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RELATIVE APPLICATIONS OF INTEGRATING ENVIRONMENT, CLOTHING AND PERSONAL EQUIPMENT ON MILITARY OPERATIONS

by

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ABSTRACT

This report deals with the development, thermal properties, and implications of research provided by certain models and thermal manikins used by thermal physiologists and clothing researchers. Particular attention is given to the heat and mass transfer properties of chemical protective overgarments from the United States and other NATO countries. The focus is also directed to the hierarchy, application of coefficients generated from the use of various copper models and thermal manikins, and the further development of operational and rational thermoregulatory models used for the prediction of heat strain useful in protective clothing and military systems.

INTRODUCTION

This paper addresses the role and relative applications of electrical thermal models and manikins and their general impact on the field of thermal physiology and clothing research. Also discussed is the application of thermal and physiological coefficients for military needs derived to a great extent from such manikins that are applied towards prediction of thermal tolerance limits. The information gained by the use of models is an invaluable part of the focus directed towards the interactions of human-environment-clothing-and task performance as presented in the scheme in Figure 1.

This servo-control scheme outlines the critical elements to research into military clothing and task performance. Much of the research is directed toward protective measures or attenuation against internal or environmental extremes which cannot be compensated by normal heat exchange processes. This scheme contrasts with the focus of civilian clothing research which is geared largely on establishing thermal comfort requirements (or zones). Interestingly, both objectives trace their roots to early quantification gained by the experimentation with thermal manikins and electrical models which are still actively used today.

A. HISTORICAL PERSPECTIVE

Before the 1940s, there was little attention on quantification of clothing properties other than sparse accounts from the Harvard Fatigue Laboratory, the John B. Pierce Foundation Laboratory, the Russell Sage Institute and various other research institutions in the United Kingdom, particularly the Shirley Institute (1,29,39). Scientists from such laboratories were interested, for the most part, in thermal properties affecting clothed human subjects. A fundamental (and now universal) unit which appeared early in 1941 first expressed the insulating effects of clothing in terms of the clo unit. This unit was coined by Gagge, Burton and Bazett (17). This unit along with the met (1 met = to about 100 watts of energy production) provided a standardized and practical measure for both metabolic activity and thermal insulation which could be expressed in both metric and English nomenclature. To review briefly here, if thermal equilibrium is to be attained without the necessity of major physiological adjustments, the three factors concerned with such a balance at an optimal skin temperature are heat production of the body (M), the insulating value of the clothing (I_T) and the environmental temperature (T_a). The use of practical units for thermal activity and insulation provided a uniform system to describe comfortable conditions in relation to the heat exchange of humans with the environment.

The proposed thermal activity was originally defined as 50 kcal per hour per square meter[1] of the surface area of the individual. This unit was called one met. The unit for thermal insulation of clothing was rationalized then as the insulation to maintain, in comfort, a sitting (resting) subject in a normally ventilated room (air movement, V = 10 cm/s) at a temperature of 21° C and a humidity of less than 50%. This unit was described as one clo. Since thermal insulation is the resistance offered to flow of heat, its measure is done by considering the ratio of the difference in temperature between two surfaces to the flow of heat per unit surface area that results. The heat transmitted through the clothing was estimated by Gagge et al. (17) as 38 (76% of 50) kcal/(m² •h). The total insulation (I_T) which is the sum of the insulation of the clothing, I_{cl}. and that of the ambient air, I_a, is given by the equation:

$$I_T = (I_{cl} + I_a) = \{33\text{-}21\}/38 = 0.32, \qquad K/[kcal/(m^2 \bullet h)] \tag{1}$$

****

1./ This deviation from SI units here is only for historical interest; {One kcal/(m² •h) x 1.163 = W•m⁻²}

where 33° C signifies the "comfortable average skin temperature". From previous work by Winslow et al. at the John B. Pierce Laboratory (38), the values for the insulation of air (I_a) were calculated by Burton (7,8) by the use of the following empirical equation:

$$I_a = 1/[0.61 \cdot (T_a/298)^3 + 0.19 \cdot V \cdot (298/T_a)], \qquad \text{clo} \qquad (2)$$

where, T_a is in ° C and air velocity (V) is in $cm \cdot s^{-1}$, I_a is thus equivalent to 0.14 K/[kcal/($m^2 \cdot h$)] in the definition above. The insulation of intrinsic clothing, which is equal by definition to one clo becomes

$$I_{cl} = 0.32 - 0.14 = 0.18. \qquad K/[kcal/m^2 \cdot h)] \text{ or} \qquad (3)$$
$$= 0.1547 \ m^2 \cdot K \cdot W^{-1}$$

Equation 2 was originally calculated by Burton (6) for T_a ranges of 25 to 40° C at various air movements and found to vary less than 0.1 clo (+ or -0.016 $m^2 \cdot K$ per watt) so he suggested that the temperature factor could be eliminated in calculation of the value for insulation of air. Developments to Burton's equation show that the boundary air layer may be expressed in clo units by (6):

$$I_a = 6.46/(h_r + h_c), \qquad \text{clo} \qquad (4)$$

where, 6.46 converts Equation 3 units of $K \cdot m^2 \cdot W^{-1}$ to clo units. This analogy has been applied very usefully in manikin and human studies as a non-dimensional (ND) cooling efficiency coefficient, in which

$$F_{cl} = I_a/(f_{cl} \cdot I_t), \qquad (5)$$

in Equations 4 and 5 the linear radiation coefficient, h_r, is a function of surface and air temperature, h_c is the respective convective heat transfer coefficient (a function of V where $h_c = 8.6\ (V)^{.52}$); f_{cl} is a factor which modifies the boundary layer insulation as clothing surface area increases, roughly 15%-25% for each clo unit (6,32). The clo unit originally equaled the insulative value of a normal business suit (the fashion and weight in 1941) at 21.1° C (70° F). An alternative unit introduced around 1946 by Pierce and Rees [cited in ref. 14] of the Shirley Institute was the tog unit, a smaller unit of resistance roughly equivalent to light summer clothing [1 tog = 0.645 clo or 0.1 $m^2 \bullet K \bullet W^{-1}$].

Clothing insulation was initially estimated from human evaluations by Belding et al. in 1945 (1). Using Burton's I_a - the insulation value of air, they determined I_T as:

$$I_T = (I_{cl} + I_a), \quad \text{clo} \qquad (6)$$
$$= \{6.46(T_{sk}-T_a)A_d\}/[M\ -0.68\ E+0.97\dot{m}_b(0.67\Delta T_{re}+0.33\Delta\ T_{sk})$$

where 6.46 = the reciprocal of the clo value, (Equation 4).

- M = metabolic heat production, W
- A_d = Dubois surface area, m^2
- E = evaporative heat loss from successive weighing of the clothed subjects (g/h) x 0.68 W•h/g or 2426 $kJ \bullet kg^{-1}$
- $\dot{m}_b$ = weight of the unclothed subject, kg
- ΔT_{re} = rate of rectal temperature change, °C
- ΔT_{sk} = rate of fall of average skin temperature excluding hands, feet and head, °C

Belding (2) found that under equivalent environmental conditions (i.e., comparable T_a and rh), the most exact physiological studies still produced anywhere from 5 to 15% errors in thermal insulation values. In contrast, manikin values generally give no greater than 2% errors in the hands of experienced persons (6,18,23,32). The insulative value is affected by a multitude of factors that are difficult to control in human studies; some include:

1. the fabric's thermal conduction and extent of trapped air layers;
2. how the fabric is dispersed over the skin surface area;
3. variation in skin temperature distribution and heat flow at various sites;
4. variations in the clothing surface covering the skin, none on the face and hands, presence of arteriovenous anastomosis (AVAs) in the extremities and vasodilatory activity in the face (18,26,27).

Other concerns present with clothing resistance determinations on humans are associated with time factors and measurement limitations. Generally, the clothing insulation values determined on human subjects must be taken without the influence of insensible perspiration becoming a factor and in an environment where thermal equilibrium is possible. In the transient phases of an experiment, absolute clothing insulation is highly variable and dependent on heat capacity of the clothing which is usually a function of pre-conditioning temperatures (18,26,41). Typically, if heat content of an ensemble to be measured during the transient period is larger than that present at steady-state, initial clothing insulation measurements are wholly disparate. Therefore, a limitation of using human experimentation for routine determinations of thermal insulation is in the calculation of heat content (or heat debt) especially when the body is losing excessive heat.

In order to discriminate more closely between insulating values of various whole ensembles that were being developed for military use, faster access to data was needed. Electrically-heated manikins were essential. This became evident in early offshoots of a physiological study by Belding in 1943 (Breckenridge, personal communication) at the Harvard Fatigue Laboratory on electrically-heated flying suits and in another study by him on heated casualty blankets with built-in thermostats. In both cases, Belding worked closely with an initial contractor (the General Electric Co.) during development of a copper manikin. This manikin allowed alterations in the surface temperatures of the hands and feet without alterations in the rest of the body.

Other first generation models also appeared in many laboratories. An early thermal manikin (38) constructed for the John B. Pierce Laboratory by the Bridgeport Brass Co. was done by molding 0.8 mm copper sheeting over a papier-mache structure that had a surface area of 1.8 m^2. In this manikin, power was provided by 16 variable wattage light bulbs which were enclosed in copper mesh cages. Each cage was located at various segments of the body which simulated the temperature distribution of a "comfortably cool" person (in agreement with the classic clo definition), while nude and at rest in $T_a = 30°C$. Heat input in this manikin was variable up to 400 watts.

The Quartermaster Climatic Research Laboratory (QM) (a predecessor to USARIEM) around this time period was also experimenting with prototype manikins. One early model was constructed of stovepipe and sheet metal. It lacked arms and a head and had a robust torso with a central electrical heater and a fan to circulate air within its shell. The earliest rigorous copper manikins used by the QM were patterned after the Belding manikin (13).

The concepts using the clo value in heat copper manikins assessed the dry heat exchange properties adequately and many other laboratories between the years 1949-1959 built their own (22,25,35). Some were single circuit controlling a constant average skin surface temperature, in conformity with the original definition of clo and others had specialized circuits for evaluation of variable heat flow through different areas of the skin surface (27,28).

A missing attribute was the insensible factor present in humans which is impeded by clothing and is activated by thermoregulatory sweating. In 1937, Gagge (15) described the skin wettedness component (w) as the ratio of evaporative heat loss of the total skin surface area wet with sweat to the maximum possible only limited by the environment (E_{max}). The latter property was strongly related to the evaporative heat transfer coefficient and the water vapor transfer gradient. Thus, water vapor which accumulates within clothing raises the local humidity and, therefore, slows down the rate of sweat evaporation and removal of latent heat possible. Limited studies up to 1949 initially addressed the quantification of this vapor impedance factor. One of these produced an artificial "sweating" apparatus made up of a cylinder of wet blotting paper that was internally heating (14). In 1955, Whelan et al. (37) showed a relationship between clothing and impedance to water diffusion. However, the impedance to moisture diffusion compared masses of still air rather than transient properties which are affected by convection and radiation.

In 1961, Woodcock (40) introduced a new parameter, denoted as an index of the permeability of clothing to water vapor, based on his studies with wetted, unheated cylinders. He coined the parameter "permeability index" or i_m. The original measurement was with a wet cylinder in an uncontrolled, but precisely measured insulated room, from which the i_m could be calculated using a similar analogy for evaporative heat transfer that was done previously for sensible heat flow. This allowed the formulation of a transfer characteristic as the ratio of the thermal resistance of the clothing layer plus the overlying air layer (i.e., I_T) to the resistance to evaporative heat loss per unit of vapor difference across clothing plus the air layer (I_T/R_e). By definition, i_m is a non-dimensional constant which has the theoretical value of 1.0 for nude skin-air layers and from 0 to 1.0 for additional layers depending on extent of "moisture impedance". Figure 2 describes the upper limits based on the original analysis of i_m in terms of environmental zones described by low permeability and highest permeability (i_m=1).

In the mid-1960s many of Woodcock's assumptions were modified for operation with heated copper manikins. Breckenridge devised a cotton "skin" which fitted lightly around the complete surface area of a manikin. In terms of i_m and the ratio i_m/I_T (Fig. 2), this allowed, as a key component, the measurement of total evaporative heat loss of the "skin" on a life-sized model if the cotton skin was completely wetted and thereby 100% skin wettedness occurred. We have included in the figure, the psychrometric range of CB clothing based on i_m to total thermal insulation. The evaporation from such a manikin's surface (E_{sk}) is described as

$$E_{sk} = \{i_m/I_T \times 2.2\} (P_{s,sk} - P_a) \qquad W \cdot m^{-2} \qquad (7)$$

The term in brackets is the effective evaporative heat transfer coefficient over the skin-clothing-ambient gradient, where I_T is expressed in clothing resistance units, $m^2 \cdot {}^\circ K \cdot W^{-1}$.

B. MODERN APPLICATIONS OF THERMAL AND EVAPORATIVE PROPERTIES

Research involving clothing properties from the 1970s to the present has blossomed partly as an outcome of the sound theoretical and experimental analysis of the heat and mass transfer properties derived from the various thermal manikins. Many of the properties used earlier to describe human heat exchange with thermal manikins have now been successfully applied to other models. Figure 3 describes a flow diagram which portrays roughly some of the various offshoots of research activity occurring today in many laboratories throughout the world.

Table I gives an example of the extent of usage of these models since 1962 in our Institute. Figure 3 and Table I illustrate that the use of manikins and models has grown dramatically. A curious spark has occurred to the research involved in the human biophysical evaluation as well due, in part, to the experimentation with manikins. Most of the human research involving clothing biophysics and physiological responses is dedicated to develop (10,12,27,28), apply (6,32), and formulate specific coefficients (20) for use in predictive modeling of heat exchange.

At our Institute numerous electrical models and copper manikins are used for heat and water vapor transmission analysis; these include:

1. Wettable flat plates: To a great extent, scientists around the late 1940s still utilized flat plate or guarded ring cylinders (14,39,41) for their thermal insulation measurements which avoided many of the above experimental problems. In the flat plate apparatus, a central heated plate is thermostatically controlled at a set temperature and it is guarded below and at the sides by other heated elements maintained at the same temperature. The given fabric is laid smoothly over the measuring area and guard ring, and the rate of heat flow through the fabric into the air is analyzed by the energy required to maintain the source at constant temperature.

Information obtained with heated copper manikins relative to the dry thermal insulation of clothing has supplemented and displaced thermal resistance evaluations acquired with flat plates. However, studies with flat plates remain valuable because although insulative layers tend to be homogeneous in their thermal layers, this does not hold on highly curved surfaces. As such, layers of insulation which are parallel on a flat surface (i.e., almost 4 clo/inch) are not on curved surfaces due to compression. As manikin studies show, either the thermal conductivity is reduced (by an added trapped air space) or the external heat transfer coefficient is altered by air movement. Yet the geometrical configuration of the human body surface area also affects the convective and radiative properties which cannot be simulated by flat plates or cylinders. As shown in Figure 3, various laboratories have perfected newer devices (12,28) with which transient heat and mass transfer analysis is possible.

2. Copper Hand: A sectional copper hand is used for the analysis of dry heat exchange and insulative properties of prototype handwear items. The hand has 23 thermally isolated sections. Another articulating aluminum hand, recently acquired by USARIEM, will be used for more rugged (outdoor) field surveys of handwear. A polystyrene model has also been developed by Swedish investigators (11).

3. Copper Feet: A sectionalized copper foot was developed in the early 1960s which had 12 separate measuring sections. Each of the sections' temperature set points were controlled by manual adjustments of power with 12 separate heaters which was a tedious process. Each evaluation of a specific footwear item required almost two days (5). Around 1978, two new copper feet were developed, incorporating 27 separate measuring sections (Figure 4A). These feet are controlled by an automatically-adjusted power supply system, which is also controlled by a microprocessor that adjusts the temperature levels of each of the sections (Figure 4B). Additionally, the feet are more highly representative of the human foot than was the older model. Generally, all foot sections in the

USARIEM model can be brought to within + or -0.1° C of a selected set point within one hour and steady-state, required for dry sensible heat evaluations with thick footwear, occurs around four hours. Studies with these models show that the orientation of the foot with respect to the air motion affects the distribution of the boundary air insulation. The new models are used extensively to categorize sectional insulation values of many footwear items from various nations. The discernment of instep and toe regional insulation (i.e., critical zones for cold weather footwear) is now possible.

Until recently, only the weighted value for total footwear insulation (I_T), compared to the standard U.S. Army combat or vapor barrier boots, was used as the reference criterion for comparison of various prototypes from different manufacturers or countries. A recent study from our laboratory (18,31) showed that the regional distribution is an equally important factor which our copper feet can assess. Table II gives results from that study (34) in which a standard method, employing a regionally-heated copper foot, was developed to ascertain effects of surface moisture on boot insulation. In this method, regional insulation values are first determined under dry conditions, then during a "soak" in shallow water, and finally followed by a recovery evaluation after the soaking. Table II of a typical boot evaluation shows clearly the decreases in insulation evident by the environmental challenge (water soak) especially in the lower parts of the foot.

4. Copper Manikins: Our Institute has a complete collection of the original copper manikins used in the early Harvard Fatigue Laboratories, the Quartermaster Laboratory manikins, and under a Memorandum of Agreement, the original Wright-Patterson Air Force copper manikins developed by Hall (22) and used successfully for evaluation of sensible heat transfer in the Gemini and Apollo Programs (10). These copper manikins are roughly divided into three types. The first type are single circuit manikins which allow the measurement of total

clothing insulation and i_m without the control of surface temperature which stays around 33° C. The second type of manikins do allow temperature control of specific regions and dry insulation is currently measured exclusively in these. The third type of manikin is a sectional one in which variable heat flow can be introduced to the various sections. These allow regional heat and water vapor measurements occurring with devices such as auxiliary cooling vests or chemical protective garments. All of the above static (non-moving) manikins are being modified and refurbished with individual direct current power supplies which shall allow full computer control and data acquisition capabilities as in our copper foot models.

5. Articulated, Moveable Copper Manikin: This is the newest addition to the array of electrical devices in the Institute. In general, the body contours of the manikin, by design, are similar to those of the early 1943 manikins built by the General Electric Co. (13). As shown schematically in Figure 5, the total body surface area corresponds to the surface area of the early manikin. However, a more facile clearance for clothing under the arms and between the legs is present. The articulation around the arms also provides more ample clearance for the hands and hips while moving. The manikin is divided into nineteen separate zones which are capable of being heated and monitored independently. As evident in Figure 5, five overlapping sections (the support plates, etc.) have been combined in this diagram into 14 sections for convenience. Characteristically, all sections and joints are built of electro-deposited copper with a 2.4 mm uniform thickness except at joints, hands and feet. These latter sections are cast with aluminum which was hardcoated to prevent electrolysis with the copper. Research is now progressing to secure the optimum electrical power inputs to each section which are controlled by a computer. The amount of heat input (electrical power) evident in Figure 5, represents heat loss from the manikin in a given section

when at steady-state. Within the elbows, hands and feet, and the knees, separate cartridge heaters are present to provide the necessary heat in these regions. Computer programming for the on-line reading of each individual section temperatures and converting these data into power adjustment instructions for the controller has been developed. Figure 6 illustrates the maximum deviation of a selected set point temperature of two typical sections. Almost all sections presently can be brought to within + or -0.1° C of a selected section set point temperature.

One of the advantages of this articulated-moveable manikin is the fact that it has the capabilities of generating a walking motion up to 1.56 $m \cdot s^{-1}$ and, therefore, this mobility allows the study of thermal exchanges in clothing that are associated with movement; such studies are an intense area of research for providing coefficients in thermal modeling of thermal tolerance. In a recent study with the articulated manikin, the sectional heat transfer coefficients were mapped out while the manikin simulated walking. The manikin was not internally heated, a procedure in keeping with Woodcock's (9,40) original studies of unheated flat plates. Our study addressed the effect of the walking motion, per se, on convective heat exchange. A new naphthalene sublimation plate technique was developed closely analogous to the Nishi naphthalene sphere studies (30). However, in the present study naphthalene disks, following the contours of the copper manikin, were affixed to various body segments in a flush configuration rather than outside the air boundary layer. The manikin then simulated walking at four different gaits (0.2 to 0.9 $m \cdot s^{-1}$) under constant air temperature (30° C) at different ambient wind speeds (0.4 to 0.7 $m \cdot s^{-1}$). The amount of naphthalene weight loss via its sublimation was translated to the effective convective heat transfer coefficient (h_c, $W \cdot m^{-2} \cdot K^{-1}$) based on the Chilton-Colburn j-factor analogy between heat and mass transfer (30).

C. THE DEVELOPMENT OF OPERATIONAL AND RATIONAL MODELS FOR PREDICTION OF THERMAL STRAIN

By far the greatest impact of the fundamental studies with thermal manikins and biophysical devices has been the blend of thoughts of researchers active in clothing studies. This has produced a hierarchy of levels of analysis (19,28) recently adopted for a NATO handbook on clothing research (36). Figure 7 depicts five levels of analysis that have been proposed; the lowest level (I) is the most economical but less information is often obtained while the highest level (V) is more cost and labor intensive. At mid-level in the hierarchy is probably where the greatest use occurs of data collected by thermal manikin research.

One of the earliest attempts to model human performance was by Belding and Hatch (3) in their Heat Stress Index (HSI) which included elements of Gagge's skin wettedness properties. The clothing coefficients derived from the Woodcock and Breckenridge research (6,40) were used initially by Givoni and Goldman in 1972 to develop an operational heat stress model (20). The latter model was used to predict deep body temperatures and heart rate responses to wide environmental zones where individuals would reach thermal equilibrium or become a heat casualty dependent on clothing, work level and various other factors such as load carriage, terrain coefficients, solar coefficients, etc. (20,21,33). These different research focuses produced two dissimilar approaches to thermal modeling which, curiously, utilize the same heat and mass transfer coefficients and environmental factors initially derived empirically with manikins. One approach shown in Figure 3 is the "rational" approach which derives its foundation from servo-mechanistic feedback analysis employing the body heat balance equation (16,18,26). A wealth of research has produced sound indices using the heat balance equation such as Operative temperature, Standard Effective temperature and Humid Operative temperature that have lead to a recent unification of clothing parameters (16,32). The other approach is directed to heat stress and strain risk analysis which is a more empirical attribute that necessitates definitions to military operational activities (i.e., prediction of heat or cold casualties, hypovolemic levels where status of water requirements and level of heat acclimation of an individual are critical properties). Recent developments to this approach (33) have been made by the formulation and refinement of specific coefficients which were incorrect in early models. A calculator-operator interaction with menu-driven options is available that utilize a USARIEM database evaluation of clothing properties, and extend many of the approaches originally formulated by Woodcock and Breckenridge. Typical values are given in Table III.

An example of the utility of the USARIEM operational model features is in its prediction of limits to work and water requirements of individuals exercising in chemical protective clothing.

One such prediction that follows the hierarchy approach (Fig.7) first includes both thermal manikin studies and prediction modeling in which data are directly relevant to efficacy of chemical protective garments in wide environmental zones. The typical ensembles investigated were the Battle Dress Overgarment (BDO) alone, BDO with Battle Dress Uniform (BDU) and the BDO with BDU plus the Shell Containment Avoidance Liquid Protection Suit (SCALP). All of these ensembles were first evaluated by copper manikin testing in a closed condition which consists of protective mask, hood, gloves and helmet liner. The chemical protective systems were subjected to three different wind speeds in an all-weather chamber to measure the effect on dry and evaporative cooling to predict the tolerance times of soldiers wearing these uniforms.

The insulation (clo) and vapor permeability index (i_m) of the uniforms at various wind speeds were as follows:

System	Wind ($m \cdot s^{-1}$)	clo	i_m	i_m/clo
a. BDO alone, closed	0.6	1.97	.34	.17
b. BDO+SCALP, closed	0.6	2.46	.17	.07
b. BDO+BDU	0.6	2.44	.30	.12
c. BDO+BDU+SCALP	0.6	2.55	.16	.06
c. BDO+BDU	1.2	2.06	.34	.17
d. BDO+BDU+SCALP	1.2	2.48	.24	.10
c. BDO+BDU	2.3	1.78	.34	.19
d. BDO+BDU+SCALP	2.3	2.24	.27	.12

These data are then entered to the model (Table IV). The input characteristics of environment and work rate are shown in Table IV. In this run, the maximum work times predicted and water requirements considered that the soldiers are fully heat acclimated, the sky (solar load is maximum) is clear, wind speed is 1 $m \cdot s^{-1}$ and the unit will receive less than 5% heat casualties. Metabolic heat production in this program is characterized as 175, 250, 425 and 600 watts which describe very light, light, moderate and heavy work, respectively.

From the maximum work time data in Table IV, users have a clear indication that wearing of the BDU+BDO configuration is performance limiting in itself. The addition of subsequent layers such as the SCALP will not show major decrements of performance (range 21 to 23 min in both environments at heavy work) and only in less stressful thermal environments or lower work levels will differences between these two configurations begin to appear (77 to 100 min at very light work rates). Rectal temperature approaches 39.5° C (103° F) (or indirectly heat storage, in J/g). The following values can be typically used as critical thresholds for heat storage levels:

EXTENT OF HEAT CASUALTY (probability value)	*HEAT STORAGE (J/g)
Limited but UNCOMFORTABLE	4.78
25% CHANCE	7.17
50% CHANCE	9.56
75% CHANCE	11.95
DEFINITE	12

*e.g., kcal x 4186/70kg = J/g for standard man, where the body specific heat constant is 0.97 $W \cdot h \cdot kg^{-1} \cdot K^{-1}$ [3.49 $kJ \cdot kg^{-1} \cdot K^{-1}$].

An individual slightly uncomfortable, but with total body temperature in a tolerable level would have heat storage less than 4.8 J/g (<80 kcal). If a standard man's (body surface area = 1.8 m^2) metabolic heat production is at 145 W/m^2 (2.5 met), the rate of heat dissipation, mostly by sweat evaporation, must be greater than 169 W or 4 g/min. These levels have potential application to the user for describing discrete zones of heat strain with various clothing materials as evident by a comparison of the model.

In our Institute a multitude of prototype chemical protective overgarments have been evaluated through the years. Table V is a general comparison of the predictive heat strain with separate comparison of i_m/I_T included from static manikin evaluation of the clothing heat transfer properties. The interesting pattern which appears is that the criterion for relative ranking of evaporative heat transfer (i_m/I_T) corresponds, to an extent, with the prediction of relative ranking of physiological heat strain status in which a CB ensemble becomes oppressive and heat content becomes a limiting factor in endurance.

Another extremely useful application of both the use of heat transfer coefficients and modeling human interaction concerns human performance with microclimate cooling. By knowing the thermal insulation and vapor permeability properties of a garment along with the heat transfer potential options available from the cooling process and reasonable physiological responses, a prediction of efficacy of an air-cooling vest against heat strain can be determined. Table VI gives the results of such a recently developed prediction model. The model evaluation is set to recognize the fact that the human is integrating thermal signals from within (core and skin temperature) and outside the body (garment properties and environmental stress) in order to remain at a zone which is neither excessively cool nor hot. By this option, the model informs the user (or operator of the air-cooling device) whether the cooling vest is functional or not. Table VI shows one of multiple iterations possible in the model in which a person might become excessively cooled by a vest with inlet temperature of 25° C and 4 $\ell \cdot s^{-1}$ (eg. 8.47 cfm) air flow when doing limited work (i.e., 2 mets). Alternatively, this same person would incur minimal heat storage at 4 mets activity level under the same air cooling and clothing characteristics.

D. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper has pointed out that the use of thermal manikins is indeed a vital property in thermoregulatory studies which have impact on humans. One of the challenges which have critical bearing on human interaction with the thermal environment is the use of protective clothing that serves as a barrier to harmful liquids and vapor but causes variable heat intolerance limits in humans. Often the magnitude of protection offered by these ensembles can only be assessed by measuring the length of time that a harmful dose of a chemical passes through a known surface. In cases where the chemical is toxic, only thermal models or manikins can be used for such studies. Prediction of activity levels, sweating properties and other heat transfer parameters are essential. Currently, a robotic manikin is being developed with such intentions to aid in the assessment of protective clothing (4). One interesting feature is in the plan for a manikin "skin" which should provide a hermetically sealed barrier between the environment and the manikin interior. A candidate considered for this skin prototype is chlorinated polyethylene which has purported application in the simulation of thermal sweating. This property should call for important research in the future. Along with the development and testing of adequate thermal and mass coefficients from articulated manikins, such advancements as these in the future promise interesting developments and insights to human physiological interaction with the environment.

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FIGURE LEGENDS

Figure 1. Servo-control scheme of the human-clothing-environmental interaction.

Figure 2. Characteristic upper limits of ambient conditions depicted on a psychrometric chart (ambient water vapor pressure as a function of dry-bulb temperature (T_a) in terms of Woodcock's permeation constant (40).

Figure 3. Flow diagram of various laboratories during research with manikins and thermal models for prediction of the clothing to environment interactions.

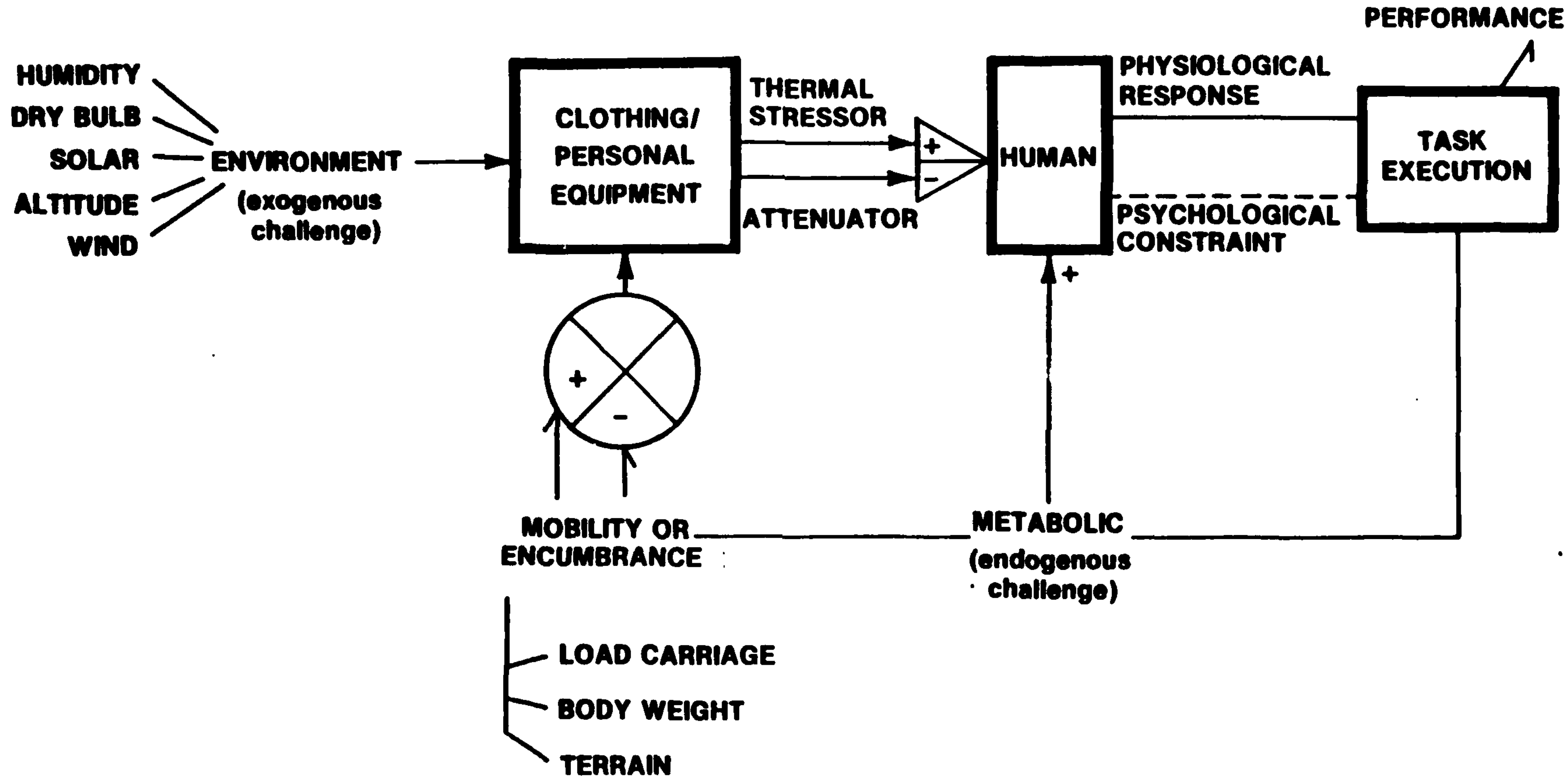
Figure 4A. System block diagram of the automated foot model.

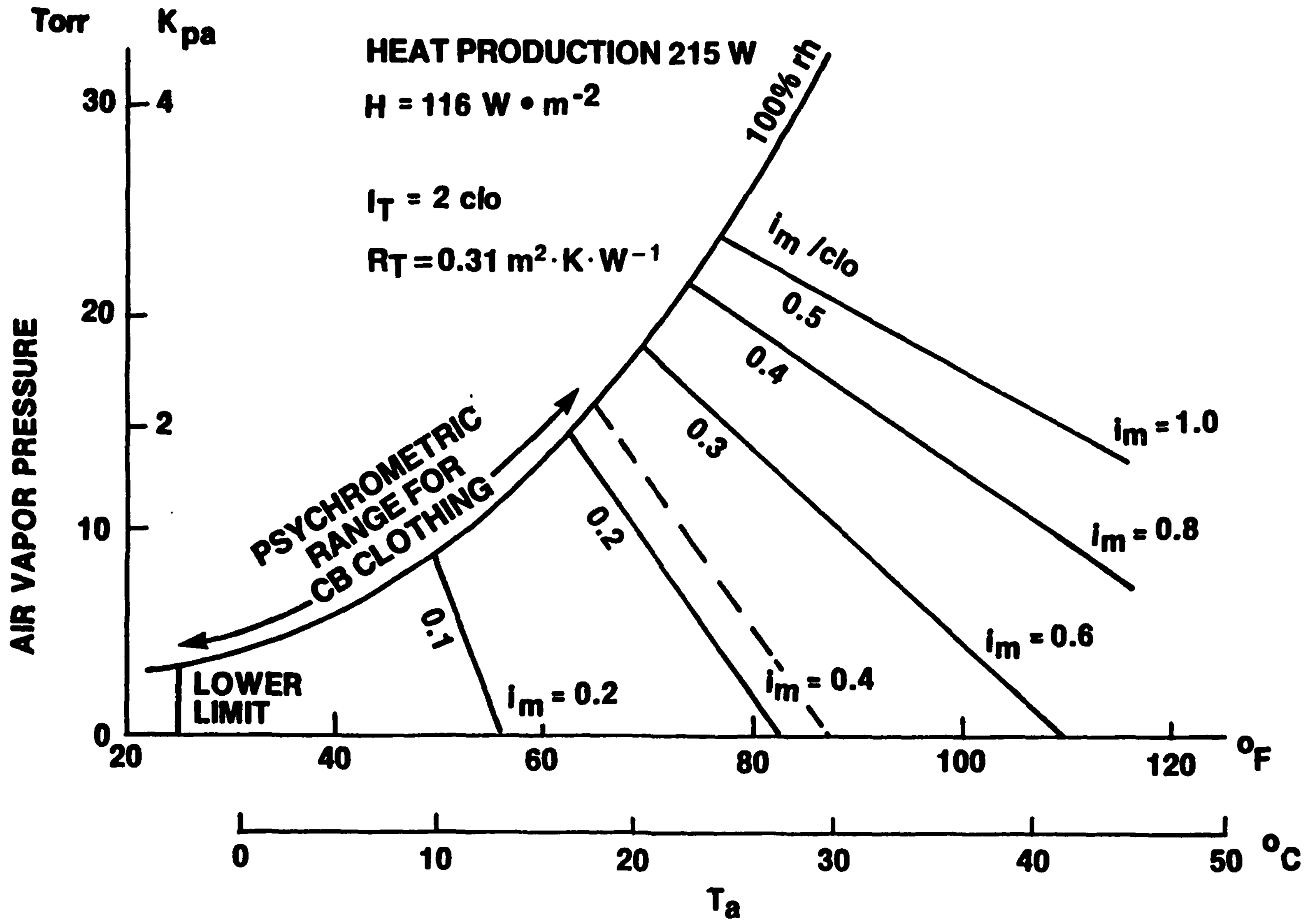
Figure 4B. Exploded diagram of the automated foot model showing the location of sections and thermistors where thermal insulation is ascertained.

Figure 5. USARIEM articulated moveable manikin.

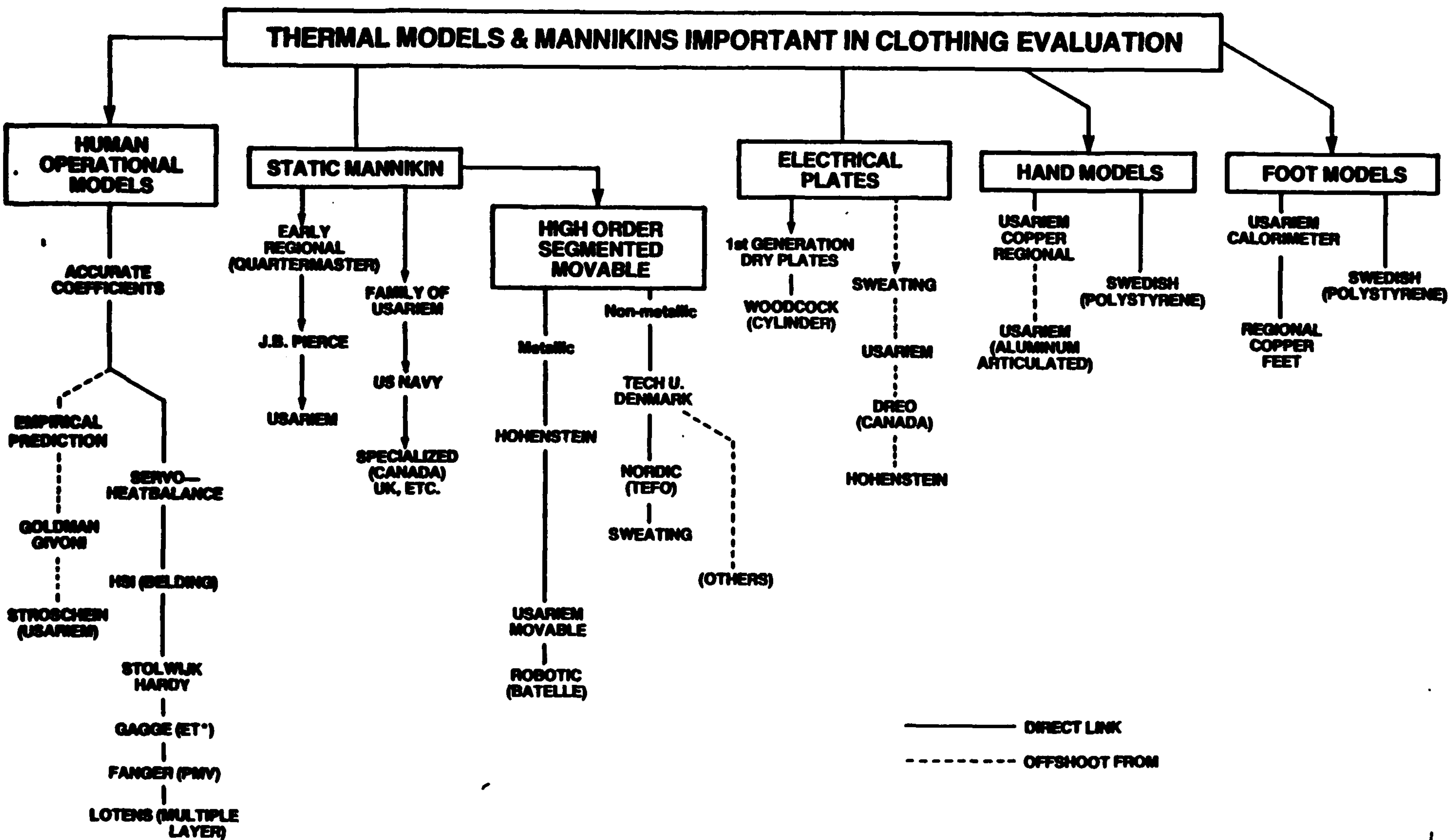
Figure 6. Temperature deviation of foot and head sections of the manikin shown in Figure 5.

Figure 7. Five levels of activity ascribed to research entailing clothing properties, manikin and human interaction.


HUMIDITY
DRY BULB
SOLAR
ALTITUDE
WIND
ENVIRONMENT
(exogenous challenge)
CLOTHING/ PERSONAL EQUIPMENT
THERMAL STRESSOR
ATTENUATOR
+
-
HUMAN
+
PHYSIOLOGICAL RESPONSE
PSYCHOLOGICAL CONSTRAINT
PERFORMANCE
TASK EXECUTION
+
-
MOBILITY OR ENCUMBRANCE
METABOLIC
(endogenous challenge)
LOAD CARRIAGE
BODY WEIGHT
TERRAIN



HEAT PRODUCTION 215 W
H = 116 W • m-2
IT = 2 clo
RT = 0.31 m2·K·W−1
Torr
Kpa
AIR VAPOR PRESSURE
100% rh
im /clo
0.5
0.4
0.3
0.2
0.1
im = 1.0
im = 0.8
im = 0.6
im = 0.4
im = 0.2
PSYCHROMETRIC RANGE FOR CB CLOTHING
LOWER LIMIT
oF
oC
Ta


THERMAL MODELS & MANNIKINS IMPORTANT IN CLOTHING EVALUATION
HUMAN OPERATIONAL MODELS
ACCURATE COEFFICIENTS
EMPIRICAL PREDICTION
GOLDMAN GIVONI
STROSCHEIN (USARIEM)
SERVO—HEATBALANCE
HSI (BELDING)
STOLWIJK HARDY
GAGGE (ET*)
FANGER (PMV)
LOTENS (MULTIPLE LAYER)
STATIC MANNIKIN
EARLY REGIONAL (QUARTERMASTER)
J.B. PIERCE
USARIEM
FAMILY OF USARIEM
US NAVY
SPECIALIZED (CANADA) UK, ETC.
HIGH ORDER SEGMENTED MOVABLE
Metallic
HOHENSTEIN
USARIEM MOVABLE
ROBOTIC (BATELLE)
Non-metallic
TECH U. DENMARK
NORDIC (TEFO)
SWEATING
(OTHERS)
ELECTRICAL PLATES
1st GENERATION DRY PLATES
WOODCOCK (CYLINDER)
SWEATING
USARIEM
DREO (CANADA)
HOHENSTEIN
HAND MODELS
USARIEM COPPER REGIONAL
USARIEM (ALUMINUM ARTICULATED)
SWEDISH (POLYSTYRENE)
FOOT MODELS
USARIEM CALORIMETER
REGIONAL COPPER FEET
SWEDISH (POLYSTYRENE)
DIRECT LINK
OFFSHOOT FROM

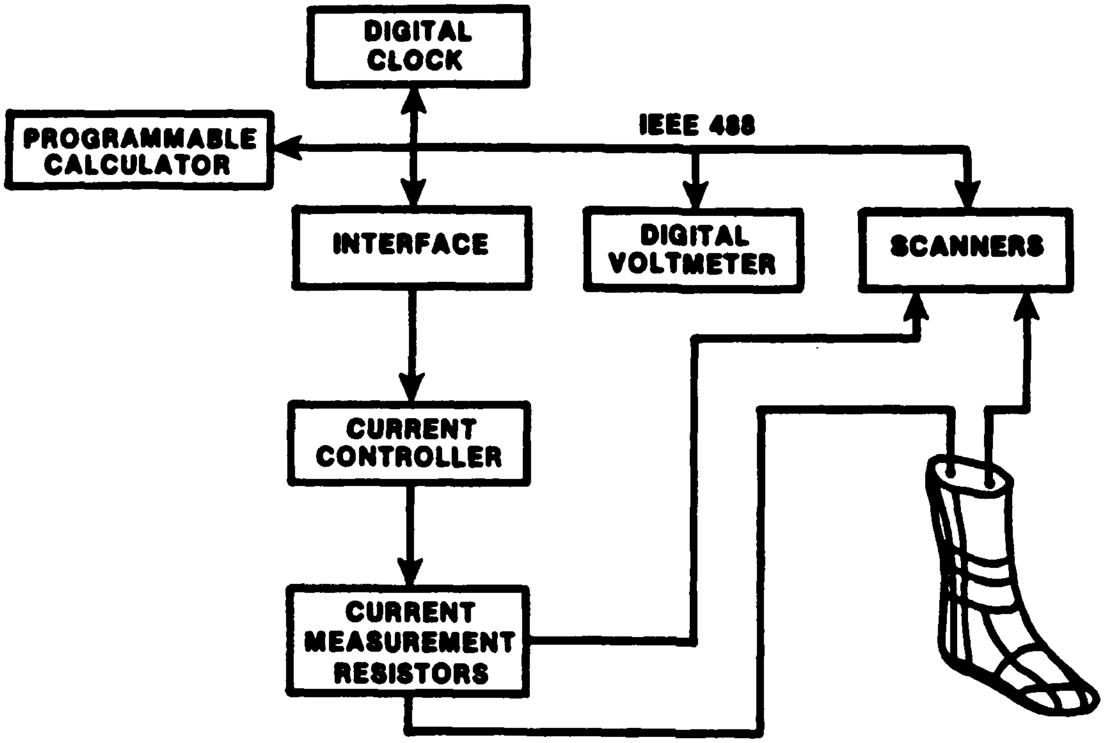


Figure 4A.System block diagram of the automated foot model.

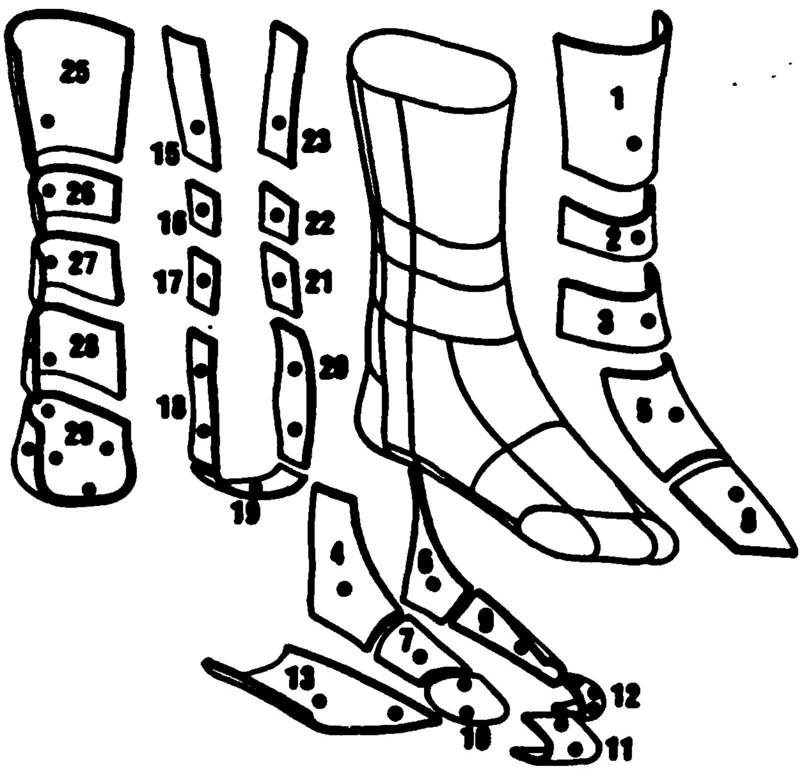
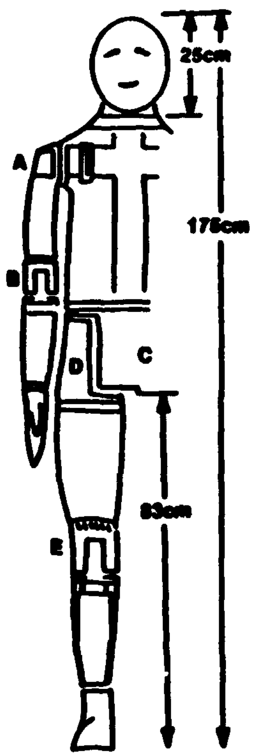


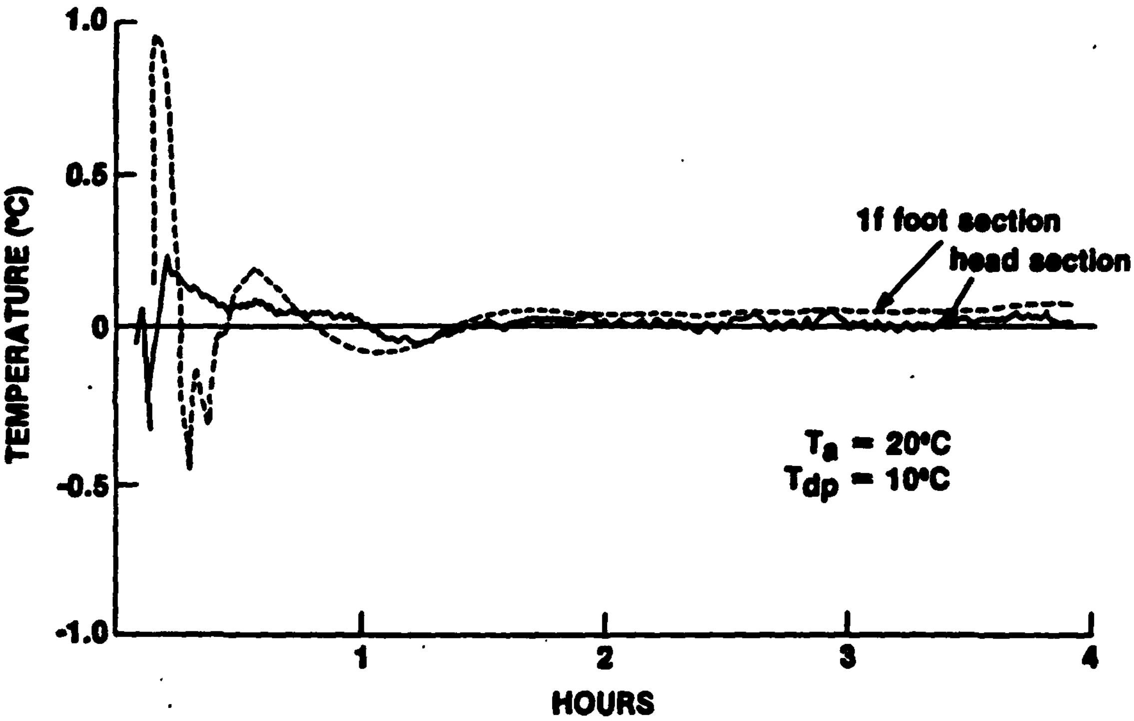
Figure 4B.Exploded diagram of the automated foot model showing the location of sections and thermistors.

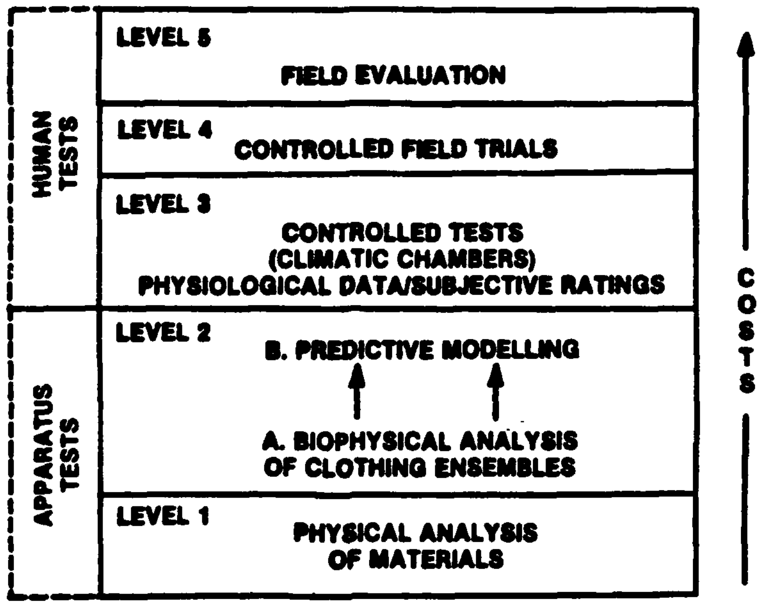


AREA AND POWER CONSTANTS FOR USARIEM ARTICULATED MANIKIN

ARTICULATION	SECTION	SURFACE AREA (m^2)	% TOTAL	DESIGN HEAT (W)
	HEAD	0.130	8.3	69.4
	TORSO	0.336	19.9	168.0
A	UPPER ARMS	0.144	8.6	72.0
	LOWER ARMS	0.062	3.7	31.1
	HANDS	0.102	6.1	51.0
B	ELBOWS*	0.034	2.0	17.0
	WAIST	0.020	1.2	10.0
C	ABDOMEN	0.107	6.4	53.4
D	RT HIP	0.084	5.0	41.8
	LF HIP	0.084	5.0	41.8
	THIGHS	0.219	13.0	109.5
E	KNEES**	0.052	3.1	26.1
	CALVES	0.167	9.9	83.8
	FEET	0.131	7.8	65.5
	WHOLE BODY	1.68	100.	approx.500W/m^2
	UPPER BODY	0.94	56.	"
	LOWER BODY	0.74	44.	"

*BENDING EXPOSES AN ADDITIONAL 20.9 cm^2 TO UPPER ARM SECTION AND SOME 9.0 cm^2 TO LOWER SECTION; **BENDING EXPOSES 23.5 cm^2 TO UPPER AND 20.3 cm^2 TO LOWER LEG SECTION.


1.0
0.5
0
-0.5
-1.0
TEMPERATURE (°C)
1f foot section
head section
T_a = 20°C
T_{dp} = 10°C
1
2
3
4
HOURS



LEVEL 5
FIELD EVALUATION
LEVEL 4
CONTROLLED FIELD TRIALS
LEVEL 3
CONTROLLED TESTS
(CLIMATIC CHAMBERS)
PHYSIOLOGICAL DATA/SUBJECTIVE RATINGS
LEVEL 2
B. PREDICTIVE MODELLING
A. BIOPHYSICAL ANALYSIS
OF CLOTHING ENSEMBLES
LEVEL 1
PHYSICAL ANALYSIS
OF MATERIALS
HUMAN TESTS
APPARATUS TESTS
COSTS

Table I. Database Evaluations of Various Military Clothing Items at USARIEM (1962- present)

Manikin or apparatus	Number of studies
1. Sleeping systems (clo only)	136
2. Static manikins (both clo and i_m)	376
3. Regional manikins (both clo and i_m)	37
4. Footwear* (clo only)	102
5. Handwear items (clo only)	127
6. Sweating plates*8 (clo and i_m)	72
Total	**850**

Data are combined evaluations; * = older foot model (< 1978) was not wholly representative of shape of the foot and a new 26-sectional model appeared in 1980; ** = includes many plates appearing earlier than 1978 which measured only dry heat flow.

Table II. Insulation (I_T, in clo units) of a typical leather/synthetic boot, before, during and after a 7-hour water (5 cm level) soak.

	I_T DRY	I_T DURING SOAK	DECREASE (%)	I_T AFTER	RECOVERY (%)
TOTAL FOOT	1.35	1.23	-9	1.19	88
SOLE	1.67	1.33	-20	1.39	83
HEEL & TOE	1.32	1.08	-18	1.05	80

Foot insulation values are in clo (x 0.155 $m^2 \cdot K \cdot W^{-1}$)

Table III. BEST AVAILABLE VALUES FOR TYPICAL U.S. MILITARY CLOTHING

CLOTHING	i_m	I_T	i_m/clo
COLD-DRY	0.43	4.3	0.10
ECWCS*	0.45	3.6	0.13
COLD-WET	0.40	3.2	0.13
UTILITY FATIQUES	0.41	1.40	0.29
BATTLE DRESS UNIFORM	0.41	1.34	0.31
CHEMICAL PROTECTIVE (WITHOUT MASK,HOOD, GLOVES	0.34	1.97	0.17
{MOPP 4 WITH MASK,HOOD, AND GLOVES}	0.30	2.44	0.12
{MOPP 4 PLUS BODY ARMOR, GROUND TROOPS}	0.29	2.2	0.13

FROM USARIEM DATA BASE COPPER MANIKING MEASUREMENTS (0.3 $M \cdot S^{-1}$ AIR MOTION);*ECWCS IS CURRENT EXTENDED COLD WEATHER CLOTHING SYSTEM.

Table IV. *Predicted Requirements for CB Work Tolerance With Various Ensembles

Environment	Work Rate Classification	BDO+BDU Work Time (min)	BDO+BDU Maximum Water Canteen/hr	BDO+BDU+SCALP Work Time (min)	BDO+BDU+SCALP Maximum Water Req Canteen/hr
DESERT 49° C) 20% RH	Very Light	100	1.9	94	2.3
	Light	63	2.4	61	2.4
	Moderate	37	2.4	36	2.4
	Heavy	23	2.4	22	2.4
TROPIC 35° C) 75% RH	Very Light	83	1.9	77	2.4
	Light	57	2.3	55	2.4
	Moderate	35	2.4	34	2.4
	Heavy	22	2.4	21	2.4

*From USARIEM heat stress prediction.

Table V. Thermal Insulation (clo) and vapor permeation (i_m/clo) properties of typical chemical protective clothing with a relative ranking of predictive heat strain as a worst case scenario (still air= 0.6 $m \cdot s^{-1}$, light work, tropical conditions).

System	I_T (clo)	i_m/I_T	Predicted worst heat strain (rank)
1.Impermeable butyl (Typical)			
a) Worn alone, open	1.58	0.08	2
b) Worn alone, closed	2.05	0.04	1
c) Worn alone, with terry coverall	2.05	0.13	4
2. French			
a) With integral hood, open	2.42	0.15	6
b) Without integral hood, open	2.31	0.17	8
c) Without integral hood, closed	2.57	0.13	4
3. United Kingdom			
a) With integral hood, open	2.18	0.18	9
b) Without hood, open	2.08	0.19	10
c) Without hood, closed	2.27	0.14	5
4. The Netherlands			
a) With integral hood, open	2.35	0.15	6
b) Without hood, open	2.23	0.17	8
c) Without hood, closed	2.49	0.11	3
5. The US Army {Standard Battle Dress Overgarment BDO}			
a) Standard OG without hood, open	2.24	0.16	7
b) Standard OG without hood, closed	2.55	0.11	3
c) 70-mil hood with current BDO	2.01	0.16	7
d) Butyl Hood with BDO	2.01	0.13	4
e) BDO+BDU+ SCALP	2.55	0.06	2
[2] *f) Battle Dress Uniform	1.49	0.26	*

[2] *BDU included for illustrative purposes (not a CB protective ensemble); open = without mask, butyl hood, with open collar; closed= mask, gloves, hood and all apertures closed.

TABLE VI. TYPICAL MICROCLIMATE COOLING ITERATIONS.

Input Summary	Microclimate Simulation
Dry bulb temperature = 49 °C Relative humidity = 20% Activity level = 2 Met Clo value = 2.56 Vest flow rate = 4 L/s Average skin temp = 35 °C Rectal temperature = 38.5 °C Iteration time = 100 min	Total Evaporation= 68.94 Total Dry Heat Loss= 290.3 Evaporation [without vest]= 30.45 watts Sensible heat gain [without = 65.7 watts vest] Total heat storage= -167 watts,vest body [M+ garment +vest]cooling Core/skin temps down/up by = -2.0 °C/h Heat storage based on mean = 79.7 watts body temperature [95 W or less, no heat casualty without auxiliary cooling]
Activity level = 4 met	Total heat storage= 24.9 watts Core/skin temperatures up/down = 0.30 °C/h