ABSTRACT

Heat strain for six young, healthy, acclimatized men (mean age 26.2 yrs., weight 84.1 Kg) was measured during moderate exercise at various ambient conditions (21.5^{o}C, 28.0^{o}C, 31.5^{o}C with sunshine) while wearing fully encapsulating chemical protective suits with SCBA. The total weight of the protective ensemble was 26.3 Kg. The subjects performed a total of 35 minutes (20 minutes exercise, 5 minutes rest, 15 minutes exercise) of zero grade walking on a treadmill set for 4.83 Kph (3.0 mph). The average level of energy expenditure for this exercise, determined from $\dot{V}_{O2}$ measurements was 383 Kcal/hr. Heart rat e and mean skin temperature rose significantly as ambient temperature increased. Under the most adverse ambient conditions (31.5^{o}C with sunshine) the mean heart rate and skin temperature were elevated 39.6 bpm and 4.1^{o}C, respectively, over those recorded for control conditions. Significant increases in rectal temperature were not noted. A mean difference in weight loss was only observed with significance between control conditions and the most severe ambient environment (31.5^{o}C with sunshine). The five minute recovery heart rate (5MRHR), recorded at minute 25 after 20 minutes of exercise increased significantly as ambient

conditions become more adverse. The mean 5MRHR were 91.7 bpm (control), 95.8 bpm (21.5°C), 108.7 bpm (28°C), and 116.4 bpm (31.5°C with sunshine).

It is concluded that wearers of impermeable protective clothing show progressive increases in heat strain as ambient temperature increase. This study indicates recovery heart rate is probably the best indicator of heat tolerance endpoints for work in encapsulating, impermeable protective clothing. Recovery heart rates are easily measured with inexpensive equipment. More study is required, however, before specific recovery heart rates can be identified as a conservative endpoint.

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INTRODUCTION

Technical advances in development of chemically impermeable clothing now allow an individual to enter and work in nearly every hazardous environment. As a result, employees of hazardous materials handling and waste site clean up companies, given proper training and equipment, may work in relative safety, insulated from the chemicals with which they deal.

However, chemical protective clothing, while insulating from the potentially lethal environments, encloses workers in an environment which is also potentially lethal. The impermeable fabric encapsulates the worker in a microclimate of 100% humidity, eliminating evaporative cooling. In addition, convective and conductive modes of heat exchange are severely curtailed or eliminated because the protective garment prevents air movement and significantly reduces skin contact with objects of lower temperature. Radiant heat losses are minimized, while radiant heat gains during work in sunlight may be significant. Since heat dissipation is effectively prevented, thermal gains through metabolic activity are stored in the human body causing excessive water loss, cardiac burden, and possible life threatening elevation in body temperature over short time periods (<60 min). Thus, as thousands of people, some of whom may be unfit or too old, enter the hazardous material handling work force, the potential for severe heat related injuries grows.

Although this threat has been well demonstrated by a number of studies, to date there are no generally accepted heat stress monitoring techniques to adequately protect the hazardous material handler from injurious physiological strain. Safety guidelines for site work in impermeable garments have been proposed, but anedoctal evidence seems to indicate they are lacking. The primary shortcomings of these guidelines are their inability to account for individual differences in weight, fitness, age, and acclimatization. Many incorporate environmental safety indexes which are either inappropriate for work in impermeable clothing or difficult to calculate and apply consistently.

This study reviews recently proposed heat strain monitoring techniques. An exercise regimen was developed to test the effectiveness of these techniques in predicting the limits of safe work in impermeable chemical protective clothing for various individuals.

HEAT PRODUCTION, TRANSFER, AND TEMPERATURE REGULATION IN HUMANS

Humans are homeothermic. Under normal conditions the body maintains a constant body core temperature of $37 \pm 1^{o}C$ ($99.6 \pm 1.5^{o}F$). This condition of thermoequilibrium is accomplished through mechanisms allowing generation, distribution, and storage of heat. Specifically, heat loss from the body must equal metabolic heat production plus external heat gain. Thermal regulation is usually described by the following statement:

$$(M-W) \pm R \pm C - E = S$$

(M-W) = Total metabolism - external work performed

= Metabolic heat production

R = Radiant heat exchange

C = Convective heat exchange

E = Evaporative heat exchange

S = Change in body heat content

A value of S other than zero will result in a change of body temperature. A positive S will elevate body temperature. Under these conditions heat strain is said to have occurred. If thermal regulation is achieved through a balance of (M-W), R, C, and E then heat strain has not occurred. This may be in spite of the fact that an individual is under conditions of heat stress such as high ambient temperature or humidity. Heat stress without accompanying heat strain is a concern only from a psychological standpoint. Hot environments may result in worker irritabiilty, low morale, and reduced productivity. Heat strain, on the other hand, is a definite physiological change that can cause injury.

The heat balance equation is described in detail by others (5,39,40,41). This paper will develop individual components of the equation only to the extent necessary to quantify unique conditions of heat stress imposed by impermeable, encapsulated suits.

A. Metabolic Heat Production

Metabolism in a broad sense is the conversion of food into cellular chemical energy utilized to perform work. The efficiency of converting chemical energy into work is approximately 20% (41). Thus, in doing work, as in muscle contraction, 80% of the chemical energy expended converts to heat. As work increases, more heat is generated which must be dissipated. Therefore, the term

$$(M-W)$$

represents chemical energy produced minus that amount used to perform work. M-W equals total internal heat produced by the body over a set period of time. Heat production is normally quantified in terms of kilocalories per hour (Kcal/hr), although British thermal units per hour (Bth/h) and watts are sometimes used.

It should be noted that most work energy is also ultimately converted to heat. For example, some of the mechanical work performed by the heart in pumping blood converts to heat as the blood overcomes friction while moving through vessels. In a like manner, the movement of a muscle during contraction produces heat. Only the amount of energy required for actual work (i.e., the movement of an external object) is lost from the body before conversion to heat. Thus, in practice, the energy cost of a task (total chemical energy utilized) equals metabolic heat load (39).

Even at rest, work is performed and energy is expended by the body. The heart pumps blood (mechanical work), unequal concentrations of ions are maintained across cell membrane (electrical and osmotic work), and protein is synthesized (chemical work). Each of these activities produces heat and contributes to the basal metabolic rate. Basal metabolic heat production for a 70 Kg (154 lbs) man is between 60 and 70 Kcal/hour (40,41).

Using ergonomic guidelines (2) or empirical formulas (42) metabolic heat production can be estimated for work in impermeable, encapsulated garments. Under normal conditions an individual performing light work at a hazardous waste site will spend 40 minutes being outfitted in an encapsulated chemical protective suit. After that period he could skirt the perimeter of the site monitoring for vapors and perform simple tasks requiring light to moderate hand and arm movement such as securing valves and covering leaking drums. The majority of this time will be spent simply standing or walking while he moves from the command post to the site, identifying chemicals, manipulating detection equipment, and moving back from the site and through the decontamination line. Therefore, under normal conditions his metabolic heat load may be estimated by task analysis as shown in Table 1.

Assuming the specific heat of the human body is 0.83 Kcal/Kb-$^{\circ}$C, the 230 Kcal of heat produced during this forty minute period, if not dissipated, will elevate the body temperature by 3.96°C.[1] As will be seen in the following section, this heat dissipation is not easily accomplished due to the unique restrictions of impermeable, encapsulated garments.

B. External Heat Transfer to the Environment

Internal heat transfer depends upon a temperature gradient between the body core and the skin temperature. If the skin temperature is lower than the body core, heat will "flow" to the skin. In a like manner, heat exchange between the skin and the environment is controlled by the difference in temperature between the skin and ambient air. When the temperature of the skin is higher than the surroundings, body heat will be lost. Heat will be gained if the

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1 $\frac{230 \text{ Kcal}}{70 \text{ Kg/man} \times 0.83 \text{ Kcal/Kg-}^{\circ}\text{C}} = 3.96^{\circ}\text{C}$ in 40 minutes.

temperature of air surrounding the body is higher than that of the skin.

Major avenues of external heat transfer are convection, radiation, conduction, convection, and evaporation. Conduction, energy exchange between atoms or molecules in contact, can be a factor if the skin is in contact with a dense object. This is a major route of heat transfer for an individual immersed in water. Conduction is not a significant factor in heat exchange from the skin to air.

Radiation is heat transfer by electromagnetic energy and does not require physical contact for the exchange of heat. Warming of objects by the sun is of course the best example of radiative heat transfer. However, all dense objects radiate heat, with the amount being governed by the temperature differential between objects. Common emitters or absorbers of radiation, in addition to the sun, include walls, the ground and large objects. Whether an object is an emitter or absorber depends on its temperature. Radiant heat exchange is a function of the fourth power absolute temperature difference between surrounding objects and skin temperature (39). If surrounding objects are hot (>35^{o}C, 95^{o}F), the body will gain heat. If surrounding objects are at low temperature (<20^{o}C, 68^{o}F) a nude individual may lose 70% of his metabolic heat production by radiation (41). Radiant heat loss is greatly influenced by the amount of exposed skin. Moreover, many areas of the body radiate heat to opposing skin surfaces (i.e., fingers, inner thighs).

Conduction or heat exchange by kinetic energy between atoms and molecules in contact is a major route of heat transfer for an individual immersed in water. Conduction is not a significant component of heat exchange between skin and air. The thin, still layer of air next to the skin is in thermal equilibrium with the skin. This condition of equilibrium is reached by conduction. However, once equilibrium is reached the air layer at the surface becomes an insulator, virtually eliminating further conductive heat transfer. For this reason, most literature sources state that conduction plays an insignificant role in heat transfer with the environment unless the body is immersed in water. This statement is misleading since conduction along with radiation <u>drives</u> convective heat transfer. However, formulas describing convection normally include conductive thermal energy movement. For the purposes of this paper, conductive processes will be ignored with the understanding that this becomes a part of the empirical equation describing convection.

Convective heat transfer entails the movement of warm air away from the skin surface to be replaced by cooler air which in turn is warmed by the skin. Convection implies physical movement of quantities of atoms and molecules because of different certain kinetic energy states. Conduction and radiation heat exchange at the skin create these kinetic energy state differences in the air adjacent to the skin. Air flow, of sufficient velocity to sweep away the thin, insulating layer of air around the skin, plays a major role in convective heat transfer occurring.

Evaporation as a mechanism of heat loss occurs because it takes energy to accomplish a physical phase change. For the human body, the warm skin supplies the energy to evaporate sweat. As the skin loses energy it cools and in turn cools the blood just below the skin surface. Even at low ambient temperatures and work loads evaporation occurs. This insensible perspiration can account for 20 to 25 percent of basal metabolic heat loss (41). Profound sweating is initiated by the hypothalamus when nonevaporative mechanisms of heat exchange are not sufficient to dissipate excess heat. Sweating is most effective at conditions of low humidity. As will be seen in ensuing sections of this paper, impermeable encapsulated suits all but eliminate evaporation as an effective mechanism of heat exchange.

Radiation, conduction, and convection are capable of either adding or subtracting heat from the human body. Evaporation can only remove body heat. If thermal regulation is to be maintained the above mechanisms for heat transfer must allow dissipation of heat equal to metabolic heat production. If this does not occur the hypothalamus will initiate other physiologic responses to counter heat imbalances. One response to excess heat loads is diversion of blood to the cutaneous bed. This pooling of blood at the skin surface in severe cases can lead to collapse and cardiovascular injury without significant increases in body temperature. The hypothalamus may also allow body temperature to rise in an attempt to find a new point of thermal equilibrium. Often this occurs in conjunction with the shunting of blood to the periphery. If equilibrium cannot be reached at temperature with the range of 35-40°C then serious injury occurs.

Heat Strain for Monitoring Techniques

A. Wet Bulb Globe Temperature Modification

For several years, the Wet Bulb Globe Temperature Index (WBGT) has been internationally accepted as the simplest and most suitable technique for correlating environmental factors with worker heat load(15). WBGT Index[2] is incorporated with work load to set a work rest regime designed to maintain worker body core temperature below 38°C. Ramsey (1) in 1977 modified the WBGT Index to account for impermeable clothing. Under this system, 5°C is substracted from the WBGT Index any time a worker wears fully encapsulating, impermeable protective clothing. Engineering and work practices should be instituted any time the measured WBGT is at or above the adjusted WBGT threshold. The drawback of this monitoring method is the significant role of humidity in WBGT calculations (3).

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[2] WBGT (outdoors) = 70% of natural wet bulb temperature + 20% of globe temperature + 10% of the dry bulb temperature.

Ambient humidity does not contribute to heat stress for workers in chemical protective suits since they are encased in a microclimate of 100% humidity. Moreover, the 5°C substraction from threshold WBGT level was essentially a best estimate without the benefit of experimental data. More recent studies (4) indicate that physiological stress can occur even at low ambient temperatures, a situation for which the WBGT would not account.

Nonetheless, the Ramsey modification to the WBGT Threshold Level represented the first offer of a guideline designed to predict the additional stress of impermeable clothing. As a result, other studies of workers in impermeable clothing in normal industrial settings (4) and asbestos removal operation (5) have shown heat strain occurred at a 2.8 to 5°C lower WBGT index than workers not wearing impermeable clothing.

B. Adjusted Temperature Schedule for Heat Stress Monitoring

A recent U.S. Government manual of occupational safety and health for hazardous waste sites (6) suggests heat stress mointoring be based on an adjusted ambient temperature. Monitoring includes measurement of rest period heart rate, oral temperature and body water loss. The effect of radiative heat loads is accounted for by an empirical adjustment, specifically adding thirteen times the percent sunshine to the ambient temperature ($^{\circ}$F). Percent sunshine is estimated by judging what percent of time the sun is not covered by clouds thick enough to produce a shadow. The adjusted temperature is used to set the frequency of physiological monitoring.

This manual has been widely promulgated and represents a major effort to consistently limit heat stress among workers wearing impermeable garments. However, the ambient temperature based monitoring schedule has certain limitations. First, it was based on work levels of 250 Kcal/hr for fit, acclimatized workers. Workers in fully encapsulated suits routinely expend high amounts of energy because of the heavy loads carried (work boots, breathing apparatus, tools, instruments) and the nature of waste site work (barrel moving, shoveling). Secondly, adjusted temperature values will be arbitrary because estimations of percent sunshine will vary depending from one observer to the next. In addition it is not clear when or for what time period percent cloud cover should be determined.

Finally, the Manual recommends worker monitoring for ambient temperatures above 70^{o}F (21^{o}C). Study subjects exercising in neutral (7) and low ambient temperatures (6) showed significant physiological strain, suggesting neutral or low ambient temperatures do not assist removal of metabolic heat quickly enough under certain conditions of work.

C. Body Fluid Loss or Sweat Rate

Use of fluid loss or sweat rate as an indication of the magnitude of heat stress is intuitive to anyone ever exposed to a hot humid environment. Towards the end of World War II the Royal Navy developed a heat stress index based on the sweat loss endured by personnel standing a four hour naval watch in the hot, humid machinery spaces of a ship (9). In recent years, sweat rate has come to be recognized as a highly variable response to heat from which no reliable index may be developed. Individual capacity to sweat may vary since the number of sweat glands may vary among individuals, even if they are of equal body size (10). Acclimatization increases sweat rate, paradoxically indicating that greater body fluid loss up to a point, suggests greater heat tolerance. Fatigue of sweat mechanisms occurs during prolonged exposures to hot environments. This fatigue may be greater in a humid environment (12) such as the 100% humidity within an impermeable suit. Kraning et al. (11) elicited the same sweat rates from study subjects by means of exercise and from thermal environmental stress. They concluded different physiological states (heart rate, cardiac output, etc.) can be associated with equal sweat rates.

However, the importance of proper hydration should not be underestimated. Fatalities, originally diagnosed as heat stroke, have been found to be the result of severe dehydration, accelerated by heat stress (24). Reference (6) recommends a minimal ingestion of 4 to 6 liters of water during the normal work day with body water loss not exceeding 1.5 percent of total body weight. It has been suggested (12) that hydration levels can be more accurately determined measuring the specific gravity of urine.

D. Body Temperature

Deep core body temperature is a direct measurement of heat storage within the body. The goal of most work and engineering practices is to keep the body temperature from exceeding 38°C (15,16). Since body temperature is the criterion for measurement for heat strain, it would appear monitoring of body temperature would be the most reliable way to prevent injury. Unfortunately, in order to measure body core temperature reliably certain obstacles must be overcome.

Body temperature can be obtained rectally or orally. Oral temperature may be obtained with relative ease between work cycles. Drinking and mouth breathing fifteen minutes prior to oral temperature measurements invalidate the reading. Anedoctal evidence indicates that even under moderate work loads, mouth breathing occurs when a SCBA face piece is worn. Oral temperatures are therefore less than the corresponding deep core body temperature. Generally a safety margin of +0.6°C must be added to oral measurements in order to estimate body temperature (17). Rectal temperature although more accurate will never be consistently used in routine work conditions.

Periodic measurement of body temperature, whether oral or rectal, are "after the fact" measurements that may not be timely enough to prevent heat stroke. Lethal cases of heat stroke have been reported when the victim's temperatures, upon hospital admission was as low as 36.6°C (23). Shibolet et al. (24) described "light heat stroke" cases including multiple organ damage where rectal temperature spiked and then fell to 39°C before emergency treatment began.

Although rectal temperature probes allow an accurate continuous measurement of deep core body temperature, they are not an indicator of rapid changes in body heat content because of the large heat capacity and relatively small circulation within the pelvis (18). Other more centrally located organs, like the oesophagus, are more sensitive to temperature changes in central blood but for obvious reasons are impractical as monitoring sites. The insensitivity of rectal temperature to changing heat load has been demonstrated in studies showing rectal temperature lagging well behind accumulation of heat within the body (19,20,21,22). Shvartz and Benor (21) believe body heat storage may be underestimated by 10-20 $Kcal/m^2/hr$[3] as a result of the lag in rectal temperature.

The overriding consideration against using body temperature measurement as the primary or sole safeguard against heat injury is that heat injury can occur at normal or subnormal body temperature levels. In a study which will be discussed more fully in a subsequent section, collapse or

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3A 70 Kg, 185 cm adult male would have 1.92 m^2 of skin surface area near collapse was provoked in exercising subjects when rectal temperatures never rose above 38.5°C.

E. Convergence of Body and Skin Temperature

Circulating blood is the primary means for movement of core body heat to the surface of the body where heat exchange with the surrounding environment occurs. As discussed, cooling of the skin surface may occur even if ambient temperature exceeds skin temperature. Essential to body core heat dissipation in the maintenance of the core and the skin temperature gradient. A convergence of skin and body core temperatures eliminates the ability of the blood to transfer heat from the core. When the temperature gradient is lost, body heat is stored, resulting in a rise in body temperature.

If a gradient is not reestablished injury shortly ensues. As a result, rapid rises in skin temperature have been observed to cause heat exhaustion even when rectal tempertaures have been low (<39.0°C) and exposure periods have been less than 30 minutes (21,27). These studies concluded that exhaustion probably occurred because of maximum vasodilation of the cutaneous capillary bed and subsequent reductions in blood volume circulating to central organs.

U.S. Army researchers, in a study of exercising soldiers wearing chemically protective clothing and rain suits (27), were able to predict skin and rectal temperature convergence by predicting rectal temperature as a function of time (18) and linear extrapolation of skin temperature readings from the first ten minutes of exercise.

Simultaneously measuring skin temperature and core temperature of workers clad in impermeable clothing might be an effective monitoring technique. Individual differences such as weight, height, sex, and clothing type would be minimized since the individuals serve as their own controls. The Army study demonstrated that convergence preceeds subjective symptomatology or other signs (high heart rate or rectal temperature) of impending injury or collapse. This extra lead time is important since hazardous material handlers must allow five to twenty minutes for decontamination procedures before removal of their protective clothing.

The obvious drawback of this monitoring method is the inconvenience under field conditions. Radiotelemetry has to be used. Furthermore, even among the most regimented hazardous waste handlers, the measurement of rectal temperature will be resisted. The Army study was able to predict rectal temperature over time to within $\pm 0.01^{\circ}C$ using a formula developed by Givonia and Goldman (12). However, these predictions were conducted under laboratory conditions and require an accurate value for external and metabolic heat loads. At best, heat loads could only be estimated within a range for routine work. Metabolic heat production from nonroutine work, as during an emergency, could not be determined.

Iampietro (29) predicted the approach of tolerance limits in hot environment using skin temperature alone. A review of several studies (19,20,27) where rectal and skin temperature were recorded over time indicates that for exercising men in impermeable garments mean skin temperature converged with rectal temperature at 38°C (±0.5°C). Cessation of work and removal of impermeable clothing when mean skin temperature reached 37°C, as suggested in reference (31), apparently provides an adequate safety margin and a positive temperature gradient.

Mean skin temperature may be averaged using a number of sites on the body. Mitchell (30) evaluated a number of proposed methods using from 1 to 12 points. A weighted average of three sites; chest (50%), forearm (14%), and calf (36%) was shown to provide a mean skin temperature within 1°C of the actual value 96% of the time and within 0.2°C, 44% of the time. A document prepared for NIOSH (31) contends skin surface temperature throughout the entire body becomes practically uniform when work is performed in impermeable clothing. This report suggested that one site, the medial thigh, would provide skin temperatures most representative of the average, and would be the least susceptible to radiant heat sources. If so, monitoring skin temperature through the use of appropriate radiotelemetry could be performed with relative ease. When the medial thigh temperatures approached 37°C the hazardous material handler could stop work and begin the decontamination process necessary for suit removal and cool down.

Of the studies that measured skin temperature during work or exercise in impermeable clothing, temperatures were seen to approach 37°C quite rapidly (Table II). Extremely hot environments or intense exercise accelerated the process. This validates a conclusion from previous research (26,27) that at least 75% of the total change in skin temperature occurs during the first ten minutes of exposure to a hot environment. Using values from Table II and substracting a minimal margin of safety for ten minutes of decontamination would generally allow an actual work period of less than 20 minutes, depending on environmental conditions. On the other hand if a T_{sk} of 37°C is taken as an end point for work cessation and initiation of decontamination procedures then actual work time would generally fall within the limits of the supplied air available from a SCBA. It appears from the above studies that skin temperature of 37°C provides adequate warning of approaching heat collapse or injury.

F. Heart Rate

During work in heat the circulatory system has a dual role. Initially, it transports the oxygen needed for accelerated metabolic processes. Later, as these processes generate heat, blood must transfer excessive heat from the core to the periphery. After prolonged work in heat these two functions are in conflict when oxygen laden blood is diverted from central organs to the skin surface. As a result of peripheral vasodilation and diminished blood volume in the core the heart rate increases beyond what is normally expected as a demand of work. This increase during heat stress has been studied thoroughly (10,32,33,34,35). Heart rate is increased still further by impermeable clothing (5,19,20,22,27,36). Thus, increases in heart rate are appropriate indicators of heat strain. Moreover, heart rate is more sensitive to changes in heat stress (i.e. environment) than rectal temperature. In fact, for short work durations (<1 hr) in impermeable clothing heat strain may be represented solely by heart rate (38).

Environmental heat stress has been shown to slow the recovery of heart rate after work (35). Thus, recovery heart rate has been suggested as an estimator of strain (35,37). Researchers at Dupont (14) developed heart rate recovery criteria for hot job evaluation by comparing heart rate during the first minute of rest (P_1) to heart rate after 3 minutes of rest (P_3). They tentatively concluded that a P_1-P_3 value above 10 beats per minute, when P_1 was above 90 bpm, signaled the end of safe work in heat. In a more recent study (38), Pennsylvania State University investigators exercised subjects in impermeable clothing at a work load of 600 Kcal/hr. They found the recovery heart rate five minutes after work cessation correlated closely with a physiological limit of heat tolerance. They reasoned that recovery heart rate, if impervious clothing is not removed, is indicative of the portion of heat load supported by peripheral circulation. A low recovery heart rate represents a greater ability to compensate for heat load, low cardiovascular strain and tolerance to heat stress.

Kamon (35) showed that increased recovery heart rate during intermittent work in heat indicated increasing strain. Recovery heart rate measurement for hazardous material handlers in the field would appear to be a practical approach to heat strain monitoring. Workers wearing impermeable clothing could be placed on a work rest regimen. During rest the recovery heart rate could be determined at the end of each rest period using either radiotelemetry, allowing the site safety officer to monitor the worker, or through the use of an inexpensive jogger's heart rate monitor, which the worker could read. This approach requires a judgement of the recovery heart rate that would be an appropriate end point. The heart rate recovery criteria developed by DuPont (14) would likely not be appropriate. The DuPont study evaluated recovery for workers resting in an environment allowing sweat evaporation. For obvious reasons, hazardous material handlers could not be afforded the opportunity to remove their protective clothing during rest.

HYPOTHESIS

The use of environmental indices to identify heat tolerance end points for work in impermeable suits is inappropriate. The encapsulated suit creates its own microclimate where evaporative, convective and radiative modes of heat exchange are all but eliminated. As a result, physiological strain occurs during work in impermeable clothing even in neutral environments (21°C, 50% RH).

A heat strain monitoring method for workers in encapsulated protective clothing should account for external heat stress and individual differences in age, weight, skin surface area, fitness, acclimization, and work rate.

Recovery heart rate and average skin temperature are both appropriate indicators of heat strain. A specific recovery heart rate or mean skin temperature for an individual can be identified as a conservative endpoint for work in impermeable, encapsulating clothing.

METHODS

Six healthy male members of the U.S. Coast Guard National Strike Force, a pollution response group, volunteered for the study. The physical characteristics of each subject are presented in Table III. Each subject was acclimatized and experienced in the use of self contained breathing apparatus (SCBA) and impermeable protective clothing.

The subjects performed a total of 35 minutes (20 minutes exercise, 5 minutes rest, 15 minutes exercise) of zero grade walking on a treadmill set for 3 mph (4.83 kph). This speed and grade of walking were chosen to elicit an energy expenditure comparable to the work load of a hazardous material handler performing moderate work (Table I, IA). Exercise periods were performed under four different conditions. These conditions are detailed in Table IV but briefly involved exercise in coveralls at 21.5°C and exercise in encapsulated chemical suits at 21.5°C, 28°C and 31.5°C with sunshine. It should be noted that Condition 4 was outside where environmental conditions could not be controlled precisely, either between subjects or during a particular exercise period.

For the control condition (Condition 1) the subjects wore cotton under-shorts, T-shirt, dark blue coveralls, firemen's boots, and a pressure-demand SCBA.[4] In addition, each subject wore 5.44 Kg (12 lbs) of divers' weights to compensate for the weight of the chemical protective clothing worn for Conditions 2-4. Thus, the total weight of the gear worn was 26.3 Kg (58 lbs).

For Conditions 2-4 test subjects wore cotton under-shorts, T-shirt, white disposable coveralls,[5] SCBA, firemen's boots, and a totally encapsulating, coated chemical protective suit[6] with outer gloves of butyl rubber (Figure 1). The total weight of the protective equipment was 26.3 Kg (58 lbs).

Prior to each exercise period the subjects were required to consume 0.5 l of pure water. Body weight was determined to within 0.25 lbs before and after the exercise period. During the exercise, skin temperature was determined for the forearm, left chest at a point 3 cm above the nipple, left medial inside thigh and left medial outside calf using

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4 SURVIAIR[R]

5 TYVEK[R]

6 U.S. Coast Guard prototype fabricated from Teflon[R] coated Nomex[R]

standard thermocouples[7] Rectal temperature was recorded using a flexible thermocouple[8] inserted 15 cm beyond the anal spincter. Air temperature within the chemical protective suit was measured near the midriff and within the suit's hood, 6 cm from the visor, using probes.[9] Heart rate was measured with a pulse rate monitor[10] designed for runners and cyclists. Thermocouples were compared to a standard mercury thermometer and found to be accurate to within $\pm 0.05^{\circ}C$. The heart rate monitor was compared to a pulse determined by radial palpitation and found to be precise at all heart rates.

During the exercise, skin temperature, rectal temperatures, and heart rate were recorded every two minutes. Interior suit temperatures were recorded every four minutes.

Prior to the study, a US Coast Guard Ad Hoc Committee, consisting of physicians and engineers, was convened to review the protocol. This committee dictated that the

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7Yellow Spring Instruments (YSI) Thermometer (Model 49TA) with Series 400 probes (No. 409B and 421).

8YSI 401 vinyl probe

9YSI 408 "Banjo" probes.

10Polar Electro (PE-2000).

exercise regimen would be terminated if any of the following occurred: heart rate exceeding 80% of maximum [0.8 times (220-subject's age)], rectal temperature exceeded 39°C, the test subject requested to discontinue the exercise.

The submaximal exercise level for the 3 mph treadmill walking in protective equipment was determined by indirect calorimetry. The visor was removed from the chemical protective suit to allow $\dot{V}o_2$ measurement of oxygen consumption while the subject performed treadmill walking (3 mph) wearing 26.3 Kg of protective equipment. $\dot{V}o_2$ was measured using a Beckman oxygen analyzer. $\dot{V}o_2$ measurements were not made under conditions of heat strain since subjects performed the treadmill walking in a neutral, laboratory environment, with the suit's visor removed and for a period only long enough to allow $\dot{V}o_2$ to stabilize. Thus, $\dot{V}o_2$ presented in Table II is a reflection of the energy expenditure required by the pace and weight of the equipment, and not heat strain associated with prolonged exercise while fully enclosed in the chemical protective suit.

A medical screening test, developed by Pennsylvania State University (38), was used to determine heat tolerance. This test was administered to each subject at a point approximately midway through the study period. This test was modified from the original format to allow adaptation for treadmill use. Each subject walked for 20 minutes at 3.5 mph in an impermeable rain suit and fireman's boots.

The grade of the treadmill varied, depending upon subject weight, to elicit approximately 600 Kcal/hr of work from each subject. At the end of 20 minutes the subjects rested for 5 minutes, during which their five minute recovery heart rate was measured. This recovery heart rate was equated to the Pennsylvania State table of physiological limits of heat tolerance. The results of this test for each subject are shown in Table II.

RESULTS

Mean heart rate, skin and rectal temperatures during the course of the 40 minute exercise period are presented in Figures 2 and 3. Table V ranks the six study subjects in ability to tolerate the exercise regimen.

Heart rate during steady state exercise showed significant elevations as the severity of environmental conditions progressed from Condition 1 (the control) to Condition 4 (in sunlight and 31.5^{o}C mean ambient temperature). Use of protective clothing in a neutral environment (21.5^{o}C, Condition 2) significantly ($p < 0.025$) elevated the average heart rate from that of control conditions (Condition 1) by 9.7 bpm after 20 minutes of exercise and 11.5 bpm after 36 minutes of exercise. Heart rate was further significantly ($p < 0.025$) increased by raising the ambient temperature (28^{o}C, Condition 3). For Condition 3, the mean heart rate was 12.33 and 15,8 bpm above Conditions 2 after 20 and 36 minutes of exercise, respectively. When the test subjects were exercised in the most adverse environmental conditions (Condition 4) significant heart rate increases beyond those recorded in Condition 3 were not noted after 20 minutes. However, after 36 minutes significant ($p < 0.025$) increases were noted;

specifically a mean rate of 16.6 bpm above Condition 3 and 39.6 bpm above those recorded for the control (Condition 1).

The five minute recovery heart rate (5RHR) recorded at minute 25 after rest increased significantly ($p < 0.05$) as environment conditions became more adverse (Figure 3). Mean five minute recovery heart rates 25 minutes into the exercise regimen were 91.7 ± 10.5 S.D., 95.83 ± 14.0 S.D., 108.7 ± 22.6 S.D. and 116.4 ± 16.8 S.D. for Condition 1, 2, 3, and 4, respectively. For the first three conditions, test subjects were able to decrease their heart rate during rest by $14.8 \pm 0.7\%$ on average from the rate recorded after 20 minutes of steady state work. However, for the most severe condition, Condition 4, the subjects' heart rate decreased an average of only $4.9 \pm 4\%$. This recovery percentage may have been even lower if Subject B, who showed the most strain during Condition 3 exercise had been allowed to participate in the Condition 4 test.

Individual rectal temperature (T_{Re}) generally rose during the course of exercise under all conditions. However, increases in T_{Re} during exercise were not significant when compared to the control condition (Condition 1). $38.1^{o}C$ was the highest individual T_{Re} observed during any of the tests.

Mean skin temperature ($\bar{T}_{Sk}$) significantly ($p < 0.025$) and progressively increased as the environmental conditions for the exercise increased in severity (Condition 1 to 4). During Condition 4, $\bar{T}_{Sk}$ reached $37^{o}C$ for four of the five test subjects and approached to within 0.2°C of the rectal temperature for three subjects.

Average body weight loss slightly increased with increasing heat stress. Average percent body weight loss was 0.32, 0.62, 1.05, and 1.25 for Conditions 1, 2, 3 and 4, respectively. A mean difference in weight loss between test conditions was only observed with significance ($p < 0.01$) when the control condition (Condition 1) was compared to the most severe environment (Condition 4).

During exercise in Condition 3, the test was terminated for Subject B after 36 minutes when his HR exceeded 80% of maximum. It was decided he would not participate in the test under Condition 4. During tests at Condition 4, exercises were terminated after 34 minutes for Subjects G and C when their heart rate also exceeded 80% of maximum.

DISCUSSION

According to the results of this study subjects performing moderate work in fully encapsulated protective clothing exhibited marked, incremental elevations in heart rate and skin temperature as levels of environmental stress increased. This physiological strain was in addition to strain induced by the weight of the extra protective equipment (26.3 Kg) or the use of the SCBA.

A. Subject Size As A Prediction of Heat Tolerance

The ability of each subject to tolerate exercise in heat is shown in Table V.

Subject W tolerated all the tests exceedingly well. Subject W was the second oldest of the group. He is a smoker, and he exercises infrequently. Subject W was the largest of the 6 participants (100 Kg, 2.27 m^2 of skin surface area). The treadmill test required 32% of his maximum exercise level. Subject W's size and relative ease in performing the tests are in direct contrast to Subject B, the least heat tolerant of the group. Although fit and the most experienced in use of protective ensembles, Subject B was the smallest (65.75 Kg, 1.84 m^2 skin surface area). The exercise required 38.6% of his maximum exercise level. It may be that the significant weight of protective ensembles can be better managed in heat by larger people. I note that Subject M, the second largest member of the study and the most fit (28.7% maximal exercise level) tolerated the tests with almost the same degree of ease as Subject W.

B. <u>Use of Sweat Rate As An Endpoint</u>

This study found no significant correlation between body water loss and the degree of environmental stress. As pointed out earlier, prolonged work in impermeable clothing may decrease the sweat rate while physiological strain increases. It appears body weight loss cannot provide a reliable indication of heat tolerance endpoints. This is not to say that keeping a hazardous material handler well hydrated is not an essential practice. Under any field conditions, measures to prevent dehydration, like those outlined in Reference (6), must be closely adhered to.

C. <u>Use of An Environmental Index</u>

Air temperature and movement, water vapor pressure, and radiant heat are the environmental factors which, along with metabolic heat, determine the degree of heat stress to which a working individual is subjected. Encapsulating impermeable garments effectively eliminate the contributions ambient water vapor pressure and air velocity make to the total heat load imposed on an individual. In addition, radiant heat loads may be curtailed, depending on the color of the encapsulating fabric and amount of air between the fabric and the skin.

This study found significant ($p < 0.05$) increases in heart rate (HR) and mean skin temperature T_{Sk} with increases in ambient temperature (T_a) and black globe temperature (T_g). However, no linear relationship could be seen between indexes of physiological strain (HR, T_{Sk}, T_R) and increases in environmental factors (T_a, T_g, RH, wind velocity). Changes in the ambient temperature and temperature of the microclimate with the suit, measured at the waist and hood, appeared to correlate more closely with rises in T_{Sk} and HR than changes in T_a. This suggests that the light buff color of the suit reflected a significant portion of solar radiation. Suit temperatures were on the average 3.2^{o}C above ambient temperatures, apparently the result of metabolic heat radiating from the skin surface. Assuming 100% humidity within the suit, a WBGT Index Threshold Limit Value (15) could be calculated using suit temperature estimated from T_a. However, the use of this estimated threshold limit value in safely regulating work could not be tested.

More work needs to be done to quantify the impact of solar radiation on workers in impermeable protective clothing. It has been suggested (43) radiative environmental heat loads could possibly be disregarded at certain times of the year. If so, then work limits could be developed solely from dry bulb temperature and metabolic rates.

Custance (44) developed a table for "closed" impermeable suit times for various T_a at a moderate work level (250 Kcal/hr). Results of this study would appear to fall within the limits suggested by Custance (30 minutes at 85-90^{o}F, 60 minutes at 80-85^{o}F).

It is obvious traditional heat stress indices were not developed for workers encased in impermeable garments. However, a modified index similar to the WBGT index suggested above may prove appropriate upon additional study. The drawback to this approach is its general application without adjustment for individual differences. It is reiterated that because of the nature of the protective clothing and the type of work performed an individual cannot always be immediately removed from his hot environment upon the onset of heat collapse or injury. Thus to be safe, an environmental index must be conservative, perhaps too conservative to be generally employed in the field without the force of law.

D. Body Core Temperature

As expected, T_{re} did not respond readily to changes in the environment or metabolic heat output. This study was not intended to strain individuals to a point where heat injury and a specific T_{re} could be linked. However, as mentioned earlier, low T_{re} do not preclude the possibility of heat injury. Apparently, T_{re} is unable to accurately reflect physiological strain and rapid changes in overall body temperature. Mean body temperature can be predicted from T_{re}, T_{Sk} and HR measurements (45). However, this method is not practical for the field determinations.

E. Skin Temperature

Convergence of T_{Sk} and T_{re} has been shown to predict heat tolerance endpoints. From a thermodynamic prospective, this criterion appears reasonable, since a loss of temperature gradient signals the end of heat dissipation. If a $\bar{T}_{Sk}$ of $37^{\circ}C$ is taken as a conservative endpoint as suggested by Reference (31) then moderate work could be performed for the length of time that supplied air is available (≈40 min) for all conditions except Condition 4. Applying this $37^{\circ}C$ T_{Sk} endpoint to Condition 4 would allow an average work time of 20 minutes.

Recently (31), inside medial thigh temperature of $37^{\circ}C$ has been suggested as an estimator of $\bar{T}_{Sk}$ for workers in impermeable garments. This study showed medial thigh temperatures consistently underestimated $\bar{T}_{Sk}$ by at least $1^{\circ}C$, when compared to a three point mean averaging system (30) for skin temperature.

Under Condition 4, a $\bar{T}_{Sk}$ of $37^{\circ}C$ was reached on an average of 13.75 minutes before 80% of maximum HR was exceeded. Under Condition 3, which was indoors, a $\bar{T}_{Sk}$ of $37^{\circ}C$ coincided with the attainment of a sustained 80%

maximum HR. This rapid elevation of skin temperature during Condition 4 was the apparent result of solar load, high suit temperature or both. This suggests that $\bar{T}_{Sk}$ would be a more conservative estimator of heat tolerance endpoints than HR for work in sunlight.

The 3 point skin harness used for this study was not convenient to attach. To be used in the field it would require modification for telemetry and microprocessing. It is unfortunate that the medial thigh was not found to accurately reflect mean skin temperature. Finally, skin temperature measurement obviously would not be appropriate if the worker elects to wear a cooling garment.

F. Recovery Heart Rate

A sustained 80% of maximum heart rate was selected as an endpoint for this test. Since treadmill exercise for this study was steady state, this endpoint is not reasonable for field conditions. However, a recovery heart rate, determined while the worker rests in the suit, is easily obtainable and convenient under field conditions. For the six test subjects, suppression of the 5 minute recovery heart rate (5MRHR) preceeded signs of significant physiological strain (working HR > 80% max, $T_{Sk} > 37^{o}C$). Furthermore, when the 5 MRHR after 20 minutes of exercise was below 106 bpm the subjects were able to complete the remaining 15 minutes of exercise without significant physiological strain. Although this study cannot recommend a specific heart rate as an endpoint, expanded study could probably establish a recovery heart rate which will indicate an endpoint of heat tolerance for a select population.

Recovery heart rates are easy to determine. This study used a jogger pulse monitor purchased at a local sports shop for $65.00. This instrument easily allows the worker to determine his own 5 MRHR. At a small additional expense (when compared to the $3500 encapsulated suit telemetry could be employed to allow a site safety officer to monitor a number of hazardous material handlers at once.

G. Use of the Pennsylvania State University Heat Tolerance Screening Test

With one exception, the Pennsylvania State Screening Test (38) was able to accurately rank order the test subjects as to their ability to tolerate exercise in heat (Table 5). Subject W who had the highest Penn State score (>99%) was the most tolerant of the exercises. Subject B, who scored relatively low on the Penn State Test, was the least heat tolerant of the six test subjects.

Subject M, however, had the lowest Penn State score (77%), yet tolerated the study exercises almost as well as Subject W. When questioned, Subject M indicated that, on the night prior to the Penn State Test, he had slept only 2 to 4 hours. Furthermore, immediately prior to the test M had sunbathed for an hour at the local health club. Given Subject M's obvious ability to tolerate heat on other days, the anomalous test score suggests that the Penn State Test may only predict heat tolerance for the time in which it is given. Lack of rest, illness, or prior exposure to heat diminishes heat tolerance. Thus the value of the Penn State Test lies in its ability to evaluate cardiovascular fitness and should not be used exclusively to determine a worker's potential to routinely tolerate heat stress.

CONCLUSIONS

This study indicates recovery heart rate shows the most promise as an indicator of heat tolerance endpoints for work in encapsulated, impermeable protective clothing. Recovery heart rates are easily measured with inexpensive equipment. More study is required, however, before specific recovery heart rates are identified as a conservative endpoint.

Measurement of a worker's mean skin temperature, heart rate, and rectal temperature serves as the best overall indicator of heat strain. Unfortunately, T_{Re} and T_{Sk} cannot be determined practically in the field.

More studies of individuals clad in impermeable protective clothing and working in sunlight are needed. Apparently, these studies have not been conducted because of difficulty in controlling the environment, as shown in this report. In addition, a rigorous mathematical model of heat exchange between an individual and the encapsulated suit microclimate, and between the microclimate and the environment is needed to understand the impact of the environment on the physiological condition of the worker.

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Table I

Estimation of Energy Expenditure from AIHA Ergonomic Guides (2) for Moderate Work at a Hazardous Waste Site

	Energy Expenditure per Minute (Kcal/min)	Number of minutes for Each Task	Energy Expenditure During 40 Minutes of work (Kcal)
Walking (2.5 mph) with 58 pound load	6.9	20	138
Standing with moderate arm and trunk work	3.0-4.0	10	30-40
Standing	0.6	10	6
Basal rate for 70 Kg man	1.0-1.5	40	40-60
TOTAL			214-244 or 321-366 Kcal/hr

Table IA

Use of Givoni-Goldman Formula (42) to Select a Treadmill Pace Requiring 321-366 Kcal/hr of Energy Expenditure

$$V = 2.5 + \left(\frac{\frac{M}{W+L} - 2.3}{0.32}\right)^{0.606}$$

where:

V = walking speed, Km/hr
L = external load, 26.3 Kg for protective ensemble
W = body weight, Kg
M = metabolic rate, Kcal/hr

Example: A 70 Kg subject should walk at a rate of 4.87 Km/hr (3.0 mph) to expend 350 Kcal/hr.

Table II

Mean Skin Temperature (T_{sk}) Increases with Impermeable Clothing

Minutes Required to Reach 37°C T_{sk}	Rectal Temp At 37°C Tsk	Ambient Temperature	Heart Rate at 37°C T_{sk}	Exercise Intensity	Source Reference #
28	37.4°C	33°C	82	at rest	22
8	37.6°C	33°C	125	walking	
8	37.6°C	33°C	125	walking, 5 Km/hr	22
30	38.1°C	24.3°C	170	walking, 41% Vo_2 max	19
36.1°C at end of 30 minutes	37.7°C	24.3°C	118	walking, 21% Vo_2 max	19
20	37.3	77°F	~180	60% of aerobic capacity	20
20.5	37.5	46°C		225W (200 Kcal/hr)	27
31	37.7	35°C		225W (200 Kcal/hr)	27

Table III

Test Subject Characteristics

	G	C	W	T	B	M
Age	25	27	29	31	23	27
Weight (Kg)	79.0	84.2	100.0	79.0	65.7	96.5
Height (cm)	182.9	177.0	189.2	177.0	182.9	177.0
Skin surface area[1] (m^2)	2.01	2.07	2.27	1.97	1.84	2.14
V_{O2} (ml/min) for the treadmill exercise	1290	1440	1205	1505	1245	1100
% exercise[2] level	34.6	37.4	32	42.9	38.6	28.7
Energy expenditure (Kcal/hr) for the treadmill exercise	380.8	425.1	355.7	444.3	367.5	324.7
Percentile score for heat tolerance test[3]	~87	~87	>99	~96	~83	~77

[1] DuBois method (40)

[2] V_{O2}/max V_{O2} for the treadmill exercise

[3] Pennsylvania State University Medical Screening Test (38)

Table IV

Environmental Conditions to Which Test Subjects Were Exposed

	Condition			
	1	2	3	4
Ambient Temperature (T_a)	$21.5+0.5^{\circ}C$	$21.5\pm0.5^{\circ}C$	$28^{\circ}C\pm0.5^{\circ}C$	$31.5\pm2^{\circ}C$
Globe Temperature (T_g)	$21.5\pm0.5^{\circ}C$	$21.5\pm0.5^{\circ}C$	$28.5^{\circ}C\pm1.0^{\circ}C$	$49^{\circ}C\pm5^{\circ}C$
Asspirated Wet Bulb	$16.2\pm0.25^{\circ}C$	$16.2\pm0.25^{\circ}C$	$24.0\pm0.5^{\circ}C$	$25.2\pm0.5^{\circ}C$
Natural Wet Bulb	$18.3\pm0.5^{\circ}C$	$18.3\pm0.5^{\circ}C$	$25\pm0.5^{\circ}C$	$30\pm1^{\circ}C$
Relative Humidity	55%	55%	70%	66 ± 3%
Wind Velocity	<80 m/min	<80 m/min	<80 m/min	80-400 m/min
WBGT	$18.3\pm0.5^{\circ}C$	$18.3\pm0.5^{\circ}C$	$25.9\pm0.5^{\circ}C$	$34.0\pm5^{\circ}C$

Table V

Heat Tolerance Rank Order of Test Subjects

Subjects	Rank	Maximum Heart Rate During Exercise	Max 5 Minute Recovery Heart Rate	Minimum $T_{Re}-T_{Sk}$ difference	Weight of Protective Ensemble as % of Subj Body Weight	Comparative Rank Order for Medical Screening Test[2]
W	1	121 (Min 40, Cond 4)	90 (Cond 4)	0.8°C (Cond 4)	26.3	1
M	2	149 (Min 40, Cond 4)	115 (Cond 4)	0°C (Cond 4)	27.3	5
T	3	157 (Min 36, Cond 4)	123 (Cond 4)	0.3°C (Cond 4)	33.3	2
C	4	166 (Min 38, Cond 3 and Min 35, Cond 4)	118 (Cond 4)	0.5°C (Cond 4)	31.2	3 (tie)
G	5	164 (Min 40, Cond 3) 169 (Min 36, Cond 4)	128 (Cond 4)	0.1°C (Cond 4)	33.3	3 (tie)
B[1]	6	163 (Min 36, Cond 3)	141 (Cond 3)	1.2°C (Cond 3)	40.0	4

[1] Subject did not participate in Condition 4 exercise.

[2] Pennsylvania State University Heat Tolerance Medical Screening Test (38)

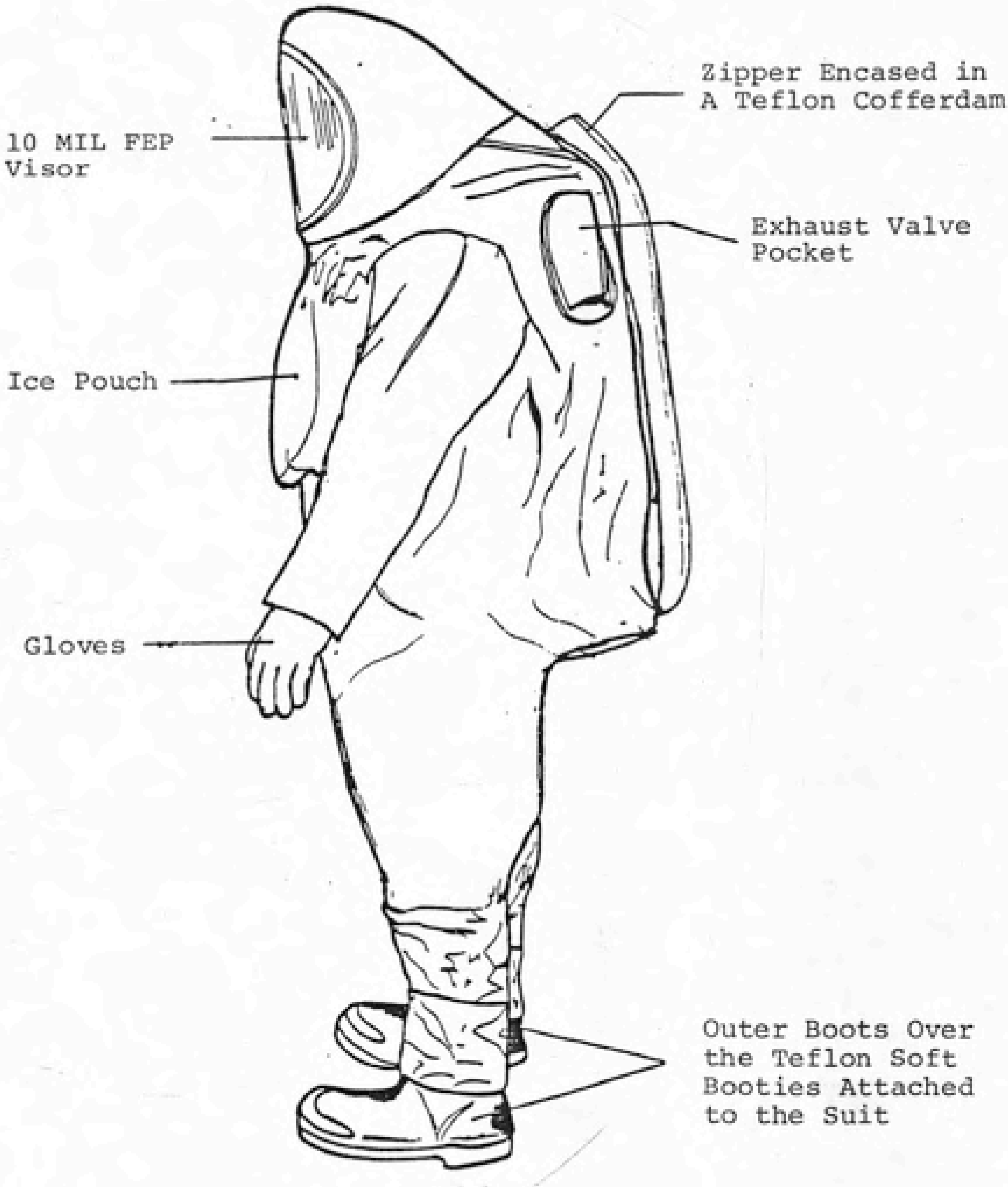


Figure 1. Total Encapsulating Suit Design.

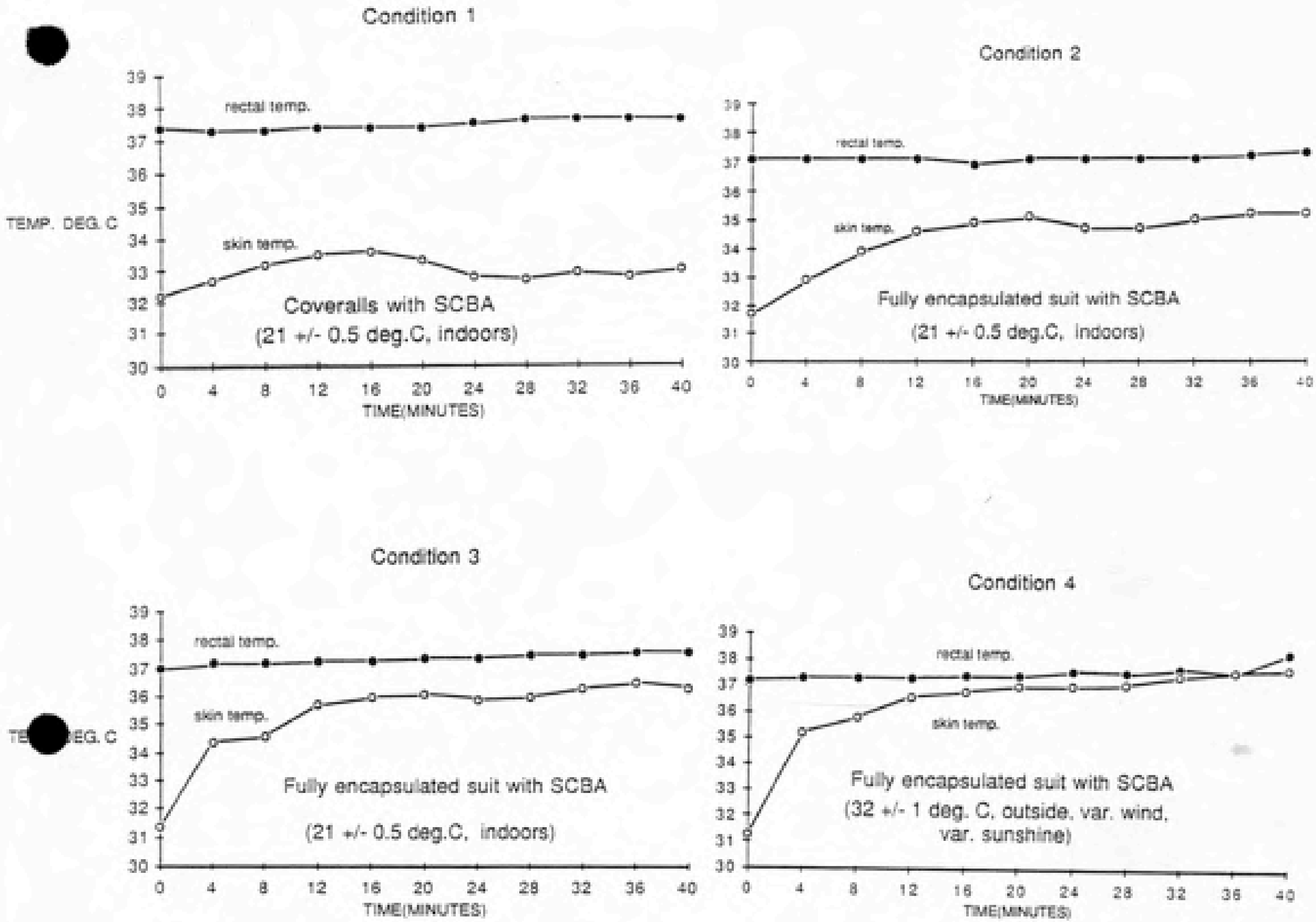
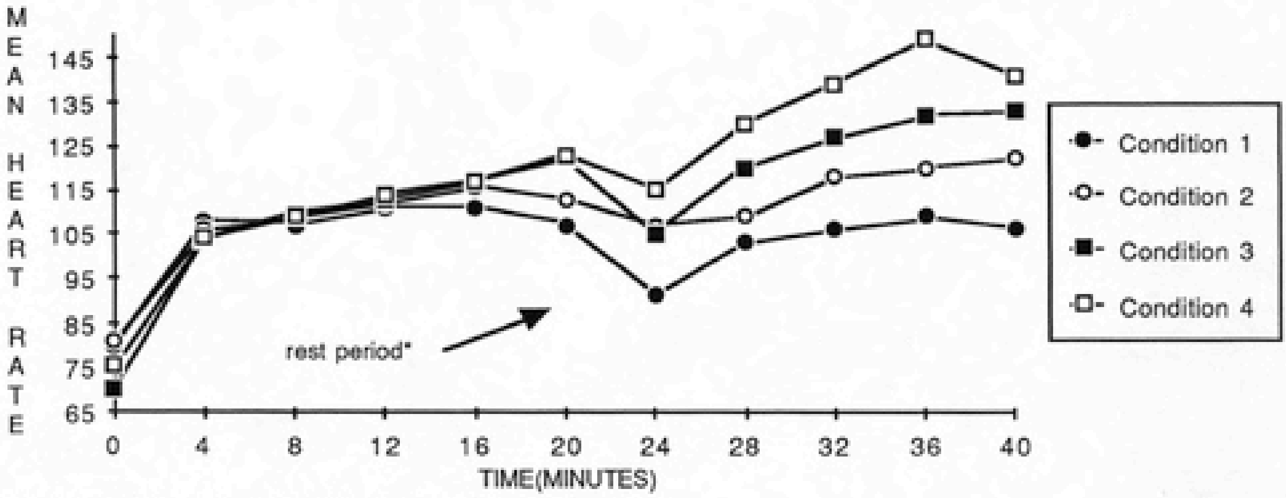


FIGURE 1

AVERAGE MEAN SKIN TEMPERATURE AND AVERAGE RECTAL TEMPERATURE OVER THE COURSE OF THE 40 MINUTE EXERCISE PERIOD

MEAN HEART RATE FOR FIVE SUBJECTS OVER THE COURSE OF THE 40 MINUTE EXERCISE



*Rest period: From time 20 to 25 minutes

FIGURE 2