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ENVIRONMENT, CLOTHING AND PERSONAL
EQUIPMENT, AND MILITARY OPERATIONS

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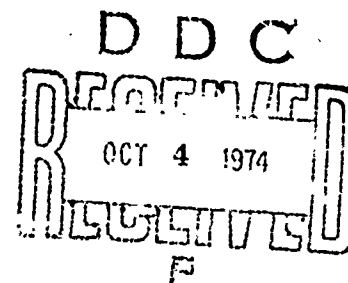Natick, Massachusetts

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INTRODUCTION:

Although the interaction between the psychological state of a soldier and his military performance is still not well defined, the interaction between his physiological status and his military performance is becoming much more predictable. In addition to working on such classic environmental injuries as heat stroke and frostbite, the U.S. Army Research Institute of Environmental Medicine also looks at: (a) such anthropometric features as stature, race and weight; (b) physiologic status with respect to physical work capacity, physical condition, age, state of acclimatization, hydration, sweat capacity and fatigue; (c) clothing and equipment with respect to their weight, thermal insulation (clo), the interference with sweat evaporation (i_m) and the design, fit and closures (pumping coefficients); (d) the physiological demands imposed by the assigned mission and its duration; and finally, (e) the terrain, ambient temperature, humidity, wind, precipitation and solar load of the environment. The interaction of these five types of factors suggests whether or not the soldiers in a unit will be physically able to complete a scheduled mission on time, with or without discomfort or difficulty, or will be so plagued by physical exhaustion, heat exhaustion or cold that the mission cannot be accomplished unless special precautions are taken or the scheduling of the mission is altered.

This paper will present a model for analysis of these interactions, will identify some specific environmental medical factors contributing to mission accomplishment problems, and will indicate the possibilities of a trade-off analysis of various solutions. Psychological research studies are being carried out on the interaction between environmental stress, physiological strain and mission perform-

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ance, motivation and fatigue, but are not yet sufficiently advanced for incorporation.

The model presented does however provide a framework for identifying necessary additional human physiological and psychological studies, and for integrating new research findings to the solution of practical military problems.

Since, like most predictive models, the responses are predicted for a defined population, it is difficult to predict the response of a given individual with any great reliability, although the probable factors which must be considered in an individual case are identified. However, the most fruitful use of such a model is in defining:

(a) for the TACTICIAN - the physiological limits of his men, given their clothing, equipment, and the probable environment for a proposed mission.

(b) for the SURGEON - the probabilities of occurrence of environmental injuries (freezing and non-freezing cold injuries, heat exhaustion or stroke, physical exhaustion) and possible approaches to their prevention.

(c) for the CLOTHING AND EQUIPMENT DEVELOPER - the protection provided the soldier by his product, as well as the burden it imposes and the benefits of any proposed changes.

(d) for INDUSTRY, LABOR and HEW SPECIALISTS - the range of safe and/or comfortable environmental working conditions (this military relevant information is, in many areas, either all that is necessary, or all that may be available in any organized format).

METHODS:

Essentially the model, (as shown in Figure 1.) is a systems analysis of the stress imposed upon the soldier by his physical environment, clothing, equipment and mission. The model compares these stress demands with the physiological resources established by body size, age and sex, and modified by fitness, relative work load and acclimatization status, and also (although at present in very limited degree) the ability to mobilize these resources as modified by psychological factors. Finally, the model assesses the impact of any imbalance, in terms of such physiological strain responses as altered sweat production, hydration, heat production, body temperatures, heat content, and heart rate.

The model essentially looks at the classic physiologic heat balance equation of the human body and calculates the soldier's metabolic heat production (M) while performing a given mission (4,9), the solar heat load (Rs) if any (1), and the radiant and convective heat exchanges (R+C) allowed by the difference between his mean average skin temperature ($\bar{T}s$) and environmental temperature (T_a)(14). The net body heat balance may be negative as a result of these

M+Rs ± (R+C) exchanges (e.g., in a cool environment with inadequate clothing or low work levels), in which case falling deep body temperature (T_{re}) leads to shivering (20) and whole body hypothermia (2) or to cooling of extremity skin temperatures (T_{finger}), etc., to critical levels (23). Such heat losses can be predicted as a function of environmental temperature, clothing (including handwear, headwear, and footwear) and the mission activity level (18). Such problems occur because: (a) the capacity of the body to produce heat by shivering is limited (20); (b) truly adequate clothing insulation (clo) for extreme cold is unacceptably bulky and restrictive (16), and (c) the heat flow from the deep body heat stores to the extremities is drastically constricted as central temperature (T_{re}) is maintained to the detriment of extremity temperatures (T_{finger}, etc.)(12).

If, on the other hand, the balance of M+R ± (R+C) calculates out to a positive quantity, this represents the required evaporative cooling (E req)(5) which the body must attempt to eliminate by evaporation of sweat (15). While man does tolerate heat stress better than cold, i.e., regulates body heat content much more efficiently in warm environments (11), the maximum evaporative cooling capacity (E_{max}) is limited (5) because: (a) the capacity of the body to produce sweat is limited (15); (b) any clothing, and especially such military items as body armor or NBCW protective clothing, has a limited permeability (i_m) which interferes with sweat evaporation (8,10) and (c) at high ambient humidities (ϕ_A) the difference between the vapor pressure of sweat at skin temperature (Ps) and ambient vapor pressure ($\phi_A P_A$) may not be enough to allow all the sweat produced, and allowed to transfer by the clothing, to evaporate (5). The unevaporated sweat will soak the skin and clothing, leading to the discomfort of a damp skin (13) or drip off the body without providing any cooling, uselessly depleting body water resources and thus contributing to the problem of dehydration (25) and heat exhaustion as cardiovascular stress become excessive (6) while body heat storage, and thus deep body temperature continues to rise toward heat stroke levels (15,19).

The heat imbalances predicted from the heat balance equation are expressed in kilocalories. An analysis of the approximate altered body heat storage (ΔS) of men during maneuvers, or carefully controlled chamber exposures, can be carried out by calculating a mean body temperature (T_B), assuming 2/3 of the total body weight (W) is represented by deep body temperature (T_{re}) and 1/3 by mean skin temperature ($\bar{T}s$)(14). Starting from a comfortable state of T_{re} at 98.6°F (37°C) and Ts at 92°F (33°C), the calculated mean body temperature (T_B) is 35°C. Taking the specific heat of the body as 0.83 kcal/kg°C, for a man weighing 70 kg each °C change in mean body temperature represents a change of 58 kcal (i.e., 0.83 x 70). Thus measured changes in body temperature can be directly related to the change in heat storage of the body, and the predicted imbalances in the heat

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balance equation can be related to changes in body temperature (13).

RESULTS:

The model consists of a number of blocks, many already validated and published, some partially validated and others still being refined. A list of the input parameters that must be supplied (identified by ?) and calculated inputs (identified by !) is given in Table I; references for these input parameters are also included in Table I. Essentially, the inputs consist of factors (a) describing the soldier in characteristics from which his physiological capacities can be estimated, (b) factors describing his load, march rate, the terrain and grade (or other mission descriptors) from which the work demands and his heat production can be estimated, and finally (c) factors for his clothing insulation (clo), vapor permeability (i_m) and how these change with air or subject movement (pumping coefficient). The heat losses by radiation and convection, and the maximum evaporative heat loss, can be calculated from these three clothing parameters (clo, i_m and pumping coefficient), as a function of the ambient temperature, vapor pressure and wind. Subroutines are available for solar heat load (1), if any, and dehydration (25)(although not yet fully validated) and are being evaluated for extremity cooling (23) and developed for water immersion heat loss (3).

The model calculates a theoretical equilibrium state (5) at which, by adjusting deep body and skin temperatures, and shivering heat production or sweat production, the heat balance equation of the body can be satisfied; i.e., there would be no additional changes in heat storage or debt. Such equilibrium levels may be unattainable, or lethal, but the body will strain to achieve them. The outputs of the model describing these strains, are tabulated in Table II. A large number of validating and ad-hoc studies examining these input-output relationships have led to empiric derivation of the necessary time constants and delay times for the various physiologic responses to specific stress inputs; at present, the total response pattern for heart rate (16) and deep body temperature (5) as a function of time can be graphed with considerable confidence, both for acclimatized and unacclimatized men (7). Similar factors are being validated for extremity cooling (23) and dehydration (25).

Table III lists the critical levels for ambient environmental conditions, mean skin, finger and deep body temperatures, altered body heat content (storage or debt), dehydration, heat production and heart rate. When possible, a critical threshold is specified for levels of comfort, discomfort, performance decrement, tolerance and actual damage.

The combination of these input factors in Table I, output factors in Table II and critical thresholds in Table III allows the model to flag the times of occurence of these critical states;

Table IV lists the various flags used, in four categories: comfort related; work related; heat related; cold related.

DISCUSSION:

Any prediction model, although perhaps theoretically useful and interesting, is only of limited use until validated across a range of military populations and until some estimate of the standard error of prediction is available. The prediction of heat production (4,9, 22) has been thoroughly validated across a range of military and civilian populations and appears to be good to ±10%, which is about the usual precision of its measurement in the field. The prediction of troop mobility, i.e., distance covered per unit time or time to reach a given destination as a function of load (22) and terrain (24) has been validated on average soldiers (26) but requires more validation.

Prediction of deep body temperature in the heat as a function of ambient hot-wet or hot-dry environmental conditions (17), standard military uniforms (5), body armor (10,17) and NBCW protective clothing and mission activity (14,21) is also well validated and appears accurate to ±0.2°C (5) for a number of the combat arms, but may need some adjustment for elite military units. Prediction of heart rate for these situations (5) is also well developed, but for high heart rates the effects of physical condition and age need more work; nevertheless, the prediction for the standard volunteer military subjects available in the laboratory has a standard error of estimate of 6 to 10 beats per minute (15). More work is planned to characterize other military populations.

The effects of heat acclimatization are well defined and appear valid enough for practical use (7) although a wide range of hot-wet as well as hot-dry conditions has not been studied. The solar load prediction (1) also seems quite valid, but the effects on the soldier of combined metabolic and solar heat loads require more work. The effects of dehydration are just beginning to be incorporated into the model (25). Nevertheless, the overall heat tolerance prediction capability of the model has been tested in control field studies and a number of large scale maneuvers (the METOXE series and 69-10) and has proven to be quite practical for preventing heat casualties and establishing appropriate work-rest cycles. The trade-off analyses allowed by the model have also been extremely valuable during the development phases of new uniforms (21) and protective clothing and equipment (17).

On the cold side, the whole body cooling prediction model has been well validated in limited environmental chamber studies of sleeping bags and also in one field study. The extremity cooling model has proven most useful in design of handwear and footwear, and in prediction of the "worst case" cooling responses, but individual variability in the pattern of spontaneous rewarming (Cold Induced

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Vaso Dilatation) severely complicates absolute prediction of extremity
temperature (18). Since, however, such "worst case" prediction is
generally applicable to a soldier who is thoroughly chilled or fright-
ened it is still quite useful.

Current research emphasis is on improving the accuracy of the
mobility and heart rate prediction to include various levels of phys-
ical fitness, age and motivation, extending the validation of the heat
stress elements to include solar load and a wider range of dehydration
conditions and, finally, developing more information to validly apply
extremity cooling and whole body cooling prediction to field opera-
tions in the cold.

CONCLUSIONS:

The model presents the interaction of multidisciplinary
factors drawn from (a) the theoretical physics of heat transfer,
(b) the biophysics of clothing, (c) the physiology of metabolic heat
production, distribution and elimination, and (d) related meterologi-
cal considerations. The model is extremely useful now for clothing
and equipment developers since its rank ordering of the effects of
their products has proven to be extremely accurate. In its present
state, it is a useful guide for tactical planners, albeit a conserva-
tive one for two reasons; it has not been studied over a broad cross
section of military units in the laboratory and, although its valida-
tion in field operations has included many of the combat arms of the
Army and a few studies on Marines, the lack of motivation or realism
common to such non-combat operations leads to a conservative estimate
of performance capability on the one hand, while overlooking the
degradation of performance that can be induced by the fear and pres-
sures of actual combat. The model does provide the surgeon with a
useful prediction of the relative risks of thermal environmental inju-
ry, the factors contributing to such risk and their relative propor-
tions, but such prediction is for groups of subjects, not for indivi-
duals. It is also useful for engineers designing environmental condi-
tioning equipment, for energy conservation planners and for developing
industrial work regulations as proposed under the recent OSHA legis-
lation. Finally, the model can perhaps be most useful to the scien-
tist who developed it and to the Army Research Institute of Environ-
mental Medicine in: (a) evaluating what additional research is needed;
(b) deciding whether a proposed research study will provide militarily
relevant information, and whether the environmental conditions select-
ed are sufficiently strenuous to obtain measurable physiological dif-
ferences between the parameters being studied, but not too strenuous
to permit collection of meaningful data without undue risk to the
subjects; and (c) in providing expert guidance and consultation to a
wide range of military and civilian agencies.

References

1. Breckenridge, J.R. and R.F. Goldman. Solar Heat Load in Man. J. Appl. Physiol. 31: 659-663, 1971.
2. Gee, Gin K. and R.F. Goldman. Prediction of Whole Body Cooling. Biophysical J. 13: 213a, 1973.
3. Gee, Gin K. and R.F. Goldman. Heat Loss of Man in Total Water Immersion. The Physiologist 16: 318, 1973.
4. Givoni, B. and R.F. Goldman. Predicting Metabolic Energy Cost. J. Appl. Physiol. 30: 429-433, 1971.
5. Givoni, B. and R.F. Goldman. Predicting Rectal Temperature Response to Work, Environment and Clothing. J. Appl. Physiol. 32: 812-822, 1972
6. Givoni, B. and R.F. Goldman. Predicting Heart Rate Response to Work, Environment and Clothing. J. Appl. Physiol. 34: 201-204,
7. Givoni, B. and R.F. Goldman. Predicting Effects of Heat Acclimatization on Heart Rate and Rectal Temperature. J. Appl. Physiol. 35: 875-879, 1974.
8. Goldman, R.F. Tolerance Time for Work in the Heat When Wearing CBR Protective Clothing. Mil. Medicine. 128: 776-786, 1963.
9. Goldman, R.F. Energy Expenditure of Soldiers Performing Combat Type Activities. Ergonomics. 8: 321-327, 1965.
10. Goldman, R.F. Physiological Costs of Body Armor. Mil. Med. 134: 204-210, 1969.
11. Goldman, R.F. Environmental Limits, Their Prescription and Proscription. Intl. J. Environ. Stu. 5: 193-204, 1973.
12. Goldman, R.F., R.W. Newman and O. Wilson. Effects of Alcohol, Hot Drinks, or Smoking on Hand and Foot Heat Loss. Acta Physiol. Scand. 87: 498-506, 1973.
13. Goldman, R.F. Comfort, A Non-Subjective Approach. In: Proc. Kansas State University Visiting Lecturers. 1973.
14. Goldman, R.F. Quantitative Prediction of Physiological and Psychological Effects of Thermal Environment in Man. Archives des Sciences Physiologiques. 27: 73-78, 1973.
15. Goldman, R.F., E.B. Green and P.F. Iampietro. Tolerance of Hot, Wet Environments by Resting Men. J. Appl. Physiol. 20: 271-277, 1965.
16. Goldman, R.F. and A. Teitlebaum. Increased Energy Cost with Multiple Clothing Layers. J. Appl. Physiol. 32: 743-744, 1972.
17. Haisman, M.F. and R.F. Goldman. Physiological Evaluation of Armored Vests in Hot-Wet and Hot-Dry Climates. Ergonomics 16: in press, 1974.
18. Hanson, H.E. and R.F. Goldman. Cold Injury in Man: A Review of its Etiology and Discussion of its Prediction. Mil. Med. 134: 1307-1316, 1969.

19. Iampietro, P.F. and R.F. Goldman. Tolerance of Men Working in
    Hot Humid Environments. _J. Appl. Physiol._ _20:_ 73-76, 1965.
20. Iampietro, P.F., J.A. Vaughan, R.F. Goldman, M.B. Krieder,
    F. Masucci and D.E. Bass. Heat Production from Shivering.
    J. Appl. Physiol. _15:_ 632-634, 1960.
21. Joy, R.J.T. and R.F. Goldman. A Method of Relating Physiology
    and Military Performance: A Study of Some Effects of Vapor
    Barrier Clothing in Hot Climate. _Mil. Med._ _133:_ 458-470, 1968.
22. Kennedy, S.J., Goldman, R.F. and J. Slauta. The Carrying of
    Loads within an Infantry Company. US Army Natick Laboratories,
    Rpt C&PLSEL 108, May 1973.
23. Molnar, G., O. Wilson and R.F. Goldman. Analysis of Events
    Leading to Frostbite. _Intern. J. Biometeorol._ _16:_ 247-258, 1972
24. Soule, R.G. and R.F. Goldman. Terrain Coefficients for Energy
    Cost Prediction. _J. Appl. Physiol._ _32:_ 706-708, 1972.
25. Soule, R.G. and R.F. Goldman. Dehydration and Exercise Perform-
    ance in the Heat. _J. Sports Med._ in press, 1974.
26. Soule, R.G. and C.K. Levy (R.F. Goldman). Voluntary March Rate
    over Natural Terrains. _Fed. Proc._ _31:_ abs., 1972.

FIGURE 1   Diagram of a systems analysis of the
stress inputs and physiological strain
output responses of "the soldier"

STRESS   **STRAIN**

Physical
  Temperature   Deep body temperature
  Humidity   Mean skin temperature
  Wind   Finger/toe temperature
  Uniform   ┌─────────────────┐   Body heat storage/debt
  Equipment Load   │   The Soldier   │   Sweat production
  Mission   └─────────────────┘   Dehydration
                              ↑   Heat production

Physiological   <u>Military Unit Modifiers</u>
  Age/Sex
  Height/Weight   Infantry
  Physical Condition   Combat Support
  Acclimatization   Combat Service Support
  Relative Work Load   Airborne
                         Special Forces
Psychological   etc.
  Motivation
  Rank
  Experience
  Training
  Fear

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TABLE I   Input Parameters

Input #		Reference
1	Height?	-
2	Weight?	-
3 +	Sex?	-
4	Calculated surface area!	-
5	Effective area (heat rash, gas mask, etc)?	-
6	Load carried (clothing & equipment)?	12, 22
7 +	Load carriage factor (any inefficiencies)?	15, 22
8	Terrain factor?	24
9	% Grade?	4
10	Specified march rate?	4
11	Predicted (march rate! or heat production)!	4, 22, 26
12	Uniform insulation (clo)?	1, 5, 10, 17
13	Uniform vapor permeability (i_m/clo)?	5, 10, 13, 17
14	Air or subject motion modifier?	5, 13, 14, 17
15 -	Factor for sweat cooling efficiency (λ)?	5
16 +	Handwear, footwear, headwear insulation?	13, 14, 18
17	Initial core temperature?	-
18	Estimated final skin temperature?	5
19 +	Calculated core-skin conductance!	in preparation
20	Initial heart rate?	6, 7
21 +	Age?	-
22 +	Physical condition?	7, 14, 22
23 -	Maximum work capacity!	5
24 -	Motivation factor?	11, 22
25	Acclimatization status?	7
26 +	Initial hydration status?	25
27 +	Available drinking water?	22
28 +	Extremity of concern?	18
29	Air temperature?	11
30	Relative humidity?	11
31	Wind speed?	5, 11
32 +	Solar heat load subroutine?	1
33 -	Water immersion subroutine?	3
34 +	Mission activity?	4, 9
35	Duration of rest-work-recovery?	5, 6
36	Time interval of interest?	-

*Note: a + indicates information available for programming now but
more validation may be needed; a - indicates more research needed.

TABLE II   Outputs

A) At theoretical equilibrium (N.B. may be lethal):
   1   Core temperature rise from work
   2   Core temperature change by non-evaporative heat transfer
   3   Core temperature rise from limited evaporation
   4   Equilibrium (final) core temperature
   5   Decrease if fully acclimatized
   6   Equilibrium (final) heart rate
   7   Required evaporative cooling
   8 - Sweat production required
   9 - Rate of dehydration
  10   Maximum evaporative potential
  11   % Sweat wetted skin surface
  12   Cooling power
  13   Effective uniform insulation
  14   Effective uniform vapor permeability
  15 - Extremity circulatory heat input
  16 - Extremity time constant
  17 - Equilibrium (final) extremity temperature

B) Tabulated values as a function of time for:
   1   Core temperature
   2 - Mean skin temperature
   3   Heart rate
   4 - Extremity temperature

C) Graphic display of time pattern response of:
   1   Core temperature
   2   Heart rate
   3 - Extremity temperature

*Note: a - indicates more work is required before output is
reliable.

TABLE III Environmental and Physiological levels with respect to Comfort, Discomfort, Performance, Decrement, Tolerance and Bodily Damage

	COMFORT	DISCOMFORT	PERFORMANCE↓	TOLERANCE TIME	DAMAGE
T_A	78°F	f(clo &RH)	-	+240°F-25 min -100°F-30 min	-
R.H.	50% RH	< 5 mm Hg >18 mm Hg	-	'20°F,100%-20 min	-
Wind	~0.5 mph	>10 mph ?	>15-20 mph	-	-
$\bar{T}_s$	92°F	88°F	86°F ?	77°F	<60°F >115°F
$T_{\beta in}$	>70°F	<68°F	<60°F	40°F	<30°F
T_{re}	98.6°F ±	-	~ 100.8°F ~ 96.8°F	>103°F < 95°F	>106°F < 83°F
ΔS	±25 kcal	±80 kcal	± ?	±160 kcal(50%)	±240 kcal ?
ΔH_2O	0%	>2%	>4%	>~ 6%	>15-20%
M	100 kcal/hr	>300 kcal/hr	>425 kcal/hr	>600 kcal/hr~1 hr	>900 kcal/hr
H.R.	60-80/min	>30/min †	-	~180/min-f(age)	>180/min

TABLE IV   Flags for Critical Levels of Comfort, Performance
or Environmental or Work Stresses

CRITERION

COMFORT RELATED:

Uncomfortable sweating	> 20% wet skin
Threshold of work discomfort	HR ↑ 30b/min
Threshold of heat stress discomfort	$\Delta S \sim$ +25 kcal
Threshold of cold stress discomfort	$\Delta S \sim$ -25 kcal

WORK RELATED:

Exceeds maximum work capacity	>∼ 17 kcal/min
Exceeds voluntary hard work level	> 7 kcal/min
Work endurance difficult beyond:	
(a) 8 hours	5-6 kcal/min
(b) 2-3 hours	7-8 kcal/min
(c) 1 hour	10 kcal/min
(d) ∼15 min	12-15 kcal/min

HEAT RELATED:

Exceeds voluntary heat endurance	$\Delta S \sim$ +80 kcal
25% heat exhaustion collapse risk	$\Delta S \sim$ +120 kcal
50% heat exhaustion collapse risk	$\Delta S \sim$ +160 kcal
75% heat exhaustion collapse risk	$\Delta S \sim$ +200 kcal
Increasing heat stroke risk	Tre > 106°F

COLD RELATED:

Loss of manual dexterity	fingers < 60°F
Onset of shivering	$\Delta S \sim$ -80 kcal
Violent shivering	$\Delta S \sim$ -150 kcal
Non-freezing cold injury risk	any skin ≤ 40°F
Freezing cold injury risk	any skin < 31°F
Increasing hypothermia risk	Tre < 95°F

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the author and are not to be construed as official or as reflecting
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