DTIC FILE COPY

①

AD-A206 036

PREDICTION MODELING OF PHYSIOLOGICAL RESPONSES AND SOLDIER PERFORMANCE IN THE HEAT

Kent B. Pandolf, Leander A. Stroschein,
Richard R. Gonzalez and Michael N. Sawka

US Army Research Institute of Environmental Medicine
Natick, Massachusetts 01760-5007

Accession For
NTIS GRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes

Dist	Avail and/or Special
A-1	

Running Head: Computer Prediction Modeling

Mailing Address: Dr. Kent B. Pandolf
Director, Military Ergonomics Division
US Army Research Institute of
Environmental Medicine
Natick, Massachusetts 01760-5007

DTIC
S ELECTE D
31 MAR 1989
E

QUALITY INSPECTED 4

This document has been approved for public release and sale; its distribution is unlimited.

89 3 30 056

ABSTRACT

Over the last two decades, our laboratory has been establishing the data base and developing a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work at various environmental extremes. Individual predictive equations for rectal temperature, heart rate and sweat loss as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as energy expenditure, state of heat acclimation and solar heat load have been evaluated and appropriate predictive equations developed. Currently, we have developed a comprehensive model which is programmed on a Hewlett Packard 41 CV hand-held calculator. The primary physiological inputs are deep body (rectal) temperature and sweat loss while the predicted outputs are the expected physical work-rest cycle, the maximum single physical work time if appropriate, and the associated water requirements. This paper presents the mathematical basis employed in the development of the various individual predictive equations of our heat stress model. In addition, our current heat stress prediction model as programmed on the HP 41 CV is discussed from the standpoint of propriety in meeting the Army's needs and therefore assisting in military mission accomplishment.

Key words: clothing; computer prediction modeling; environmental factors; exercise; physiological responses.

INTRODUCTION

Over the last two decades, the Military Ergonomics Division of the US Army Research Institute of Environmental Medicine has been establishing the data base and developing a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work in various environmental extremes. Individual predictive equations for rectal temperature [5], heart rate [6] and sweat loss [17] as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as energy expenditure [10], state of heat acclimation [7] and solar heat load [1] have been evaluated and appropriate predictive equations developed. Suitable data bases to evaluate the predictive importance of cardiorespiratory physical fitness [11,15], gender [12,14,16] and state of hydration [12,13] have been established. Our upper physiological limits during experimentation (rectal temperature $\leq 39.5°C$, heart rate ≤ 180 beats$\cdot$min^{-1}) are within safe bounds and any errors in associated predictions within these limits should not materially endanger soldier performance.

Over this same time period, our Division has also attempted to program these predictive equations on various desk-top and hand-held calculators with the express purpose of developing a comprehensive heat stress model for predicting soldier performance to physical work, clothing and the environment. The initial computer program was written on a Hewlett Packard 9810A desk-top calculator with the outputs being the predicted rectal temperature and heart rate responses. As the technology advanced, we adapted these computer programs for the Hewlett

Packard 65 hand-held calculator with similar outputs to those of the desk-top version. Currently, we have developed a more comprehensive model which is programmed on a Hewlett Packard 41CV hand-held calculator. The current model deals with the interaction of various multi-disciplinary factors such as (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 meteorological considerations. The primary physiological inputs are deep body (rectal) temperature and sweat loss while the predicted outputs are the expected physical work-rest cycle, the maximum single physical work time if appropriate, and the associated water requirements.

This paper presents the mathematical basis employed in the development of the various individual predictive equations of our heat stress model. In addition, our current heat stress prediction model as programmed on the HP 41CV is discussed from the standpoint of propriety in meeting the Army's needs and therefore assisting in military mission accomplishment.

MATHEMATICAL BASIS

Unless otherwise stated, all terminology for abbreviations and units of measurement follow the usage recommended by the Système international d'unites (SI units) and the International Union of Physiological Sciences.

Rectal Temperature Prediction

The general formula for predicting the final equilibrium rectal temperature (T_{ref}) as suggested by Givoni and Goldman [5] is

$$T_{ref}(^{O}C)=36.75+\underbrace{0.004(M-W_{ex})}_{\text{(Metabolic)}}+\underbrace{0.0011\ H_{(r+c)}}_{\text{(Dry Heat) (Exchange)}}+\underbrace{0.8\ \exp[0.0047(E_{req}-E_{max})]}_{\text{(Evaporative Heat) (Exchange)}} \qquad [1]$$

Equation 1 is comprised of three components

(1) the metabolic component $[36.75+0.004\ (M-W_{ex})]$

where $M = 1.5W+2.0(W+L)(L/W)^2+\eta(W+L)[1.5(V_w)^2+0.35GV_w]$ [2]

as originally published by Pandolf et al. [11]

and $W_{ex} = 0.098\ G(W+L)V_w$ [3]

as suggested by Givoni and Goldman [5]

where M =metabolic rate, (watt)

W_{ex}=external work, (watt)

W =nude body weight,(kg)

L =clothing and equipment weight,(kg)

η =terrain factor

V_w =walking velocity, $(m \cdot s^{-1})$

G =grade, (%)

(2) the dry heat exchange component $[0.0011\ H_{(r+c)}]$

where $H_{(r+c)} = 6.45\ A_D(T_{db}-\bar{T}_{sk})/I_T$ [4]

as inferred by Givoni and Goldman [5]

where A_D =body surface area, (m^2)

T_{db} =dry bulb temperature, $(^{\circ}C)$

$\bar{T}_{sk}$ =average skin temperature, $(^{\circ}C)$

I_T =total insulation including air layer (I_a) and intrinsic clothing, (I_{cl})

(3) the evaporative heat exchange component $\{0.8\ \exp[0.0047(E_{req}-E_{max})]\}$

as indicated by Givoni and Goldman [5]

where $E_{req} = (M-W_{ex})+H_{(r+c)}$ [5]

and $E_{max} = 14.21\ i_m/I_T\ A_{Deff}\ (P_{sk} - \phi_a P_a)$ [6]

where e = base of natural log

i_m = permeability index (N.D.)

A_{Deff} = effective surface area for evaporation, (m^2)

P_{sk} = water vapor pressure at the skin, (mm Hg)

ϕ_a = relative humidity, (%)

P_a = saturated water vapor pressure of air at T_{db}, (mm Hg)

and other abbreviations as described above.

In order to compute physical work-rest cycles, the time patterns of rectal temperature have been analyzed for three different conditions: (a) the time pattern for resting subjects under various heat stress conditions referred to as resting T_{ret} (resting rectal temperature at any time t); (b) the elevation pattern for rectal temperature during physical work at the given climatic conditions referred to a working T_{ret} (rectal temperature at any time t after beginning physical work); and (c) the recovery rectal temperature after cessation of physical work referred to as recovery T_{ret} (rectal temperature at any time t after completion of physical work). These three equations have been presented and discussed in detail elsewhere [5].

. . . .

INSERT FIGURES 1 AND 2 ABOUT HERE

. . . .

Figure 1 presents a comparison for 12 volunteer male subjects of the predicted (lines) and measured (points) time patterns for rectal temperature during one hour cycles of rest, physical work and recovery as originally published by Givoni and Goldman [5]. These findings indicate that the prediction of rectal temperature from the proposed equations is in good agreement with the experimental observations covering a wide range of metabolic rates, climatic conditions and clothing properties.

All of the predictive formulae for rectal temperature presented and discussed above pertain to an exercise-heat acclimated individual. In order to characterize the non- and partially-acclimated individual, these equations were modified for the purpose of describing the acclimation process as the final equilibrium rectal temperature or for the general time pattern of rectal temperature as $\Delta\ T_{ref(accl)}$ and $\Delta\ T_{ret(accl)}$, respectively [7]. Figure 2 illustrates mean daily patterns of rectal temperature during seven days of exercise-heat acclimation with the points representing the average measured values for 24 subjects [7]. In general, there is good agreement between the measured and predicted patterns.

Figure 3 shows the comparison of predicted and observed rectal temperature responses for 12 soldiers while wearing three different military clothing ensembles during tests under two different climatic conditions in Australia. These data which were collected by a group independent of our Institute are in quite good agreement with the predicted values, and in all but two instances, the observed responses are within ± 1 S.D. of predicted.

. . . .

INSERT FIGURE 3 ABOUT HERE

. . . .

The general equation for predicting sweat loss response (Δm_{sw}) as a function of exercise, environmental and clothing interactions as proposed by Shapiro et al. [17] is

$$\Delta m_{sw}(g \cdot m^{-2} \cdot h^{-1}) = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455} \qquad [7]$$

where Δm_{sw} = change in body weight from sweat loss and other abbreviations as described earlier.

This prediction equation was derived from over 250 experimental exposures to a wide range of climatic conditions (ambient temperature, 20-54°C and relative humidity, 10-90%) while wearing various clothing ensembles (light clothing and heavy clothing of high permeability or low permeability) at different metabolic rates (rest to moderate physical work). Therefore, this formula can be employed over a wide range of E_{req} (50-360, $W \cdot m^{-2}$) and E_{max} (20-525, $W \cdot m^{-2}$). In the present form, this formula is more applicable for predicting water requirements; however, it can be presented in appropriate units ($W \cdot m^{-2}$) for predicting the rate of sweat loss [17].

. . . .

INSERT FIGURE 4 ABOUT HERE

. . . .

A comparison of predicted and measured Δm_{sw} for 111 individual exposures involving 24 soldiers is illustrated in Figure 4. These experiments considered ambient temperatures ranging from 35-49°C, relative humidities from 20-75%, different clothing ensembles and both resting and exercise evaluations. A correlation coefficient between the predicted and measured sweat loss of $r = 0.94$ was observed over a wide range of sweating responses.

. . . .

INSERT FIGURE 5 ABOUT HERE

. . . .

Figure 5 displays a comparison of four different methods for predicting sweat loss utilizing the experimental findings of Shapiro et al. [17] derived from 34 soldiers. Lustinec's equation [8] employs a linear relationship between sweat rate and E_{req} for low skin wettedness but a non-linear relationship between sweat rate, E_{req} and E_{max} for high skin wettedness. Givoni and Berner-Nir [4] developed a prediction equation for expected sweat rate structured from the exponential function of the ratio E_{req}/E_{max}. Macpherson [9] developed the predicted four hour sweat rate index (P4SR) which incorporates ambient temperature, wet-bulb temperature, wind speed and correction for the particular clothing. With our equation, the predicted sweat loss was within the ±20% range for 29 out of the 30 experimental conditions that were evaluated with only one condition (37°C, 80% rh, walking in a sweat suit) greater than 20% from the measured value ($r=0.95$). Lustinec's equation showed eight conditions out of the 30 beyond the ±20% range (four additional conditions were beyond the equation's range) while for Givoni and Berner-Nir's equation 14 conditions were out of the ±20% range, and for the P4SR method 12 conditions were beyond the ±20% range (2 additional conditions were beyond this nomogram's range). Thus, the present formula was seen to predict steady-state sweat loss more accurately than other methods especially for extreme climatic conditions [17]. However, these same authors state that the present prediction equation may have some limitations at very high sweat rates.

The general formulas for predicting the final equilibrium heart rate (HR_f) as proposed by Givoni and Goldman [6] for heat acclimated individuals are

$$HR_f(\text{beats}\cdot\text{min}^{-1})=65+0.35(I_{HR}-25) \text{ for } 25\leq I_{HR}\leq 225 \qquad [8]$$

$$HR_f(\text{beats}\cdot\text{min}^{-1})=135+45[1-e^{(0.01[I_{HR}-225])}] \text{ for } I_{HR}\geq 225 \qquad [9]$$

where $I_{HR}=100(T_{ref}-36.75)+0.4\ W_{ex}$

The time patterns for heart rate responses of heat acclimated individuals necessary to predict work-rest cycles have been described for work and rest at any time t as working HR_t and resting HR_t, respectively [6]. In addition, these same authors have presented a formula to predict the time pattern for heart rate recovery from the cessation of physical work towards the appropriate equilibrium resting level as recovery HR_t [6]. Further, Givoni and Goldman [7] published a predictive equation to describe the equilibrium heart rate responses expected for non- and partially- acclimated individuals. The computational adjustments necessary to predict the time patterns of heart rate during rest, work and recovery from work for non- and partially-acclimated persons are also displayed in this same reference.

. . . .

INSERT FIGURE 6 ABOUT HERE

. . . .

A comparison between predicted and measured final equilibrium heart rate responses from our own investigations (n=33) and the investigations [9,18] of others (n=75) as originally presented by Givoni and Goldman [6] is shown in Figure 6. For both our own observations and the observations of others, the agreement between the measured and the predicted heart rate responses is excellent as shown in the figure.

CURRENT HEAT STRESS PREDICTION MODEL

As stated earlier, the current version of our heat stress prediction model is programmed on a standard Hewlett Packard (HP) 41CV hand-held calculator. The only major modifications to the standard HP 41CV involve (a) the addition of a specially designed portable eprom (Hand Held Products, Inc.) for 32K added memory and (b) a redesigned touch pad. With the 32K of added memory, the HP 41CV presents 36K of memory of whic'. 8K is currently programmed. The redesign of the touch pad for the HP 41CV to incorporate our heat stress prediction modeling needs is shown in Figure 7.

. . . .

INSERT FIGURE 7 ABOUT HERE

. . . .

As seen in Figure 7, the prefix keys ("select","disp","comp"and "disp units") are located near the center of the touch pad. Above these prefix keys the user observes keys for parameters which describe the soldier. The three rows of keys immediately below the prefix keys describe the environment. The bottom row of keys are output or information keys.

The top row of keys are used to set the computer programming parameters for the soldier's clothing system. Separate keys are designated for Mission Oriented Protective Posture (MOPP) levels I-IV which are based on the protective clothing and equipment worn. The various levels of MOPP provide a flexible clothing system to protect soldiers against suspected chemical agents during chemical warfare which may help facilitate mission accomplishment. In addition, 21 other clothing systems are available in a clothing menu which is displayed in

Table 1. This table shows the description of the particular clothing system and the display given on the HP 41CV. Each of the 25 clothing systems which are available to the user have individual coefficients which describe the thermophysical properties of the clothing as a function of the work rate and effective wind velocity. This concept has been presented in some detail elsewhere [5].

. . . .

INSERT TABLE 1 ABOUT HERE

. . . .

The second row of keys from the top sets the internal parameters for the soldier's metabolic work rate. Individual keys are available to describe light, moderate and heavy physical work which are categorized as 250, 425 and 600 W, respectively. If another known metabolic rate is desired, it can be entered using the "metab rate" key. While the preferred units for metabolic rate are watt, values can be entered in $kcal\cdot hr^{-1}$, $BTU\cdot hr^{-1}$, or METS. This same key can be used to input the components necessary to compute the metabolic rate where body weight (kg), external load (kg), walking speed ($m\cdot s^{-1}$), grade (%), and a terrain coefficient are necessary [see 11]. The multiplication factors necessary to compute metabolic rate as a function of terrain are presented in Table 2. Finally, an additional key ("func") is available, but yet unprogrammed, to possibly compute metabolic rate for other modes of locomotion than walking such as running, lifting, etc..

. . . .

INSERT TABLE 2 ABOUT HERE

. . . .

The third row of keys from the top are to individually categorize casualties ("caslt") as light, moderate or heavy, and to describe state of heat acclimation as either non-acclimated ("non-accl") or fully acclimated ("accl"). Light, moderate and heavy casualties are described as less than 5% casualties, about 20% casualties, and greater than 50% casualties, respectively. These casualty categories are also based on individual upper limits for deep body temperature which were developed from information by Goldman [3] and scientific results provided by Israel Defence Forces Technical Reports.

The first row of keys below the prefix keys address the ambient air temperature (T_a) and relative humidity (%rh). The T_a can be entered in either ^oC or ^oF while relative humidity can be evaluated as per cent relative humidity, wet bulb temperature (^oC or ^oF), dew point or vapor pressure. If this information is not available to the user, input keys for our standard hot-wet (35^oC, 75% rh) or hot-dry (49^oC, 20% rh) climatic conditions are available.

The second row of keys below the prefix keys allow the user to provide input concerning the wind speed. While the preferred units are $m \cdot s^{-1}$, the expected wind speed ("wnd spd") can be entered in units of mph, $km \cdot hr^{-1}$, $ft \cdot sec^{-1}$ or knots. Calm, breezy or windy conditions are categorized as 0.5, 2.0 and 4.0 $m \cdot s^{-1}$, respectively.

The third row of keys below the prefix keys address the impact of the solar heat load. The internal parameters used in considering solar heat load were developed from the concept of mean radiant temperature [2] as applied to clothing heat exchange by Breckenridge and Goldman [1]. Categorizations are cloudy, partly cloudy ("prt cloudy") or clear sky with allowance for the indoors where there is no appreciable solar load.

The output keys are at the bottom of the calculator. The "wrk cycle" key provides output for the calculated work-rest cycle, and the one time only maximum work period with time periods in minutes. The "water req" key allows the user to compute the water requirements during work, rest and combined in canteens per hour or quarts per hour. One of the output keys remains uncommitted and remains available for future use.

. . . .

INSERT TABLE 3 ABOUT HERE

. . . .

Table 3 illustrates the predicted physical work-rest cycles and associated water requirements for four different military scenarios. The required inputs are the clothing worn, physical work rate, casualty level, acclimation state, environmental conditions, wind speed and solar heat load. The expected outputs are the physical work-rest cycle (min), one time only maximum work period (min), and the associated water requirements (canteens per hour). Compared to Scenario 1, the results of Scenario 2 illustrate the importance of the solar load in reducing both the physical work-rest cycle and one time only maximum work period while increasing the associated water requirements. Results from Scenario 3 display the dramatic reduction in the work component of the work-rest cycle and the associated reduction in the one time only maximal work period while wearing MOPP IV. The results from Scenario 4 show the benefits of reducing the metabolic work rate from heavy to moderate in terms of improvement in the work component and the work-rest cycle and enhancement of the one-time only maximum work period. Hopefully, the military user can employ this calculator to help avoid unnecessary casualties associated in the environmental heat extremes, and by predicting appropriate work-rest cycles and water requirements facilitate the achievement of mission objectives.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the many significant contributions of Mr. John R. Breckenridge and Drs. Baruch Givoni and Ralph F. Goldman in the development of this project, and the technical assistance of Mrs. Edna R. Safran in preparing the manuscript.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Approved for public release; distribution unlimited.

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

This report was published in large part by Pandolf, K.B., L.A. Stroschein, L.L. Drolet, R.R. Gonzalez and M.N. Sawka. Prediction modeling of physiological responses and human performance in the heat. Comput. Biol. Med. 16, 319 (1986).

REFERENCES

1. Breckenridge, J.R. and R.F. Goldman. Solar heat load in man. J.Appl.Physiol. 31,659 (1971).
2. Gagge, A.P. Effective radiant flux, an independent variable that describes thermal radiation on man. In: Physiological and behavioral temperature regulation. J.D. Hardy, A.P. Gagge, and J.A.J. Stolwijk (eds), Charles C. Thomas, Springfield, pp. 34-45 (1970).
3. Goldman, R.F. CW protective clothing: the nature of it performance degradation and some partial solutions. Handbook of the thirteenth commwealth defence conference on operational clothing and combat equipment. pp.66-68 (1981).
4. Givoni, B. and E. Berner-Nir. Expected sweat rate as a function of metabolism, environment, and clothing. Res.Rep.UNESCO. Israel Institute of Technology, Haifa (1967).
5. Givoni, B. and R.F. Goldman. Predicting rectal temperature response to work, environment, and clothing. J. Appl. Physiol. 32,812 (1972).
6. Givoni, B. and R.F. Goldman. Predicting heart rate response to work, environment, and clothing. J. Appl. Physiol. 34,201 (1973a).
7. Givoni, B. and R.F. Goldman. Predicting effects of heat acclimatization on heart rate and rectal temperature. J. Appl. Physiol. 35,875 (1973b).
8. Lustinec, K. Sweat rate, its prediction and interpretation. Arch. Sci. Physiol. 27,A127 (1973).
9. Macpherson, R.K. Physiological responses to hot environments. Medical research council special report series no. 298. Her Majesty's Stationary Office, London, pp.219, 294-299 (1960).

10. Pandolf, K.B., R.L. Burse, and R.F. Goldman. Role of physical fitness in heat acclimatisation, decay and reinduction. Ergonomics 20,399 (1977a).

11. Pandolf, K.B., B. Givoni, and R.F. Goldman. Predicting energy expenditure with loads while standing or walking very slowly. J. Appl. Physiol. 43,577 (1977b).

12. Sawka, M.N., M.M. Toner, R.P. Francesconi, and K.B. Pandolf. Hypohydration and exercise: effects of heat acclimation, gender and environment. J. Appl. Physiol. 55,1147 (1983).

13. Sawka, M.N., R.P. Francesconi, N.A. Pimental, and K.B. Pandolf. Hydration and vascular fluid shifts during exercise in the heat. J. Appl. Physiol. 56,91 (1984).

14. Shapiro, Y., K.B. Pandolf, and R.F. Goldman. Sex differences in acclimation to a hot-dry environment. Ergonomics 23,635 (1980a).

15. Shapiro, Y., K.B. Pandolf, B.A. Avellini, N.A. Pimental, and R.F. Goldman. Physiological responses of men and women to humid and dry heat. J. Appl. Physiol. 49,1 (1980b).

16. Shapiro, Y., K.B. Pandolf, B.A. Avellini, N.A. Pimental, and R.F. Goldman. Heat balance and transfer in men and women exercising in hot-dry and hot-wet conditions. Ergonomics 24,375 (1981).

17. Shapiro, Y., K.B. Pandolf, and R.F. Goldman. Predicting sweat loss response to exercise, environment and clothing. Eur. J. Appl. Physiol. 48,83 (1982).

18. Wyndham, C.H., N.B. Strydom, J.F. Morrison, F.D. Dutoit, and J.G. Kraan. Responses of unacclimatized men under stress of heat and work. J. Appl. Physiol. 6,681 (1954).

FIGURE LEGENDS

FIGURE 1. Comparison of predicted (lines) and measured (x) patterns of rectal temperature (T_{re}) during one hour cycles of rest, exercise and recovery for 12 soldiers as published by Givoni and Goldman [5]. Subjects wore shorts, standard fatigue uniforms (STD) or protective overgarments over fatigues (OG) in climatic conditions of either 35^o or 49^oC ambient temperature with vapor pressures of 20 or 30 mm Hg at wind speeds of $0.5\ m{\cdot}s^{-1}$.

FIGURE 2. Comparison of predicted (lines) and measured (dots) patterns of rectal temperature as a function of day of acclimation for 24 soldiers walking for an attempted 100 min at 49^oC, 20% rh as published by Givoni and Goldman [7].

FIGURE 3. Comparison of predicted and observed rectal temperature responses of 12 soldiers while wearing three different military clothing systems each under two different climatic conditions.

FIGURE 4. Relationship between predicted and measured sweat loss for 111 individual responses involving 24 soldiers as published by Shapiro et al. [17].

FIGURE 5. Comparison of four methods of predicting sweat loss using data from our Division derived from 34 soldiers as published by Shapiro et al. [17]. The solid line represents the line of identity while the dashed lines represent the ±20% range from the line of identity.

FIGURE 6. Relationship between predicted and measured final heart rate responses: left, from our own Division studies (n=33); right, from observations (n=40) by Macpherson [9] and observations (n=35) by Wyndham et al. [18] as published by Givoni and Goldman [6].

FIGURE 7. The redesigned touch pad of the Hewlett Packard 41CV which encompasses the input parameters of our heat stress prediction model.

TABLE 1. CLOTHING MENU

	DISPLAY	DESCRIPTION
1.	:AVIAT	Aviators
2.	:AVIAT+ARM	Aviators + armor (mask+hood)
3.	:AV+OG+ARM	Aviators +OG+armor (MOPP IV)
4.	:AV+UK+UNDW	Aviator+UK underwear (MOPP IV)
5.	:BDO+RAIN	BDO + rainsuit
6.	:BDU	BDU
7.	:BDU+ARMOR	BDU + armor
8.	:BDU+RAIN	BDU + rainsuit
9.	:CVC	CVC
10.	:CVC+CBR, MI	CVC + CBR (MOPP I)
11.	:CVC+CBR, MIV	CVC + CBR (MOPP IV)
12.	:DESRT CAMOF	Desert camouflage
13.	:DESERT TAN	Desert tan
14.	:EOD+FATIGUE	EOD over fatigues
15.	:FIRE+FATIG	Firefighters over fatigues
16.	:FUEL HANDLR	Fuel handlers (TAP)
17.	:MOPP I	MOPP I
18.	:MOPP II	MOPP II
19.	:MOPP III	MOPP III
20.	:MOPP IV	MOPP IV
21.	:PONCH+FATIG	Poncho over fatigues
22.	:TROP CAMOFL	Tropical camouflage
23.	:TROP FATIG	Tropical fatigues
24.	:TROP FA+ARM	Tropical fatigues + armor
25.	:UTIL FATIG	Utility fatigues

TABLE 2. MULTIPLICATION FACTORS FOR ENERGY COST AS A FUNCTION OF TERRAIN

TERRAIN	η
BLACKTOP SURFACE	1.0
DIRT ROAD	1.1
LIGHT BRUSH	1.2
HARD PACKED SNOW	1.3
HEAVY BRUSH	1.5
SWAMPY BOG	1.8
LOOSE SAND	2.1
SOFT SNOW	1.3+0.08 (CMS. OF SNOW PRINT DEPTH LEFT BY FOOT)

TABLE 3. PREDICTED PHYSICAL WORK-REST CYCLES AND WATER REQUIREMENTS ASSOCIATED WITH FOUR DIFFERENT MILITARY SCENARIOS

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
INPUTS:				
	MOPP 1	MOPP 1	MOPP 4	MOPP 4
	HVY.WRK.	HVY.WRK.	HVY.WRK.	MOD.WRK.
	HVY.CASLT.	HVY.CASLT.	HVY.CASLT.	HVY.CASLT.
	ACCL.	ACCL.	ACCL.	ACCL.
	HOT DRY	HOT DRY	HOT DRY	HOT DRY
	WINDY	WINDY	WINDY	WINDY
	CLOUDY	CLEAR SKY	CLEAR SKY	CLEAR SKY
RESULTS:				
	Time W:R:M=33*27*84	Time W:R:M=28*32*74	Time W:R:M=14*46*52	Time W:R:M=24*36*87
	Water W:R:C=2.3*0.9*1.7	Water W:R:C=2.4*1.1*1.7	Water W:R:C=2.4*1.1*1.4	Water W:R:C=2.2*1.1*1.6

W:R:M=work:rest:maximum work [time periods (minutes)]
W:R:C=work:rest:combined [water requirements (canteens per hour)]

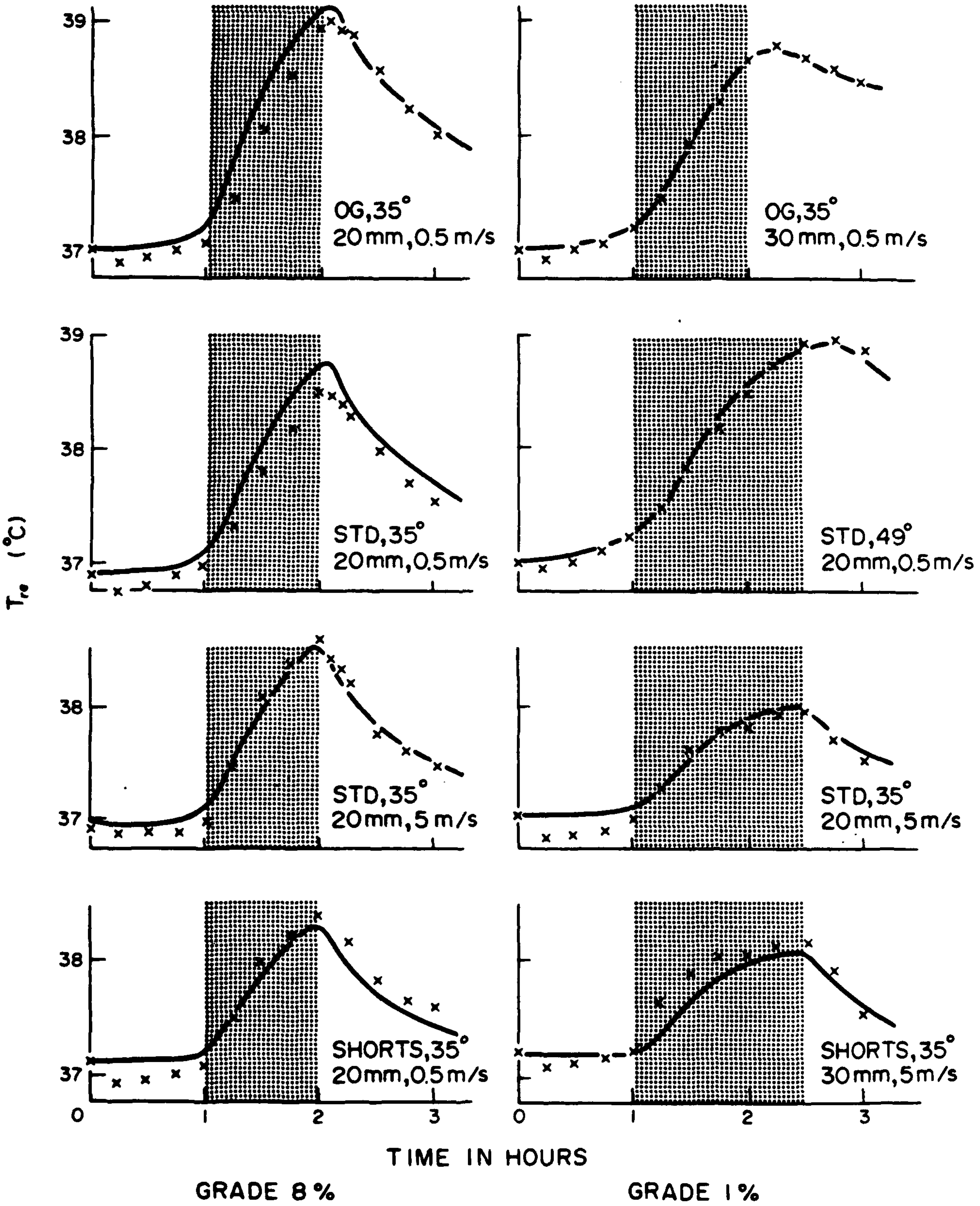
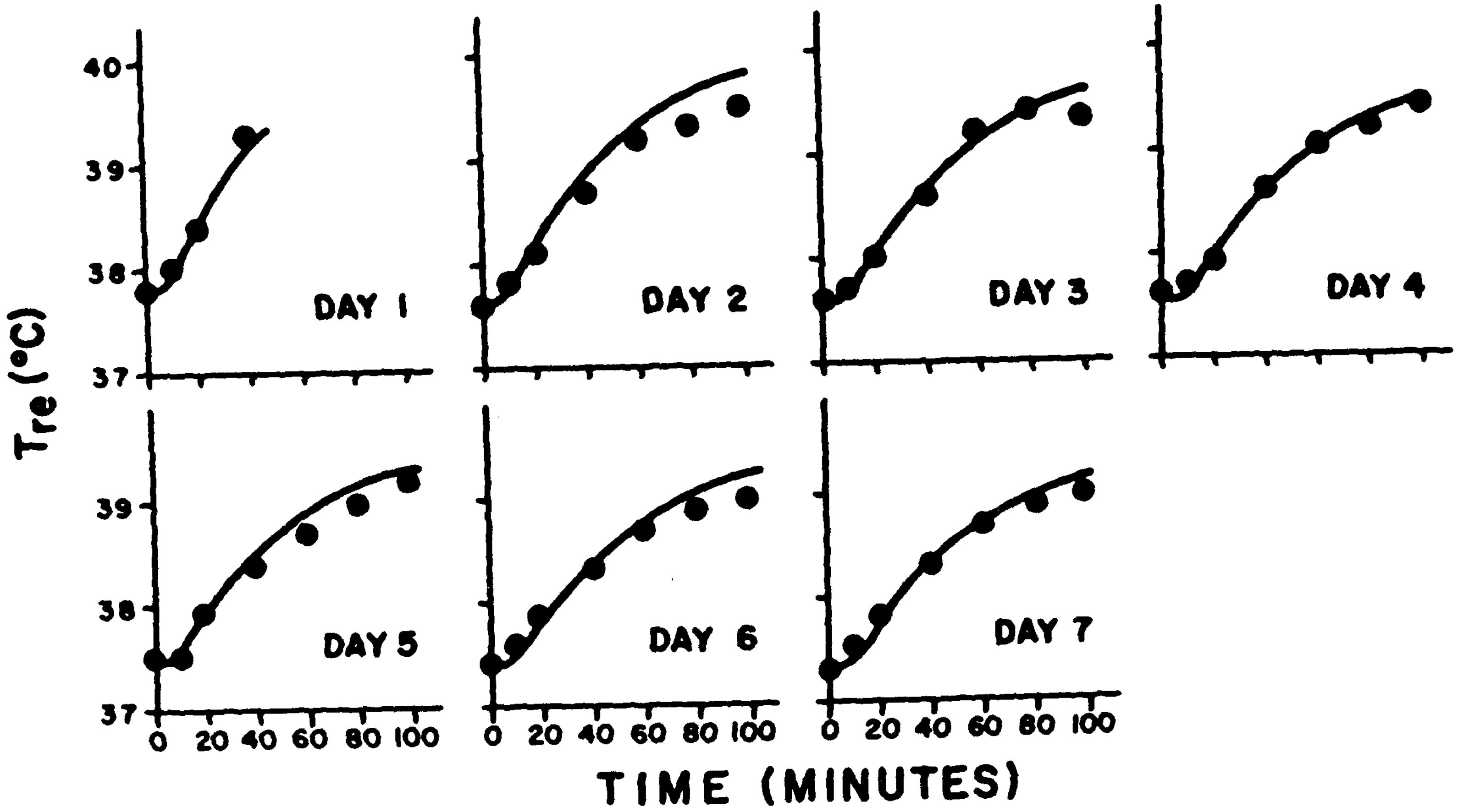

39
38
37
OG,35°
20mm,0.5m/s
OG,35°
30mm,0.5m/s
39
38
37
T_{re} (°C)
STD,35°
20mm,0.5m/s
STD,49°
20mm,0.5m/s
38
37
STD,35°
20mm,5m/s
STD,35°
20mm,5m/s
38
37
SHORTS,35°
20mm,0.5m/s
SHORTS,35°
30mm,5m/s
0
1
2
3
0
1
2
3
TIME IN HOURS
GRADE 8%
GRADE 1%

FIG.1

FIG. 2


40
39
38
37
T_{re} (°C)
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 7
0
20
40
60
80
100
TIME (MINUTES)

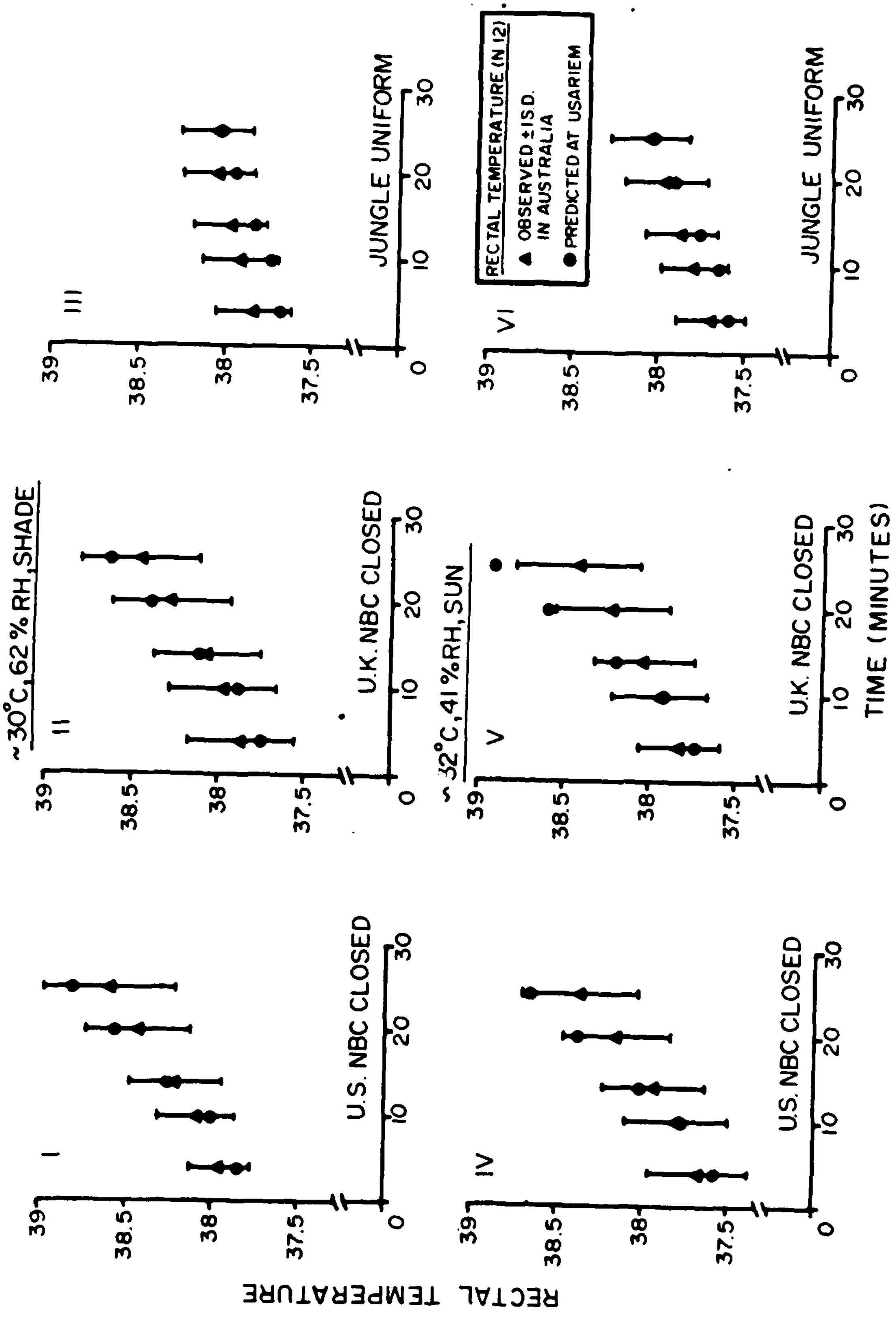

RECTAL TEMPERATURE
TIME (MINUTES)
~30°C, 62% RH, SHADE
~32°C, 41% RH, SUN
I
II
III
IV
V
VI
U.S. NBC CLOSED
U.K. NBC CLOSED
JUNGLE UNIFORM
RECTAL TEMPERATURE (N 12)
▲ OBSERVED ±1 S.D. IN AUSTRALIA
● PREDICTED AT USARIEM
39
38.5
38
37.5
0
10
20
30

FIG. 3

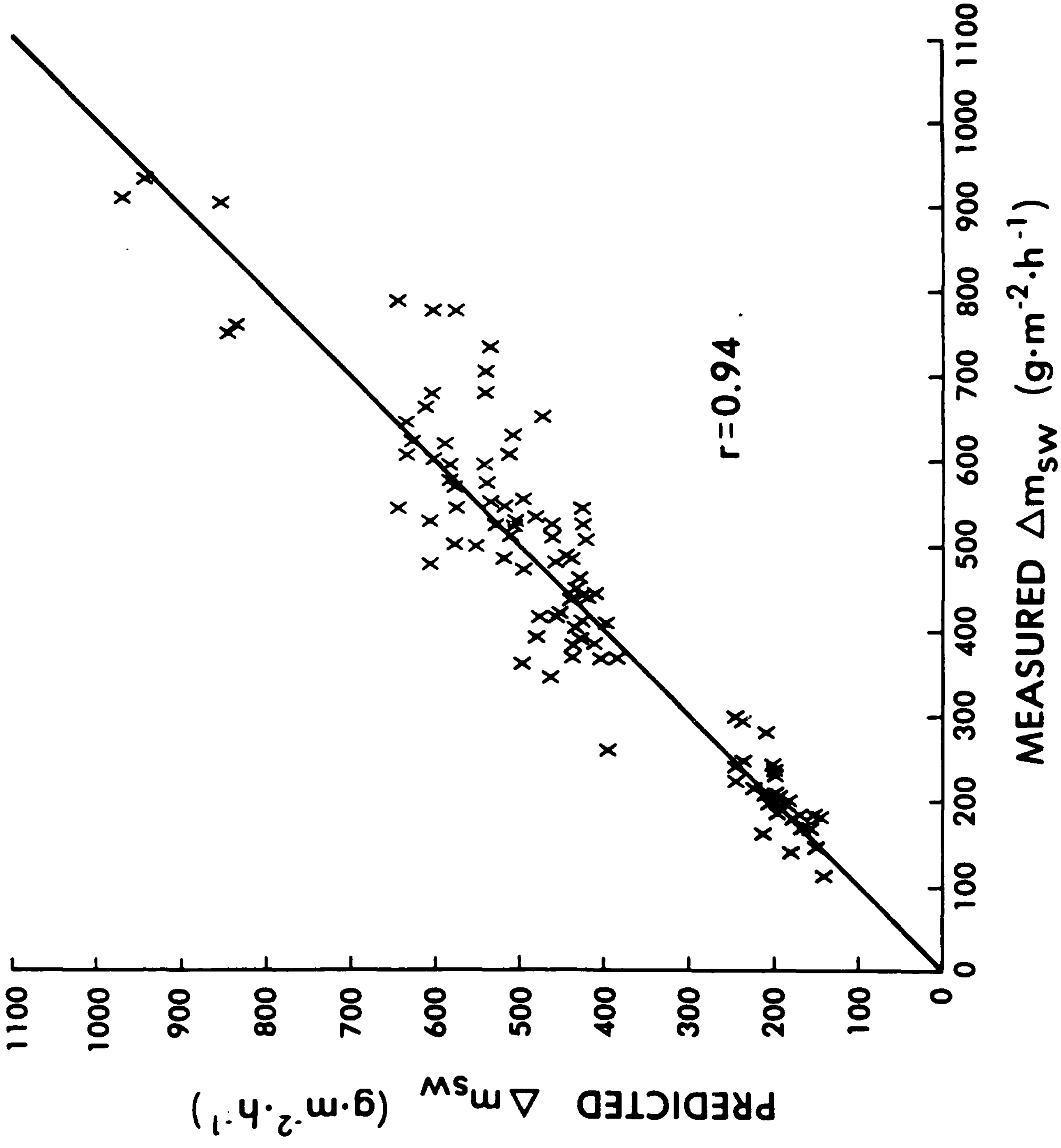

PREDICTED Δm_{sw} $(g \cdot m^{-2} \cdot h^{-1})$
0
100
200
300
400
500
600
700
800
900
1000
1100
MEASURED Δm_{sw} $(g \cdot m^{-2} \cdot h^{-1})$
r=0.94

FIG. 4

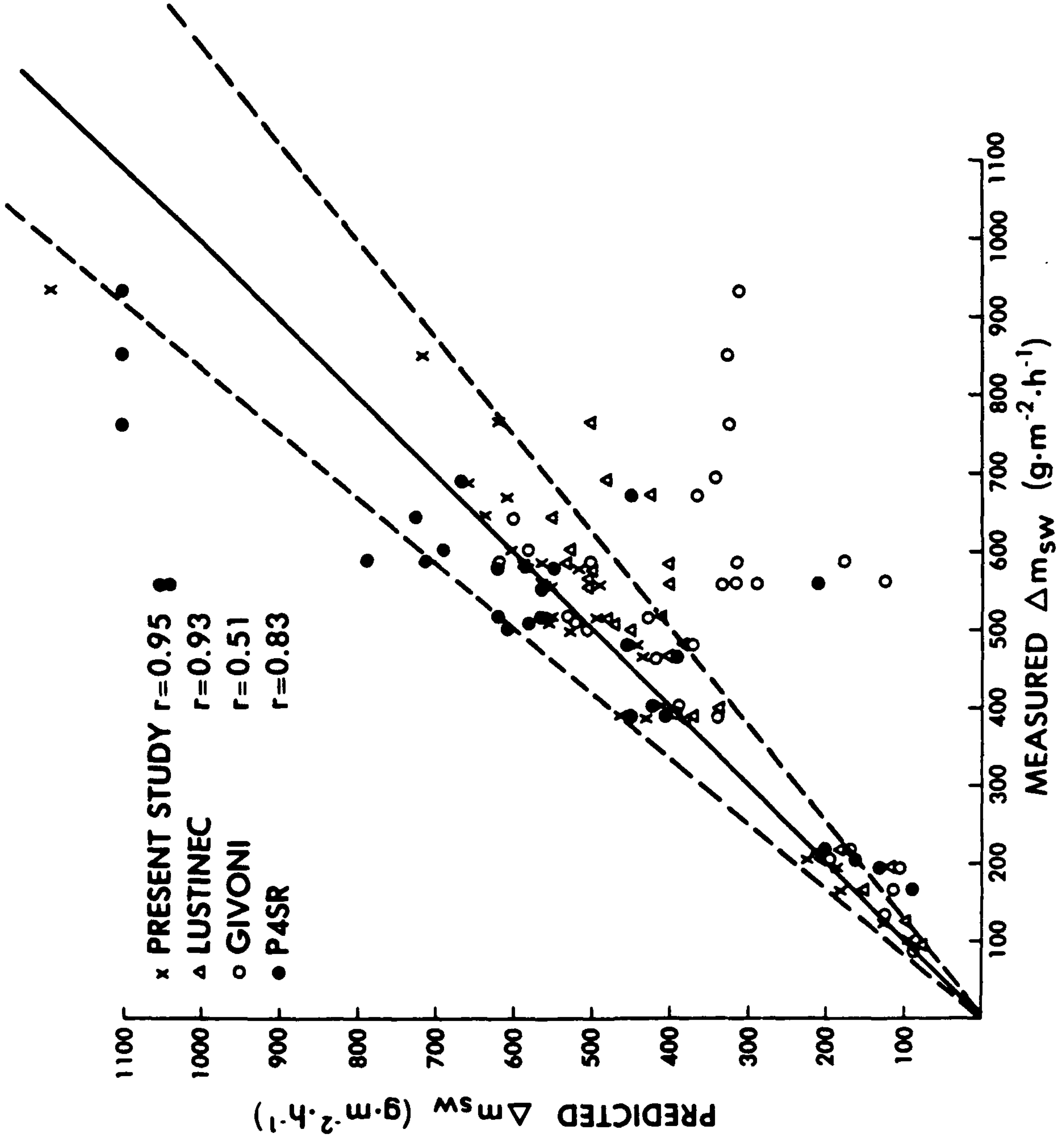

× PRESENT STUDY r=0.95
▵ LUSTINEC r=0.93
○ GIVONI r=0.51
● P4SR r=0.83
MEASURED Δ m_sw (g·m^-2·h^-1)
PREDICTED Δ m_sw (g·m^-2·h^-1)
100
200
300
400
500
600
700
800
900
1000
1100

FIG.5

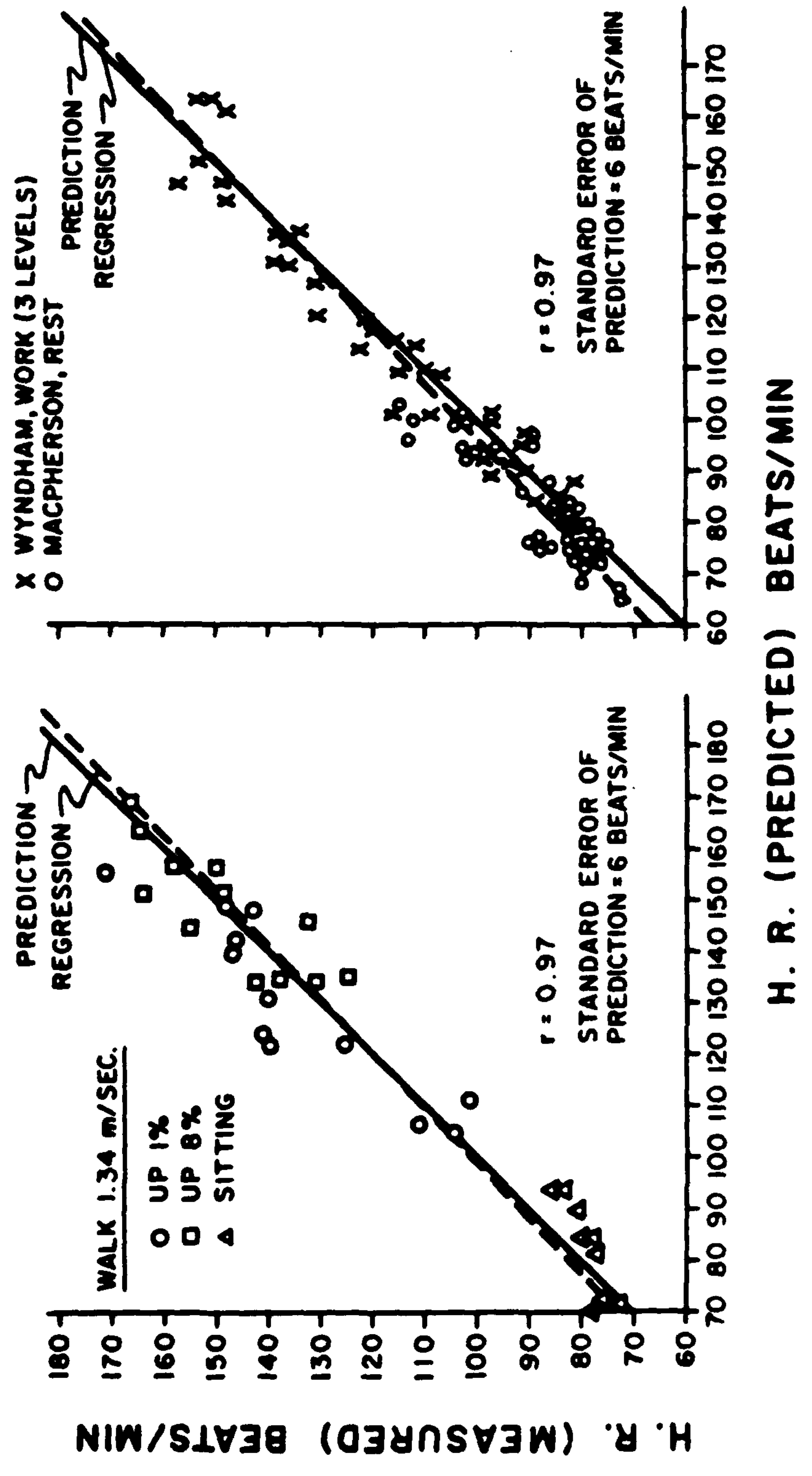

H. R. (MEASURED) BEATS/MIN
180
170
160
150
140
130
120
110
100
90
80
70
60
WALK 1.34 m/SEC.
○ UP 1%
□ UP 8%
△ SITTING
PREDICTION
REGRESSION
r = 0.97
STANDARD ERROR OF PREDICTION = 6 BEATS/MIN
70 80 90 100 110 120 130 140 150 160 170 180
X WYNDHAM, WORK (3 LEVELS)
O MACPHERSON, REST
PREDICTION
REGRESSION
r = 0.97
STANDARD ERROR OF PREDICTION = 6 BEATS/MIN
60 70 80 90 100 110 120 130 140 150 160 170
H. R. (PREDICTED) BEATS/MIN

FIG. 6

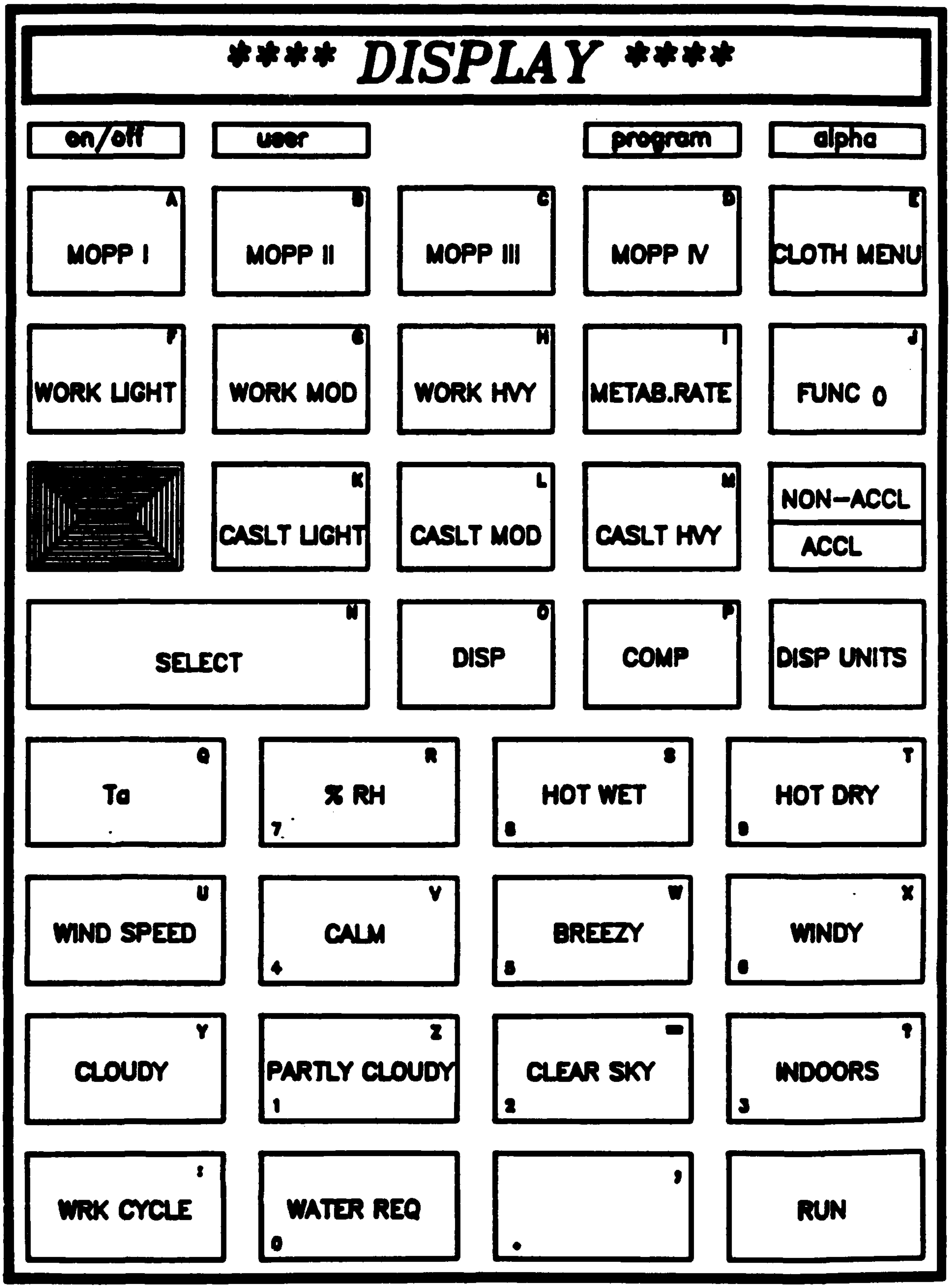

**** DISPLAY ****
on/off
user
program
alpha
A
MOPP I
B
MOPP II
C
MOPP III
D
MOPP IV
E
CLOTH MENU
F
WORK LIGHT
G
WORK MOD
H
WORK HVY
I
METAB.RATE
J
FUNC 0
K
CASLT LIGHT
L
CASLT MOD
M
CASLT HVY
NON-ACCL
ACCL
N
SELECT
O
DISP
P
COMP
DISP UNITS
Q
Ta
R
% RH
7
S
HOT WET
8
T
HOT DRY
9
U
WIND SPEED
V
CALM
4
W
BREEZY
5
X
WINDY
6
Y
CLOUDY
Z
PARTLY CLOUDY
1
=
CLEAR SKY
2
?
INDOORS
3
:
WRK CYCLE
WATER REQ
0
,
.
RUN

FIG. 7