0±.1	37.0±.3	36.1±.4
5 Index Finger	22.6→20.3	22→19.6	26.6±1.0	33→28.2	36.5±.2	35.0→30	37.6±.2
6 Upper Chest	---	35.5±.2	29.9±.8	34.6±.2	35.7±.1	36.0±.8	42.6→35.2
7 Sternum	32.4±.2	31.6±.2	32.8±.5	34.9±.1	36.1±.2	39.3±.2	36.7±.2
8 Mid-Abdomen	30.8±.1	30.1±.3	33.2±.4	34.4±.1	38.7±.3	35.4±.1	33.6±.2
9 Left Thigh (Anterior)	---	27.0±.3	29.3±.4	33.8±.1	34.9±.1	35.5±.2	36.2±.4
10 Left Leg (Anterior)	27.9±.3	27.1±.6	28.3±1.3	32.7±.4	34.0±.1	35.2±.1	35.9±.2
11 Toe	19.5→20.3	21.5→19	21.5±.8	31.5→28	35.4±.3	36.3±.1	37.1±.1
12 Neck (2-3 Cervical Vert.)	32.2±.4	32.2±.8	29.9±.8	34.1±.2	35.3±.3	36.1±.3	36.8±.1
13 Upper Back (2-3 Thoracic Vert.)	33.0±.2	32.4±.5	31.3±.4	34.8±.3	35.4±.1	35.7±.3	35.5±.4
14 Mid-Back (6-7 Thoracic Vert.)	33.0±.2	30.2±.3	31.9±.2	34.7±.2	34.5±.2	35.8±.1	34.7±.2
15 Lower Back (Lumbar Region)	33.4±.1	31.4±.2	27.9±.5	34.6±.4	33.3±.5	38.3±.2.4	35.0±.3
16 Right Buttock	30.6±.1	32.1±.3	29.6±.5	31.7±.3	33.6±.2	35.8±.2	36.1±.3
17 Right Thigh (Posterior)	31.2±.2	28.5±.2	29.9±.5	33.8±.1	35.5±.5	35.8±.2	37.3±.4
18 Right Leg (Posterior)	28.3±.3	25.8±.5	28.2±1.0	32.5±.3	34.5±.3	35.9±.1	36.7±.3
19 Right Heel	21.4→19	23.5→20	22.1±.6	31.4→28	34.4±.3	35.7→34	36.2±.2
Mean (Gross)	29.6±.3	28.9±.4	29.7±.7	33.3±.2	35.3±.3	36.0±.4	36.3±.3
Mean (Weighted)	30.4±.3	29.6±.4	30.1±.7	33.7±.2	35.2±.3	36.1±.4	36.2±.3

Rectal Temperature (t_r)

Rectal (or core) temperature varies as a function of activity level and is environment independent for ambient conditions extending well above the comfort zone. A complete discussion of rectal temperature variations with activity and environmental conditions follows below. Diurnal sensitivity must always be considered along with effects of leg experience (72).

Skin Temperature (t_s)

Figure 6-29 represents the preferred skin temperatures at different body sites at rest in still air under sea level pressures. Table 6-57 shows variations in skin temperature at various locations on the human body for a range of ambient temperatures between 68 and 95°F (20 and 35°C) at rest in air at sea level pressure.

An expression weighting the various stations of the human body for use in determining mean skin temperature for Apollo design purposes is as follows (148):

$$t_s \text{ (mean)} = \frac{12t_{back} + 12t_{chest} + 12t_{abdomen} + 14t_{arm} + 19t_{thigh} + 13t_{leg} + 5t_{hand} + 7t_{head} + 6t_{foot}}{100} \qquad (43)$$

Table 6-58 gives thermal properties of the skin which may be used in evaluation of tolerance thresholds.

Below 23°C ambient air temperature,only a fraction of the area of the body is regulated in accordance with the expression (111).

$$f = \frac{A_r}{A_b} = \frac{9}{33 - t_a} \qquad (44)$$

where A_r = area of body regulated
A_b = total surface area of the body
t_a = ambient air temperature (°C)

Figures 6-59a, 6-59b, 6-60a, b, c, 6-61, 6-62, and 6-63 represent the response of body core (rectal) and skin temperature to heat stress produced by ambient conditions and metabolic loads. Corresponding curves for atmospheres other than air at sea level are under study (73). Response of body temperatures to various thermal and metabolic conditions in ventilated and liquid-cooled suits is summarized in Figures 6-52, 53, 55, and Reference (149).

Figures 6-100, 6-102c, and 6-107 represent response of various body temperatures to the cold. Skin temperature responses of different populations

Table 6-58

Properties of the Skin

(After Blockley(30) from Data Compiled by Buettner(40) and Stoll(193))

Approximate values of the physical dimensions of whole skin for the "average man": 154 lb, 5'7"

Weight	8.8 lb	4 kg
Surface area	20 sq ft	1.8 m^2
Volume	3.7 qt	3.6 liters
Water content	70 - 75%	
Specific gravity	1.1	
Thickness	0.02 - 0.2 in.	0.5 - 5.0 mm

Approximate values for thermal properties of skin:

Heat production	240 kcal/day
Conductance	9 to 30 kcal/m^2hr °C
Thermal conductivity (k)	$(1.5 \pm 0.3) \times 10^{-3}$ cal/cm sec °C, at 23 - 25°C ambient
Diffusivity (k/ρc)	7×10^{-4} cm^2/sec (surface layer 0.26 mm thick)
Thermal inertia (kρc)	90 to 400 $\times 10^{-5}$ cal^2/cm^4 sec $(°C)^2$
Heat capacity	~0.8 cal/gm

Skin temperature and thermal sensation:

Pain threshold for any area of skin 113° F (45° C)

When mean weighted skin temperature is:	The typical sensation is:
above 95° F (35° C)	unpleasantly warm
93° F (34° C)	comfortably warm
below 88° F (31° C)	uncomfortably cold
86° F (30° C)	shivering cold
84° F (29° C)	extremely cold

When the hands reach:	When the feet reach:	They feel:
68° F (20° C)	73.5° F (23° C)	uncomfortably cold
59° F (15° C)	64.5° F (18° C)	extremely cold
50° F (10° C)	55.5° F (13° C)	painful and numb

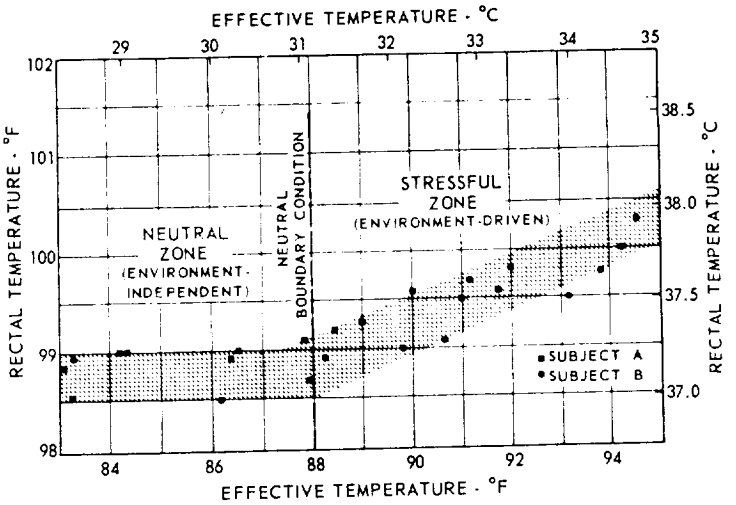
Approximate optical properties of skin:

Emissivity (infrared)	~0.99
Reflectance (wave-length dependent)	Maximum 0.6 to 1.1μ Minima <0.3 and >1.2μ
Transmittance (wave-length dependent)	Maxima 1.2, 1.7, 2.2, 6, 11μ Minima 0.5, 1.4, 1.9, 3, 7, 12μ
Solar reflectivity of surface	
Very white skin	42%
5 "white" subjects	28 - 40%, average 34%
6 "colored" subjects	19 - 24%, average 21%
Very black skin	10%
Solar penetration--very white skin	45.5% passes 0.1 mm depth 39.6% passes 0.2 mm depth 32.0% passes 0.4 mm depth 19.0% passes 1.0 mm depth 10.2% passes 2.0 mm depth
Solar penetration--very dark skin	75% passes 0.1 mm depth 40% absorbed in the melanin layer 35% passes 0.2 mm depth

Figure 6-59

Body Temperatures at Rest

a. Body Temperature as a Function of Effective Temperature in Heat (After Blockley[30] Adapted from Macpherson[140])



This graph relates the final rectal (core) temperature of resting men to a range of environmental heat stress. Each data point shows the level of rectal temperature observed in two men wearing coveralls and seated while exposed to dry bulb temperatures from 90 to 120°F and wet bulb temperatures from 83 to 88°F (E. T.'s from below 84 to above 94°F). In the region labeled "neutral zone," which extends well above the comfort zone, while other parameters such as skin temperature, heart rate, and sweat rate are increased with each successive increase in stress, core temperature remains independent of the environmental heat stress. Further increases in heat stress index beyond the "Neutral Boundary Condition" for the activity, clothing, and state of training concerned produce progressively higher core temperatures. This state of affairs characterizes the "stressful zone," where rectal temperature is environment-driven, and the probability of breakdown, or failure to compensate, becomes progressively higher, particularly for untrained or unacclimatized men.

b. Midpoint Rectal and Skin Temperatures as a Function of Reference Operative Temperature at Rest.

Mean values for the collected series are shown by characteristic symbols. Least Square regression lines have the following equations:

$$t_r = 37.8$$

$$t_s = 34.8 + 0.056(t_{or})$$

(After Blockley et al[27])

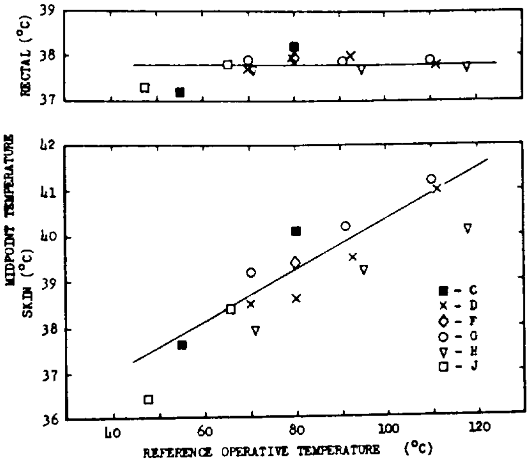


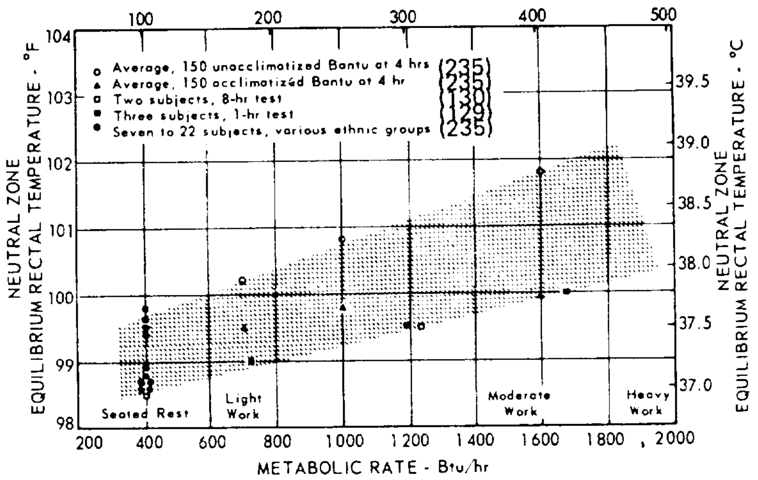
Figure 6-60

Body Temperature at Work in Heat

a. Variations in Rectal Temperature at Sea Level as a Function of Activity

(After Blockley(30) Adapted from Hanifan et al(96). Based on Data from Lind(129, 130), Strydom and Wyndham(195), and Wyndham et al(235))

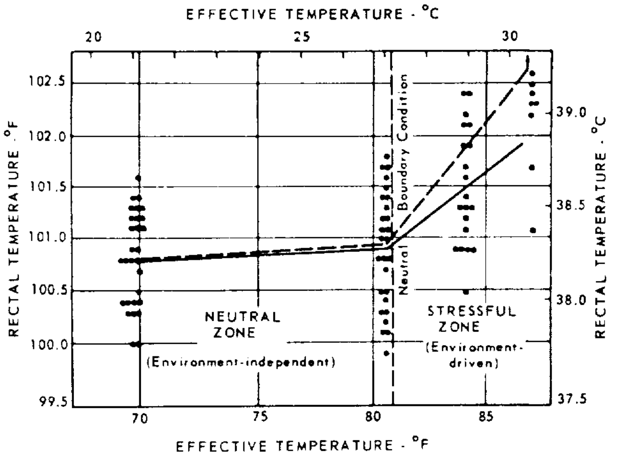
For each level of work, there appears to be a characteristic internal or core temperature at equilibrium which is unaffected by the environment so long as the neutral boundary condition (Figure 6-59a) is not exceeded. As shown here, the characteristic internal (i.e., rectal) temperature for a particular work load varies between groups; both physical training and training for work in the heat (acclimatization) produce lower values. Superficial differences between ethnic groups appear to be due to habit patterns and experience relative to working under hot conditions.



Note that persons completely untrained for a particular activity or exercise would probably show rectal temperatures considerably higher than those indicated in this chart for African natives recruited for mine labor.

b. Rectal Temperatures and Stress Zones for Work in the Heat at Sea Level.

(From Blockley(30) Adapted from Leithead and Lind(127))

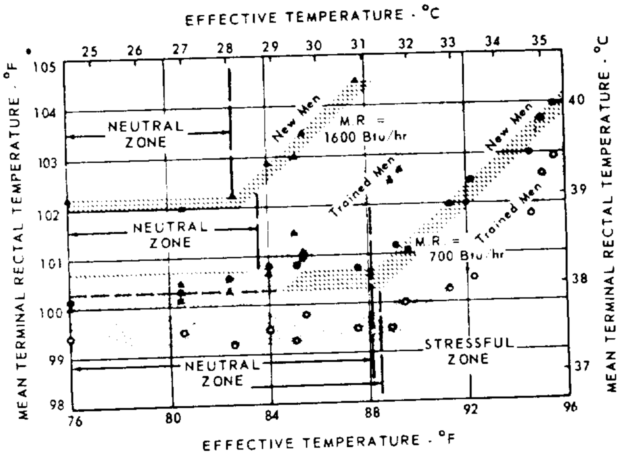


Final rectal temperatures are shown as a function of environmental heat stress for working men in figure b. Each point represents a single exposure of a different man--approximately 30 men in each environment, or a total of 128 untrained subjects. The task was three hours of treadmill marching at 3.5 mph wearing shorts; the metabolic rate was 300 kcal/hr. Only in the two environments that lie in the Neutral Zone did all subjects complete the task. In the two hotter climates, 25% and 57% of the subjects had to be removed before the end of the period because of excessive heart rates or rectal temperature, to prevent collapse or damage. The dashed line on the graph connects the median values of final rectal temperature for all subjects, while the solid line connects the means for those subjects completing the full three hours.

igure 6-60 (continued)

c. Rectal Temperatures and Stress Zones for Work in the Heat at Sea Level.

(After Blockley(30) Drawn from Data of Wyndham et al(235))



In figure c, each point is the average of a group of ten men; the chart thus summarizes data from approximately 460 individuals, 2 work rates, and 15 different humid environments. The vertical lines delineate the boundary conditions separating the "Neutral" (environment-independent) and "Stress-ful" (environment-driven) zones before and after training.

Clearly illustrated is the effect of heat training (acclimatization) on the equilibrium rectal temperature, and the small, probably insignificant effect of training on the location of the Neutral Boundary. Note that in the "Neutral" zone, heat-trained men working at 1600 Btu/hr maintain body temperatures as low as or lower than novice workers working at 700 Btu/hr, however, when both groups are in the "Stress Zones" for their respective work levels, the difference between their mean body temperatures is 1.5°F. For comparison, new men working at 1600 Btu/hr have temperatures 1.5°F higher than similar men working at 700 Btu/hr, when both are in their neutral zone of environments.

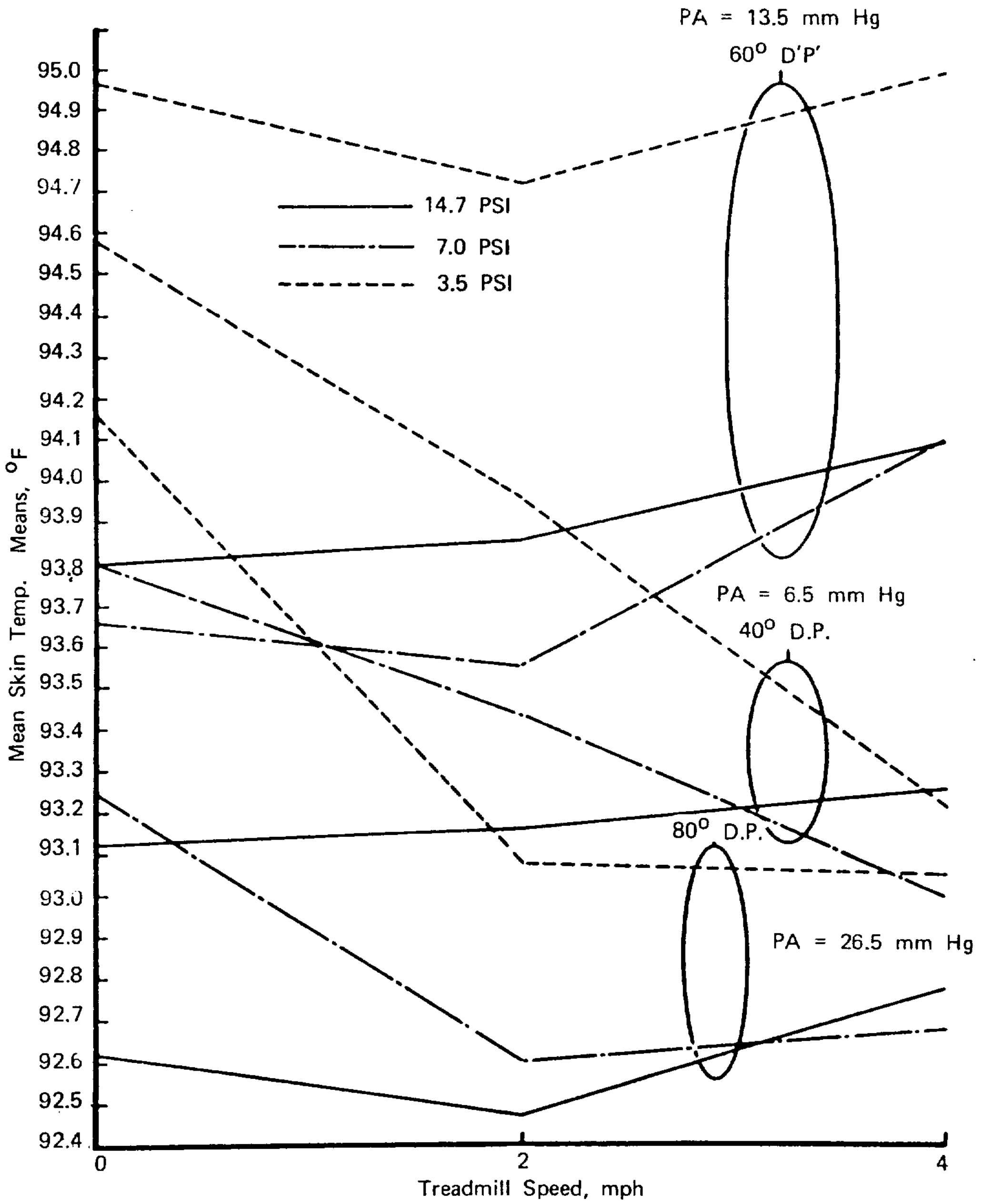


Figure 6-61

Mean Skin Temperature, °F, as a Function of Treadmill Speed, Miles Per Hour, at 95°F Dry Bulb in Shirt-Sleeve Environment

(After Wortz(232))

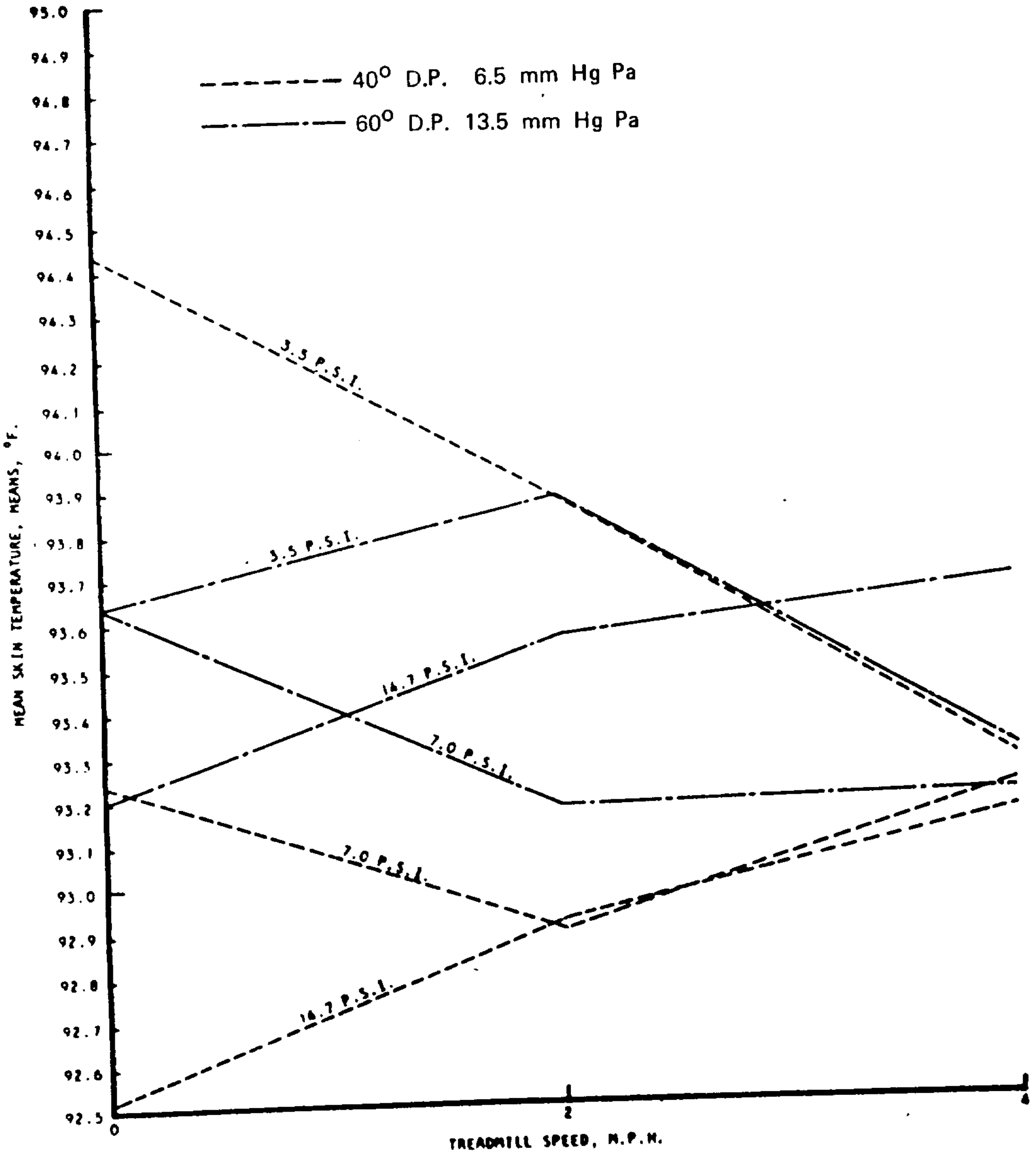


Figure 6-62

Mean Skin Temperature, °F, as a Function of Treadmill Speed, Miles Per Hour, at 75°F Dry Bulb in Shirt-Sleeve Environment.

(After Wortz(232))

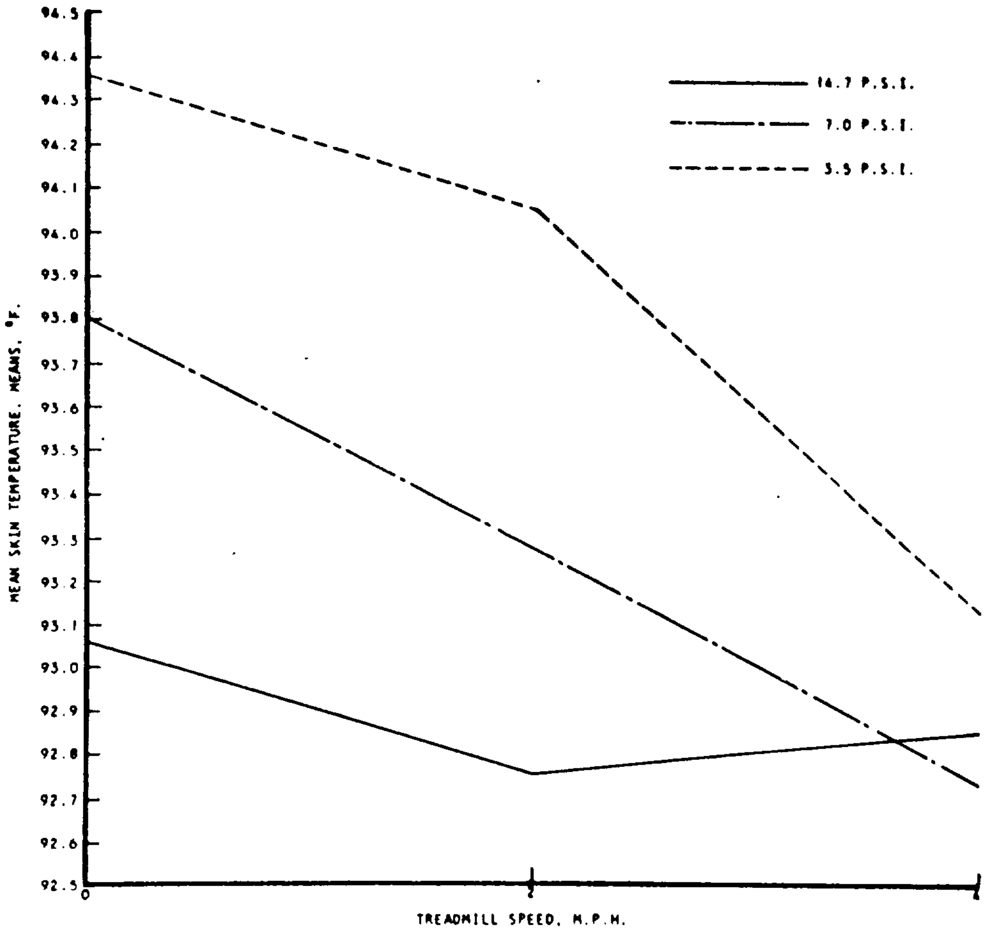


Figure 6-63

Mean Skin Temperature, °F, as a Function of Treadmill Speed, Miles Per Hour, at 55°F Dry Bulb in Shirt-Sleeve Environment.

(After Wortz(232))

ɜleep under varied environmental temperature are available (72). The .eral increase in Clo value required for comfort in a cool environment ·ing sleep must always be considered.

Figure 6-29 and Tables 6-64 and 6-65 represent odd aspects of the thermal ɩracteristics of "the average man" at rest which can be used in the analysis local thermal effects and tolerances in air at sea level.

eating and Respiratory Water Loss

Heat stress may be measured by the rate of water loss by the body. alysis of the evaporative heat exchange mode in unusual atmospheres has ən presented above. Tables 6-26 to 6-33, Equations 23-26, and Figures 29 to 6-34, and 6-50 may be used to obtain appropriate data for design and erational analysis under the specific limitations noted.

In addition to these data for space operations, Figures 6-66 to 6-69 present the sweat production rates to be expected under survival conditions Earth. Additional data on sweating are available in Water (No. 15) and ference 215.

Inside a liquid-cooled suit, a heavily working man may have a high core mperature but a low skin temperature. The expected sweat response may us be altered as seen in Figure 6-70. Retention of CO_2 may also alter the t point of sweating. The sweating rate in 6% CO_2 at sea level air may be)0% greater than in normal air (42).

Figure 6-71 represents the sensitivity of water loss through respiration metabolic rate, ambient pressure and dewpoint (115). Rates of nonthermal veating are about 80-220 gms/hr from covered areas and 20-40 gms/hr om the rest of the skin (26, 34, 215). This can be increased by psychoenic stimuli of many types (2, 215).

eat Stress Indices

In the non-compensable zones of thermal control, performance and olerance have an inverse exponential relationship with exposure time. igure 6-72 reflects the general time-tolerance relationship for extremes f ambient air temperature under sea level conditions.

Figure 6-73 shows the physiological impairment which may be anticipated ue to extremes of body temperature. The tolerance limits reflect the borders f physiological collapse to be used for rough evaluation of situations.

Under conditions of heat stress, the mode of evaporative heat loss cannot ompletely compensate for the difference between total heat load and heat osses via other modes. This lack may be attributable to failure to achieve sufficiently high perspiration rate or by failure to achieve a sufficiently igh evaporation rate. Even though the perspiration rate is adequate to maintain thermal balance, conditions of high humidity and/or low ventilation

Table 6-64

Physiological and Thermal Characteristics of the "Average" Man

(After Breeze(36))

CHARACTERISTIC	METRIC UNITS	ENGLISH UNITS	REFERENCE N
Weight	68-72 kg	150-160 lbs.	66
Height	170 cm.	68-69 inches	66
Total Body Surface Area	1.8 sq. meters	19.5 ft^2	66
Volume	0.07 $meters^3$	2.5 ft^3	66
Specific heat	0.8 cal/gm-°C	0.8 Btu/lb-°F	66
Heat Capacity (using 160 lb. man)	57.6 cal/°C	128 Btu/°F	66
Body temperature (rectal)	37°C	98.6 0.5°F	66
Body surface temp.	33-34°C	91-93°F	65
Body and clothing Surface temperature (ave. - 1 Clo)	28°C	82.2°F	108
Body temperature $(2/3\ t_r + 1/3\ t_s)$	35.6°C	96.1°F	98
Body percent water	70%	70%	65
	HUMAN SKIN		
Weight	4.0 kg	8.8 lbs.	192, 193
Surface Area	1.8 $meters^2$	19.5 ft^2	192, 193
Volume	3.6 liters	3.7 Quarts	192, 193
Water Content	70-75%	70-75%	192, 193
Specific Gravity	1.1	1.1	192, 193
Thickness	0.5 mm (Eyelids) to 5 mm (back)	0.02 to 0.2 inches	192, 193
Heat production	13% (Body's Metabolic Heat Prod.)	13%	192, 193

Table 6-64 (continued)

CHARACTERISTIC	METRIC UNITS	ENGLISH UNITS	REFERENCE NO.
Conductance	9→ 30 kgCal/m^2-hr.-°C		192, 193
Thermal Conductivity (k)	1.5 ± 0.3 X 10-3 Cal/cm-sec-°C at 23-25°C Ambient		192, 193
Diffusivity $(k/_\rho\ C_p)$	7 x 10^{-4} cm^2/sec (Surface Layer 0.26 mm Thick)		192, 193
Thermal Inertia $(k/_\rho\ C_p)$	90-400 X 10^{-5} cal^2/cm^4-sec-°C^2		192, 193
Heat Capacity (Cp)	0.8 cal/gm-°C	0.8 Btu/lb-°F	192, 193
Emissivity (Infrared) Skin and Clothing Reflectance (Wave Length Dependent)	- 0.99 - 0.94 MAX. 0.5→1.1μ MIN. 0.3 and 1.2μ		192, 193
Transmittance (Wave Length Dependent)	MAX. 1.2, 1.7, 2.2, 6, 11μ MIN. 0.5, 1.4, 1.9, 3, 7, 12μ		192, 193

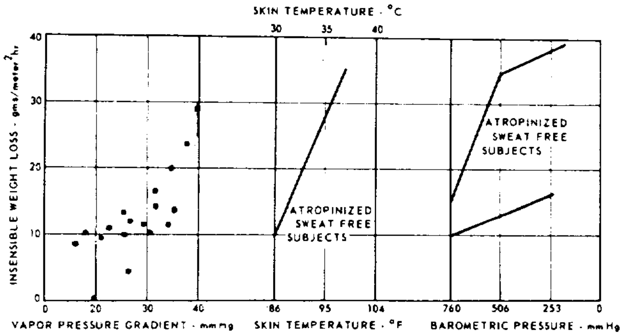
TERM	DEFINITION
Clo	Insulation value of that quantity of clothing that will maintain comfortable thermal equilibrium in a man sitting at rest in an environment of: (a) 70°F air and wall temperature, (b) less than 50% rel. humidity, and (c) 20 ft/min air movement.
1 Clo $= \frac{0.18 \text{ Deg. F}}{\text{kg-cal/Hr}}$	{In combined units {For 1.8 m^2 Surface Area
1 Clo $= \frac{0.04536 \text{ Deg. F.}}{\text{Btu/Hr}}$	{1 kg-cal = 3.968 Btu
Heat Capacity of Body Periphery 40 Btu/°F	Outer layer to skin as opposed to body core. Approximately 1.0 inches thick.
Resistance of Periphery	Function of body activity and is equivalent to 0.16 to 0.70 Clo

Table 6-65

K ρ C of Various Body Tissues

(After Breeze(36))

	VALUES FROM DIRECT MEASUREMENT (LITERATURE)				
Tissue	K (Thermal Conductivity) gm. cals/cm sec °C x10^{-5}	ρ(density) gms/cm^3	C (Thermal Capacity) gms. cals/gm °C	Kρ C (Thermal Inertia) Cals^2/cm^4 °C^2 sec x10^{-5} Computed	Measured
Fat	43 ± 10	0.92	0.55	22 ± 7	26
Muscle	83 ± 30	1.27	0.91	96 ± 34	113 (moist) 56 (dry)
Skin, Dead	70	1.20	0.81	70	66
Skin, Living					90 (no blood flow) 125 (normal)
Bone					50



Loss of water through the skin by diffusion is influenced by the vapor pressure gradient, the skin temperature, and the barometric pressure. On the left, water loss in grams per square meter of body surface per hour is plotted against the difference in vapor pressure in the air and vapor pressure at the skin, as reported by four different authors (34, 93, 216, 239). In the center, a high skin temperature is seen to be related to a high diffusion loss. Warm skin free of sweat was produced by high atropine dosage (216). On the right, the graph shows an increase in diffusion as the barometric pressure is lowered (93, 216).

Figure 6-66

Insensible Water Loss from the Skin as a Function of Absolute Humidity, Skin Temperature, and Barometric Pressure.

(After Blockley(30) Drawn from Data of Brebner et al(34), Hale et al(93)) Webb et al(216) and Zollner et al(239))

Figure 6-67

Water Loss by Sweating Under Different Environmental Conditions (After Blockley[30] Adapted from a, Adolph[3]; b, MacPherson[140] Robinson et al[170], Tavlor and Buettner[196], and Webb et al[216]; c, Adolph[3]; d, Thompson Ramo Wooldridge, Inc.[203])

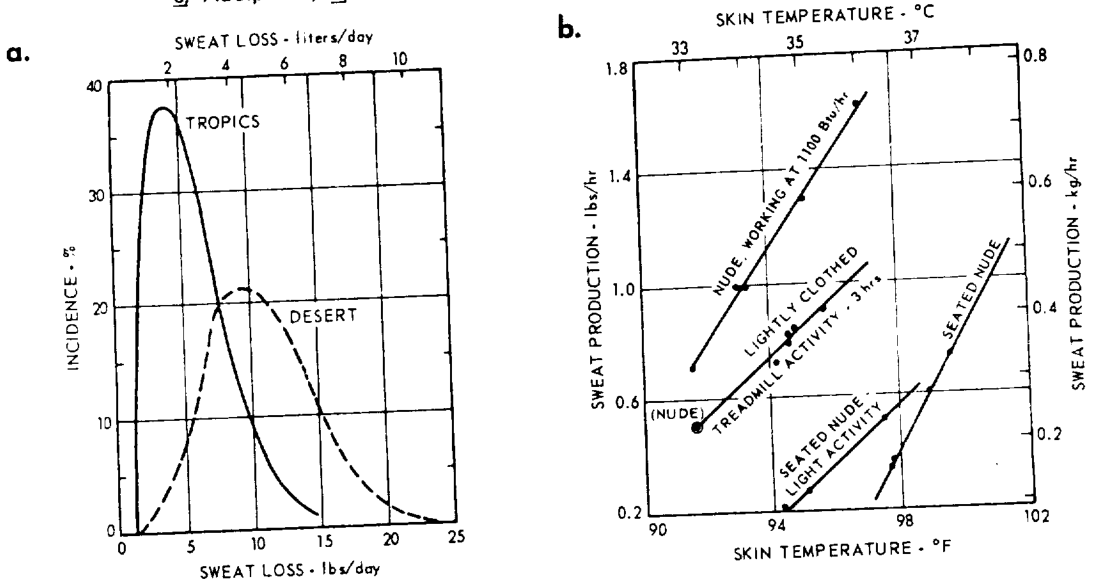


Figure a shows the frequency distribution of daily sweat production for 26 men in the tropics and 97 men in the desert. In figure b, various sweat rates during various laboratory procedures are plotted as a function of skin temperature, to show how variable this relationship is. Air temperature influences sweating in men sitting still in the desert sun, as shown in figure c. Figure d shows sweating and evaporative heat loss varying with air temperature and activity level.

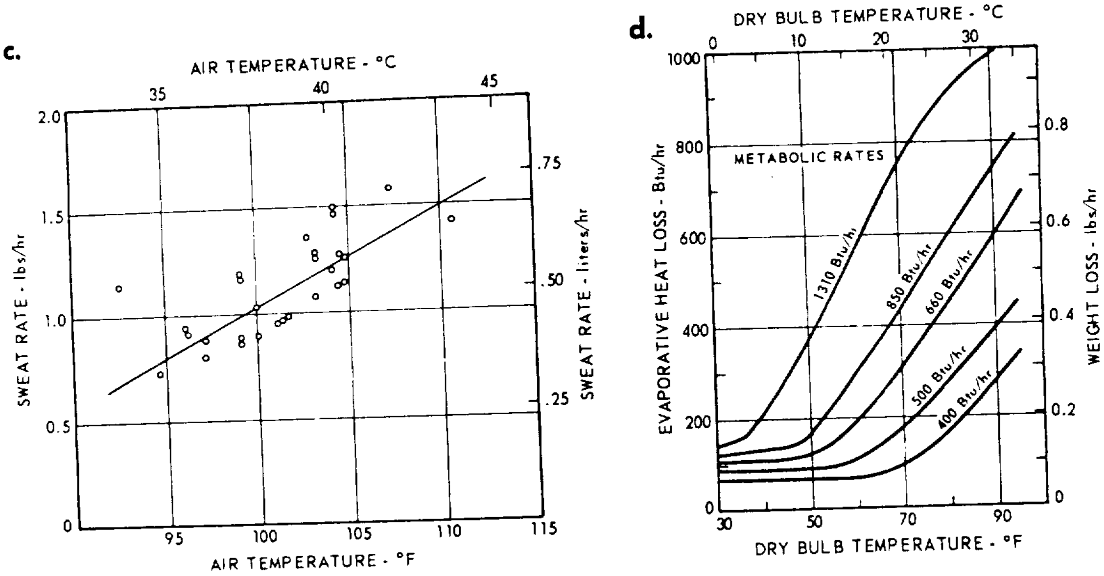
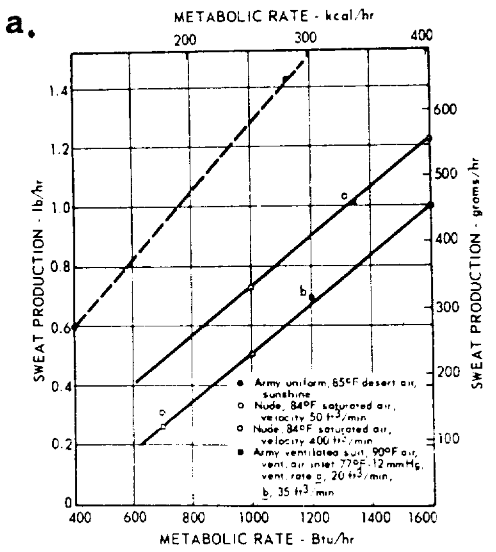


Figure 6-68

Sweating Rates; Water Replacement

Sweat production is a highly variable quantity both within and between individuals. This chart is intended merely to indicate orders of magnitude and some of the sources of variability. Missing entirely from this picture is the question of the physiological cost of producing sweat, which is a function of the body temperatures and work rates at which a given sweat rate is achieved. Rates as high as 2 lbs/hr can be maintained for many hours if sufficient water is ingested, but rates between 3 and 4 lbs/hr cannot be sustained for 6 hours. When the skin is totally wet, the maximum achievable sweat rate is drastically reduced.

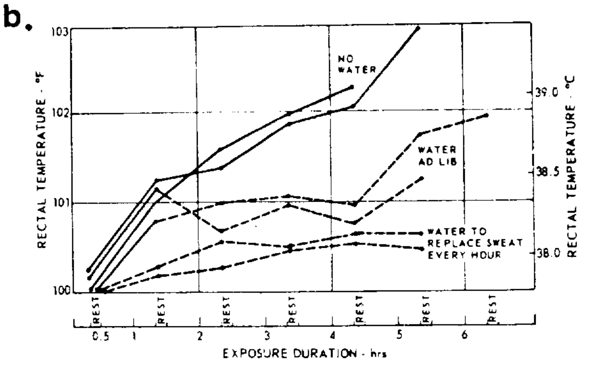
(After Blockley(30) from data of Adolph(3), Craig(59), Gerking and Robinson(84), and Wyndham et al(235))



Data are plotted here from six experiments on one subject, "fully acclimatized," of "better than average stamina," marching at 3.5 mph up a 2.5% grade, at 100°F and 20 mm Hg, with a 10-minute rest every hour. The more water drunk, the lower was the rectal temperature. Experiments with nude subjects resting at 110°F and vapor pressure of 25 mm Hg showed that they were able to maintain equilibrium only if they replaced water continuously. It may be concluded that failure to replace completely the water lost in sweat, hour by hour, leads to elevation of body temperature and excessive physiological strain. Thirst or the desire to drink is unreliable as an indication of the requirement for water intake to make up for heavy sweating.

Other work by the same authors has shown that replacement of salt at regular meal times is adequate, in contrast to the situation illustrated here for water.

(After Blockley(30) adapted from Pitts et al(161))



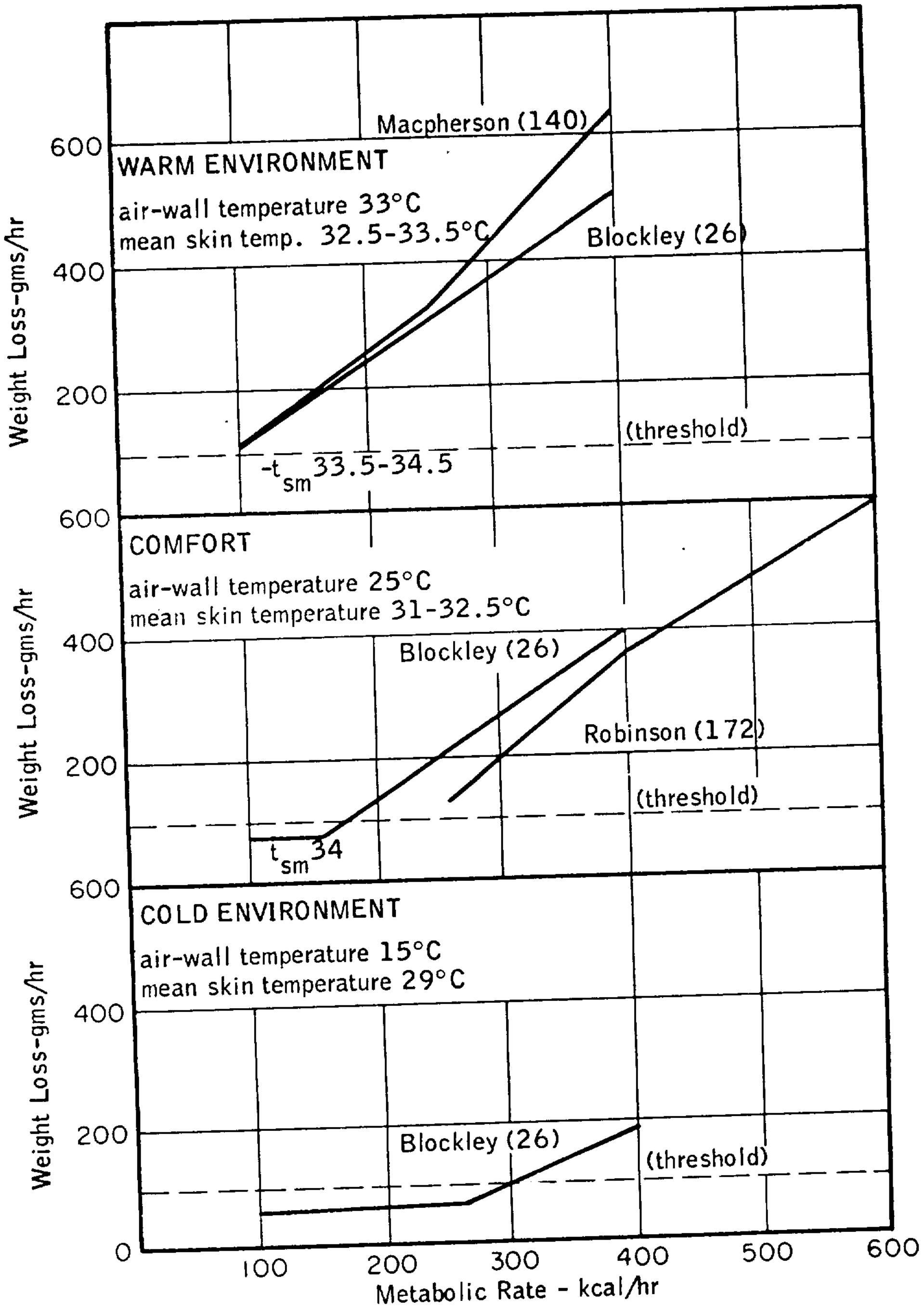


Figure 6-69

Sweat Rates as Functions of Metabolic Rate in Warm, Comfortable, and Cold Environments for Men in Shorts. The Threshold for Sweating is Taken to be a Rate of Weight Loss of 100 gm/hr.

(After Webb(215))

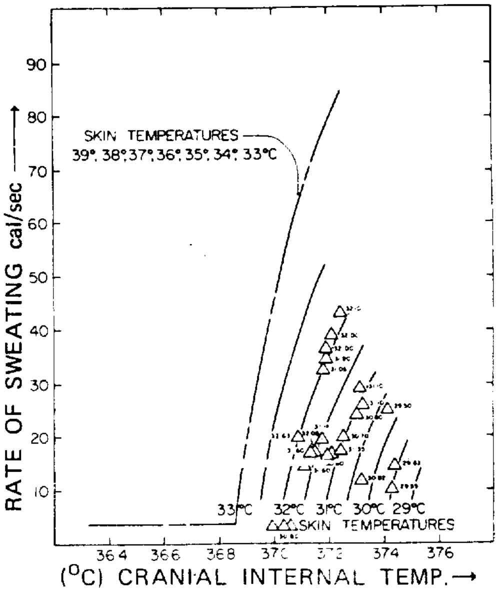


Figure 6-70

Intensity of Thermoregulatory Sweating of a Metabolically Active Man During Cold Reception at the Skin. Sweating Rates Were Plotted Against Internal Cranial Temperatures. Measurements Obtained at Similar Skin Temperatures Were Connected with "Best Lines." At Given Cranial Internal Temperature, Sweating Rates are Seen to be Diminished by Approximately 40 cal/sec for Every Degree C Decrease in Level of Skin Temperature.

(After Benzinger et al(17))

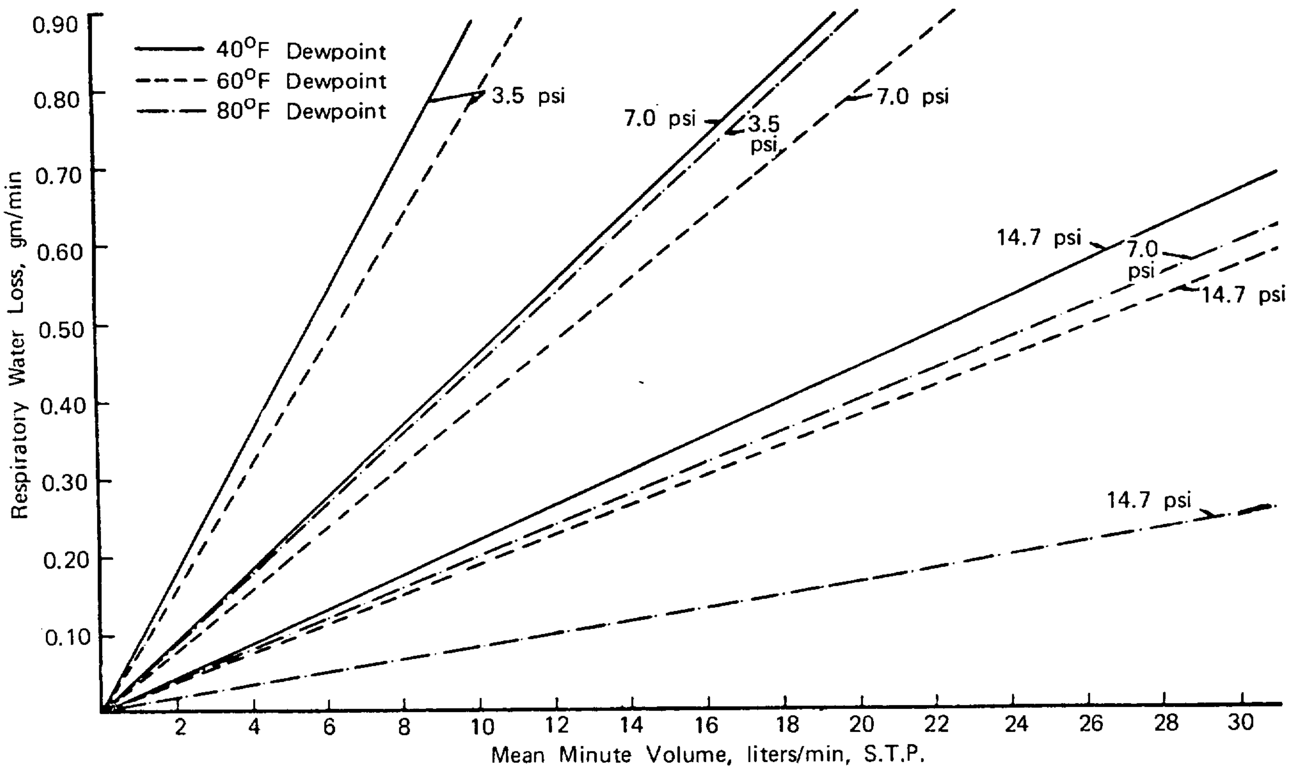


Figure 6-71

Respiratory Water Loss, Grams Per Minute, as a Function of Minute Volume, Liters Per Minute at STP, for All Work Rates and Drybulb Temperatures.

(After Wortz et al(232))

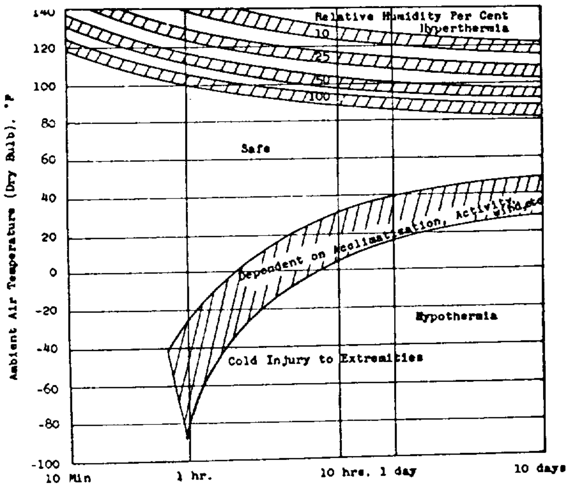


Figure 6-72

Approximate Human Time-Tolerance Temperature with Optimum Clothing

(After Breeze[36])

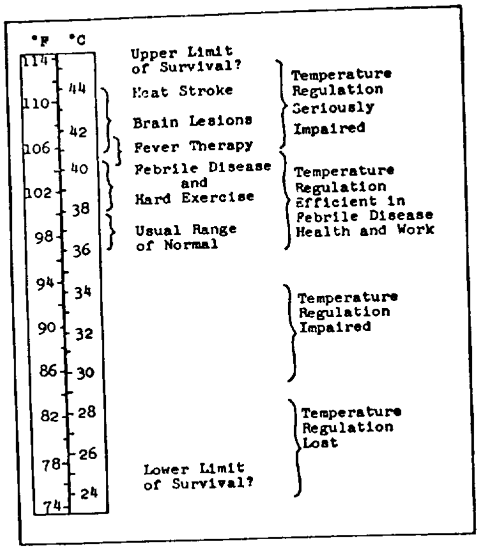


Figure 6-73

Human Body Temperature Extremes Defining Zones of Temperature Regulations

(After Breeze[36])

rates may limit evaporation rate to values below that required for adequate cooling.

The following equation can be used to determine the maximum conditions under which thermal balance can be maintained at rest, in air at S.L. (97).

$$q_m + 22(t_w - t_s) + 2\sqrt{\overline{V}}(t_w - t_s) = 10\overline{V}^{.0.4}(p_s - p_a) \qquad (45)$$

where q_m = energy of metabolism

t_w = mean radiant temperature of the walls (°F)

t_s = mean skin temperature (°F)

$\overline{V}$ = effective air velocity (ft/min)

p_s = vapor pressure of water at skin temperature (mm Hg)

p_a = vapor pressure of water in the atmosphere

Some environmental correlates of comfort and stress have already been covered in Section 2. The more physiologically determined indices will now be reviewed. A more detailed critique of the physically and physiologically determined heat stress indices is available (139).

The Belding-Hatch Heat Stress Index (HSI) (15)

This heat stress index is defined as the ratio of evaporation rate required for thermal balance to maximum perspiration rate safely attainable for prolonged periods -- both expressed in liters (of sweat) per hour, or:

$$HSI = \frac{E_r}{E_m} \times 100 \qquad (46)$$

The criteria on which heat stress index is based are:

1) body heat storage will not exceed the limit represented by a mean skin temperature of 95°F, and

2) E_m will not exceed 1 liter per hour-equivalent to 2400 BTU/hr (400 kcal/hr).

Figure 6-74 and Table 6-75 can be used as indicated to estimate the physiological and general function impairment of an 8 hr exposure at sea level to several stressful thermodynamic parameters.

The P4SR Index

The sweat rate can be used as a predictor of thermal stress in another way. The predicted four-hour sweat rate (P4SR) uses only the rate of sweating as a criterion of heat stress in environments that are hot enough to cause sweating (234). On the basis of British experimental work, empirical nomograms have been developed for predicting the probable amount of sweat in liters that would be secreted over a 4-hour period by fit, acclimatized men under different environmental conditions (67, 140, 186). A P4SR nomogram is seen in Figure 6-76.

The group of curves S1 and S2 in the center of the nomogram, running downwards from right to left, is the scale from which the basic 4 hr sweat rate (B4SR) is read. If the predicted 4 hr sweat rate (P4SR) is required for men sitting in shorts, the calculation is very easy as the P4SR is the same as the B4SR. All that is necessary is to join the appropriate point on the drybulb scale to the wetbulb temperature on the wetbulb scale corresponding to the air movement. The P4SR is given by the point where this line intersects the curve on Scales S1 and S2 corresponding with the air movement. Otherwise the P4SR is calculated in three stages.

In the first stage W. B. may require modification depending on the amount of radiation, the metabolic rate or the character of clothing. In the second stage the nomogram is used to obtain the B4SR and in the third stage the P4SR is obtained by adding certain constants to the B4SR depending on the metabolic rate (see wet bulb equivalent of metabolic rate in inset) and clothing. A P4SR of 4.5 liters was provisionally adapted as the upper limit of tolerance for physically fit men. Details regarding the 3 stage modification are available (140).

The P4SR, although derived under rather different conditions than expected in space flight, offers some hope if suitably extended (215). It was originally based on several types of experimental data taken on heat-acclimatized young men in Singapore and in environmental chambers. However, it is unsafe to use it as a means of predicting sweat rate unless all the conditions are similar to those originally used. Used with care, it does allow prediction of thermal effect in a number of different situations (26). The limitations are chiefly those of a narrow range of activity (up to 250 kcal/ m^2hr), limited clothing combinations, and the fact that all the subjects were heat acclimatized.

It is recommended that the P4SR not be used for predicting sweat rate, but for comparing environments in terms of thermal stress, to be followed by experimental evaluation of the environments, with sweat production being taken as one dependent variable (85). The data of Blockley which are shown in Figure 6-69 are examples of such usage of the index. More such usage could lead to useful extension of the P4SR scale to cover the environmental and physiological conditions of flight.

Body Storage Index (27)

The body storage index (q_s) is defined as the steady state rate of heat loss or gain to the body which results from imbalance in the biothermal equation. The body storage equation is:

$$q_s = \frac{WC_p}{A_b} \cdot \frac{dt_b}{d\theta} \ \text{BTU/ft}^2\text{hr} \qquad (47)$$

where W = body weight (lb)

C_p = 0.83 = spec. ht. of body (BTU/lb°F)

A_b = body surface area (ft^2)

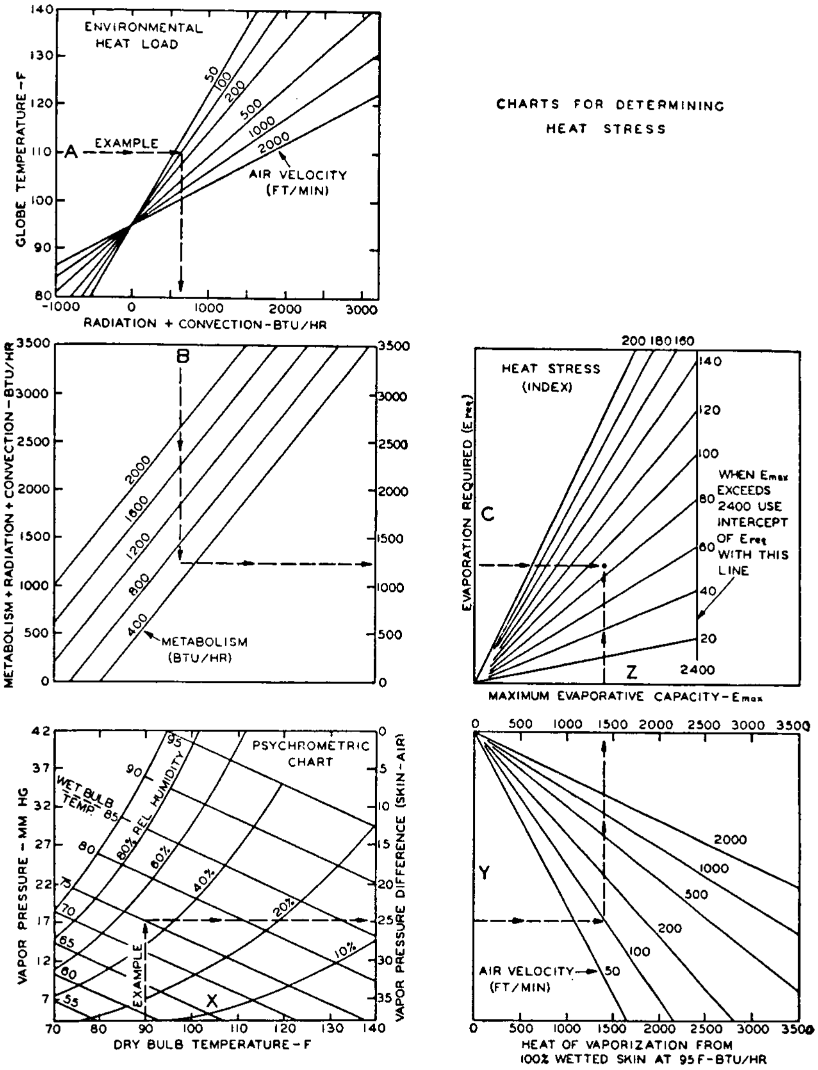
$\frac{dt_b}{d\theta}$ = rate of body temperature change (°F/hr)

and where $t_b = 0.33\ t_s + 0.67\ t_r$

Tolerance Time in Heat

The maximum tolerance time (θ_t) for heat gain which represents an emergency maximum for thermal stress is inversely proportional to the heat storage index:

$$\theta_t = 3300/q_s \text{(minutes) or } 55/q_s \text{ hrs.}$$



Example: Determine Heat Stress Index for worker doing light arm work while standing at a bench.

Metabolism	*600 Btuh*

Environmental conditions:

Globe thermometer temperature	*110 deg*
Dry-bulb temperature	*90 F*
Wet-bulb temperature	*75 F*
Air velocity	*100 fpm*

Solution: Follow the broken lines from the globe thermometer temperature and from dry-bulb temperature to their intersection on above diagram C to read a heat stress index of 90.

Figure 6-74

Flow Charts for Determining Heat Stress Index Values at Sea Level Conditions.

(After ASHRAE(7))

Table 6-75

Evaluation of Index of Heat Stress

(After ASHRAE(7))

Index of Heat Stress °F	*Physiological and Hygienic Implications of 8-Hr Exposures to Various Heat Stresses*
−20 −10	Mild cold strain. This condition frequently exists in areas where men recover from exposure to heat.
0	No thermal strain.
+10 20 30	Mild to moderate heat strain. Where a job involves higher intellectual functions, dexterity, or alertness, subtle to substantial decrements in performance may be expected. In performance of heavy physical work, little decrement expected unless ability of individuals to perform such work under no thermal stress is marginal.
40 50 60	Severe heat strain, involving a threat to health unless men are physically fit. Break-in period required for men not previously acclimatized. Some decrement in performance of physical work is to be expected. Medical selection of personnel desirable because these conditions are unsuitable for those with cardiovascular or respiratory impairment or with chronic dermatitis. These working conditions are also unsuitable for activities requiring sustained mental effort.
70 80 90	Very severe heat strain. Only a small percentage of the population may be expected to qualify for this work. Personnel should be selected (*a*) by medical examination and (*b*) by trial on the job (after acclimatization). Special measures are needed to assure adequate water and salt intake. Amelioration of working conditions by any feasible means is highly desirable, and may be expected to decrease the health hazard while increasing efficiency on the job. Slight "indisposition" which in most jobs would be insufficient to affect performance may render workers unfit for this exposure.
100	The maximum strain tolerated daily by fit, acclimatized young men.

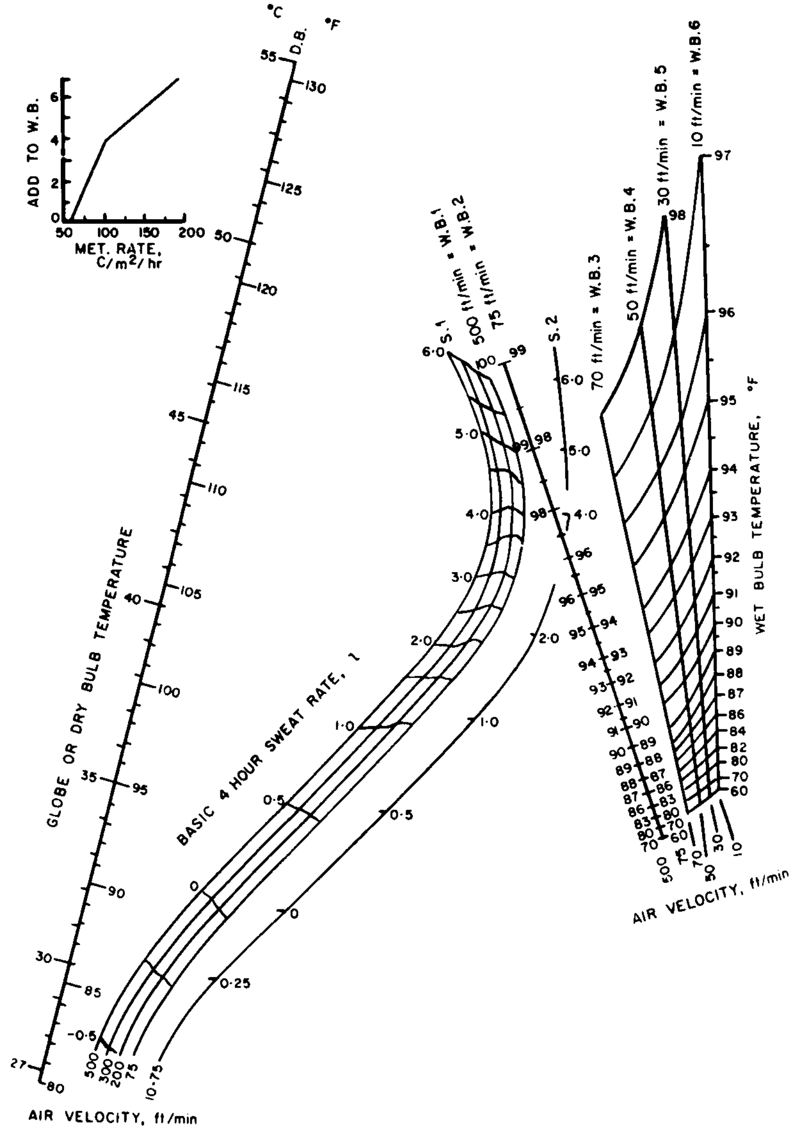


Figure 6-76

Nomograph for the Prediction of 4-Hr Sweat Loss (P4SR)

(After MacPherson$^{(140)}$)

The tolerance and general performance limits as a function of time and body heat storage are seen in Figure 6-77 (29). The heat storage at tolerance is inversely related to the rate of heat storage (88). There is recent evidence that men actively exercising in space suits can store up to 1000 BTU's in actively working muscle (233). This storage must be kept in mind during analysis of tolerance times in exercising subjects.

Figure 6-78 allows performance to be predicted through the heat storage index by following the dotted line and instructions. It should be remembered that these curves are for pilots undergoing normal resting activity in aircraft cabins. This fact must be considered in applying heat storage indices to predictive performance curves. Tolerance time can also be related to other heat stress indices (88, 139, 228).

Figure 6-79 indicates the conservative nature of earlier tolerance limits. The dashed lines represent the tolerance time levels more recently established (117) and reconfirmed(88). It will be noted that these are nearly double the solid-line limits established by earlier papers. It suggests that engineers, designing in terms of earlier tables, have been more restricted than necessary or have enjoyed a wide margin of safety even in the response of the most sensitive occupants. The ranges represented by these tables also reflect individual differences between subjects as well as differences in motivation. The dashed lines probably represent the capabilities of highly motivated space crews in top physical condition, and free of immediately prior physiological stresses.

The W/D index has often been used as a measure of tolerance time. Figure 6-80 represents the roles of exercise and W/D index in determining the time to collapse. Figure 6-81 uses the reference operative temperature. There are high correlations between the final skin temperature, rate of rectal temperature rise, rate of heart rate increase as linear functions of the W/D index (88). Comparison of the tolerance time for the heat stress using the Craig, effective temperature, P4SR and WGBT (aspirated) indices is available (88). These indices of heat stress tolerance can be used in limited sea level conditions related to post-landing emergencies and remote field-station operations.

Performance Under Heat Stress

As a general "rule-of-thumb" performance begins to deteriorate in any given condition at about 75% of the physiological tolerance limit. This is seen in Figures 6-77 and 6-81. Highly motivated individuals may prove capable of exceeding normally established performance and tolerance limits (202). However, excessive penalties in recovery time may be required if normal limits are exceeded. Even though no other stresses are anticipated or evident, it is suggested that the 75% of the average tolerance limit level not be exceeded until the significance of deconditioning which occurs during space flight is better understood. The synergism between prior dehydration by the diuresis of weightlessness and heat tolerance is discussed in Water (No. 15).

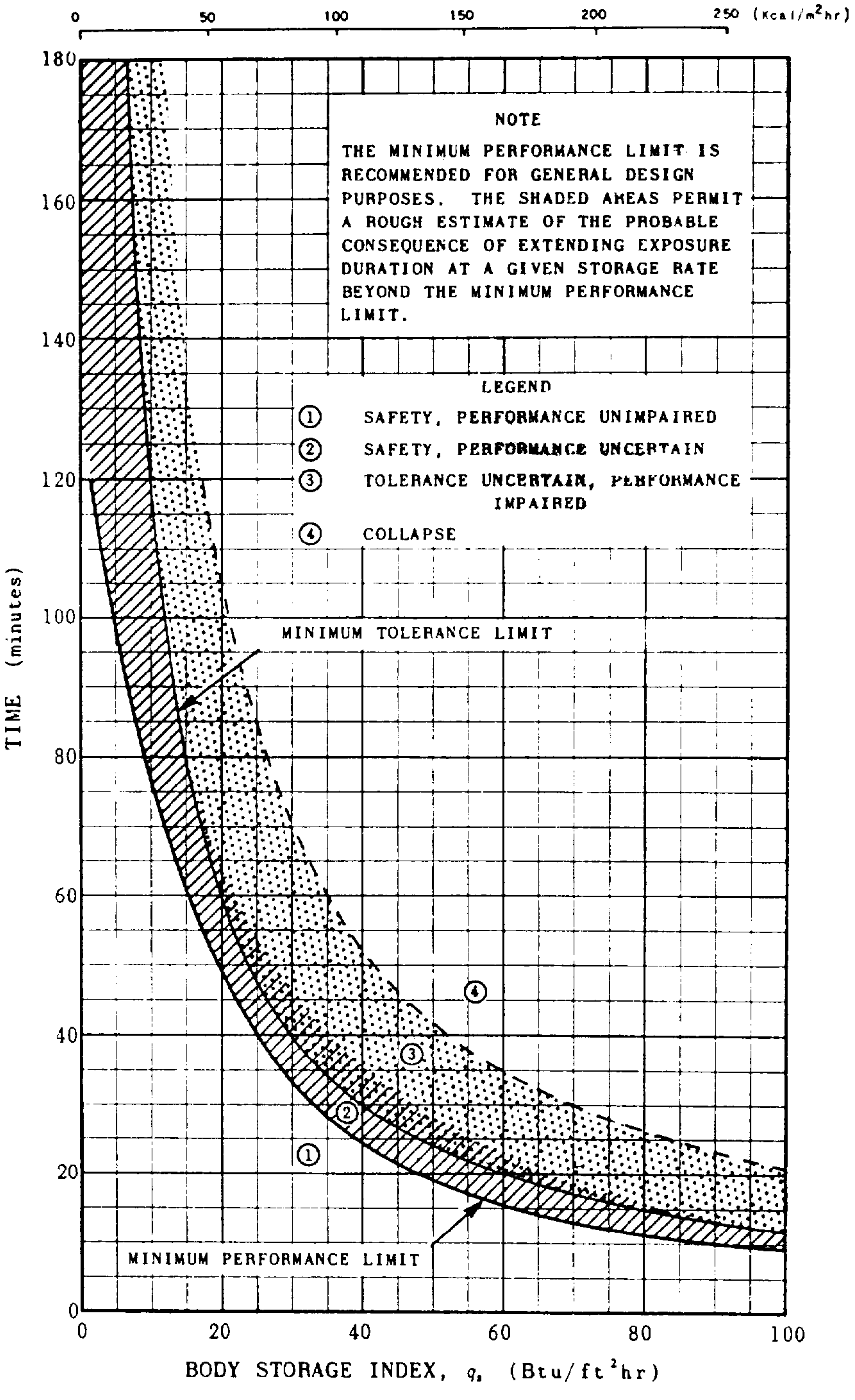
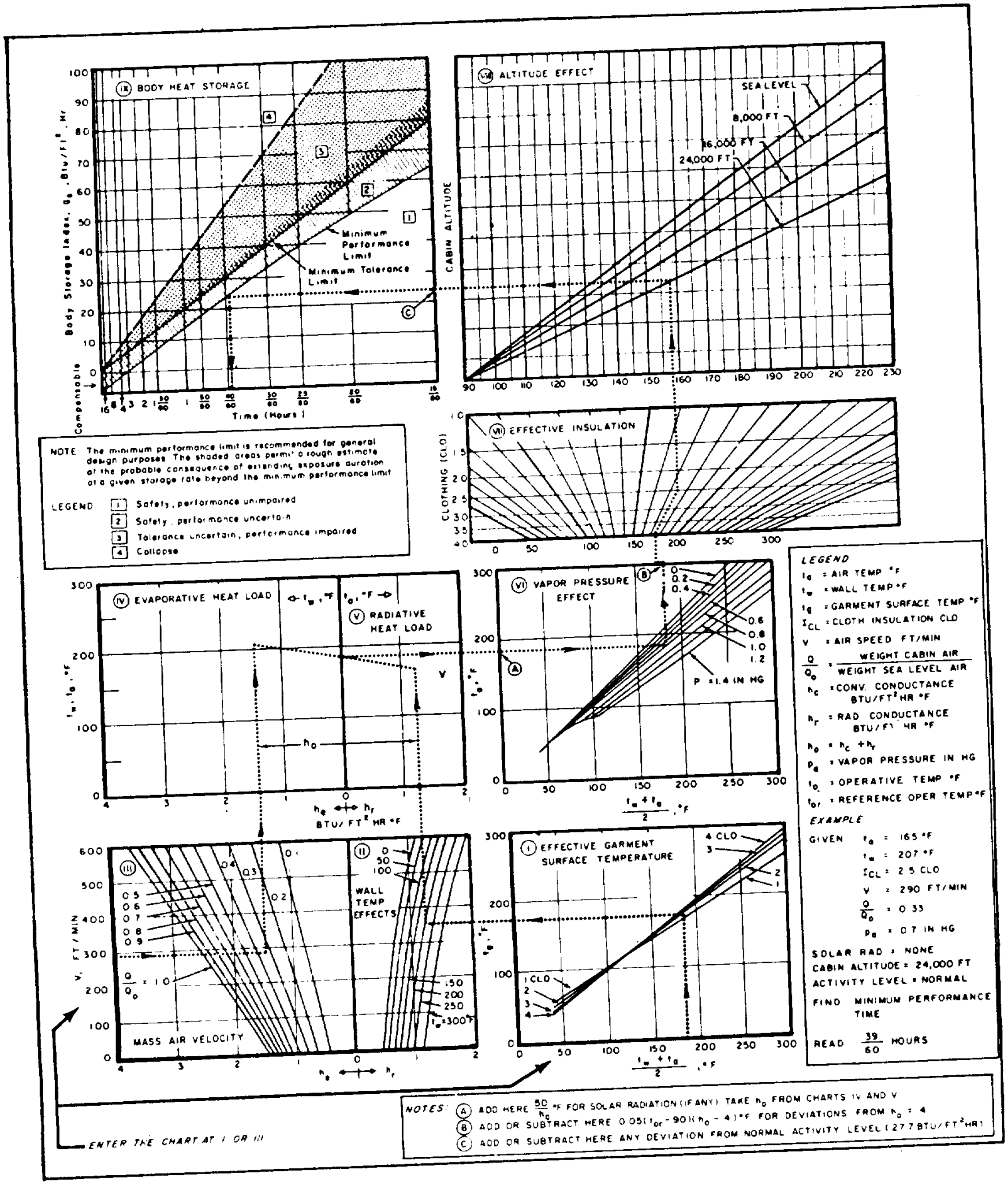


Figure 6-77

Performance and Tolerance Limits: Transient Zone

(After Blockley et al(27))



NOTE The minimum performance limit is recommended for general design purposes. The shaded areas permit a rough estimate of the probable consequence of extending exposure duration at a given storage rate beyond the minimum performance limit.

LEGEND
- 1 Safety, performance unimpaired
- 2 Safety, performance uncertain
- 3 Tolerance uncertain, performance impaired
- 4 Collapse

LEGEND

t_a = AIR TEMP °F
t_w = WALL TEMP °F
t_g = GARMENT SURFACE TEMP °F
I_{CL} = CLOTH INSULATION CLO
V = AIR SPEED FT/MIN
$\frac{Q}{Q_o} = \frac{\text{WEIGHT CABIN AIR}}{\text{WEIGHT SEA LEVEL AIR}}$
h_c = CONV. CONDUCTANCE BTU/FT^2 HR °F
h_r = RAD CONDUCTANCE BTU/FT^2 HR °F
$h_o = h_c + h_r$
p_a = VAPOR PRESSURE IN HG
t_o = OPERATIVE TEMP °F
t_{or} = REFERENCE OPER TEMP °F

EXAMPLE

GIVEN t_a = 165 °F
t_w = 207 °F
I_{CL} = 2.5 CLO
V = 290 FT/MIN
$\frac{Q}{Q_o}$ = 0.33
p_a = 0.7 IN HG
SOLAR RAD = NONE
CABIN ALTITUDE = 24,000 FT
ACTIVITY LEVEL = NORMAL
FIND MINIMUM PERFORMANCE TIME
READ $\frac{39}{60}$ HOURS

NOTES:
Ⓐ ADD HERE $\frac{50}{h_o}$ °F FOR SOLAR RADIATION (IF ANY) TAKE h_o FROM CHARTS IV AND V
Ⓑ ADD OR SUBTRACT HERE $0.05(t_{or} - 90)(h_o - 4)$ °F FOR DEVIATIONS FROM h_o = 4
Ⓒ ADD OR SUBTRACT HERE ANY DEVIATION FROM NORMAL ACTIVITY LEVEL (27.7 BTU/FT^2 HR)

Figure 6-78

Exposure Limits for Crew Members in a Space Cabin with an Air Atmosphere at 1 g. (After AFSCM 80-3[4])

Exercise performance decreases during hyperthermia (169). When mea body temperature was raised from control values of 35.5°C up to 38.1°C, th average treadmill times to exhaustion were reduced from control values of 4.63 minutes down to 3.31 minutes. Average reduction of 50% in $\dot{V}O_2$ max and 10% in O_2 debt (associated with a 15% decrease in blood lactate) were noted, though the oxygen requirement per minute of running time was unchanged from control values. Changes were attributed to conflicting demanc between cutaneous and muscular circulation.

Figures 6-81 to 6-88 reflect performance decrements as a function of ambient and effective temperature. Figure 6-88 reviews the previous data related to effective temperature for fine mental work. There are, of course certain limitations in the resulting performance curve. First, there are limits on the generality of the curve. It most adequately represents the performance threshold of artificially-acclimatized, military personnel durin learning or re-acquisition of highly stress-sensitive mental tasks. As such, the curve properly represents the lower-limit of an "impairment zone." Th threshold for some mental tasks, or for subjects highly practiced on tasks, or for naturally-acclimatized subjects may lie somewhat higher (i.e., in the zone between the present curve and the recommended physiological limit). Secondly, because the curve is plotted in terms of effective temperature, there is the danger of assuming that all the combinations of temperature, humidity and air speed which yield a given effective temperature also produc the same degree of performance decrement. This is undoubtedly not the cas Eventually performance decrements should be separately determined for a large number of combinations of temperature, humidity and air movement and reported in a tri-dimensional chart. However, such voluminous data are not yet available, and it is fortunate that the effective temperature scale could be used for establishing a tentative threshold for unimpaired mental performance. A recent review of this problem is available (157).

Table 6-89 summarizes the physiological response to heat. The debilitating effects of heat have received much attention (80, 127, 131, 221). Figure 6-73, and 6-74 set gross symptoms for different temperatures. Table 6-90 represents a classification of the symptoms to be expected.

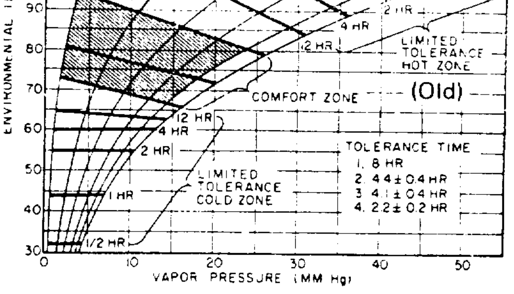
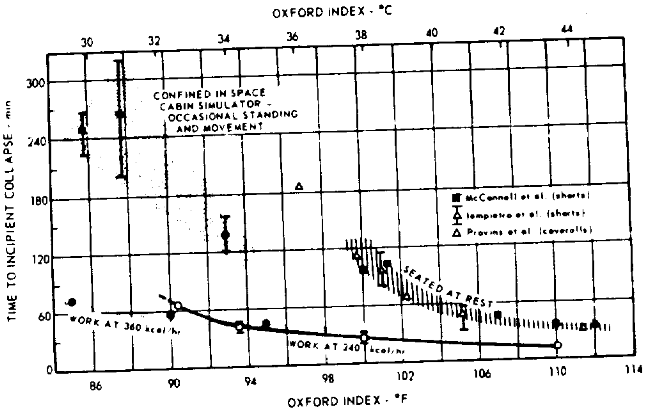


Figure 6-79

Maximum Tolerable Environments According to Duration of Exposure for Sitting, Clothed Subjects Under Sea Level Conditions in Aircraft Design. (See Text)

The tolerance limit at high temperature is based on faintness, dyspnea, nausea, and restlessness as an endpoint. Points 1,2,3, and 4 and the dashed lines for tolerance time represent more recent data and point out the conservative nature of previous design limits.

(After Trumbull(204) from data of Kaufman(117), Winslow et al(225), Taylor(197), and others.



The effect of activity on tolerance time for untrained men at sea level is shown for a wide range of heat stress conditions. Vertical bars indicate the range of times to incipient collapse. The dramatic influence of metabolic rate on endurance time in hot environments is emphasized here. The use of the "Oxford Index" (Fig. 6-12) permits intercomparison of environments ranging from very hot and dry to very humid and warm (vapor pressures as low as 7 mm Hg and as high as 70 mm Hg). Note the increase in variability at the milder conditions; It is in this same environmental stress zone that the effects of training for work in the heat ("acclimatization") are most striking, endurance times for trained men being several times as high as those of the same men when they are unused to heat stress.

Figure 6-80

Activity Level and Heat Tolerance

(After Blockley(30) from Data of Blockley(25), Provins et al(162), Iampietro et al(110), Kaufman(117), Leithead and Lind(127), and McConnell and Yaglou(134))

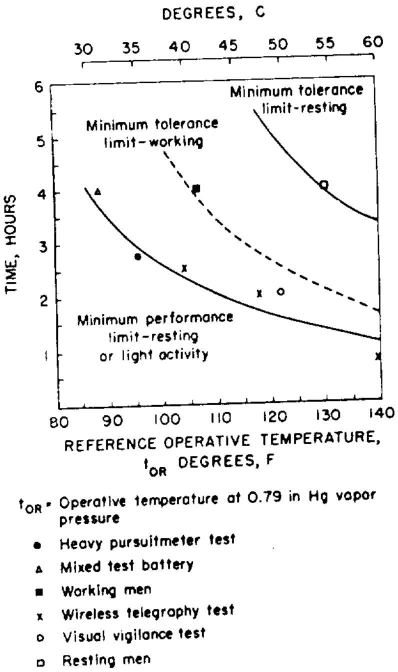


Figure 6-81

Performance and Tolerance Limits in the Quasi-compensable Zone for Lightly Dressed Men.

(After Blockley et al(27))

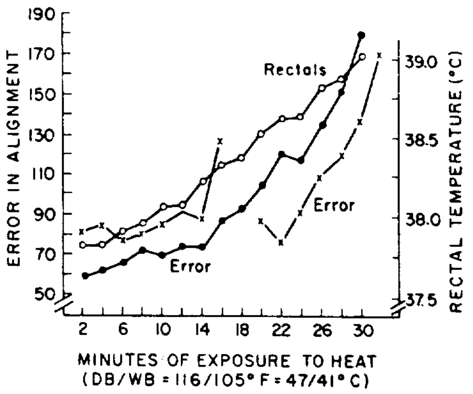


Figure 6-82

Continuous Error and Rectal Temperature Curves are the Means of Six Subjects. Interrupted Error Curve Based on One Subject. The Break Represents an Insertion of a Two-Minute Rest Period During Which Time the Subject Remained in the Environment.

(After Teichner(202) Adapted from Pepler(156))

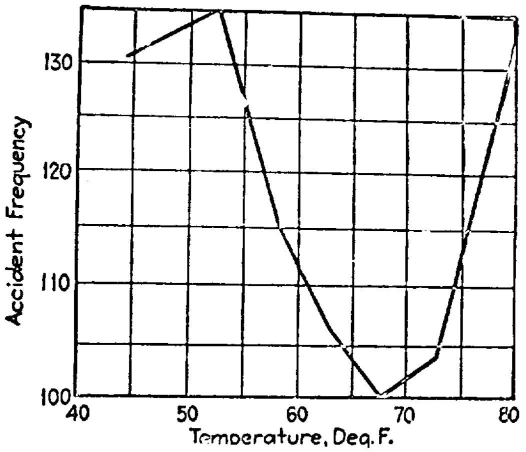


Figure 6-83

Frequency of Accidents in Relation to Cabin Air-Temperatures.

(After Breeze(36))

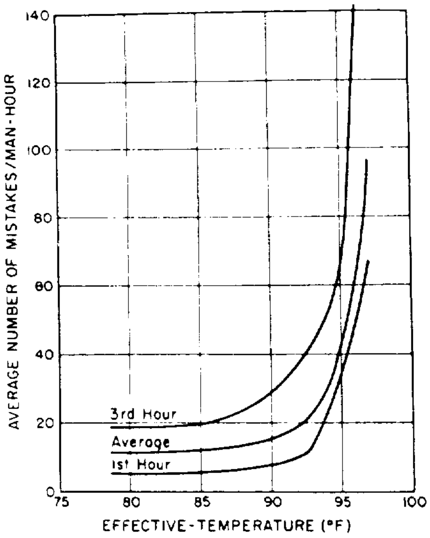


Figure 6-84

Combined Performance Averages for 11 Wireless Telegraph Operators Under Conditions of Extreme Heat.

(After Mackworth(137))

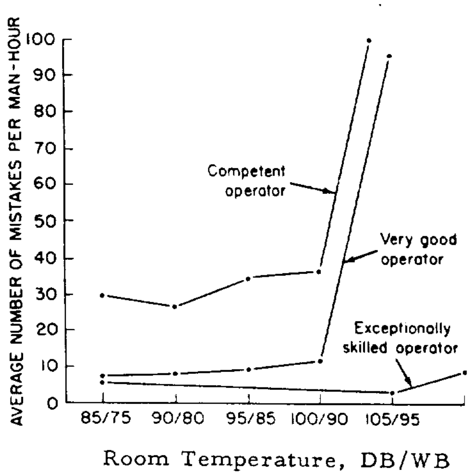


Figure 6-85

Room Temperature and Frequency of Error in Memory-Coordination Task.

(After Mackworth(137))

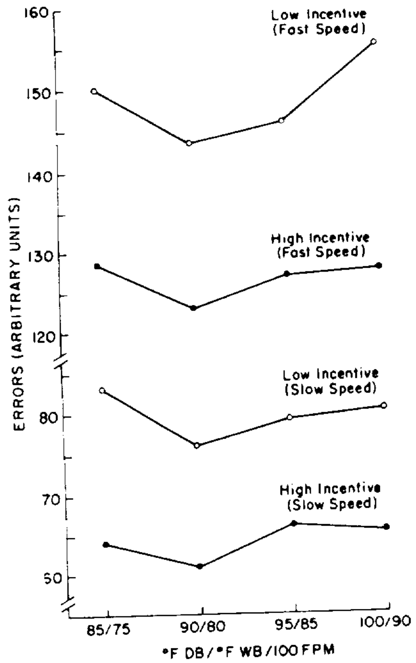


Figure 6-86

Effects of Incentives, Target Speed and Environmental Warmth on the Accuracy of Manual Tracking.

(After Teichner(202) Adapted from Pepler(156))

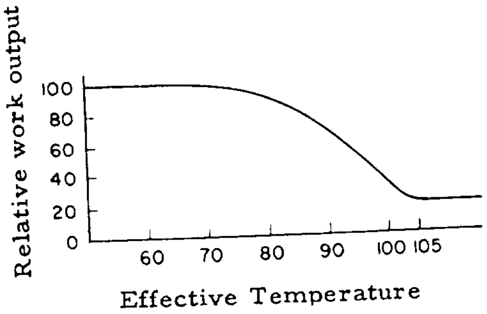


Figure 6-87

Relative Output of Hard Physical Labor (as % of Maximum ft-lbs/hr) at Various Effective Temperatures.

(After Yaglou(238))

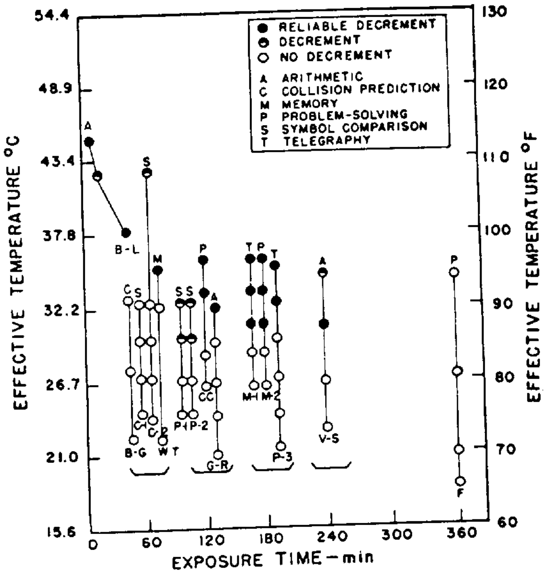


Figure 6-88

Summary Characteristics for the 14 Experiments on Performance Degradation at High Temperatures. Each Experiment is Represented by a Vertical Line with Initials of the Investigator(s) Beneath It. The Circles on a Line Are Test Temperatures. Solid Circles indicate Statistically-Reliable Impairment in Performance Half-Filled Circles Indicate Decrements Which Were Not Evaluated (or Were Improperly Evaluated) Statistically; and Open Circles Indicate No Decrement. Alphabetic Symbols Beneath the Vertical Lines Initials of Authors Quoted in Source Reference.

(After Wing(223))

Table 6-89

Effects of Environmental Temperature Change: Values are for Resting State

(After Spector(189))

		Increase of Environmental Temperature			Decrease of Environmental Temperature		
		Single Exposure Response		Repeated or Continued Exposure	Single Exposure Response		Repeated or Continued Exposure
Animal	Variable	General	15-20°C Inc.		General	15-20°C Dec.	
Man	Blood volume	Increase		Increase			Decrease
	Cardiac output	Increase		Return toward normal	Decrease		Return toward normal
	Food intake	Decrease	Variable	Decrease	Increase	Variable	Increase
	Heart rate	Increase	5/min	Return toward normal	Decrease	-5/min	Return toward normal
	Heat production	0 or slight ≠1		Some decrease	Increase	50 to 100 Cal^2	Increase
	Manual skill	Deteriorates		Return toward normal	Deteriorates		Return toward normal
	Packed cell volume	Slight decrease	-2 to 3%	Decrease	Slight increase	2 to 3%	Increase
	Rectal temperature	Increase	0.5 to 1°C	Return toward normal	Decrease	-1 to 2°C	Return toward normal
	Skin temperature	Increase	10 to 15°C	Return toward normal	Decrease	-10 to 15°C	Return toward normal
	Output of urine	Decrease	-200 to 500^3	Sustain low level	Increase	200 to 500^3	Sustain high level
	Blood flow^4	Decrease		Return toward normal	Increase		Return toward normal
	Water intake	Increase	400^3	Sustain high level	Decrease	-400^3	Sustain low level

/1/ No change or slight increase
/2/ Per sq m/hr.
/3/ ml/da.
/4/ Visceral

Table 6-90

Classification of Debilitating Effects of Heat

(After Buskirk and Bass(53))

Disorder	Cause	Symptoms	Prevention/First Aid
Heat Cramps	Excessive loss of salt in sweating with inadequate replacement	Pain and muscle spasm; pupillary constriction with each spasm. Body temperature normal or below normal	Normal diet and fluid intake. Rest, administer salt and water
Heat Exhaustion	Cardiovascular inadequacy; dehydration	Giddiness; headache; fainting; rapid and weak pulse; vomiting; cold, pale, clammy skin; small rise in body temperature	Frequent and early replacement of water, frequent pauses. Rest in shade in recumbent position. Administer fluids.
Heat Stroke	Failure of temperature regulatory center, due to excessively high body temperature	High body temperature; irritability, prostration, delirium; hot, dry, flushed skin. Sweating diminished or absent	Adequate pacing of activity, avoidance of severe effort by unacclimatized men in hot environment. Alcohol spray bath or immersion in cold water. Medical emergency requiring a physician.

Figure 6-91 represents the humidity and temperature maxima for cases of total heat stroke. Treatment of thermal emergencies in space has been reviewed (52).

Acclimatization to Heat

Acclimatization can alter the response of humans to heat loads (11, 35, 71, 74, 75, 96, 112, 124, 127, 129, 171, 235, 236). Figures 6-92 and 6-93 represent examples of the improvement in function which is possible through heat acclimatization. The major physiological adaptations in heat acclimatization have been summarized (71): "Deep tissue temperature is returned to the normal level set by the metabolic rate of the task in a cool environment, but neither total body temperature nor mean skin temperature are returned to their levels in the cool environment. Mean skin temperature is adjusted to a level which permits thermal equilibrium between the body and the environment on the one hand, and on the other, maintains an internal thermal gradient which permits the transport of the deep heat to the surface without overtaxing the circulation . . ." These conditions are attained almost wholly as a result of the increased evaporative cooling in which the efficiency, rate, and total volume of sweating are favorably improved by acclimatization.

Acclimatization is well retained for 1 to 2 weeks, after which it is lost at a variable rate. Most men lose the major portion of their acclimatization in 1 month -- a few are able to retain it for 2 months. Men who remain in good physical condition retain their acclimatization best. Repeated exposures to heat are required at intervals not exceeding 1 month, if a high degree of acclimatization is to be maintained for long periods of time. Newer techniques, pioneered by Fox in England concentrate on raising core temperature to the same fixed level each day, so that thermal strain, rather than the stress, remains constant throughout the acclimatization process (74). Improvement continues for longer periods and to greater levels than the standard exposure techniques. Heat acclimatization may not be as important in hot, wet environments where increased evaporative cooling cannot be produced even if there is an increased sweat secretion, since no increase in the internal thermal gradient between "core" and skin can be achieved (88). However, techniques for acclimatization en route to hot-wet climatic conditions are under study (165).

The practical value of heat acclimatization in space operations is still a controversial issue (52, 173). Current NASA opinion is centered on the concept that excellent physical conditioning of the astronaut will be adequate to cover anticipated thermal emergencies and not impose further on the already overburdened training schedule of the astronauts. The issue of interference with resistance to acceleration by the vasodilatory effects of heat acclimatization has been raised (see Acceleration, No. 7). Simultaneous heat and cold acclimatization is also a problem in future lunar and planetary operations (see discussion of this under cold acclimatization). More work in this area is necessary before formal recommendations can be stated.

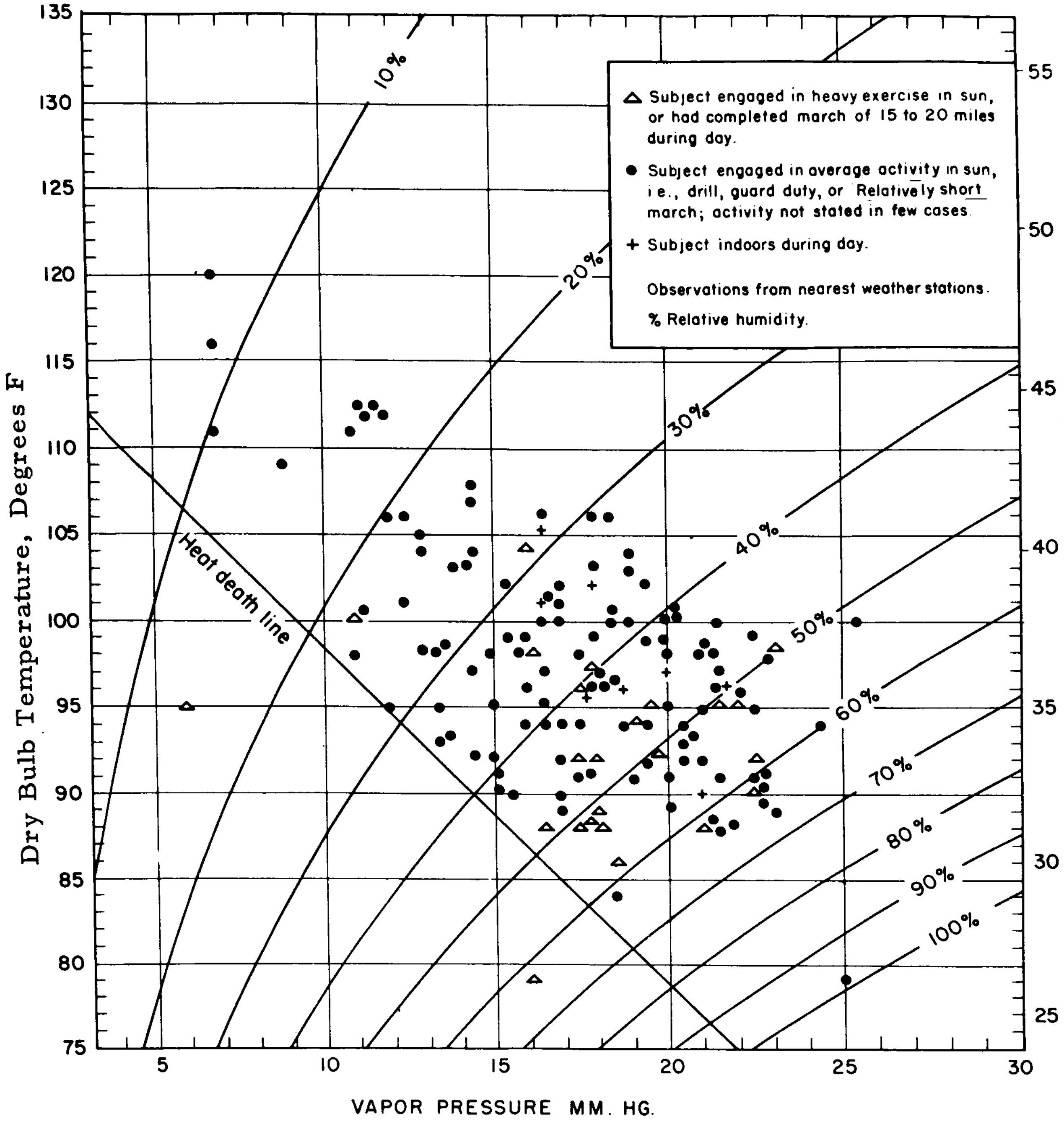


Figure 6-91

Humidity and Maximum Temperature on Day of Onset of 157 Cases of Fatal Heat Stroke in the U.S. Army, 1942-44.

(After Schickele(178))

Figure 6-92

Acclimatization to Heat

(After Blockley(30), Adapted from a. Wyndham et al(235), b. Lind and Bass(129))

a.

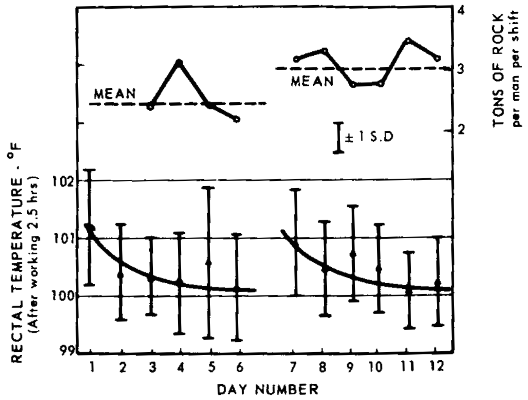


Figure a shows the results obtained with the standard acclimatization procedure used in South African gold mines to prepare laborers recruited from remote villages for work in saturated environments underground. The duration of the daily work period is five hours, and the work is shoveling rock under close supervision. For the first six days the Effective Temperature was 84° F; the next six days the E. T. was 89.5° F and the amount of rock shoveled was increased. Note the fall in rectal temperature--the curves are means for over 100 men, the bar shows ±1 S. D. --during each of the six-day work periods.

b.

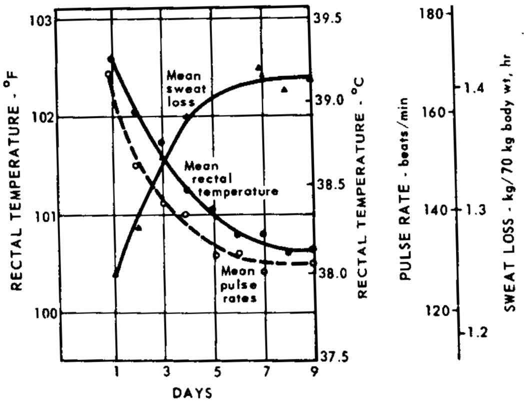


Figure b illustrates the results of a technique used at the U. S. Army laboratories at Natick, where men marched at 3.5 mph for 100 minutes each day in an environment of 120° F dry bulb, 80° F wet bulb, 200 ft/min air velocity (E. T. 89° F, vapor pressure 15 mm Hg). The value of the shorter exposure period technique in preparing men to work for long periods such as five hours or more in the heat is the subject of considerable controversy.

Newer techniques, pioneered by Fox in England, concentrate on raising core temperature to the same fixed level each day, so that thermal strain, rather than the stress, remains constant throughout the acclimatization process. (74)

Figure 6-93

Improvement in Function from Heat Acclimatization

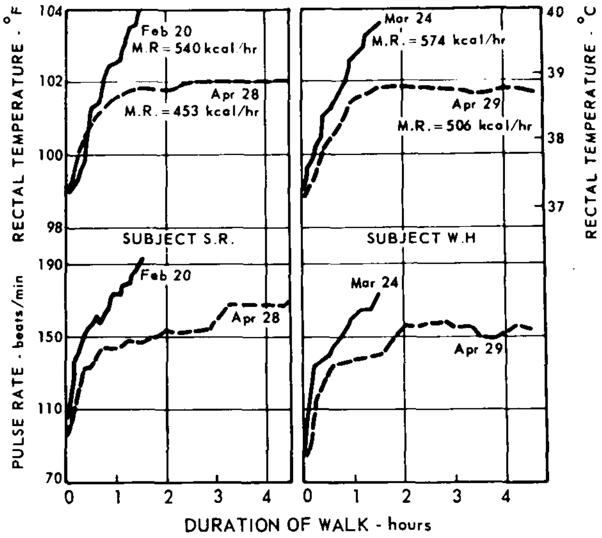
a.

These data dramatically illustrate acclimatization to heat as shown by the lowering of body temperatures and heart rates of two men walking at 3.5 mph on a 5.6% grade in room temperature of 104° F, vapor pressure 13 mm Hg(E. T. 84° F).

(1) Subject S. R. was acclimatized by 23 exposures to these conditions between February 20 and March 20. After March 20 his only exposures were on April 16 and 28.

(2) Subject W. H. was acclimatized by 11 exposures between March 24 and April 8. After April 8 his only exposures were on April 22 and 29.

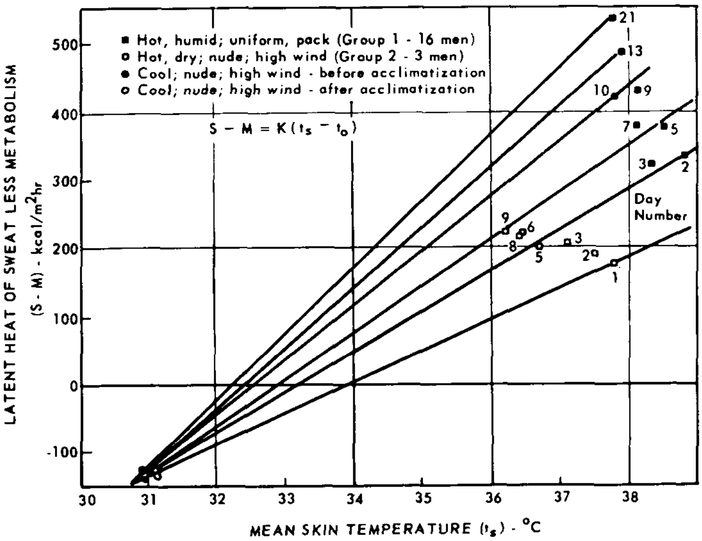
On the first exposure, the experiment was terminated by the collapse of the subjects at 90 minutes. After acclimatization, the men were still maintaining equilibrium with ease after 4.5 hours.



(After Blockley(30), Adapted from Robinson et al(171))

Figure b is a diagrammatic presentation of mean results from two studies of the heat acclimatization phenomenon. Subjects in both groups were drawn from the same Army population at Fort Knox, Kentucky. The two studies are related by means of a parameter combining the sweat rate (expressed as its caloric value if evaporated) and metabolic rate. The slope of the straight lines in the diagram represents an estimate of the sensitivity of the sweat response to increases in temperature of the peripheral tissues or blood (expressed as a function of surface temperature and metabolic heat output). It can be seen that when men are unclothed and the air is dry, sweat rate changes but little, but the skin temperature needed to produce that amount of sweat becomes steadily lower in successive exposures; when the climate is humid, and evaporation is impeded by clothing, the skin temperature does not change much on successive days, but the quantity of sweat produced at that temperature is enormously increased as acclimatization progresses.

b.



(After Blockley(30), Adapted from Hanifan et al(96), Eichna et al(71), and Horvath and Shelly(105))

Skin Pain and Heat Pulses

Tables 6-64, 6-65, 6-94, and Figure 6-95 cover the pain thresholds for the skin from conductive, radiant and convective heating. In general, the pain threshold is reached when the skin attains a temperature of 45°C. Figure 6-96 shows the influence of skin temperature on the thresholds of three sensations, pain from heat, warmth, and cold (69). The average value of the cold thresholds between 16°C and 24°C air temperature is -0.25, ±0.061 millical/cm^2/sec., and increased (absolute energy change) to -0.67, ±0.073 millical/cm^2/sec. between 35°C and 40°C. There was no change in the warmth thresholds, which were +0.32, ±0.081 millical/cm^2/sec and +0.32, ±0.075 millical/cm^2/sec., respectively, for the above air temperatures. Indirect evidence is offered that the rise in the cold thresholds in the higher environmental temperatures is associated with vasodilation of the blood vessels in the skin. The face and the neck are most sensitive to thermal stimuli and the backs of the hands are next (99).

The ability of the body to withstand high heat pulses is shown in Figure 6-97. A computer program is available for evaluation of time-temperature histories of the skin at different depths following heat pulses (211).

COLD STRESS

Exposures to cold stress are not as likely to occur during space flight as heat stress. This is due primarily to man's capability for generating heat and the relative ease with which he can be insulated against heat loss to the space environment by provision of adequate clothing. Except for nocturnal operations on the lunar surface, the likelihood of cold exposure after return to Earth is much greater and must be considered in the design of survival gear and plans for recovery (173).

A simplified heat loss equation can be obtained from Equation 1 indicating that the total heat lost from the body surface to the environment, $\bar{H}$, is (54):

$$\bar{H} = q_s + q_m = K(t_s - t_a) + q_e \qquad (48)$$

where $\bar{H}$ = total heat loss

K = a constant which depends on humidity, ventilation, and clothing

t_s = average skin temperature

t_a = ambient air temperature

q_e = evaporative heat loss

If evaporative heat loss is ignored, as it can be in the cold, the equation becomes:

$$\bar{H} = K(t_s - t_a) \qquad (49)$$

Heat loss from the interior of the body to the surface is similar:

$$\bar{H} = K' (t_b - t_s) \qquad (50)$$

Table 6-94

Pain from Conductive Heating

(After Blockley[30], Adapted from North American Aviation[152])

Body Area	Clothing Worn	Metal Surface Temperature	Average Tolerance Time seconds
Hand	Bare skin	120	10-15
Kneecap	Bare skin	117	34
	Bare skin	120	5
Fingertip	AF/B-3A leather gloves	150	12.6
	AF/B-3A leather gloves	160	7.3
Hand - palm	AF/B-3A leather gloves	150	25.2
	AF/B-3A leather gloves	175	9.7
	AF/B-3A leather gloves	185	8.0
Forearm	SAC alert suit	150	20.6
	SAC alert suit	175	8.0
Upper arm	K-2B light AF flight coverall	150	7.5
	SAC alert suit	150	31.3
	Alert suit plus Brynje net string underwear	300	7.2
	K-2B suit	150	18.1
	K-2B suit plus Brynje underwear	150	61.9
Buttocks	SAC alert suit	150	70.3
	Alert suit plus Brynje underwear	300	21.7
	K-2B suit	150	32.5
	K-2B suit plus Brynje underwear	150	+90
Mid-thigh	SAC alert suit	150	35.6
	Alert suit plus Brynje underwear	300	13.1
	K-2B suit	150	13.6
	K-2B suit plus Brynje underwear	150	+90
Kneecap flexed	SAC alert suit	150	14.4
	Alert suit plus Brynje underwear	175	9.5
	K-2B suit	150	7.3
Calf muscle	SAC alert suit	150	14.4
	Alert suit plus Brynje underwear	300	11.4
	K-2B suit	150	13.2
	K-2B suit plus Brynje underwear	150	66.1
Upper arm	MD-3A wool-nylon anti-exposure suit	300	12.0
	MD-3A wool-nylon anti-exposure suit	400	10.2
Forearm	MD-3A suit	250	15.9
Palm of hand	Aluminized asbestos glove	250	13.5
Back of hand	Aluminized asbestos glove	250	5.2
Palm of hand	Arctic mitten	300	18.7
	Arctic mitten plus B-3A glove	300	37.0
	Arctic mitten plus B-3A glove	400	27.6
	Pigskin '800°F' heat glove	300	30.7
	Pigskin '800°F' heat glove	400	21.0
	Pigskin '800°F' heat glove	500	18.5

Notes: Light touch pressure (less than 1 psi) applied to heated metal surface. The elbow and knee sometimes received second degree burns without pain.

Figure 6-95

Pain from Radiant and Convective Heating

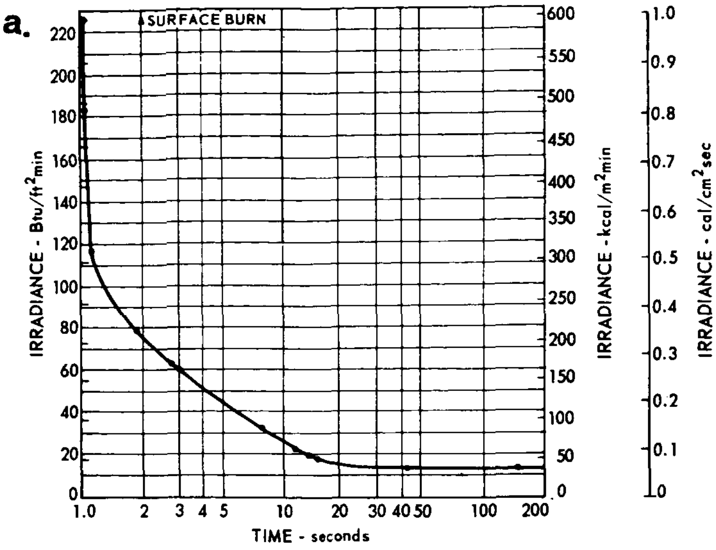
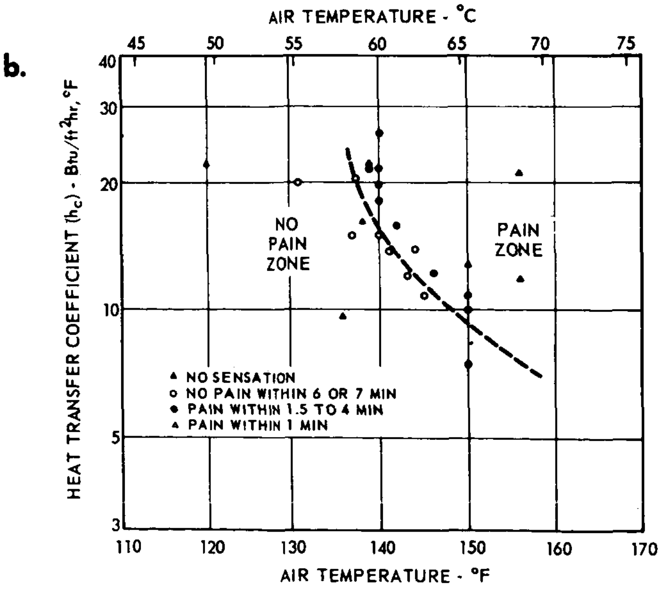


Figure a shows the time to reach strong skin pain from radiant heating, with radiation sources ranging from the simulated intense thermal flash of a nuclear weapon (approximately 100 Btu/ft^{2}min) to the slow heat pulse associated with re-entry heating, where the heating is partly convective as well. The curve is derived from experiments involving heating of single small areas of forehead or forearm or exposed areas of skin of a subject in flight clothing, and of the whole body surface. The pain threshold is reached when the skin temperature comes to 45° C, and a skin temperature of 46° C is intolerably painful. For small skin areas the curve becomes asymptotic at about 18 Btu/ft^{2}min, which means that at this level and below, the blood supply to the skin is carrying off the heat as fast as it arrives, and heat is stored in the body; how long this can go on with the total body exposed is not established.

(After Blockley(30), Adapted from Buettner(40), Hardy(101), Kaufman et al(118), Stoll and Greene(191), and Webb(217))



These data indicate the dividing line between painful and non-painful heating for air at various temperatures, versus the heat transfer coefficient, which depends on air density, air velocity, and surface areas and shape. The data were obtained by exposing a small segment of the cheek to a flowing air stream through a padded hole in the wall of a cylindrical tube. h_c was computed from air velocity and duct geometry.

(After Blockley(30), Adapted from North American Aviation(152))

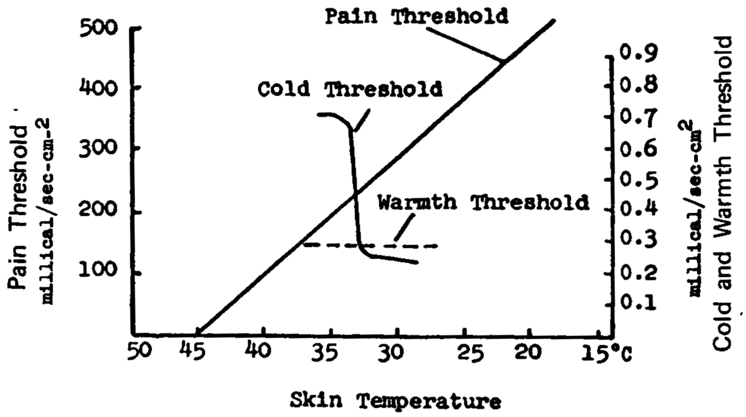


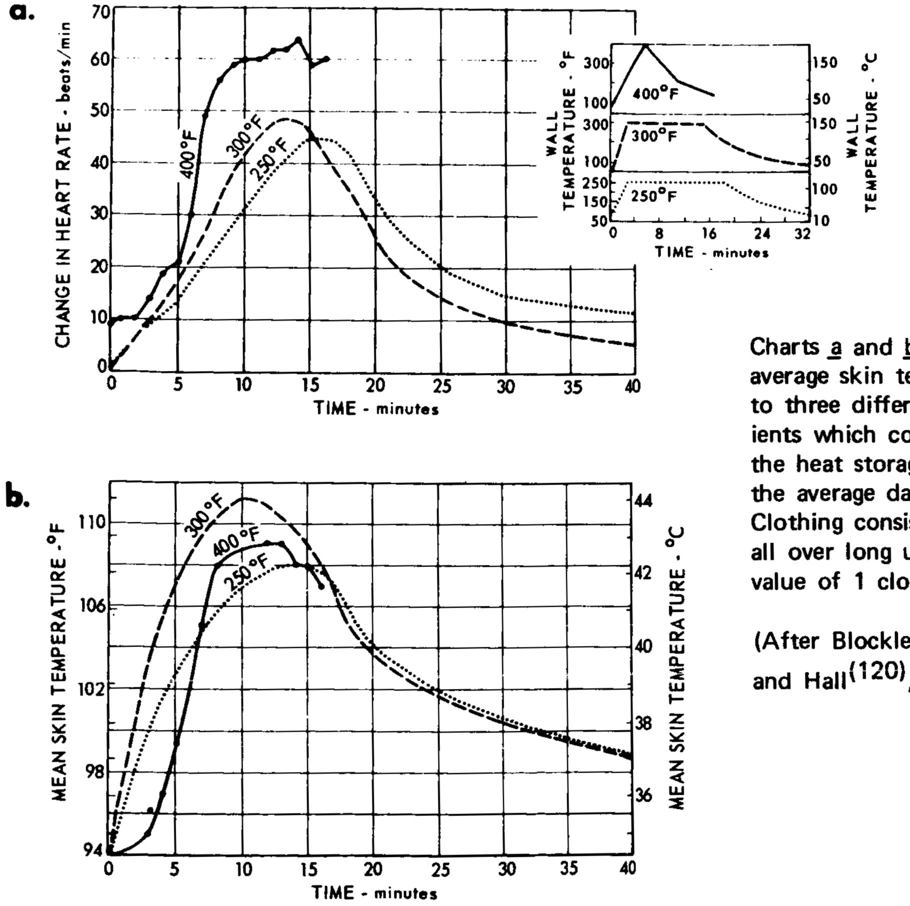
Figure 6-96

Influence of Skin Temperature Upon Thresholds of Warmth, Cold, and Pain.

(After Breeze[36])

Figure 6-97

Tolerable Heat Pulses



Charts a and b show the pulse responses and average skin temperatures of subjects exposed to three different severe heat exposure transients which come close to both pain limit and the heat storage limit. Each curve represents the average data from five or six subjects. Clothing consisted of a standard flying coverall over long underwear with an insulation value of 1 clo.

(After Blockley[30], Adapted from Kissen and Hall[120], Kaufman[117], and Webb[217]) gure 6-97 (continued)

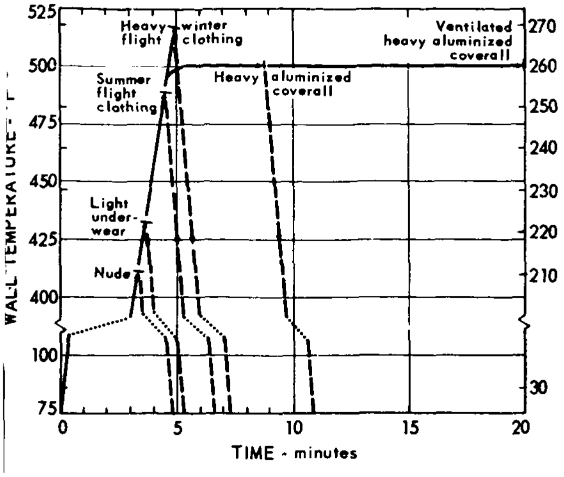
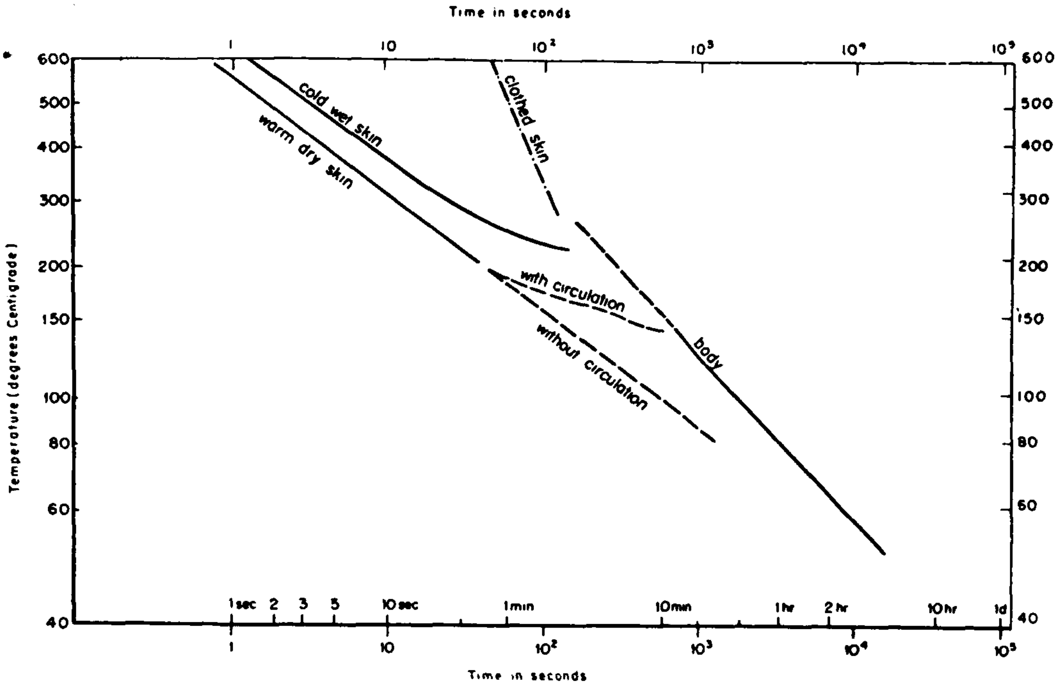


Chart c shows the increase in tolerance times (voluntary limit when surface pain becomes unbearable) for subjects exposed to a heat pulse where wall temperature was increased at 100°F/min, and the subjects wore clothing affording various degrees of protection. Each limit represents average data for from 3 to 10 subjects. When an aluminized surface was used with a heavy coverall, the protection increased again; exposures were changed in form – the increase in wall temperature was stopped at 500°F and that temperature held until tolerance was reached. Adding ventilation with air at about 85°F allowed these exposures to last beyond 20 minutes.

(After Blockley[30], adapted from Kissen and Hall[120], Kaufman[117], and Webb[217])

d.



Tolerance time for man in a hot environment. The time scale indicates pre-pain time for exposure of the skin to radiant heat, and escape time for curve marked body. The latter refers to a lightly clad man with face exposed. The temperature scale denotes room temperature for the body curve and radiation temperatures for curves referable to the skin. The curve marked warm dry refers to experiments with an initially dry skin, and a skin temperature initially of about 30°C. A tourniquet was applied to obtain the data marked without circulation. The cold wet curve utilized skin exposed wet at an initial skin temperature of about 15°C. The clothed skin curve was obtained using skin covered with 1 cm insulating cloth with an initial skin temperature near 30°C.

(After Buettner[41] from the data of Blockley and Taylor[28], Pfleiderer and Buettner[160]) where K' = a constant which depends on tissue conditions

t_b = internal body or core temperature

Since heat loss ($\overline{H}$) is the same in both equations, then:

$$K' (t_b - t_s) = K (t_s - t_a) \qquad (51)$$

and

$$K'/K = (t_b - t_s)/(t_s - t_a) \qquad (52)$$

which is called a "thermal circulation index" because if humidity, ventilation and clothing are held constant, then K'/K will depend largely on circulation (197). This ratio may be used as an index of the physiological state of the tissue or of physiological stress in the cold. From it may also be derived the heat loss of circulatory convection (54).

Inspection of K'/K shows that the most important quantities are air, body, and skin temperatures. As discussed under Heat Stress, body temperature is usually estimated with rectal temperature; skin temperature is taken as an average of selected points on the body surface each appropriately weighted by the surface area it represents. The value of q_s depends upon t_b, t_s, the mass changing temperature and specific heat of the tissue. This highly simplified equation 48 hides a number of complexities and does not isolate the specific contributions of radiative, convective, conductive, and evaporative heat losses (See Figure 6-56 and Equations 39, 40, 41). More detail is available (48, 54, 151).

Shivering ensues when heat losses to the environment exceed the metabolic energy being produced by the body. The shivering reaction increases skeletal muscle activity (without doing measurable work) and results in an increase in metabolic heat production. A two-fold increase in metabolism due to shivering has been observed after exposure to an ambient temperature of 41°F (5°C) for more than one hour. A five-fold increase in metabolism due to shivering is considered to be the maximum attainable (43). While shivering may add enough to metabolic heat production to prevent further heat loss it is never sufficient to replace heat already lost. The shivering response may be triggered by the rate of temperature fall of the body and not the temperature per se (47).

The body does not similarly respond to warm environments by reducing metabolic heat production. Instead, as body temperature increases, metabolic heat production increases in accordance with Van't Hoff's law (i.e., a 10°C rise in temperature will increase the velocity of a chemical reaction by a factor K, where $2 < K < 3$).

For a body at rest the temperature coefficient of metabolism can be expressed mathematically:

$$q_m = a_{(BMR)} (1 + 0.12\Delta\, t_b) \qquad (53)$$

where Δt_b = rise in body temperature above 37°C - (°C).

Figure 6-55 covers shivering thresholds of skin temperature during several metabolic loads.

Cold Stress Tolerance

The effective loss of about 80 kcal/m^2 or 31 BTU/ft^2 has been taken as the maximum heat loss a person can tolerate with severe discomfort (189). The heat available for loss can therefore be taken as $0.75\ q_m + 80\ \text{kcal/m}^2$ where q_m is the metabolic rate in $\text{kcal/m}^2\text{/hr}$. Sleep of unacclimatized Caucasians will be disturbed by restlessness at 50% of this loss rate. The lowest ambient temperature at sea level which can be tolerated for prolonged thermal equilibrium is a function of the exercise rate, insulation, wind speed, and several other variables. A rough estimate of this critical temperature at very low wind velocities may be obtained by the equation (189):

$$t_a = \frac{5.56\, t_s - (I \times H)}{5.56} \qquad (54)$$

t_s = mean skin temperature in °C assumed to be 32°C in the cold.

I = total insulation against convective and conductive loss in Clo units where 1 Clo = insulation maintaining a temperature difference of .18°C for a flow of 1 $\text{kcal/m}^2\text{/hr}$.

H = total heat available for convective and radiative loss or 0.75 times the metabolic rate (q_m) in $\text{kcal/m}^2\text{/hr}$ under equilibrium conditions.

Figure 6-98 may be used as a rough estimate of relative comfort levels at different metabolic rates and under different ambient temperature and insulation conditions. It is invalid for wind speeds above 20 ft/min.

An empirical expression for the total cooling power of the environment, disregarding evaporation, is called Windchill (109):

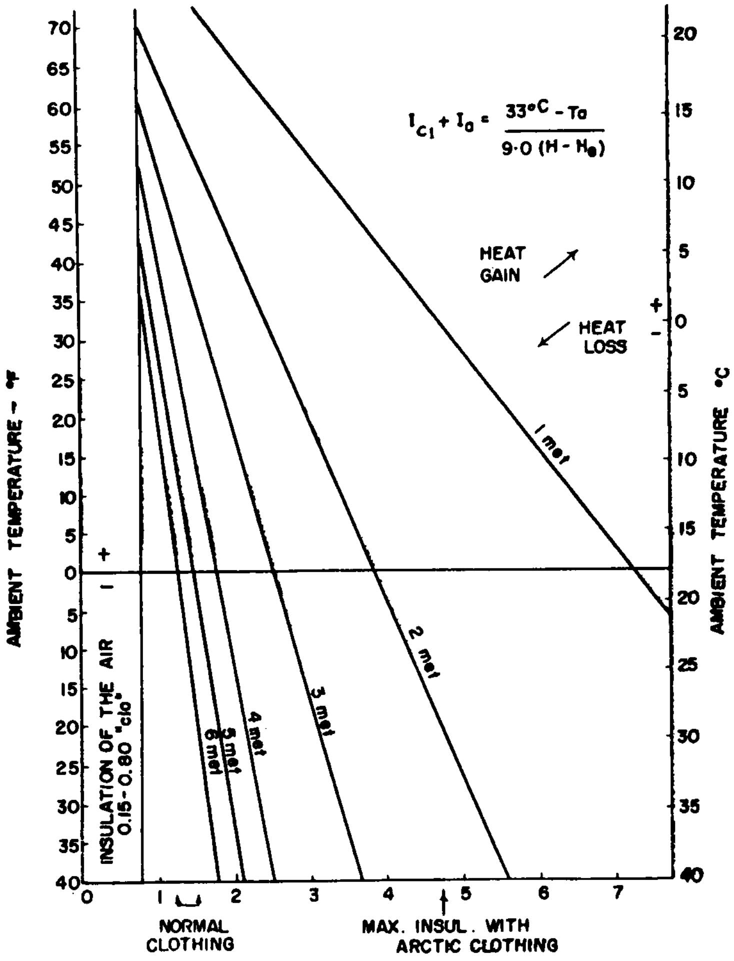
$$K_c = (\sqrt{\bar{V} \times 100} + 10.5 - \bar{V})\ (33 - t_a) \qquad (55)$$

where K_c = windchill, i.e., total cooling in kilogram calories per square meter per hour

$\bar{V}$ = wind velocity in meters per second

t_a = air temperature in °C

While K_c is not representative of human cooling, and is probably not very closely representative of physical cooling either, windchill has come into common use as a single-valued index of the severity of the temperature-wind combinations. As such it provides a descriptive quantity against which human cooling phenomena can be evaluated. A nomogram, giving rapid approximations of windchill is provided as Figure 6-99. When the



1 met = 50 kcal/hr·m^2

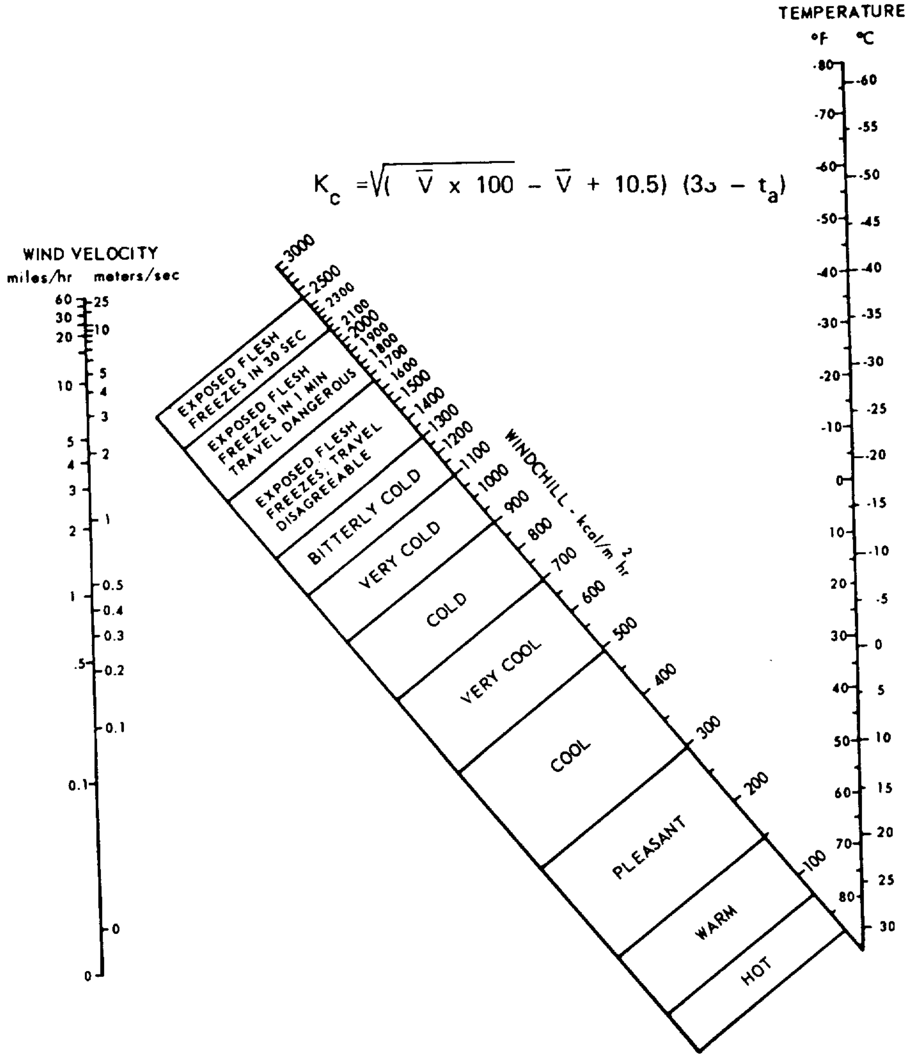
1 Clo = 0.18°C/kcal·m^2·hr

This chart shows the approximate relationship between ambient temperature and the units of insulation (expressed as "Clo") required to maintain thermal comfort. It will, in addition, indicate the varying degrees of heat loss (or gain) and levels of thermal equilibrium under varying degrees of heat production and exercise. No estimates can be made with this diagram to include the effects of wind velocity greater than 20 ft/min.

Figure 6-98

Comfort Levels at Various Ambient Temperatures with Different Levels of Heat Production

(After Adams$^{(1)}$)



$$K_c = \sqrt{(\ \bar{V} \times 100} - \bar{V} + 10.5)\ (33 - t_a)$$

In outdoor cold weather, the wind velocity has a profound, sometimes decisive, effect on the hazard to men who are exposed. The windchill concept dramatizes this well known fact by providing a means for quantitative comparison of various combinations of temperature and wind speed. Note for example that -50° F with an air movement of 0.1 mph has the same windchill value, and therefore is predicted to produce the same sensation on exposed skin, as -15° F with a wind of only 1 mph or +14° F with a wind of 5 mph. The windchill index does not account for physiological adaptations or adjustments and should not be used in a rigorous manner. It is based on field measurements by Paul Siple during World War II of the rate of cooling of a container of water.

Figure 6-99

Windchill Nomogram

(After Blockley(30), Adapted from Consolazio et al(58) and Siple and Passell(184)) rate of body heat production is greater than the windchill, excess heat is removed by evaporation; under bright, sunny conditions, the nomogram values should be reduced approximately 200 kg. cal. Figure 6-100 represents the heat lost by men under different windchill conditions in the nude.

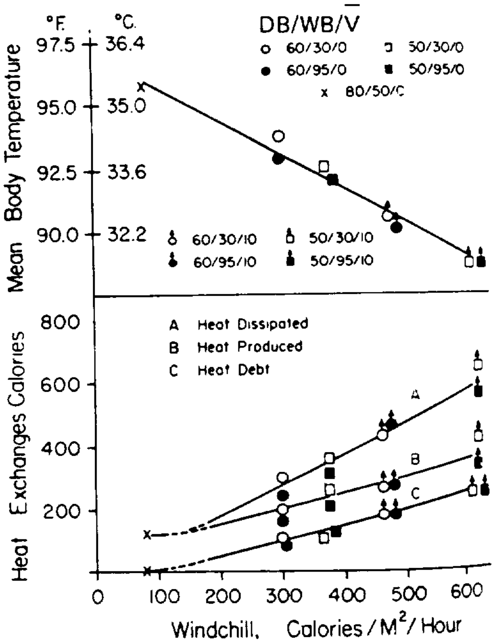


Figure 6-100

The Relationship of Mean Body Temperature and Heat Exchanges of Six Men to Windchill, after 100 Minutes of Exposure in the Nude.

The conditions are coded as dry bulb temp (^{o}F)/ relative humidity (%)/ windspeed (mph).

(After Iampietro, Bass, and Buskirk$^{(109)}$)

In military operations or when the wetting of feet is a problem, the freezing of flesh begins at variable levels lower than 1400 windchill. Well-trained and acclimatized men can tolerate a higher windchill index (222). The windchill index has often been criticized because it is not feasible to express the effect of wind on heat loss without references to the amount of clothing being worn. The same wind speed will increase the heat loss of a lightly clad man very greatly, but increases only slightly the heat loss of a heavily clothed man. These objections can be avoided by using the windchill values as index numbers on a relative scale and not expressing them in actual amounts of heat loss in kcal x m^{-2} x hr $^{-1}$. Used in this manner it has been found to provide an index corresponding quite well with the discomfort and tolerance of man in the cold. This is because the tolerance will be determined by the parts of the body which are usually unprotected, such as the face and hands. The windchill then applies to the naked face or the bare hands, where the pathological effect of cooling first will appear.

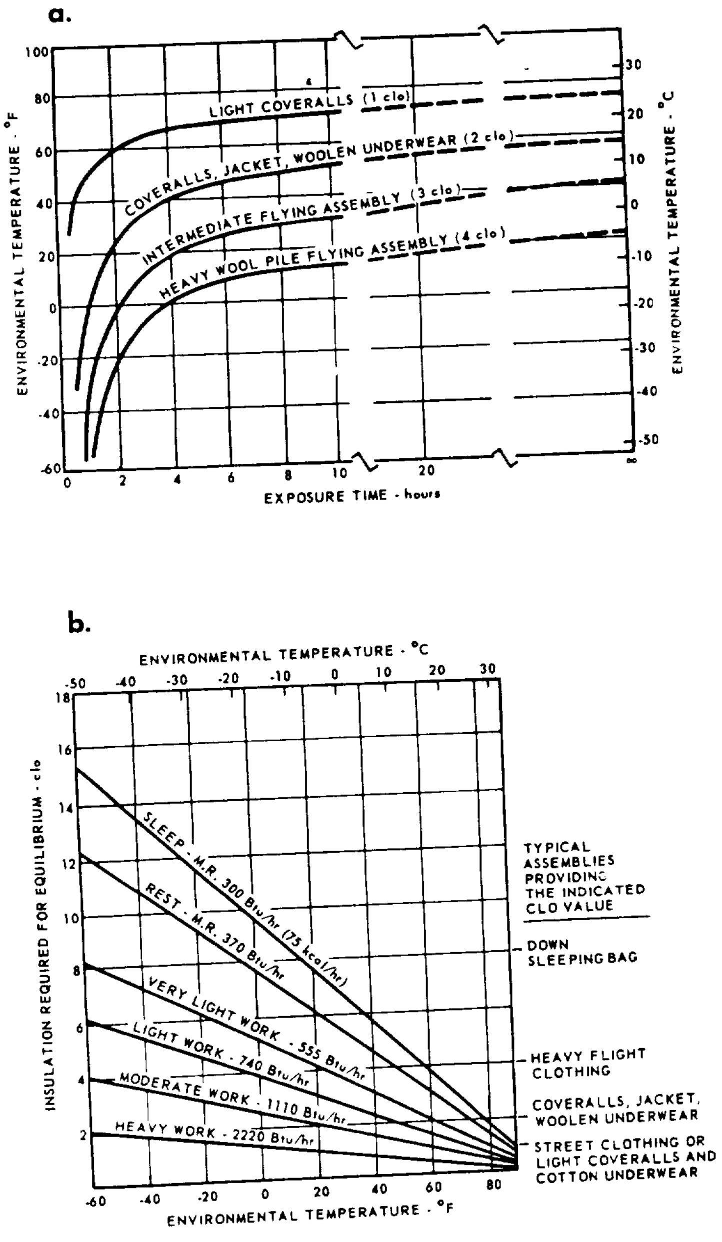
Figures 6-101 and 6-102 indicate the insulation required in cold air at sea level for comfort and thermal equilibrium. Table 6-89 represents the physiological response to cold air.

For ocean recovery in winter months, the rate of cooling in water is of importance. Figure 6-103 is a nomogram for estimating tolerance time to cold water immersion (187). Figure 6-104 is a graphic presentation of

Figure 6-101

Insulation Required in Cold Air at Sea Level

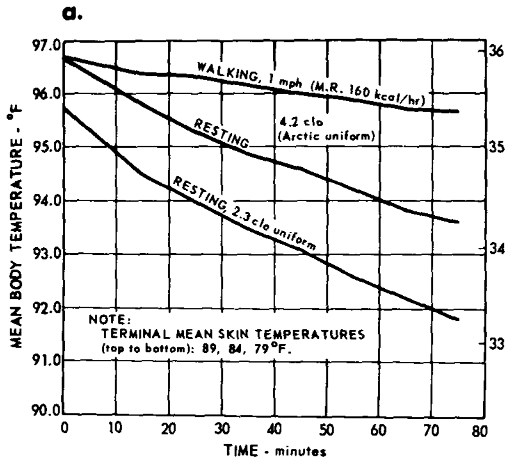
(After Blockley(30), Adapted from Burton and Edholm(48), and Taylor(197))



The amount of clothing insulation that is adequate for a particular cold environment depends on the length of time one is to be exposed and the activity level, or metabolic heat production rate. Chart a shows the influence of exposure time for low activity, sitting (pilot activity), while chart b illustrates the effect of metabolic rate on the insulation required for continuous exposure which requires maintaining heat balance indefinitely. Both charts are slightly unrealistic--the first because of the uncertainty as to appropriate criteria for tolerance limits, and the second because no activity, even sitting, is continued indefinitely. Note also that clothing insulation of more than 4.5 clo at one atmosphere becomes almost impossibly bulky, and even this amount of insulation is unattainable in ordinary footgear and handgear; thus the predictions of this diagram cannot be achieved in practice without taking special precautions to protect hands and feet (e.g., by electrical heating) or by using non-anthropomorphic protective enclosures.

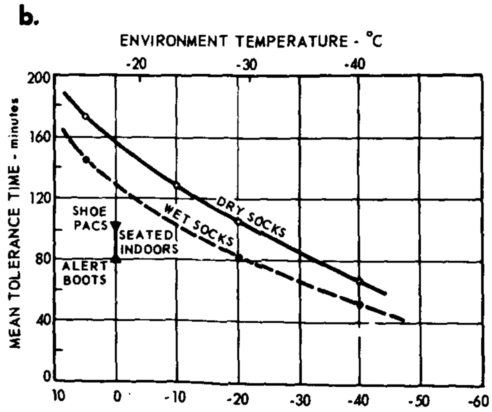
Figure 6-102

Cold Tolerance of Active Clothed Subjects



(After Blockley(30), Adapted from data of Veghte and Clogston(208))

Tolerance to cold wearing inadequate body insulation is shown in figure a, which illustrates the principles underlying estimation of tolerance time in severe cold stress situations. The data are averages for four subjects studied outdoors in Alaska. Temperatures were all within a few degrees of the average, -32°C (-26°F), and wind velocity ranged from zero for the 2.3 clo tests to 65 ft/min for the resting experiments with the 4.2 clo uniform. The rate of fall of the body temperature (0.67 X rectal + 0.33 X skin) is a measure of the rate of negative storage, reflecting the imbalance between heat production and heat loss by the body. It has been estimated that serious discomfort results from a total heat debt of 150 kcal. The survivable limit of heat debt is uncertain; it would in any case be heavily dependent on the procedures and facilities for rewarming. Most practical experiments are necessarily terminated at the point of incipient tissue damage–temperature of 4°C (39°F) or less at some local surface. It may be that death from hopelessness is a more frequent sequel of real exposures beyond this point than the incurring of an intolerable heat debt.



Cold tolerance at rest wearing adequate body insulation is shown in figure b for increasingly cold environments. The prime limiting factor in voluntary tolerance of cold distress is the development of painfully cold feet. (The hands are more easily protected inside the clothing.) Even when the total body insulation is an impractical 5.9 clo (close to wearing a sleeping bag), ordinary footgear limits tolerance time at 0°F (shown by the vertical bar) to 77-104 minutes, which are average times for five men. The chart shows that the improvement so far achieved with insulated boots is not impressive, particularly if the socks become wet. There is a distinct risk of tissue damage when any part of the skin reaches 39°F (4°C). Most men refuse to continue before this point is reached.

(After Blockley(30), Adapted from Carlson(54), and Skrettingland et al(185))

Figure 6-102 (continued)

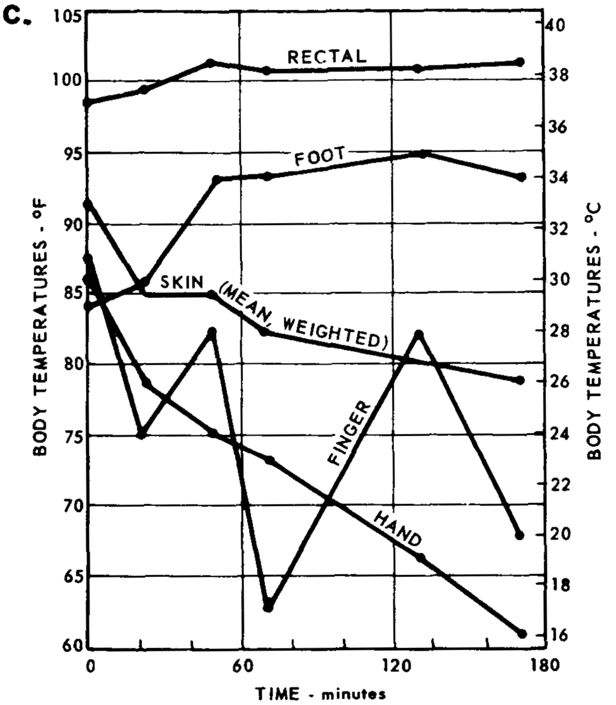
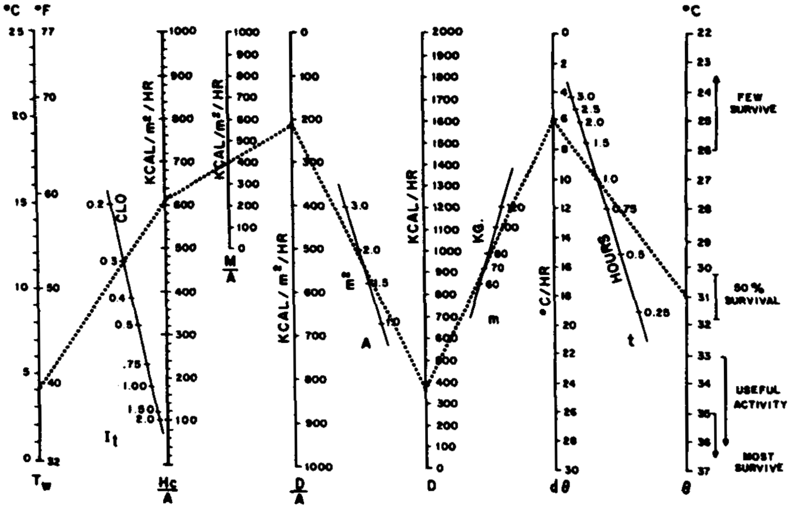


Figure c is a record of body temperatures while marching at -38°F (-39°C) for one subject who was dressed in long underwear, wool shirt and sweater, army field jacket and trousers with liner, arctic felt boots, two pairs of socks, mittens and wool gloves. He walked six miles on hard-packed snow, with his metabolic rate averaging 220 kcal/m^2hr. The wind velocity was 8 mph, so that the windchill index was 1850 ("travel dangerous, flesh freezes 1 min").

These data illustrate the fact that rectal temperature can be maintained at its customary level during work in severe cold, provided sufficient clothing is worn. In such situations, the constant dangers are of freezing of under-protected areas and sweating of over-protected parts of the body. As soon as the activity is reduced or stopped, excessive heat loss occurs from the area wetted by sweat during work, and a precipitous drop in body temperature may result.

(After Blockley(30), Adapted from Milan(144))



To relate the many factors involved in estimating tolerance in cold water, the nomogram below has been devised where one knows or can assume: water temperature (T_W); insulation of clothing and tissue (I_t); metabolic heat production per unit surface area (M/A); the immersed surface area (A); body mass (m); and exposure time (t). As shown by the dotted example line (for a nude man in water at 4°C, a metabolic rate of 400 kcal/m^2hr, an immersed surface area of 1.75 m^2, a body mass of 75 kg, and an exposure time of one hour) the nomogram predicts: heat loss to the environment H_c/A; heat debt per unit surface area (D/A); heat debt (D); change in mean body temperature (d θ); and mean body temperature (θ).

Figure 6-103

Nomograph for Estimation of Tolerance Times to Cold Water Immersion. (See text for use)

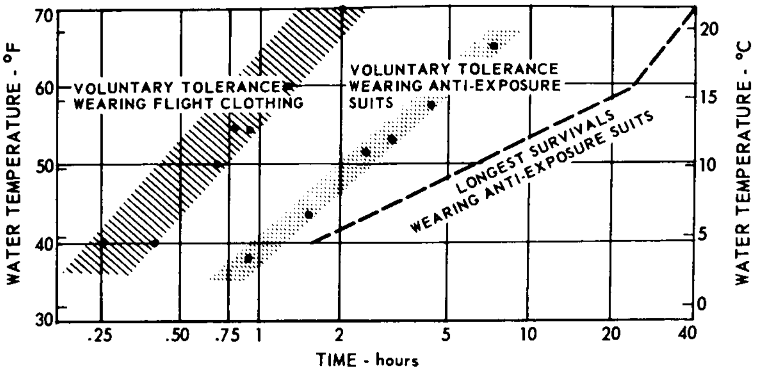
(Adapted from Smith and Hames(187) by Gillies(85) and Blockley(30))

Figure 6-104

Survival in Cold Water

(After Blockley(30), Adapted from Beckman and Reeves(13), Damato and Radliff(62) Hall et al(95), McCance et al(133), Molnar(147), U.S. Navy(205), and Barnett(10))

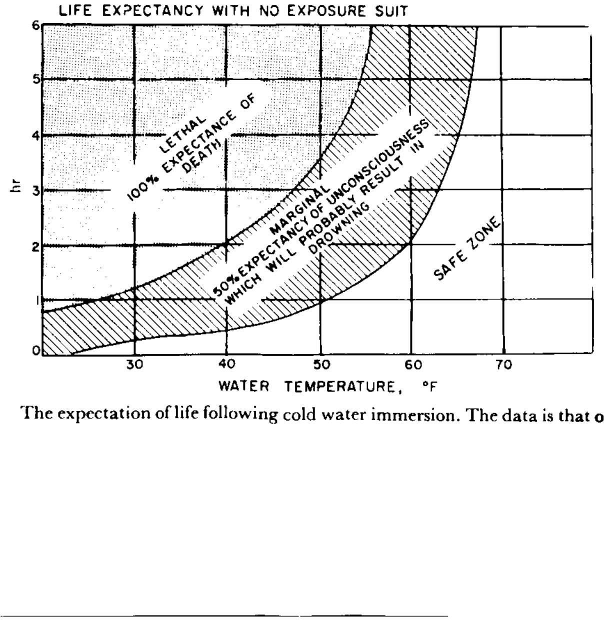
a. Voluntary Tolerance to Cold Water



The "voluntary tolerance, flight clothing" zone in figure a shows the average results from numerous experimental studies, including a recent one using a diver's "wet suit" in conjunction with a flight suit and long underwear. Such experiments are typically terminated when the subject declines to accept the discomfort any longer, or reaches a skin temperature below 50°F. The second limit shown, pertaining to men protected by potentially waterproof garments, reflects the fact that hands and feet cannot be adequately insulated and remain functional. Nude men in 75°F water reach within 12 hours one or another tolerance limit (rectal temperature below 95°F, blood sugar below 60 mg/100 ml, or muscle cramps).

The extent to which real survival time would exceed this limit is difficult to predict, due to the importance of injury, equipment available, and such psychological factors as belief in the possibility of rescue. An analysis of over 25,000 personnel on ships lost at sea during 1940-44 showed that of those who reached life rafts, half died by the sixth day if the air temperature was below 41°F (5°C); survival time increased with increasing air temperature.

b. Life Expectancy in Cold Water with No Exposure Suit



The expectation of life following cold water immersion. The data is that of Molnar.

practical experience in cold water tolerance with routine flight clothing and anti-exposure suits. Figure 6-105 represents the time to reach critical core and skin temperatures after exposure to cold water in several types of exposure suits. Recent developments in isotopic heating devices make practical the use of exposure garments heated for long periods of time (176).

In cold air, injury to the extremities is often a limiting factor in human performance (42). Figure 6-106 represents the power required to attain given skin temperatures of hand and foot in electrically heated gloves and socks with subjects in air temperature of -40°F in a 10 mph wind. Performance is severely hindered if temperature of fifth finger falls below 55°F (55).

Figure 6-107 represents a typical physiological response of a body immersed in cold water and rewarmed. The pathophysiology and treatment of hypothermia and cold injury in space operations have been recently reviewed (52).

Performance in the Cold

Exercise performance decreases during hypothermia (169). When the mean body temperature is decreased from a control value of 35.5°C to 33.3°C, and thermal gradients from core to skin increased from 2.7°C to 10.1°C, mean treadmill times to exhaustion decreased from 4.6 minutes to 4.1 minutes. The VO_2 max decreased 5%, O_2 requirement per minute of running increased 6%. There was no significant difference in average values of O_2 debt and lactate values from controls. The decreased efficiency in the cold is attributed to increased tension and viscosity in cold muscles and from the fact that in the cold, a greater proportion of the energy appeared to come from anaerobic sources than in the control runs.

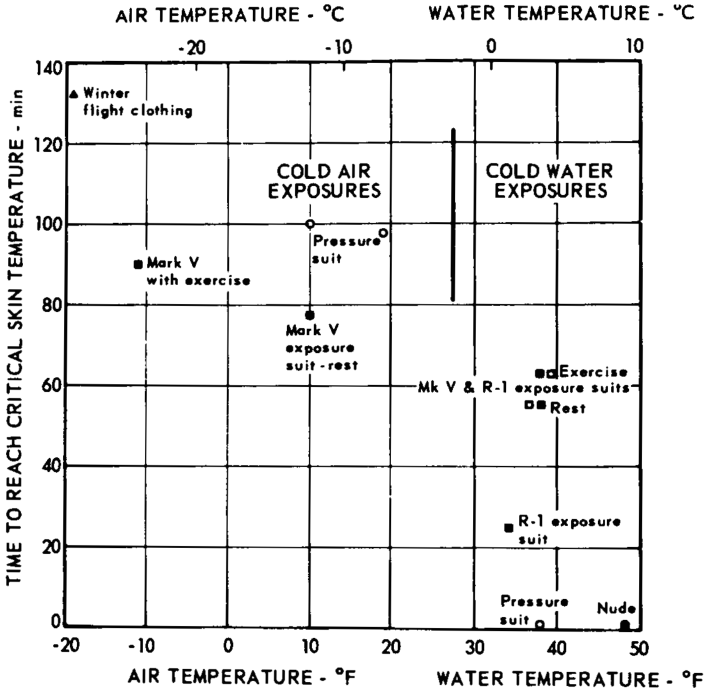
Skilled motor performance shows a progressive loss with continued cold exposure (202). The sensitivity of skin to cold stress is seen in Figure 6-96 and Tables 6-58, 6-64 and 6-65.

Tactual sensitivity is markedly affected by lowered skin temperature. A numbness index has been developed based upon the individual's ability to discriminate the separateness in space of two straight edges upon which the finger is placed (V-test or two-edge limen) (138). Figure 6-108 shows the great difference in the size of gap required to detect the presence of the gap under varying conditions of air temperature and wind speed. Exposure was for approximately three min. The numbness index is the difference in just detectable gap between control data obtained before exposure, at the end of exposure, and at varying intervals following exposure. The data are clear in showing a great loss in tactual sensitivity under the more extreme conditions and a slower recovery following them. Figure 6-109 shows data using both the V-test and the classical two-point (aesthesiometer) test to describe the relationship between tactual acuity and digital temperature (145, 146). It is clear that there is no difference between the two types of stimulation. The minimum detectable gap appears to be approaching infinity at skin temperatures slightly greater than freezing. In the case of individual subjects, gaps of 14 millimeters could not be discriminated at skin temperatures slightly above the freezing point.

Figure 6-105

Clothing Tests in Cold Air and Water

a. Time to Reach Critical Skin Temperature in Cold Air and Water



The relative protection of various types of aircrew clothing in water immersion and exposure to cold air is illustrated in this graph, which shows the time required to reach a critical mean skin temperature of 76° F in each assembly. The criterion of 76° F is based on the general observation of extreme discomfort when this point is passed; in most of the experiments summarized here, some subjects requested termination of the exposure at or near the time when the group average reached this point. The clothing assemblies were: winter flight clothing--the assembly specified by the Alaskan Air Command, USAF; the Navy anti-exposure suit assembly, Mark V; the (obsolete) Air Force anti-exposure suit assembly, R-1; and an Air Force pressure suit with bladders in torso, arms, and legs, designated CSU 4/P. Note for comparison the data point for nude exposure to water at 48° F. The value of exercising in cold air, and the lack of an advantage in cold water, is evident.

(After Blockley(30), Adapted from Barnett(10))

b. Estimated Survival Times in Cold Water with Latest Survival Clothing*

Suit	Water Temp.	Air Temp.	Time *
R1-A	1.9° C	-18° C	5 hrs
R1-A	0° C	1° C	18 hrs
CWU-12/P	12° C	15° C	15 hrs
CWU-3/P	7° C	12° C	10 hrs

* Estimated time (in hours) required for subjects' rectal temperatures to reach 31°C. Rapid rewarming of hypothermic subject in 42°C water required for resuscitation.

(After Milan(143))

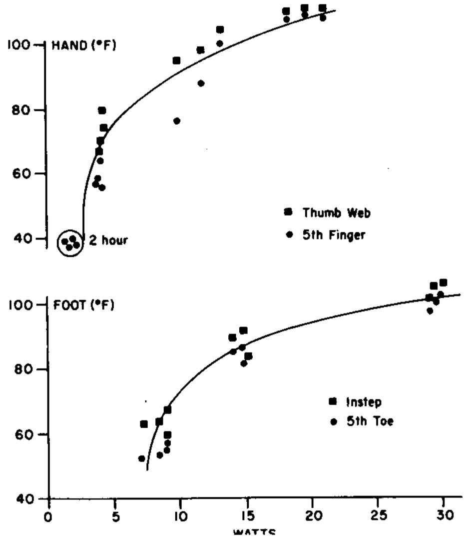


Figure 6-106

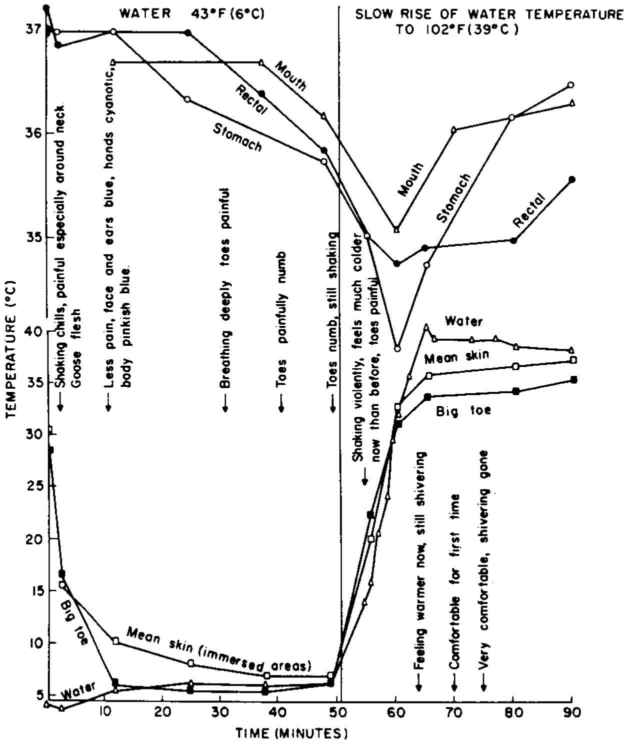
The Hand and Foot Temperatures Maintained as a Function of the Power Used for Auxiliary Heated Gloves and Socks. Air Temperature is -40°F with a 10 mph Wind. Body Core was wound in a U.S Army Quartermaster 4.3 Clo Cold-Dry Standard Clothing Ensemble.

(After Goldman[87])

Figure 6-107

Changes in Body and Skin Temperature of Subject Immersed in Water at 6°C(43°F) for 52 Minutes. The Water Was then Warmed to 39°C· Note the Sharp Fall of Gastric, Oral, and Rectal Temperatures Initially on Warming.

(After Behnke and Yaglou[14])



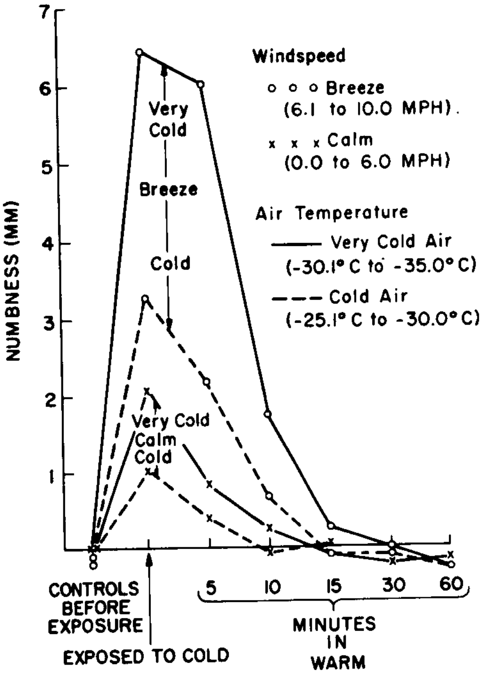


Figure 6-108

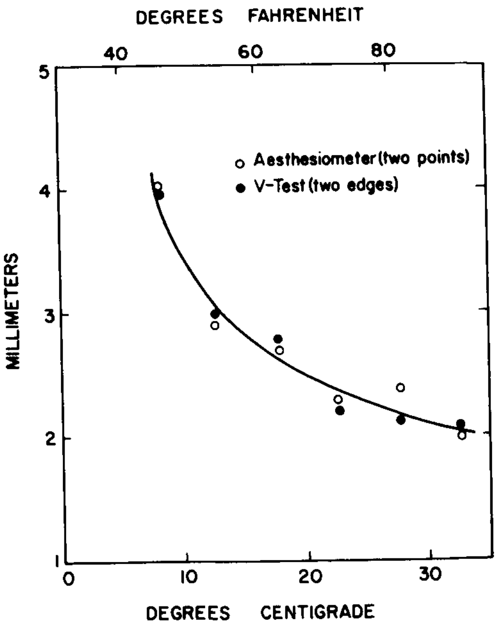
Comparison of the Effects of Windspeed and Air Temperatures on the Numbness Index in Air at Sea Level

(After Macworth[138])

Figure 6-109

Comparison of the Two-Edge and Two-Point Thresholds as a Function of the Skin Temperature in Air at Sea Level.

(After Mills[146])



The minimum pressure on the skin required for detection is inversely proportional to skin temperature (146). Threshold amplitude of vibration of the skin depends on relatively small changes in skin temperature, the greatest sensitivity to vibration occurring when the skin temperature (of the wrist) was increased about 4°C above normal; above and below this optimum, sensitivity decreased (218).

General performance is also altered by cold in a complex way. Figure 6-110 shows the effects of various combinations of air temperature and velocity (and thus windchill) on the manual dexterity of soldiers. Complete arctic uniforms were worn except as indicated. During the test trials the subjects removed the heavy arctic gauntlet and performed with only the wool trigger-finger insert. The results are based upon a total of 530 soldiers sorted into the various subgroups of the experiment. It may be seen that performance time increased in direct proportion to the windchill and that mean skin temperature and digital temperature were roughly inversely proportional to windchill. The rate of cooling is an important factor (56, 82, 83). There is clearly a relationship between performance and the skin temperatures. However, analysis of these data and those of Figure 6-111 indicates that the direct dependence of performance on finger and skin temperatures may be relatively small; that other factors of a psychological or physiological nature may be of equal or possibly greater importance. Total body cooling is not as significant a factor as finger temperature in dexterity tests (82, 83). It has been shown that cooling of the hand decreases finger flexibility(126).

The speed of reaction of men to simple visual signals is also affected by the cold (201). The relative loss is not as great as that of tactual sensitivity, but it is greater than that of manual dexterity. Figure 6-112 shows a comparison of these three phenomena for appropriately dressed, but unacclimatized men in terms of the percentage loss relative to optimum thermal conditions. Figure 6-113 shows degradation of pursuit performance at low temperature.

It is thus reasonable to expect losses in the cold for all types of performance which depend upon any of these functions, as well as tasks of eye-hand coordination (199) and intellectual tasks requiring fast reactions such as the code test (106). So far there has been nothing reported to indicate that intellectual tasks not requiring fast reaction times, motor skills or tactual sensitivity are affected by cold exposure, at least short of the accumulation of a serious heat debt.

Acclimatization to Cold

Recent evidence is contrary to the older view that under cold conditions increased voluntary caloric intakes and other compensatory processes result from low temperature as such; rather, they may result from the increased energy expenditures associated with field activities (8, 33, 54, 63, 206). Whatever the direct cause, the result contributes to a beneficial increase in heat production, vasomotor, and renal control. The major known physiological changes, both short and long term, which are produced in the cold are shown in Table 6-89. Inspection of this table shows that acclimatization

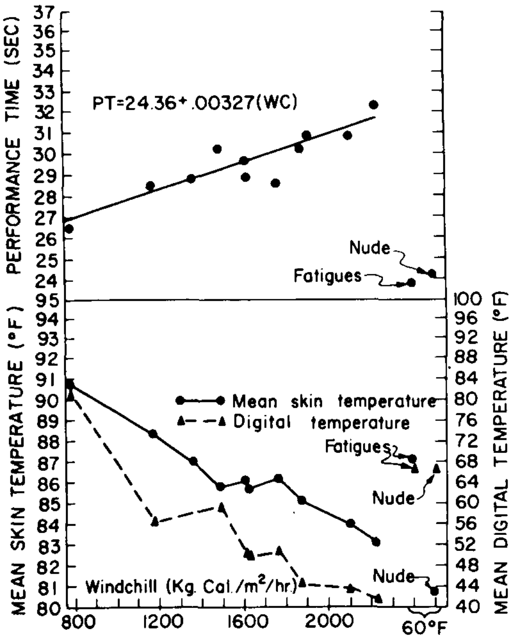


Figure 6-110

Performance Time, Skin and Digital Temperature as a Function of Windchill. Arctic Clothing Worn Except Where Indicated. Hand Exposed During Performance Only. Follows Approxi-Mately 35 Minutes of Exposure.

(After Teichner(200))

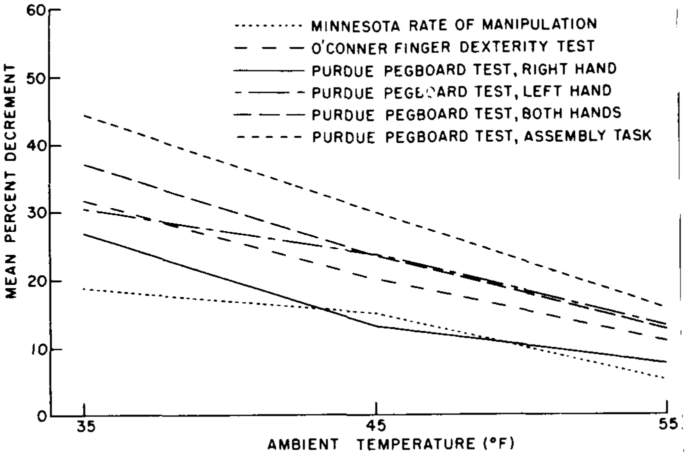


Figure 6-111

Percent Decrement in Performance as a Function of Ambient Temperature at Sea Level

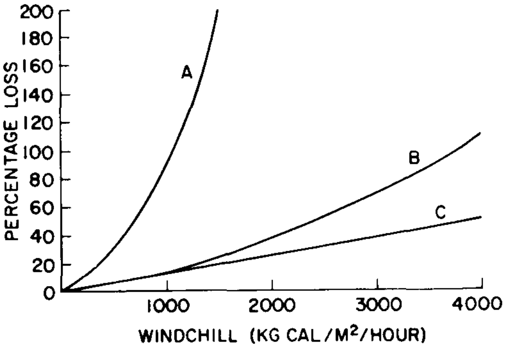
(After Dusek(68))

Figure 6-112

Minimum Effects of the Cold on Selected Functions. Each Curve is an Estimated Percentage Loss of the Indicated Type of Performance for Appropriately Dressed but Unacclimatized Men.

A) Tactual Sensitivity of the Bare Hand
B) Simple Visual Reaction Time
C) Manual Skill

(After Teichner(201))



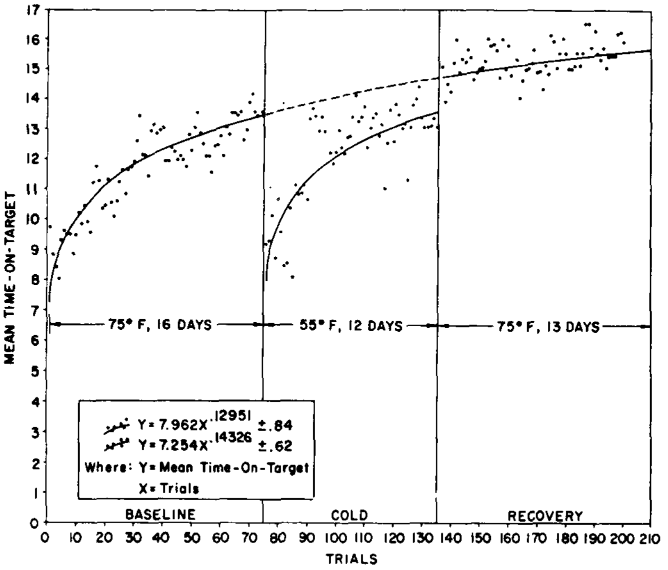


Figure 6-113

Rotor Pursuit Performance as a Function of Practice Under Different Conditions of Temperature

(After Teichner and Kobrick[198])

takes the form of increased levels of some functions and the return to normal of others. Data have been obtained on the cold acclimatization of skills (138, 198, 202) as shown in Figure 6-113. Discussions of the problems of acclimatizing astronauts to cold are available (52, 173). The value of such an approach to increasing the performance and survival capabilities of astronauts during emergencies in such missions as lunar night operations has not as yet been established.

As to the question of conflicts in the simultaneous acclimatization to heat and cold, it has been found that fully acclimatized men retain acclimatization to heat during 14 days of severe cold exposure (5-1/2 hours per day at -20°F). (190). Conversely, it has been suggested that artificially or seasonally acquired "cold acclimatization" is unaffected by a 21-day heat exposure (64). These findings do not conclusively prove but only suggest that heat and cold acclimatization are not mutually exclusive; they can coexist in an individual, and the loss of one usually occurs not as a result of the other, but as a result of the absence of an adequate acclimatizing stimulus. No serious conflicts between cold acclimatization and acclimatization to other stress parameters of lunar flight are apparent, though studies on these combined adaptations are distinctly limited. Much remains to be done in this area.

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