

Heat stress in protective clothing

Interactions among physical and physiological factors

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NUNNELEY SA. Heat stress in protective clothing: interactions among physical and physiological factors. *Scand J Work Environ Health* 1989;15(suppl 1):52-57. Data from experiments on animals and humans have supported the development of computer models that predict human response to various combinations of the three main heat stress factors work, clothing, and environment. However, recent application of such models shows that the validity of their output is limited in part by the need to represent more faithfully the interactions among the primary heat stress factors and certain physiological variables. Examples of such interactions include the weight and stiffness of protective outfits increasing the metabolic cost of a task, profuse sweating that wets clothing and alters its heat transfer characteristics, task-related movements altering air exchange rates through clothing, individual aerobic capacity affecting thermoregulatory response to a given metabolic load, and sweat retention in clothing raising skin wettedness and possibly inducing sweat suppression. This paper reviews recent research in these areas and identifies certain areas where further data are needed.

Key terms: clothing, computer models, sweat, thermal stress, work.

Modern civilization seems to provide ever more reasons for people to work in hostile environments requiring them to wear special clothing for protection from the effects of hazards such as hypoxic atmospheres, toxic chemicals, and mechanical forces. Unfortunately, the clothing and associated respiratory equipment often create a heat stress problem, the seriousness of which ranges from discomfort to impaired performance, illness, collapse, and even death. The effects of work in heavy, impermeable clothing have been illustrated well by studies on men wearing firefighter outfits under mild and hot conditions (1-3).

Heat balance is possible only when the sum of the environmental and metabolic heat load on the body is matched by outward heat flow to the environment. The physical processes involved are understood well, as are simple clothing effects on convective, radiative, and evaporative heat exchange. A number of authors have developed predictive equations and charts for heat stress [eg, Kenney et al (4), Shapiro et al (5), and Vogt et al (6)]; yet it is often difficult to predict reliably the heat stress and strain which may result from a given combination of conditions. More complex computer models are also used, as reviewed by Lotens (7). But they often disagree, and it is still necessary to check their output against data from human subjects (8). In our laboratory my colleagues and I are using both the Texas model (9) and that of the US Army Research Institute for Environmental Medicine (10) to explore the effects of semipermeable and impermeable cloth-

ing on personnel working under a range of climatic conditions (11). Comparison of computer model output with experimental results reveals certain systematic errors, such as a tendency to underestimate the amount of sweat which will evaporate from subjects engaged in treadmill walking while dressed in heavy ensembles.

The validity of output from computer models is limited by their failure to simulate adequately the more complex, second-order effects of clothing on heat balance. Specifically, an improved understanding is needed of the interactions among the environment, the clothing, the wearer, and the task being performed. Figure 1 is a simplified representation of this multidimensional problem. This paper reviews current knowledge on these topics and identifies some areas where further research is needed.

Clothing adds work

Protective clothing increases the metabolic cost of performing a task by adding weight and by otherwise restricting movement. The binding or hobbling effect of multilayered clothing adds measurably to work, eg, treadmill walking in arctic clothing raises oxygen consumption by about 10 % over the value for a lightly clothed subject carrying the same weight (12, 13). Clothing can also require added movement to compensate for problems such as restricted visual fields, failure of communication, or loss of manual dexterity.

The effect of added weight on work load depends in part upon the task, eg, a heavy suit poses little problem for a stationary worker but presents a severe handicap for a firefighter climbing a ladder or stairwell.

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Walking uphill with added weight is considerably more stressful than an equivalent increase in power output induced by steeper climbing (figure 2) (14). Weight distribution is also important, since a load carried on the legs and feet causes a greater increase in metabolism than does the same weight placed on the hands, torso, or head (figure 3) (15). The difference is probably due to the cyclic up-and-down displacement of the lower limbs, which produces internal heat without measurable external work.

Clothing complicates evaporation

Evaporation of sweat normally provides a powerful physiological cooling mechanism for humans under warm work conditions, taking up $0.68 \text{ W} \cdot \text{s}$ (0.58 kcal) of heat for each gram of water vaporized. For a nude subject, environment-driven heat storage should theoretically occur only when E_{req} approaches E_{max} , where E_{req} is the evaporative cooling required to allow human heat balance under a given set of conditions and E_{max} is the maximal amount of evaporation which can be supported by the environment (16). In fact, heat strain in nude subjects occurs at lower values due to the tendency to drip sweat (17). Clothing both inhibits evaporation by creating a humid microclimate and diminishes the cooling effect of the evaporation which does take place, so that thermal strain occurs at $E_{\text{req}}/E_{\text{max}}$ values which are well below the value for nude subjects.

The resistance of clothing materials to the passage of water vapor can be determined in vitro by techniques analogous to those for measuring thermal insulation using "sweating" heated plates or manikins. The

results are generally expressed as a dimensionless number along a continuum from zero (impermeable) to unity (unclothed control). As with insulation measurements, these static values neglect the effects of body motion and resulting convective exchange between the microclimate and the outside environment. Several laboratories have attempted to remedy these deficiencies by developing techniques to monitor conditions in the microclimate. Holmér & Elnäs (18) drew air sam-

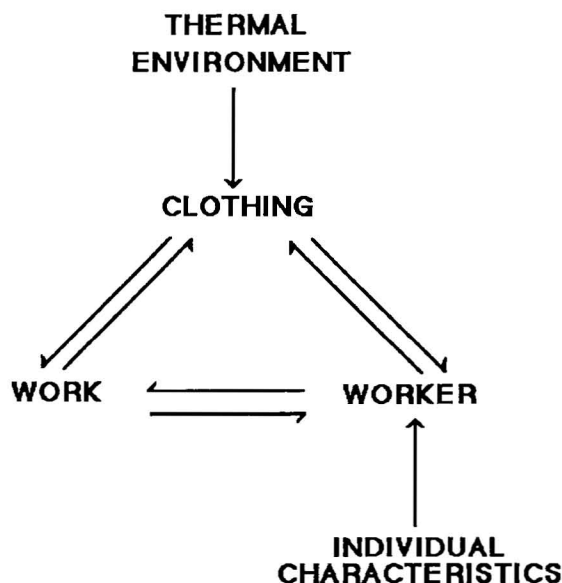


Figure 1. Diagram of heat stress factors. Arrows represent the interactions among the factors which are the focus of this paper.

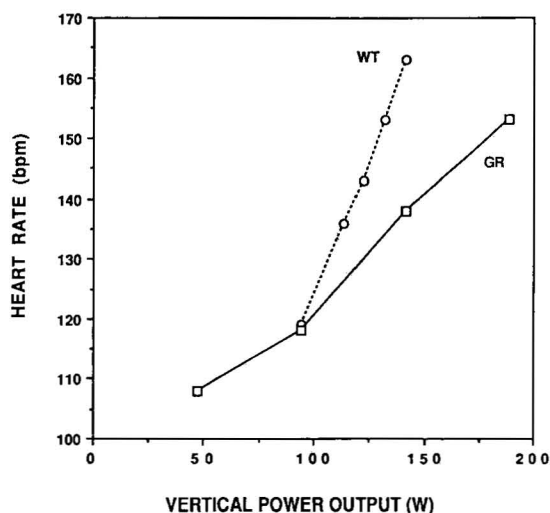


Figure 2. Heart rate plotted against vertical power output. The values are means for ten subjects who walked on an inclined treadmill at 1.34 m/s . The power requirement was increased by raising the treadmill grade (GR) or by adding backpack weight (WT) at a fixed grade of 10%. Data from reference 14.

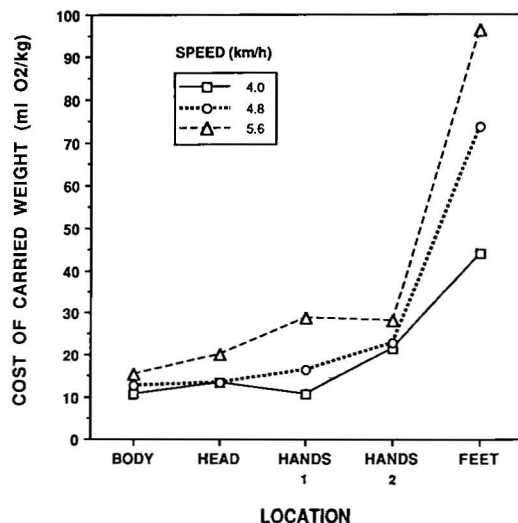


Figure 3. Metabolic cost of weight carried at different sites of the body. The values are means for ten subjects who walked on a level treadmill at the speeds indicated. Hands 1 and 2 represent weights of 4 or 7 kg/hand, respectively. Redrawn from reference 15.

ples from the microclimate and calculated water vapor pressure using general gas equations. Others have determined dewpoints at selected skin sites (19). An alternative approach is to have subjects work at a fixed rate under warm, dry conditions until they reach a thermal steady state, then progressively raise ambient humidity until the core temperature shows an upward inflection, the result being the "critical evaporative coefficient" for the clothing ensemble (20, 21).

Evaporative efficiency (E) is the proportion of secreted sweat which actually evaporates and thus provides potential body cooling. For nude subjects, E is determined from body weight loss if no dripping takes place, or dripped sweat can be quantified after being caught in an oil-filled pan located beneath the subject (22). For clothing studies *in vivo*, the usual technique is to weigh the nude subject and the clothing (or the clothed subject) before and after heat exposure and calculate E as the ratio between clothed weight loss and nude weight loss. The usefulness of this technique is severely limited because it assumes that all secreted sweat either evaporates from the skin or stays in the clothing. Thus the procedure ignores the possibility of external dripage, fails to address the reduction in the cooling effect of evaporation from the clothing rather than the skin, and provides no information on the time course of these processes.

Unfortunately, none of the techniques described can account for the complex realities of heat transfer for a profusely sweating worker in a multilayer clothing system, where secreted sweat may either evaporate at the skin or wick into the clothing and there may evaporate, drip or remain trapped (figure 4). In impermeable suits, sweat may evaporate at the skin, condense on the inner surface of the impermeable layer, and then wet intervening layers and decrease their thermal insulation in the process.

Only sweat vaporized at the skin delivers maximal effect; evaporation from clothing provides reduced body cooling because the site of the phase change is remote from the skin and much of the heat comes from the environment (23, 24).

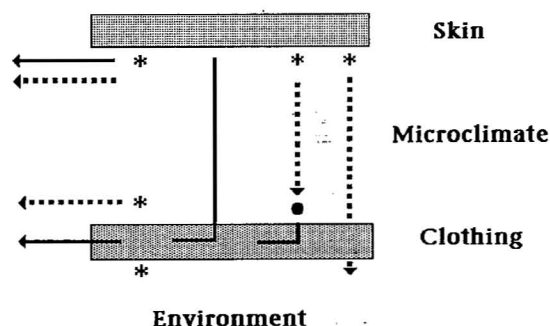


Figure 4. Diagram of pathways for secreted sweat. (Asterisks = sites of evaporation, filled circle = condensation, broken lines = water vapor, solid lines = liquid water)

Impermeable clothing prevents any sweat evaporation and is a potential hazard to the wearer even at moderate environmental temperatures. Provision of ventilation may be of little help, since backpack blowers generally supply only about $28 \text{ l} \cdot \text{min}^{-1}$ of ambient air, insufficient to provide meaningful thermal relief (3). Brown (25) showed that much higher air flows, on the order of $100 \text{ l} \cdot \text{min}^{-1}$, are required to produce effective cooling. Artificially enhanced evaporation from an outer garment could prove useful under some conditions. A wetted cover over an impermeable suit could remove a significant amount of heat given low atmospheric humidity and a generous water supply. The effectiveness of such cooling would also depend upon the presence of minimal insulation between the impermeable layer and the skin.

Movement ventilates clothing

Body movement increases heat exchange through clothing by ventilating the microclimate with ambient air. This "pumping" means that the actual insulation and vapor-barrier characteristics of an ensemble may be much lower than the values measured on a static manikin. The magnitude of pumping depends upon many factors, among them clothing design and fit, external thermal conditions, and body movements. Sealed impermeable clothing virtually eliminates the pumping effect, although motion increases external convection.

The need to quantify pumping led to the development of moving, heated manikins which allow the determination of insulation and vapor transmission while their limbs are swung. Figure 5 shows results from such a manikin both for static standing and for "cycling" on an externally-driven ergometer. The cycling motion reduced measured insulation by about 0.2 clo for each of three conventional clothing combinations (26).

Although moving manikins are helpful, they provide only a minimal simulation of human motion, and several laboratories have attempted to measure pumping on human subjects. An early attempt involved measurement of tracer gas washout curves (27, 28). A more recent technique employs a steady-state measurement in which a stream of tracer gas (carbon dioxide in air) is introduced into the clothing and an equal volume of mixed gas is withdrawn; this procedure permits the calculation of microclimate air exchange without the need to seal the clothing (29). Figure 6 illustrates the effect of treadmill walking and clothing layers on ventilation at the surface of the thigh.

Vogt and his co-workers (30) examined the effect of pumping on subjects pedaling an ergometer. Various components of thermal exchange were teased out with the use of a matrix of environmental conditions which controlled convective and radiant heat exchange. In this case pumping increased convection by about 28 %, much more than on the cycling manikin; the

difference was attributed to the added effect of human respiratory movement, as well as to oscillations of the arms and trunk. They calculated that movement provided an air exchange of about 70 l/min through the microclimate and demonstrated that pumping may reduce radiant exchange when air temperature is close to skin temperature and produce a paradoxical "increase" in insulation (30). Thus the magnitude and even the direction of the pumping effect depend upon specific conditions.

Wearer alters clothing characteristics

Individual factors affecting heat exchange in clothed humans include the fit of the garments and the disposition of any apertures, both of which control the effective insulation by altering convective exchange between the microclimate and the external environment.

Sweat rate is another factor with wide interindividual variation. Sweat-wetting can seriously reduce clothing insulation value and thus improve the linkage between skin and the environment, a change which may be either an advantage or a disadvantage depending upon environmental conditions. In addition, wetting tends to diminish cooling efficiency. When known amounts of water are infiltrated into clothing ensembles, the cooling effect per gram of water evaporated declines progressively as clothing wetness increases (24).

Individual characteristics affect heat strain

Thermal physiologists often distinguish between externally imposed thermal stress and the resulting physiological changes or thermal strain. Response to heat stress is strongly influenced by a variety of human characteristics, making it nearly impossible to predict the heat strain which will occur in an individual exposed to a given set of environmental conditions (31, 32).

While the metabolic cost of carrying weight (ie, work efficiency) is usually treated as constant from one worker to another, the physiological effect of a fixed load varies with the size and physical conditioning of the wearer. A sealed suit with a self-contained breathing apparatus (SCBA) weighing 25 kg represents a 25 % weight increase for a 100-kg person but a 50 % load for a 50-kg subject, and heart rate during work rises directly in proportion to added weight expressed as the percentage of body weight (14). The added work will also use a greater percentage of aerobic capacity in a small person, or in one with low aerobic capacity, and will produce a higher core temperature even in the absence of environmental heat load.

In fact, the assumption of relatively constant work efficiency needs reexamination. Recent studies on subjects pedaling a cycle ergometer have revealed a significant range among individuals (Nadel, personal

communication). The phenomenon of "work load creep" in prolonged experiments is also well known but little studied. It appears likely that high levels of cardiovascular stress and hyperthermia may decrease efficiency and produce an increase in heat production per unit of external work, thus a positive feedback loop being formed.

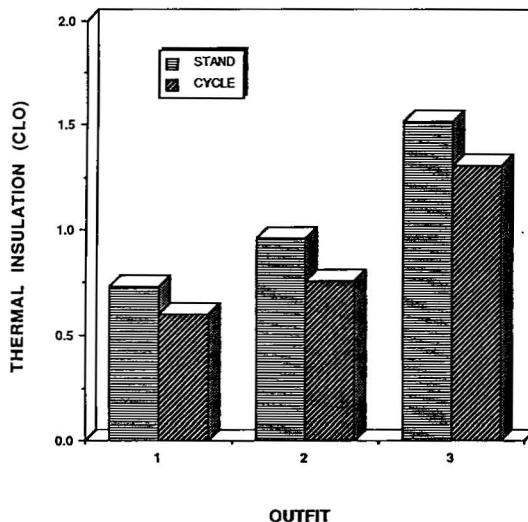


Figure 5. Thermal insulation measured on a heated manikin either standing static or seated on an externally-driven cycle ergometer. Outfits are as follows: 1 = briefs, t-shirt, cotton shirt and trousers, 2 = same as 1 plus jacket, 3 = same as 2 plus "thermo-suit." Redrawn from reference 26.

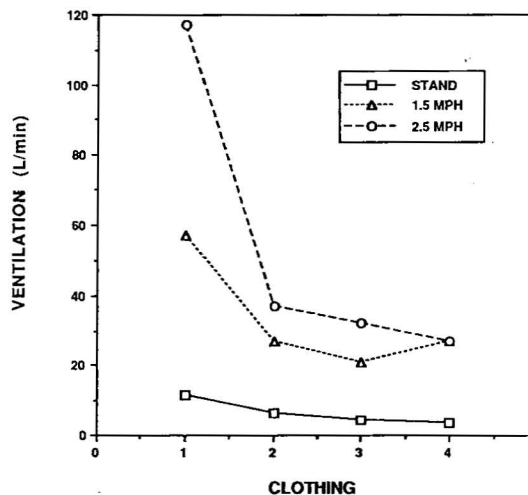


Figure 6. Ventilation at the thigh measured with the subject standing still or while walking on a treadmill at 1.5 or 2.5 miles per hour (mph) (1.5 miles = 2.4 km, 2.5 miles = 4.0 km). The clothing layers over the thigh are as follows: 1 = none, 2 = cotton trousers, 3 = coverall over trousers, 4 = same as 3 with apron added. Plotted from data of reference 29.

Individual sweat rates also affect stress-strain relationships. Sweat-wet clothing next to the skin is not only uncomfortable, but also tends to reduce sweat rates gradually through a process variously known as sweat suppression or hydromeiosis — the divergent names reflecting controversy over the mechanism involved.

Secretion of sweat which fails to provide body cooling produces dehydration and discomfort without thermal benefit. Thus the high sweat rates associated with heat acclimatization may prove a liability for persons wearing heavy clothing. This possibility leads to speculation concerning the possible benefits of artificial sweat suppression, possibly through the use of atropine (24). The benefit could be amplified under some conditions, since atropine not only suppresses sweat secretion, but also increases cutaneous blood flow (33).

Summary and concluding remarks

Clearly there is much yet to be learned about the physical and physiological aspects of thermal exchange in protective clothing systems. A better understanding is needed of the interactions between the environment, clothing, task, and worker to support the development of predictive models which are valid over the entire spectrum of thermal conditions encountered among industrial and military applications. Particularly challenging areas needing improvement include the following: (i) representation of intermittent or changing work load and/or environmental conditions, (ii) quantification of cumulative effects due to dehydration and fatigue, (iii) changes to the metabolic cost of real-world tasks due to clothing, worker characteristics, thermal stress and fatigue, (iv) quantification of pumping effects with respect to interactions between clothing, tasks and the environment, (v) physiological effects on tolerance for work in protective clothing, including the roles of aerobic fitness, strength training and heat acclimatization, (vi) characterization of sweat-related heat exchange in complex clothing systems, especially with regard to continued sweat production, progressive wetting of clothing layers, evaporation from outer layers, and dripage, (vii) the possible role of natural or artificially-induced sweat suppression, and (viii) the relationship between heat storage (core temperature) and heat casualty incidence (which requires an improved understanding of relevant physiological factors and the epidemiology of human heat illness).

One potential pitfall to be avoided in modeling is the temptation to produce specific predictions which look impressive but are not adequately supported by data. For instance, it is hardly appropriate to output estimated tolerance time limits to the nearest minute when other components of the model produce an error range of several percentage points. Any use of models should clearly differentiate among predictions which lie in the thoroughly validated sector as opposed to

those which represent scanty validation or speculative extrapolation from known conditions.

The rewards of better understanding of these areas should include the ability to identify critical experimental parameters, to predict hazardous conditions, and to minimize human experimentation. The ultimate beneficiaries will be those whose work takes them into environments which test the limits of human capacity to perform useful work under hazardous or hostile conditions.

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