MEASURING THE THERMAL INSULATION AND PERMEABILITY OF
PROTECTIVE CLOTHING USING A COPPER MANIKIN

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Since the passage of the Occupational Safety and Health Act in 1970,
the United States government, employers, and employees have increased
their efforts to reduce hazards in the workplace. Numerous standards
concerning work conditions and practices have been developed by government
agencies (particularly the Occupational Safety and Health Administration)
and industry groups. Although few of these standards specify the types of
protective clothing that should be worn for different job assignments,
some firms require workers to wear special clothing and frequently provide
them with it. Some firms even take responsibility for the care, repair,
and replacement of the items. However, many employees who are given
protective garments wear them incorrectly or refuse to wear them at all
because the items make the wearers feel hot (1).

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 pro-
tective clothing systems. Advertisements and specification sheets empha-
size these attributes to prospective buyers. Unfortunately, the comfort
properties of these garments are considered less important and often are
ignored completely in the design process. For example, some protective
garments cover a large portion of the body and are quite heavy and cumber-
some to wear. Many garments are designed to be worn over other garments
in a layered fashion also. These features can increase the wearer's heat
production during activity as well as restrict heat flow from the body to
the environment (4).

Many garments are treated with special finishes or coatings such as
those which impart chemical resistance and flame resistance. These treat-
ments often lower the permeability of the fabric, and consequently, inhi-
bit the evaporation of moisture from the body. The permeability of cloth-
ing becomes increasingly important in environmental conditions where heat
balance can be achieved only by evaporation of sweat.

Although protective clothing reduces the probability that a person
will be injured due to hazards in the workplace, it should not simulta-
neously increase the probability that a worker will suffer thermal discom-
fort and heat-related physiological problems. Garments that entrap 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.

Whether or not a worker will suffer from heat stress problems in hot
industrial environments depends upon the degree to which his/her clothing
ensemble alters heat transfer between the body surface and the environ-
ment. The total heat transfer is equal to the dry heat transfer (i.e.,
conduction, convection, and radiation from the body) plus the evaporative
heat transfer (i.e., evaporation of moisture from the skin). Researchers
at the U.S. Army Research Institute of Environmental Medicine in Natick,
Massachusetts have developed test methods for measuring and quantifying
the resistance to heat transfer of military clothing assemblies (4).

These techniques were used in this study to measure the thermal insulation value (I_T) and evaporative impedance (i_m/I_T) of protective clothing worn in hot industrial environments.

Experimental Procedure

Sample Selection

Several work clothing manufacturers were contacted concerning the types of work clothing worn in different industrial environments, particularly those characterized by high air temperatures and high mean radiant temperatures. A variety of clothing items were obtained from the manufacturers. The items included shirts, pants, coveralls, gloves, and specialty protective items. These garments were evaluated as components of representative work clothing ensembles and over a standard work clothing ensemble (i.e., KSU uniform). Characteristics of selected ensembles are given in Table 1.

Procedure for Measuring the Thermal Insulation Value

The insulation of a clothing system is the resistance to dry heat transfer defined in terms of a clo unit. (See references 3 and 5 for more information.) An electrically heated copper manikin was used to measure the clo value of each work clothing ensemble. The manikin was placed in an environmental chamber and dressed in the garments. Experimental conditions in the chamber were controlled as follows: air temperature = 26.7 ± .5 C; air velocity = 0.1 m/s; and relative humidity = 50%. A proportional temperature controller was used to keep the skin temperature of the manikin at 33.3 ± .5 C. A variable transformer decreased the amount of power to the hands and feet so that the average temperature of the extremities was 29.4 ± .5 C. Temperature measurements from 16 skin thermistors and 4 air thermistors were recorded digitally at specified intervals on paper tape. The average power used to heat the manikin during a 1-hour test period was measured using a watt-hour meter.

The total thermal insulation value (I_T) was calculated using the following equation:

$$I_T = \frac{K A_s (\overline{T}_s - T_a)}{H} \qquad [1]$$

where I_T = total thermal insulation of clothing plus boundary air layer (clo); K = constant = 6.45 clo - w/C - m^2; A_s = manikin surface area m^2; $\overline{T}_s$ = mean skin temperature (C); T_a = ambient air temperature (C); H = power input (w).

The total insulation value (I_T) of a clothing ensemble was reported as an average of two replications because all pairs of individual values were within ± 3%.

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

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \qquad [2]$$

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.

The value of I_a (0.72) was obtained by operating the manikin without clothing and using the equation for calculating I_T. The clothing area factor (f_{cl}) for each ensemble was determined using a photographic method. A planimeter was used to calculate the surface area of the garments and the nude manikin from the pictures. The f_{cl} was calculated as the surface area of the clothed manikin divided by the surface area of the nude manikin.

Procedure for Measuring the Permeability Index

Woodcock (7) defined the permeability index (i_m) as the ratio between the actual evaporative heat transfer of a clothing system and the ideal evaporative heat transfer characterized by a wet bulb system. The actual evaporative heat transfer can be determined by subtracting the measured dry heat transfer from the measured total heat transfer. The evaporative heat transfer of an ideal system is:

$$H_e = \frac{K A_s}{I_T} S (P_s - \emptyset_a P_a) \qquad [3]$$

where H_e = evaporative heat transfer (w); K = constant = 6.45 clo - w/C - m^2; A_s = surface area (m^2); I_T = total thermal insulation of clothing plus boundary air layer (clo); S = Lewis constant = 2.2 C/mmHg vapor pressure; P_s = saturated vapor pressure at T_s (mmHg); P_a = saturated vapor pressure at T_a (mmHg); $\emptyset_a$ = ambient air relative humidity (%).

Consequently, the permeability index (i_m) was determined as follows: (See above equations for definition of terms.)

$$i_m = \frac{H - \frac{K A_s}{I_T} (\overline{T}_s - T_a)}{\frac{K A_s}{I_T} S (P_s - \emptyset_a P_a)} \qquad [4]$$

A "sweating" copper manikin was used to measure the total heat transfer permitted by the work clothing ensembles and to determine i_m. The procedure was similar to the one used to measure clo values. However, the manikin skin temperature was 32.8 ± .5 C, and the relative humidity in the chamber was approximately 60%. In addition, the manikin was covered with a wet cotton knit "skin" to simulate skin saturated with sweat. The cotton "skin" was sprayed with distilled water as the manikin was dressed. Although the garments were not sprayed, they became damp after a series of tests. When the system reached equilibrium, a 10-minute test was conducted. Longer test periods were not possible because parts of the "skin" would begin to dry out. Three 10-minute tests constituted one replication, and two replications were conducted.

A psychrometric table was used to determine P_s and $\emptyset_a P_a$ at the mean skin temperature and dew point temperature respectively. The gradient for

evaporative heat transfer is the difference between P_s and $\emptyset_a P_a$. The parameter S is the Lewis relation which converts the vapor pressure difference to an effective temperature difference (5, 7).

Once the clo value and permeability index were determined for the clothing ensembles, the evaporative impedance was calculated. The evaporative impedance (i_m/I_T) is a coefficient of evaporative heat transfer that is a function of air velocity (4).

Results and Discussion

The thermal insulation values, clothing area factors, permeability indexes, and evaporative impedance values are presented in Table 2. Differences in heat transfer characteristics were expected among the clothing items because they differed in textile characteristics and/or garment design. However, meaningful comparisons can be made between some items.

Thermal Insulation

Garments in ensembles 504 and 507 were made of the same fabrics and were identical in design except for sleeve length. Long-sleeved 504 had a I_{cl} value of 0.61, whereas short-sleeved 507 had a value of 0.57. Garments in ensembles 505 and 507 were made of identical fabrics, but had different design features. The shirt/pants ensemble (including belt) had an I_{cl} of 0.70, whereas the coverall ensemble had a value of 0.84.

Protective clothing items were tested as ensembles with the KSU standard uniform, so that differences between ensembles would be due to differences in these garments. For example, the ensembles consisting of aluminized coats worn over the KSU uniform had different clo values because of different coat lengths. Short coat ensemble 524 had an I_{cl} value of 1.36, whereas the long coat ensemble 525 had a value of 1.74.

It appears that for a given type of garment, work clothing often is heavier and warmer than is conventional clothing. This difference is due primarily to the different types of fabrics that are used. In addition, many odd types of work garments are worn for protective purposes, and the insulation provided by these items varies considerably.

Clothing Area Factor

The f_{cl} values for the ensembles are listed in Table 2. In general, the f_{cl} values calculated for the work clothing were slightly higher than those reported in the literature for conventional clothing (6). However, the f_{cl} value measured in this study for the KSU uniform (i.e., 1.19) was the same as that reported by Fanger (2). More research is needed to develop an accurate and reproducible method for measuring the clothing area factor. The photographic method was very expensive, time-consuming, and difficult to use. Slight differences in the drape of the clothing on the manikin could change the f_{cl} by about 10%. Consequently, differences in f_{cl} could be found for the same garments depending upon how the manikin was dressed.

Permeability Index and Evaporative Impedance

In hot industrial environments, the skin to air temperature gradient for dry heat loss is small or negative. Consequently, the evaporative impedance becomes more important than the clo value alone in evaluating

heat transfer in protective clothing systems. The permeability index (i_m) and evaporative impedance (i_m/I_T) are reported for each ensemble in Table 2. Although theoretically the i_m values could range from 0 for a system with no evaporative heat loss to 1 for a system that had little or no impedance to evaporative heat transfer (4), values greater than 0.50 are seldom obtainable for a motionless nude manikin in relatively still air.

The ensembles containing the coats and arm protectors with aluminized coatings had the lowest i_m values of all the ensembles. This finding was expected because the aluminized fabric was impermeable to liquids and water vapor. Most of the evaporation in these ensembles occurred in areas not covered by the protective garments.

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. However, experimental error was at least ± 0.01 and as much as ± 0.03 for the worst cases.

The evaporative impedance is actually a measure of the transmissibility of moisture from the skin to the environment. The ensembles with lighter weight pants and shirts had the highest amount of evaporative transfer. The two ensembles with the aluminized coats had the lowest evaporative cooling because of the impermeable nature of the coats. The effect of wearing this type of impermeable garment also was illustrated by an evaporative impedance of 0.22 for the aluminized arm protectors over the KSU uniform (512). In addition, the heavy flame retardant cotton ensembles 500 and 502 allowed little transmission of moisture. Their i_m/I_T values were 0.23 and 0.21 respectively. 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, particularly when they cover large portions of the body.

The evaporative impedance values found for work clothing seemed to be slightly lower than those reported for similar military ensembles (4). This discrepancy is probably due to the lower air velocity and higher relative humidity levels used in these experiments. In general, the i_m values were slightly lower than those reported in military studies resulting in a lower coefficient of evaporative cooling for most garments.

Conclusions

Measurement of the thermal insulation (clo) value and evaporative impedance (i_m/I_T) of work clothing systems provides useful information for comparing these systems with regard to heat stress associated with wearing the clothing in hot environments and/or while working at high activity levels. Results of this study indicated that the clothing items which provide the most protection to the wearer from industrial hazards often restrict the amount of body heat loss that is possible through radiation, convection, conduction, and particularly evaporation. Although the copper manikin measurements are useful in ranking work clothing assemblies, they should be supplemented by physiological chamber studies so that human and other environmental factors can be taken into account also. Whether or not a worker will suffer heat stress problems depends upon these factors and their net effect upon the heat exchange between the worker and his/her environment. Ideally, these variables could be manipulated by employers/employees so as to prevent heat stress and at the same time, maintain efficient productivity.

References

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TABLE 1. CHARACTERISTICS OF WORK CLOTHING ENSEMBLES

Ensemble	Component Garments*	Fabric Construction	Fabric Weight (g/m²)	Fiber Content	Finishes
500	shirt 101	satin weave	375.0	100% cotton	flame retardant
	pants 201	twill weave	468.0	100% cotton	flame retardant
502	shirt 104	twill weave	447.6	100% cotton	flame retardant
	pants 204	twill weave	451.0	100% cotton	flame retardant
503	shirt 106	plain weave	152.6	65% polyester 35% cotton	durable press soil release
	pants 207	twill weave	254.3	65% polyester 35% cotton	durable press
504	shirt 109	leno weave	152.6	65% polyester 35% cotton	durable press soil release
	pants 207	twill weave	254.3	65% polyester 35% cotton	durable press
505	shirt 105	twill weave	230.6	100% SEF modacrylic	anti-static acid-resistant
	pants 203	twill weave	230.6	100% SEF modacrylic	anti-static acid-resistant
506	shirt 110	twill weave	203.5	100% cotton	flame retardant
	pants 205	twill weave	322.1	100% cotton	flame retardant
507	shirt 111	leno weave	152.6	65% polyester 35% cotton	durable press soil release
	pants 207	twill weave	254.3	65% polyester 35% cotton	durable press
527	coverall 313	twill weave	230.6	100% SEF modacrylic	anti-static acid-resistant
KSU uniform	shirt KSU	twill weave	135.6	65% polyester 35% cotton	
	pants KSU	twill weave	247.5	65% polyester 35% cotton	
525	coat 305**	basket weave	634.1	100% PFR rayon	aluminized coating
524	coat 315**	basket weave	644.3	100% PFR rayon	aluminized coating
509	facemask 316**	filling knit	220.4	100% Nomex aramid	
511	hood 321**	felt	1085.0	90% reprocessed 10% other fibers	flame retardant
514	apron 322**	satin weave	305.2	100% cotton	flame retardant
510	hip leggings 319**	satin weave	305.2	100% cotton	flame retardant
512	arm protectors 323**	basket weave	644.3	100% PFR rayon	aluminized coating
513	arm protectors 324**	plain weave	505.3	100% cotton	flame retardant
520	gloves 320**	filling knit		50% Kynol novoloid 50% Nomex aramid	

* Component garments are worn with underwear, shoes, socks, and in some cases, with a T-shirt or belt.

** Garment is worn with the KSU uniform.

TABLE 2. THERMAL INSULATION AND EVAPORATIVE IMPEDANCE VALUES OF WORK CLOTHING

Ensemble Code & Description*	Total Clo (I_T)	Clothing Area Factor (f_{cl})	Intrinsic Clo (I_{cl})	Permeability Index (i_m)	Evaporative (i_m/I_T)
500 shirt 101 pants 201,USTB	1.45	1.36	0.93	0.34	0.23
502 shirt 104 pants 204,USTB	1.51	1.39	1.00	0.32	0.21
503 shirt 106 pants 207,USB	1.20	1.20	0.61	0.38	0.32
504 shirt 109 pants 207,USB	1.23	1.14	0.61	0.39	0.32
505 shirt 105 pants 203,USB	1.28	1.22	0.70	0.38	0.30
506 shirt 110 pants 205,USB	1.31	1.23	0.73	0.36	0.27
507 shirt 111 pants 205,USB	1.16	1.20	0.57	0.39	0.34
527 coverall 313 UST	1.41	1.25	0.84	0.39	0.28
KSU uniform KSU shirt KSU pants,US	1.25	1.19	0.65	0.39	0.30
525 coat 305 KSU uniform,US	2.19	1.58	1.74	0.30	0.14
524 coat 315 KSU uniform,US	1.89	1.34	1.36	0.33	0.17
509 facemask 316 KSU uniform,US	1.32	1.14	0.70	0.37	0.28
511 hood 321 KSU uniform,US	1.42	1.15	0.80	0.36	0.25
514 apron 322 KSU uniform,US	1.33	1.26	0.77	0.40	0.30
510 hip leggings 319, KSU uniform, USB	1.39	1.24	0.82	0.40	0.29
512 arm protectors 323, KSU uniform US	1.41	1.30	0.86	0.31	0.22
513 arm protectors 324, uniform US	1.32	1.28	0.77	0.37	0.28
520 gloves 320 KSU uniform,US	1.30	1.20	0.71	0.38	0.29

* U = underwear; S = shoes and socks; T = T-shirt; B = belt.

Discussion

Linde:

At the beginning of your speech you defined an intrinsic clothing value and you measured that value by taking total clothing insulation first and then subtracting insulation of the nude copper manikin. Did I understand that right?

McCullough:

It is the relationship of the value for the still air layer measured for the nude man, divided by the clothing area factor, that is what it is subtracted of.

Linde:

I see. But you take also into account the air layer outside the clothing, and of course the surface of the clothing will be more than the surface of the copper manikin?

McCullough:

This is a way of estimating that.

Holmér:

Are people likely to work in this aluminized clothing with just the KSU uniform? Or did you measure values for maybe an overall or something?

McCullough:

No, we only used this, so we could use comparisons between garments, which were similar. Although they many times do put a coat over a basic work clothing, which is similar to that outfit, the only difference would be, that they might have gloves and some type of head gear also. We tested a lot of these items, but because of time I could not go into all those.

Gert Nilsson:

I have a question concerning measurement of ambient temperature and ambient vapour pressure. Were those parameters measured as the average

values for the room or were they measured close to the surface of the manikin?

McCullough:
We measured air temperature along the entire height of the body in the chamber on equal distance from the body and then we looked in a psychometric table to find out what the vapour pressure of the air would be.

Gert Nilsson:
At what distance from the manikin did you measure? I think if you measure very close to the surface, you may come up with different values and it is really those values very close to the surface that we are interested in.

McCullough:
We were not measuring vapour pressure, we just measured air temperature, the vapour pressure is extrapolated from a table.

Gert Nilsson:
I see, but don't you think, that the temperature close to the surface would be different from the temperature at a distance of about 10 cm away from the manikin?

McCullough:
Oh yes, if you measure right on the other side of the clothing surface, but that is not how the procedure has been defined.