No. 2888 (RP-411)

A Comprehensive Data Base for Estimating Clothing Insulation

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ABSTRACT

ASHRAE Standard 55-1981 and Chapter 8 of ASHRAE Handbook--1981 Fundamentals specify the environmental conditions that are thermally acceptable to most people at different levels of clothing insulation and metabolic activity. It is necessary for users of these documents to determine what types of clothing provide different amounts of insulation. The purpose of this study was (1) to expand the current data base of insulation (clo) values for garments and clothing ensembles commonly worn in indoor environments and (2) to develop and compare different methods for estimating clothing insulation. The clo values of 115 different garments and 60 representative ensembles were measured using a standing, electrically heated manikin in a climate-controlled chamber. Regression analysis was used to relate a number of variables to garment and ensemble insulation. A new computer model, which calculates local and total body heat loss (or clothing insulation), was developed also. The relative accuracy of the predictive equations and model was determined and discussed.

INTRODUCTION

ASHRAE Standard 55-1981, "Thermal Environmental Conditions for Human Occupancy," and Chapter 8 of ASHRAE Handbook--1981 Fundamentals specify the environmental conditions that are thermally acceptable to most people at different levels of clothing insulation and metabolic activity (ASHRAE 1981 a & b). Therefore, it is necessary for users of these documents to know what types of clothing provide different amounts of insulation. To meet this need, the standard and handbook contain a list of clo values for selected garment types and a formula for estimating the insulation provided by a total clothing ensemble.

The standard is designed so that users can describe the types of garments that people are wearing in a given environment and estimate the levels of clothing insulation. The clo values are then used to determine the specific environmental conditions necessary for thermal comfort at different activity levels from figures in the standard. People also can use the standard to prescribe the type of clothing that occupants should wear in a given environment to achieve comfort. For example, engineers may be limited with respect to changes that they can make in some environments such as a cold storage warehouse. However, they can specify the insulation/activity levels necessary for thermal comfort and recommend types of ensembles that will provide adequate insulation. The information in the standard and handbook is also useful for researchers who must either control or evaluate clothing in their studies, but who do not have facilities for measuring clothing insulation.

Unfortunately, the information concerning clothing insulation given in the standard and handbook is incomplete and inaccurate in some places, according to recent research findings. Specifically, few design variations and fabric variations for a particular garment type are given in the list of insulation values. Some garment types commonly worn in indoor environments (e.g., work clothing, sleepwear, shorts) are not included either. The accuracy of the summation formula for estimating clothing insulation should be verified also, using a more comprehensive data set of garment and ensemble clo values. Furthermore, new methods of predicting clothing insulation are needed.

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Therefore, the purpose of this study was (1) to expand the current data base of garment and ensemble insulation (clo) values, (2) to develop and compare methods for estimating clothing insulation, and (3) to recommend revisions for ASHRAE Standard 55-1981 and ASHRAE Handbook--1981 Fundamentals regarding clothing insulation.

METHODOLOGY

Clothing Selection

A variety of garments were purchased or constructed in summer, winter, and/or typical fabrics. The designs were selected by considering (1) variation in the amount of body surface area covered, (2) longevity of style with regard to fashion obsolescence, (3) looseness or tightness of fit, and (4) fabric overlap. Nightwear (i.e., robes, pajamas), common work garments (i.e., coveralls, overalls), and special garments (i.e., sweat shirt, sweat pants) also were included since clo values for these types of garments are not listed in the ASHRAE documents. Clothing items for the head and hands were not included because these garments cover only a small amount of body surface area and are rarely worn by people in indoor environments. Clothing designed to protect people from hazards (e.g., chemicals) and/or extreme environments were not included in this study.

Ensembles for study were selected by considering variations in (1) the number of garment layers on different parts of the body, (2) the amount of body surface area covered by the clothing, and (3) the type of garments worn (i.e., skirts vs. trousers, work clothing, sleepwear, loungewear, athletic wear, office wear, etc.).

Measurement of Clothing Insulation Values

The thermal insulation values of the clothing were measured using an electrically heated manikin housed in an environmental chamber. The manikin is made of anodized copper formed to simulate the size and shape of a typical man (i.e., 1.8 m^2). The manikin is instrumented with 16 skin temperature thermistors and heated internally to approximate the skin temperature distribution of a human. A proportional temperature controller was used to regulate the heating of the manikin so as to produce a mean skin temperature of 33.3 $\pm$ 0.5°C. A variable transformer controlled power to the extremities to maintain a lower mean skin temperature of 29.4 $\pm$ 0.5°C in the hands and feet. Four ambient temperature thermistors were used to measure the air temperature in the chamber which was set at 22.2 $\pm$ 0.5°C. Air velocity in the chamber was limited to 0.1 m/s. Mean radiant temperature was calculated to be within less than 0.5°C of air temperature, and relative humidity was approximately 50%.

The garments were tested on the copper manikin (1) individually and (2) with other clothing items--as part of typical indoor ensembles. The manikin was dressed carefully according to written instructions to avoid measuring errors resulting from inconsistent dressing procedures. When the system reached steady state, the power was monitored continuously for 30 minutes using a watt-hour meter. Readings from the skin temperature and air temperature thermistors were printed digitally on paper tape every 10 minutes during the test period; then the individual values were averaged. The total insulation (I_T) of a garment or ensemble--including the air layer around the clothed body--was calculated as follows:

$$I_T = \frac{K\,(\bar{T}_s - T_a)\,A_s}{H} \qquad (1)$$

where

I_T = total thermal insulation of clothing plus air layer, clo

H = power input, W

K = units constant = 6.45 clo · W/m^2 · °C

A_s = manikin surface area, m^2

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

T_a = ambient air temperature, °C

This procedure was repeated two additional times on different days; the average of the three replications was recorded as the total clo value.

The effective clothing insulation (I_{cle}), or the insulation attributed to clothing as compared to the nude situation, was determined by subtracting the resistance of the air film (I_a) from I_T as follows:

$$I_{cle} = I_T - I_a \tag{2}$$

The value for I_a (0.71 clo) was obtained by operating the manikin without clothing in the same environmental conditions and using Equation 1.

The intrinsic or basic clothing insulation (I_{cl}), or the insulation from the skin to the clothing surface, was determined as follows:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \tag{3}$$

Measurement of the Clothing Area Factor

Values for the clothing area factor (f_{cl}) were obtained using the photographic method described by Olesen et al. (1982). Photographs of the manikin were taken from three azimuth angles: 0° (front view), 45°, and 90° (side view) by turning the manikin on a revolving stand. Two 35 mm cameras with lenses of the same focal length were used to take each set of three photographs from 0° (horizontal) altitude and 60° altitude. The pictures were printed on 10 x 25 cm photographic paper, and the manikin's projected surface area was measured using a planimeter. The clothing area factor was calculated as:

$$f_{cl} = \frac{\Sigma A_{cli}}{\Sigma A_{ni}} \tag{4}$$

where

f_{cl} = clothing area factor

A_{cl} = projected surface area of clothed manikin

A_n = projected surface area of nude manikin

Measurement of the Body Surface Area Covered by Clothing

The manikin's surface was modified so that the body surface area covered by a garment or ensemble could be determined from photographs. The manikin's surface was divided into a grid of small areas about 3 x 3 cm and into 17 major segments (McCullough and Jones 1984). The location and surface area of each square and segment were recorded. The amount of body surface area covered by clothing was determined using photographs of the manikin nude and clothed. The percent of each body segment covered by clothing was estimated and multiplied by the percent of total body surface area represented by the segment. The total amount of surface area covered by clothing was found by adding these percentages for all segments.

Measurement of Clothing Circumferences at Different Locations on the Body

In developing a computer-based model for calculating local and total body heat loss (see discussion later), the insulation provided by the air trapped between clothing layers in an ensemble needed to be quantified. Air layer thicknesses were determined by measuring clothing circumferences at different locations on the body for successive layers of garments.

Tape was placed on the manikin to mark the exact locations where the circumference measurements were to be taken. These included the chest/back, upper arm, lower arm, abdomen/buttocks, thigh, and calf. A stick was also marked at the appropriate height where all of the circumference measurements were to be taken. First the nude body circumferences were measured and recorded. Then the innermost garment in an ensemble (e.g., briefs) was put on the manikin, and the appropriate clothing circumferences were measured. To do this, one person used the marking stick to locate the exact position of the circumference measurement(s) and marked it on the garment with a few pins. The person then measured the garment circumference with a string, being careful not to compress the garment in any way. The string was held up to a measuring stick mounted on the wall to get the correct measurement. Another person repeated the measurement, and the average was recorded as the circumference value. Then the next garment in the ensemble was put on the manikin over the first, and the appropriate circumference measurements were taken. This procedure was continued until all the garment layers in an ensemble had been measured.

When skirt or dress ensembles were measured, the two thighs and two calves were treated as one body cylinder. Sometimes a garment overlapped another on only part of a body segment (e.g., T-shirt and long-sleeve shirt on upper arm segment). When this happened, the difference in circumferences was estimated or additional measurements were taken at new locations.

The thickness of the air layers between the manikin and the first garment layers and between additional garment layers were determined by subtracting the fabric thickness and smaller radius from the larger radius. When a tight-fitting garment was worn over a loose-fitting one (e.g., sweater over a shirt), the circumference measurements were decreased. To avoid calculating a negative value for the air layer thickness, the last two fabric thicknesses were summed (treated as one) and subtracted from the outermost radius along with the other radius (McCullough and Jones 1984).

RESULTS AND DISCUSSION

A table of garment insulation values measured on standing manikins was compiled from sources in the literature and reported in the final report for this project (McCullough and Jones 1984). Articles that reported garment and/or ensemble insulation values measured on manikins were indicated with an asterisk in the reference list of this report also.

Most of the garment data collected in this study are presented by garment type in Table 1. The insulation values, clothing area factor, weight, and amount of body surface area covered are reported for each garment. Data collected for the 60 ensembles are given in the larger report (McCullough and Jones 1984).

Regression Analysis

We had originally planned to merge data from different laboratories with the new data collected in this study and use this comprehensive data set to develop equations for predicting clothing insulation. Unfortunately, there are many data omissions for variables that are related to clothing insulation in other studies. In addition, interlaboratory variance due to slight differences in dressing procedures, clothing fit, manikin instrumentation, and environmental conditions could influence the clo values of garments and ensembles and affect the results. Consequently, regression analyses were conducted using data collected in this project only. The garment data set and the ensemble data set are representative of the types of clothing worn by people in indoor environments. Therefore, the regression equations reported here should be applicable to most types of clothing.

A number of variables that could be related to garment and/or ensemble insulation were used to develop a series of linear and quadratic regression equations. The equations were developed with the Y intercept equal to zero and with the actual Y intercept determined by the data set. Both types of equations were developed so that trade-offs in the simplicity and accuracy of the equations could be evaluated. Surprisingly, none of the quadratic forms of the equations offered any significant improvement in predictability over the linear equations with a Y intercept. Consequently, these equations were not reported. The linear regression equations for garments and ensembles are given in Tables 2 and 3 respectively. All of these regression models were significant at the 0.0001 level.

The predictability of the equations can be judged by comparing the magnitude of the adjusted R^2 values. However, when the Y intercept is forced through zero, a different calculation is used, resulting in artifically high R^2 values (Searle 1971). Consequently, these parameters cannot be used to compare the effectiveness of linear regression equations with Y intercepts equal to zero to those with Y intercepts greater or less than zero. In order to compare the predictability of the equations, the standard derivation of error (s) for each prediction equation was reported.

$$\underline{s} = \sqrt{\frac{\Sigma\ (\text{predicted value} - \text{measured value})^2}{n}} \tag{5}$$

Since this term is squared and then summed, it weights the errors according to their squares rather than linearly. Thus, larger errors cause the value of s to increase relatively more than smaller errors do. The value of $\underline{s}$ is also dependent upon the units used and the variability associated with the parameter being predicted. For example, the standard deviation associated with an equation predicting I_{cl} clo for garments should not be directly compared to an $\underline{s}$ value for an equation predicting f_{cl} for ensembles. The standard deviations of equations with Y intercepts forced through zero and comparable equations with Y intercepts derived from the data indicate that the former, more simple version of the equation has a greater amount of error associated with its predictability than does the linear regression equation of the form $Y = A + BX$ (Tables 2 and 3).

The Relationship Between f_{cl} and I_{cl}

The clothing area factor is dependent upon many parameters including garment design, fabric stiffness or drape, and support materials used in garment construction. The clothing area factor has been measured using photographic methods, and variations in methodology have been summarized by McCullough and Jones (1983).

Measuring the f_{cl} with a photographic method is time-consuming and expensive, and the resulting measurement is not very precise. Slight differences in the drape of the clothing on the manikin can change the f_{cl} significantly. The looseness or tightness of fit and body position (e.g., seated) also affect the f_{cl}. Consequently, differences in f_{cl} can be found for the same garment depending upon how the manikin is dressed.

Because of the difficulties associated with the measurement of f_{cl}, researchers have tried to estimate f_{cl} values for use in calculating I_{cl} from I_T for garments and ensembles. Authors have suggested the general relationship of $1.15 f_{cl}$/clo ($f_{cl} = 1.0 + 0.15\ I_{cl}$) (Fanger 1970; Hollies and Goldman 1977, p. 8), and Gagge suggested a 25% increase in f_{cl}/clo in a discussion of data reported by Seppanen et al. (1972). Some authors have tried to establish the relationship between I_{cl} (clo) values and f_{cl} values using regression analysis, where the Y intercept was forced through $f_{cl} = 1.0$ (the area factor for a nude body).

1. $f_{cl} = 1.0 + 0.26\ I_{cl}$ for garments and $f_{cl} = 1.0 + 0.29\ I_{cl}$ for ensembles; calculated by McCullough and Jones (1983) using Sprague and Munson (1974) data.

2. $f_{cl} = 1.0 + 0.43\ I_{cl}$ for garments and $f_{cl} = 1.0 + 0.34\ I_{cl}$ for ensembles; calculated by McCullough and Jones (1983) using McCullough et al. (1983) data.

3. $f_{cl} = 1.0 + 0.26\ I_{cl}$ for ensembles (Olesen and Nielsen 1983).

The relationship between f_{cl} and I_{cl} was reexamined in this study using the representative set of 115 garments and 60 ensembles. The f_{cl} values ranged from 1.00 to 1.48 for individual garments and from 1.07 to 1.49 for ensembles. The results indicate that the correlation between f_{cl} and I_{cl} is weak and that only a rough approximation of f_{cl} can be expected if it is estimated from I_{cl} alone. Specifically, the equation for garments was $f_{cl} = 1.0 + 0.46\ I_{cl}$ and for ensembles, $f_{cl} = 1.0 + 0.31\ I_{cl}$ (Tables 2 and 3). The variety of garments and ensembles contributes to a wide scattering of the data as evidenced by large standard errors and Figures 1 and 2. Theoretically, there is little reason to expect a good correlation between the clothing area factor and clothing insulation (McCullough and Jones 1983). The only way to achieve a linear relationship is by simultaneously changing the insulation thickness and fraction of the body surface area covered. Although there is a tendency for this to occur in clothing systems, it is only through a fortuitous combination of changes of both variables that a single curve or line would result.

There appears to be no reliable way to estimate the clothing area factor (f_{cl}); even measurement is approximate. However, the relationship of $f_{cl} = 1.0 + 0.31\ I_{cl}$ is a rough estimate for indoor ensembles. The uncertainty associated with f_{cl} values is reflected in I_{cl} values. Differences between the I_{cl} values of some ensembles could be due to measurement or estimation error in determining f_{cl} rather than to real differences in insulation. Also, real increases in f_{cl} do not alter the heat transfer permitted by some garment types. For example, increases in the size and shape of a skirt have little meaning with respect to heat transfer because the fabric (i.e., insulation) hangs away from the body.

Clothing Weight as a Predictor of Clothing Insulation

Clothing weight is a substitute variable that indicates how much clothing a person is wearing. For example, when a garment such as a sweater is added to an ensemble, the weight of the ensemble and its insulation are increased simultaneously (McCullough and Wyon 1983). ASHRAE Standard 55-1981 suggests that the relationship of 0.35 clo/kg of clothing weight can be used to estimate I_{cl} (ASHRAE 1981a). Research has shown, however, that weight alone is not a good predictor of insulation. For example, McCullough et al. (1983) used a manikin to measure the insulation values of a variety of garments, each constructed with three fabrics of different weights and similar insulation values. The results indicated no major differences in garment clo values due to fabric weight variations.

Olesen and Nielsen (1983) reported the relationship of 0.59 clo/kg of garment weight and 0.57 clo/kg of ensemble weight (omitting shoes) using I_{cl} data for a wide variety of clothing items. However, the standard deviations associated with these equations indicate that they are rough estimates.

In the present study, garment weight ranged from 0.03 to 1.54 kg, and ensemble weights ranged from 0.17 to 2.63 kg. For the regression analysis, shoes were removed from the data set because they (1) cover a small amount of body surface area, (2) are made of materials other than textiles, and (3) provide more weight relative to insulation than other types of garments. Although garment weight had little relationship to garment insulation, ensemble weight without shoes was a fairly good predictor of ensemble insulation (Tables 2 and 3). The relationship of 0.74 clo/kg of clothing weight had a standard deviation of 0.22 for I_{cl} data when the Y intercept was forced through zero, but $\underline{s}$ = 0.14 when the equation with the Y intercept term was used. Clothing in this data set generated a higher clo/kg relationship than others reported in the literature. Obviously, weight is not an accurate predictor of clothing insulation (Figure 3), and regression coefficients are dependent upon the type of clothing used in the data set. However, it is very simple for people to measure clothing weights, so these relationships may be useful to some people for rough approximations of insulation.

Body Surface Area Covered by Clothing as a Predictor of Insulation

Measures of clothing insulation such as I_{cl}, I_{cle}, or I_T are "average" values for the whole body, in that they are equivalent to an insulation spread uniformly over the whole body that would result in the same total heat loss from the body. However, it is important to realize that the body is not uniformly covered, and the heat loss from different areas of the body will differ due to the uneven covering. This fact is important when clothing is added to provide more insulation. Adding clothing to a particular area of the body will only reduce the heat loss from that area; it will have no effect on the heat loss from other areas. Ultimately, adding more and more insulation to a given body area can only reduce the heat loss from that area to zero. The heat loss from the other areas may still be quite large, so the overall heat loss will still be large. Thus, the insulation value will be small, even though a part of the body is very heavily clothed. Therefore, when a garment is added to an ensemble and it covers parts of the body that were not previously covered, the impact on the insulation provided by the ensemble will be greater than if the additional garment was placed over other garments that were already reducing heat loss on a local basis.

A recent study by McCullough et al. (1983) was the first to relate the amount of body surface area covered by garments to clothing insulation. The relationship of I_{cl} = (0.0083 x BSAC) - 0.071 (where BSAC is the percent of the body surface area covered) was found for a variety of garments constructed in three different fabrics. The relationship between the amount of body surface area covered by an ensemble and its clo value was not strong because the variation in BSAC and I_{cl} was limited (i.e., most ensembles covered all of the body except the hands and head).

In this study, larger and more representative data sets were used to predict garment and ensemble insulation values from the percent of body surface area covered by clothing. The amount of body surface area covered by garments explained 80% of the variability in garment insulation, with the standard deviation as low as 0.10 clo (Table 2). The equation, I_{cl} = (0.00973 x BSAC) - 0.0832, was similar to that reported in the earlier study, but it reflects the warmer garments found in this data set. Figure 4 illustrates that BSAC equations for garment insulation are ineffective in predicting the clo value of garments that cover most of the body because the variability in insulation among these garments is due to variability in fabric insulation.

Only about half of the variance in ensemble insulation can be explained by changes in the amount of body surface area covered by clothing (Table 3, Figure 5). Most of the ensembles in the data set covered about 80% to 85% of the body, and variations in clo value were due to other factors such as fabric insulation and layering.

Multiple Regression Equations for Predicting Clothing Insulation

Garments. Fabric thickness--as a proxy for fabric insulation--was used with the amount of body surface area covered to predict garment insulation. The equation for I_{cl} data explained 93% of the variance in garment insulation with a standard deviation of 0.06 clo (Table 2). Using the BSAC term in the equation twice yielded good predictability: I_{cl} = (0.00790 x BSAC) + (0.00131 x FAB THICK x BSAC) - 0.0745. Figure 6 plots the predicted garment insulation values vs. the garment insulation values measured on the manikin. Most of the data points are close to the line representing the ideal 1:1 correlation. The accuracy of this equation is remarkable considering the ease with which the two predictor variables can be determined.

Ensembles. An attempt was made to relate the amount of fabric layering on different parts of the body with ensemble insulation. To do this, the percent of body surface area not covered by clothing (BSAC 0), covered by one layer of clothing (BSAC 1), covered by two layers of clothing (BSAC 2), etc., was determined for each ensemble. A linear stepwise regression analysis was conducted so that we could determine how much layering information was necessary (i.e., would significantly improve the predictability of the equation). The resulting equation for predicting ensemble insulation was based on the amount of body surface area not covered by clothing and the amount of body surface area covered by one garment layer. This equation (Table 3) was as effective in predicting ensemble insulation as was the equation based on the adjusted ensemble weight (R^2 = 0.78). Consequently, all of these variables were combined into an equation as follows: I_{cl} = (0.255 x AWT) + (-0.00874 x BSAC 0) + (-0.00510 x BSAC 1) + 0.919. This multiple regression equation has improved predictability with R^2 = 0.84 and s = 0.12 (using I_{cle} data, s = 0.10). This method of estimating ensemble insulation is relatively good (Figure 7).

Predicting Ensemble Insulation from the Sum of Component Garments' Clo Values

The insulation provided by an ensemble will be less than the sum of the component garments' clo values because (1) the insulation is not distributed evenly over the entire body, (2) the addition of garments may cause fabric and air layer compression in some areas, and (3) the addition of more garments usually increases the surface area for heat loss (f_{cl}). Sprague and Munson (1974) were the first to use regression analysis to estimate ensemble insulation from the sum of the I_{cl} values of the component garments measured on a manikin. They developed one equation for men's clothing, I_{cl} = (0.727 x Sum I_{cl}) + 0.113, and one for women's clothing, I_{cl} = (0.770 x Sum I_{cl}) + 0.050. Based on this work, the authors of ASHRAE Standard 55-1981 recommended using 0.82 x Sum I_{cl} to estimate ensemble I_{cl} (ASHRAE 1981a). Later research found the ASHRAE formula to be a better predictor of ensemble insulation than the Sprague and Munson equations by comparing the average of the absolute deviations of the predicted values from the measured values (McCullough et al. 1982; McCullough et al. 1983).

Olesen and Neilsen (1983) developed the following summation equation for estimating ensemble insulation: I_{cl} = (0.73 x Sum I_{cl}) + 0.17. When they forced the Y intercept through zero, the equation was the same as that used in ASHRAE Standard 55-1981. Goldman (1981) also reported a summation formula: I_{cl} = (0.69 x Sum I_{cl}). In the present study, the regression equations based on the sum of the clo values of the garments in an ensemble explained over 93% of the variance in ensemble insulation (Table 3). Specifically, the relationship of I_{cl} = (0.676 x Sum I_{cl}) + 0.117 was found. This equation results in lower predictions than those of Sprague and Munson (1974), which gave lower estimates than Olesen and Nielsen (1983). However, the relationship is a strong one (s = 0.07) with little data scatter about the regression line (Figure 8). Differences in the regression coefficient probably reflect variations in the data sets used in these studies. In the present study, summation equations based on I_{cle} data for garments also were developed for predicting ensemble I_{cle} (Table 3).

Olesen and Nielsen (1983) also used regression analysis to predict ensemble insulation (I_{cl}) from the sum of the I_{cle} values of the component garments in the ensemble. They found that ensemble I_{cl} = (0.85 x Sum I_{cle}) + 0.25 and, when the Y intercept was forced through zero, I_{cl} = (1.01 x Sum I_{cle}). The results of our study are very similar to those of Olesen and Nielsen (Table 3). It appears that the sum of the garment I_{cle} values in an ensemble is a good approximation of the ensemble's I_{cl} value. The advantage of using this relationship is that measurement or estimation of f_{cl} is unnecessary. For the same reason, it would be impractical to estimate ensemble I_{cle} from the sum of garment I_{cl} values; consequently, this relationship was not quantified.

Based on the high R^2 values and low s values associated with the summation equations, one might conclude that these formulas offer the most accurate predictions of ensemble insulation.

This conclusion would be correct only if the clo values for the component garments in the ensemble were measured on a manikin. A few laboratories have large inventories of garments whose clo values have been measured on a manikin. Researchers at these facilities may use summation equations to help them create different ensembles with specific insulation values for use in human subject research. However, if a person had access to a thermal manikin and needed to know the insulation provided by a few specific ensembles, he/she would simply measure them.

The majority of people who want to estimate clothing insulation do not have access to a manikin or to garments whose clo values were measured with a manikin. Consequently, people who use the summation equations in the literature to estimate ensemble insulation usually estimate the clo values of the component garments too. Therefore, the error associated with the estimates of all of the garment clo values should be considered when comparing the accuracy of the summation formulas to other equations for predicting ensemble insulation.

Predicting Ensemble Insulation with Summation Formulas Using Estimated Garment Insulation Values

The most accurate predictions of garment insulation values resulted from the equations based on fabric thickness and the percent of body surface area covered by the garment (Table 2). These equations were used to predict insulation values for each of the garments in the data set. These predicted garment clo values were then used in summation equations to estimate the insulation provided by all of the ensembles tested in this study. As expected, the most accurate garment prediction equation combined with the best summation formula yielded the most accurate prediction of ensemble insulation. For I_{cl} data, the following set of equations gave the most accurate prediction of ensemble insulation (s = 0.11): Garment I_{cl} = (0.00790 x BSAC) + (0.00131 x FAB THICK x BSAC) - 0.0745 and Ensemble I_{cl} = (0.676 x Sum I_{cl}) + 0.117. For I_{cle} data, these equations were the best (s = 0.09): Garment I_{cle} = (0.00534 x BSAC) + (0.00135 x FAB THICK x BSAC) - 0.0549 and Ensemble I_{cle} = (0.756 x Sum I_{cle}) + 0.0791. The accuracy of these predictions is remarkable considering that data for the predictor variables can be determined simply and quickly, without complicated and expensive equipment like a manikin (Figure 9). In addition, the standard deviations are acceptable since a change of 0.1 clo results in a preferred temperature change of 1 F (0.6°C) (ASHRAE 1981a).

People have used the chart of garment clo values and the summation formula given in ASHRAE Standard 55-1981 to estimate clothing insulation. However, no one has tried to quantify the error associated with comparing specific clothing items to those in a chart for the purpose of estimating garment insulation. In addition, no one has evaluated the predictability of summation equations when garment clo values that are estimated from a chart are used in them. Therefore, a small study was designed to address these issues. Specifically, a detailed chart of garment clo values was developed based on data collected in this project. Garments were organized by type (e.g., skirts), design variations were illustrated, and clo value ranges were given based on fabric thickness and garment fit. About 45 seniors in a clothing and textile curriculum were given a lecture on variables that affect clothing insulation and detailed instructions on how to use the chart (i.e., they were trained to simulate the best possible use conditions). Students were then asked to estimate the clo values of two sets of 30 garments and to calculate the clo value of several ensembles composed of garments from the sets using a summation equation. The students' predictions were compared to the actual garment and ensemble clo values measured on the manikin. No attempt was made to "clean" the data by removing mathematical errors or careless mistakes. The variability associated with most of the estimates was unacceptable (see McCullough and Jones 1984 for standard deviations). Since the garments in each set were the actual garments from which the chart was developed, students actually had a better chance of making accurate comparisons with the chart than if we had used garments never before tested. Obviously, the accuracy of estimating garment clo values from a chart to predict ensemble insulation is low and dependent upon (1) the variability in insulation associated with a garment type (i.e., long robes vs. pantyhose) and (2) the number and types of garments in the ensemble.

The Development of a Computer Model for Predicting Ensemble Insulation

A simple, computer-based model for calculating body heat loss and clothing insulation was developed and verified using the comprehensive data set for ensembles. The model is based on straight forward heat transfer relationships. There is no novel theory used in the model, but it does represent the first time that detailed heat transfer calculations have been made and tested with an extensive data base.

The model divides the body into 12 segments, with symmetrical halves of the body being treated as one segment (i.e., both thighs are one segment). Each segment can be further divided into subsegments if necessary, so that each segment consists of a part of the body surface that is at a uniform temperature and is uniformly clothed. One dimensional heat transfer calculations are made to determine the heat loss from each subsegment by:

$$\dot{Q}_i = A_i \frac{T_{si} - T_a}{R_i} \tag{6}$$

where

$\dot{Q}_i$ = rate of heat loss for subsegment i

A_i = skin surface area for subsegment i

T_{si} = skin temperature for subsegment i

T_a = air temperature of the environment

R_i = thermal resistance of the air layers and clothing insulation subsegment i

The thermal resistance is just the sum of the individual resistances:

$$R_i = A_o \left[\sum_{j=1}^{n} \left(\frac{R_{aj}}{A_{j-1}} + \frac{R_{cj}}{A_j} \right) \right] + \frac{R_a}{A_n} \tag{7}$$

where

R_i = thermal resistance of the air layers and clothing insulating subsegment i

A_o = skin surface area

R_{aj} = thermal resistance of the jth air layer

R_{cj} = thermal resistance of the jth layer of fabric

A_j = surface area for the jth layer of fabric

R_a = thermal resistance of the outer air layer

n = number of fabric layers

If n = 0, then the summation term in Equation 7 drops out. Equations 6 and 7 assume that the radiant temperature of the environment is the same as the air temperature; otherwise, a more complex formulation is required.

The total heat loss from the body ($\dot{Q}_T$) is simply the sum of the heat losses from the individual subsegments. The total heat loss may be the desired information in many applications. However, it can also be used to calculate I_T for the clothing system:

$$I_T = \frac{A_T (\bar{T}_s - T_a)}{\dot{Q}_T} C \tag{8}$$

where

I_T = total thermal insulation of clothing plus air layer

A_T = total body surface area

$\bar{T}_s$ = area averaged skin temperature

T_a = air temperature of the environment

C = units constant

$\dot{Q}_T$ = total rate of heat loss for the body

The model calculates the thermal resistance of the air layer by:

$$R_{aj} = \frac{1}{h_R + k_a/t_{aj}} \tag{9}$$

where

R_{aj} = thermal resistance of the jth air layer

h_R = linearlized radiation coefficient that accounts for direct radiation between layers

k_a = thermal conductivity of air

t_{aj} = thickness of the jth air layer

The term k_a/t_{aj} is the conductance of air assuming it is non-convective (stagnant).

The model calculates the thermal resistance of the fabric by using the 1.6 clo/cm of fabric thickness relationship. The added thickness due to seams, pockets, facing, etc., is ignored; however, it may be reflected in larger air layer thicknesses because these garment features may result in larger segment circumference measurements. The value of R_a depends upon the air velocity of the environment. It was set at 0.7 clo for the results reported here (which is typical of the insulation measured for a nude manikin in a still air environment).

The parameters h_R and k_a are important for the model since most of the thermal resistance occurs in the air layers. The value of h_R was set at 1.0 BTU/hr$\cdot$ft$^2\cdot$F, which is based on the relationship for h_R used by Azer (1976). The value of k_a was set at 0.19 BTU$\cdot$in/hr$\cdot$ft$^2\cdot$F, which is based on tabulated data for air thermal conductivity. These values were then adjusted to improve the agreement between the model predictions and the measured values for the data base. The final values were set at h_R = 0.87 BTU/hr$\cdot$ft$^2\cdot$F and k_a = 0.17 BTU$\cdot$ in/hr$\cdot$ft$^2\cdot$F.

These equations and parameters constitute the mathematical formulation of the model. However, a considerable amount of information must still be supplied to the model before ensemble insulation can be estimated. These inputs include skin temperatures, air layer thicknesses, fabric thicknesses, fabric surface areas, and the skin surface area for each subsegment. A typical clothing ensemble would have 15-20 subsegments.

The skin surface area covered by a given subsegment was determined by inspection of photographs of the manikin dressed in an ensemble and in each of the component garments. Boundaries of each of the 12 major body segments were clearly marked on the manikin. The area of these segments was measured precisely, and the fraction of each segment covered by a uniform set of fabric layers was estimated. Fabric thicknesses were measured according to ASTM D 1777 using a 3 in diameter presser foot and 0.01 psi pressure (ASTM 1982). Where this was not possible, thicknesses were estimated. For example, a micrometer was used to measure the thickness of shoes in various places, and an average value was recorded. Air layer thicknesses were determined by measuring clothing circumferences at different locations on the body for successive layers of clothing in an ensemble. All of these data were recorded on a data sheet for eventual input into the computer. The skin temperature of each of the 12 segments was based on the average value for that segment for a wide range of clothing, and it was not changed for different clothing systems. Therefore, skin temperatures for the segments were constant in the model for all ensembles.

Ensemble insulation values (I_T) predicted with the model are plotted against the actual ensemble clo values measured on the manikin in Figure 10. There is little scatter about the line representing the ideal 1:1 correlation, and the standard derivation associated with the model predictions is 0.09 clo. Therefore, the model is a good method for estimating ensemble insulation and one that does not involve the use of a thermal manikin. Once a computer program for the model is written, use of the model is relatively easy. (A listing of the computer program for the model is given in McCullough and Jones 1984.) However, determining the locations, size, and composition of the body subsegments based on garment layering in an ensemble and determining the air layer thicknesses for each subsegment based on circumference measurements is a complex and time consuming process--particularly if a large number of ensemble clo values need to be estimated.

The model is simple in concept but theoretically sound. It gives results that are reasonably accurate and that behave correctly. It can be used, not only to estimate overall insulation or body heat loss, but also to give a valid indication of how specific changes will affect the result. For example, manikin data show that adding a vest to a typical suit ensemble does not significantly increase I_T. The model generates the same result since the chest and back body segments are already well insulated without the vest. Likewise, data show that adding a hat to a relatively warm ensemble has a major effect on I_T. The model gives the same prediction also. Since the rest of the body is well insulated, much of the heat loss is from the head, and the hat blocks this loss. Simple regression equations and summation formulas cannot accurately simulate these types of changes. Therefore, the model can be very useful to researchers and clothing designers who want to predict how changes in the composition of an ensemble with respect to garment design, fit, or fabric thickness (i.e., insulation) can affect the insulation provided by the ensemble.

CONCLUSIONS

The major conclusions of this study are:

1. The relationship between I_{cl} and f_{cl} is very weak; however, the relationship of $f_{cl} = 1.0 + 0.31\ I_{cl}$ is a rough estimate for indoor ensembles ($s = 0.07$).

2. The most accurate equation for estimating garment insulation found in this study was based on fabric thickness and the percent of body surface area covered by the garment: I_{cl} = (0.00790 x BSAC) + 0.00131 x FAB THICK x BSAC) - 0.0745 where s = 0.06. Using body surface area covered as a single predictor variable gives a fairly good estimate of garment insulation (s = 0.10).

3. Ensemble weight without shoes and the amount of body surface area covered by different numbers of fabric layers are each fairly good predictors of ensemble insulation. Together, these variables provide a relatively good estimate of ensemble insulation: I_{cl} = (0.255 x AWT) + (-0.00874 x BSAC 0) + (-0.00510 x BSAC 1) + 0.919 where s = 0.12.

4. Summation formulas that estimate ensemble insulation from the sum of the clo values of the component garments give accurate predictions of ensemble insulation--when the garment clo values are measured on a manikin. For example, ensemble I_{cl} = (0.676 x Sum I_{cl}) + 0.117 has a standard deviation of 0.07. When garment insulation values are estimated using fabric thickness and the amount of body surface area covered and then used in summation equations, the prediction of ensemble insulation is still good (s = 0.11). However, when garment insulation values are estimated from a chart of known clo values and are used in a summation formula, the accuracy of the resulting prediction for ensemble insulation is variable and unacceptable.

5. A newly developed computer model provided the most accurate predictions for ensemble insulation (s = 0.09 clo) of any method examined in this study. However, a considerable number of data are required to use it.

UTILIZATION OF THE FINDINGS

ASHRAE Standard 55-1981 was developed to help engineers design HVAC systems that would provide environmental conditions that are thermally acceptable to most people, considering their activity level and clothing insulation. Only general approximations of clothing insulation are needed for this purpose. We recommend that a table containing descriptions of ensembles and their insulation values be included in the standard. The ensembles should represent a wide range of garment types (e.g., sleepwear, work clothing, office attire) and variations in the amount of insulation and its distribution over the body. Data collected and cited in this study can be used to develop the chart. Simple equations for estimating ensemble insulation from variables such as clothing weight (without shoes) together with the percent of body surface area covered by clothing can be included in the standard also. Most importantly, users of the standard should be referred to Chapter 8 of ASHRAE Fundamentals for more specific information on clothing insulation.

ASHRAE Handbook--1981 Fundamentals needs to be expanded and revised to accommodate the needs of reseachers, HVAC engineers, and educators who need more specific information on environmental factors, human physiology, and clothing insulation. We recommend that data collected and cited in this study be used to develop a chart of garment insulation values for inclusion in Chapter 8. The chart would include examples of a wide range of indoor garments with variations in type (e.g., coveralls, suit jackets, robes), design (e.g., different sleeve lengths), and fabric (e.g., warm, cool). Garment illustrations should be provided along with other descriptive data (e.g., f_{cl}). A detailed chart of ensemble insulation values and descriptive data should be included also. The most accurate methods of estimating clothing insulation should be given in ASHRAE Fundamentals. The regression equations of the form Y = A + BX should be used because they give more accurate predictions than equations with the Y intercept forced through zero. For example, the most accurate regression equation for estimating ensemble insulation involved first estimating the insulation values of the component garments from fabric thickness and the amount of body surface area covered and then using these garment clo values in a summation equation for predicting ensemble insulation. Information concerning the relationship between f_{cl} and I_{cl} should be revised also.

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ACKNOWLEDGMENTS

The authors would like to thank ASHRAE, particularly members of TC 2.1, for their support of this project. We would like to express our appreciation to Dr. Ralph F. Goldman, Project Monitor, for his expertise and assistance throughout the project, and to Dr. Bjarne W. Olesen for his suggestions.

TABLE 1
Characteristics of Garments

Design Description and Fabric Type	Garment Weight (kg)	Body Surface Area Covered (%)	f_{cl}	I_{cle} (clo)	I_{cl} (clo)
Shirts					
Long-sleeve, bow at neck (broadcloth)	0.206	52	1.13	0.25	0.33
Long-sleeve, shirt collar (broadcloth)	0.196	51	1.12	0.25	0.33
Long-sleeve, shirt collar (flannel)	0.309	51	1.12	0.34	0.42
Short-sleeve, shirt collar (broadcloth)	0.156	43	1.10	0.19	0.25
Short-sleeve, sport shirt (double knit)	0.228	40	1.02	0.17	0.18
3/4 length sleeve, boat neck* (broadcloth)	0.142	46	1.11	0.27	0.34
Cap sleeve, boat neck* (broadcloth)	0.113	36	1.09	0.21	0.27
Sleeveless, scoop neck (broadcloth)	0.117	30	1.08	0.13	0.18
Tube top (double knit)	0.067	12	1.01	0.06	0.07
Long-sleeve, sweat shirt (fleece-backed knit)	0.284	45	1.06	0.34	0.38
Sweaters					
Long-sleeve, V-neck (thin knit)	0.215	44	1.04	0.25	0.28
Long-sleeve, V-neck cardigan (thin knit)	0.215	39	1.04	0.23	0.26
Short-sleeve, V-neck (thin knit)	0.188	35	1.04	0.20	0.23
Short-sleeve, V-neck cardigan (thin knit)	0.188	30	1.04	0.17	0.20
Sleeveless, V-neck (thin knit)	0.130	28	1.03	0.13	0.15
Long-sleeve, round neck (thick knit)	0.424	45	1.06	0.36	0.40
Long-sleeve, round neck cardigan (thick knit)	0.424	39	1.06	0.31	0.35
Sleeveless, round neck (thick knit)	0.301	29	1.04	0.22	0.25
Long-sleeve, turtleneck (thin knit)	0.231	47	1.05	0.26	0.29
Long-sleeve, turtleneck (thick knit)	0.459	47	1.06	0.37	0.41
Suit Jackets and Vests (lined)					
Single-breasted suit jacket (denim)	0.518	50	1.12	0.36	0.44
Single-breasted suit jacket (tweed)	0.652	50	1.12	0.44	0.52
Double-breasted suit jacket (denim)	0.562	50	1.13	0.42	0.50
Double-breasted suit jacket (tweed)	0.702	50	1.13	0.48	0.56
Work jacket (duck)	0.885	55	1.21	0.39	0.51
Vest (denim)	0.150	21	1.05	0.10	0.13
Vest (tweed)	0.185	21	1.05	0.17	0.20
Trousers and Coveralls					
Straight, long, fitted (denim)	0.298	45	1.09	0.15	0.21
Straight, long, fitted (tweed)	0.404	45	1.09	0.24	0.30
Straight, long, loose (denim)	0.354	45	1.20	0.20	0.32
Straight, long, loose (tweed)	0.459	45	1.20	0.28	0.40
Walking shorts(denim)	0.195	25	1.06	0.08	0.12
Walking shorts (tweed)	0.251	25	1.06	0.17	0.21
Short shorts (denim)	0.164	18	1.05	0.06	0.09
Sweat pants (fleece-backed knit)	0.345	44	1.10	0.28	0.34
Work pants (duck)	0.832	46	1.21	0.24	0.36
Overalls (denim)	0.854	55	1.18	0.30	0.41
Coveralls (gabardine)	0.995	81	1.21	0.49	0.61
Insulated coveralls (multicomponent)	1.313	81	1.23	0.96	1.09
Skirts					
A-line, ankle length (denim)	0.284	45	1.34	0.23	0.41
A-line, ankle length (tweed)	0.378	45	1.34	0.28	0.46
A-line, 6" below knee (denim)	0.288	40	1.25	0.18	0.32
A-line, 6" below knee (tweed)	0.384	40	1.25	0.25	0.39
A-line, 6" above knee (denim)	0.179	28	1.12	0.10	0.18
A-line, 6" above knee (tweed)	0.238	28	1.12	0.19	0.27
A-line, knee length (denim)	0.229	35	1.18	0.14	0.25
A-line, knee length (tweed)	0.305	35	1.18	0.23	0.34

Design Description and Fabric Type	Garment Weight (kg)	Body Surface Area Covered (%)	f_{cl}	I_{cle} (clo)	I_{cl} (clo)
Straight, knee length, with slit (denim)	0.194	34	1.15	0.14	0.23
Straight, knee length, with slit (tweed)	0.259	34	1.15	0.22	0.31
Bias flair, knee length (denim)	0.286	35	1.22	0.13	0.26
Bias flair, knee length (tweed)	0.380	35	1.22	0.22	0.35
Full gathered, knee length (denim)	0.271	35	1.19	0.14	0.25
Full gathered, knee length (tweed)	0.359	35	1.19	0.22	0.33
Knife pleated, knee length (denim)	0.410	35	1.19	0.16	0.27
Knife pleated, knee length (tweed)	0.539	35	1.19	0.26	0.37
Dresses					
Long-sleeve, shirt collar, A-line (broadcloth)	0.254	69	1.21	0.32	0.44
Long-sleeve, shirt collar, A-line (tweed)	0.280	69	1.21	0.47	0.59
Long-sleeve, shirt collar, A-line, belt (broadcloth)	0.283	69	1.18	0.35	0.46
Long-sleeve, shirt collar, A-line, belt (tweed)	0.327	69	1.18	0.48	0.59
Short-sleeve, shirt collar, A-line, belt (broadcloth)	0.237	61	1.15	0.29	0.38
Sleeveless, scoop neck, A-line (broadcloth)	0.153	48	1.19	0.23	0.34
Sleeveless, scoop neck, A-line (tweed)	0.414	48	1.19	0.27	0.38
Sleepwear					
Long-sleeve, long gown (tricot)	0.260	81	1.49	0.29	0.52
Long-sleeve, long gown (flannel)	0.435	81	1.49	0.46	0.69
Long-sleeve, short gown (tricot)	0.180	66	1.25	0.24	0.38
Long-sleeve, short gown (flannel)	0.305	66	1.25	0.39	0.53
Short-sleeve, long gown (tricot)	0.239	74	1.44	0.25	0.47
Short-sleeve, short gown (tricot)	0.157	59	1.20	0.21	0.33
Sleeveless, long gown (tricot)	0.217	65	1.42	0.20	0.41
Sleeveless, short gown (tricot)	0.138	50	1.18	0.18	0.29
Thin strap, long gown (tricot)	0.157	58	1.33	0.18	0.36
Thin strap, short gown (tricot)	0.094	42	1.12	0.15	0.23
Hospital gown (print cloth)	0.270	57	1.23	0.31	0.44
Long-sleeve, long pajamas (broadcloth)	0.327	80	1.30	0.48	0.64
Long-sleeve, long pajamas (flannel)	0.447	80	1.30	0.57	0.73
Short-sleeve, long pajamas (broadcloth)	0.297	71	1.26	0.42	0.57
Long pajama trousers (broadcloth)	0.149	45	1.20	0.17	0.29
Body sleeper with feet (knit fleece)	0.599	86	1.38	0.72	0.92
Robes					
Long-sleeve, wrap, long (velour)	0.690	80.5	1.40	0.53	0.73
Long-sleeve, wrap, long (terrycloth)	1.196	80.5	1.43	0.68	0.89
Long-sleeve, wrap, long (pile knit)	1.535	80.5	1.47	1.02	1.25
Long-sleeve, wrap, short (broadcloth)	0.298	68	1.24	0.41	0.55
Long-sleeve, wrap, short (velour)	0.556	68	1.25	0.46	0.60
3/4 length sleeve, wrap, short (velour)	0.514	63	1.20	0.43	0.55
Long-sleeve, button front, long (broadcloth)	0.268	82	1.47	0.43	0.66
Long-sleeve, button front, long (velour)	0.586	82	1.48	0.49	0.72
Long-sleeve, button front, short (broadcloth)	0.260	69	1.32	0.40	0.57
Long-sleeve, button front, short (velour)	0.472	69	1.33	0.45	0.63
Short-sleeve, button front, short (broadcloth)	0.231	61	1.28	0.34	0.50
Underwear/Footwear					
Briefs (knit)	0.065	12	1.01	0.04	0.05
Panties (tricot)	0.027	12	1.01	0.03	0.04
Bra (knit/foam)	0.044	5	1.01	0.01	0.02
Half slip (tricot)	0.065	32	1.11	0.14	0.21
Full slip (tricot)	0.082	40	1.12	0.16	0.24
T-shirt (knit)	0.105	32	1.03	0.08	0.10
Thermal long underwear top (knit)	0.200	49	1.06	0.20	0.24
Thermal long underwear bottoms (knit)	0.210	44	1.06	0.15	0.19
Pantyhose(knit)	0.039	51**	1.00	0.02	0.02

Design Description and Fabric Type	Garment Weight (kg)	Body Surface Area Covered (%)	f_{cl}	I_{cle} (clo)	I_{cl} (clo)
Ankle length athletic socks (knit)	0.049	7	1.01	0.02	0.03
Calf length athletic socks (knit)	0.082	14	1.01	0.03	0.04
Calf length dress socks (knit)	0.053	13	1.01	0.03	0.04
Knee socks (thick knit)	0.068	20	1.01	0.06	0.07
Thongs/sandals (vinyl)	0.346	5	1.01	0.02	0.03
Hard-soled street shoes (vinyl)	1.006	7	1.03	0.02	0.04
Slippers (quilted fleece)	0.186	9	1.04	0.03	0.06
Soft-soled athletic shoes (canvas)	0.182	7	1.03	0.02	0.04

* These shirts are cut fuller than the others for a loose fit.
**In the regression analysis, 12% BSAC was used because only the panty provided insulation.

TABLE 2
Garment Regression Equations*

Equation**	Adjusted R^2	Standard Deviation
$I_{cl} = (0.687 \times AWT) + 0.146$	0.62	0.14
$I_{cl} = (0.961 \times AWT)$	0.85	0.17
$I_{cl} = (0.00973 \times BSAC) - 0.0832$	0.80	0.10
$I_{cl} = (0.00824 \times BSAC)$	0.94	0.11
$I_{cl} = (0.0102 \times BSAC) + (0.0431 \times FAB\ THICK) - 0.164$	0.86	0.09
$I_{cl} = (0.00776 \times BSAC) + (0.0212 \times FAB\ THICK)$	0.94	0.10
$I_{cl} = (0.00790 \times BSAC) + (0.00131 \times FAB\ THICK \times BSAC) - 0.0745$	0.93	0.06
$I_{cl} = (0.0653 \times BSAC) + (0.00133 \times FAB\ THICK \times BSAC)$	0.97	0.07
$I_{cle} = (0.570 \times AWT) + 0.0879$	0.68	0.10
$I_{cle} = (0.734 \times AWT)$	0.87	0.12
$I_{cle} = (0.00724 \times BSAC) - 0.0639$	0.69	0.10
$I_{cle} = (0.00609 \times BSAC)$	0.90	0.10
$I_{cle} = (0.00773 \times BSAC) + (0.0446 \times FAB\ THICK) - 0.147$	0.80	0.08
$I_{cle} = (0.00553 \times BSAC) + (0.0249 \times FAB\ THICK)$	0.91	0.10
$I_{cle} = (0.00534 \times BSAC) + (0.00135 \times FAB\ THICK \times BSAC) - 0.0549$	0.91	0.06
$I_{cle} = (0.00433 \times BSAC) + (0.00137 \times FAB\ THICK \times BSAC)$	0.97	0.06
$f_{cl} = (0.448 \times I_{cl}) + 1.01$	0.63	0.08
$f_{cl} = (0.458 \times I_{cl}) + 1.00$	0.86	0.08

* The regression equations predicting I_T are the same as those for I_{cle} except that 0.71 should be added to the Y intercept. Predictive equations for I_T and I_{cle} are more accurate than comparable equations for I_{cl}.
**AWT = weight (kg) omitting data for shoes, BSAC = body surface area covered by garment (%); FAB THICK = fabric thickness (mm).

TABLE 3
Ensemble Regression Equations

Equation*	Adjusted R^2	Standard Deviation
$I_{cl} = (0.835 \times SUM\ I_{cle}) + 0.161$	0.93	0.08
$I_{cl} = (.100 \times SUM\ I_{cle})$	0.99	0.10
$I_{cl} = (0.676 \times SUM\ I_{cl}) + 0.117$	0.94	0.07
$I_{cl} = (0.770 \times SUM\ I_{cl})$	0.99	0.09
$I_{cl} = (0.476 \times AWT) + 0.351$	0.77	0.14
$I_{cl} = (0.740 \times AWT)$	0.94	0.22
$I_{cl} = (0.0179 \times BSAC) - 0.550$	0.53	0.20
$I_{cl} = (0.0110 \times BSAC)$	0.94	0.22
$I_{cl} = (-0.0158 \times BSAC\ 0) + (-0.00884 \times BSAC\ 1) + 1.44$	0.78	0.14
$I_{cl} = (0.382 \times AWT) + (0.00614 \times BSAC) - 0.0297$	0.80	0.13
$I_{cl} = (0.386 \times AWT) + (0.00571 \times BSAC)$	0.98	0.13
$I_{cl} = (0.255 \times AWT) + (-0.00874 \times BSAC\ 0) + (-0.00510 \times BSAC\ 1) + 0.919$	0.84	0.12
$I_{cle} = (0.756 \times SUM\ I_{cle}) + 0.0791$	0.94	0.07
$I_{cle} = (0.838 \times SUM\ I_{cle})$	0.99	0.07
$I_{cle} = (0.432 \times AWT) + 0.250$	0.78	0.13
$I_{cle} = (0.621 \times AWT)$	0.95	0.17
$I_{cle} = (0.0160 \times BSAC) - 0.551$	0.53	0.18
$I_{cle} = (0.00914 \times BSAC)$	0.93	0.20
$I_{cle} = (-0.0140 \times BSAC\ 0) + (-0.00836 \times BSAC\ 1) + 1.25$	0.79	0.12
$I_{cle} = (0.345 \times AWT) + (0.00512 \times BSAC) - 0.0676$	0.80	0.12
$I_{cle} = (0.365 \times AWT) + (0.00412 \times BSAC)$	0.97	0.12
$I_{cle} = (0.233 \times AWT) + (-0.00754 \times BSAC\ 0) + (-0.00495 \times BSAC\ 1) + 0.764$	0.86	0.10
$f_{cl} = (0.225 \times I_{cl}) + 1.08$	0.55	0.06
$f_{cl} = (0.305 \times I_{cl}) + 1.00$	0.95	0.07

*SUM I_{cle} = sum of I_{cle} values (clo) for garments in each ensemble; SUM I_{cl} = sum of I_{cl} values (clo) for garments in each ensemble; AWT = weight (kg) without shoes; BSAC = body surface area covered by ensemble (%); BSAC 0 = body surface area not covered by clothing (%); BSAC 1 = body surface covered by one layer of clothing (%).

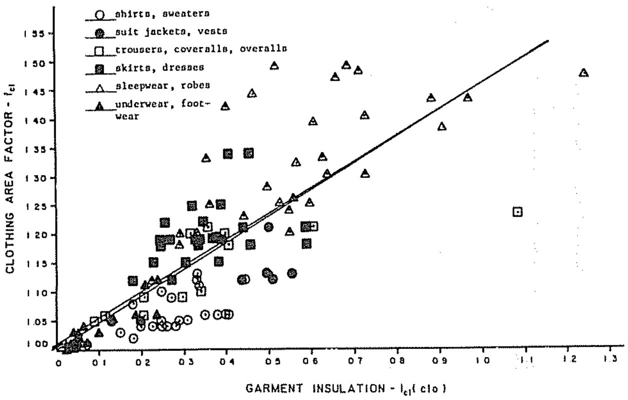

Figure 1. The relationship between garment insulation (I_{cl}) and the clothing area factor (f_{cl})

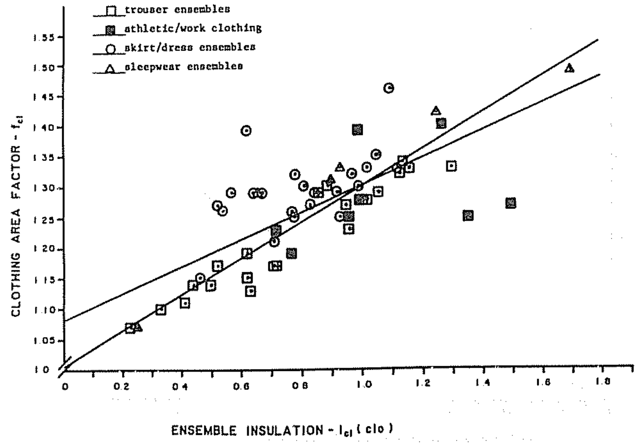

Figure 2. The relationship between ensemble insulation (I_{cl}) and the clothing area factor (f_{cl})

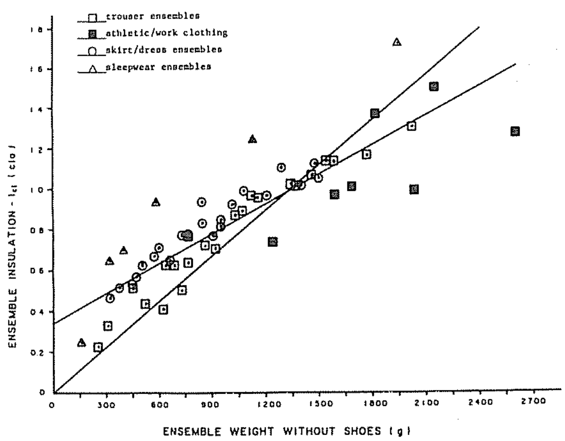

Figure 3. The relationship between ensemble weight without shoes and ensemble insulation (I_{cl})

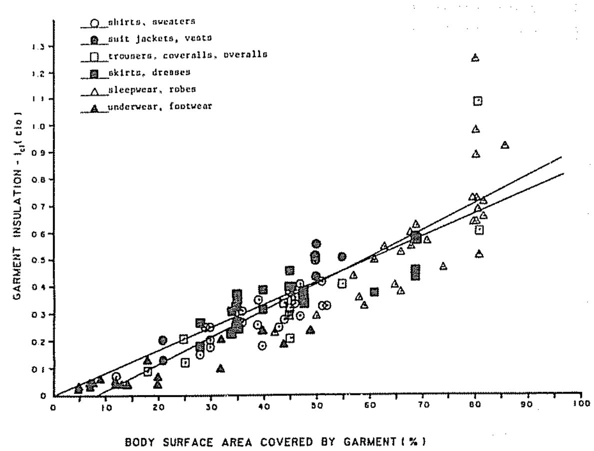

Figure 4. The relationship between the percent of body surface area covered by a garment and the garment insulation (I_{cl})

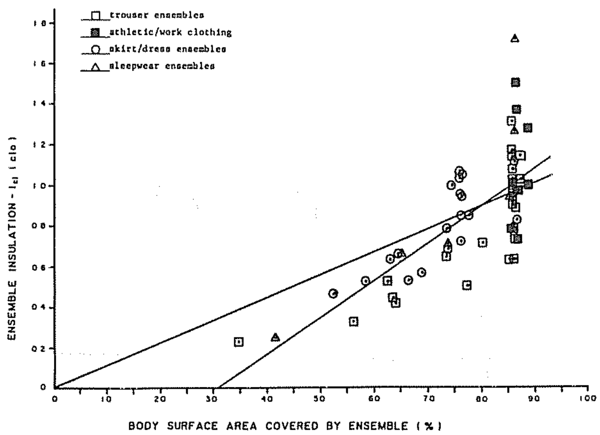

Figure 5. The relationship between the percent of body surface area covered by an ensemble and ensemble insulation (I_{cl})

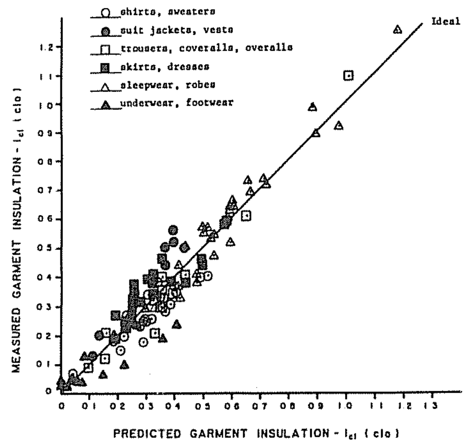

Figure 6. Predicting garment insulation (I_{cl}) from fabric thickness and the percent of body surface area covered by a garment

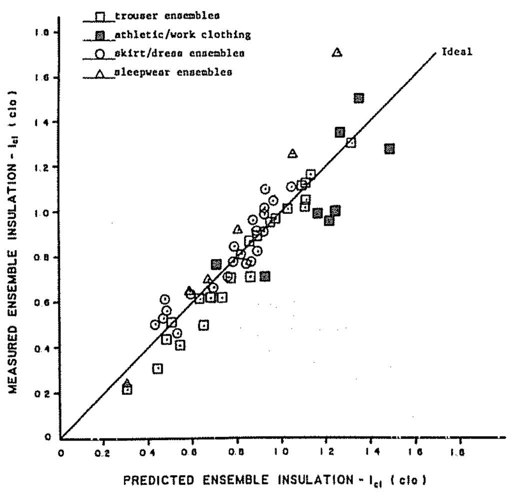

Figure 7. Predicting ensemble insulation (I_{cl}) from ensemble weight (without shoes) and the amount of body surface area covered by different number of fabric layers

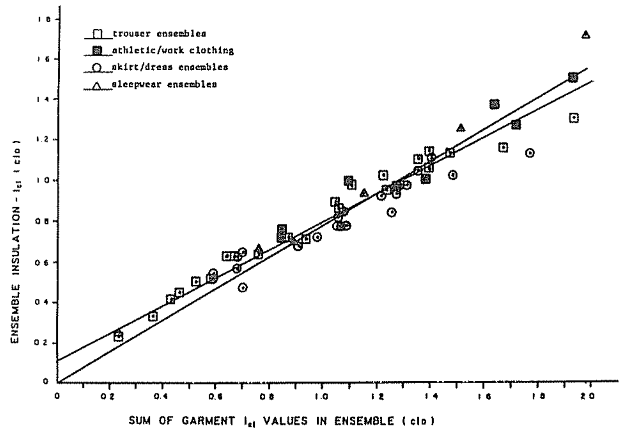

Figure 8. Predicting ensemble insulation (I_{cl}) from the sum of the I_{cl} values of the component garments in the ensemble

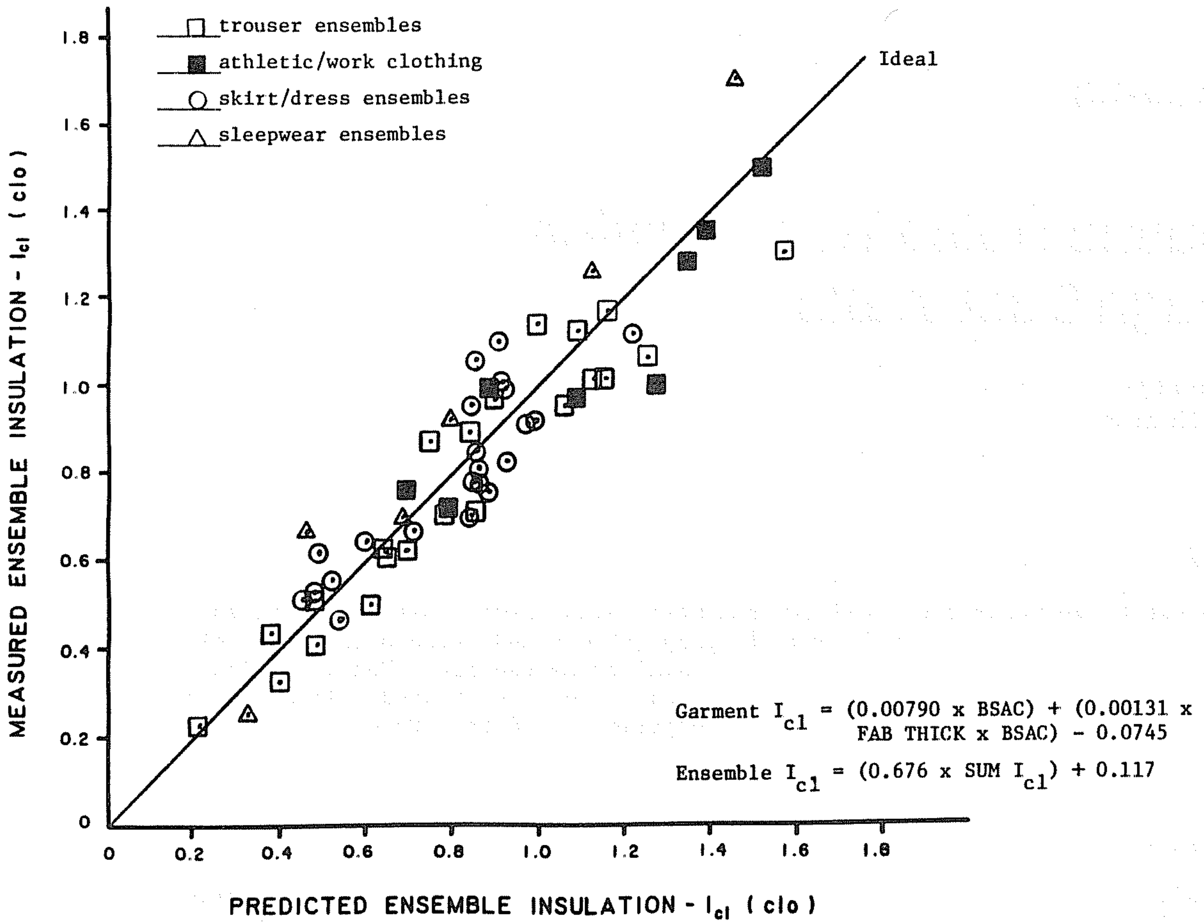

Figure 9. Predicting ensemble insulation (I_{cl}) from estimated garment I_{cl} values

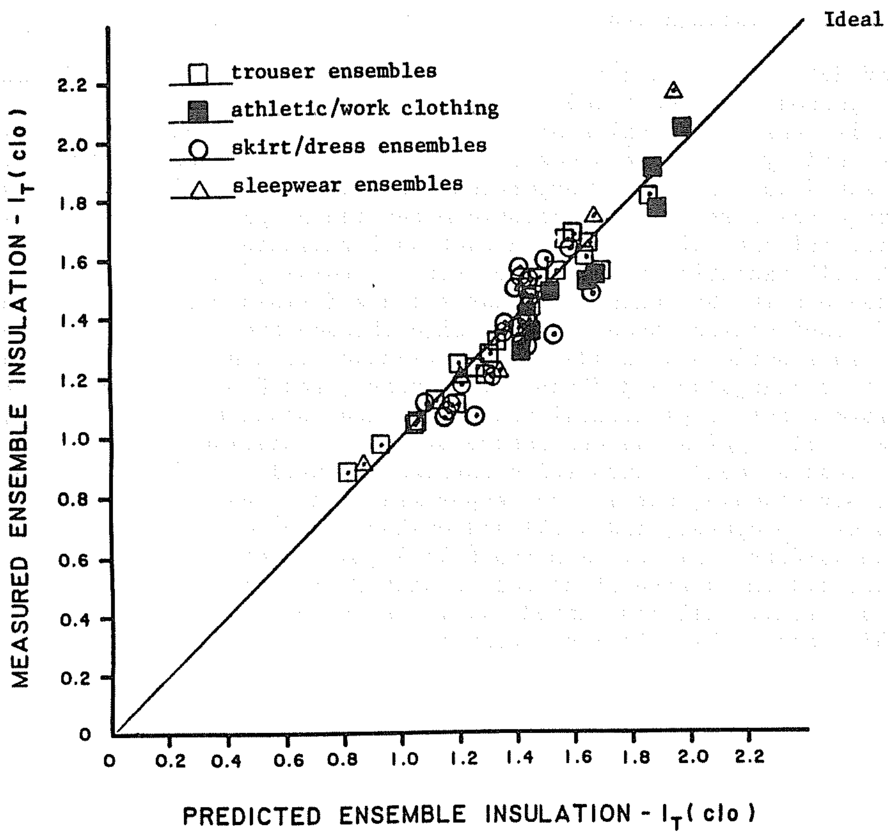

Figure 10. Predicting ensemble insulation (I_T) from a computer model