PHYSIOLOGICAL AND PERCEPTUAL ASSESSMENT OF THERMAL COMFORT AND HEAT STRAIN IN GARMENT WEAR TESTS USING SLEEVES: AN ALTERNATIVE TO FULL-GARMENT TESTS OF CHEMICAL PROTECTIVE CLOTHING

by

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Clothing and Textiles

(ABSTRACT)

This study was conducted to explore the feasibility of using sleeves, along with both physiological and perceptual measurements, to assess the thermal comfort and heat strain in chemical protective clothing wear tests. The effect of body sites, i.e. the arms and the chest, and the effect of a Tyvek® coverall on skin temperature and sweat amount were investigated as well. Ten male subjects were selected from college students. Each subject was assigned to wear a garment of either T-shirt and pants or a changeable left-sleeved Tyvek® coverall with or without an experimental sleeve on the left arm. Three experimental sleeves were of the same style, but made of three different fabrics: Tyvek®, Pro/Shield I®, and Pro/Shield II®. Each subject wore an assigned garment and pedaled on a cycle ergometer in an environmentally-controlled room. Skin temperature, sweat amount,

and subjective comfort evaluations were recorded and later analyzed by repeated-measures ANOVA.

Results showed there is a feasibility in using a sleeve with a T-shirt/pants standard garment for assessing thermal comfort in chemical protective garment wear tests. The T-shirt/pants standard garment yielded more consistent and reliable results than did the Tyvek®-coverall standard garment. Under the same conditions, there were no significant differences in skin temperature and sweat amount among the left and right upper arms and the chest. The Tyvek® sleeve in this study impeded the transfer of heat by the greatest amount, followed by the Pro/Shield II® sleeve and the Pro/Shield I® sleeve, respectively.

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CHAPTER I

INTRODUCTION

Thermal comfort is an important aspect of chemical protective garments, in addition to such garments' abilities to protect and allow mobility. Ineffective heat transfer characteristics of fabrics, together with working conditions that are hot and humid, contribute directly to the development of heat stress and heat illness in workers (Santee & Wenger, 1989). A number of studies have assessed thermal discomfort and heat stress during the wearing of chemical protective clothing, and many studies have used physiological and perceptual measurements as tools to assess comfort. Comfort assessments in research have mostly been with full garments. To date, there is no precedent for using garment parts in studies to assess comfort related directly to chemical protective clothing. However, some researchers (Hatch, Wilson, & Maibach, 1987; Wester, Hatch, & Maibach, 1985; Wilson & Dallas, 1990) have used pieces of fabrics placed on the arms to study comfort. Zimmerer, Lawson, and Calvert (1986) have validated the reliability of forearm skin as a test site. Hyun, Hollies, and Spivak (1990) documented the effectiveness of using garment parts, instead of whole garments, in their study to quantify subjective measurements in garment-comfort assays. The research team also proposed the use of garment parts as an alternative to full garment wear testing. Using garment parts, instead of full garments, to assess thermal discomfort and heat strain

caused by wearing chemical protective clothing, may be more convenient and may reduce experiment time and cost.

This research explores the feasibility of using garment sleeves, along with both physiological and subjective measurements, to assess the thermal comfort and heat strain associated with wearing protective garments. This research can serve as a building block to future research. The implication for other researchers is the potential to use garment parts in thermal comfort assessment. Moreover, the findings of this research will provide information about various fabrics' suitability for use in chemical protective garment assemblies.

CHAPTER II

LITERATURE REVIEW

The first two sections of this chapter provide basic information about heat and moisture transfer through textile materials, including influencing factors and measurements. The next section addresses thermal comfort, heat stress, and heat strain, including definitions, thermoregulation, and factors affecting thermal comfort. The last section focuses on physiological and perceptual assessment.

Heat Transfer through Textile Materials

The main purpose of clothing is to maintain normal body temperature and to protect the body against varying external conditions. That is, clothing assists in maintaining equilibrium between the heat production by the body and the heat loss to the environment. Clothing should minimize heat loss in cold weather and should enhance heat transfer in hot climates. Because poor heat dissipation characteristics of protective clothing impede the use of such garments, heat transfer to reduce discomfort caused by wearing protective clothing is of interest in this study.

Modes of Heat Transfer

Heat is a form of energy that moves from places where the temperature is high to where it is low. Heat can transfer by four modes: conduction, convection, radiation, and

evaporation. Conduction of heat in stationary substances occurs when a temperature gradient exists, causing vibrational motions of free electrons (in solids) and molecules (in liquids and gases) and resulting in transfer of heat from higher to lower temperature zones. Unlike conduction, convection involves the bulk movement of fluid (liquids or gases). Heat is also exchanged by radiation across a gap between two surfaces. The human body is a source of infra-red radiation. Heat transferred by the three aforementioned ways is known as sensible heat (Kerslake, 1972). Parsons (1993) defines evaporation as a heat transfer process similar to convection, but also requiring an initial change of state from liquid to vapor (by latent heat) at the skin surface and subsequent diffusion of vapor across a boundary layer into ambient air. In contrast to the first three modes, the driving force for this vapor diffusion is the concentration gradient, not the temperature gradient, and the quantity transferred is mass (Kerslake; Parsons).

Evaporative Heat Loss

Morris (1953) stated that, under normal resting conditions, about 25 per cent of the heat loss from the body is by evaporation, with about a third of this loss from the lungs by insensible perspiration and the remainder (about 16 per cent of the total heat loss from the body) from the surface of the skin by sensible perspiration or sweating. Fourt and Hollies (1970) showed that, when environmental temperature is above 30°C, the heat loss by evaporation becomes a main route to dissipate heat (Figure 1). In warm and hot

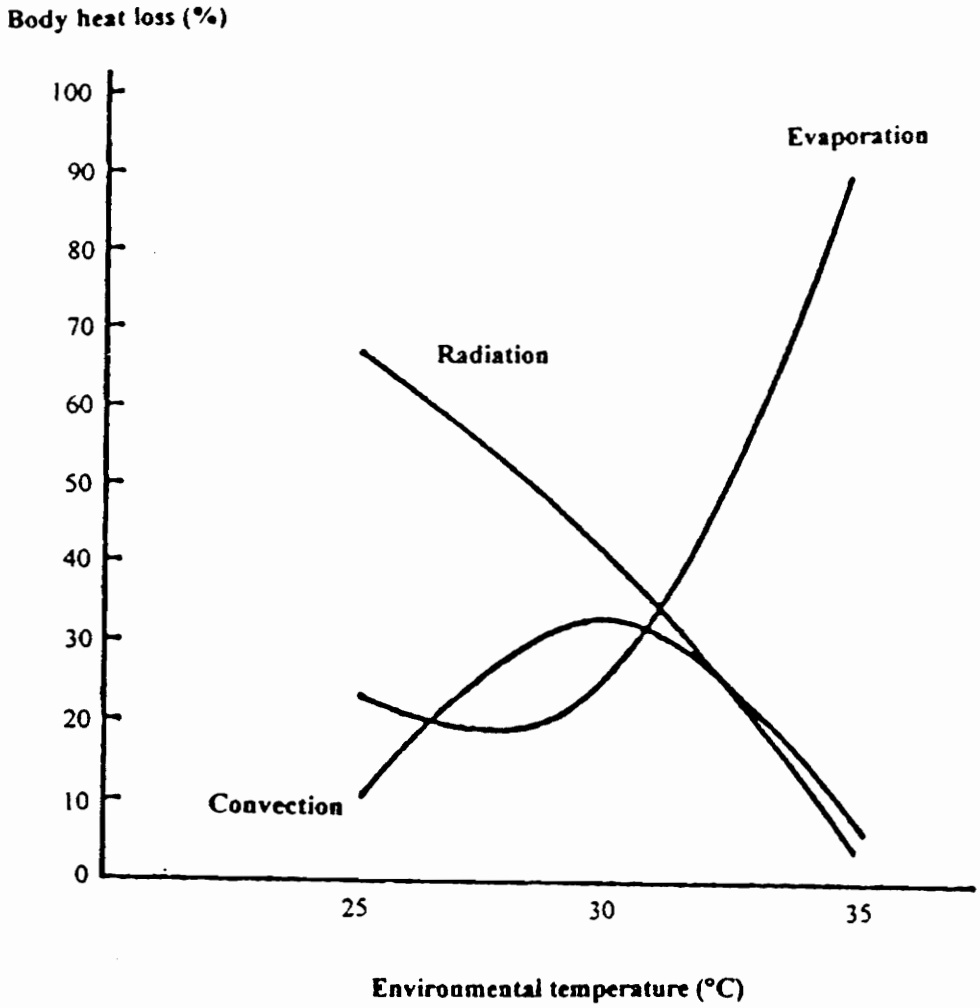

Figure 1. Contributions of modes of heat transfer in distinct environmental temperatures. (Reprinted from Clothing: Comfort and Function (p.247), by L. Fourt and N. R. S. Hollies, 1970, by courtesy of Marcel Dekker, Inc.)

conditions, evaporation is enhanced by sweating, when the skin becomes covered with a film of water.

Evaporation is a very important channel of heat transfer since the latent heat of water is quite large (2,500 kJ/kg). When the body evaporates water or sweat from the skin, a great amount of heat is used to change the state of water from liquid to vapor, causing great dissipation of heat. However, if the vapor condenses within the clothing or is absorbed by hygroscopic fibers, the heat of evaporation is liberated within the clothing and the sweat is relatively ineffective in cooling the body. Therefore, strongly hygroscopic materials are not recommended for users who perform exertion exercise or are in tropical conditions (Farnworth & Dolhan, 1985; Yasuda, Miyama, & Muramoto, 1994). Moreover, Yasuda et al. state that, for hygroscopic fabrics, the temperature of the fabric rises before that of the air spaces between the skin and the clothing, and the dominant factor causing the temperature to rise in those air spaces is the heat liberated by the fabric's absorption of water vapor.

Gonzalez, Breckenridge, Levell, Kolka, and Pandolf (1984) stated that, with a clothing assembly containing an impermeable layer, the total heat transfer from sweat-wetted skin to the outside environment involves both sensible and evaporative heat transfer to the impermeable layer. After this layer, heat is transferred to the clothing surface by sensible flows. Breckenridge (1967) explained the mechanism of evaporative heat transfer between the skin and a vapor barrier as a cyclic process without a net water loss. When there is a temperature gradient, heat is absorbed by skin to evaporate sweat,

is transferred across insulating layers along with vapor, and then is condensed on the impermeable layer having lower temperature than the skin. Subsequently, wicking of the condensate back to the skin sustains the cycle.

Heat Transfer through Moist Fabrics

Heat transfer in moist fabrics takes place through three modes: conduction, evaporation and radiation (Schneider, Hoschke, & Goldsmid, 1992). Infra-red radiation occurs in smaller amount as compared to the other two modes (Schneider et al.). Stuart and Holcombe (1984) developed a model from which heat transfer due to conduction and infrared radiation can be calculated for fibrous materials. Because the conductivity of water is 23 times greater than that of air, the effective thermal conductivity of moist fabrics is substantially higher than that of dry fabrics (Schneider et al.).

Schneider et al. (1992), in studying the effects of fiber sorption properties on evaporative heat transfer, used fabrics made of four fibers: wool, cotton, polypropylene, and porous acrylic fibers. The results indicated that differential fiber sorption properties influence heat and mass transfer by evaporation up to the point when the fibers are saturated with water, but after the saturation point all fibers behave similarly. The researchers explained the phenomena in terms of the distribution of water molecules within the fibers and fabrics. During initial moisture regain of absorbent fibers (0-15% regain for wool and 0-10% regain for cotton), no water evaporates from wool and cotton fabrics; therefore, there is no heat flux due to evaporative heat transfer. Water molecules

are absorbed into the structure of the materials and bound within fibers in the form of internal layers. On the other hand, moistened nonabsorbent fibers show a rapid increase in evaporative heat loss, because water molecules are only adsorbed on the fiber surfaces and are easily evaporated by heat. For absorbent fibers, rapid increase in evaporative heat loss occurs only after reaching the moisture regain limit. For any saturated fabric made of either absorbent or nonabsorbent fibers, the evaporative heat flux first plateaus and then starts to rise rapidly again at 200% regain when free water is present on the fabric surface. That is, sorption properties of either absorbent or nonabsorbent fibers have an influence on evaporative heat loss up to the point when the fibers reach saturation.

Factors Influencing Heat Transfer

Several factors concerning clothing and textiles govern heat exchange between the skin and the environment for the clothed human body. Each of these factors will be discussed.

Fabric thickness and entrapped air. The heat conductivity of a fabric is mainly determined by the fabric's thickness and entrapment of air. Research on the thermal resistance of apparel textiles (Holcombe & Hoschke, 1983; Morris, 1955; Obendorf & Smith, 1986; Peirce & Rees, 1946) has established that the thermal resistance of dry fabrics, or ones containing very small amounts of water, depends on their thickness. Because air is a poorer heat conductor than water or textile materials, garments with

several layers of thick, entrapped air are good insulators but poor heat dissipaters. Normally, the thermal insulation of either fabrics or air layers is expressed in terms of "Clo". One clo is similar to the thermal insulation of a business suit worn in Philadelphia, New Haven, or Toronto (Fourt & Hollies, 1970); stated in physical terms, one clo of thermal insulation is 0.18 °C m^2 hr/kg cal.

Insulation by entrapped air is affected by motion. During work, body movements result in increased circulation of the air enclosed within the clothing ensemble, causing more convective and evaporative heat loss. The resistance of the textile layers within the clothing is nearly independent of motion, whereas the resistance of enclosed air changes with motion. The resistance of entrapped air may decrease as much as 50 % during stationary slow cycling and walking (Neilsen, Olesen, & Fanger, 1985).

Air permeability. Convective heat loss and evaporation depend on the air permeability of textile materials. The tortuous air flow path, or irregular geometry of fabric pores, reduces the air permeability of fabrics and causes ineffective heat dissipation (Epps & Song, 1992; Obendorf & Smith, 1986). The effect of yarn and fabric characteristics on air permeability has been studied by Epps and Song.

Branson, DeJonge, and Munson (1986) investigated the thermal comfort of subjects wearing three fabrics: chambray, Gore-Tex, and Tyvek. Subjects wearing ensembles of a Gore-Tex fabric and those wearing 100 % cotton chambray experienced a similar level of comfort, whereas subjects wearing ensembles of Tyvek perceived thermal discomfort. The microporous film in Gore-Tex has pores that are large enough for

moisture vapor and air. These micro-sized pores greatly contribute to the fabric's air permeability, resulting in effective heat transfer (Branson et al.).

Fiber and fabric characteristics. Research on the thermal resistance of apparel textiles (Holcombe & Hoschke, 1983; Morris, 1955; Peirce & Rees, 1946) has demonstrated that fabric construction and fiber conductivity do not significantly contribute to the thermal resistance of dry fabrics. However, Schneider et al. (1992) have shown that the sorptive attributes of fibers influence the effective thermal conductivity of moist fabrics. Fabrics with absorptive fibers conduct greater amounts of heat than do those with nonabsorptive fibers, when the fabrics directly contact other materials. In contrast to conductive heat loss, evaporation occurs in a greater amount on fabrics with nonabsorptive fiber with low regain (0-15%).

Garment design and fit. McCullough, Jones, and Zbikowski (1983) established that garment design and fit determine the amount of enclosed air which, in turn, affects the heat transfer process. Neilsen, Desiree, and Nilsson (1989) found that, in warm conditions, a loose-fitting inner layer would allow for more effective evaporation than would a tight-fitting one. Watkins (1995) addressed the advantages of fitted, ventilating net underwear made of synthetic fibers such as nylon and polypropylene. In addition to the good wickability of the fibers, the open fabric structure enhances heat loss by all four modes, although the garment is fitted to the body.

Branson et al. (1986) examined the effect on thermal comfort of three protective-clothing designs made in three test fabrics. Design 1 included long-sleeved, traditionally

styled shirt and denim jeans. Only the shirt was varied in the test fabrics of Tyvek®, Gore-Tex®, and chambray. Design 2 was a coverall made of the test fabrics. Design 3 was similar to design 2, but it featured raglan sleeves rather than the dropped armscye and the back-front yoke of design 2. One of the findings was that, for a given test fabric, garment design did not influence subjects' thermal comfort to the extent that fabrics did.

In addition to factors concerning clothing and textiles, some other factors that affect heat transfer from the body to the outside environment are air temperature, mean radiant temperature, and body size and body surface area of subjects (Kerslake, 1972).

Measurement of Thermal Resistance of Textile Materials

Because the major concern in clothing is to minimize the thermal stress, warm or cold, imposed on man by the environment, there is good reason to measure the thermal insulation of clothing. Fourt and Hollies (1970) and Morris (1955) described three major techniques widely used to measure thermal resistance of clothing. Those three types are (a) constant temperature method, (b) rate of cooling or warming method, and (c) disk or heat flow meter method. The guarded hot plate is the most common form of type (a), and it has been adopted as a standard method by ASTM and specified as the ASTM method D1518-64.

In addition to the aforementioned methods, Schneider et al. (1992) have developed a transient technique used to measure the effective thermal conductivity of textile fabrics containing varying amounts of water. This technique takes less time to

complete than other heat transfer tests, and it eliminates the possibility of moisture redistribution in the fabric which can occur when the guarded hot plate is used.

Moisture Transmission through Clothing Materials

Moisture in both vapor and liquid states is among the various factors contributing to clothing comfort. In many applications, the performance of fabrics as moisture barriers is crucial. The use of fabrics in protective clothing to protect against pesticides is one such situation. For protective purposes, the fabrics must prevent the passage of liquid but must not impede moisture vapor transmission which is one of the most effective means in the body's regulation of heat. Therefore, this section will focus mainly on water vapor transmission.

Mechanisms

When there is a moisture concentration gradient across a fabric, water molecules will travel along the direction of the gradient by combinations of the following mechanisms : (a) adsorption or diffusion of water vapor displacing air which surrounds the textile, including air in interstices; (b) absorption of moisture (gaseous or liquid state) on the body side and movement of this moisture through the fabric before desorption of such moisture to the outside environment; and (c) wicking, the liquid transport through capillary interstices within the yarns or fabric or along the fiber surfaces (Adler & Walsh, 1984).

As recognized, fabrics are composed of two main components, i.e., fibers and air, which play different roles in moisture transport. The fiber component possesses moisture sorption capacities, whereas the air component takes part in the moisture permeability (Wehner, Miller, & Rebenfeld, 1988). That is, while moisture vapor transport occurs predominantly through the air spaces of the fabric, moisture accumulation occurs almost exclusively in the fiber portion of the fabric.

Dynamics of Water Vapor Transport through Fabrics

With regard to the dynamics of water vapor transport through fabrics, Wehner et al. (1988) explained vapor transmission in terms of moisture flux and moisture sorption. Moisture flux is a term used to describe the flow of moisture from high concentration to lower concentration. Moisture sorption includes adsorption, absorption and desorption of moisture in both liquid and vapor states. During the transient period, or before moisture equilibrium is reached, fabrics will absorb moisture from an environment of higher moisture content if they have initially equilibrated with an environment of lower moisture content. On the other hand, fabrics will desorb moisture if they have been conditioned previously at higher moisture content than that of the new environment. As a consequence of the concentration gradient, moisture flux will occur through the fabrics in both cases. The interaction between the rate of moisture sorption by the fabrics and the rate of moisture flux across the fabrics will occur until steady-state fabric moisture regain and moisture transmission rate are achieved (Wehner et al., 1988). Hollies, Kaessinger,

and Bogaty (1956), Hollies, Kaessinger, Watson, and Botagy (1957), and Wehner et al. concluded that the fiber type and the moisture sorptive capacities of fabrics strongly affect the duration of the non-steady state. However, under the steady state, the sorptive capacities of a fabric become less dominant because the moisture regain of the fabric is in equilibrium with the moisture in the surrounding environment. The dominant mechanism of moisture transmission under the steady state is water vapor transport through the air spaces of the fabric (Fourt & Harris, 1947).

Measurement of Moisture Vapor Transmission

A variety of techniques is available to evaluate the water vapor transport characteristics of clothing materials (Day & Sturggeon, 1986; Farnworth & Dolhan, 1984; Gibson, 1993; van Beest & Wittgen, 1986). Theoretically, all the techniques have the identical variable of interest, namely, water vapor resistance, which is typically expressed in terms of the thickness of still air whose resistance is equivalent to the water vapor resistance of the fabric; however, discrepancies are found between the results in the distinct methods. Gibson compared the two most common methods, i.e., sweating guarded hot plate test and upright cup method. The latter has been accepted in the ASTM method E96-80 for testing the water vapor resistance of textile materials, because of its simple procedure and inexpensive equipment. The upright cup, or cup/dish, method accounts solely for the mass transfer effect, whereas the hot plate method accounts for both heat and mass transfer effects. Both techniques include, in the observed water vapor

resistance, the resistance of the air layer between the fabric and the outside environment which is a source of data scatter; however, the cup/dish method has another inherent problem. The observed resistance obtained from the cup/dish method includes the resistance of the still air layer between fabric and water. This layer of still air has a higher resistance than the fabric itself. Therefore, Gibson recommended that the cup/dish method should be used only for testing materials with high water vapor resistance.

Factors Contributing to Moisture Vapor Transmission

Several factors, including fabric properties, influence water vapor transmission characteristics of clothing materials. This subsection describes such factors.

Fabric air permeability and porosity. Moisture vapor is transferred from skin to the outside environment mainly by diffusing through the air spaces of fabrics. Therefore, fabrics with higher air permeability and porosity (less density) will transport greater amounts of moisture than will those with lower air permeability and porosity (higher density). Dullien (1975) reported the strong dependence of permeability on porosity. Moreover, Wehner et al. (1988) found large changes in air permeability resulting from rather small porosity changes, which supported Dullien's findings. On the other hand, Gregory (1930) found that, under pressure, vapor diffusion through fabrics is independent of the rate of air passage.

Fabric thickness. Thickness directly influences water vapor permeability. The thicker the fabric, the longer the distance of passage of water vapor. Therefore, fabrics requiring high vapor transmission are usually thin. In addition, the sorptive capacity of fibers, especially of absorbent fibers, induces dimensional changes in fabrics under conditions of high relative humidity and results in increased thickness (Wehner, Miller, & Rebenfeld, 1987).

Fiber and fabric structure. Fourt and Harris (1947) showed that, normally, fibers affect water vapor resistance only when the fiber volume exceeds 30-40% of the total volume of a fabric. Fabrics having proportionately less fiber volume exhibit very similar water vapor resistance due to the sufficient availability of low-resistance pathways through air spaces in the fabrics.

Gregory (1930) showed that, under pressure, the effect of fabric air permeability on water vapor permeability or resistance is less for fabrics made of absorbent, low-resistance fibers such as cellulosic fibers and wool fibers than for fabrics made of nonabsorbent, high-resistance fibers. Absorbent, low-resistance fibers do not block the passage of water vapor even in the tightest fabric weaves, indicating that water vapor transports mainly through the substances of the fibers themselves. In contrast, the vapor resistance of fabrics having nonabsorbent fibers increases tremendously when fabric density increases. That is, the main pathway of water vapor through these materials is the air space between fibers and yarns.

According to Fourt, Craig, and Rutherford (1957), cotton is a better fiber choice

for high water vapor transmission along the fiber surface and within the fiber than are fibers with low moisture sorptive capacities. Fourt et al. also reported no differences in vapor transmission for cottons of quite distinct wall thickness.

As described earlier, moisture transmission during the transient condition is a combination of moisture transfer through air spaces of fabrics and moisture sorption by fibers. Unlike the transient state, the moisture vapor transmission through fabric interstices is a dominant mechanism under steady state. Gibson (1993) provided a similar idea that, under the steady-state condition, water uptake by fibers themselves can be ignored in most cases unless the fibers and yarns swell significantly causing dimensional changes in them and in fabrics. Thus, the sorptive capacities of fibers play their most important roles, by far, during the transient state.

Some researchers (Mecheels, Demeler, & Kachel, 1966; Wehner et al., 1987) have studied the effect of swelling, due to the nature of fibers themselves and relative humidity, on water vapor transmission as fabric porosity and thickness are influenced. The consensus is that, under the steady state, more or less intensive swelling has no influence on the moisture vapor transmission of fabrics. However, during the transient condition, dimensional swelling of the individual fibers is postulated to cause fabric structure alterations as the fibers absorb moisture. The magnitude of the dimensional changes, i.e., the extent of increase in the radius of curvature of the fibers and yarns, depends on fiber type and fabric structure. Wehner et al. showed that, as relative humidity increases, fiber swelling causes fabric porosity to decrease and that this effect is

more severe in constrained fabrics. In constrained fabrics, the more severe decrease in porosity with fiber swelling occurs because the constraint of a fabric at the two ends limits the longitudinal (or fabric length) change, while the fiber radius can increase more freely.

Environment. The rate of moisture vapor diffusion increases with increasing ambient temperature (Fourt & Hollies, 1970) and with increasing wind velocity in the environment (Gibson, 1993). The rate of diffusion decreases with increasing relative humidity in the environment (Fourt & Harris, 1947; Wehner et al., 1987).

In cases of microporous and hydrophilic films, the rate of vapor diffusion in microporous polytetrafluoroethylene (PTFE) and polyurethane films showed little variation with relative humidity, but the resistance of fabrics and films with hydrophilic coatings increased substantially as relative humidity decreased (Farnworth, Lotens, & Wittgen, 1990).

Finishes. Mecheels, Demeler, and Kachel (1966) investigated the effects of a water repellent finish and of a polyoxymethylene cross-linking finish on moisture transfer. The researchers found that a) the water repellent finish reduced moisture transfer of fabrics, and b) the chemical cross-linking of cotton did not reduce the rate of moisture transmission to a noteworthy extent. These differences were concluded from the effects of the finishes on the wettability of the fibers, which has a strong influence on moisture transfer by fabrics. With the water repellent finish, the wettability of the fiber is

reduced tremendously, whereas, with the cross-linking finish, the wettability is decreased only some extent.

Wickability and Wettability

Hatch (1993) defined wicking as a horizontal or vertical movement of liquid through a given fabric area by capillary action. Wettability is a textile's ability to when the contact of the fabric surface comes in contact with a specified liquid under specified conditions. The wettability of the fiber surface has a significant influence on the transfer of heat and moisture vapor by a fabric (Fourt & Harris, 1968; Fourt & Hollies, 1970; Hatch; Mecheels et al., 1966); therefore, it plays an important role in comfort. Mecheels et al. revealed that, even in the absence of a temperature gradient, increased wetting of a fiber surface due to wicking results in increased moisture transfer values at a variety of humidity levels, even as low as 50% relative humidity.

The chemical nature of the fiber contributes to its wickability. Polypropylene, a hydrophobic fiber, has been claimed to have much higher wickability than do hydrophilic fibers such as cotton, and the high wickability enhances the transfer of moisture from the skin to the outside environment (Farnworth & Dolhan, 1985). The low wickability of cotton is due to water being attracted to the numerous hydroxyl groups of the polymer.

Moisture Transport between Fabrics

Adler and Walsh (1984) and Farnworth and Dolhan (1985) stated that, between

adjacent layers of fabric, moisture is transported as liquid from one layer to another only if either the water content of the wet layer is very high (100% by weight) or if the wet and dry layers are held together under pressure. For the most part, moisture travels between layers by vapor diffusion. This diffusion mechanism is accompanied by wicking only when there is a sufficient amount of water to fill the capillaries formed between fibers and yarns, normally above the maximum absorption capacity of fibers.

Alder and Walsh (1984) found, however, that two knitted fabrics laid next to each other as layers do not seem to transport moisture between the fabric layers by wicking, even when the maximum absorption capacities of component fibers are achieved. The possible explanation is that knitted fabrics have a low degree of interfabric contact, which does not allow the occurrence of significant wicking between fabrics. However, intrafabric wicking would be possible.

Thermal Comfort and Heat Strain

A hindrance to the adoption of chemical protective clothing has been the contradictory requirements to provide adequate protection against pesticide penetration and to provide thermal comfort in conditions of high temperature and humidity which can easily cause thermal discomfort and heat stress. Branson and Sweeney (1990a) defined clothing comfort as "a state of satisfaction indicating physiological, psychological, and physical balance among the person, his/her clothing, and his/her environment" (p.371). Thermal comfort, as a subset of clothing comfort, is defined as "that condition of mind

which expresses satisfaction with the thermal environment" (ASHRAE, 1981, p. 8.19). The Environmental Protection Agency, or EPA, (1993) defined heat stress as "the buildup in the body of heat generated by the muscles during work and of heat coming from warm and hot environments" (p.1). Kerslake (1972) stated that an object could be subjected to stress imposed from outside, which will induce strain in the object. In the case of human heat stress, the stress is defined solely in terms of environment, including clothing, and heat strain is a consequence of the stress and the physiological characteristics of the subject. Therefore, heat build-up in the body and heat from the environment in the EPA definition are comparable to a stress that causes thermal strain or physiological responses of the body in Kerslake's definition. Heat stress cannot be expressed independently of physiological responses, however, because a person reacts to the environment or stress differently depending on his/her physiological state. In most studies, heat stress and heat strain have been used interchangeably, although the two terms are not synonymous.

Thermoregulation and Physiological Responses to Heat

The human body generates heat by a metabolic process in the active tissues--primarily at skeletal muscles. At the same time, the body exchanges (gains or loses) heat with the environment by conduction, convection, radiation and evaporation.

Heat generated by a tissue or organ must be removed to maintain thermal balance. The transfer of heat from the body core to the skin occurs by a) tissue conduction, and b) blood convection which is a main path (Houdas & Ring, 1982). Heat at the skin, then,

further exchanges with the environment by conduction, convection, radiation, and evaporation. Basal evaporative heat loss occurs by insensible perspiration through the respiratory tract and by sensible perspiration, or sweating, through the skin. A larger amount of heat is exchanged through the skin (Houdas & Ring).

The body's temperature sensors are located in the core and the shell, whereas the temperature regulation center which maintains the heat balance is located in the hypothalamus. Normally, the deep body core temperature is about 37°C, or 98.6°F. Changes in the core temperature of ±2°C severely affect body functions and task performance, and deviations of ±6°C are usually lethal (Fourt & Hollies, 1970). Thermal homeostasis is achieved by (a) regulation of the blood flow, (b) change in external work or exercise, and (c) change in clothing (Fourt & Hollies).

Parsons (1993) and Powers and Howley (1994) explained human physiology and thermoregulation in hot environments as follows. Thermal receptors, or thermosensors, located in the skin detect increased environmental temperature. The skin-temperature receptors transmit neuron impulses to the central nervous system (CNS): the spinal cord and the brain. The integration of thermal conditions of the body takes place in the hypothalamus, the body's thermostat. An increase in body core temperature above a set point, approximately 98.6°F (37°C) in humans, results in the hypothalamus initiating physiological responses to increase heat loss. The vasomotor control center increases cutaneous blood flow by vasodilation, resulting in increased skin temperature and thereby increasing heat loss by conduction, convection, and radiation. In order to dilate

cutaneous vessels, central blood volumes must be decreased, causing a fall of the stroke volume and an increase in heart rate. If heat transfer is not sufficient, the hypothalamus will stimulate the sweat glands, resulting in evaporation to cool the skin. When core temperature returns to the set point, the stimulus to promote both sweating and vasodilation is removed; this reaction is called "a negative feedback" (Powers & Howley). Finally, if transfer of heat by such modes is still not sufficient, muscular activities must be reduced to lower the amount of energy generated through metabolic processes; otherwise the body core temperature will exceed a tolerable limit.

Heat balance can be expressed by the following equation (Parsons, 1993):

$$M-W = E+R+C+K+S,$$

where M is the rate of metabolic energy production, and W is the rate of external working. The difference, M-W, is the remaining energy which is released as heat. E, R, C and K are the rates of heat transfer by evaporation, radiation, convection and conduction respectively. When combined together, all of the rates of heat production and loss provide a rate of heat storage (S) in tissues. A body in heat balance has a heat storage rate of zero. If there is heat gain, the heat storage term will be positive and body temperature will rise. On the other hand, if there is heat loss, the heat storage term will be negative and body temperature will fall.

Individuals experience thermal discomfort when their bodies cannot achieve heat balance, and, eventually, may experience heat strain when their bodies deviate severely from heat balance. Fourt and Hollies (1970) reviewed several signs of heat stress on the

body. The first sign is sweat rate. When produced sweat has reached one-third of the maximal evaporative capacity, sweat begins to drip off the skin. At the onset of sweating, the first area to sweat is, generally, the forehead, followed in order by the upper arms, hands, thighs, feet, and, finally, back and abdomen. Circulatory activities are also indicators of heat strain. Cardiac output enlarges mostly by a higher heart rate (a reduction in systolic blood pressure). The body core temperature will rise, and this rise should be counteracted before the temperature exceeds the sustainable limit. The water balance within the body is another sign of heat strain. Fourt and Hollies indicated that a loss of body water of only one or two percent of body weight could critically affect the ability of the body to control its functions. Other reactions developed during work or exercise in excessive heat are sensations of discomfort such as prickly heat and heat cramps. Excellent descriptions of heat disorder classifications, their signs and symptoms, as well as their treatments are provided by the United States Environmental Protection Agency (1993), by Fourt and Hollies (1970), and by Parsons (1993).

Psychological Responses to Heat

Regarding thermal sensation, Schmidt (1978) stated that the thermal receptors in the skin not only participate in thermoregulation but also serve as the sensors of conscious temperature sensation. The receptors transmit neuron impulses to the CNS but, in this case, the integrators are the thalamus nonspecific nuclei. As a result of an integration, a person may express his thermal perception by words or gesture.

Regarding moisture sensation, the skin contains no sensors for moisture. Humans sense moisture by touch, pressure, or temperature sensors. For example, a person senses the dripping of sweat down the body or feels cool when sweat is evaporated. Figure 2 summarizes physiological and psychological responses to an increased heat load.

Human Thermal-Environment Factors Influencing Heat Strain

Six major factors affect heat strain in humans, i.e., air temperature, radiant temperature, humidity, air velocity, clothing, and activity (Parsons, 1993). Conditions with high air temperature, radiant temperature, and humidity can easily induce heat disorder. Much research has been conducted to define the upper limit of air temperature and humidity in which one can maintain heat equilibrium (Robinson, 1945). Fourt and Hollies (1970) noted that air movement enhanced heat transfer by convection and evaporation. Santee and Wenger (1989) studied the effect of humidity and fabrics on heat strain. Humidity adversely affected the performance of subjects wearing protective garments. The findings also showed that the selection of fabric systems could make a significant difference in physiological strain experienced during heat exposure in chemical protective clothing. Tanaka, Brisson, and Volle (1978) investigated heat exposure under impermeable protective clothing. The micro-climate between the skin and such a clothing system is one of high ambient temperature, high humidity, and low wind velocity. The lack of air movement not only reduces heat convection but also keeps a still air layer at the skin surface, whereas humidity impedes sweat evaporation.

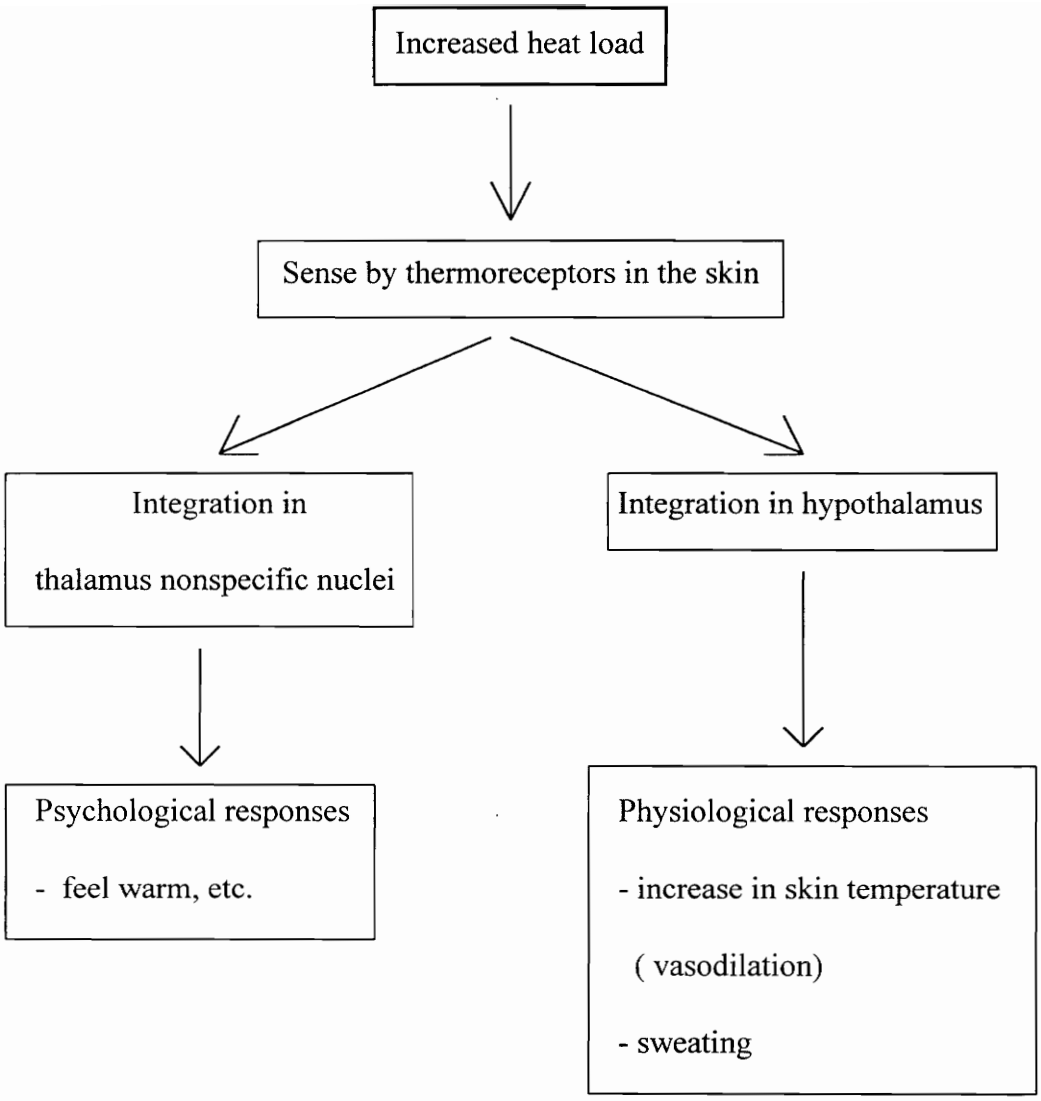

Figure 2. A summary of physiological and psychological responses to heat load.

Impermeable clothing greatly increases the risk of heat strain and reduces time of working. The use of ventilated panels in such clothing can circumvent the impermeable layer by introducing more moving air under the clothing (Webb, 1959).

Regarding the effect of activity on heat strain, Keighley (1985) presented the physiological rates of work at different levels of activity as well as the relationship between work rates and water evaporation from the skin. The Environmental Protection Agency (1993) has listed various tasks by approximate workload involved. Heavy or prolonged work can easily cause heat strain because the harder the task, the more heat produced, the hotter a worker gets, and the more frequently rest breaks are needed.

The Limit of Physiological Strain

With regard to the upper limit of physiological strain, Webb (1959) defined two types of limits, namely, the performance limit and the physiological tolerance limit. The performance limit is the point where impaired function occurs, and the physiological tolerance limit is the point where one is overwhelmed by heat exposure, resulting in a collapse. Blockley, McCutchan, Lyman, and Taylor (1954) found that the performance limit was reached in about three-fourths of the time required to reach the physiological tolerance limit. Martin and Goldman (1972) found, with a large group of young healthy men, that a heat storage of 160 kcal can result in a high probability of heat casualties. Also, as the body heat storage values reached 80 kcal, the usual level at which discomfort becomes acute, the volunteers began withdrawing from the test. Santee and Wenger

(1989) set the physiological limit of their study at either a sustained heart rate of 180 beats/min for five minutes or a rectal temperature of 39.5°C (103°F), in compliance with the U.S. Army Research Institute for Environmental Medicine (USARIEM) Type Protocols for Human Research Studies of Exercise and Physical Training and Human Research Studies of Thermal Stress.

Physiological and Perceptual Assessment of Thermal Comfort and Heat Strain

Thermal comfort and thermal strain can be assessed by a variety of methods classified as physical, biological, physiological, and psychological. Much research has used physiological measurement and/or the psychological method to assess thermal comfort and thermal strain. Over the course of 50 years, numerous studies have investigated the relationship between physiological responses and subjective perceptions, i.e., thermal sensation, of subjects being exposed to warm and hot environments (Berglund & Cunningham, 1986). Berglund and Cunningham listed several regression equations representing the relationship between physiological responses, particularly skin wettedness, and subjective responses under warm and hot conditions. The good relationship found and the potential of physiological and subjective assessment are reasons to use both techniques in this study.

Physiological Assessment

Physiological assessment of thermal comfort and heat strain usually involves a

person exercising on a treadmill or cycle ergometer to provide biological indicators of the effect of heat load. Andreen, Gibson, and Wetmore (1953) believed that the treadmill is the more desirable machine for comfort studies because it offers a customary, everyday form of exercise. The physiological measures that are widely used to assess heat stress are heart rate, body core temperature, mean body temperature, skin temperature, and rate of sweating.

Heart rate can provide a general index of body strain because thermal stress, causing the strain, can affect the electrical activity of the heart, as represented by an electrocardiogram (ECG) (Parsons, 1993). Measurement of heart rate can be achieved by several means, such as a stethoscope, an electrocardiogram, and a portable pulse reading device.

Numerous methods, as well as a number of accessible places, are available for measuring body (or core) temperature. Parsons noted that measurement of aural temperature and oral temperature are widely used methods, particularly in medical applications. Tanaka et al. (1978) provided equations for computing mean body temperature and rectal temperature. Martin and Goldman (1972) also gave an equation for mean body temperature which differed slightly from the one given by Tanaka et al. Houdas and Ring (1982) listed body temperatures measured at different sites compared to rectal temperature.

Skin temperature can be measured by placing sensors on the skin or by measuring thermal radiation. Houdas and Ring (1982) stated that the variation of skin temperature

due to ambient conditions differs with the particular skin area, even in thermal neutrality (the state of a person at rest and maintaining thermal balance without thermoregulatory mechanisms). The skin temperature of the extremities, especially the feet, varies the most with ambient temperature, that of the forehead and trunk varies the least, and that of the proximal limbs varies to an intermediate degree (see Table 1). Houdas and Ring also noted that, at an ambient temperature of 95°F, the skin-temperature difference over the body is minimal, and that the lower the ambient temperature, the greater the range of the skin temperature over the body. Tanaka et al. (1978) provided an equation for computing mean skin temperature. Parsons found that, for measuring skin temperature on the human body, fewer points are needed for assessment in the heat and more sites are required in the cold.

The rate of sweating can be assessed by measuring body mass loss in a given time (Parsons, 1993). The method is to weigh a subject nude before exposure (N_B), clothed before exposure (C_B), clothed after exposure (C_A), and nude after exposure (N_A). The amount of sweat trapped in clothing and of sweat evaporated are determined by:

$$\text{Sweat trapped in clothing} = (C_A - N_A) - (C_B - N_B)$$

$$\text{Sweat evaporated} = (N_A - N_B) - [(C_A - N_A) - (C_B - N_B)].$$

Phillip (1984) developed a sweat patch that occluded the skin so that, during wear, all moisture on the skin was collected and retained in contact with skin. The patch's first application was for diagnostic purposes to study alcohol consumption. Burns and Buselt (1995) described the failings of the occlusive sweat patch as follows: (a) the patch

Table 1

Skin temperature distribution of a nude person in thermal neutrality, and at colder and warmer temperatures[1]

Body site	**Skin temperature (°F) in**				
	Cool environment		Neutrality	Hot environment	
	68°F	77°F	86°F	95°F	104°F
Forehead	91.2	93.0	94.6	96.6	97.0
Hand	75.2	77.7	91.2	96.6	97.9
Forearm	81.9	86.5	92.5	96.4	98.1
Upper arm	82.4	87.4	92.1	97.0	99.1
Chest	89.4	91.0	94.1	96.8	98.2
Upper Abdomen	88.3	90.9	93.9	95.9	97.2
Lower Abdomen	87.3	92.3	94.5	95.4	97.0
Thigh	82.2	86.9	92.1	95.2	97.3
Shin	78.4	84.0	90.9	95.7	97.5
Foot	71.1	80.8	88.0	96.1	98.6

[1] Derived from Human body temperature: Its measurement and regulation (p.97), by Y. Houdas and E.F.R. Ring, 1982, New York: Plenum Press.

irritates the skin after a day, and (b) there are problems of perspiration leakage. Burns and Buselt also described a new, nonocclusive sweat patch developed from wound dressings. The nonocclusive dressings, constructed of very thin polyurethane and acrylate adhesives, allow the moisture of perspiration to evaporate; a medical-grade cellulose blotter paper located between the skin and the dressing serves as a sweat collector. The rate of sweating can be determined by the difference in the patch's weight before and after exposure. This new sweat patch is the selected means of measuring sweat amount in this study due to its ease of application and suitability for small test sites, for example, arms.

As to the effectiveness or sensitivity of the physiological measures, Andreen et al. (1953) indicated that average skin temperature is a sensitive parameter capable of distinguishing relatively small environmentally-induced changes, whereas heart rate is a less sensitive criterion. However, Gagge, Stolwijk and Hardy (1967) and Winslow, Herrington and Gagge (1937) found that, in warm conditions, the sweating response is a more important determinant of comfort than are skin temperature and body core temperature.

Perceptual Assessment

Many studies on clothing comfort in the past three decades have been conducted using subjective evaluation or psychological assessment (Hollies, Custer, Morin, & Howard, 1979), due to the researchers' belief in man's perceptual abilities which have

existed for thousands of years (Hollies, 1989). Pontrelli (1977) proposed a clothing comfort model entitled "Comfort Gestalt". The researcher grouped major parameters causing a person to feel comfort or discomfort into three categories: physical stimuli, psycho-physiological stimuli and a filter (or stored modifiers). The physical and psycho-physiological stimuli are featured as filtering through a screen of stored modifiers to result in an individual's comfort judgment. The physical stimuli involve variables specific to environment, transport properties, level of activity and garment, whereas the psycho-physiological stimuli include state of being, end-use and occasion of wear, style, fit, and tactile aesthetics. The filter consists of past experience, prejudices, expectations, imagery and lifestyle.

Psychological scaling, as a means of subjective assessment for an individual to express his comfort or discomfort, has been documented as the most universal approach in assessing clothing comfort (Branson & Sweeney, 1990a, 1990b; Gagge et al., 1967; Hollies, 1971). Subjects usually are provided the scale and asked to mark the place representing their sensation. Hollies (1977) discussed the six elements of psychological scaling together with the scale types and data handling techniques. Parsons (1993) stated that the subjective methods allow easy collection of invaluable data on psychological responses, but that they should not be used as primary measures of heat or cold strain on humans. The ability of a person to make a rational judgment may be impaired in severe conditions.

A number of subjective scales have been used in thermal comfort assessment. The most common of these scales are the seven-point scales of Bedford and ASHRAE (Parsons, 1993). The McGinnis Thermal Scale is another widely used scale in thermal comfort studies. Hollies (1971) stated that, in his experience, the McGinnis scale had proved effective for both assessing thermal stress and checking subject safety in severe climates. Branson et al. (1986) assessed the human perception of thermal sensation and thermal comfort by nine-point rating scales, together with semantic differential scales consisting of a series of bi-polar adjectives. The results obtained from the perceptual measurement corresponded to those taken from physiological measurement, which confirms the reliability of human perception in comfort assessment. Morris, Prato, Chadwick, and Bernauer (1985) used subjective evaluation scales to study the relationship of moisture transport properties of warmup-suit fabrics to comfort evaluated by subjective scales. The scales used in that study included wetness sensation scale, thermal sensation scale, and comfort sensation scale. Under heat stress or physical exertion, when excess sweat exists, the moisture properties of an inner layer become important to thermal and overall comfort. Among the scales mentioned here, those developed by Morris et al. were selected in the current study because they include the wetness sensation scale, which can indicate (a) the influence of moisture flow, between and within clothing, on thermal comfort, and (b) the clothing layering effect, whereas other scales can assess thermal comfort only broadly. The other reason for selecting these

scales is to be able to compare the results with the findings of former research which used the same scales.

Exercise Protocols in Chemical Protective Clothing Studies

The majority of studies on thermal comfort, using either physiological or psychological assessment, had used the human resting state as the standard condition, until Asmussen (1967) described the exercise state as a second experimental standard (Gagge, Stolwijk, & Saltin, 1969). To date, many studies to assess comfort in chemical protective clothing have used exercise to simulate actual work in the field. For example, Martin and Goldman (1972), Santee and Wenger (1989), and Tanaka, Brisson and Volle (1978) had subjects exercise on a treadmill. Andreen, Gibson and Wetmore (1953) used both a treadmill and a cycle ergometer in their study. Gagge et al. (1969) incorporated a cycle ergometer in the experiment. In Branson, DeJonge and Munson's (1986) study, a step exercise was selected.

Different work loads and work rates have been used in the studies cited above. Work load is the amount of work accomplished, whereas work rate is work performed per unit time (Powers & Howley, 1994). For example, Keighley (1985) noted that the work rates of sleeping, sitting, gentle walking, and active walking are 60, 100, 200, and 300 watts, respectively. Branson et al.(1986) used a three met work rate to simulate the amount of human work performed in applying pesticides by tractor and air-blast sprayer. Met is defined as a metabolic equivalent of approximately 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (Powers &

Howley, 1994). Tanaka et al. (1978) set the treadmill at five kilopounds per hour to simulate the work amount of pesticide handlers in a field.

Psychological and Physiological Responses during Exercise

Gagge et al. (1969) observed both psychological and physiological responses of subjects during steady-state exercise at a range of work rates and ambient temperatures. Along with measuring physiological changes, Gagge et al. had subjects indicate their thermal sensation and their warm discomfort. Each of the subjects, wearing shorts and a T-shirt, pedaled 50 revolutions per minute (rpm) on a bicycle ergometer at work rates of 25%, 50% and 75% maximal oxygen uptake, while in ambient conditions of 40% RH, and 10°C, 20°C and 30°C. The exercise period at each work rate in each ambient condition was about 20 minutes. According to the results for this steady- state exercise, thermal sensation correlated best with either the skin or ambient-air temperature, and correlated poorly with sweating. On the contrary, warm discomfort was governed by skin sweating. Rectal temperature was proportional to the work rate and was dependent on ambient temperature. Skin temperature appeared to depend on the ambient temperature and not on work rate. Heart rate varied primarily with work rate, but, at any given work rate, heart rate dropped slightly at the colder ambient temperatures. Sweating increased with skin conduction (a factor which can be also interpreted as a measure of skin blood flow.)

Assessment of Clothing Comfort by Using Garment Parts

Most research in thermal comfort has been conducted using full garments, especially when physiological measurement has been the primary means of assessment. However, some studies in skin sensation related to clothing comfort have used garment parts instead of the whole garments. In most of this research, forearms or upper arms have been chosen as the test sites. For example, Wester, Hatch, and Maibach (1985) investigated the effects of the insulative nature of certain fabrics on the alteration of human capillary blood flow by using pieces of fabrics placed on the upper arms of subjects, rather than whole garments. Zimmerer et al. (1986) studied skin wetness due to wearing wet vs. dry disposable or cloth diapers by having subjects wear samples on their forearms. The researchers validated that the adult volar forearm skin was a reliable test site on adult subjects. Using the Zimmerer et al. model, Wilson and Dallas (1990) placed two-inch-square wet diaper patches on the forearms of adult subjects to examine the relationship between diaper wetness and the ability of diapers to keep the skin dry. Hatch, Wilson, and Maibach (1987) studied the alteration of the wetness state of the skin due to the wearing of apparel fabrics by sedentary and exercising subjects; the research team placed patches of triacetate and polyester woven dress-weight fabrics on the subjects' forearms.

In 1990, Hyun et al. (1990) studied skin sensation perceived when wearing clothing by incorporating the use of the "Human Perception Analysis (HPA)" technique of Hollies (1971) in a "Sleeves Program". The researchers first developed a newly

expanded set of perception terms, which was elicited from subjects wearing only portions of fitted sleeves, and then they applied the rating system in a pilot study where the full garments were worn. The responses of subjects from the sleeves program corresponded to those from the full-garment pilot study. That is, the Sleeves Program proved useful not only as a screening test, but also as an alternative to full garment wear testing.

The success in using garment parts in earlier research suggests the idea of using sleeves to assess thermal comfort and heat strain in the present research.

Summary of Literature Review

Pesticide handlers required to wear protective garments have faced thermal discomfort and risks of thermal stress due to hot working conditions and the poor heat and moisture dissipation of the garments. Kerslake (1972) defined human heat stress as an environment, including clothing, and heat strain in a subject as a consequence of the stress. Parsons (1993) described six major factors affecting heat strain on humans, i.e., air temperature, humidity, radiant temperature, air velocity, clothing, and activity. To keep thermal homeostasis in a hot environment and in the clothed condition, the human body transfers heat and moisture through clothing to the outside environment. Heat exchange occurs by combinations of the following modes: conduction, convection, radiation, and evaporation. Morris (1953) noted that evaporation of sweat can account for up to 25 per cent of total heat loss of the body. Moisture from evaporation, as well as

some amount of liquid sweat, is transferred through clothing by adsorption, absorption, and wicking (Adler & Walsh, 1984).

Assessment of thermal comfort and thermal strain in clothing comfort research can be achieved by physiological measurement and/or subjective assessment during exercise. The widely used physiological measures are heart rate, skin temperature, body core temperature, mean body temperature, and rate of sweating. Andreen et al. (1953) indicated that average skin temperature is a sensitive parameter capable of distinguishing relatively small environmental changes, whereas Gagge et al. (1967) and Winslow et al. (1937) found that, in warm conditions, the sweating response is a more important determinant, and thus indicator, of comfort than are skin temperature and body core temperature. Psychological scaling, a means of human perception assessment, has been documented by Branson and Sweeney (1990a), Gagge et al., and Hollies (1977) as the most universal approach in clothing comfort research. Berglund and Cunningham (1967) listed several regression equations representing the relationships between physiological responses, particularly skin wettedness, and subjective responses under warm and hot conditions. The common scales for assessing thermal environments are the seven-point scales of Bedford, ASHRAE, and The McGinnis Thermal Scale. Morris et al. (1985) used three subjective evaluation scales to study the relationships of moisture transport properties of warmup-suit fabrics to comfort.

Asmussen (1967) described the exercise state as a second experimental standard, the first being the resting state, in comfort studies of wearing chemical protective clothing

(Gagge, Stolwijk, & Saltin, 1969). Different work rates have been used to simulate the actual work in the field. For example, Branson, DeJonge, and Munson (1986) used a three-met work rate to simulate the amount of work performed in applying pesticides by tractor and air-blast sprayer.

Although most comfort studies have used full garments, some studies (Hatch et al., 1987; Wester et al., 1986; Wilson & Dallas, 1990; Hyun et al., 1990) have used garment parts. Zimmerer et al. reported that the volar forearm skin was a reliable site on adult subjects. The effectiveness of using garment parts in previous clothing comfort studies suggests the idea of studying thermal comfort by using only portions of garments.

CHAPTER III

SETTING OF THE PROBLEM

Conceptual Framework

In warm and hot environments, when the amount of heat gain exceeds that of heat loss, the body's heat load increases, resulting in thermal discomfort and heat stress. The American Society of Heating, Refrigeration and Engineering (1981) defined thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (p. 8.19). The Environmental Protection Agency (1993) defined heat stress as "the buildup in the body of heat generated by the muscles during work and of heat coming from warm and hot environments" (p.1). Kerslake (1972) defined heat strain as a consequence of heat stress, indicated by physiological responses of the subject.

Wearing a chemical protective suit with poor heat dissipation characteristics, while working in a hot environment, can easily cause thermal discomfort and heat strain in workers because heat built up in the body (active tissues or organs) cannot be transferred effectively to the outside environment. Figure 3 describes the development of heat load in the body and the responses of the body to the increased heat load, under conditions of exercising in a hot environment and wearing a protective garment, e.g., a coverall, which inhibits heat flow.

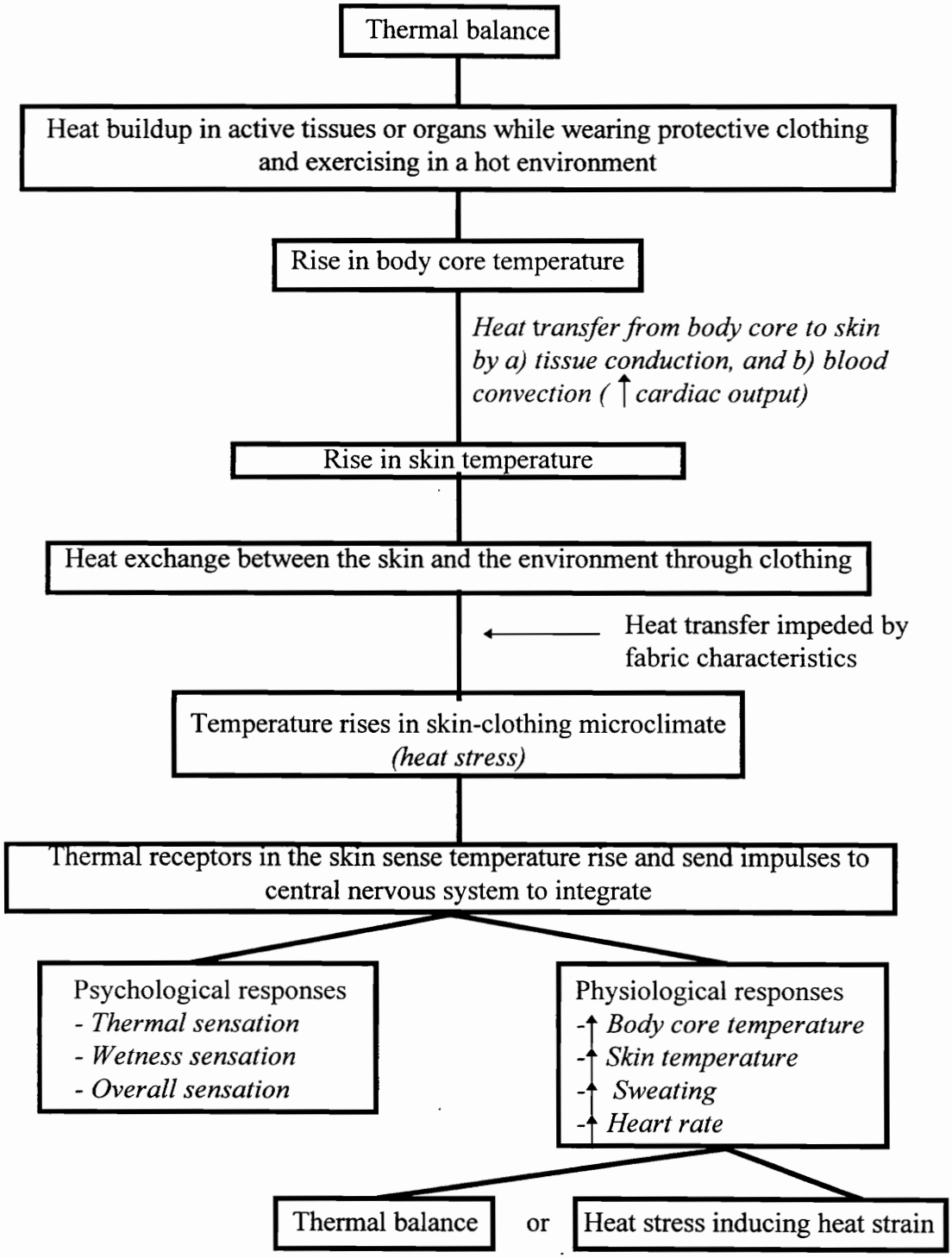

Figure 3. Development of heat load in the body and the responses of the body to the heat load, while wearing protective clothing and exercising in a hot environment.

The response of the body to heat load when regular clothing is worn with a protective sleeve on only one arm is similar to that when a full protective garment is worn. Of course, in the protective-sleeve-only case, heat transfer is impeded mostly on arm as compared to other body sites. In this case, as in the full-garment case, thermal receptors under the skin will detect the increased microclimate temperature and then send the impulses to the central nervous system, causing the body to respond by increasing skin temperature and sweat amount.

Conceptual Definitions

Thermal balance: a state of the body in which there is no excess heat storage in tissues, and the amount of heat stored in the body equals the amount of heat released from the body (Parsons, 1993).

Thermal comfort: "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 1981, p.8.19).

Heat stress (or Thermal imbalance): "the buildup in the body of heat generated by the muscles during work and of heat coming from warm and hot environments" (EPA, 1993, p.1), or an environment, including clothing, that induces heat strain in humans (Kerslake, 1972).

Heat strain: a consequence of thermal stress, indicated by the physiological responses of the subject (Kerslake, 1972).

Heat load: an increased amount of heat gained in the body due to either increased metabolic rate or increased ambient temperature.

Chemical protective clothing: garments worn to prevent contact of pesticides or other chemicals with the body.

Perceptual measurement of thermal comfort and heat strain: a measurement means in which subjects evaluate their thermal comfort and thermal strain by expressing their thermal perception via subjective evaluation scales.

Physiological assessment of thermal comfort and heat strain: a measurement means using a person's physiological responses (e.g., heart rate, body temperature, skin temperature, sweat amount) to heat load, as indicators of thermal discomfort and heat strain.

Microclimate: the environment between the skin and clothing (Hollies, 1977).

Heart rate (beats/min.): a number expressing the cyclic contraction and relaxation of the heart per unit time.

Body core temperature: the temperature of the inner body, or the vital organs (Parsons, 1993); normally, the temperature is 37°C (98.6°F).

Skin temperature: the temperature of the outer tissues of the body, varying with the external environment and the thermoregulation of the body (Parsons, 1993).

Sweat: liquid produced and secreted by the sweat glands through the skin.

Purpose Statement and Specific Objectives.

The purpose of this research was to explore the feasibility of using sleeves, instead of full garments, in wear tests to assess the thermal comfort and thermal strain associated with chemical protective garments. The thermal comfort and thermal strain in wearing sleeves of the same style, but made of three different fabric types, on a standard garment, were investigated by both perceptual and physiological measurements taken while subjects exercised. Perceptual measurement was accomplished using subjective evaluation scales developed by Morris et al. (1985). Physiological measures in this study are skin temperature and sweat amount.

Objectives of this research were:

1) to determine the difference between body sites, i.e., upper arms and chest, on measured skin temperature and sweat amount while subjects were wearing a standard garment consisting either of T-shirt and pants or of a Tyvek® coverall over the T-shirt and pants.

2) to investigate the effects of three different fabric types, as used in chemical protective sleeves, on the skin temperature, sweat amount, and subjective comfort evaluation measured while subjects were wearing the T-shirt/pants standard garment, or the Tyvek®-coverall standard garment over the T-shirt and pants.

3) to compare the results of skin temperature and sweat amount obtained in this study with those obtained in the companion study[2], described in Appendix A, that used the same fabrics and experimental design but used full garments.

Research Hypotheses

The following research hypotheses were generated based on empirical results in previous research and on the conceptual framework. The hypotheses all involve variables other than the environmental conditions of the room in which the subjects exercised during the experimental trials; that is, the room had standard settings for temperature and humidities, as described in the previous chapter.

Hypotheses for objective 1.

H1: At any given time interval during exercise, when a standard garment consisting either of T-shirt and pants or of a Tyvek® coverall over the T-shirt and pants, skin temperature will not differ between the right and the left arms, but will differ between the arms and the chest.

H2: While wearing a standard garment consisting either of T-shirt and pants or of a Tyvek® coverall over the T-shirt and pants, sweat amount collected from the beginning

[2] The term "companion study" in this research refers to Hennessey's (1997) study which investigated the effect of five different fabrics, used in chemical protective clothing, on thermal comfort and thermal stress. To compare the results, this current study uses the same test fabrics and experimental protocol as Hennessey, but experimental fabrics are assembled in sleeves rather than coveralls.

to the end of the exercise will not differ between the right and the left arms, but will differ between the arms and the chest.

Rationale:

The temperature distribution and sweat amount over an area of the body depend on the localized thermal and moisture balances. Because the right and left arms are symmetrical, when they are exposed to the same conditions, heat and moisture balances on both arms should be the same. That is, under a given condition at a given time, the arms should have the same skin temperature and sweat amount, and therefore, either arm can be used as a test site for an experimental sleeve.

Under a particular condition at a given time, differences in skin temperature and sweat amount of the arms vs. the chest should be observed. The reason is that the arms and the chest have distinct anatomical structures, and, also, have different distribution patterns of thermal receptors and sweat glands which contribute directly to skin temperature and sweating.

Hypotheses for objective 2.

H3: At any given time interval during exercise, when the T-shirt/pants standard garment is worn, skin temperatures (on the left arm) will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

H4: At any given time interval during exercise, when the Tyvek®-coverall standard garment is worn over the T-shirt and pants, skin temperatures (on the left arm) will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

H5: When the T-shirt/pants standard garment is worn, sweat amount (collected on the left arm from the beginning to the end of the exercise) will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

H6: When the Tyvek®-coverall standard garment is worn over the T-shirt and pants, sweat amount (collected on the left arm from the beginning to the end of the exercise) will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

H7: When the T-shirt/pants standard garment is worn, subjects' wetness-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

H8: When the Tyvek®-coverall standard garment is worn over the T-shirt and pants, subjects' wetness-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

H9: When the T-shirt/pants standard garment is worn, subjects' thermal-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

H10: When the Tyvek®-coverall standard garment is worn over the T-shirt and pants, subjects' thermal-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

H11: When the T-shirt/pants standard garment is worn, subjects' overall comfort-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

H12: When the Tyvek®-coverall standard garment is worn over the T-shirt and pants, subjects' overall comfort-sensation ratings called out by subjects during exercise will be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

Rationale:

Fourt and Hollies (1970) noted that, in hot environments, the body loses heat mainly by evaporation which is usually accompanied by sweating. Preliminary tests on the experimental fabrics in this research indicate that Tyvek® and Pro/Shield II® have the

same amount of moisture vapor transmission and the same wickability. Pro/Shield I®, on the other hand, transfers moisture vapor about 1.5 times faster than either of those two, and also has better wickability. Therefore, in the tests with subjects, Pro/Shield I® should transfer a greater amount of heat than would Tyvek® and Pro/Shield II®, and should give results consistent with lower heat load in the subjects than would either of those two fabrics. When subjects wear only a T-shirt and pants without any experimental sleeve, heat can transfer more freely from the body to the outside environment on both arms. Thus, skin temperature and sweat amount when wearing a T-shirt and pants only should be the lowest, as compared to the other cases.

Hypotheses for objective 3.

H13: For any given time interval, the experimental fabric order, with respect to skin temperature measured in the current study while subjects exercised in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants, will be the same as the order regarding skin temperature observed by Hennessey (1997).

H14: The experimental fabric order, with respect to sweat amount collected in the current study from the beginning to the end of the exercise in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants, will be the same as the fabric order regarding sweat amount observed by Hennessey (1997).

Rationale:

Based upon the literature review, some studies in clothing comfort used garment parts, particularly in arm areas, instead of full garments to assess comfort. Zimmerer, Lawson, and Calvert (1986) noted the reliability of arms as test sites for skin sensation assessment. Hyun, Hollies and Spivak (1990) showed the usefulness of using sleeves in perceptual measurement of clothing comfort. Due to the effectiveness of using arms for perceptual assessment of clothing comfort in those and other previous studies, it was expected that arms with protective sleeves would yield the same rank order of responses to heat load as would the trunk with a full protective garment, when environment and work rate are controlled.

Parsons (1993) maintained that, although subjective methods are easy to use to collect data on psychological responses, they should not be used as primary measures of thermal strain. In severe conditions, the ability of a person to make a rational judgment may be impaired. Therefore, sweat amount and skin temperature were chosen over subjective evaluation scales as the parameters to compare results of the current study with results of Hennessey (1997).

Research Assumptions

The following assumptions were made in conducting the research.

1) The same minimum level of physical fitness across the research subjects resulted from the subjects' selection through screening with the health questionnaire.

2) There is no significant variation among the subjects in the estimated work rates obtained from the PWC test on each.

3) Loss of sweat due to evaporation through a sweat patch is negligible.

4) Amount of sweat at rest is minimal and can be ignored.

5) Because all trials are performed in an environmentally controlled room, there are no extraneous variables due to the environmental conditions.

6) Machine and operator errors are of a random nature, and all instruments used for this research yield accurate and consistent results.

7) Fabrics used in this research are consistent through the lot with respect to physical properties, and any variations in these properties that may exist in the fabrics are of random occurrence.

Research Limitations

1) With the aim of minimizing experimental risks, the physical work capacity test (PWC) is used, instead of the maximal test, to assess maximal oxygen consumption of subjects for estimating work rate at 40% of maximal oxygen consumption (VO_2max).

2) Subjects are only in the age range of 18 and 28 years.

3) The number of trials performed by each subject per day is limited to one to prevent exhaustion and heat disorder of subjects.

4) The results are not generalizable to other garment parts beyond the sleeve, which is the part used in this research.

CHAPTER IV

EXPERIMENTAL METHODS

This study examined the feasibility of using experimental sleeves, instead of full garments, for assessing research subjects' thermal comfort and heat strain associated with wearing chemical protective garments. In order to test the feasibility of using sleeves in thermal comfort assessment, some results obtained from this study were compared with results obtained from Hennessey's (1997) study; Hennessey used the same experimental protocol and the same test fabrics, but experimental fabrics were assembled in coveralls rather than sleeves only.

Ten male subjects were selected through a health questionnaire to participate in a total of seven trials each. In each trial, the subject was randomly assigned to put on a standard garment, with or without an experimental sleeve on the left arm, before entering the environmentally controlled room (86°F, 60%RH). Once in the room, the subject rested for 30 minutes and then pedaled on a stationary bicycle for 45 minutes at the intensity of about 40% of his maximal oxygen consumption determined by the physical work capacity test. Heart rate, skin temperature, body temperature, the rating of perceived comfort, and the rating of perceived exertion were taken every five minutes throughout each exercise session. Sweat amount was determined at the end of the session. Heart rate, body temperature, and rating of perceived exertion served as safeguards to prevent

subjects from exhaustion. Data were analyzed by repeated measures design and by randomized complete block design.

The contents of this chapter include details on subjects, the test environment, fabrics and test specimens, experimental trials and garments worn in each trial, experimental procedure, and data analysis.

Subjects

Male students at Virginia Polytechnic Institute and State University were recruited as volunteers to participate in the study. The reasons for using only male subjects were a) reduction of extraneous variables, or elimination of variations, due to sex-related difference in physiological factors and in physical performance; and b) males are the major users of chemical protective clothing. The first contact with the volunteers was made by posting flyers around campus. Initial criteria for selecting subjects were the following ranges of age, height, and weight, respectively: 18-28 years, 67-70 inches, and 150-180 pounds.

The volunteers were screened for health issues using the questionnaire shown in Appendix B, which was developed from the Physical Activity Readiness Questionnaire (PAR-Q) (Powers & Howley, 1994). Subject selection from the health screening required that a) the individual answer "Yes" to questions 1-4 and "No" to questions 6-14; and b) his answer to question 5 include no signs or symptoms of heat illness, or heart or lung disease.

One week prior to the beginning of the experiment, the subjects were given an explanation of the experiment before giving their written informed consent(Appendix C). They were oriented to the equipment and the procedures used in the experiment. At each visit, of a total of eight trials per subject including the physical work capacity test, the subjects signed the informed consent form.

Table 2 summarizes the anthropometric data, age and nationality, and work rates of the test subjects.

Environment

The experiment was conducted, from June to August 1996, in the environmentally controlled laboratory in the Department of Clothing and Textiles at Virginia Tech. To enable comparison with the results of Hennessey's (1997) study, the test environment was set at 86°F, the average daily maximal temperature in Roanoke, Virginia (NOAA, 1990-1992), and 60% relative humidity (RH), the average humidity at 1:00 p.m. eastern standard time in Roanoke (NOAA, 1990-1992). The conditions of this room were controlled from the Physical Plant of Virginia Tech. A portable temperature and humidity recorder was used to measure and record the conditions.

Equipment

The Pocket-Polygraph™ Vitalog HMS-5000 (Vitalog Respironics Inc., Redwood, CA), a physiological monitoring and actuating system, was used for measuring and

Table 2

Anthropometric data, age and nationality, and work rates for test subjects

Subject	Age (years)	Height (inches)	Weight (lbs)	Nationality	Work rate (watts)
1	24	70.00	172	African-American	80
2	28	67.25	160	Thai	75
3	20	67.25	158	Japanese	80
4	19	71.25	180	Thai	84
5	23	70.50	160	Thai	73
6	23	67.25	159	Thai	65
7	26	70.00	168	Thai	64
8	25	67.00	159	Korean	64
9	27	67.00	174	Thai	63
10	27	67.00	157	Thai	62

recording subjects' skin temperature and heart rate. Body temperature was measured by a Flexible™ oral, digital thermometer (Becton Dickinson and Company, Frankin Lakes, NJ).

Schwinn™ Airdyne Windsprint (Schwinn, Boulder, CO), a stationary ergometer, served as the exercise tool. The pedaling resistance could be adjusted in three levels. Powers, or work rates, shown on the panel were expressed in both watts and kilopond-meter/minute (kpm/min.). The rider's cadence of pedaling also was shown on the panel. A metronome was employed to provide a pedaling cadence which resulted in each subject's target work rate in the experimental trails.

The sweat patch used in the experiment was assembled with three layers: a nonadhering dressing (Tegaderm™, 3M Health Care, St. Paul, MN) made of polyurethane and acrylate adhesives; a release liner of Saran Wrap® polyvinylidene chloride film; and a sweat collection pad, a medical grade cellulose blotter (Hermitage™ Poly Pads by Hermitage Hospital, Niantic, CT). The collection pads and the Saran Wrap were cut into squares of 2.5 cm^2 (one-inch square). Figure 4 is a diagram of the sweat patch, showing the Saran Wrap release liner between the dressing and the collection pad placed directly next to the skin.

The subjective evaluation scales developed by Morris et al. (1985), and the rating scale of perceived exertion, or RPE, (six-to-twenty scale), as shown in Tables 3 and 4, were employed to assess subjects' perceptions. The scales were magnified on a chart so

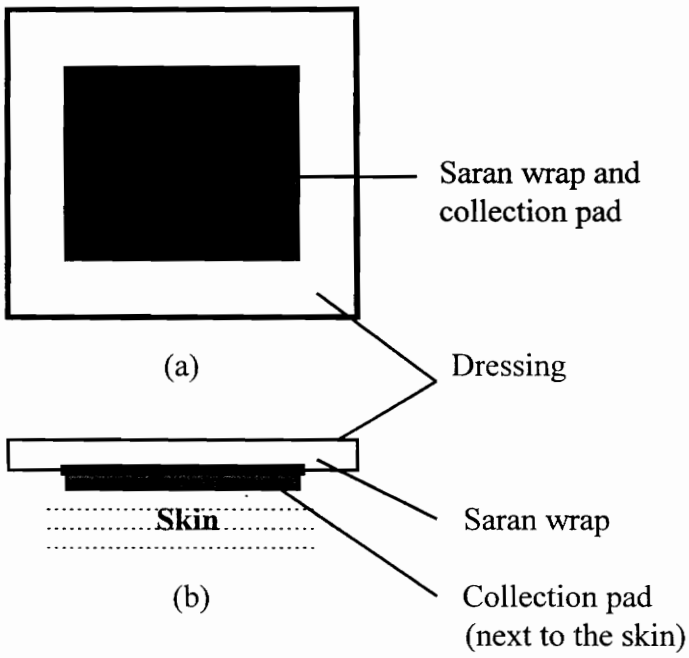

Figure 4. Schematic representation of a sweat patch from (a) bottom view, and (b) side view.

Table 3

Subjective evaluation scales[3]

Wetness sensation scale	Thermal sensation scale	Comfort sensation scale
1. Dry	1. Very Cold	1. Comfortable
2.	2. Cold	2.
3. Slightly Wet	3. Cool	3. Slightly Uncomfortable
4.	4. Slightly Cool	4.
5. Moderately Wet	5. Neutral	5.Moderately Uncomfortable
6.	6. Slightly Warm	6.
7. Very Wet	7. Warm	7. Very Uncomfortable
	8. Hot	
	9. Very Hot	

[3]M. A. Morris, H. H. Prato, S. L. Chadwick, and E. M. Bernauer, "Comfort of warm-up suits during exercise as related to moisture transport properties of fabrics," 1985, Home Economics Research Journal, 14, p.165. Copyright © 1985 by Sage Publications. Reprinted by permission of Sage Publications.

Table 4

Borg's rating of perceived exertion[4], RPE (six-to-twenty scale)

6	
7	Very, Very Light
8	
9	Very Light
10	
11	Fairly Light
12	
13	Somewhat Hard
14	
15	Hard
16	
17	Very Hard
18	
19	Very, Very Hard
20	

[4] From "Psychological bases of physical exertion," by G. A. V. Borg, 1982, Medicine Science in Sports and Exercise, 14, p.377-381. Copyright © 1982 by Williams and Wilkins. Reprinted by permission of Williams and Wilkins. This scale is Borg's original rating scale of perceived exertion, where the rankings 6-20 approximate the heart rate values from rest to maximum (60-200 beats/min.). Besides serving as good indicators of subjective effort, the RPE are helpful in knowing when a subject is approaching exhaustion and in prescribing exercise intensity.

that subjects could see and call out the numbers corresponding to their perceptions while they pedaled.

Fabrics and Test Specimens

Two types of standard garments were used in this study. Standard garment No.1 (SG1) was composed of a 100% cotton, white short-sleeved T-shirt (Fruit of the Loom®) and a pair of 100% cotton, khakis work pants (Duxbak®). The pants were long, somewhat tapered in the legs, and described on the label as anti-wrinkle. Standard garment No.2 (SG2) consisted of SG1 and a Tyvek® coverall, as the coverall was worn over SG1. Tyvek® (DuPont, Fabric Style 1422A), a spunbonded fabric, is made of sub-micron denier, high-density polyethylene filaments that are bonded with heat and pressure. This fabric is widely used for chemical protective purposes in both practical applications and research.

The study included two additional chemical protective fabrics, Pro/Shield I® and Pro/Shield II® (both from Kappler Safety Group, Guntersville, AL), which were made into experimental sleeves of the same pattern as the sleeves in the Tyvek® coverall. Pro/Shield I® is a thermally bonded tri-laminate fabric consisting of a middle layer of meltblown polypropylene sandwiched between two outer layers of spunbonded polypropylene. Pro/Shield II® is a bi-laminate of spunbonded polypropylene and microporous polypropylene film. Pro/Shield I® and Pro/Shield II® were selected for this research because the manufacturer (Kappler Safety Group) described them as permeable

to water vapor, but impervious to water-based liquids; these two fabrics also have a slightly hairy surface texture which is less like paper than is Tyvek®. Table 5 shows physical characteristics of the test fabrics of the fabrics in the T-shirt and pants.

Figure 5 illustrates standard garments No.1 and No. 2, and an experimental sleeve on the standard garments. Before initiating the experiment, standard garment No.1 (T-shirt and pants) as well as provided socks, were laundered five times according to AATCC Test Method 143, with AATCC Standard Reference Detergent 124, to eliminate shrinkage and appearance problems. The pants were reused throughout the experiment, whereas new T-shirts and socks were provided and used for each trial. The reason for not reusing T-shirts and socks was due to their shrinkage problem which affected heat and moisture transfer.

Standard garment No.2, as shown in Figure 5, was a coverall with a zipper up the front. The coverall had been designed to fit closely at the wrists and ankles by elastic, for increased protection against penetration of pesticides. For purposes of this research, the coverall's left sleeve was made detachable, so experimental sleeves could be attached in its place. The detachability allowed the reuse of standard garment No.2, with alternating experimental sleeves, in the trials to assess comfort and heat stress.

An experimental sleeve, made of Tyvek® or Pro/Shield I® or Pro/Shield II® and having an elasticized wrist, was attached to the left armscye of standard garment No.1 or

Table 5

Physical characteristics of test fabrics (at 70°F, 65% RH, after conditioning for ≥24 hours)

Test fabrics	Weight[1] (g/m^2)	Thickness[2] (cm)	Moisture vapor transmission[3] ($g/m^2/24$ hrs)	Capillary retention[4] (g)	Capillary transmission[4] (g)	Capillary		
						retention[5] in T-shirt fabric (g)	retention[5] into test fabric (g)	transmission[5] through test fabric (g)
Tyvek®	41.05	0.0164	841.40	0.0004	0.0006	0.4322	0.0005	0.0061
Pro/Shield I®	64.17	0.0559	1346.23	0.0007	0.0011	0.4261	0.0000	0.0081
Pro/Shield II®	64.14	0.0583	841.40	0.0005	0.0000	0.4239	0.0003	0.0063
Jersey knit	168.18	0.0868	2013.35	0.3457	0.0985	-	-	-
Duck	964.08	0.0875	842.89	0.3633	0.0954	-	-	-

[1] Measured according to ASTM D3776-85 method.
[2] Measured according to ASTM D1777-64 (1975) method.
[3] Measured according to ASTM E96-95 (Procedure D) method.
[4] Tested according to the method used by Sarin (1994). 0.5 ml of an artificial perspiration solution was pipetted onto the inner side of the test fabric to simulate how sweat from the body comes into contact with clothing. Retention is that amount of the 0.5-ml solution held within the fabric structure after 10 minutes. Transmission is that amount of the 0.5 ml solution which moved through the fabric and was absorbed by the blotter underneath.
[5] Tested according to the method used by Sarin (1994). 0.5 ml of an artificial perspiration solution was pipetted onto the inner side of the jersey T-shirt fabric when layered with the test fabric to simulate how sweat from the body comes into contact with clothing. Retention is that amount of the 0.5-ml solution held within the fabric structure after 10 minutes. Transmission is that amount of the 0.5-ml solution which moved through the fabric and was absorbed by the blotter underneath.

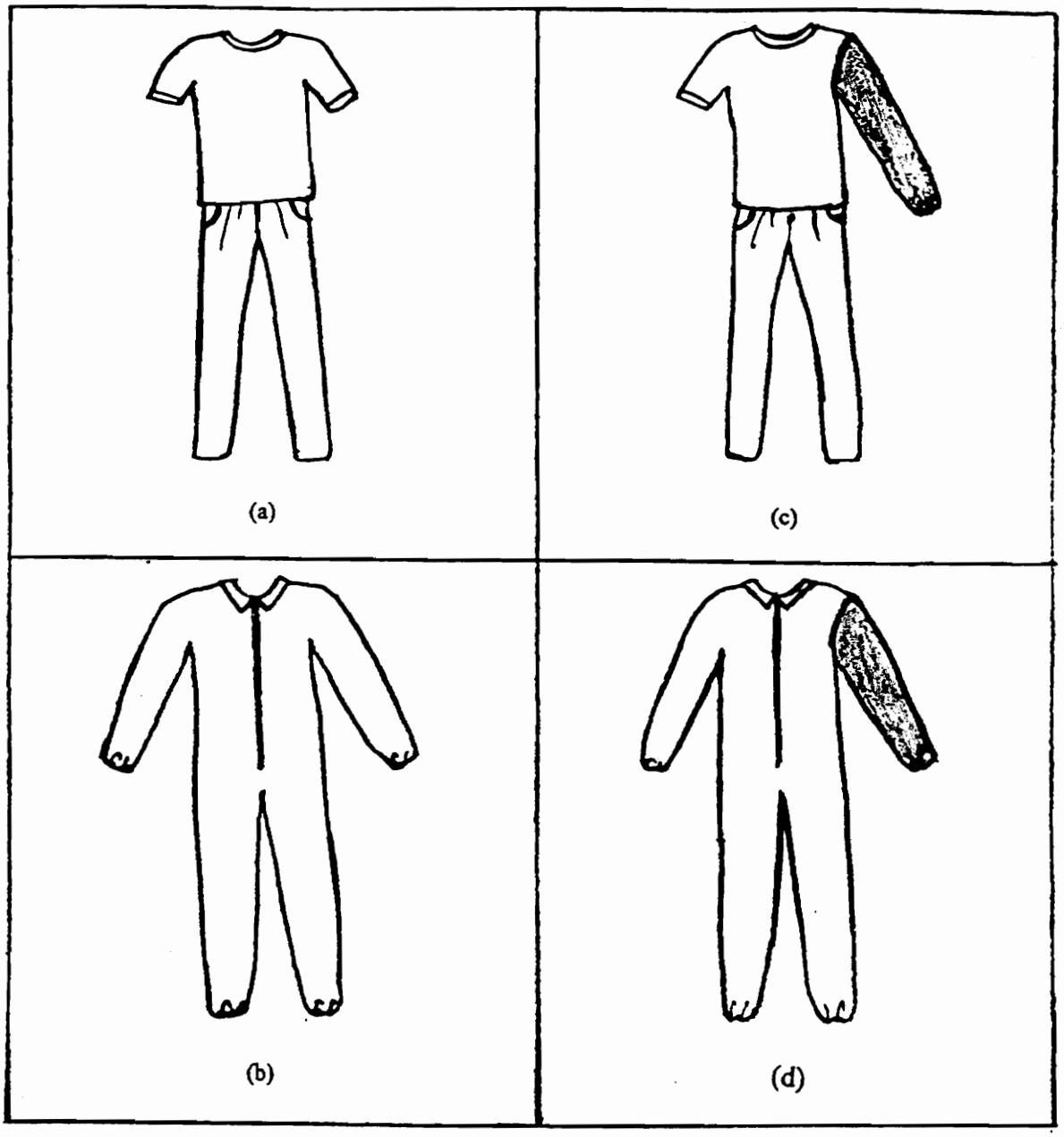

Figure 5. Schematic representation of standard garment No.1 (a), standard garment No.2 (b), standard garment No. 1 with an experimental sleeve on the left arm (c), and standard garment No.2 with an experimental sleeve on the left arm (d).

No.2 with duck tape[5] of half-inch width. Standard garment No.2 was prepared for the trials by reinforcing its left armhole all the way around with a layer of duck tape to prevent tearing of the Tyvek® fabric due to repeated attachment and detachment of the experimental sleeves. Moreover, to minimize extraneous effects of the tape, two layers of duck tape were also applied on the right armscye of that garment. Likewise, standard garment No.1 was taped with two layers of duck tape around the right armscye as well as the left armscye, with or without an experimental sleeve over the T-shirt sleeve.

Experimental Trials and Garments Worn in Each Trial

Each subject performed a total of 8 trials: a trial of the physical work capacity test and 7 subsequent trials of the main experiment. In each trial, including the physical work capacity test, the subject wore his own underpants and sneakers, together with provided socks and the assigned garments. In the physical work capacity test, a subject also wore standard garment No.1 (SG1) consisting of a pair of pants and a T-shirt without duck tape around the armholes.

[5] The researcher investigated the best way to attach (and detach) an experimental sleeve to (from) the standard garments by experimenting with duck tape, velcro, and sewing. As a consequence of repeated sewing and unsewing, the armhole seam of a Tyvek® coverall ripped. Using velcro caused some gaps in the connection, which could affect heat and moisture transfer from the body. As compared to a velcro-attached sleeve, subjects felt more comfortable with a duck tape-attached sleeve. Moreover, in places where Tyvek® suits are used, workers usually use duck tape to attach things to their suits or to cover tears on the suits.

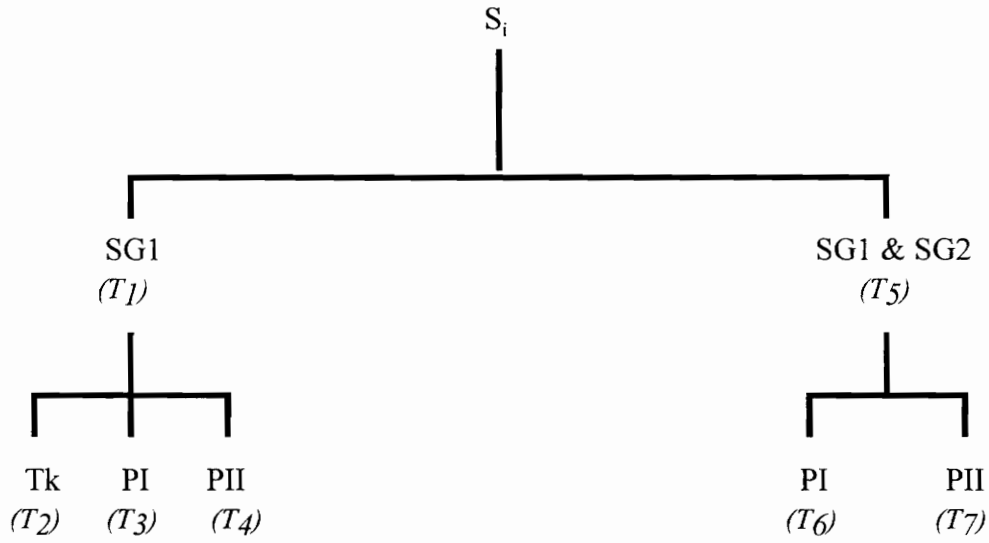

Figure 6. Schematic representation of the distribution of experimental trials *(T_j)* and garments worn in each trial for each subject (S_i). SG1 stands for Standard Garment 1, consisting of a T-shirt and pair of pants. SG2 is Standard Garment 2, a Tyvek® coverall. Tk, PI, and PII stand for the experimental left sleeves of Tyvek®, Pro/Shield I®, and Pro/Shield II®, respectively.

In the main experiment, as shown in Figure 6, each subject participated in 7 trials. All garments used in the trials had duck tape as described in the previous section. In trial 1, the subject wore SG1 without an experimental sleeve. In trials 2-4, the subject wore SG1 together with a sleeve of an experimental fabric (Tk, PI, or PII) over the left sleeve of the T-shirt. In trials 5-7, the subject wore SG2 over SG1 (SG1 served as an undergarment). The subject wore SG1 and SG2, with both of the original Tyvek® sleeves of SG2, to perform trial 5. In trials 6 and 7, a sleeve of PI or of PII replaced the left sleeve of SG2.

Experimental Procedure

After each subject's orientation, he was scheduled for the physical work capacity (PWC_{170}) test. The PWC_{170} measures the maximal oxygen intake, an indicator of physical fitness. Each subject was asked to perform steady-state exercise at increasing work rates, until a target heart rate was reached. A rate of 170 beats/min. is considered a normal target rate for the freshman-to-junior, male or female, college population (Powers & Howley, 1994). The "PWC_{170} test" refers to a physical work capacity test in which the target heart rate is about 170 beats/min. After a subject completed the PWC test, he was scheduled for the seven main trials.

The physical work capacity test (PWC). The physical work capacity test, at a target heart rate of 170 beats/min., was used to determine work capacity at the intensity of about 40% of a subject's maximal oxygen consumption. To perform this test, a subject

wore a provided T-shirt and pair of pants and socks plus his own sneakers. He was prepared for heart rate monitoring by adhering, to his chest, three electrocardiogram (ECG) leads connected to the Vitalog before entering the environmentally controlled room. Heart rate was recorded every minute from the beginning of the rest period to the end of the test. In the room, the subject rested on the bicycle for 10 minutes and then pedaled, without pedaling resistance, to warm up for two minutes. Then, the subject pedaled at 150 kilopond-meter/minute (kpm/min.), or 24.45 watts, for three minutes. The work rate was controlled by pedaling speed (revolutions per minute, or rpm) and pedaling resistance levels. At the end of the third minute, the YMCA cycle ergometer protocol (Appendix D) was applied to select work rates for submaximal exercise. If the heart rate in the third minute was:

- less than 80, the second work load would be 750 kpm/min. or 122.25 watts;
- 80-89, the second work load would be 600 kpm/min. or 97.80 watts;
- 90-100, the second work load would be 450 kpm/min. or 73.35 watts;
- greater than 100, the second work load would be 300 kpm/min. or 48.90watts.

The second stage lasted six minutes. The third and the fourth work loads for any one subject were set according to the loads below his second load, and each stage took six minutes. The exercise was terminated when the subjects' heart rate was around 170 beats/min. Every three minutes during the exercise, the investigator asked the subject to call out ratings of perceived exertion. The work rates recorded from the panel of the bicycle and the averaged heart rates of the last two minutes of each stage were used to

plot, for each subject, a graph of work rate (X-axis) vs. heart rate (Y-axis). A line of best fit for the relationship between work rate and heart rate was drawn. The work rate that corresponded to a heart rate of 40% of the predicted heart rate range served as the work rate at about 40% of the maximal oxygen consumption (VO_2max). The heart rate range was the difference between the predicted maximal heart rate and the heart rate at rest. The maximal heart rate was predicted by the following formula:

$$Hrmax = 220 \text{ beats/min.} - \text{subject's age},$$

whereas the averaged heart rate of the last two minutes at rest was used as the heart rate at rest.

The criteria for removal of a subject from the chamber during the test were (a) heart rate of (220 - his age) beats/min, (b) nausea, vomiting, or disorientation, or (c) request by the subject. No subject was removed during the test, as none of these criteria were met.

Experiment. Subjects were instructed not to take alcohol, medication, or other drugs for a 12-hour period preceding the experiment. The night before a subject's test, he was phoned to remind him of these instructions, his scheduled appointment time, and the importance of at least a six-hour sleep. Subjects were asked not to eat or drink anything except water one hour before their scheduled tests.

Upon arrival on a scheduled date, a subject changed into a short-sleeved T-shirt, a pair of pants, socks, and sneakers. The investigator provided all those garments except the sneakers. The investigator separately preweighed three non-reusable sweat collection

pads, in the environmentally-controlled room in which the pads had equilibrated, and recorded their weights. Three temperature sensors and three ECG leads were connected to the Vitalog monitor. The subject was prepared for heart rate and skin temperature monitoring as well as sweat collection. Figure 7 illustrates the sites of the ECG leads on a subject's trunk and of the sweat patches and temperature sensors on the subject's chest and arms. The investigator used alcohol swabs to clean the subject's skin surface at those sites, and allowed the skin to dry thoroughly before attaching the ECG leads, temperature sensors, and sweat patches. To collect sweat, the sweat collection pad was placed next to the skin, while the dressing served as an outer layer.

Then, if required for a particular trial, the subject put on an additional sleeve or garment assigned to him for that trial. The order of treatments, or sleeves/garments, was randomized within each subject. Before entering the environmentally controlled room, the subject was weighed.

Once in the environmentally controlled room, the subject was seated on a chair for a 30-minute acclimatization. During this period, the subject could drink up to 16 oz. of water. After acclimatization, the subject started pedaling on the bicycle without resistance for a two-minute warm-up. After the two-minute warm-up, the subject pedaled for 45 minutes at the work rate obtained from the previous PWC_{170} test. Two-minute cool-down was provided after the exercise. Seven measurements were taken every five minutes during the acclimatization and the exercise, and after the cool-down. The seven measurements were: heart rate and skin temperature (both by the

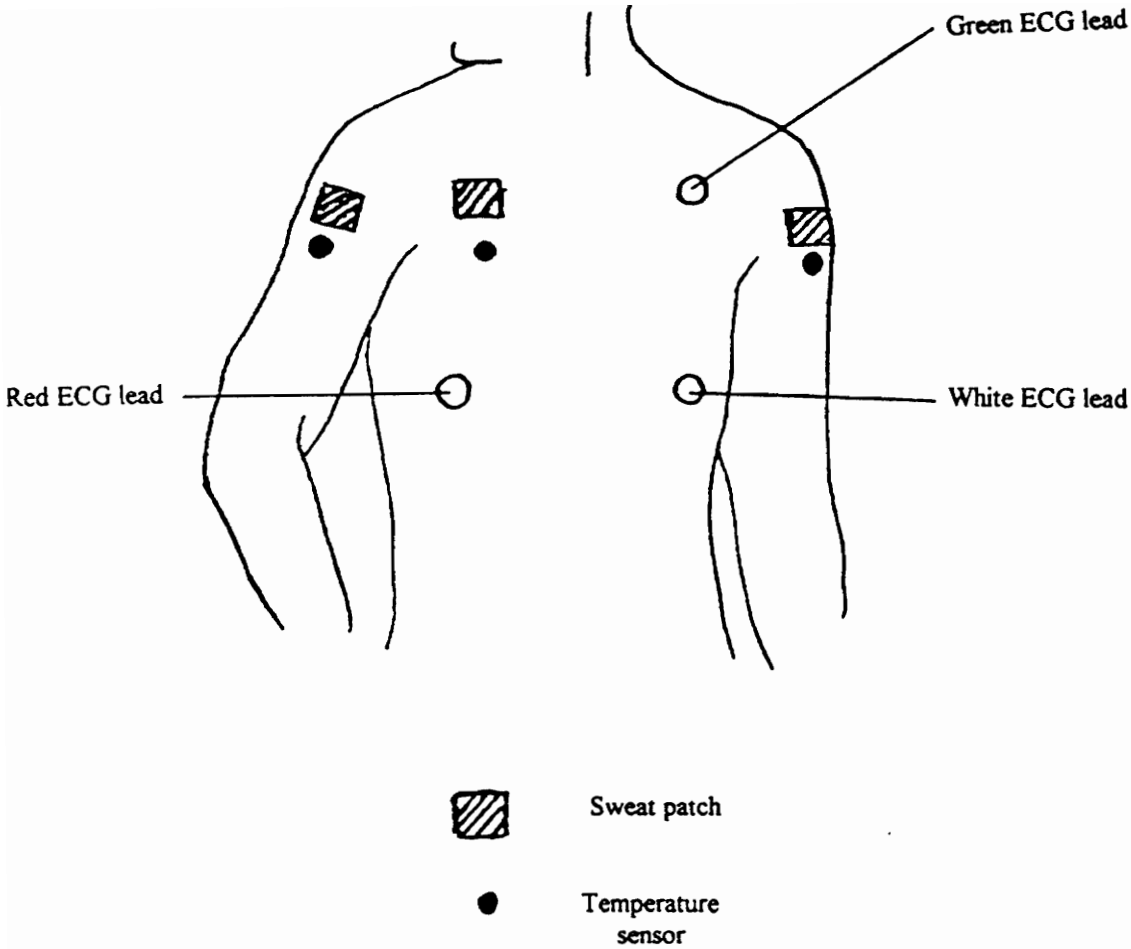

Figure 7. Schematic representation of positions of ECG leads, temperature sensors, and sweat patches on the subject.

Vitalog); body temperature (by an oral, digital thermometer); the subject's called-out ratings of his wetness, thermal, and comfort sensations (using the Morris et al. (1985) scale); and the subject's called-out ratings of perceived exertion (using Borg's six-to-twenty scale). Heart rate, skin temperature and body temperature were recorded simultaneously, and the sensory ratings were taken within 15 seconds of those three measurements. Once again, heart rate, body temperature, and rating of perceived exertion served as safeguards. To determine sweat amount, at the end of the cool-down, each of the sweat collection pads was removed from the subject's body by forceps and then weighed immediately in the environmentally-controlled room to avoid evaporation of the sweat. Sweat amount, after the cool-down following the 45-minute exercise, was the difference of the pre-weight and the final weight of the sweat in milligrams (mg) divided by the area of the pad (cm^2).

The subject was removed from the environmental room to an unconditioned room and weighed again. Then, the subject changed to his own clothes and was given 16 oz. of water for every pound of weight loss to prevent dehydration. Thirty-minute recovery was provided to observe signs of distress before the subject was released.

The criteria for removing a subject from the chamber during the test were (a) heart beat of (220 - his own age) beats/min, (b) body temperature of 102.2°F, (c) rating of perceived exertion of 17, (d) nausea, vomiting, or disorientation, or (e) request by the subject. No subjects were removed during the test, as none of these criteria were met.

Data Analysis

To test hypotheses 1-12, statistical analysis was performed using software of the SAS Institute. The data analysis for the research hypotheses 1-12 employed the repeated measures design, a type of analysis of variance, with within-subject variables and with every subject serving in every cell. Each subject served as an experimental unit on which each independent variable was measured repeatedly. The analysis was accomplished by the ANOVA statement to set the error sum of square equal to zero. The error term of each effect was the error of the interaction between the effect and subject. In the statistical analysis, the significance level of $p \leq 0.05$ was set for rejecting any of the null hypotheses of no difference between means in the variable of interest. When such a null hypothesis was rejected, post hoc analysis ensued by the Fisher's Least Significant Difference (LSD) test to elucidate which of the means in the relevant variable differed significantly. Hypotheses 13 and 14, on the relation between results in this research and in Hennessey's (1997) research, did not lend themselves to statistical testing. Graphical and numeric comparison was the approach taken. Details follow on data analysis procedures specific to individual hypotheses.

Hypotheses 1, 3, and 4. To test hypotheses 1, 3 and 4, the repeated measures design with three within-subject variables was applied.

- *Dependent variable.* The dependent variable, common to the testing of these three hypotheses, was skin temperature measured every 5 minutes from the beginning to the end of the 45-minute exercise.

- *Independent variables.* The independent variables, all of them within-subject variables, were the following.

a) Seven garment options: SG1; SG1 with Tk sleeve; SG1 with PI sleeve; SG1 with PII sleeve; SG1 & SG2; SG1 & SG2 with PI sleeve; and SG1 & SG2 with PII sleeve.

b) Three body sites: the right and left arms, and the chest, for skin-temperature measurement.

c) 10 five-minute intervals of time from the beginning to the end of the 45-minute exercise.

- *Model.* The following is the model for this repeated measures design, which includes the effects of each independent variable and their interactions.

$$Y_{ijkm} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \pi_m + (\alpha\pi)_{im} + (\beta\pi)_{jm} + (\gamma\pi)_{km} + (\alpha\beta\pi)_{ijm} + (\beta\gamma\pi)_{jkm} + (\alpha\gamma\pi)_{ikm} + (\alpha\beta\gamma\pi)_{ijkm} + \varepsilon_{ijkm},$$

where y_{ijkm} denotes skin-temperature response; μ the overall skin-temperature mean; α_i the effect of the ith garment; β_j the effect of the jth body site; γ_k the effect of the kth time interval; π_m the effect of the mth subject; and ε_{ijkm} the experimental error.

Hypotheses 2, 5 and 6. To test hypotheses 2, 5 and 6, the repeated measures design with two within-subject variables was applied.

- *Dependent variable.* The dependent variable, common to the testing of these three hypotheses, was sweat amount (mg/cm^2), the difference between a sweat collection pad's pre-weight and its weight at the end of the cool-down directly after 45 minutes of cycling.

- *Independent variables.* The two within-subject independent variables were the following.

a) Seven garment options: SG1; SG1 with Tk sleeve; SG1 with PI sleeve; SG1 with PII sleeve; SG1 & SG2; SG1 & SG2 with PI sleeve; SG1 & SG2 with PII sleeve.

b) Three body sites: the right and left arms, and the chest, where sweat was collected.

- *Model.* The following is the model for this repeated measures design, which includes the effects of each independent variable and their interactions.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \pi_k + (\alpha\pi)_{ik} + (\beta\pi)_{jk} + (\alpha\beta\pi)_{ijk} + \varepsilon_{ijk},$$

where y_{ijk} denotes the sweat-amount response; μ the overall sweat amount mean; α_i the effect of the ith garment; β_j the effect of the jth body site; π_k the effect of the kth subject; and ε_{ijk} the experimental error.

Hypotheses 7-12. To test hypotheses 7-12, the repeated measures design with two within- subject variables was applied.

- *Dependent variables.* The dependent variables were the following.

a) For hypotheses 7 and 8, rating of wetness sensation.

b) For hypotheses 9 and 10, rating of thermal sensation.

c) For hypotheses 11 and 12, rating of overall comfort sensation.

- *Independent variables.* The independent variables were the following.

a) Seven garment options: SG1; SG1 with Tk sleeve; SG1 with PI sleeve; SG1 with PII sleeve; SG1 & SG2; SG1 &SG2 with PI sleeve; and SG1 &SG2 with PII sleeve.

b) 10 five-minute intervals of time from the beginning to the end of the 45-minute exercise.

- *Model.* The following is a general model for this repeated measures design, which includes the effects of each independent variable and their interactions.

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \pi_k + (\alpha\pi)_{ik} + (\beta\pi)_{jk} + (\alpha\beta\pi)_{ijk} + \varepsilon_{ijk},$$

where y_{ijk} denotes the ratings of wetness, or thermal, or overall comfort sensation response; μ the overall mean rating of wetness, or thermal, or overall comfort sensations; α_i the effect of the ith garment; β_j the effect of the jth time interval; π_k the effect of the kth subject; and ε_{ijk} the experimental error.

<u>Hypotheses 13 and 14.</u> Histograms were used to facilitate the comparison of the experimental fabrics' rank orders in the current study and in Hennessey's (1997) study. Hypotheses 13 an d14 respectively concern the rank orders on skin temperature and sweat amount.

a) To determine and compare the three experimental fabrics' rank orders on skin temperature, histograms were plotted of skin temperature (X-axis) vs. experimental fabric types, i.e., Tyvek®, Pro/Shield II®, and Pro/Shield I® (Y-axis), at each of four time intervals during exercise: the beginning, 15 minutes, 30 minutes, and 45 minutes. There were two data sets of the skin temperature for each of the four time intervals--the left arm skin temperature data from the current study and the averaged skin temperature data from Hennessey (1997).

b) To determine and compare the three experimental fabrics' rank orders on sweat amount, histograms were plotted of three data sets for each of the three different experimental fabrics, i.e., Tyvek®, Pro/Shield II®, and Pro/Shield I® . The first data set was the averaged sweat amount observed by Hennessey (1997). The other two sets were from the current study; one set from subjects wearing T-shirt and pants as the standard garment, the other from subjects wearing a Tyvek® coverall over the T-shirt and pants.

CHAPTER V

RESULTS AND DISCUSSION

This chapter contains four sections. The first three sections are organized according to the dependent variables as in the following order: skin temperature, sweat amount, and the subjective comfort evaluations by the subjects. The last section focuses on the comparison between the current study's results and Hennessey's (1997) results.

Skin Temperature

This section reports results on the aspects of research objectives 1 and 2 which deal with determining the effects on skin temperature of the three body sites and the three fabric types in the investigation. The section also addresses the three associated hypotheses concerning those effects, because of the simultaneous testing of the effects through repeated-measures analysis of variance with three within-subjects independent variables. The within-subjects variables, which constituted the main effects in the analysis of variance, were garment options, body sites, and five-minute time intervals. As the previous chapter explained, the garment option variable has seven categories which account for the two standard garments (T-shirt and pants denoted as one garment, and the Tyvek® coverall over the T-shirt and pants as the other), and for sleeves alternated on the standard garments. The body sites are the chest and the two arms, and the five-minute time intervals are from start to finish in the 45 minutes of cycling. The inclusion

of the time-interval variable enabled testing of the effects of the body sites and the garment options on skin temperature by time intervals, as stated in hypotheses 1, 3, and 4.

Table 6 summarizes the overall results of the repeated measures analysis of variance. The results show that, at the 5% significance level, the garment, site, and time main effects were significant, as were the interaction among those three variables (second-order interaction) and the interactions between garment and site and between site and time (first-order interactions). The interaction of garment and time was not significant. The significant second-order interaction among garment, site, and time means that the first-order interaction between any two of those independent variables interacted with the other independent variables. That is, the garment-body site interaction effect on measured skin temperature interacted with the effect of time intervals on measured skin temperature. The body site-time interaction effect on measured skin temperature interacted with the effect of garment options on measured skin temperature. Likewise, the garment-time interaction effect on measured skin temperature interacted with the effect of body site on measured skin temperature. The garment-time interaction was not significant, however.

The significance of the second-order interaction among garment, site, and time led to further analysis of the first-order interaction of those same variables at each level of the third of those variables. The interaction plots between garment options and time intervals at each body site (Figure 8) and between body sites and time intervals for each garment option (Figure 9) show that, at every body site, measured skin temperature

Table 6

Analysis of skin temperature with repeated measures on garment options, body sites, and five-minute time interval

Source	df	SS	MS	F	p
Subject	9	497.060	55.229	-	-
Garment	6	801.205	133.534	14.87	0.0001
Subject * Garment	54	484.983	8.981	-	-
Site	2	382.182	191.091	28.71	0.0001
Subject * Site	18	119.792	6.655	-	-
Time	9	865.681	96.187	24.05	0.0001
Subject * Time	81	323.889	3.999	-	-
Garment * Site	12	214.278	17.856	4.30	0.0001
Subject * Garment * Site	108	448.335	4.151	-	-
Garment * Time	54	51.858	0.960	0.62	0.9845
Subject * Garment * Time	486	753.429	1.550	-	-
Site * Time	18	24.467	1.359	3.56	0.0001
Subject * Site * Time	162	61.917	0.382	-	-
Garment * Site * Time	108	31.193	0.289	1.44	0.0035
Subject * Garment * Site * Time	972	195.157	0.201	-	-

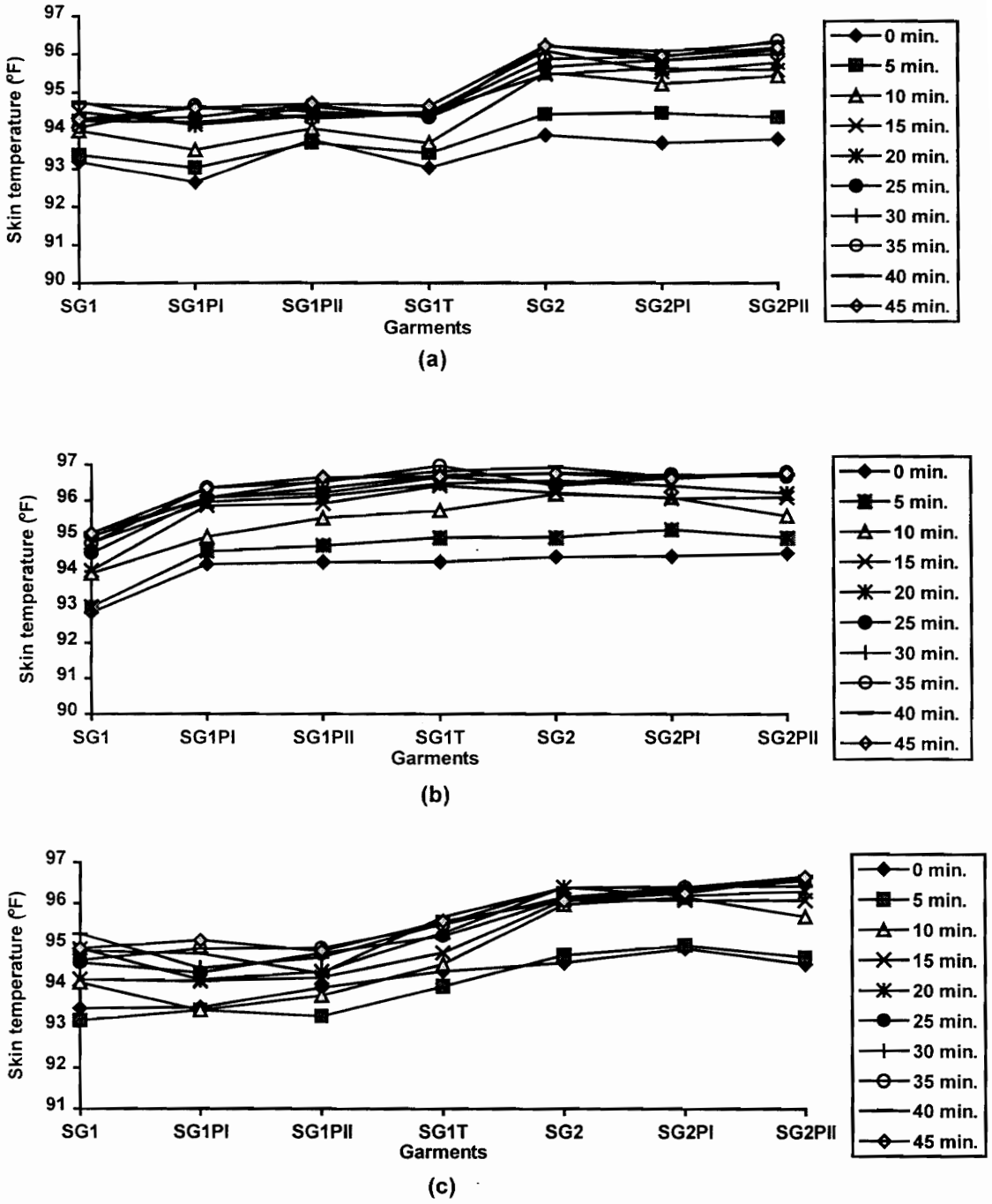

Figure 8. Schematic representation of interactions between garment options and time intervals on (a) the chest, (b) the left, and (c) the right arms.

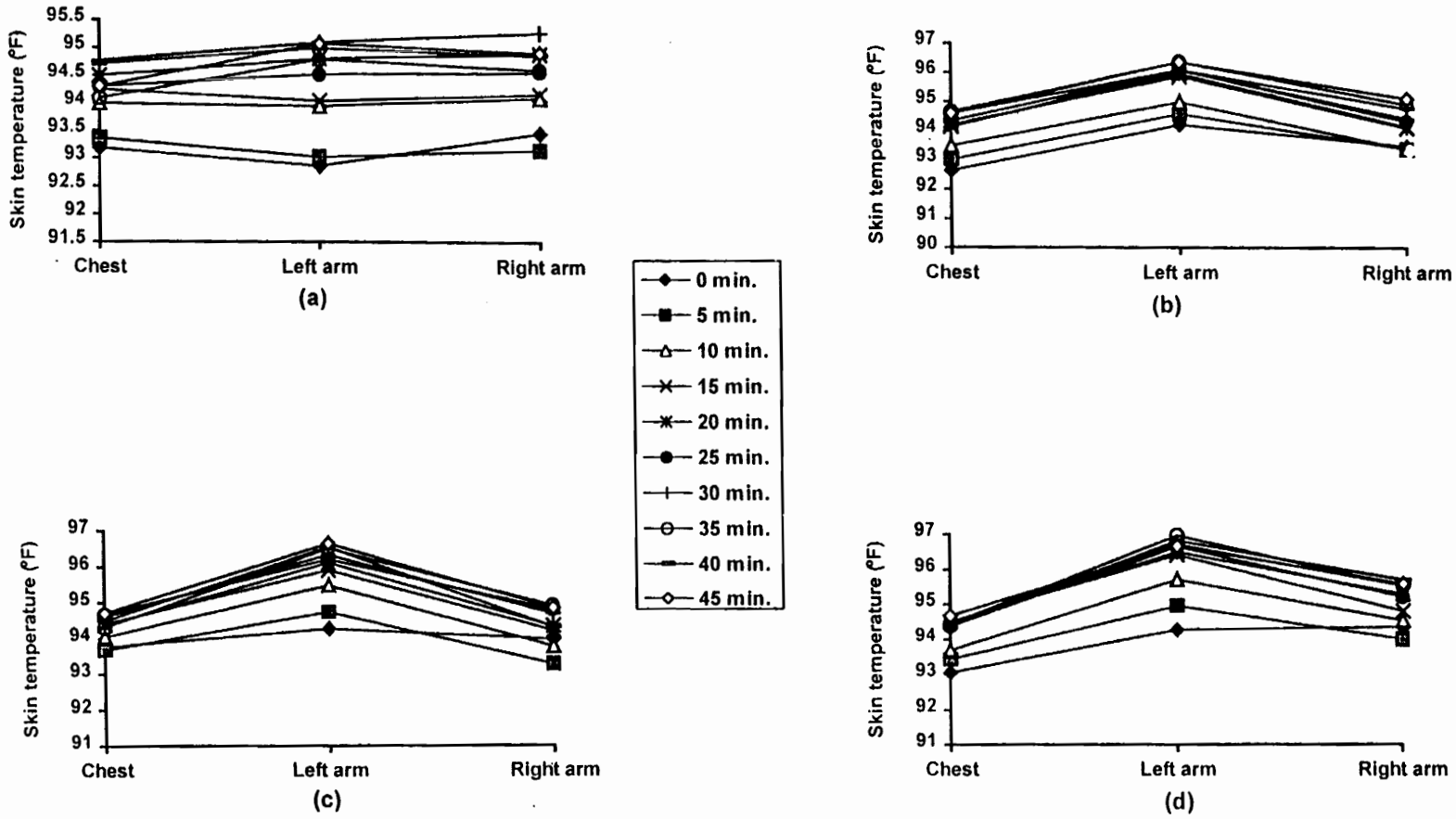

Figure 9. Schematic representation of interactions between body sites and time intervals when (a) SG1, (b) SG1PI, (c) SG1PII, and (d) SG1T were worn.

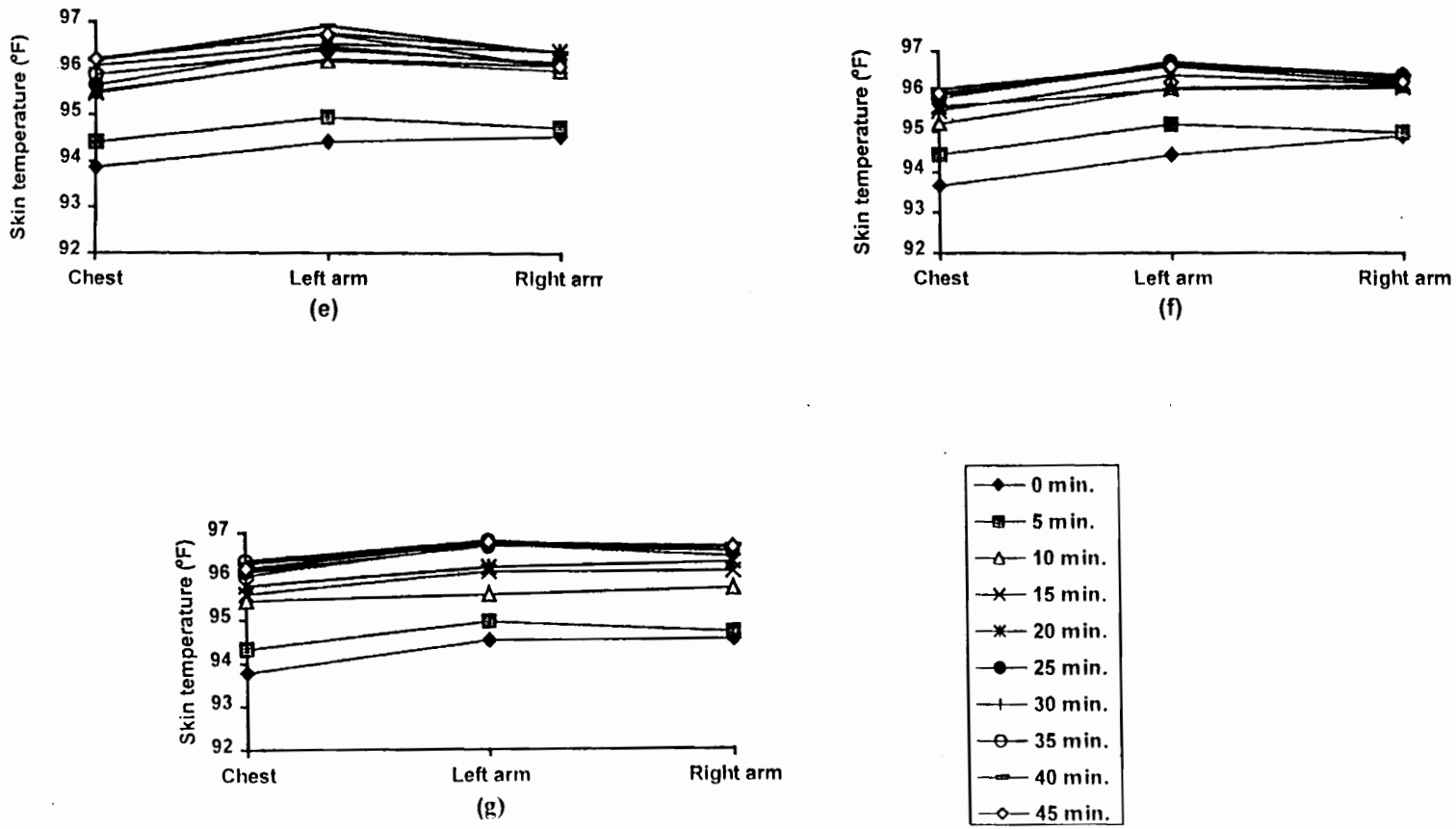

Figure 9. (cont.) Schematic representation of interaction between body sites and time intervals when (e) SG2, (f) SG2PI, and (g) SG2PII were worn.

increased with exercise time. The greatest temperature increments occurred in the first 15-20 minutes, after which the increments were smaller because, based on heat transfer principles, the greater the temperature gradient between the core and the skin, the higher the rate of heat transfer. Further statistical analysis of the above interactions was not conducted because of the obvious trend of increasing skin temperature with exercise time, and because of the inclusion of the time-interval variable to enable testing the effects of the body sites and the garment options on skin temperature.

The interaction between the garment-site interaction and the time intervals was investigated by analyzing the garment-site interaction at each time interval (Appendix E). Because of the significant (0.05 level) interactions between garment options and body sites, at every time interval, further analysis was conducted on the effect of each of those two variables on measured skin temperature, at individual levels of the other variable and time intervals. This effect is called simple main effect. Therefore, in this case, there were two types of simple main effects: a) simple effect of body sites for each garment option and time interval; and b) simple effect of garment options at each body site and time interval.

Simple effect of body sites for each garment option and time interval. In the analysis of the simple effect of body sites for each garment option and time interval (Appendix F), at the 5% significance level, the effects of body sites were not significant, at every time interval, when subjects wore SG1, and SG2. The insignificance of the body site effect on measured skin temperature was also observed after the first five

minutes of exercising in SG2PII. Table 7 lists mean skin temperatures (insignificantly different among body sites) and standard deviations with the wearing of SG1, SG2, and SG2PII.

When garments other than SG1, SG2, and SG2PII were worn, the body site effects, for each combination of garment options and time intervals, on measured skin temperature were significant (see Appendix F). The Fisher's least significant difference comparison was applied to study the significant differences (Table 8). For any given experimental sleeve, when the T-shirt/pants standard garment was worn, skin temperature on the left arm with that experimental sleeve was higher than skin temperature on the right arm and on the chest; that is the experimental sleeve impeded transfer of heat from the arm to the outside environment. When SG2PI was worn, skin temperatures on the left and the right arms were not significantly different, suggesting that a Pro/Shield I® sleeve and a Tyvek® sleeve may have a similar effect on heat transfer from the body.

Simple effect of garment options at each body site and time interval. To investigate the effects of the experimental fabrics on measured skin temperature, the simple effect of garments at each body site and time interval, was examined. Table 9 exhibits the results of the analysis. The garment effects were significant (0.05 level) at almost every level of the combinations of the other two variables; that is, at each body site and time interval, each garment differently affected skin temperature. To observe and compare how each garment affected skin temperature at different body sites and at

Table 7

Mean skin temperatures (averaged over 10 subjects and insignificantly different among body sites) and standard deviations with wearing SG1, SG2 and SG2PII

Garment	Body site	M (°F)	SD (°F)
SG1[1]	Right arm	94.4	1.4
	Left arm	94.3	1.6
	Chest	94.1	1.4
SG2[2]	Left arm	96.2	1.3
	Right arm	95.9	1.1
	Chest	95.5	1.4
SG2PII[3]	Left arm	96.1	1.4
	Right arm	96.0	1.0
	Chest	95.6	1.2

[1] SG1 stands for the T-shirt/pants standard garment without an experimental sleeve.
[2] SG2 stands for the Tyvek®-coverall standard garment worn over the T-shirt and pants.
[3] SG2PII stands for the Tyvek® coverall (worn over the T-shirt and pants) with a Pro/Shield II® sleeve on the left arm.

Table 8

Least significant differences of mean skin temperatures from the beginning to the end of the exercise on each body site with wearing SG1T, SG1PI, SG1PII, and SG2PI

Garment	M (°F)		
	Left arm	Right arm	Chest
SG1T[1]	96.2_{a}	95.0_{b}	94.1_{b}
SG1PI[2]	95.6_{a}	94.2_{b}	94.0_{b}
SG1PII[3]	95.9_{a}	94.4_{b}	94.3_{b}
SG2PI[4]	96.1_{a}	$96.0_{a, b}$	95.4_{b}

Note. Means in the same row that do not share subscripts differ at $p<0.01$ in the Fisher's least significant difference comparison.

[1] SG1T stands for the T-shirt/ pants standard garment with a Tyvek® sleeve on the left arm.
[2] SG1PI stands for the T-shirt/ pants standard garment with a Pro/Shield I® sleeve on the left arm.
[3] SG1PII stands for the T-shirt/ pants standard garment with a Pro/Shield II® sleeve on the left arm.
[4] SG2PI stands for the Tyvek® coverall (worn over the T-shirt and pants) with a Pro/Shield I® sleeve on the left arm.

Table 9

Analysis of garment effects at each body site and time interval

Time (min.)	Site	Source	df	SS	MS	F	p
0	Left arm	Garment	6	19.689	3.282	4.73	0.0006
5	Left arm	Garment	6	32.072	5.345	7.53	0.0001
10	Left arm	Garment	6	34.891	5.815	4.45	0.0010
15	Left arm	Garment	6	38.185	6.364	5.48	0.0002
20	Left arm	Garment	6	21.422	3.570	3.83	0.0030
25	Left arm	Garment	6	36.275	6.046	7.13	0.0001
30	Left arm	Garment	6	22.172	3.695	4.62	0.0007
35	Left arm	Garment	6	31.154	5.192	6.52	0.0001
40	Left arm	Garment	6	27.320	4.553	5.49	0.0002
45	Left arm	Garment	6	21.812	3.635	5.20	0.0003
0	Chest	Garment	6	13.092	2.182	1.79	0.1194
5	Chest	Garment	6	20.294	3.382	2.42	0.0381
10	Chest	Garment	6	45.356	7.563	4.93	0.0011
15	Chest	Garment	6	25.968	4.328	3.09	0.0112
20	Chest	Garment	6	36.656	6.109	4.37	0.0011
25	Chest	Garment	6	37.645	6.274	5.08	0.0003
30	Chest	Garment	6	44.471	7.412	4.66	0.0007
35	Chest	Garment	6	44.676	7.446	6.10	0.0001
40	Chest	Garment	6	47.303	7.884	5.89	0.0001
45	Chest	Garment	6	42.625	7.104	6.37	0.0001
0	Right arm	Garment	6	18.797	3.133	4.02	0.0021
5	Right arm	Garment	6	36.220	6.037	5.22	0.0003
10	Right arm	Garment	6	76.270	12.712	8.96	0.0001
15	Right arm	Garment	6	56.908	9.485	5.44	0.0002
20	Right arm	Garment	6	53.900	8.983	9.01	0.0001
25	Right arm	Garment	6	49.820	8.303	5.47	0.0002
30	Right arm	Garment	6	42.908	7.151	6.76	0.0001
35	Right arm	Garment	6	37.944	6.324	4.12	0.0018
40	Right arm	Garment	6	52.683	8,.780	8.08	0.0001
45	Right arm	Garment	6	29.985	4.998	4.36	0.0012

each time interval during exercise, averaged skin temperatures at each body site, at each time interval, were plotted against garment types (Figure 10). The Fisher's least significant difference test was also employed to study differences, among the different garments, in the skin temperatures measured at each body site from the beginning to the end of the exercise (see Table 10).

Testing of hypothesis 1. It was hypothesized that, at any given time interval during exercise, while wearing a standard garment consisting either of T-shirt and pants or of a Tyvek® coverall over the T-shirt and pants, skin temperature would not differ between the right and the left arms, but would differ between the arms and the chest.

As shown by the results in Appendix F, for SG1 and SG2, the standard garments without experimental sleeves, the body site effect was not significant at the 5% level. That is, under the same exposed conditions, measured skin temperatures on the left and right arms and the chest were not significantly from each other in the cases of those garments. Therefore, hypothesis 1 was not supported.

The small difference in mean skin temperature between the left and the right arms, with wearing either SG1 or SG2 (see Table 7), suggests that both arms would react to an increased heat load in the same manner and even in quite similar amount. Therefore, either arm can be used as a test site, and the findings on one arm can be inferred from the other arm. The small difference in mean skin temperature between the arms and the chest, with wearing either of the standard garments, implies that the arms and the chest may react to an increased heat load in similar way and amount. So, there may be

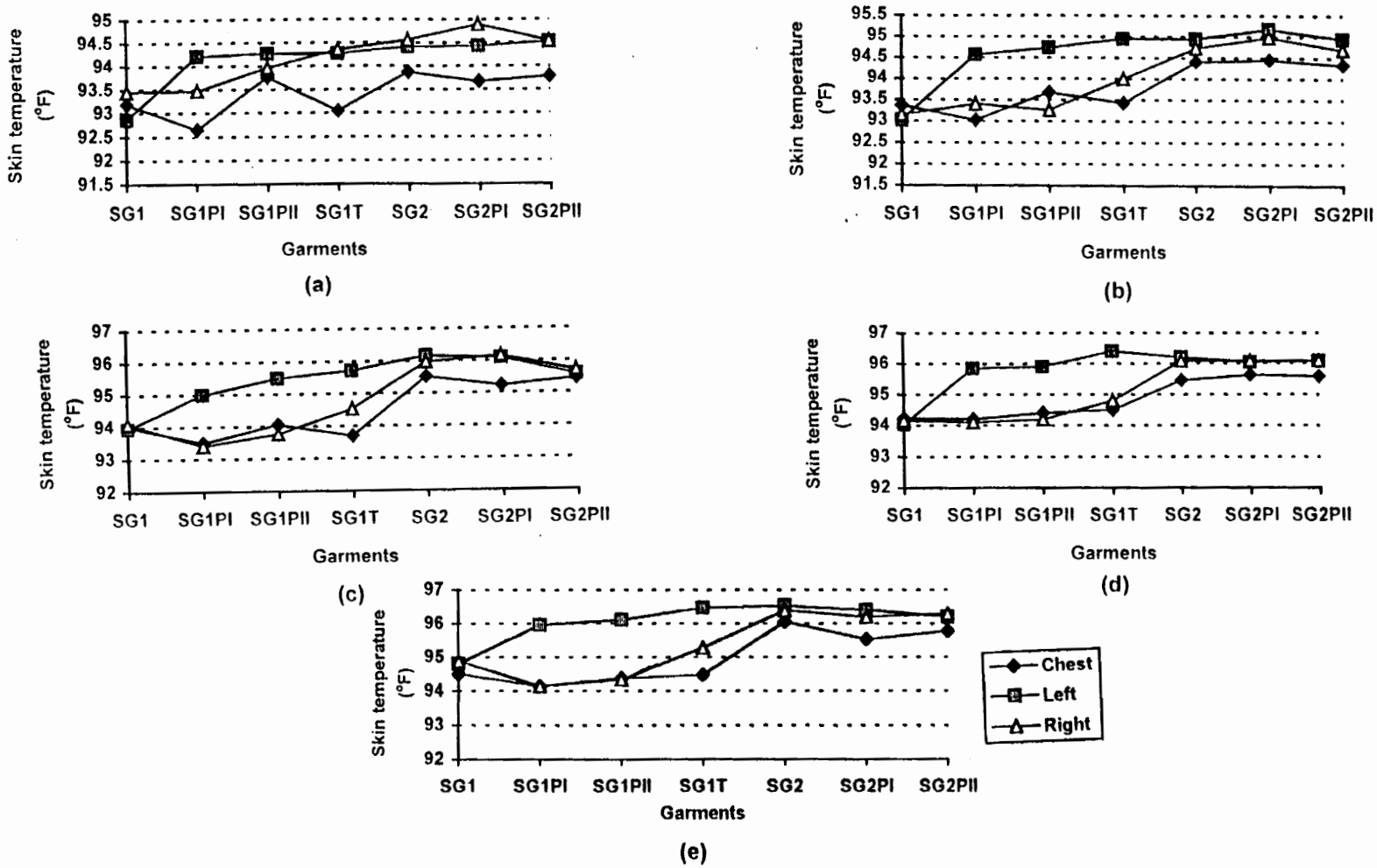

Figure 10. Garment effects on skin temperature at each body site at the beginning (a), five-minute (b), 10-minute (c), 15-minute (d), and 20-minute (e) of exercise.

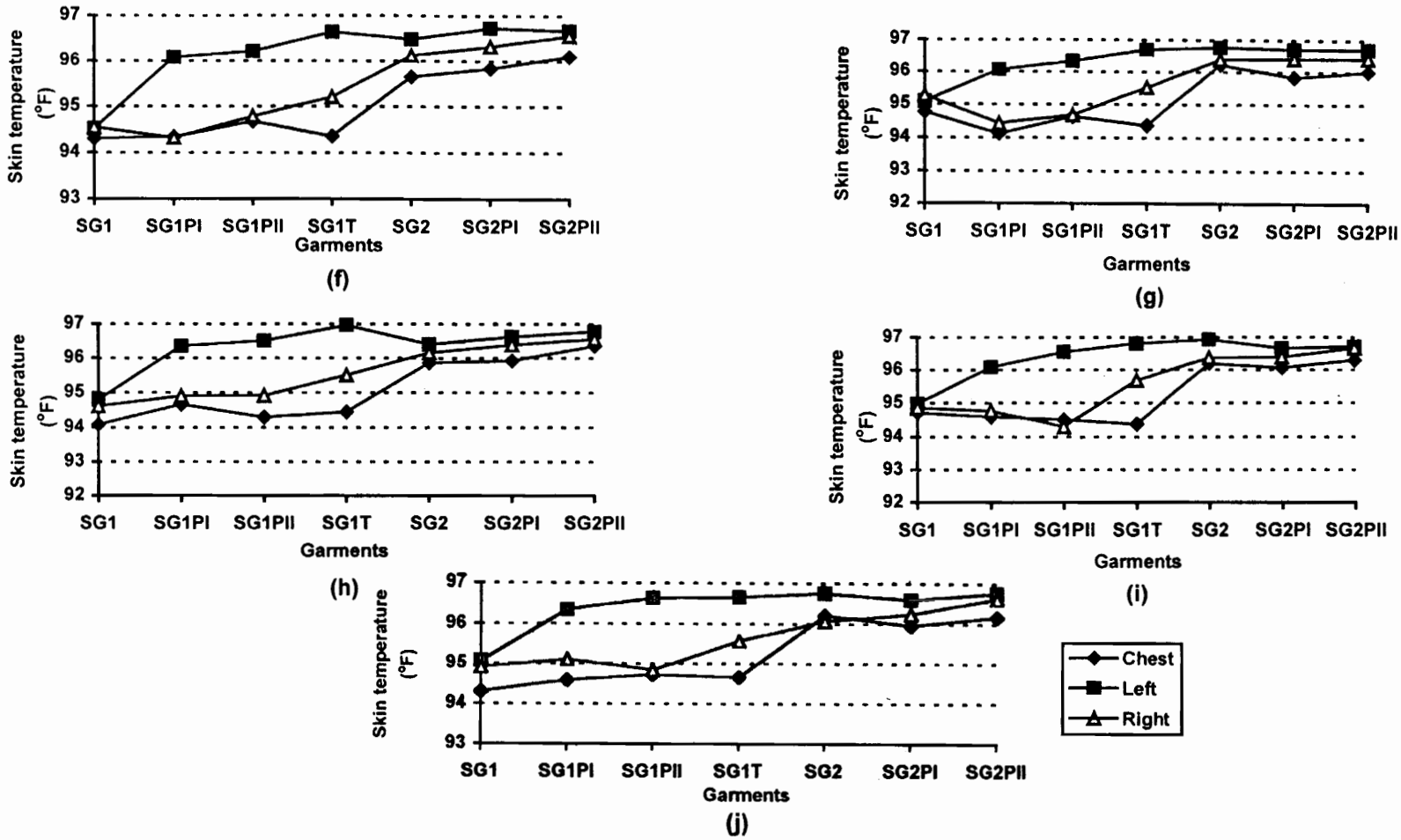

Figure 10. (cont.) Garment effects on skin temperature at each body site at the 25-minute (f), 30-minute (g), 35-minute (h), 40-minute (i), and 45-minute (j) of exercise.

Table 10

Fisher's least significant differences of mean skin temperatures by body site with wearing each garment

Left arm		Chest		Right arm	
M (°F)	Garment	M (°F)	Garment	M (°F)	Garment
96.2_{a}	SG2	95.6_{a}	SG2PII	96.0_{a}	SG2PII
96.2_{a}	SG1T	95.5_{a}	SG2	96.0_{a}	SG2PI
96.1_{a}	SG2PI	95.4_{a}	SG2PI	95.9_{a}	SG2
96.1_{a}	SG2PII	94.4_{b}	SG1PII	95.0_{b}	SG1T
95.9_{a}	SG1PII	94.1_{b}	SG1	$94.4_{b,c}$	SG1
95.6_{a}	SG1PI	94.1_{b}	SG1T	94.3_{c}	SG1PII
94.3_{b}	SG1	94.0_{b}	SG1PI	94.2_{c}	SG1PI

Note. Means in the same column that do not share subscripts differ at $p<0.01$ in the Fisher's least significant difference comparison.

possibility of using an arm, instead of the trunk (or the chest), as a test site to assess thermal comfort.

Notice in Table 7 that mean skin temperatures measured on the arms were slightly higher than those measured on the chest; this is in agreement with findings by Houdas and Ring (1982) which are in Table 1. Houdas and Ring found that, in a warm environment, which is comparable to the skin-garment microclimate in the current study, skin temperature on the upper arm was slightly higher than that on the chest.

Testing of hypothesis 3. It was hypothesized that, at any given time interval during exercise, when the T-shirt/pants standard garment was worn, skin temperatures (on the left arm) would be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

As noted previously with reference to Table 9, the simple effect of garments, at all but one of the combinations of body sites and time intervals, was significant at the 0.05 significance level. Those results led to further analysis as shown in Figure 10 and Table 10. At any given time interval, the left arm skin temperature with wearing SG1 was always lower than that with wearing other garments (Figure 10), and mean skin temperatures on the left arm were significantly different between SG1 and each other garment in the study (see Table 10). These results indicate the effect of the experimental sleeves on skin temperature. Wearing SG1 resulted in the lowest skin temperature

because no experimental fabric having poor heat dissipation properties was present to impede heat transfer from the body to the outside environment.

Figure 10 and Table 10 also show that, at any given time, when the T-shirt/pants standard garment was worn with alternating experimental sleeves on the left arm, left arm skin temperature was highest with the Tyvek® sleeve, followed in order by the Pro/Shield II® sleeve and the Pro/Shield I® sleeve. Therefore, hypothesis 3 was judged to be supported although the left arm skin temperatures did not differ significantly among the experimental fabrics. The fabric trend seen for the left arm skin temperature was not observed for the right arm nor the chest.

Subjects wearing a Tyvek® sleeve, as opposed to a Pro/Shield II® sleeve, over the left sleeve of the T-shirt experienced higher skin temperature on the left arm, even though these two fabrics had quite similar moisture vapor and liquid transmission characteristics (see Table 5). The lower skin temperature with Pro/Shield II may be due to better wicking as a consequence of that fabric's slightly hairy surface texture on its inner side and the microporous film on its outer side. During exercise, the hairy surface of Pro/Shield II® may adsorb and wick moisture from the skin, through its vapor-permeable microporous film, to the outside environment, thereby enhancing the heat dissipation through sweating and evaporative heat loss. Tyvek® with paper-like texture, on the other hand, does not have fibers protruding from the fabric surface to enhance its wickability.

In comparing the left-arm skin temperature when wearing the T-shirt/pants standard garment with a Pro/Shield I® sleeve vs. with a Tyvek® or a Pro/Shield II® sleeve,

the Pro/Shield I® sleeve resulted in lower skin temperature, although the differences were not significant (Table 10). Pro/Shield I® may result in lower skin temperature because it has almost two-fold better moisture vapor transmission than do the other two fabrics. The hairy surface texture of Pro/Shield I® also may enhance wicking of sweat from the skin and evaporative heat loss.

Testing of hypothesis 4. It was hypothesized that, at any given time interval during exercise, when the Tyvek®-coverall standard garment was worn over the T-shirt and pants, skin temperatures (on the left arm) would be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

From Figure 10 and Table 10, no consistent fabric trend over time was observed when the Tyvek®-coverall standard garment was used, regardless of the body sites. Therefore, hypothesis 4 was not supported.

A possible explanation of a lack of consistent fabric trend in these cases, is that the Tyvek® coverall caused the chimney effect [6] which fluctuates skin temperature. In addition to the zipper on the front trunk, the coverall is elasticized at the wrists and ankles, which makes it similar to a closed system and leave an opening around the neckline as the main path of heat transfer from the body. It may be that, due to the paper-like texture and, perhaps the poorer wickability of Tyvek® fabric as compared to the other

[6] Watkins (1995) defined chimney effect as the rising of warm, moisture-laden air.

two experimental fabrics, only a limited amount of heat built up by the active muscles during exercise could transport through the coverall. Otherwise, the heat was restrained to flow between the skin and the garment, raising the microclimate temperature. As to the fact that the warm air rises, heat in the microclimate leaks through the opening of the neckline, resulting in inconsistent microclimate temperature which, in turn, fluctuates skin temperature. In addition to the opening around the neckline, fluctuation of skin temperature may be caused by forcing out of heat through intermittent gaps around the wrists and the ankles by the pumping motion of the body during the exercise.

Based on observed skin temperatures on the right arm and on the chest (Figure 10 and Table 10), wearing the Tyvek®-coverall standard garment with any given experimental sleeve, resulted in higher skin temperature on those sites than did wearing the T-shirt/pants standard garment with that experimental sleeve. As compared to the jersey T-shirt fabric, Tyvek® has much poorer moisture vapor transmission and capillary penetration and transmission, although it is much lighter and thinner (Table 5). The better moisture properties of the T-shirt fabric may result from the nature of cotton fiber and the knitted structure. Cotton absorbs moisture in greater amount than does polyethylene, of which Tyvek® is made, and the open structure of the knitted T-shirt fabric allows easier moisture and heat transfer than does the tight, nonwoven structure of Tyvek®. The hairy surface texture of jersey knit also enhances wickability and absorption of the T-shirt.

Sweat Amount

This section reports results on the aspects of research objectives 1 and 2 which deal with determining the effects on sweat amount of the three body sites and the three fabric types in the investigation. The section also addresses the three associated hypotheses concerning those effects, because of the simultaneous testing of the effects through repeated-measures analysis of variance with two within-subjects independent variables. The within-subjects variables, which constituted the main effects in the analysis of variance, were garment options and body sites. As pointed out previously, the garment option variable has seven categories which account for the two standard garments (T-shirt and pants denoted as one garment, and the Tyvek® coverall over the T-shirt and pants as the other), and for sleeves alternated on the standard garments; the body sites are the chest and the two arms. The testing of hypotheses 2, 5, and 6 is reported in this section

Table 11 summarizes the results of the repeated measures analysis of variance. Neither the garment-site interaction effect nor the main effect of each independent variable on measured sweat amount was significant at the 5% level. That is, sweat amount was not significantly different a) for the different garments, nor b) among the left and right upper arms and the chest. Table 12 exhibits mean sweat amount and standard deviation on each body site when each garment was worn. The rather high standard deviations of sweat amount as compared to the means may be a consequence of the

Table 11

Analysis of sweat amount with repeated measures on garment options and body sites

Source	df	SS	MS	F	p
Subject	9	5.436	0.604	-	-
Garment	6	0.015	0.025	0.72	0.6384
Subject*Garment	54	1.883	0.035	-	-
Site	2	0.078	0.039	0.79	0.4670
Subject*Site	18	0.879	0.049	-	-
Garment*Site	12	0.056	0.005	0.68	0.7713
Subject*Garment*Site	108	0.749	0.001	-	-

Table 12

Mean sweat amount (averaged over 10 subjects) and standard deviation on each body site when each test garment was worn

Garments	Sweat amount (mg/cm^2) on					
	Left arm		Chest		Right arm	
	M	SD	M	SD	M	SD
SG1	52.60	32.27	53.59	18.08	55.47	24.47
SG1T	56.37	36.53	61.80	33.43	55.61	33.07
SG1PI	60.66	30.04	61.31	30.81	55.96	26.80
SG1PII	49.48	29.69	64.60	36.96	50.02	17.39
SG2	64.27	49.80	66.54	33.56	56.00	43.03
SG2PI	59.79	40.83	65.82	30.83	54.20	39.03
SG2PII	69.07	40.21	69.65	37.23	63.60	40.51

difference among subjects in their sweat production.

Testing of hypothesis 2. It was hypothesized that, while wearing a standard garment consisting either of T-shirt and pants or of a Tyvek® coverall over the T-shirt and pants, sweat amount collected from the beginning to the end of the exercise would not differ between the right and the left arms, but would differ between the arms and the chest.

As seen in Table 12, the mean sweat amounts on the three body sites were very close when SG1 was worn, and were much closer than when SG2 was worn; however, as reported in Table 11, sweat amount did not differ significantly (5% level) among body sites for any of the garment options. The low sweat amount on the right arm, as compared to the other two body sites, when subjects wore SG2 may have resulted from unknown extraneous variables. Though hypothesis 2 was not supported, the conclusion that, under the same exposed conditions, or when other variables were being controlled, the three body sites would respond to a given increased heat load in the same manner could not be made because of the insignificant body site effect among test garments and the high standard deviations within sites and garments. Moreover, the unknown extraneous variables and the high standard deviation reduce the usefulness of sweat amount as a measurement of thermal comfort and thermal strain.

Testing of hypothesis 5. It was hypothesized that, when the T-shirt/pants standard garment was worn, sweat amount (collected on the left arm from the beginning to the end of the exercise) would be highest in the garment with a Tyvek® sleeve and the garment

with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve, and then the garment without any experimental sleeve.

From Table 12, when SG1 was used, sweat amount observed on the left arm was highest on the garment with a Pro/Shield I® sleeve, followed in order by the garment with a Tyvek® sleeve, the garment without an experimental sleeve, and the garment with a Pro/Shield II® sleeve. Therefore, hypothesis 5 was rejected. Because Pro/Shield I® has about two times the moisture vapor transmission of the other two experimental fabrics (see Table 5) and also has fibers protruding from the fabric surface, evaporative heat transfer and moisture wicking through the Pro/Shield I® sleeve should be better than through the other sleeves. When heat and moisture can transfer efficiently, thermal stress in the body decreases, reducing sweat production. As stated by Parsons (1993) and Powers and Howley (1994), the hypothalamus will stimulate the sweat glands, resulting in evaporation to cool the skin, when heat transfer by conduction, convection, and radiation is not sufficient. The other reason why the observed trend is not reasonable is that the left arm sweat amount of wearing SG1 was greater than that of wearing SG1PII, which is contrary to the fact. Wearing SG1 should result in greater amount of heat transfer than wearing SG1PII because heat can transfer directly from the skin to the environment without the hindrance of protective sleeve.

The difference in mean sweat amounts among body sites as well as among test garments were quite small (see Table 12). This may be due to the saturation of collection

pads during the trials. To avoid the saturation, larger collection pads should be used, or the sweat collection time should be decreased.

Testing of hypothesis 6. It was hypothesized that, when the Tyvek®-coverall standard garment was worn over the T-shirt and pants, sweat amount (collected on the left arm from the beginning to the end of the exercise) would be highest in the garment with a Tyvek® sleeve and the garment with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I® sleeve.

According to the results in Table 12, when the Tyvek®-coverall standard garment was worn over the T-shirt and pants, the fabric ranking from highest to lowest sweat amount was Pro/Shield II®, Tyvek®, and Pro/Shield I®. This ranking occurred for the left arm and for the other two body sites. Therefore, hypothesis 6 was not supported. The above fabric ranking was not the same as the fabric ranking from the left arm skin temperature of wearing a T-shirt/pants standard garment. The high standard deviations make the fabric ranking, regarding sweat amount of wearing a Tyvek® coverall, less reliable as compared to the ranking, regarding the left arm skin temperature of wearing T-shirt and pants. However, both rankings were alike in the way that Pro/Shield I®, which has better moisture vapor transmission than the other two fabrics and has slightly hairy surface texture, was the best fabric, of the three experimental fabrics, in terms of thermal comfort.

For a given experimental sleeve, sweat amount at every body site was higher when the Tyvek®-coverall standard garment was used than when the T-shirt/pants

standard garment was used. The poorer heat and moisture transfer characteristics of the Tyvek® coverall as compared to the T-shirt may be due to the nature of fibers and the fabric constructions, which contribute directly to the physical characteristics of the fabrics as described in the previous section.

Subjective Evaluations

This section reports results on the aspects of research objectives 1 and 2 which deal with determining the effects on subjects' wetness, thermal, and overall comfort sensations of the three fabric types in the investigation. The section also addresses the six associated hypotheses concerning those effects, because of the simultaneous testing of the effects through repeated-measures analysis of variance with two within-subjects independent variables. The within-subjects variables, which constituted the main effects in the analysis of variance, were garment options and five-minute time intervals. As previously, the garment option variable has seven categories which account for the two standard garments (T-shirt and pants denoted as one garment, and the Tyvek® coverall over the T-shirt and pants as the other), and for sleeves alternated on the standard garments; the five-minute time intervals are from start to finish in the 45 minutes of cycling. The inclusion of the time-interval variable enabled testing of the effects of the garment options on the subjective evaluations by time intervals, as stated in hypotheses 7-12.

Table 13 summarizes the repeated measures analysis of variance of the wetness, thermal, and overall comfort ratings. The garment-time interaction effects on wetness, thermal, and overall comfort sensations were not significant at the 5% significance level, whereas the garment and the time effects on those three sensations were significant. The significant main effects were further studied by the Fisher's least significant difference comparison, and the results are shown in Tables 14 and 15.

From Table 15, subjects could distinguish larger differences in each of the three sensations between five-minute intervals during the first 15-20 minutes of exercise than they could after that period. The possible explanation is that an increased exercising time increased heat produced by active tissues, which increased heat load. When the heat load increased, the ability of a person to make rational judgment may be impaired (Parsons, 1993). As stated by Pontrelli (1977) that the judgment of clothing comfort is also influenced by past experience; therefore, the subjects' feeling at the first 15-20 minutes of exercise may affect their comfort judgment after that period. The other possible explanation is that, perhaps, the subjects' microclimate changes really were marginal after 20 minutes.

Testing of hypotheses 7-12. It was hypothesized that, during exercise, while wearing the T-shirt/pants standard garment (or the Tyvek®-coverall standard garment over the T-shirt and pants), subjective ratings of wetness (or thermal, or comfort) sensation would be highest on the garment with a Tyvek® sleeve and with a Pro/Shield II® sleeve, followed by the garment with a Pro/Shield I®, and then the garment without

Table 13

Analyses of wetness (a), thermal (b), and overall comfort (c) sensations with repeated measures by garment options and time intervals

Source	df	SS	MS	F	p
Subject	9	540.880	60.098	-	-
Garment	6	143.157	23.860	5.62	0.0001
Subject*Garment	54	229.100	4.243	-	-
Time	9	1096.480	121.831	38.62	0.0001
Subject*Time	81	255.520	31.155	-	-
Garment*time	54	31.100	0.576	1.30	0.0828
Subject*Garment*Time	486	215.500	0.443	-	-

(a)

Source	df	SS	MS	F	p
Subject	9	321.601	35.733	-	-
Garment	6	99.937	16.656	14.83	0.0005
Subject*Garment	54	186.349	3.451	-	-
Time	9	416.887	46.321	36.83	0.0001
Subject*Time	81	101.870	1.258	-	-
Garment*time	54	16.463	0.305	1.04	0.405
Subject*Garment*Time	486	142.680	0.294	-	-

(b)

Table 13 (cont.)

Source	df	SS	MS	F	p
Subject	9	654.149	72.683	-	-
Garment	6	106.997	17.833	6.59	0.0001
Subject*Garment	54	146.231	2.708	-	-
Time	9	620.320	68.924	36.63	0.0001
Subject*Time	81	152.423	1.882	-	-
Garment*time	54	15.260	0.283	0.85	0.7688
Subject*Garment*Time	486	161.797	0.333	-	-

(c)

Table 14

Fisher's least significant difference in wetness, thermal, and overall comfort sensation ratings by garment options

	Garment						
	SG1	SG1PI	SG1PII	SG1T	SG2	SG2PI	SG2PII
Wetness	3.90_{c}	3.91_{c}	$4.03_{b,c}$	3.68_{c}	5.00_{a}	4.68_{a}	$4.52_{a,b}$
Thermal	$6.44_{b,c}$	$6.60_{a,b,c}$	$6.32_{b,c}$	6.29_{c}	7.17_{a}	7.25_{a}	$7.00_{a,b}$
Overall	3.46_{c}	$3.72_{b,c}$	3.66_{c}	3.71_{c}	4.52_{a}	4.35_{a}	$4.34_{a,b}$

Note. Means in the same row that do not share subscripts differ at $p<0.01$ in the Fisher's least significant difference comparison.

Table 15

Fisher's least significant difference in wetness, thermal, and overall comfort sensation ratings by time interval

Time	Sensation		
(min.)	Wetness	Thermal	Overall comfort
45	5.47_{a}	7.47_{a}	4.94_{a}
40	5.45_{a}	$7.37_{a, b}$	$4.84_{a, b}$
35	5.31_{a}	$7.39_{a, b}$	$4.74_{a, b}$
30	5.16_{a}	$7.19_{a, b, c}$	$4.63_{a, b, c}$
25	$4.90_{a, b}$	$7.16_{a, b, c}$	$4.41_{b, c}$
20	$4.49_{b, c}$	$6.89_{b, c}$	$4.17_{c, d}$
15	4.08_{c}	$6.71_{c, d}$	3.86_{d}
10	3.40_{d}	6.33_{d}	3.34_{e}
5	2.43_{e}	5.76_{e}	2.73_{f}
0	1.76_{f}	4.99_{f}	1.99_{g}

Note. Means in the same column that do not share subscripts differ at $p<0.01$ in the Fisher's least significant difference comparison.

any experimental sleeve on the left arm (only when the T-shirt/pants standard garment was used).

From Table 14, the fabric rankings, with respect to each of the subjective ratings, when wearing the standard garment of either a T-shirt and pants or a Tyvek® coverall were not the same hypothesized. Therefore, none of the hypotheses 7-12 was supported by the findings.

Subjects perceived themselves to be drier, cooler, and more comfortable when wearing SG1, SG1PI, and SG1PII, and SG1PII than when wearing the other three garments probably because the T-shirt/pants standard garment absorbed and transferred moisture better than the Tyvek® coverall, resulting in a smaller rise in microclimate temperature and less amount of sweat dripped down the body. The above findings were in agreement with physiological responses as explained in the previous sections. Because, in hot environments, the ability of an individual to make a rational judgment becomes impaired (Parsons, 1993), subjective evaluations were excluded as parameters to determine the feasibility of using sleeves, instead of full garments, to assess thermal comfort in the current study.

Examination of the Feasibility of Using a Sleeve

This section addresses research objective 3 on comparing results on skin temperature and sweat amount in this study with those obtained in the companion study by Hennessey (1997). The section also addresses the two associated hypotheses.

Because of different sets of subjects and slightly different experimental procedures, histograms were used as a tool to facilitate the comparison of the three experimental fabrics' rank orders with respect to skin temperature and sweat amount, in the current study and in Hennessey's (1997) study.

Hennessey (1997) studied the effects of five different protective coveralls on thermal comfort and heat stress, by using both physiological and perceptual measurements, in neutral and hot environments. The hot environment was equivalent to the condition used in the current study. Hennessey measured skin temperatures on the back and the chest, and averaged them to obtain the mean skin temperature. Sweat was collected on the chest, the back and the upper arm, and the mean sweat amount over the three body sites was obtained. The means of these two parameters were reported; values at individual body sites are not available.

Hennessey (1997) found that, in the hot environment which is equivalent to the condition used in the current study, there was no significant differences in skin temperature nor in sweat amount among the experimental fabrics. At the 15-minute and 45-minute intervals, skin temperature was highest in the Tyvek® coverall, followed by the Pro/Shield II® coverall, and then the Pro/Shield I® coverall. The descending order for skin temperature at the 30-minute interval was slightly different: Pro/Shield II®, Tyvek®, and Pro/Shield I®. Hennessey also found that the Tyvek® coverall resulted in highest sweat amount, followed by the Pro/Shield II® coverall, and then the Pro/Shield I® coverall.

Testing of hypothesis 13. It was hypothesized that, for any given time interval, the experimental fabric order, with respect to skin temperature measured in the current study while subjects exercised in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants, would be the same as the order regarding skin temperature observed by Hennessey (1997).

Because fabric orders on the left arm skin temperature of wearing the Tyvek®-coverall standard garment over the T-shirt and pants were not consistent over time intervals (see Figure 10), the experimental fabric order, with respect to skin temperature measured in the current study while subjects exercised in the Tyvek®-coverall standard garment over the T-shirt and pants was not used as a parameter to test the feasibility of using sleeves, instead of full garments. Therefore, in this subsection, only fabric ranking on the left arm skin temperature of wearing the T-shirt/pants standard garment is addressed in comparing to Hennessey's fabric ranking.

As pointed out previously for the results in this study with the T-shirt/pants standard garment, at every time interval, the left arm skin temperature was highest in the garment with a Tyvek® sleeve, followed in order by the garment with a Pro/Shield II®, sleeve, and the garment with a Pro/Shield I® sleeve. Figure 11 illustrates the comparison of the mean left-arm skin temperatures, when the T-shirt/pants standard garment was used in the current study with the mean skin temperatures (averaged over two body sites) of Hennessey (1997). In theses cases, the fabric order was the same in the two studies at

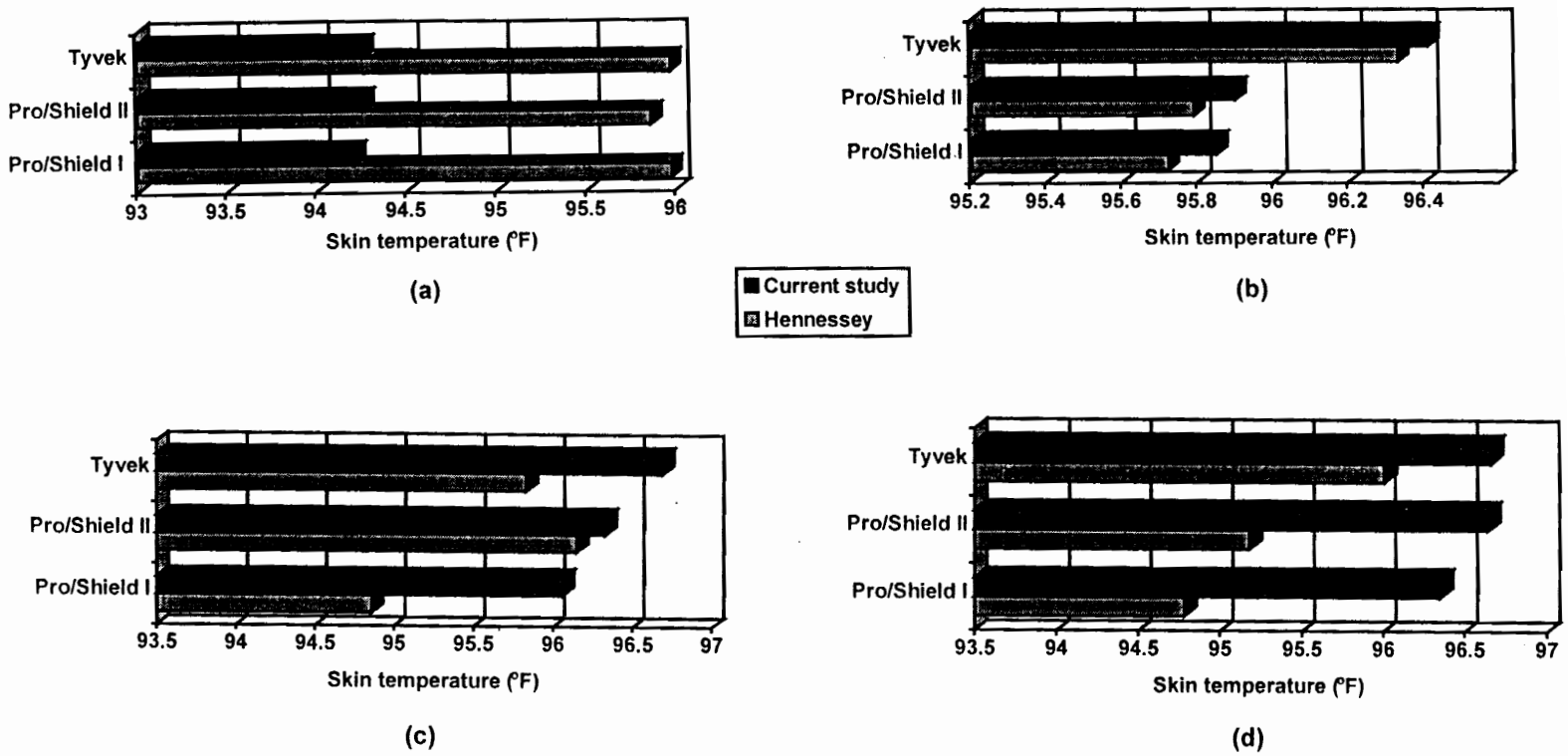

Figure 11. Comparisons of the mean left-arm skin temperatures, when the T-shirt/pants standard garment was used in the current study with the mean skin temperatures (averaged over two body sites) of Hennessey (1997) at the beginning (a), the 15-minute (b), the 30-minute (c), and the 45-minute (d) intervals of exercise.

the 15-minute and the 45-minute intervals of exercise (or agreed two out of three time intervals), which may suggest the feasibility of using a sleeve, instead of a full garment, to assess thermal comfort and heat strain associated with of wearing chemical protective clothing.

However, because the fabric rankings in the two studies were not the same at all time interval, hypothesis 13 was not fully supported. Perhaps the feasibility could be assessed with more confidence if the comparison were made with the temperature on the left arm, or some other site, rather than with an averaged temperature over multiple sites.

It may be noted that Figure 11 also indicates higher skin temperatures observed at the beginning of the exercise in Hennessey's (1997) than in the current study for every experimental fabric. This is believed to be due to the hindrance to heat transfer of the full coveralls. After the beginning, however, skin temperatures observed in the current study were greater than those in Hennessey's study. For any given experimental fabric, the difference in skin temperature between the two studies became greater over the exercise time. The different increments in the difference skin temperatures between two studies may have resulted from the variation in skin temperature on a particular body site in a hot environment. Houdas and Ring (1985) noted that, in high ambient temperature, or in the hotter skin-clothing microclimate in this case, skin temperature on the upper arms varies more than that on the trunk.

Testing of hypothesis 14. It was hypothesized that the experimental fabric order, with respect to sweat amount collected in the current study from the beginning to the end

of the exercise in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants, would be the same as the fabric order regarding sweat amount observed by Hennessey (1997).

Figure 12 shows the comparison of the mean sweat amounts (averaged over three body sites) from Hennessey's (1997) study with the mean sweat amounts (on the left arm) from the current study with both the T-shirt/ pants and the Tyvek®-coverall standard garments. The ranking of the three experimental fabrics are all different. Therefore, hypothesis 14 was not supported.

However, Hennessey's (1997) fabric ranking regarding sweat amount was the same as that regarding skin temperature at the 15-minute and the 45-minute intervals, which confirms the effects of the three different experimental fabrics on thermal comfort and heat strain. The feasibility of using a sleeve, instead of a full garment, in thermal comfort studies could not be concluded using sweat amount because of the high standard deviations of sweat amounts in the current study. To generate comparable data, the same set of subjects should participate in both studies and the size of the sweat collection pads should be increased. Sweat collection time should also be decreased to prevent the saturation of the pads during a trial.

As to the consequence of the testing of hypotheses 13 and 14, there is feasibility of using sleeve, instead of a whole garment in garment wear testing to assess thermal comfort and heat strain associated with wearing chemical protective clothing, when the T-shirt/pants standard garment was used. Based on standard deviations of means, skin

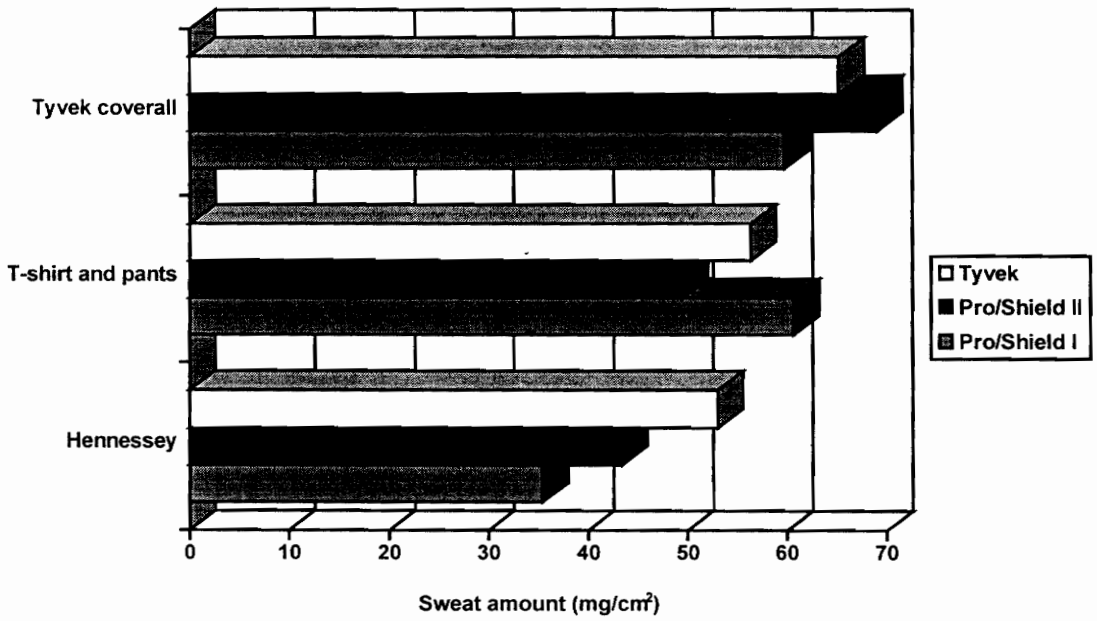

Figure 12. Comparison of the mean sweat amounts (averaged over three body sites) from Hennessey's (1997) study with the mean sweat amounts (on the left arm) from the current study with both the T-shirt/ pants and the Tyvek®-coverall standard garments.

temperature seems to be a better parameter for the comparison between the two studies than does sweat amount . Further studies should be conducted to validate the findings.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was to explore the feasibility of using sleeves, instead of full garments, in wear tests to assess the thermal comfort and heat strain associated with chemical protective clothing. To study if the upper arms and the chest respond to heat load in the same way, the differences in skin temperature, sweat amount, and subjective evaluations during exercise at three body sites (both upper arms and the chest) were investigated. The effect of three experimental fabrics on skin temperature and sweat amount was of interest; thus, the effects on skin temperature and sweat amount of sleeves made of those fabrics were compared to the effects on those parameters of full garments made of the same fabrics, as observed by Hennessey (1997). Fourteen research hypotheses were formulated based on previous research and the theoretical framework. Following is a summary of the results of the hypothesis testing.

The first two hypotheses concerned the effect of body sites on skin temperature and sweat amount. The results showed that, under the same conditions, the upper arms and the chest responded to heat load in the same way, indicated by nonsignificant differences in measured skin temperature and sweat amount. That is, either upper arm can be used as a test site and the response of the arm to the heat load is similar to the response of the torso to the amount of heat load. The results also showed that, in the warm test environment, skin temperatures observed on the arms were slightly higher than

those observed on the chest, which is in agreement with the findings of Houdas and Ring (1982).

Hypotheses 3 and 4 concerned the effect of three experimental sleeves as well as a Tyvek® coverall on skin temperature measured on the left arm where subjects wore an experimental sleeve. Although, when wearing the T-shirt/pants standard garment, the difference in the left arm skin temperature among the experimental sleeves was not significant, the Tyvek® sleeve resulted in highest skin temperature, followed in order by the Pro/Shield II® sleeve, and the Pro/Shield I® sleeve. The same fabric ranking was consistent over the exercise period. On the contrary, when wearing the Tyvek®-coverall standard garment, this consistent fabric ranking did not occurred; the inconsistency may result from the chimney effect. Therefore, the T-shirt/pants combinations may be a more useful standard garment than a Tyvek® coverall.

Hypotheses 5 and 6 were formulated to test the effect on sweat amount of the three experimental sleeves. The nonsignificant effect of the experimental sleeves on sweat amount collected on the left arm was in agreement with the findings on skin temperature. However, the unreasonable fabric ranking and the high standard deviation indicated that sweat amount was a less useful measurement as compared to skin temperature.

Hypotheses 7-12 were employed to study the effect on wetness, thermal, and overall comfort sensations of three experimental sleeves. The effects of the three experimental sleeves on each of the three subjective sensations were not significant,

which corresponded with the results of the physiological responses, i.e., skin temperature and sweat amount. For a given experimental sleeve, subjects wearing a T-shirt and pants perceived themselves to be drier, cooler, and more comfortable than when wearing a Tyvek® coverall as a standard garment.

The feasibility of using sleeves, instead of a full garment, to assess thermal comfort and heat strain in chemical protective clothing wear tests was investigated through hypotheses 13 and 14. Hypothesis 13 was that, for any given time interval, the experimental fabric order, with respect to skin temperature measured in the current study while subjects exercised in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants, would be the same as the order regarding skin temperature observed by Hennessey (1997). Because of the inconsistent fabric rankings observed in the current study when wearing the Tyvek-coverall standard garment, only the fabric ranking when wearing the T-shirt/pants standard garment was used in comparison. As a consequence of the fabric ranking comparison between the two studies, this hypothesis was mostly supported because of the agreement in two out of three cases. Hypothesis 14 was that the experimental fabric order with respect to sweat amount collected in the current study from the beginning to the end of the exercise in either the T-shirt/pants standard garment or the Tyvek®-coverall standard garment over the T-shirt and pants would be the same as the fabric order regarding sweat amount observed by Hennessey (1997). Hypothesis 14 was not supported because the fabric rankings of the two studies were not in agreement.

Besides the results of the testing of hypotheses 13 and 14, it may be noted that Hennnessey's fabric ranking on sweat amount was the same as the consistent fabric ranking on the left arm skin temperature when the baseline garment was a T-shirt and pants, in the current study. Therefore, in general, there is a feasibility of using sleeves, instead of a full garment, to assess thermal comfort of wearing chemical protective clothing.

CHAPTER VII

IMPLICATIONS AND FUTURE RESEARCH

It was found in this study that there may be a feasibility of using sleeves, instead of a full garment, in wear tests to assess thermal comfort and heat strain associated with wearing chemical protective clothing. This chapter addresses implications of the current study and its findings, and also further research that may be conducted to validate the findings of the current study and to advance knowledge of comfort.

Implications

The current study is exploratory, examining the feasibility of using sleeves, instead of a full garment, to assess thermal comfort and heat strain in chemical protective wear tests. According to the current experiment, such feasibility may exist when a T-shirt and pants are used as the standard garment with the sleeves. The use of sleeves as an alternative to a full garment reduce cost and time in conducting experiments. Therefore, the current study can serve as a building block for other researchers who wish to study the effects on thermal comfort and heat strain of other protective fabrics without utilizing whole garments.

The nonsignificant differences in skin temperature and sweat amount among the three body sites, i.e., the upper arms and the chest, suggested the potential to use one of those body site as a test site, as an alternative to the other in studying clothing comfort.

The ability to use alternative test sites may be specially useful when only small amount of fabrics are available.

A consistent fabric ranking regarding the left arm skin temperature was found when the T-shirt/pants standard garment was worn, which was in agreement with Hennessey's (1997) findings. The ranking that was found suggests that, if the protective abilities of the investigated fabrics are comparable, Pro/Shield I® is more suitable for use in chemical protective garment assemblies than are Tyvek® and Pro/Shield II®.

Future Research

To validate the current study's findings on the feasibility of using sleeves, further studies may be conducted in which a group of subjects performs two tests using the same experimental fabrics and having the same experimental protocol and environment; however, in one test, subjects would wear T-shirt and pants with experimental sleeves, and, in the other test, the subjects would wear a coverall, or a jacket, made of the same fabric as the experimental sleeve. Skin temperature and sweat amount could be measured at the same body site, though not simultaneously. Using the same group of subjects in those two tests is expected to reduce the effect of unknown extraneous variables. It may be more useful if such studies are conducted in real field tests.

Further research is also needed to determine the feasibility of using sleeves for assessing the thermal comfort associated with a wider range of fabric types and environmental conditions. Additional design work on sweat collection should also be

undertaken in an effort to achieve improved effectiveness of sweat amount as a parameter to assess thermal comfort.

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Appendix A. The Companion Study by Hennessey

Hennessey (1997) studied the effects of five distinct protective fabrics, which had been made into coveralls, on perceptual and certain physiological responses of the body. The five experimental fabrics were Tandec®, Tyvek®, Pro/Shield I®, Pro/Shield II®, and nonwoven cotton fabric with a polypropylene microporous film. The experiment was conducted in two types of environments, a neutral environment (72°F and 49% RH) and a hot and humid one (84°F and 60% RH). Each of five subjects participated in a total of 10 trials. In each trial, each subject wore an assigned coverall and exercised in a selected environment. The orders of the coveralls and the environments were randomized within each subject. A subject acclimatized in an environmentally-controlled room, which was either neutral or hot, for 30 minutes, and then exercised, on a stationary bicycle at a constant work rate of about 40% of his maximal oxygen consumption for 45 minutes. After the exercise, a two-minute cool-down was provided. The perceptual responses measured during the exercise were wetness, thermal, and overall comfort sensations and ratings of perceived exertion, whereas the physiological responses were skin and body temperatures, heart rate, sweat amount, and fluid loss. The present study used skin temperature and sweat amount measured in a hot and humid environment as the parameters to assess the feasibility of using sleeves, instead of a full garment, in chemical protective clothing wear tests. For that reason, only Hennessey's results for skin

temperature and sweat amount in the hot and humid environment were used in the assessment.

Hennessey (1997) measured skin temperatures on the back and the chest and averaged them to obtain mean skin temperature. Sweat was collected on the chest, the back, and one of the upper arms. Mean sweat amounts were obtained by averaging the sweat amounts measured at those three body sites. Hennessey found that, in the hot environment which is equivalent to the condition used in the current study, there were no significant differences in skin temperature nor in sweat amount among the experimental fabrics. At the 15-minute and 45-minute intervals of exercise, skin temperature was highest in the Tyvek® coverall, followed in order by the Pro/Shield II® coverall and the Pro/Shield I® coverall. The fabric ranking at the 30-minute interval was slightly different from the others, i.e., Pro/Shield II®, followed by Tyvek® and then Pro/Shield I®. Hennessey obtained the following fabric ranking was in ascending order of average sweat amounts: Tyvek®, Pro/Shield II®, and Pro/Shield I®.

Appendix B. Health-Screening[1] for Research on Thermal Comfort

The purpose of this study is to explore the feasibility of using sleeves, instead of full garments, to assess the thermal comfort and thermal stress associated with wearing chemical protective garments. Participation in this study is entirely voluntary. Before you participate in the main experiment, you will be asked to fill out the questionnaire and to perform the PWC_{170} test. The PWC_{170} estimates your work rate at 40% of your maximal oxygen consumption, determined while you pedal at increasing work load on a stationary bicycle. This test takes about 30 minutes. In the main experiment, you will participate in a total of 7 trials. In each trial, you will wear a pair of test sleeves, with or without a pair of layering sleeves, and have thirty minutes of acclimatization before pedaling for 45 minutes at the work rate obtained from the previous PWC_{170} test. The environmental conditions in the room where you will pedal are 86°F with 60% RH. Discomfort may result from the high temperature and humidity. Although risks in this experiment are minimal, knowing your health condition and medical history is a good way to prevent an unexpected situation.

[1]Developed from Physical Activity Readiness Questionnaire (PAR-Q).

Please answer the following questions about your demographic information, health condition and medical history.

YES	NO	
___	___	1. Are you within the age range of 18-28 years?
___	___	2. Are you within the height range of 67-70 inches?
___	___	3. Do you weigh between 150 and 180 lbs.?
___	___	4. Do you work out at least 2 hours a week?
___	___	5. Have you ever been in a hot and humid environment for a long time? If you have, how did you feel? _____ _____
___	___	6. Have you ever had heat exhaustion, heat stroke or fainted when you were exposed to heat and/or heavy exercise?
___	___	7. Do have any history of heart disease or high blood pressure?
___	___	8. Do you frequently have pains in your heart and chest?
___	___	9. Do you have a history of diabetes?
___	___	10. Do you have a history of asthma or lung disease?
___	___	11. Are you on any medications at this time?
___	___	12. Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise, or might be made worse with exercise?
___	___	13. Are you not accustomed to vigorous exercise?

___ ___ 14. Do you know of any reason, or any other current or chronic medical conditions, that might affect your ability to safely participate in this study?

If your answer to number 14 above is yes, explain: _____

_____

_____ _____

Date Volunteer's Name

Appendix C. Subjects' informed consent

Research Purpose

I hereby consent to voluntarily engage in this experiment for which the purpose is to explore the feasibility of using garment sleeves in the assessment of thermal comfort and thermal stress induced by chemical protective clothing.

Procedures

Before I undergo the experiment, I certify that to the best of my knowledge, I am in good health. Further, I have completed the questionnaire presented to me by the investigator and have provided correct responses to the questions as indicated on the history form. I understand that, prior to my undergoing the experiment, I will be interviewed by an investigator who will, in the course of interviewing me, determine if there are any reasons which would make it undesirable or unsafe for me to participate in the experiment. Consequently, I understand that it is important that I provide complete and accurate responses to the interviewer and recognize that my failure to do so could lead to possible unnecessary injury to myself during the experiment.

The tests which I will undergo are comprised of two parts: the PWC_{170} test and the main experiment. In the PWC_{170}, I will perform a steady-state exercise with an increasing work load on a stationary bicycle. This test takes about 30 minutes. The main experiment consists of seven trials. In each trial, I will wear portions of garments provided by the investigator and have thirty minutes of acclimatization before pedaling at

the work rates established from the previous PWC_{170} test. The environmental condition to be used is 86°F with 60% RH. Throughout the tests, the investigator will monitor my skin temperature (by the Vitalog), body temperature (by an oral thermometer), and heart rate (by the Vitalog), and I will be asked to rate my perceived comfort. The investigator will also collect my sweat on the arms. I understand that the exercise in each trial will continue for 45 minutes or until I begin to feel fatigue, nausea, shortness of breath, or chest discomfort. If I choose, I can request to stop the exercise if I feel any of the above symptoms. Moreover, if my heart rate is extremely high and/or body temperature is greater than 39°C, I will be required to withdraw from the test.

Risks

I have been informed, and I understand, that risks of harm or injury in this experiment associated with this participation are minimal. The potential discomfort is that which may result from the length and heat stress of the experiment. However, there are very slight risks of heart attack or death. The investigator is certified by the American Heart Association to provide basic CPR in the event of a problem, and an emergency telephone will be available for Virginia Tech Rescue Squad and 911 Rescue.

Benefits

Benefits of this study are 1) knowing the feasibility of using sleeves to assess thermal comfort and thermal stress associated with wearing chemical protective garments, and 2) knowing the effect of layering on thermal comfort and thermal stress.

I understand that no guarantee of benefits has been made to encourage me to participate.

I may receive a synopsis or summary of this research when completed.

Confidentiality

I understand that each participant will be identified by code, and the investigator promises not to divulge the identity. Neither the individual's social security number nor his name will be used as identifiers. The results of this study will be kept strictly confidential. At no time will the investigator release the results of the study, identified for a certain subject, to anyone other than individuals working on the project without the subject's written consent.

Compensation

I understand that I voluntarily participate in this study. There is no financial compensation for participation in this study.

Freedom to Withdraw

I may withdraw at any time without penalty. I am free not to answer any questions or respond to experimental situations without penalty.

Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University, and by the Department of Clothing and Textiles.

Release

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby release, hold harmless, and indemnify the investigator conducting this experiment, Virginia Polytechnic Institute and State University, and its employees from any and all liability or responsibility for any injury or illness which may arise out of my participation in this experiment.

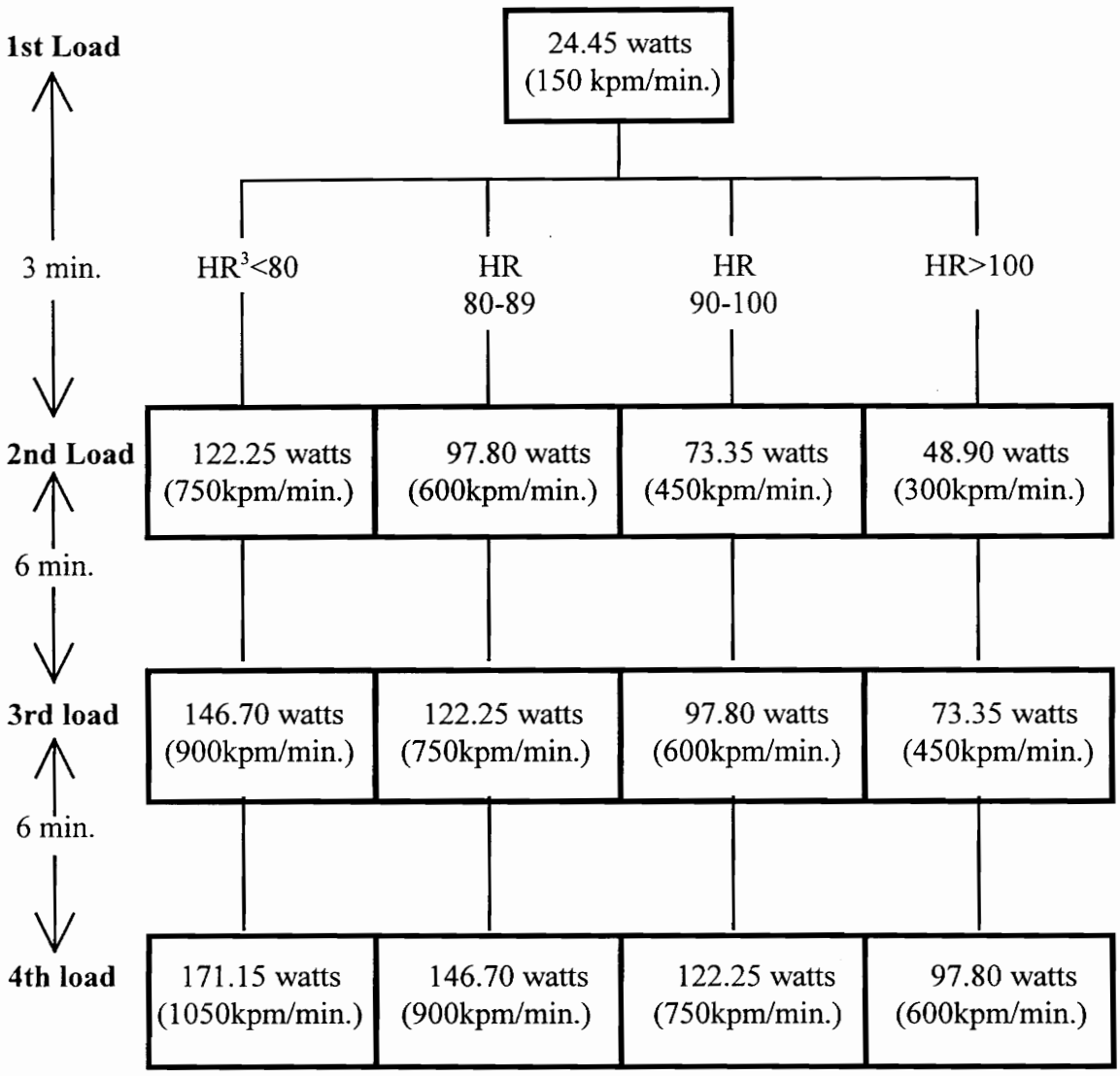
If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Date	Subject Signature	Witness/Investigator Signature

Should I have any questions about this research or its conduct, I may contact:

Angkhana Tultrairat Investigator	951-9277 Phone
Marjorie Norton Faculty Advisor	1-5731 Phone
E.R. Stout Chair, IRB Research Division	1-9359 Phone

Appendix D. YMCA protocol for submaximal cycle ergometer tests[2]



[2]Reprinted from Exercise Physiology (p. 322), by Scott K. Powers and Edward T. Howley, 1994, with permission of the YMCA of the USA, 101 N. Wacker Drive, Chicago, IL 60606.
[3]HR stands for heart rate (beats/min.).

Appendix E. Analysis of garment-site interaction at each time interval

Time (min.)	Source	df	SS	MS	F	p
0	Garment	6	36.737	6.123	3.89	0.0027
0	Site	2	25.183	12.591	13.30	0.0003
0	Garment . Site	12	14.841	1.237	2.20	0.0162
5	Garment	6	69.846	11.641	4.96	0.0004
5	Site	2	24.719	12.359	13.76	0.0002
5	Garment . Site	12	18.740	1.562	3.41	0.0003
10	Garment	6	126.615	21.102	6.36	0.0001
10	Site	2	31.758	15.879	15.08	0.0001
10	Garment . Site	12	29.922	2.493	4.42	0.0001
15	Garment	6	90.223	15.037	5.39	0.0002
15	Site	2	33.181	16.590	20.06	0.0001
15	Garment . Site	12	30.838	2.570	3.39	0.0003
20	Garment	6	84.206	14.034	6.48	0.0001
20	Site	2	43.055	21.527	17.42	0.0001
20	Garment . Site	12	27.771	2.314	3.99	0.0001
25	Garment	6	100.855	16.809	6.88	0.0001
25	Site	2	48.645	24.322	23.80	0.0001
25	Garment . Site	12	22.885	1.907	3.30	0.0004
30	Garment	6	84.235	14.039	6.32	0.0001
30	Site	2	51.734	25.867	26.14	0.0001
30	Garment . site	12	25.318	2.110	3.44	0.0003
35	Garment	6	89.811	14.968	6.28	0.0001
35	Site	2	49.401	24.701	22.23	0.0001
35	Garment . Site	12	23.963	1.997	3.42	0.0003

Time (min.)	Source	df	SS	MS	F	p
40	Garment	6	95.604	15.934	8.23	0.0001
40	Site	2	48.539	24.270	25.15	0.0001
40	Garment • Site	12	31.702	2.642	4.01	0.0001
45	Garment	6	74.930	12.488	7.13	0.0001
45	Site	2	50.435	25.217	24.08	0.0001
45	Garment • Site	12	19.491	1.624	2.69	0.0034

Appendix F. Analysis of body site effect at individual levels of garment options and time intervals

Garment	Time (min.)	Source	df	SS	MS	F	p
SG1	0	Site	2	1.769	0.885	2.29	0.1302
	5	Site	2	0.578	0.299	0.76	0.4824
	10	Site	2	0.106	0.053	0.11	0.8982
	15	Site	2	0.235	0.118	0.14	0.8720
	20	Site	2	0.862	0.431	0.54	0.5937
	25	Site	2	0.372	0.186	0.25	0.7816
	30	Site	2	1.305	0.652	0.69	0.5126
	35	Site	2	2.659	1.330	1.49	0.2525
	40	Site	2	0.365	0.183	0.16	0.8507
	45	Site	2	3.332	1.666	2.02	0.1613
SG1T	0	Site	2	10.739	5.369	3.63	0.0475
	5	Site	2	11.953	5.976	5.43	0.0143
	10	Site	2	20.519	10.259	8.50	0.0025
	15	Site	2	21.071	10.536	10.85	0.0008
	20	Site	2	20.208	10.104	11.87	0.0005
	25	Site	2	26.701	13.351	16.53	0.0001
	30	Site	2	26.960	13.478	12.95	0.0003
	35	Site	2	32.024	16.012	25.38	0.0001
	40	Site	2	29.585	14.792	16.91	0.0001
	45	Site	2	20.008	10.004	8.78	0.0022
SG1PI	0	Site	2	12.275	6.138	10.71	0.0009
	5	Site	2	13.027	6.514	11.58	0.0006
	10	Site	2	15.831	7.915	12.47	0.0004
	15	Site	2	19.144	9.572	15.32	0.0001
	20	Site	2	22.034	11.017	14.00	0.0002
	25	Site	2	20.535	10.268	19.21	0.0001
	30	Site	2	21.858	10.926	12.64	0.0004
	35	Site	2	16.811	8.406	16.42	0.0001
	40	Site	2	13.507	6.753	8.29	0.0028
	45	Site	2	16.699	8.349	14.20	0.0002
SG1PII	0	Site	2	1.290	0.645	2.54	0.1065
	5	Site	2	11.593	5.796	12.54	0.0004
	10	Site	2	17.142	8.571	18.58	0.0001

Garment	Time (min.)	Source	df	SS	MS	F	p
SG1PII	15	Site	2	17.343	8.671	9.43	0.0016
	20	Site	2	20.751	10.376	14.31	0.0002
	25	Site	2	14.582	7.281	10.41	0.0010
	30	Site	2	18.898	9.449	21.16	0.0001
	35	Site	2	16.919	8.460	12.37	0.0004
	40	Site	2	31.041	15.521	24.50	0.0001
	45	Site	2	23.218	11.609	26.94	0.0001
SG2	0	Site	2	2.601	1.300	1.79	0.1960
	5	Site	2	1.477	0.739	1.33	0.2883
	10	Site	2	2.339	1.170	1.90	0.1782
	15	Site	2	3.281	1.641	2.19	0.1408
	20	Site	2	1.225	0.612	1.06	0.3685
	25	Site	2	3.447	1.724	2.38	0.1214
	30	Site	2	1.536	0.768	1.71	0.2087
	35	Site	2	1.460	0.730	0.91	0.4207
	40	Site	2	2.961	1.481	3.33	0.0590
	45	Site	2	2.601	1.300	2.09	0.1523
SG2PI	0	Site	2	7.629	3.815	7.15	0.0052
	5	Site	2	2.918	1.459	4.62	0.0239
	10	Site	2	5.426	2.713	3.94	0.0381
	15	Site	2	1.251	0.625	0.78	0.4738
	20	Site	2	4.227	2.114	4.77	0.0218
	25	Site	2	4.059	2.029	5.71	0.0120
	30	Site	2	4.011	2.006	5.40	0.0145
	35	Site	2	2.555	1.278	2.44	0.1151
	40	Site	2	1.769	0.8845	2.05	0.1574
	45	Site	2	2.108	1.054	2.42	0.1169
SG2PII	0	Site	2	3.722	1.861	5.19	0.0166
	5	Site	2	1.892	0.946	3.66	0.0464
	10	Site	2	0.318	0.159	0.47	0.6323
	15	Site	2	1.693	0.847	1.87	0.1823
	20	Site	2	1.519	0.759	1.45	0.2610
	25	Site	2	1.834	0.917	1.48	0.2546
	30	Site	2	2.491	1.245	2.24	0.1350
	35	Site	2	0.935	0.468	0.83	0.4537
	40	Site	2	1.013	0.507	0.84	0.4484
	45	Site	2	1.959	0.980	1.54	0.2421

Appendix G. Manuscript Draft

Physiological and Perceptual Assessment of Thermal Comfort and Heat Strain in Garment Wear Tests Using Sleeves: An Alternative to Full-Garment Tests of Chemical Protective Clothing

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Category: Textiles, fiber and polymer science

Physiological and Perceptual Assessment of Thermal Comfort and Heat Strain in Garment Wear Tests Using Sleeves: An Alternative to Full-Garment Tests of Chemical Protective Clothing

(ABSTRACT)

This study was conducted to explore the feasibility of using sleeves in garment wear tests for assessing the thermal comfort of chemical protective clothing by comparing measured skin temperature and sweat amount to those found by Hennessey's (1997). The effect of body sites, i.e. the arms and the chest, and the effect of a Tyvek® coverall on skin temperature and sweat amount were investigated as well. Results showed there is a feasibility in using a sleeve with a T-shirt/pants standard garment for assessing thermal comfort in chemical protective garment wear tests. The T-shirt/pants standard garment yielded more consistent and reliable results than did the Tyvek®-coverall standard garment. Under the same conditions, there were no significant differences in skin temperature and sweat amount among the left and right upper arms and the chest. The Tyvek® sleeve in this study impeded the transfer of heat by the greatest amount, followed by the Pro/Shield II® sleeve and the Pro/Shield I® sleeve, respectively.

Physiological and Perceptual Assessment of Thermal Comfort and Heat Strain in Garment Wear Tests Using Sleeves: An Alternative to Full-Garment Tests of Chemical Protective Clothing

Thermal comfort is an important aspect of chemical protective garments, in addition to such garments' abilities to protect and allow mobility. Ineffective heat transfer characteristics of fabrics, together with working conditions that are hot and humid, contribute directly to the development of heat stress and heat illness in workers (Santee & Wenger, 1989). A number of studies have assessed thermal discomfort and heat strain during the wearing of chemical protective clothing (for example, Branson, DeJonge, & Munson, 1986), and many studies have used physiological and perceptual measurements as tools to assess comfort (for example, Santee & Wenger, 1989). Comfort assessments in research have mostly been with full garments. So far, there is no evidence of using garment parts in studies to assess comfort related directly to chemical protective clothing. However, some researchers (Hatch, Wilson, & Maibach, 1987; Wester, Hatch, & Maibach, 1985; Wilson & Dallas, 1990) have used pieces of fabrics placed on the arms to study comfort. Zimmerer, Lawson, and Calvert (1986) have validated the reliability of forearm skin as a test site. Hyun, Hollies, and Spivak (1990) have documented the effectiveness of using garment parts, instead of whole garments, in their study to quantify subjective measurements in garment comfort studies. The research team also proposed the idea of using garment parts as an alternative to full garment wear testing. The proposal, together with the documented effectiveness of using garment parts,

suggests the idea of using garment parts to assess thermal discomfort and heat strain caused by wearing chemical protective clothing. Using garment parts, instead of full garments, also may be more convenient and may reduce experiment time and cost.

The main purpose of this research was to explore the feasibility of using sleeves in garment wear tests for assessing the thermal comfort and thermal strain of chemical protective garments by comparing measured skin temperature and sweat amount to those found by Hennessey (1997)[1]. The effects of body sites, experimental sleeves, and a Tyvek® coverall on measured skin temperature and sweat amount were investigated as well.

Conceptual Framework

In warm and hot environments, when the amount of heat gain is larger than that of heat loss, the body's heat load increases, resulting in thermal discomfort and heat stress. The American Society of Heating, Refrigeration and Engineering (1981) defined thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (p. 8.19). Kerslake (1972) stated that an object could be subjected to stress imposed from outside, which will induce strain in the object. In the case of human heat stress, the stress is defined solely in terms of environment, including clothing, and heat strain is a consequence of the stress and the physiological characteristics of the subject.

Wearing a chemical protective suit with poor heat dissipation characteristics, while working in a hot environment can easily cause thermal discomfort and heat strain in

workers because heat built up in the body (active tissues or organs) cannot be transferred effectively to the outside environment. Heat build-up in the active tissues while a person works or exercises will cause thermal imbalance and rises body core temperature. To maintain homeostasis, heat from the core must be transferred to the environment through the skin and clothing. Heat transfer from the core to the skin occurs by a) tissue conduction and b) blood convection, or vasodilatation. A consequence is the rise in skin temperature. For a clothed person, heat transfer is impeded in certain amount by fabric characteristics. The hindrance of heat transfer by clothing causes the rise in the skin-clothing microclimate temperature. Thermal receptors in the skin senses the temperature rise and send impulses to central nervous system (CNS) where the integration of the impulses takes place. The CNS, then, initiates both psychological and physiological responses. The psychological responses are thermal, wetness, and comfort sensation, whereas the physiological responses are increases in heart rate, skin temperature, and sweat production. The stimulus to promote the vasodilatation and sweating will be removed after the body reachieve homeostasis. If the homeostasis cannot be achieved, a person will experience thermal strain.

Responses of body to heat load when a regular clothes is worn with an protective sleeve on one arm is in the same pattern as when a full garment is used. However, heat transfer is impeded mostly on the arm with the protective sleeve, resulting in an greater

[1] Hennessey (1997) used the same experimental protocol and the same test fabrics, but experimental fabrics were assembled in coveralls rather than sleeves only.

increased microclimate temperature on that arm, as compared to other body sites. The increased microclimate temperature will be detected by thermal receptors under the skin and, then, the impulses will be sent to central nervous system, causing response of the body by increasing skin temperature and sweat amount.

Methodology

Subjects

Male university students were recruited as volunteers to participate in the study. The volunteers were prescreened for health issues and were within the age range of 19-28 years and 67-71.25 inches in height, and weigh between 157-174 lbs.

One week prior to the beginning of the experiment, the subjects were given an explanation of the experiment before giving their written informed consent. They were oriented to the equipment and the procedures used in the experiment.

Environment

The experiment was conducted, from June to August, 1996, in the environmentally-controlled research laboratory. The test environment was set at 86°F, the average daily maximal temperature the region (NOAA, 1990-1992), and 60% relative humidity (RH), the average humidity at 1 PM (local time) in the region (NOAA, 1990-1992).

Equipment

The Pocket-Polygraph™ Vitalog HMS-5000 (Vitalog Respironics Inc., Redwood, CA), a physiological monitoring and actuating system, was used for measuring and

recording subjects' skin temperature and heart rate. Body temperature was measured by a Flexible™ oral, digital thermometer (Becton Dickinson and Company, Frankin Lakes, NJ.

Schwinn™ Airdyne Windsprint (Schwinn, Boulder, CO), a stationary ergometer, served as an exercise tool. The pedaling resistance could be adjusted in three levels. Powers, or work rates, shown on the panel were expressed in both watts and kilopond-meter/minute (kpm/min.). The rider's cadence of pedaling also was shown on the panel. A metronome was employed to provide a cadence, of pedaling, which resulted in the target work rate of each subject in the main experiment.

The sweat patch used in the experiment had three layers: a nonadhering dressing (Tegaderm™, 3M Health Care, St. Paul, MN) made of polyurethane and acrylate adhesives; a release liner of Saran Wrap® polyvinylidene chloride film; and a sweat collection pad, a medical grade cellulose blotter (Hermitage™ Poly Pads by Hermitage Hospital, Niantic, CT). The collection pads and the Saran Wrap were cut into 2.5 cm^2 (one-inch squares). The Saran Wrap served as a release liner between the dressing and the collection pad placed directly next to the skin.

Additionally, Borg's ratings of perceived exertion, or RPE, (Powers & Howley, 1994) ranging from six (very, very light) to 20 (very, very hard) was employed to assess subjective perception during exercise.

Fabrics and Test Specimens

Two types of standard garments were used in this study. Standard garment No.1

(SG1) was composed of 100% cotton, white short-sleeved T-shirt (Fruit of the Loom®) and a pair of 100 % cotton, khakis, work pants (Duxbak®). The pants were long, somewhat tapered in the legs and described on the label as anti-wrinkle. Standard garment No.2 (SG2) consisted of SG1 and a Tyvek® coverall. The Tyvek® coverall was worn over SG1. Tyvek®, or Tk, (DuPont, Style 1422A), a spunbonded fabric, is made of sub-micron denier, high-density polyethylene filaments that are bonded together with heat and pressure. This fabric is widely used for chemical protective purposes in both practical applications and research.

The study included two additional chemical protective fabrics Pro/Shield I®, or PI, and Pro/Shield II®, or PII, (both from Kappler Safety Group, Guntersville, AL), which were made into experimental sleeves of the same pattern as the sleeves in the Tyvek® coverall. Pro/Shield I® is a thermally bonded tri-laminate fabric consisting of a middle layer of meltblown polypropylene sandwiched between two outer layers of spunbonded polypropylene. Pro/Shield II® is a bi-laminte of spunbonded polypropylene and microporous polypropylene film. Pro/Shield I® and Pro/Shield II® were selected for this research because the manufacturer (Kappler Safety Group) described them as permeable to water vapor, but impervious to water-based liquids; these two fabrics also have a slightly hairy surface texture which is less like paper than is Tyvek®. Table 1 shows physical characteristics of the test fabrics and of fabrics in the T-shirt, and pants.

Table 1. Physical Characteristics of Test Fabrics (at 70°F, 65% RH, after conditioning for ≥24 hours).

Test fabrics	Weight[1] (g/m^2)	Thickness[2] (cm)	Moisture vapor transmission[3] ($g/m^2/24hrs$)	Capillary retention[4] (g)	Capillary transmission[4] (g)	Capillary		
						retention[5] in T-shirt fabric (g)	retention[5] in test fabric (g)	transmission[5] through test fabric (g)
Tyvek®	41.05	0.0164	841.40	0.0004	0.0006	0.4322	0.0005	0.0061
Pro/Shield I®	64.17	0.0559	1346.23	0.0007	0.0011	0.4261	0.0000	0.0081
Pro/Shield II®	64.14	0.0583	841.40	0.0005	0.0000	0.4239	0.0003	0.0063
Jersey knit	168.18	0.0868	2013.35	0.3457	0.0985	-	-	-
Duck	964.08	0.0875	842.89	0.3633	0.0954	-	-	-

[1] Measured according to ASTM D3776-85 method.
[2] Measured according to ASTM D1777-64 (1975) method.
[3] Measured according to ASTM E96-95 (Procedure D) method.
[4] Testing done according to the test method used by Sarin (1994). 0.5 ml of an artificial perspiration solution was pipetted onto the inner side of the test fabric to simulate how sweat from the body comes into contact with clothing. Retention is that amount of the 0.5-ml solution held within the fabric structure after ten minutes. Transmission is that amount of the 0.5 ml solution which moved through the fabric and was absorbed by the blotter underneath.
[5] Testing done according to the test method used by Sarin (1994). 0.5 ml of an artificial perspiration solution was pipetted onto the inner side of the jersey T-shirt fabric when layered with the test fabric to simulate how sweat from the body comes into contact with clothing. Retention is that amount of the 0.5-ml solution held within the fabric structure after ten minutes. Transmission is that amount of the 0.5-ml solution which moved through the fabric and was absorbed by the blotter underneath.

Figure 1 illustrates standard garments No.1 and No. 2, and an experimental sleeve on the standard garments. Before initiating the experiment, standard garment No.1 (T-shirt and pants) as well as provided socks, were laundered five times according to AATCC Test Method 143, with AATCC Standard Reference Detergent 124 to eliminate shrinkage and appearance problems. The pants were reused throughout the experiment, whereas new T-shirts and socks were provided and used for each trial. Standard garment No.2, as shown in Figure 1, was a coverall with a zipper up the front. The coverall had been designed to be closely fitted at the wrists and ankles by elastic, to increase protection against penetration of pesticides. For purposes of this research, the coverall's left sleeve was made detachable, so experimental sleeves could be attached in its place. The detachability allowed the reuse of standard garment No.2, with alternating experimental sleeves, in the trials to assess comfort and heat stress.

An experimental sleeve, made of Tyvek® or Pro/Shield I® or Pro/Shield II® and having an elasticized wrist, was attached to the left armscye of standard garment No.1 or 2 with duck tape of half-inch width. Standard garment No.2 was prepared for the trials by reinforcing its left armhole all the way around with a layer of duck tape to prevent tearing of the Tyvek® fabric due to repeated attachment and detachment of the experimental sleeves. Moreover, to minimize extraneous effects of the tape, two layers of duck tape were also applied on the right armscye of that garment. Likewise, standard garment No.1 was taped with two layers of duck tape around the right armscye as well as the left as well as the left armscye, with or without an experimental sleeve over the T-

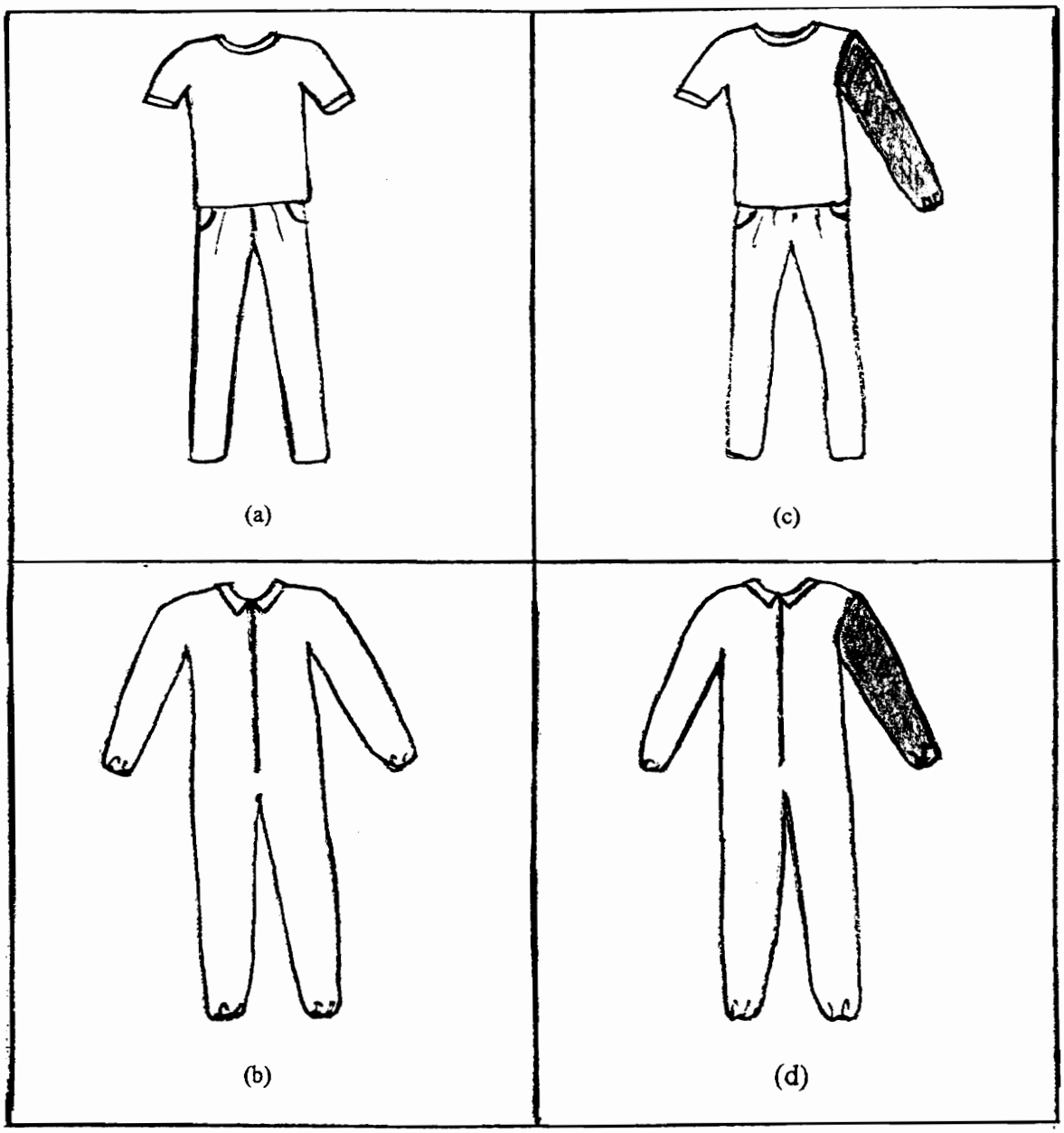

Figure 1. Schematic representation of standard garment No.1 (a), standard garment No.2 (b), standard garment No.1 with an experimental sleeve on the left arm (c), and standard garment No.2 with an experimental sleeve on the left arm (d).

shirt sleeve.

Experimental Trials and Garments Worn in Each Trial

Each subject performed a total of 8 trials: a trial of the physical work capacity test and 7 subsequent trials of the main experiment. In each trial, including the physical work capacity test, the subject wore his own underpants and sneakers, together with provided socks and the assigned garments. In the physical work capacity test, a subject also wore standard garment No.1 (SG1) consisting of a pair of pants and a T-shirt, without duck tape around the armholes.

In the main experiment, each subject participated in 7 trials. All garments used in the trials had duck tape as described in the previous section. In trial 1, the subject wore SG1 without an experimental sleeve. In trials 2-4, the subject wore SG1 together with a sleeve of an experimental fabric (Tk, PI, or PII) over the left sleeve of the T-shirt. In trials 5-7, the subject wore SG2 over SG1 (SG1 served as an undergarment). The subject wore SG1 and SG2, with both of the original Tyvek® sleeves of SG2, to perform trial 5. In trials 6 and 7, a sleeve of PI or of PII replaced the left sleeve of SG2.garment No.1 (SG1) consisting of T-shirt and a pair of pants, without duck tape around the armholes.

Experimental Procedure

The physical work capacity test at target heart rate at 170 beats/min.(PWC_{170}). This test was used to determine work capacity at the intensity of about 40% of a subject's maximal oxygen consumption. To perform this test, a subject worn provided T-shirt and a pair of pants and his own sneakers. He was prepared for heart rate monitoring by

adhering, to his chest, three electrocardiogram (ECG) leads connected to the Vitalog before entering the environmentally controlled room. Heart rate was recorded every minute from rest to the end of the test. In the room, the subject rested on the bicycle for 10 minutes and then pedaled, without pedaling resistance, to warm up for two minutes. Then, the YMCA cycle ergometer protocol for submaximal tests (Powers & Howley, 1994) was applied to select work rates for submaximal exercise. The exercise was terminated when the subjects' heart rate was around 170 beats/min. Every 3 minutes during the exercise, the investigator asked the subject to call out RPE. The work rates recorded from the panel of the bicycle and the averaged heart rates of the last two minutes of each stage were used to plot, for each subject, a graph of work rate (X-axis) vs. heart rate (Y-axis). A line of best fit for the relationship between work rate and heart rate was drawn. The work rate that corresponded to a heart rate of 40% of the predicted heart rate range served as the work rate at about 40% of the maximal oxygen consumption. The heart rate range was the difference between the predicted maximal heart rate and the heart rate at rest. The maximal heart rate was predicted as the difference between 220 beats/min. and subject's age, whereas the averaged heart rate of the last two minutes at rest will be used as the heart rate at rest.

The criteria for removal of a subject from the chamber during the test are (a) heart rate of (220 - his age) beats/min, (b) nausea, vomiting, or disorientation, or (c) request by the subject.

Experiment. Subjects were instructed not to take drugs, medication, or alcohol for a 12-hour period preceding the experiment. The night before a subject's test, he would be called by telephone to remind him of these instructions, his scheduled appointment time, and the importance of at least a six-hour sleep.

Upon arrival on the scheduled date, a subject changed into a short-sleeved T-shirt, a pair of pants, socks, and sneakers. The short-sleeved T-shirts, pants, and socks were provided by the investigator. The investigator weighed three non-reusable sweat collection pads separately and recorded their weights. The subject was prepared for heart rate and skin temperature monitoring as well as sweat collection. Sweat patches and temperature sensors were put on the subject's chest and both upper arms.

Then, the subject put on a garment assigned to him for the particular test. The order of treatments, or garments, was randomized within each subject. Before entering the environmentally controlled room, the subject was weighed.

In the environmentally controlled room, the subject was seated on a chair for a 30-minute acclimatization. During this period, the subject could drink 16 oz. of water. After acclimatization, the subject started pedaling on the bicycle without resistance for a two-minute warm-up. The subject, then, pedaled for 45 minutes at the work rate obtained from the previous PWC_{170} test. Two-minute cool-down was provided after the exercise. Four measurements were taken every five minutes from the beginning to the end of the exercise. The four measurements were: heart rate; body temperature; RPE; and skin temperature. The first three measurements served only as safeguards. To

determine sweat amount, at the end of the cool-down, each of the sweat collection pads was removed from the subject's body and weighed immediately. Sweat amount during exercise was the difference of the pre-weight and the final weight of the pad in milligrams (mg) divided by the area of the pad (cm^2).

The subject was removed from the environmental room to an unconditioned room and weighed again. The subject, then, changed, to his own clothes and was given 16 oz. of water for every pound of weight loss to prevent dehydration. Thirty-minute recovery was provided to observe signs of distress before the subject was released.

Addition to the criteria for removing a subject from the chamber in the PWC_{170} test, the subject would also be removed if his rating of perceived exertion was 17 or higher.

Data Analysis

The repeated measures design with three-within subject variables (garments, body sites, and time intervals) was applied to analyze skin temperature while the repeated measures design with two-within subject variables (garments and body sites) was applied to analyze sweat amount. Post hoc analysis was accomplished by Least Significant Difference (LSD) test.

Results and Discussion

Effect of Body Sites on Skin Temperature and Sweat Amount

Skin temperature. To investigate how the arms and the chest response to heat load, skin temperature and sweat amount were measured on both upper arms and the

chest. The results of the analysis showed that, the effect of body sites on skin temperature were not significant, at every time interval, with $F(2,18) = 0.11\text{-}2.29$, $p \leq 0.05$ when wearing SG1, and $F(2,18) = 0.91\text{-}3.33$, $p \leq 0.05$ when wearing SG2. That is, under the same exposed conditions, measured skin temperatures on the left and right arms and the chest were not significantly from each other in the cases of those garments.

Table 2 exhibits mean skin temperatures (averaged over subjects and nonsignificantly different among body sites) and standard deviations of wearing SG1 and SG2. The small difference in mean skin temperature between the left and the right arms with wearing either SG1 or SG2 suggests that both arms may react to an increased heat load in the same manner and even in quite similar amount. Therefore, either arm can be used as a test site, and the findings on one arm can be inferred from the other arm. The small difference in mean skin temperature between the arms and the chest, with wearing either of the standard garments, implies that the arms and the chest may react to an increased heat load in similar way and amount. So, there may be possibility of using an arm, instead of the trunk (or the chest), as a test site to assess thermal comfort.

Notice in Table 2 that mean skin temperatures measured on the arms were slightly higher than those measured on the chest; this is in agreement with findings by Houdas and Ring (1982). Houdas and Ring found that in a warm environment, which is comparable to the skin-garment microclimate in the current study, skin temperature on the upper arm was slightly higher than that on the chest.

Table 2. Skin Temperature Means (Averaged over Subjects and Nonsignificantly Different among Body Sites) and Standard Deviations with Wearing SG1 and SG2.

Garment	Body site	M (°F)	SD (°F)
SG1	Right arm	94.4	1.8
	Left arm	94.3	1.6
	Chest	94.1	1.4
SG2	Left arm	96.2	1.3
	Right arm	95.9	1.1
	Chest	95.5	1.4

Sweat amount. No significant differences in sweat amounts were found among body sites, $F(2,18) = 0.79$, $p \leq 0.05$. Table 3 exhibits mean sweat amount and standard deviation on each body site when each garment was worn. The sweat amounts on the three body sites were very close when SG1 was worn, and were much closer than when SG2 was worn; however, as reported in Table 3, sweat amount did not differ significantly (5% level) among body sites for any of the garment options. The low sweat amount on the right arm, as compared to the other two body sites, when subjects wore SG2 may have resulted from unknown extraneous variables. The high standard deviations may be a consequence of the differences among subjects in their sweat production. Because of the insignificant body site effect among garments worn and the high standard deviations within sites and garments, the conclusion that, under the same exposed conditions, or when other variables were being controlled, the three body sites would respond to a given increased heat load in the same manner could not be made. Moreover, the unknown extraneous variables and the high standard deviation make sweat amount be a less useful measurement than skin temperature.

Effect of Experimental Fabrics on Skin Temperature and Sweat Amount

Skin temperature. Because the garment effect on skin temperature was significant, $F(6,54) > 1.79$, $p \leq 0.05$, at every combination of body sites and time intervals. Graphs of mean skin temperature at each body site when each garment was

Table 3. Mean Sweat Amount and Standard Deviation at Each Body Site, When Each Garment was Worn.

Garments	Sweat amount (mg/cm^2) on					
	Left arm		Chest		Right arm	
	M	SD	M	SD	M	SD
SG1	52.60	32.27	53.59	18.08	55.47	24.47
SG1T	56.37	36.53	61.80	33.43	55.61	33.07
SG1PI	60.66	30.04	61.31	30.81	55.96	26.80
SG1PII	49.48	29.69	64.60	36.96	50.02	17.39
SG2	64.27	49.80	66.54	33.56	56.00	43.03
SG2PI	59.79	40.83	65.82	30.83	54.20	39.03
SG2PII	69.07	40.21	69.65	37.23	63.60	40.51

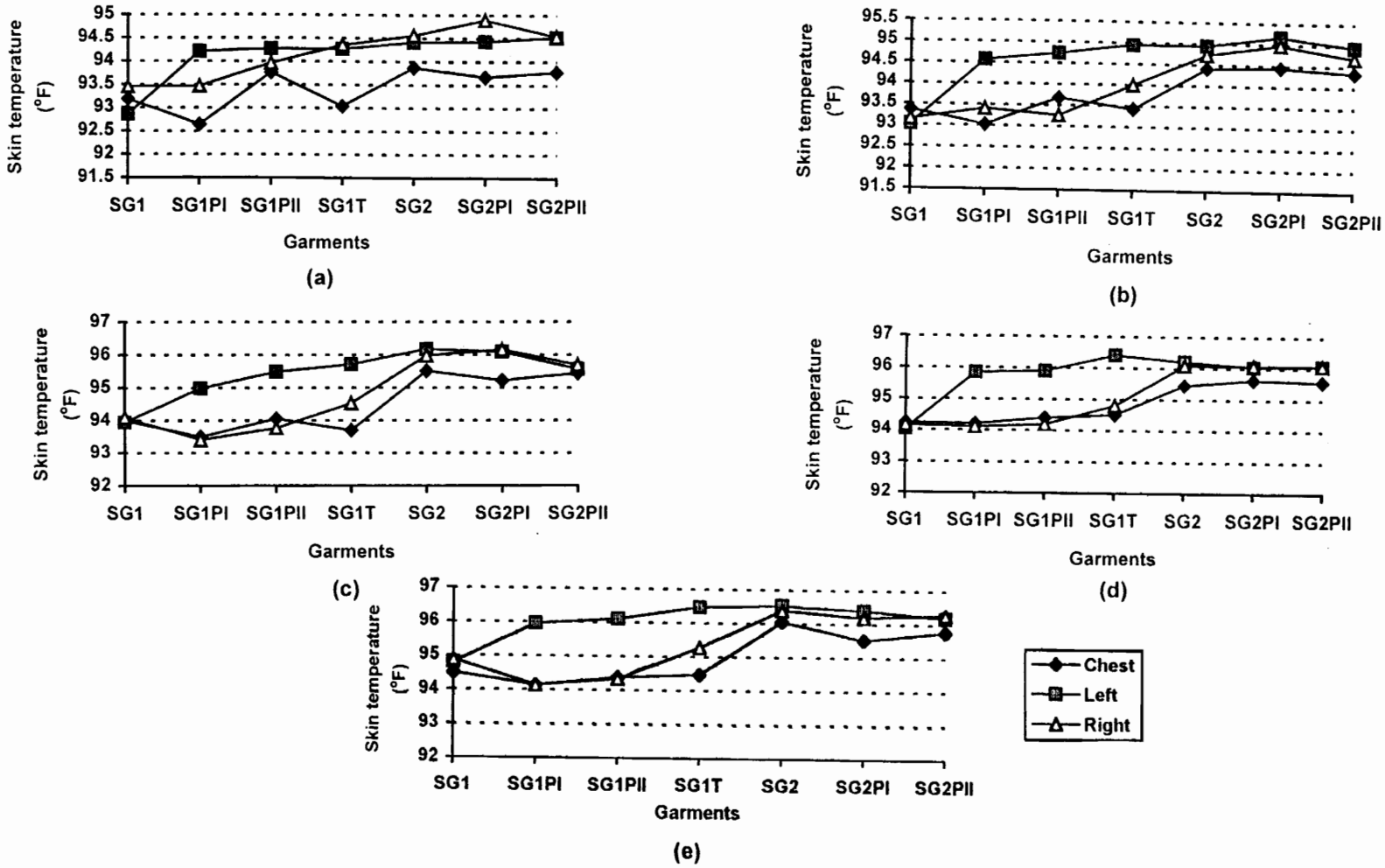

Figure 2. Garment effects on measured skin temperature at each body site at the beginning (a), five-minute (b), 10-minute (c), 15-minute (d), and 20-minute (e) of exercise.

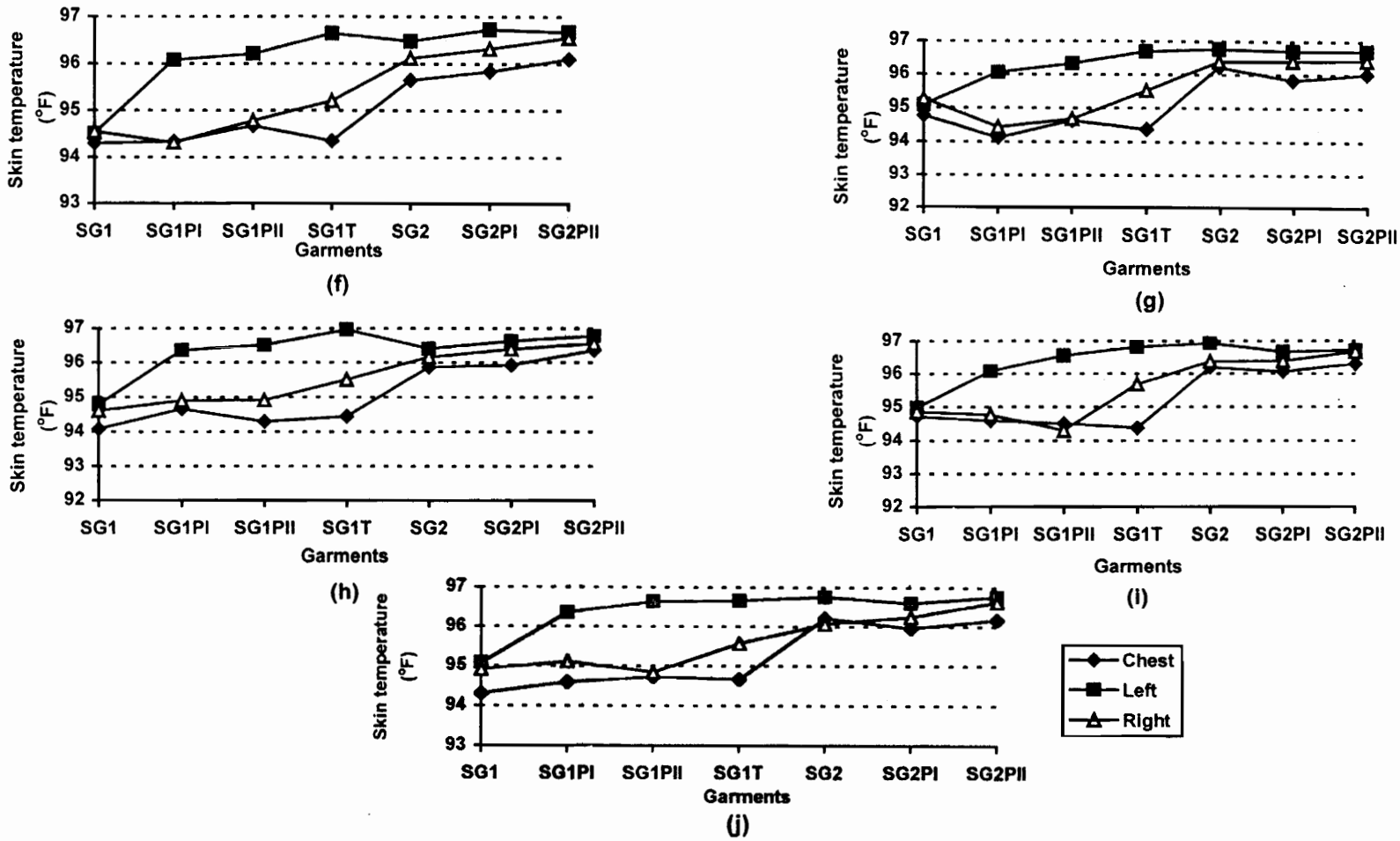

Figure 2. (cont.) Garment effects on measured skin temperature at each body site at the 25-minute (f), 30-minute (g), 35-minute (h), 40-minute (i), and 45-minute (j) of exercise.

worn (Figure 2) and the Fisher's least significant difference comparison (Table 4) show that, at any given time interval, the left arm skin temperature with wearing SG1 was always lower than that with wearing other garments and the mean skin temperatures on the left arm were significantly different between SG1 and each other garment in the study. These results indicate the effect of the experimental sleeves on skin temperature. Wearing SG1 resulted in the lowest skin temperature because no experimental fabric having poor heat dissipation properties was present to impede heat transfer from the body to the outside environment.

Figure 2 and Table 4 also show that, at any given time, when the standard garment of T-shirt and pants was worn with alternating experimental sleeves on the left arm, left arm skin temperature was highest with the Tyvek® sleeve, followed in order by that the Pro/Shield II® sleeve and the Pro/Shield I® sleeve. The fabric trend seen from the left arm was not observed for the right arm nor the chest.

Subjects wearing a Tyvek® sleeve, as opposed to a Pro/Shield II sleeve®, over the left sleeve of the T-shirt experienced higher skin temperature on the left arm, even though these two fabrics had quite similar moisture vapor and liquid transmission characteristics (see Table 1). The lower skin temperature with Pro/Shield II® may be due to better wicking as a consequence of that fabric's slightly hairy surface texture on its inner side and the microporous film on its outer side. During exercise, the hairy surface of Pro/Shield II® may adsorb and wick moisture from the skin, through its vapor-permeable

Table 4. Fisher's Least Significant Differences of Mean Skin Temperature by Body Site with Wearing Each Test Garment.

Left arm		Chest		Right arm	
M (°F)	Garment	M (°F)	Garment	M (°F)	Garment
96.2_{a}	SG2	95.6_{a}	SG2PII	96.0_{a}	SG2PII
96.2_{a}	SG1T	95.5_{a}	SG2	96.0_{a}	SG2PI
96.1_{a}	SG2PI	95.4_{a}	SG2PI	95.9_{a}	SG2
96.1_{a}	SG2PII	94.4_{b}	SG1PII	95.0_{b}	SG1T
95.9_{a}	SG1PII	94.1_{b}	SG1	$94.4_{b,c}$	SG1
95.6_{a}	SG1PI	94.1_{b}	SG1T	94.3_{c}	SG1PII
94.3_{b}	SG1	94.0_{b}	SG1PI	94.2_{c}	SG1PI

Note. Means in the same column that do not share subscripts differ at $p<0.01$ in the Fisher's least significant difference comparison.

microporous film, to the outside environment, thereby enhancing the heat dissipation through sweating and evaporative heat loss. Tyvek® with paper-like texture, on the other hand, does not have fibers protruding from the fabric surface to enhance its wickability.

In comparing the left-arm skin temperature when wearing T-shirt with a Pro/Shield I® sleeve vs. with a Tyvek® or a Pro/Shield II® sleeve, the Pro/Shield I® sleeve resulted in lower skin temperature, although the differences were not significant (Table 4). Pro/Shield I® may result in lower skin temperature because it has almost two-fold better moisture vapor transmission than do the other two fabrics. The hairy surface texture of Pro/Shield I® also may enhance wicking of sweat from the skin and evaporative heat loss.

From Figure 2 and Table 4, no consistent fabric trend over time was observed when a baseline garment of a Tyvek® coverall was used, regardless of the body sites. A possible explanation of a lack of consistent fabric trend in these cases, is that the Tyvek® coverall caused the chimney effect (Watkins, 1995) which fluctuates skin temperature. In addition to the zipper on the front trunk, the coverall is elasticized at the wrists and ankles, which makes it similar to a closed system and leave an opening around the neckline as the main path of heat transfer from the body. It may be that, due to the paper-like texture and, perhaps the poorer wickability of Tyvek® fabric as compared to the other two experimental fabrics, only a limited amount of heat built up by the active muscles during exercise could transport through the coverall. Otherwise, the heat was restrained

to flow between the skin and the garment, raising the microclimate temperature. As to the fact that the warm air rises, heat in the microclimate leaks through the opening of the neckline, resulting in inconsistent microclimate temperature which, in turn, fluctuates skin temperature. In addition to the opening around the neckline, fluctuation of skin temperature may be caused by forcing out of heat through intermittent gaps around the wrists and the ankles by the pumping motion of the body during exercise.

Based on observed skin temperatures on the right arm and on the chest, wearing the Tyvek®-coverall standard garment with any given experimental sleeve, resulted in higher skin temperature on those sites than did wearing only T-shirt and pants with that experimental sleeve. As compared to T-shirt, Tyvek® has much poorer moisture vapor transmission and capillary penetration and transmission, although it is much lighter and thinner (see Table 1). The better moisture properties of the T-shirt may result from the nature of cotton fiber and the knitted structure. Cotton absorbs moisture in greater amount than does polyethylene, of which Tyvek® is made, and the open structure of the knitted T-shirt fabric allows easier moisture and heat transfer than does the tight, nonwoven structure of Tyvek®. The hairy surface texture of jersey knit also enhances wickability and absorption of the T-shirt.

Sweat amount. As a consequence of the analysis, the garment effect on sweat amount was not significant, $F(6,54) = 0.72$, $p \leq 0.05$. To enable comparison with Hennessey's (1997) findings, the fabric ranking, based on the left arm sweat amounts was observed from Table 3) .

When SG1 was used, sweat amount observed on the left arm was highest on the garment with a Pro/Shield I® sleeve, followed in order by the garment with a Tyvek® sleeve, the garment without an experimental sleeve, and the garment with a Pro/Shield II® sleeve. The above fabric trend seems not reasonable and was not supported by physical characteristics of fabrics (see Table 1). Because Pro/Shield I® has about two times the moisture vapor transmission of the other two experimental fabrics and also has fibers protruding from the fabric surface, evaporative heat transfer and moisture wicking through the Pro/Shield I sleeve should be better than through the other sleeves. The other reason why the observed trend is not reasonable is that the left arm sweat amount of wearing SG1 was greater than that of wearing SG1PII, which is contrary to the fact. Wearing SG1 should result in greater amount of heat transfer than wearing SG1PII because heat can transfer directly from the skin to the environment without the hindrance of protective sleeve.

According to the results in Table 3, when the Tyvek®-coverall standard garment was worn, the fabric ranking from highest to lowest sweat amount, was Pro/Shield II®, Tyvek®, and Pro/Shield I®. This ranking occurred for the left arm and for the other two body sites. The above fabric ranking was not the same as the fabric ranking from the left arm skin temperature of wearing a T-shirt/pants standard garment. The high standard deviations make the fabric ranking, regarding sweat amount of wearing a Tyvek® coverall, less reliable as compared to the ranking, regarding the left arm skin temperature of wearing T-shirt and pants. However, both rankings were alike in the way that

Pro/Shield I®, which has better moisture vapor transmission than the other two fabrics and has slightly hairy surface texture, was the best fabric, of the three experimental fabrics, in terms of thermal comfort.

For a given experimental sleeve, sweat amount at every body site was higher when a Tyvek® coverall was used as a baseline garment than when a T-shirt and pants was used as a baseline garment. The poorer heat and moisture transfer characteristics of the Tyvek® coverall as compared to the T-shirt may be due to the nature of fibers and the fabric constructions, which contribute directly to the physical characteristics of the fabrics as described in the previous section.

Table 3 also exhibits that the difference in mean sweat amounts among either body sites or garments were quite small. This may be because the collection pads, which were only an inch square each, became saturated during the trials. The saturation may be a reason, in addition to the extraneous variables and the differences in sweat production due to subjects, that causes deviation in the results and make sweat amount the less useful measurement, as compared to skin temperature. To avoid the saturation, larger collection pads should be used, or the sweat collection time should be decreased.

Feasibility of Using a Sleeve, instead of a Full Garment

Hennessey (1997) studied the effects of five different protective coveralls on thermal comfort and heat stress, by using both physiological and perceptual measurements, in neutral and hot environments. The hot environment was equivalent to the condition used in the current study. Hennessey measured skin temperatures on the

back and the chest, and averaged them to obtain the mean skin temperature. Sweat was collected on the chest, the back and the upper arm, and the mean sweat amount over the three body sites was obtained.

Hennessey (1997) found that, in the hot environment which is equivalent to the condition used in the current study, there was no significant differences in skin temperature nor in sweat amount among the experimental fabrics. At the 15-minute and 45-minute intervals, skin temperature was highest in the Tyvek® coverall, followed by the Pro/Shield II® coverall, and then the Pro/Shield I® coverall. The descending order for skin temperature at the 30-minute interval was slightly different: Pro/Shield II®, Tyvek®, and Pro/Shield I®. Hennessey also found that the Tyvek® coverall resulted in highest sweat amount, followed by the Pro/Shield II® coverall, and then the Pro/Shield I® coverall.

Skin temperature. As pointed out previously for the results in this study with the T-shirt/pants standard garment, at every time interval, the left arm skin temperature was highest in the garment with a Tyvek® sleeve, followed in order by the garment with a Pro/Shield II®, sleeve, and the garment with a Pro/Shield I® sleeve. Figure 3 illustrates the comparison of the mean left-arm skin temperatures, when the T-shirt/pants standard garment was used in the current study with the mean skin temperatures (averaged over two body sites) of Hennessey (1997). In this cases, the fabric order was the same in the two studies at the 15-minute and the 45-minute intervals of exercise (or agreed two out of three time intervals), which may suggest the feasibility of using a sleeve, instead

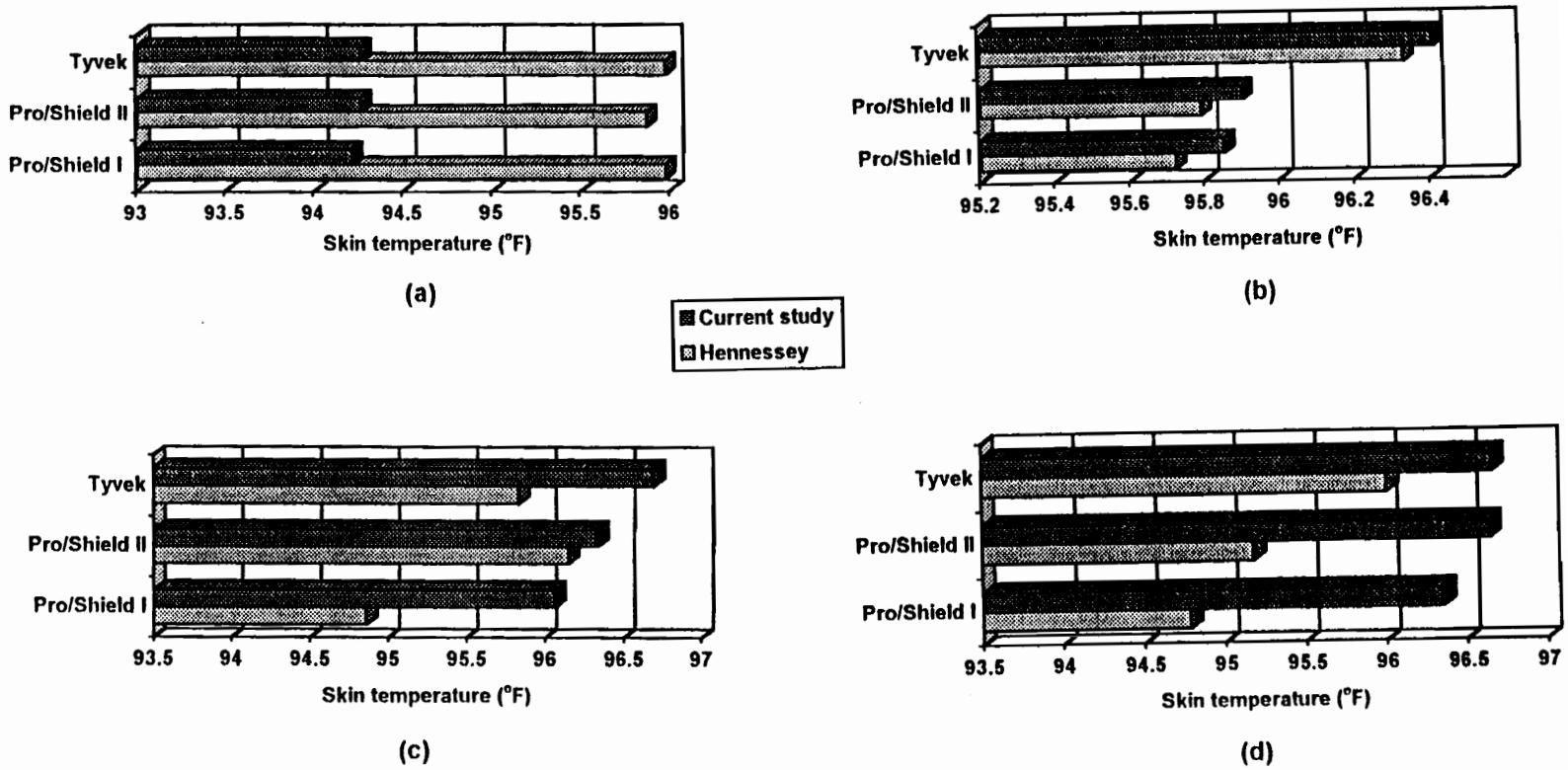

Figure 3. Comparison of mean skin temperature at the beginning (a), the 15-minute (b), the 30-minute (c), and the 45-minute (d) of the exercise.

of a full garment, to assess thermal comfort and heat strain associated with of wearing chemical protective clothing.

It may be noted that Figure 3 also indicates higher skin temperatures observed at the beginning of the exercise in Hennessey's (1997) than in the current study for every experimental fabric. This is believed to be due to the hindrance to heat transfer of the full coveralls. After the beginning, however, skin temperatures observed in the current study were greater than those in Hennessey's study. For any given experimental fabric, the difference in skin temperature between the two studies became greater over the exercise time. The different increments in the difference skin temperatures between two studies may have resulted from the variation in skin temperature on a particular body site in a hot environment. Houdas and Ring (1985) noted that, in high ambient temperature, or in the hotter skin-clothing microclimate in this case, skin temperature on the upper arms varies more than that on the trunk.

Sweat amount. Figure 4 shows the comparison of the mean sweat amounts (averaged over three body sites) from Hennessey's (1997) study with the mean sweat amounts (on the left arm) from the current study with both the T-shirt/pants and the Tyvek®-coverall standard garments. The ranking of the three experimental fabrics are all different.

However, Hennessey's fabric ranking regarding sweat amount was the same as that regarding skin temperature at the 15-minute and the 45-minute intervals, which confirms the effects of the three different experimental fabrics on thermal comfort and

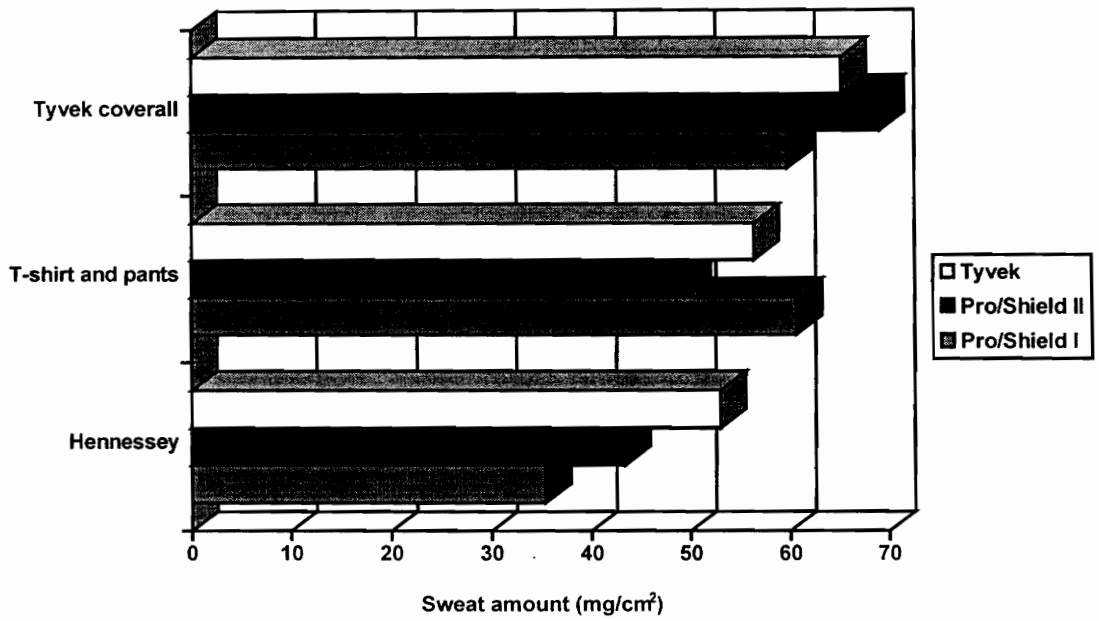

Figure 4. Comparison of the mean sweat amounts (averaged over three body sites) from Hennessey's (1997) study with the mean sweat amounts (on the left arm) from the current study with both the T-shirt/ pants and the Tyvek®-coverall standard garments.

heat strain. The feasibilty of using a sleeve, instead of a full garment, in thermal comfort studies could not be concluded using sweat amount because of the high standard deviations of sweat amounts in the current study. To generate comparable data, the same set of subjects should participate in both studies and the size of the sweat collection pads should be increased. Sweat collection time should also be decreased to prevent the saturation of the pads during a trial.

Conclusions

Skin temperature and sweat amount were utilized as tools to determine the feasibility of using sleeves, as an alternative to a full garment, to assess thermal comfort and heat stress in wear testing. Under the same conditions, the upper arms and the chest responded to heat load in the same way, indicated by nonsignificant differences in measured skin temperature. However, the above conclusion cannot be made based on sweat amount. Moreover, in this study, skin temperature seems to be a more useful measurement to assess thermal comfort than sweat amount.

The consistent fabric ranking regarding the left arm skin temperature with the T-shirt/pants standard garment was in agreement with Hennessey's (1997) fabric ranking at the 15-minute and 45-minute of exercise, suggesting the presence of the feasibility of using sleeves, instead of a full garment, to assess thermal comfort and heat strain in chemical protective wear tests. According to the ranking, if the protective abilities of the investigated fabrics are comparable, Pro/Shield I® is more suitable for protective clothing assemblies than are Tyvek® and Pro/Shield II® in terms of thermal comfort. Additionally,

to assess thermal comfort and heat stress of wearing chemical protective clothing using sleeves, the T-shirt and pants is a better baseline garment than the Tyvek® coverall.

To validate the current study's findings on the feasibility of using sleeves, further studies may be conducted in which a group of subjects performs two tests using the same experimental fabrics and having the same experimental protocol and environment; however, in one test, subjects would wear T-shirt and pants with experimental sleeves, and, in the other test, the subjects would wear a coverall, or a jacket, made of the same fabric as the experimental sleeve. Skin temperature and sweat amount could be measured at the same body site, though not simultaneously. Using the same group of subjects in those two tests is expected to reduce the effect of unknown extraneous variables. It may be more useful if such studies are conducted in real field tests.

Further research is also needed to determine the feasibility of using sleeves for assessing the thermal comfort associated with a wider range of fabric types and environmental conditions. Additional design work on sweat collection should also be undertaken in an effort to achieve improved effectiveness of sweat amount as a parameter to assess thermal comfort.

VITA

Angkhana Tultrairat was born in Bangkok, Thailand, on August 29, 1971. She received her Bachelor's Degree in Chemistry from Kasetsart University, Thailand. For her baccalaureate research, she explored a way to study the growth of plants by synthesizing an ester from extracted plant hormone. After graduation, she worked for International Laboratory Incorporated as a chemist in the research and development department.

In 1992, she received a Royal Thai scholarship and came to the United States of America for her Master's degree in Textile Science at Virginia Polytechnic Institute and State University. While in the Master's program, she was a representative of the Department of Clothing and Textiles in the Graduate Student Assembly and a member of the Virginia Tech Student Chapter of the American Association of Textile Chemists and Colorists.

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