THERMAL INSULATION VALUES AND PERMEABILITY INDEXES OF SELECTED WORK CLOTHING WORN IN HOT INDUSTRIAL ENVIRONMENTS

by

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Chapter 1

INTRODUCTION

Since the passage of the Occupational Safety and Health Act in 1970, the government, employers, and employees have increased their efforts to reduce hazards in the workplace. Specifically, the Occupational Safety and Health Administration has developed numerous standards concerning work conditions and practices which the agency actively enforces. Although few of these standards regulate the type of protective clothing and equipment that must be worn for specific job assignments, many firms have begun furnishing their employees with special clothing on a voluntary basis. Some firms also take responsibility for the care, repair, and replacement of the items. Other employers encourage workers to purchase and wear some type of protective clothing on the job. Still others allow workers to wear whatever they want and give them no guidance concerning the selection of safe work clothing.

Fortunately, technological advances in the textile industry have resulted in a variety of new fabrics for use in protective clothing, and many fiber and textile producers are currently engaged in research to develop more. Apparel producers are manufacturing more lines of work clothing too.

The primary function of protective clothing is to isolate the wearer from hazardous elements in the work environment. Consequently, safety and performance characteristics are of paramount importance in designing protective clothing systems. Advertisements and specification sheets emphasize these attributes to prospective buyers. Unfortunately, the comfort properties of these garments are considered less important and are often ignored completely in the design and manufacturing processes. The clothing's resistance to heat transfer and to moisture transfer directly affect the thermal comfort of the wearer. Garments that hold in body heat can cause problems for people who work in hot industrial environments and/or who work at an active pace (i.e., generate more body heat). In extreme cases, a worker may develop the symptoms of heat exhaustion or suffer a heat stroke.

Although protective clothing reduces the probability that a person will be injured due to hazards in the workplace, it should not simultaneously increase the probability of a worker suffering thermal discomfort and heat-related physiological problems.

Consequently, the insulation and permeability characteristics of protective clothing should be evaluated. Garments that insulate the body and prevent moisture from evaporating should be avoided in hot environments.

Small-scale test methods have been used by some manufacturers to measure the thermal and permeability properties of fabrics.

However, the test results have little correlation to the properties of an entire clothing system because several layers of different fabrics may be incorporated into a clothing ensemble. In addition, the design and fit of the garment(s) will greatly affect these values. Test procedures involving the use of a copper manikin have been developed for use in evaluating military garments. These procedures should be effective in quantifying the ability of a protective clothing ensemble to release body heat via conduction, convection, radiation and evaporation.

Therefore, the purpose of this study was to measure and compare the thermal insulation values and permeability indexes of clothing worn in hot industrial environments.

Objectives

The objectives of this study were:

1. To measure the thermal insulation value of selected garments and ensembles commonly worn by workers in hot industrial environments using a copper manikin.
2. To measure the permeability index of clothing ensembles commonly worn by workers in hot industrial environments using a "sweating" copper manikin.
3. To calculate the evaporative impedance of the clothing ensembles.
4. To compare garments which are identical in structural characteristics except for one variable (i.e., two shirts

alike except for sleeve length) with respect to thermal insulation.

5. To compare ensembles which are identical in structural characteristics except for one variable (i.e., two ensembles alike except for coat length) with respect to thermal insulation, permeability index, and evaporative impedance.

6. To compute the intrinsic clo values for all ensembles by adding the intrinsic clo values of the component garments (measured individually on the manikin).

7. To compute the intrinsic clo value for all ensembles by using the ASHRAE formula (5):

   I_{cl} (ensemble) = (I_{cl} individual items)(0.82)

8. To compute intrinsic clo values for all ensembles using Sprague and Munson's formula for men (45):

   I_{cl} (ensemble) = (0.727)(I_{cl} individual items) + 0.113

9. To compare the intrinsic clo values for ensembles either measured directly on the manikin, or estimated by the formulas in objectives 6, 7, and 8, in an effort to evaluate methods of determining intrinsic clo for ensembles.

10. To estimate for each ensemble, the clothing insulation/effective temperature combination which would yield a 6% PPD (the predicted percentage of occupants who would be dissatisfied with their thermal environment)

using the following equation (39):

$$CET^{*} = 29.75 - 7.28\ (I_{cl})$$

Assumptions

The work clothing selected for study was representative of garments and ensembles worn in hot industrial environments.

Limitations

The copper manikin used in this investigation was a nonsegmented, single-circuit copper manikin. The clo values measured for individual garments using this manikin system may be slightly lower than those measured on a segmented man. For example, garments that cover only a small portion of the body surface (i.e., fur hat) may provide alot of insulation to that body area (i.e., head). However, when measured on a single-circuit manikin, rapid heat losses from other parts of the body are being recorded also. Although the surface temperature thermistors under the garment may stay warm (and not require much electrical heat), the other body thermistors are registering lower temperatures because they are not covered. Consequently, the majority of the thermistors are triggering the proportional temperature controller to supply more power. Therefore, the power reading rises and the clo value for the garment decreases. A segmented copper manikin, on the other hand, measures the clo value for the garment decreases. A segmented copper manikin, on the other hand, measures the clo value for the garment decreases. A segmented copper manikin, on the other hand, measures the clo value for an individual garment by only using the power readings and surface areas from the body parts covered by the garment. Unfortunately, there is only one segmented manikin in the world at this time, and it was not available for use in this study.

The study was limited in scope to garments worn in hot industrial environments, and some garment types and possible combinations were not evaluated.

Definitions

1. Intrinsic clo value (I_{cl}): A means of quantifying the amount of thermal insulation provided by a clothing system; it does not take into account the insulation provided by the external air layer surrounding the clothed body (27). Also, 1 clo equals $0.18^{o}C\ m^{2}\cdot hr/kcal$ (42).
2. Total clo value (I_T): A means for quantifying the amount of thermal insulation provided by a clothing system plus the insulation due to the air layer surrounding the clothed body (27).
3. Moisture permeability index (i_m): A dimensionless measure of the evaporative potential of a clothing system, as measured by a "sweating" copper manikin (27).

4. Evaporative impedance (i_m/I_T): The ratio of the permeability index to the total clo value of an ensemble. This value indicates the obtainable fraction of the maximum sweat evaporative cooling possible in a given environment without wind (18).
5. Clothing area factor (f_{cl}): The ratio of the surface area of the clothed body to the surface area of the nude body (13).
6. Air temperature: The temperature of the air, as measured by a dry bulb thermometer (5).
7. Mean radiant temperature: The uniform temperature of a black enclosure which would produce an equal amount of heat loss by radiation from a given person placed at a given point with a given body position as the actual enclosure under examination (16).
8. Relative humidity: The ratio of the partial pressure or density of the water vapor in the air to the saturation pressure or density, or the water vapor pressure (5).
9. Fabric count: The number of warp and filling yarns contained in one square inch of fabric determined using ASTM Standard Test Method D 1910 (2).
10. Fabric thickness: The distance between two parallel surfaces while exerting a specified pressure on the material, determined using ASTM Standard Test Method D 1977 (2).

Chapter 2

REVIEW OF LITERATURE

Heat Stress in Industrial Environments

An individual's tolerance to high temperatures is related to his/her ability to sense temperature, lose heat by regulatory sweating, and lose heat by increasing the blood flow from the body core to the skin surface, where cooling is most effective. Thus, thermal equilibrium is maintained by a person being able to dissipate his/her body heat production plus any radiant and convective heat load (4). If the air temperature of the environment is at a high level, the amount of heat lost by radiation and convection decreases, and the body depends more on the evaporation of perspiration as a thermoregulatory mechanism (1). When the body cannot maintain a constant temperature, two forms of physiological responses can occur. Elevated skin temperatures can result in pain and tissue damage, and elevated body temperatures can create the associated syndromes of heat exhaustion, heat cramps, and heat stroke (1). Heat exhaustion is a result of circulatory failure in which the venous blood supply returned to the heart is significantly reduced. The failure is not one of heat regulation, but the individual's blood supply is not adequate to serve both heat regulation and other needs of the body. Early symptoms include fatigue, headaches, dizziness, nausea, vomiting, shortness of breath, flushing of the face, pulse rate above 150 beats/minute, glazed eyes, irritability, poor judgment and performance which usually precede collapse. Heat stroke, the most serious heat illness, occurs when the body temperature reaches a level where the regulatory function fails and sweating stops. The body temperature can rise to critical levels, producing the possibility of tissue damage and death (1).

In hot industrial environments, workers often experience some of these heat stress problems. Their reaction to high temperatures has a strong influence upon worker productivity, as well as on the accident, sickness, and mortality rates. Medical records concerning human tolerance of hazards in the workplace are not readily available (28), and specific statistics concerning heat stress are scarce. Representatives of the National Institute of Occupational Safety and Health (NIOSH) have indicated that the incidence of heat stress cases would be much higher if they were properly documented and if the cases were related to the total number of heat exposed workers instead of to the total plant population (11).

Specific data on the numbers of heat stress cases that occur in different industries are also difficult to find. Many of the statistics state the number of injuries, illnesses, and lost workdays without giving their specific causes. In one report from the New York State Department of Labor (1966-1970), the compensation for work injuries was tabulated. Heat prostration (heat exhaustion) accounted for 77 out of 536 compensated work injuries. Of these 77 cases, 76.6% were from industries with less than 5 cases each (33).

In another study, the medical records of a large Eastern steel plant were examined to determine possible relationships between heat injury and other factors (i.e., age, length of service, and nonheat injuries). The heat episode experience appeared to be positively correlated with total injury and with serious injury experience. In addition, 17% of the 264 employees had experienced at least one heat episode, and employees 45 years of age and older experienced more heat episodes than did those under 45 (11).

Factors Which Cause Heat Stress

Whether or not a worker will suffer heat stress related problems depends upon the interrelationship of certain environmental factors, human factors, and clothing factors. Ideally, these variables could be manipulated by a plant manager so as to prevent heat stress in workers and at the same time, maintain efficient productivity.

Environmental factors. In some industries, certain production processes either require or generate considerable amounts of heat.

Consequently, some plant areas are characterized by high air temperatures and mean radiant temperatures. Unfortunately, it is often impossible technologically and/or economically to lower these temperatures to comfortable levels. Although an increase in air velocity through the use of fans and a decrease in relative humidity with dehumidifiers would effectively lower the discomfort of workers, their use is often limited. In addition, some changes in the work environment are only possible if productivity is decreased.

Human factors. The physical characteristics of workers and their activity levels affect the probability of heat stress problems developing. For example, a person's age, percent body fat, and physical condition are all related to tolerance of the heat. When a person's activity level increases (as it does with physical work), the body generates additional heat. This heat must be released into the environment at the rate necessary to maintain thermal balance in the body. Consequently, heavy work coupled with high environmental temperatures is conducive to heat stress. Management personnel could develop work-rest schedules which would lessen worker discomfort and replace workers as they reach individual tolerance limits (22). However, determining the appropriate work-rest schedules for each job type and enforcing it rigorously would be difficult.

Clothing factors. The effects of high temperature and/or high activity levels are compounded when the worker must wear protective clothing. Some firms require workers to wear special clothing, and frequently provide them with it. Other firms do not require any protective clothing (6). Dress codes are often incorporated into procedure manuals by major companies, but smaller firms do not always have the time, personnel, or money to use in developing and enforcing regulations concerning work clothing (12). In addition, many employees who wear protective clothing (either provided by the firm or purchased voluntarily by the worker) do not wear it correctly. Sometimes a company will provide special clothing, but the workers refuse to wear the garments at all because they are too hot (6).

In the past, fashion changes and technological developments in textile and garment production have influenced the design of clothing rather than the scientific measurement of heat exchange allowed between the wearer and the environment (18). Safety features and garment performance are usually emphasized in the designing of work clothing. Other aspects such as comfort are often overlooked or considered less important. Consequently, some protective garments cover a large portion of the body and are quite heavy and cumbersome. In fact, some garments are made to wear over other garments. Thus, protective clothing ensembles often provide a high resistance to convective and radiant heat flow from the body to the environment. Many garments are also treated with special finishes such as those which impart chemical resistance and flame resistance. Some treatments lower the permeability of the fabric, which inhibits the evaporation of sweat from the body. The permeability of clothing becomes increasingly important in environmental conditions where heat balance can only be achieved by evaporation of sweat.

The primary function of protective clothing systems is to isolate the wearer from hostile conditions in his/her environment. Unfortunately, the clothing ensembles that provide the most protection to the wearer often restrict the amount of body heat loss that is possible through conduction, radiation, convection, and evaporation. If the insulation and permeability characteristics of the clothing were known, people would be better able to select clothing items for use under different environmental conditions. Thus, the type clothing worn could be manipulated to avoid extreme discomfort and heat related problems. Some protective clothing systems have already been developed which provide cooling features for the wearer of impermeable garments such as the incorporation of filtered ambient air ventilation, wettable covers, or water cooled vests (22).

Thermal Resistance of Textiles

The amount of clothing insulation, specified in terms of a clo unit (17), and its distribution over the body, directly affect conductive, convective, and radiant heat loss from the skin to the environment. There are many individual and combined factors involving fiber, yarn, fabric, and garment characteristics that affect thermal resistance. Some effects are so small, that when coupled with the body's ability to compensate for changes, they are most difficult to isolate and measure, either objectively or subjectively (47).

The thermal resistance of fabrics is usually related to the volume of air per unit area of fabric because the insulating value of air is greater than that of fibers (31). Consequently, the fabric thickness and density largely determine the resistance to heat transfer. The thicker the fabric or fabric composite, the greater the amount of trapped air, and in general, the greater the insulation value (36). Specifically, the relationship of 1.57 clo/cm (4 clo/in.) of thickness has been found for most conventional fabrics, regardless of fiber content or construction (18).

For a given thickness, a heavier fabric is likely to contain more fiber and hence be a poorer insulator. If weight is fixed, an increase in thickness carries with it a decrease in the fiber/air ratio of the fabric. This change may increase insulation, by adding "dead air" space, or may make it so porous that it is ineffective against the lightest breeze (27).

Heat transfer through textile systems is also related to bulk density. Fabrics made of higher density fibers are better insulators at a given bulk density, since the volume fraction of fibers is determined by the ratio of bulk density to fiber density. Low bulk density gives better thermal resistance (8).

Fibers entrap air because air clings to a solid surface, and consequently, impose a drag on air movement. This air drag is increased by making a denser fabric, which in turn increase garment weight, decrease porosity, and increase thermal conductivity (9). An ideal fabric would have a bulk density between the two extremes--a structure so open that it allows too much radiation and air circulation to a structure so dense that it allows too much conduction through the fibers themselves (36). As density of a fibrous mass increases, the effect of the fibers is more pronounced, and thermal conductivity of the mass will be increased (37).

Fabric structure, or arrangement of fibers in the fabric, affects thermal conductivity. In an early experiment by Finch, it was demonstrated that when fibers were arranged parallel to the direction or flow the thermal conductivity was 2 to 3 times greater than when assemblies of equal bulk densities contained fibers arranged perpendicular to the direction of heat flow (8). In addition, fabric conductivity is more sensitive to fiber arrangement as the fiber conductivity and bulk density are increased. Better thermal resistance is achieved when there is a mechanically stable arrangement of the fibers parallel to the surface (8) or an increase in the number of fibers parallel to the fiber surface (10). The best thermal insulation is achieved when fibers are at right angles to the direction of heat flow, and surrounded by a column of air (30). This is because there may be a transfer of heat by convection within the fabric, and by radiation through the interstices. Heat transfer by conduction will depend on the orientation of the fibers. When all fibers are arranged parallel to the direction of heat flow they will exert their maximum effect on total heat flow, and when arranged at right angles, exert minimum effect with random orientation between these limits (37).

The thermal resistance of fabrics can change with compression. Bogaty et al. (8) found that the application of pressure to a smooth fabric increased fabric density with little change in fiber arrangement, and consequently, thermal conductivity increased. Fabrics made of resilient fibers will maintain their thickness over a longer period of time than nonresilient ones, and thus retain their insulating properties longer. The thermal insulation becomes greater per unit thickness when reflective materials which reduce heat transfer are used in combination with nonwoven structures.

Fabric finishing processes affect thermal insulation also. The finishes alter fabric porosity, hairiness, and weight, thus determining the amount of air space present. For example, fabric tentering and napping can significantly alter the thermal character of a fabric, and chemical finishes can change the smoothness of the fabric surface (27).

Another factor which can alter thermal resistance is yarn structure. For instance the tightness of yarn twist, the spacing of yarns in fabric construction, and the type of yarn determine resiliency, density, and air permeability of a material (15).

The effect of moisture on the thermal properties of textiles has also been investigated. Hollies and Bogaty (26) found that the thermal conductivity of fabrics increases with increasing moisture content in the same manner for all fabrics. Fibers also liberate heat as they absorb moisture. Although sorption heat of textiles can be measured on fabrics in the laboratory, it has little value physiologically in clothing. In investigations where men wore clothing ensembles of wool and polyester, no consistent difference was found between the insulation provided by each ensemble in cold damp conditions (32).

The thermal insulation value of clothing depends upon the physical properties of the fabric mentioned above, and amount of body surface area covered, and the air space between the body and the fabric. Hardy et al. (24) indicated that the major function of clothing is to maintain a layer of motionless air next to the skin. This air layer provides most of the resistance to heat flow. The design or cut of garments and the way they fit affect this air layer between the skin and clothing. In fact, the space between the garment and the body has a greater effect or insulation than the kind of fiber or fabric from which the garment was made (36). In addition, fabric overlap within a garment or from the layering of garments also affects the amount of trapped air insulation.

These charactersitics vary extensively among clothing ensembles and consequently alter insulation values. Therefore, measurements of convective and radiant heat loss on small flat pieces of fabric have little correlation with the respective values associated with clothing ensembles.

Measuring the Thermal Resistance of Textiles

Researchers in government, industry, universities, and private laboratories use several methods for measuring the thermal resistance of textiles. These methods are reviewed in Clothing: Comfort and Function (16) and include the guarded hot plate and togmeter. Most of these small-scale test methods can only measure conductive, convective, and radiant heat loss on flat pieces of fabric. Because trapped air between the body and clothing contributes to insulation, entire garments should be tested so that the effects of design, drape, fit, and layering are reflected in the measurements (40). Consequently, the heated copper manikin is the most appropriate apparatus for measuring the insulation provided by clothing systems. In addiition, clothing ensembles are usually characterized by an uneven distribution of insulation over the surface of the body, and the manikin procedure will measure the net insulating effect, as well as indicate areas of higher heat loss.

Another method which quantifies the thermal resistance of clothing was recently developed by researchers at the John B.

Pierce Foundation (34). Effective values for total insulation were determined by measuring the thermal efficiency of clothing on live subjects during rest and exercise.

The manikin test procedure was selected for use in this study of protective clothing. The resistance to heat transfer is measured in terms of a clo unit (17). (The derivation of the clo value is explained in reference 27.) The value for 1.0 clo is equal to 0.18C $m^2 \cdot hr/kcal$. The reciprocal of this value, 5.55 $kcal/m^2 \cdot hr \cdot {}^oC$ or 6.45 $watts/m^2 \cdot {}^oC$, is often used in calculations for convenience (27).

The total insulation value of clothing (I_T), including the external air layer, was measured on the manikin in an environmentally controlled chamber.

The equation for calculating I_T is (27):

$$I_T = \frac{K\,(\bar{T}_s - T_a)\,A_s}{H_D}$$

where H_D = power input - W

A_s = manikin surface area - m^2

$\bar{T}_s$ = mean skin temperature - ^oC

T_a = ambient air temperature - ^oC

I_T = total thermal insulation of clothing

plus boundary air layer - clo

K = constant = 6.45 $W/m^2 \cdot {}^oC$

The intrinsic clo value of a clothing ensemble (I_{cl}) is found by subtracting the inculation provided by the air layer over the ensemble from the total clo value (I_T).

$$I_{cl} = I_T - \frac{I_a}{f_{cl}}$$

where I_{cl} = intrinsic thermal insulation of

clothing - clo

I_T = total thermal insulation of clothing

plus boundary air layer - clo

I_a = thermal insulation of air layer around

nude manikin - clo

f_{cl} = clothing area factor

Values for the clothing area factor (f_{cl}) are dependent upon the design of garments and the way they are worn on the body. In one study (45), f_{cl} values were determined by photographing different views of garments on a figure, cutting out designated areas, and weighing them. The weights of the garment pictures were then compared to those of the nude pictures. A value of 15% increase in surface area per intrinsic clo of insulation has been reported also (13,27). The value of I_a is obtained by operating the manikin without clothing and using the equation for calculating I_T to find I_a at various values of ($\bar{T}_s$ - T_a).

Permeability of Textiles

The moisture permeability of a textile system depends on the permeability of its fibers and fabric structure.

The physical property pertaining to moisture transport in fibers is the amount of moisture that can be absorbed by the fibers, or the moisture regain (27). The fiber surface and its bulk properties determine the moisture regain of a fiber, with noncrystalline areas of a fiber having the most moisture absorption (25). Also, the molecular composition and geometric arrangement of molecules influence the absorption of moisture (25). The movement of water vapor through a fiber is encouraged by increasing the pore size of the fiber. If the pore size was decreased, capillary action would be increased (27). Fourt et al. have shown that the passage of water vapor through the fiber substance itself is very small when compared with the passage of water vapor through fabrics (16).

Thus, the passage of water vapor along fiber surfaces, and especially through air spaces in the fabric, influences moisture permeability to a great extent (16). The moisture permeability of fabrics is dependent upon sufficient openness in the fabric such that the water vapor resistance of fabric is close to that of an equivalent air layer (16). The water vapor resistance of a fabric also depends on the thickness of the fabric and the tightness of the weave (16). Most fabrics restrict water transport by diffusion in proportion to their thicknes (16), regardless of hydrophobic or hydrophilic characteristics of the fibers (27).

Other physical properties of a fabric that influence moisture permeability are wicking, or the rate at which moisture is dispersed over a fabric, and the drying rate, or the rate of evaporation (27).

A factor which influences moisture permeability of a clothing ensemble is the number of layers of the ensemble. The resistance to water vapor per layer of fabric tends to decrease as the number of layers increases (44).

The vapor diffusion through farics is independent of the rate of passage of air through the fabric (14). There are relatively small differences in the vapor resistances of different fabrics when men are active, but these differences are noticed in terms of comfort when a man is sedentary. (14).

The structure and design of a garment are critical when the fabric has both limited air and vapor permeability (7). Even in a cool environment, the structure of the work environment may convert the micro-environment into one extreme heat when the garment is constructed of fabric with limited air and water permeability.

The amount of air traveling through the clothing system, or the pumping coefficient (27), is increased when the body is in motion. The body motion increases the heat exchange between a person and the environment by creating convection currents at the garment surface and within a clothing ensemble. The rate of evaporative cooling for a sweating person also increased with body motion (27).

Measuring the Permeability of Textiles

The evaporation and diffusion of water from the body is essential for comfort and heat balance. Many fiber and fabric properties such as absorption, regain, wickability, repellency, drying rate, and permeability are measured in an effort to predict the loss of moisture through textile systems (2,16). The standard technique for determining the water vapor resistance involves measuring the rate of diffusion from a surface by recording weight loss over a 12-hour period, when a dish of water is covered by the fabric (16). Spencer-Smith used a modified dish method to measure water loss from a dish of water kept at body temperature and covered with a clothing assembly (43).

Woodcock developed a dimensionless permeability index (i_m) to quantify the ability of fabrics or fabric systems to transfer moisture and the associated heat to the environment (16,48). Values for I_m can be obtained experimentally on heated copper cylinders, modified hot plates, and copper manikins. The fabric or clothing assembly is placed over a saturated surface which acts as an imperfectly exposed wet bulb thermometer. The surface temperature drops as evaporation takes place until the vapor transport through the textile system just balances the inward flow of heat through the textile (14). The permeability index is calculated as follows (27):

$$H_w = \frac{K \ A_s}{I_T} \left[(\bar{T}_s - T_a) + S \ i_m \ (P_s - \phi_a P_a)\right]$$

where H_w = power input with cotton "skin" wet - W

A_s = manikin surface area - m^2

K = constant = 6.45 $W/m^2 \cdot {}^oC$

I_T = total thermal insulation of clothing <u>plus</u> boundary air layer - clo

$\bar{T}_s$ = mean skin temperature, wet run - ^oC

T_a = ambient air temperature, wet run - ^oC

S = constant = 2.2^oC/mmHg vapor pressure

P_s = saturated vapor pressure at T_s - mmHg

P_a = saturated vapor pressure at T_a - mmHg

ϕ_a = ambient air relative humidity - %

i_m = moisture permeability index - dimensionless

The gradient for evaporative heat transfer is the difference between the vapor pressure at the surface (P_s) and the ambient vapor pressure (ϕ_a P_a) in mmHg. The parameter S is a constant which converts a vapor pressure difference to an effective temperature difference (27). The i_m values for clothing systems range from about zero for an ensemble with no evaporative transfer to abouι 0.5 for an ensemble with maximum permeability (1 for a slung wet bulb) (27).

Once the clo value and permeability index are determined for a clothing ensemble, the evaporataive imedance can be calculated. The evaporative impedance (i_m/I_T) indictes the maximum sweat evaporative cooling possible in a given environment without wind (18). Thus a person wearing an ensemble where i_m = 0.40 and I_T = 1.25 can obtain about 32% of the maximum cooling possible (0.40/1.25 = 0.32).

Summary

Heat stress is a problem in hot industrial environments. The probability that a worker will develop heat-related problems and the severity of those problems depend upon environmental, human, and clothing factors.

The human body loses heat through radiation, convection, conduction, and evaporation. Protective clothing resists this heat transfer. Consequently, in environments characterized by high air and mean radiant temperatures, protective clothing can prevent the body from releasing the amount of heat necessary to achieve thermal body from releasing the amount of heat necessary to achieve thermal balance. The problem is compounded when employees have a high activity level and generate considerable body heat. The thermal resistance of protective clothing can be quantified in terms of a thermal insulation value (dry heat transfer) and a permeability index (evaporative heat transfer). The ratio of these values, or evaporative impedance, can be used to compare protective clothing assemblies with regard to the amount of maximum sweat evaporative cooling possible in the work environment. When this information is known, a model could be developed which would quantify the interrelationships between environmental, human, and clothing factors in an effort to predict man's response to these conditions and in turn, avoid heat stress.

Chapter 3

METHODOLOGY

The purpose of this study was to measure the thermal insulation value and permeability index of selected clothing worn in hot industrial environments.

Sample selection

Several firms were contacted in an effort to plan visits to plants exhibiting high environmental temperature conditions. Instead of agreeing to the requests, both management and union personnel resisted attempts to observe workers in these industrial settings.

Consequently, several major work clothing manufacturers were visited. These producers provided information concerning the types of work clothing worn in different industrial environments, particularly those characterized by high air and mean radiant temperatures. A variety of high volume clothing items were obtained from the manufacturers; the items included 11 shirts, 7 pairs of pants, 6 coveralls, 8 specialty protective items, and 1 pair of gloves. These garments were tested individually and as components of representative work clothing ensembles. Selected protective garments were also tested in ensemble form with the KSU uniform. The KSU uniform consists of a standard work shirt, pants, underwear, socks, and shoes.

Physical characteristics of the fabrics used in the garments mentioned above are found in Table 1. Garments' attributes are given in Table 2. Components of the ensembles are found in Table 3.

Data collection

Descriptive and physical characteristics of the garments were determined using several methods.

Fabric construction was determined by visually comparing the weave of the garment to known weave patterns. Fabric count, or the number of yarns (lengthwise by crosswise) contained in one square inch of fabric, was measured by using American Society for Testing and Materials standard test method D 1910 (2). This test method also specifies the procedure for determining weight of the fabric in ounces per square yard. The fiber content of each garment was obtained from the label attached to each garment. Information regarding the application of finishes was also obtained from the label. Fabric thickness was measured by a compressometer in accordance with the ASTM D 1977 test method (2). Each entire garment was also weighted on a digital balance.

The thermal insulation values of all garments and ensembles

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

Table 1

Fabric Characteristics of Garments

Garment Code	Fabric Construction	Count (Warp and Weft/in.^{2})	Weight (oz./yd.^{2})	Fiber Content	Finishes	Thickness (in.)
101	satin weave	49 x 50	11.0	100% cotton	flame retardant	0.0298
102	satin weave	52 x 50	9.7	100% cotton	flame retardant	0.0318
104	twill weave	65 x 42	13.2	100% cotton	flame retardant	0.0345
105	twill weave	105 x 53	6.8	100% SEF modacrylic	anti-static acid-resistant	0.0128
106	plain weave	105 x 52	4.5	65% polyester 35% cotton	durable press soil release	0.0128
107	plain weave	106 x 58	4.5	65% polyester 35% cotton	durable press soil release	0.0110
108	twill weave	99 x 62	5.6	100% cotton		0.0175
109	leno weave	59 x 96	4.5	65% polyester 35% cotton	durable press soil release	0.0123
110	twill weave	93 x 56	6.0	100% cotton	flame retardant	0.0211
111	leno weave	59 x 96	4.5	65% polyester 35% cotton	durable press soil release	0.0130
112	twill weave	86 x 57	9.3	100% cotton	flame retardant	0.0238

Table 1

(continued)

Garment Code	Fabric Construction	Count (Warp and Weft/in.^{2})	Weight (oz./yd.^{2})	Fiber Content	Finishes	Thickness (in.)
KSU Shirt	twill weave	107 x 64	4.0	65% polyester 35% cotton		0.0150
201	twill weave	54 x 42	13.8	100% cotton	flame retardant	0.0340
202	satin weave	51 x 50	10.0	100% cotton	flame retardant	0.0350
203	twill weave	59 x 46	6.8	100% SEF modacrylic	anti-static acid-resistant	0.0198
204	twill weave	65 x 40	13.3	100% cotton	flame retardant	0.0372
205	twill weave	82 x 56	9.5	100% cotton	flame retardant	0.0293
206	twill weave	82 x 58	8.7	100% cotton		0.0265
207	twill weave	59 x 54	7.5	65% polyester 35% cotton	durable press	0.0190
KSU Pants	twill weave	86 x 51	7.3	65% polyester 35% cotton		0.0239
310	twill weave	85 x 60	9.0	100% cotton	flame retardant	0.0270
312	twill weave	69 x 52	8.5	100% cotton		0.0280
313	twill weave	60 x 43	6.8	100% SEF modacrylic	anti-static acid-resistant	0.0206

Table 1

(continued)

Garment Code	Fabric Construction	Count (Warp and Weft/in.^{2})	Weight (oz./yd.^{2})	Fiber Content	Finishes	Thickness (in.)
314	herringbone twill weave	53 x 60	10.5	100% cotton		0.0318
317	2 x 1 basket weave	94 x 73	6.5	100% Nomex aramid		0.0210
318	satin weave	53 x 50	9.0	100% cotton	flame retardant	0.0346
305	2 x 2 basket weave	36 x 18	18.7	100% PFR rayon	aluminized coating	0.0465
315	herringbone twill weave	56 x 36	19.0	100% PFR	aluminized coating	0.0524
316	filling knit		6.5	100% Nomex aramid		0.0418
321	nonwoven	na	3.2	90% reprocessed wool, 10% other fibers	flame retardant	2.0790
322	satin weave	53 x 48	9.0	100% cotton	flame retardant	0.0330
319	satin weave	51 x 50	9.0	100% cotton	flame retardant	0.0330
323	herringbone twill weave	56 x 36	19.0	100% rayon	aluminized coating	0.0524

Table 1

(continued)

Garment Code	Fabric Construction	Count (Warp and Weft/in.^{2})	Weight (oz./yd.^{2})	Fiber Content	Finishes	Thickness (in.)
324	plain weave	75 x 31	14.9	100% cotton	flame retardant	0.0413
320	knit filling	na	*	50% Kynol novoloid 50% Nomex aramid		*
jockey shorts	filling knit	na	*	100% cotton knit		*
socks	filling knit	na	*	100% cotton jersey knit		*
T-shirt	filling knit	na	*	100% cotton jersey knit		*
shoes	nonwoven	na	*	vinyl film		*
belt	braid	na	*	100% cotton		*

na = not apply.

* varied throughout garment so measurement not taken.

Table 2

Garment Characteristics

Garment Code	Manufacturer[1]	Design Description	Garment Weight (oz.)
101	B	long sleeve shirt-jacket collar, 2 chest pockets, snap front	25.6
102	B	long sleeve shirt-jacket collar, snap front	22.9
104	B	long sleeve shirt-jacket collar, 1 chest pocket, snap front	31.8
105	A	long sleeve shirt, 2 chest pockets, snap front, collar, cuffs	15.8
106	A	long sleeve shirt, 2 chest pockets, collar, button front, cuffs	10.4
107	A	short sleeve shirt, 2 chest pockets, collar, button front	7.9
108	A	long sleeve shirt, 2 chest pockets, collar, cuffs, button front	12.5
109	A	long sleeve shirt, 2 chest pockets, collar, cuffs, button front	10.8
110	A	long sleeve shirt, 2 chest pockets w/flaps, collar, cuffs, button front	16.6
111	A	short sleeve shirt, 2 chest pockets, collar, button front	8.5
112	A	long sleeve shirt, 1 chest pockets, collar, button front	18.7
KSU Shirt	A	long sleeve shirt, 2 chest pockets, collar, cuffs, button front	8.7
201	B	straight leg pants, 2 side pockets, 2 back patch pockets	27.4

Table 2

(continued)

Garment Code	Manufacturer[1]	Design Description	Garment Weight (oz.)
202	B	straight leg pants, 2 back patch pockets	23.0
203	A	straight leg pants, 2 side pockets, 2 back inside pockets	13.9
204	B	straight leg pants, 2 side pockets, 2 back patch pockets	30.4
205	A	straight leg pants, 2 side pockets, 2 back inside pockets	19.2
206	A	straight leg pants, 2 side pockets, 2 back inside pockets	17.3
207	A	straight leg pants, 2 side pockets, 2 back inside pockets	14.9
KSU Pants	A	straight leg pants, 2 side pockets, 2 back inside pockets	14.7
310	A	long sleeve coverall, 1 chest pocket, 2 back patch pockets, collar	35.6
312	A	long sleeve coverall, 2 chest pockets, 2 back patch pockets, collar	33.9
313	A	long sleeve coverall, 2 chest pockets, 2 back patch pockets, collar	24.8
314	A	long sleeve coverall, 2 chest pockets, 2 back patch pockets, collar	42.2
317	C	long sleeve coverall, 1 chest pocket, 2 front pockets, 2 back patch pockets, collar	23.7
318	C	long sleeve coverall, 1 chest pocket, 2 back patch pockets, collar	38.8

Table 2

(continued)

Garment Code	Manufacturer[1]	Design Description	Garment Weight (oz.)
305	B	long sleeve mid-calf length coat, snap front, collar	68.6
315	C	long sleeve hip length coat, snap front, collar	44.6
316	C	facemask, eye and nose area open	1.3
321	C	hood, face left open snap in front	6.8
322	C	apron, strap around neck and waist, knee length	8.4
319	C	leggings, wide legs, no buttock area, shoe protection flaps attach to belt	15.1
323	C	arm protectors, cover shoulder, taper to wrist, snap at wrist	14.0
320	C	gloves, ribbed cuff to mid-forearm	4.2
324	C	arm protectors, to mid upperarm, taper to wrist, snap at wrist	9.7

[1]A = RedKap Industries

B = Sager Glove Corporation

C = Wheeler Protective Apparel, Inc.

Table 3

Ensemble Combinations

Ensemble code	Components
500	shirt 101 pants 201 underwear T-shirt socks shoes belt
501	shirt 102 pants 202 underwear T-shirt socks shoes belt
502	shirt 104 pants 204 underwear T-shirt socks shoes belt
503	shirt 106 pants 207 underwear socks shoes belt
504	shirt 109 pants 207 underwear socks shoes
505	shirt 105 pants 203 underwear socks shoes belt
506	shirt 110 pants 205 underwear socks shoes belt

Table 3
(continued)

Ensemble code	Components
507	shirt 111 pants 207 underwear socks shoes belt
508	shirt 107 pants 207 underwear socks shoes belt
527	coverall 313 underwear T-shirt socks shoes
KSU uniform	KSU shirt KSU pants underwear socks shoes
525	KSU uniform coat 305 underwear socks shoes
524	KSU uniform coat 315 underwear socks shoes
509	KSU uniform facemask 316 underwear socks shoes
511	KSU uniform hood 321 underwear socks shoes

Table 3

(continued)

Ensemble code	Components
514	KSU uniform apron 322 underwear socks shoes
510	KSU uniform hip leggings 319 underwear socks shoes belt
512	KSU uniform arm protectors 323 underwear socks shoes
513	KSU uniform arm protectors 324 underwear socks shoes
520	KSU uniform gloves 320 underwear socks shoes

were determined using a dry, heated copper manikin. The permeability index of all ensembles were measured using a "sweating" copper manikin.

Instrumentation. The copper manikin, located in the Institute for Environmental Research at Kansas State University, resembles a man in its shape and body dimensions. The body measurements and clothing sizes of the manikin are given in Tables 4 and 5. The manikin's shell consists of black anodized copper. The manikin is equipped with 16 thermistors, located in various parts of the body, as shown in Figure 1. The manikin's head rests in a head frame, which is attached to a metal stand. The manikin can only stand upright when resting in the head frame or with a wire around his waist or neck and the metal stand. A power cable and thermistor wires are attached to his neck. A matrix of four thermistors is plugged into the back of his neck for measuring air temperature.

The manikin is kept in an environmentally controlled chamber measuring 2.6 x 1.5 m (8.5 x 5 ft.). The air temperature in the chamber can be varied from approximately -26.1°C (-15°F) to 66°C (150.8°F). Air temperature in the chamber is measured by a matrix of four thermistors on a wooden dowel at heights of 15.2 cm (6 in.), 76.2 cm (30 in.), 121.9 cm (48 in.), and 182.9 cm (72 in.). Varying the height of the thermistors compensates for any thermal stratification occurring in the chamber. The average air temperature is recorded on the data logger. The mean radiant

Table 4

Copper Manikin Body Measurements

Location	Measurement (cm)	(in.)
Head circumference; taken at forehead	58.42	23.00
Head; over top of head from ear to ear	30.48	12.00
Shoulder width; from tip of shoulder across back to tip of other shoulder	41.28	16.25
Back length; from nape of neck to waistline	40.64	16.00
Chest; around torso at armpit	91.44	36.00
Waist; around torso at waist	78.74	31.00
Upper hip; around torso 10.2 cm (4 in.) below waist	91.44	36.00
Lower hip; around torso 20.4 cm (8 in.) below waist	97.03	38.20
Arm length;		
underarm to wrist	45.72	18.00
tip of shoulder to wrist	63.50	25.00
Wrist; circumference	17.78	7.00
Arm girth; circumference at upper arm	29.21	11.50
Leg length or Inseam; inner leg to ankle	72.39	28.50
Leg girth; circumference at upper leg	58.42	23.00
Ankle; circumference	22.86	9.00
Foot;		
length, toe to heel	29.21	11.50
width, across widest part of foot	10.16	4.00
Neck; circumference	41.91	16.50
Crotch seam; crotch from front to back waistline	69.85	27.50

Table 5

Clothing Sizes Chart for the Copper Manikin[a]

Clothing	Size
T-shirt	Medium
Undershorts	32
Sports shirt	16 - 16 1/2 34 in. sleeve
Trousers	31 in. waist 29 in. inseam
Socks	13
Shoes	11D
Sweater	42
Jacket	36 or 38

[a] Unlike a human, the manikin is not flexible, but rigid. Thus, allowance for ease must be sufficient to open and close fasteners. The manikin does not have the same proportions as the average human body so some ready-to-wear sizes have to be altered or exact fit is sacrificed.

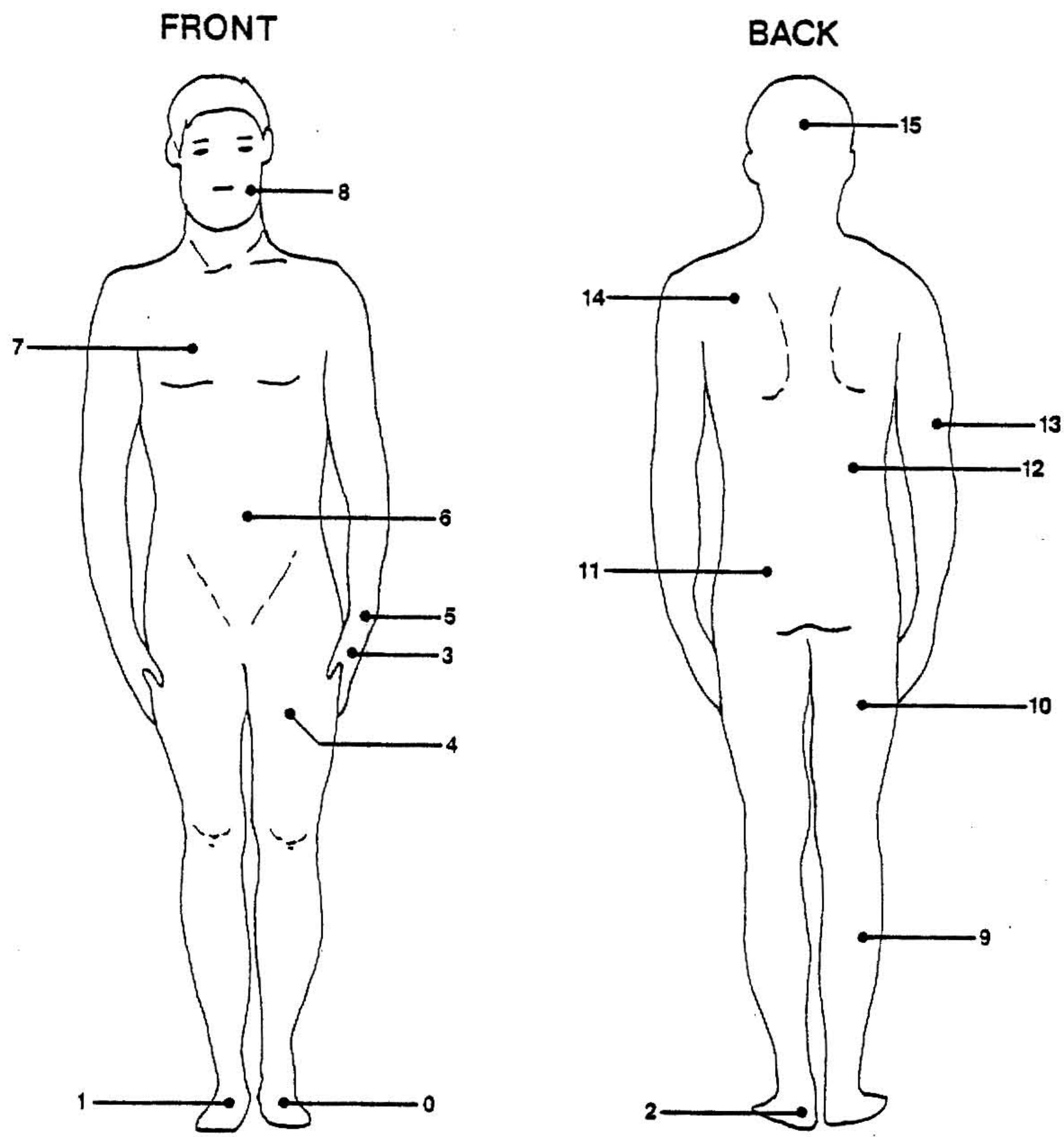

Figure 1. Location Of Thermistors On Copper Manikin

temperature of the chamber is assumed to be equal to the ambient temperature. Low levels of air velocity are produced by ceiling fans in the chamber. The velocity is measured periodically with an anemometer. Relative humidity is regulated by a humidifier located inside the chamber. The humidifier is adjusted until humidity inside the chamber reaches the desired level, as measured by a dew point hygrometer.

The control room houses the data acquisition system, which includes a proportional temperature controller, power reducer for the extremities, digital power monitor, watt-hour meter, timer, data logger, single pen chart recorder, and dew point hygrometer.

The proportional temperature controller is used to control the skin temperature of the manikin. The temperature dials are set to give the manikin an average skin temperature of 33.3 $\pm$ .5^{o}C (92^{o}F).

The variac power reducer decreases the amount of power to the hands and feet. It is adjusted so that the average skin temperature of the extremities is 29.4 $\pm$ .5^{o}C (85^{o}F).

The digital power monitor (watt meter) measures the amount of power being used to heat the manikin. The power in watts, is read on a digital display. Power measurements and elapsed time are measured by the watt-hour meter and timer during a test period.

The data logger provides many functions. The temperature of each thermistor can be given on a digital display or printed on paper tape. The data logger also records time--either actual time or the elapsed time during testing.

The dew point hygrometer measures the relative humidity in the chamber from a probe located in the right front of the chamber, about 1.8 m (6 ft.) off the floor. The dew point temperature is read on the top scale. A psychometric chart is used to convert the dewpoint temperature to relative humidity at the dry bulb temperature of the chamber.

Another piece of equipment in the control room is a single pen chart recorder. The recorder is used to determine when the power going to the manikin has stabilized and the system has reached equilibrium. It is also used to double check power monitor readings.

Procedure for Measuring Thermal Insulation Values

When measuring the thermal insulation values of clothing, the experimental conditions in the environmental chamber were controlled as follows: the air temperature was 26.7 $\pm$ .5°C (80°F), the mean radiant temperature was 26.7 $\pm$ .5°C (80°F) (assumed to be equal to ambient temperature), the relative humidity was 50%, and the air velocity was 0.1 m/s. The average skin temperature of the manikin was set at 33.3 $\pm$ .5°C (92°F), and the average skin temperature of the extremities was set at 29.4 $\pm$ .5°C (85°F).

To conduct a test, the manikin, located in the environmental chamber, was dressed in a garment or ensemble. A pulley and rope apparatus attached to the metal stand was used to lift the manikin off the floor in order to dress the lower half of his body. The manikin was then lowered to the floor and dressed in garments covering his upper torso. The arms of the manikin moved forward and backward at the shoulder joint, which allowed garments with front or back closures to be placed on the manikin with ease. For articles without these openings (i.e., a T-shirt), the arms were unlocked at the shoulder joints and raised over his head. The head frame or rope was removed, and the shirt was pulled over his arms and head. The head frame or rope was repositioned, and the arms were locked back into place. An alternate method involved cutting the center of the garment open vertically, putting it on the manikin like a shirt or jacket, then sewing the opening together with needle and thread.

After dressing, the chamber door was shut and locked. The type of garment(s), the method of dressing (i.e., all buttons buttoned, top snap unsnapped), the researcher's name, and the date were recorded on a data collection sheet. (See Figure 2.)

The manikin system was turned on using a main power switch which controlled electrical power to the temperature controller, power monitor, and data logger. The system remained on throughout the entire data collection period to avoid unnecessary waiting for the system to reach equilibrium and to increase efficiency. Maximum power was limited to 200 watts. The single pen chart recorder was turned on separately. The chart on the recorder determined when the system was at equilibrium, meaning power going to the manikin was steady. This state consisted of a straight line

Project______________________________

Garments______________________________

____

Method of Dressing________________________

____

Data		Replication 1	Replication 2
Date			
Researcher			
H_D	W	$\frac{60 \times}{14 \times}$ =	$\frac{60 \times}{14 \times}$ =
$H_D \times 0.985$*	W		
$\bar{T}_s$	°C		
T_a	°C		
ΔT	°C		
W/°C			
I_T	clo		

Remarks______________________________

____

Average I_T______________ Average W/°C______________

$$I_T = \frac{6.45\ (\Delta T)\ 1.86}{H_D \times 0.985}$$

I_a______________

f_{cl}______________

I_a/f_{cl}______________

Staple
data logger printout and
recorder chart here

$I_{cl} = I_T - (I_a/f_{cl}) =$____________

*Correction for a 1.5% power loss

Figure 2. Data Sheet for Dry Clo Measurements on the Copper Manikin

or even cycling chart on the chart recorder.

When equilibrium was reached, the average skin temperature of the manikin's body, the average skin temperature of his extremities, and the average air temperature were checked by examining the data logger printout and averaging thermistor values. If any of these temperatures were not within the limits specified for the experimental conditions, the necessary controls were adjusted, and equilibrium was re-established.

The test was started by turning the watt-hour meter and timer switches on simultaneously. The data logger controls were set so that a printout of thermistor readings was produced every 10 minutes, making a total of seven printouts per hour. The beginning and end of each test were marked on the strip chart.

After the end of one hour, the test was stopped by turning off the watt-hour meter and timer simultaneously. The number of watt hours and elapsed minutes were recorded on the data collection sheet. Also, the paper tape and chart recorder strip were attached to the data collection sheet.

The average power (H_D) used during a test was calculated using the following equation:

$$H_D = \frac{60 \times \text{Watt hours}}{14 \times \text{Minutes}}$$

H_D was multiplied by 0.985 to make an adjustment for a 1.5%

power loss from the temperature controller to the manikin.

To calculate clo, the seven ambient air temperature readings (T_a) obtained during the test were averaged. The mean skin temperature ($\bar{T}_s$) was calculated by using data from the second, fourth, and sixth printouts (i.e., three printouts). The test was discarded if the mean skin temperature or air temperature varied more than ± 0.1°C over the one hour test period. This amount of change would indicate the system was not at equilibrium when the test was conducted.

Total thermal insulation (I_T) was calculated using the following equation:

$$I_T = \frac{6.45\ (\bar{T}s - Ta)\ A_s}{H_D}$$

where $\bar{T}_s$ = mean skin temperature - °C

T_a = air temperature - °C

A_s = body surface area - m^2

H_D = power - W

I_T - total insulation value - clo

The manikin surface area (A_s) is 1.86 m^2.

The total insulation value (I_T) of a garment or ensemble was reported as an average of two replications, because all pairs of individual values were within ± 3%--the accepted confidence interval for manikin experiments--and because tests were time consuming, expensive, and complex to conduct.

Periodically, the KSU uniform (I_T = 1.25), was tested on the manikin for calibration purposes.

Determination of Intrinsic Clo (I_{cl})

The intrinsic clo (I_{cl}) of each garment and ensemble was determined. The I_{cl} value is the insulation of the garment or ensemble, not including the external air layer surrounding the garment of ensemble. Intrinsic clo was needed for comparing the four methods of determining I_{cl} of ensembles. Two of these methods were mathematical formulas using I_{cl} as a variable.

The intrinsic clo value of a clothing ensemble was found by subtracting the insulation provided the air layer over the ensemble from the toal clo value (I_T).

$$I_{cl} = I_T - \frac{I_a}{f_{cl}}$$

where I_{cl} = intrinsic thermal insulation of clothing - clo

I_T = total thermal insulation of clothing plus boundary air layer - clo

I_a = thermal insulation of air layer around nude manikin - clo

f_{cl} = clothing area factor

Determination of Clothing Area Factor (f_{cl})

The clothing area factor (f_{cl}) for each garment and ensemble was determined using a photographic method. Two photographs were taken of each item--a front view and a side view. The angle of the manikin's body and the distance from the camera to the manikin remained constant. A planimeter was used to calculate the surface area of the garment(s), the manikin under the garment(s), and the nude manikin. The surface area of the manikin that was covered by the garment(s) was subtracted from the surface area of the garment to determine the increase in surface area contributed by the garment(s). The latter area was added to the total surface area of the nude manikin and then divided by the total surface area of the nude manikin to calculate the f_{cl}.

Procedure for Measuring Permeability Index of Ensembles

The procedure for measuring the permeability index of clothing was similar to the procedure used to measure insulation. However, the manikin was covered with a wet cotton skin to simulate skin saturated with sweat.

The main power switch was turned on, which activated and power to the temperature controller, data logger, and power monitor. The power booster switch was set at 300 watts. The recorder was turned on and set at 0.1 inch/minute speed. The environmental conditions were set and checked as indicated previously for measuring thermal insulation.

The cotton jersey knit suit, made to completely cover the manikin's skin, was wet out in a small amount of distilled water in a wash pan, and wrung out slightly. The suit pieces fit the manikin very snugly, like a second skin. The lower half of the manikin's body was dressed in the wet suit and garments, with the manikin hoisted about 6 inches above the floor. The manikin was then lowered, kept upright with a rope around his neck and the metal stand, and the upper half of his body was dressed. The skin was sprayed with water as the clothes were being put on, but the garments were not sprayed. However, the garments became damp after a series of tests.

Garments without front or back openings had to be split down the front or back, then sewn on the manikin. Once the suit was on the manikin, the arms could not be detached to accommodate pull-on garments.

When dressed, the manikin was standing erect with only the support of the rope around his neck; his arms were by his sides, and he was not touching the back pole. The garments, method of dressing, date, researcher, and replication were recorded on a data collection sheet. (See Figure 3.)

The chamber door was shut and locked. The researcher waited for the system to come to equilibrium--as indicated by a drop in power from the 300+ watt level and even cycling on the chart recorder--about 10-15 minutes. The air temperature, relative humidity, and mean skin temperature were checked to see if they

Project________________________________

Garments________________________________

____

Method of Dressing__________________________

____

Replication________________ Date________________

Data		Test 1	Test 2	Test 3
Researcher				
H_w	W	$\frac{60\ x}{14\ x}$ =	$\frac{60\ x}{14\ x}$ =	$\frac{60\ x}{14\ x}$ =
H_w x 0.985*	W			
$\bar{T}_s$	°C			
T_a	°C			
ΔT	°C			
1/I**	W/°C			
P_s	mmHg			
P_a	mmHg			
T_{dp}	°C°F			
ϕ_a	%			
$\phi_a P_a$				
$P_s - \phi_a P_a$				
i_m				

Remarks________________________________

Average i_m for this replication________________

Average i_m________________ i_m/I_T________________

$$i_m = \frac{(H_w \times 0.985) - 1/I\ (\Delta T)}{1/I\ [2.2\ (P_s - \phi_a P_a)]}$$

*Correction for a 1.5% power loss.

**W/°C from dry clo value test.

Figure 3. Data Sheet for Permeability Measurements on the Copper Manikin

were 26.7 $\pm$ .5°C, 55 $\pm$ 5% RH, and 32.8 $\pm$ .5°C, respectively. The manikin's upper body garments were removed and lower body garments were stripped to the floor (leaving socks and shoes on). The manikin was wet entirely with a squirt bottle, again avoiding squirting the garments. The manikin was redressed. The insides of shoes and ankles were wetted. The chamber door was shut and locked. A mark was made on the recorder chart upon returning to the control room to indicate the position of the pen, and the chart speed was increased to 0.5 inch/minute. The timer was turned on. The system was allowed to reach equilibrium, usually taking 10-15 minutes, using the timer and recorder chart as guides. The timer was stopped and reset to zero when equilibrium was reached.

The test was started by turning on the watt-hour meter and timer simultaneously. The data logger was set to printout the thermistor readings every 2 minutes, for a total of six printouts for the 10-minute test. The beginning of the test was marked on the recorder chart, and turned to stand-by position. The scan mode timed button on the data logger was raised to stop data from being printed. This procedure was repeated three times for one replication. The watt-hours and time elapsed were recorded on the data collection sheet. The ambient air temperature was averaged from all six printouts. The average skin temperature was calculated using the second, fourth, and sixth printouts, and thermistors 1-15. The test was discarded if there was a change in mean skin temperature of more than $\pm$ .1°C from the second printout to the sixth printout.

The power (H_w) was calculated using the following equation:

$$H_w = \frac{60 \times \text{Watt hours}}{14 \times \text{minutes}}$$

H_D was multiplied by 0.985 to adjust for the 1.5% power loss from the controller to the manikin. The saturated vapor pressures P_s and P_a were found by looking up the mean skin temperature ($\bar{T}_s$) and air temperature (T_a) on a vapor pressure chart and recording the respective vapor pressures to two significant figures. The dew-point temperature (T_{dp}) was taken at the beginning and end of a testing period, then recorded as an average. The term $\phi_a P_a$ (relative humidity times saturated vapor pressure at T_a) was found in a vapor pressure chart. The term 1/I was the average W/°C used in the dry clo test of the garment or ensemble.

The permeability index (i_m) was calculated using the following equation:

$$i_m = \frac{H_D - 1/I\ (\bar{T}_s - T_a)}{1/I\ [2.2(P_s - \phi_a P_a)]}$$

where $\bar{T}_s$ = mean skin temperature - ^oC

T_a = air temperature - ^oC

H_D = power - W

$1/I$ = watts per degree of temperature difference from dry clo test--W/^oC

P_s = saturated vapor pressure at T_s - mmHg

P_a = saturated vapor pressure at T_a - mmHg

ϕ_a = relative humidity - %

i_m = permeability index - dimensionless

The average i_m for the replication was the average of the three tests, and the average i_m value was the mean of both replications (six tests). The data printouts and chart recorder strips were attached to the data collection sheets.

The i_m values were usually accurate within $\pm$ 4%. Greater accuracy was difficult to obtain because of the variability in instrumentation and the clothing itself.

The manikin ws dressed in the KSU uniform periodically during the test sequence for calibration purposes. The permeability index of the KSU uniform was 0.39.

Chapter 4

RESULTS AND DISCUSSION

In this study, a copper manikin was used to determine the thermal insulation values and permeability indexes of selected work clothing worn in hot industrial environments. The clo value measurements for the individual garments and ensembles were all within ± 3% for two replications. The variability on some of the permeability index measurements was greater. Although two reserchers collected the data, experiments were conducted in a random fashion, and no systematic error due to differences in experimental procedure was found.

Thermal Insulation Values of Garments

The thermal insulation values of individual garments are listed in Table 6. The total clo value (I_T) indicates the amount of insulation provided by the garment and the external air layer, as measured on the manikin. (The value for intrinsic clo was calculated, based on f_{cl} measurements obtained using the photographic method.)

Table 6

Thermal Insulation Values of Individual Garments

Garment Code and Description	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})
101 long sleeve shirt jacket	1.05	1.21	0.49
102 long sleeve shirt jacket	1.07	1.23	0.49
104 long sleeve shirt jacket	1.10	1.27	0.54
105 long sleeve shirt	1.04	1.18	0.44
106 long sleeve shirt	1.02	1.15	0.40
108 long sleeve shirt	1.03	1.20	0.44
109 long sleeve shirt	1.02	1.17	0.41
110 long sleeve shirt	1.05	1.17	0.44
112 long sleeve shirt	1.02	1.15	0.40
KSU long sleeve shirt	0.99	1.12	0.36
107 short sleeve shirt	0.96	1.17	0.35
111 short sleeve shirt	0.95	1.15	0.33
201 loose straight leg pants	0.92	1.18	0.32
202 loose straight leg pants	0.95	1.21	0.36
204 loose straight leg pants	0.95	1.22	0.37
203 straight leg pants	0.90	1.13	0.27
205 straight leg pants	0.92	1.14	0.30
206 straight leg pants	0.90	1.15	0.28

Table 6

(continued)

Garment Code and Description	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})
207 straight leg pants	0.87	1.13	0.24
KSU straight leg pants	0.90	1.14	0.28
310 long sleeve coverall	1.21	1.32	0.67
312 long sleeve coverall	1.21	1.31	0.67
313 long sleeve coverall	1.21	1.30	0.66
314 long sleeve coverall	1.23	1.32	0.69
317 long sleeve coverall	1.24	1.28	0.69
318 long sleeve coverall	1.20	1.33	0.67
305 long sleeve long coat	1.65	1.58	1.20
315 long sleeve short coat	1.36	1.28	0.81
316 facemask	0.77	1.02	0.07
321 hood	0.83	1.03	0.14
322 apron	0.83	1.11	0.19
319 hip leggings	0.79	1.14	0.17
323 arm protectors	0.82	1.15	0.20
324 arm protectors	0.76	1.17	0.15
320 gloves	0.77	1.01	0.07

The shirt-jackets (101, 102, 104) had higher clo values than long sleeve shirts (105, 106, 108, 109, 110) and the short sleeve shirts (107, 111). The fabrics used in the shirt-jackets were thicker and heavier than any of the fabrics contained in the long and short sleeve shirts. The thicknesses of the shirt-jackets ranged from 0.0298 to 0.0345 inches, while the other shirts ranged from 0.0110 to 0.0238 inches. The weight of the fabric varied from 9.7 to 13.2 oz./yd.^{2} for the shirt-jackets, while it was 4.0 to 9.3 oz./yd.^{2} for the other shirts. The shirt-jackets with the highest clo value (104) also had the highest weight and thickness of all shirt-jackets. However the fiber content and finish were the same for all shirt-jackets. Consequently, for a given shirt-jacket or shirt style, the increases in the weight and thickness of the garment's fabric contribute to higher insulation.

The difference in clo values between long sleeve shirts and short sleeve shirts is indicated in Table 6. Short sleeve shirt 111 and long sleeve shirt 109 were identical in structural characteristics, thus the effect of variable sleeve length can be examined. The short sleeve shirt had an intrinsic clo value of 0.33, while the long sleeve shirt had a value of 0.41.

The clo values measured for the loose fitting pants (201, 202, 204) were higher than that of the other fitted pants. In addition, the loose pants were thicker, and had a higher fabric weight than did the fitted pants.

The clo values of the coveralls were all similar.

Many different types of protective items were tested, so comparisons could not be made for the group as a whole, although there were certain items within the group that could be compared.

The two coats with an aluminized coating (305, 315) had different clo values because of their different lengths. The short coat (315) had a clo value of 0.81, whereas the long coat (305) had a greater clo value of 1.20.

Arm protectors 323 were made of 100% rayon with an aluminized coating and they covered more arm surface area than arm protectors 324 which were made of 100% cotton. Item 323 had an intrinsic clo value of 0.20, while 324 had a value of 0.15, showing how these differences affected insulation.

Thermal Insulation Values of Ensembles

The clo values obtained by testing the garments in ensemble form on the copper manikin are given in Table 7. Ensembles which were composed of the shirt-jackets and loose-fitting pants (500, 501, 502) had higher clo values than ensembles composed of long-sleeve shirts and fitted pants (503, 504, 505, 506). In addition, ensembles composed of short sleeve shirts and pants (507, 508) had slightly lower clo values than ensembles with long sleeve shirts and pants. For example, the only difference between ensembles 504 and 507 was the sleeve length; long-sleeved 504 had a clo value of 0.61, whereas short-sleeved 507 had a clo value of 0.57. The difference in insulation between the shirt types was not

Table 7

Thermal Insulation Values of Ensembles

Garment Code and Description	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})
500 shirt 101 pants 201 underwear T-shirt socks, shoes belt	1.45	1.36	0.93
501 shirt 102 pants 202 underwear T-shirt socks, shoes belt	1.51	1.35	0.98
502 shirt 104 pants 204 underwear T-shirt socks, shoes belt	1.51	1.39	1.00
503 shirt 106 pants 207 underwear socks, shoes belt	1.20	1.20	0.61
504 shirt 109 pants 207 underwear socks, shoes belt	1.23	1.14	0.61
505 shirt 105 pants 203 underwear socks, shoes belt	1.28	1.22	0.70
506 shirt 110 pants 205 underwear socks, shoes belt	1.31	1.23	0.73
507 shirt 111 pants 207 underwear socks, shoes belt	1.16	1.20	0.57

Table 7

(continued)

Garment Code and Description	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})
508 shirt 107 pants 207 underwear socks, shoes belt	1.15	1.19	0.55
527 coverall 313 T-shirt underwear socks, shoes	1.41	1.25	0.84
KSU uniform KSU shirt KSU pants underwear socks, shoes	1.25	1.19	0.65
525 coat 305 KSU uniform underwear socks, shoes	2.19	1.58	1.74
524 coat 315 KSU uniform underwear socks, shoes	1.89	1.34	1.36
509 facemask 316 KSU uniform underwear socks, shoes	1.32	1.14	0.70
511 hood 321 KSU uniform underwear socks, shoes	1.42	1.15	0.80
514 apron 322 KSU uniform underwear socks, shoes	1.33	1.26	0.77
510 hip leggings 319 KSU uniform underwear socks, shoes belt	1.39	1.24	0.82
512 arm protectors 323 KSU uniform underwear socks, shoes	1.41	1.30	0.86

Table 7

(continued)

Garment Code and Description	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})
513 arm protectors 324 KSU uniform underwear socks, shoes	1.32	1.28	0.77
520 gloves 320 KSU uniform underwear socks, shoes	1.30	1.20	0.71

as great in ensemble form as it was when individual shirts were compared.

When the protective items were tested as ensembles with the KSU uniform, their ranking in terms of thermal insulation remained the same as it did when the items were tested individually. For example, the long coat worn over the KSU uniform (525) provided more insulation than the short coat over the KSU uniform (524).

Determining the Clothing Area Factor

The f_{cl} values for individual garments and ensembles are reported in Tables 6 and 7 respectively. The f_{cl} values of the work clothing were slightly higher than those measured for similar types of conventional clothing (e.g., long sleeve shirt). However, the f_{cl} value calculated for the KSU uniform (i.e., 1.19) in this study equalled the value reported by Fanger for the same ensemble (13).

The photographic method was very expensive, time-consuming, and difficult to use. Slight differences in the drape of the clothing on the manikin showed up as large differences in the f_{cl}. Consequently, differences in f_{cl} could be found for the same garment depending upon how the manikin was dressed.

Comparison of Four Methods of Determining Ensemble Clo Values

The intrinsic clo values (I_{cl}) of ensembles were determined using four methods. (See Table 8.) One method involved actually

Table 8

Comparison of Intrinsic Clo Values of Ensembles

Determined Using Four Methods

Ensemble code	Sum of Individual Garments Measured on Manikin (I_{cl})		Ensemble Measurement on Manikin (I_{cl})	ASHRAE formula $I_{cl} = 0.82(\Sigma I_i)$	Sprague and Munson formula for $I_{cl} = 0.727(\Sigma I_i) + 0.113$
500	shirt 101	0.49	0.93	0.91	0.92
	pants 201	0.32			
	underwear	0.05			
	T-shirt	0.14			
	shoes	0.07			
	belt	0.01			
		1.11			
501	shirt 102	0.49	0.98	0.94	0.95
	pants 202	0.36			
	underwear	0.05			
	T-shirt	0.14			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		1.15			
502	shirt 104	0.54	1.00	0.82	0.99
	pants 204	0.37			
	underwear	0.05			
	T-shirt	0.14			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		1.21			
503	shirt 106	0.40	0.61	0.50	0.69
	pants 207	0.24			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.80			

Table 8

(continued)

Ensemble code	Sum of Individual Garments Measured on Manikin (I_{cl})		Ensemble Measurement on Manikin (I_{cl})	ASHRAE formula $I_{cl} = 0.82(\Sigma I_i)$	Sprague and Munson formula for $I_{cl} = 0.727(\Sigma I_i) + 0.113$
504	shirt 109	0.41	0.61	0.66	0.70
	pants 207	0.24			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.81			
505	shirt 105	0.44	0.70	0.71	0.75
	pants 203	0.27			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.87			
506	shirt 110	0.44	0.73	0.74	0.77
	pants 205	0.30			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.90			
507	shirt 111	0.33	0.57	0.60	0.64
	pants 207	0.29			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.73			

Table 8

(continued)

Ensemble code	Sum of Individual Garments Measured on Manikin (I_{cl})		Ensemble Measurement on Manikin (I_{cl})	ASHRAE formula $I_{cl} = 0.82(\Sigma I_i)$	Sprague and Munson formula for $I_{cl} = 0.727(\Sigma I_i) + 0.113$
508	shirt 107	0.35	0.55	0.62	0.66
	pants 207	0.24			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.75			
527	coverall 313	0.66	0.84	0.75	0.77
	T-shirt	0.14			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.91			
KSU Uniform	KSU shirt	0.37	0.65	0.66	0.69
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.80			
525	KSU shirt	0.37	1.74	1.64	1.57
	KSU pants	0.28			
	coat 305	1.20			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		2.00			

Table 8

(continued)

Ensemble code	Sum of Individual Garments Measured on Manikin (I_{cl})		Ensemble Measurement on Manikin (I_{cl})	ASHRAE formula $I_{cl} = 0.82(\Sigma I_i)$	Sprague and Munson formula for $I_{cl} = 0.727(\Sigma I_i) + 0.113$
524	coat 315	0.81	1.36	1.32	1.28
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		1.61			
509	facemask 316	0.07	0.70	0.75	0.75
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.87			
511	hood 321	0.14	0.80	0.77	0.80
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.94			
514	apron 322	0.19	0.77	0.82	0.84
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		1.00			

Table 8

(continued)

Ensemble code	Sum of Individual Garments Measured on Manikin (I_{cl})		Ensemble Measurement on Manikin (I_{cl})	ASHRAE formula $I_{cl} = 0.82(\Sigma I_i)$	Sprague and Munson formula for $I_{cl} = 0.727(\Sigma I_i) + 0.113$
510	hip leggings 319	0.17	0.82	0.80	0.82
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
	belt	0.01			
		0.98			
512	arm protectors 323	0.20	0.86	0.82	0.84
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		1.00			
513	arm protectors 324	0.15	0.77	0.78	0.80
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.95			
520	gloves 320	0.07	0.71	0.71	0.75
	KSU shirt	0.37			
	KSU pants	0.28			
	underwear	0.05			
	socks	0.03			
	shoes	0.07			
		0.87			

measuring the clo value of each ensemble using the copper manikin. The others involved summing the I_{cl} values measured on the manikin for each constituent garment and either using the sum as the I_{cl} value or incorporating it into predictive equations.

For all ensembles, the sum of the clo values for the constituent garments was higher than the other three values. This finding was expected because the fabrics would be compressed as they were layered in ensemble form, slightly lowering the thickness and insulation.

The ensemble I_{cl} measurements on the manikin were higher than those predicted using the formulas for the shirt-jacket and loose pants ensembles (500, 501, 502) and for the coverall (527). The highest I_{cl} values for the shirt and pants ensembles were found using the Sprague and Munson formula (45). In general, however, the ensemble I_{cl} values obtained using the formulas were similar to those measured on the manikin.

Clo Values of Work Clothing and Conventional Clothing

The clo values for individual garments (Table 6) were compared to clo values found in the literature for conventional clothing items (45).

The intrinsic clo value for a light, short sheeve shirt, as reported by Sprague and Munson (45), was 0.14. The measured intrinsic clo values ranged from 0.33 to 0.35. The I_{cl} value reported in the Sprague and Munson study for a light, long sleeve shirt was 0.22, while values obtained in this study ranged from 0.33 to 0.44. Their I_{cl} value for a heavy, long sleeve shirt was 0.29, while the values found in the research for heavy shirts were 0.44.

Heavy pants were given an I_{cl} value of 0.32 by Sprague and Munson; in this research they were 0.32-0.37. Light pants were given an I_{cl} of 0.26; in this research they ranged from 0.24-0.30.

It appears that work clothing is generally heavier and warmer for a given type of garment than is conventional clothing. This difference is due to the different types of fabrics that are used.

Permeability Index and Evaporative Impedance

The permeability index (i_m) had never been measured on the copper manikin at Kansas State University prior to this study. Thus, the technique was unfamiliar, and mastering it was a learning process. For reasons still unknown to the researchers, the variability in permeability index values was greater than that for clo values.

The lower the permeability index, the more impermeable the ensemble to the evaporation of water vapor, or sweat. All i_m values were lower than 0.50, because that is the value measured on a nude manikin (18). Ensembles 500 and 502 had lower permeability indexes than ensembles with the lighter weight, thinner pants and shirts. The values for the latter ensembles (503, 504, 505, 506) were very similar to each other and to the value of the KSU uniform, which consisted of the same types of components.

The permeability index of ensembles containing the coats with an aluminized coating were the lowest of all the ensembles. This finding was expected because the fabric of the coats was impermeable. Most of the evaporation in these ensembles occurred in areas not covered by the coats. Arm protectors 323 were constructed of the same aluminized fabric and had a low permeability index (0.31) in contrast to the 100% cotton arm protectors (0.37).

The permeability indexes of a few garments worn over the KSU uniform were slightly higher than the values measured for the KSU uniform alone. For example, the i_m values for the hip leggings ensemble (510) and the apron ensemble (514) were 0.40, while the i_m for the KSU uniform was 0.39. This variation is probably due to experimental variance and illustrates that i_m values were only accurate to $\pm$ 4%.

The evaporative impedance, or the ratio of the permeability to the total clo of an ensemble, was determined for all ensembles. (See Table 9.) The evaporative impedance is the maximum amount of evaporative cooling an ensemble possesses, expressed as a percentage. The ensembles with lighter weight pants and shirts had the highest percentage of evaporative cooling possible. The two ensembles with the aluminized coats had the lowest percentage of evaporative cooling possible, because of the impermeable nature of the coats. The effect of wearing this type of impermeable garments

Table 9

Permeability Index and Evaporative Impedance Values of Ensembles

Ensemble Code and Description	Total Clo (I_T)	Permeability Index (i_m)	Evaporative Impedance (i_m/I_T)
500 shirt 101 pants 210 underwear T-shirt, belt socks, shoes	1.45	0.34	0.23
501 shirt 102 pants 202 underwear T-shirt, belt socks, shoes	1.51	0.43	0.28
502 shirt 104 pants 204 underwear T-shirt, belt socks, shoes	1.51	0.32	0.21
503 shirt 106 pants 207 underwear socks, shoes belt	1.20	0.38	0.32
504 shirt 109 pants 207 underwear socks, shoes belt	1.23	0.39	0.32
505 shirt 105 pants 203 underwear socks, shoes belt	1.28	0.38	0.30
506 shirt 110 pants 205 underwear socks, shoes belt	1.31	0.36	0.27
507 shirt 111 pants 207 underwear socks, shoes belt	1.16	0.36	0.31

Table 9

(continued)

Ensemble Code and Description		Total Clo (I_T)	Permeability Index (i_m)	Evaporative Impedance (i_m/I_T)
508	shirt 107 pants 207 underwear socks, shoes belt	1.15	0.38	0.33
527	coverall 313 T-shirt underwear socks, shoes	1.41	0.39	0.28
KSU	KSU shirt KSU pants underwear socks, shoes	1.25	0.39	0.31
525	coat 305 KSU Uniform underwear socks, shoes	2.19	0.30	0.14
524	coat 315 KSU Uniform underwear socks, shoes	1.89	0.33	0.17
509	facemask 316 KSU Uniform underwear socks, shoes	1.32	0.37	0.28
511	hood 321 KSU Uniform underwear socks, shoes	1.42	0.36	0.25
514	apron 322 KSU Uniform underwear socks, shoes	1.33	0.40	0.30
510	hip leggings 319 KSU Uniform underwear socks, shoes, belt	1.39	0.40	0.29
512	arm protectors 323 KSU Uniform underwear socks, shoes	1.41	0.31	0.22

Table 9

(continued)

Ensemble Code and Description	Total Clo (I_T)	Permeability Index (i_m)	Evaporative Impedance (i_m/I_T)
513 arm protectors 324 KSU Uniform underwear socks, shoes	1.32	0.37	0.28
520 gloves 320 KSU Uniform underwear socks, shoes	1.30	0.38	0.29

was also illustrated by an evaporative impedance of 0.22 for the aluminized coated arm protectors over the KSU uniform (512). Apparently, special protective clothing items which are designed to resist chemicals and other hazards, may lower the amount of evaporative cooling possible in a hot environment.

Model for Predicting Satisfaction with the Environment

An equation proposed by Rohles, Konz, and Munson (39) can estimate any clothing/temperature combination at which only 6% of the people would be dissatisfied with their thermal environment. The equation is:

$$CET^* = 29.75 - (7.28)\ (I_{cl})$$

where ET* = effective temperature - °C

I_{cl} = intrinsic insulation value - clo

The clo values of ensembles evaluated in this study can be used to solve the equation for the optimum effective temperatures for satisfaction. For example, the long aluminized coat worn over the KSU uniform (ensemble 525) has a clo value of 1.74. According to the equation, only 6% of the people dressed in this ensemble will be dissatisfied if the effective temperature of the environment is 17.1°C. In addition, the CET* for ensemble 502 would be 18.8. Unfortunately, many industrial environments have temperatures at much higher levels. In fact, temperatures around 30-50°C are common in some plants. At these levels, even a short sleeve shirt and pants combination (such as 508 at 1.15 I_{cl}) cannot provide thermal comfort. The CET* projected by the formula is 21.4. In fact, some people may suffer heat stress problems. This formula is limited in that differences in air velocity or activity level are not taken into account. However, it appears that satisfaction with the thermal environment will be difficult to attain in hot industrial environments, when most types of work clothing are worn.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The copper manikin method, used to determine thermal insulation values and permeability indexes of garments and ensembles, did discriminate between the clothing items tested. Differences in thermal insulation were found between garments and ensembles with the same structural characteristics, but with slightly different designs (i.e., short sleeve vs. long sleeve). The thermal insulation values of work pants were similar, as were those of work shirts. However, there was considerable variability in the clo values measured for specialty protective items in garment and ensemble forms. For example, the ensemble composed of the heavy, long coat had the highest thermal insulation value of all the ensembles, due to the amount of body surface area it covered and its fabric characteristics. The ensemble with gloves had the smallest clo value of all ensembles consisting of protective items.

Some differences in the permeability indexes of clothing ensembles were found. The ensembles composed of protective garments were the most impermeable to evaporative heat transfer.

However, ensembles composed of conventional type fabrics had similar permeability values.

Differences in the evaporative impedance of the clothing ensembles were evident. Specifically, the ensemble containing the long aluminized coat over the KSU uniform would provide a worker with 14% of the maximum cooling possible, whereas the short sleeve shirt and pants would provide 33% of the maximum cooling possible.

Thus, these differences in thermal insulation values, permeability indexes, and evaporative impedances could be used by firms whose employees must work in hot conditions to reduce the possiblity of heat stress problems.

The ensemble clo values were used to solve an equation which predicts the effective temperature at which 94% of the people dressed in a given ensemble would be satisfied with their thermal environment. The effective temperatures necessary for thermal comfort were far below those found in hot industrial environments. According to this simple model, the temperature of the environment must be drastically reduced, or other environmental, human, and clothing factors changed to obtain thermal comfort.

The measurement of intrinsic clo of ensembles was accomplished by using four methods. The Sprague and Munson formula and the ASHRAE formula gave comparable values to those obtained from direct measurement on the manikin. Summing the clo of the individual items of the ensemble gave a much higher intrinsic clo, and should be used when only a few garments constitute an ensemble, and little or no overlap of fabric layers occurs.

Recommendations

It is recommended that the textile industry develop the technology necessary to provide work clothing that will protect the worker from harmful elements of the environment, while allowing sufficient heat exchange (particularly evaporative) to occur to prevent heat stress problems. Some textile products are available now to meet this need. For example, a new microporous polymeric film of expanded polytetrafluoroethylene (PTFF) prevents the penetration of water while allowing the diffusion of water vapor into the air.

The employers should be made aware that clothing may contribute to heat stress problems in hot industrial environments. An employer who is knowledgeable of thermal insulation values and permeability indexes may be able to suggest or supply more appropriate garments to his/her employees. When garments of lower thermal insulation and/or higher permeability are worn, there would be a decreased chance of heat exhaustion. Employees would be more comfortable, improving worker morale and production.

A complex mathematical model is needed that could predict conditions conductive to heat stress. This model should take into account environmental, human, and clothing factors. One such model is currently being used by researchers at the U.S. Army Research Institute of Environmental Medicine in Natick, Massachusetts for

for military operations.

More protective items need to be evaluated in terms of their thermal insulation and permeability characteristics because they directly affect the probability that workers will suffer heat stress problems in hot industrial environments.

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THERMAL INSULATION VALUES AND PERMEABILITY INDEXES OF SELECTED WORK CLOTHING WORN IN HOT INDUSTRIAL ENVIRONMENTS

by

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ABSTRACT

The purpose of this study was to measure and compare the thermal insulation (clo) values and permeability indexes of protective clothing worn in hot industrial environments. Several work clothing manufacturers were contacted concerning the types of garments commonly worn by workers in hot conditions. The garments obtained included 8 shirts, 3 shirt-jackets, 7 pairs of pants, 6 coveralls, and 9 specialty protective items (i.e., coats, arm protectors, hip leggings, facemasks, hoods, and gloves). The garments were evaluated individually, as well as in ensemble form. Ensembles were worn over various combinations of underwear, T-shirt, shoes, socks, and a belt. Other ensembles consisted of a specialty protective item over a standard work ensemble so that items could be compared.

An electrically heated copper manikin located in an environmentally controlled chamber was used to measure the total insulation value (I_T) for the individual garments and ensembles. The clothing area factor (f_{cl})--the ratio of the surface area of the clothed manikin to that of the nude manikin--was calculated using a photographic method. The intrinsic clo value (I_{cl}) was determined by subtracting the insulation provided by the external air layer from the total insulation value measured for each garment and ensemble. Four methods used to determine intrinsic clo of ensembles were compared. The I_{cl} value was needed to evaluate

these methods. The permeability index (i_m) and evaporative impedance (i_m/I_T) of the ensembles were measured on the manikin covered by a wet cotton skin to simulate a sweating man.

Clo values of shirts and pants made of similar types of fabrics and designs were parallel. Loose-fitting shirts and pants made of a heavier, thicker fabric had higher insulation values than the other shirts and pants. Variability also occurred among garments of identical characteristics except for design (i.e., sleeve length). The most variability in thermal insulation values occurred among specialty protective items. They cover only certain parts of the body, and are made of unconventional fabric constructions.

The permeability indexes and evaporative impedances also showed the greatest variability among specialty protective items. The permeability of the ensembles with the aluminized coats as components was the lowest, as were their evaporative impedances.

The research showed that many garments and ensembles can contribute to the possibility of heat stress when worn in hot industrial environments. A mathematical model predicted workers would not be satisfied with their thermal environment when wearing ensembles evaluated in this study. Employers should be made aware of information on thermal insulation values, permeability indexes, and evaporative impedances for use to their advantage in decreasing symptoms of heat exhaustion occurring in hot industrial environments.