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A New Simpler Method for Estimating the Thermal Insulation of a Clothing Ensemble

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ABSTRACT

The most common method for estimating the basic thermal insulation (I_{cl}) of a clothing ensemble is the use of tables with basic thermal insulation values for individual garments (I_{cli}). Sprague and Munson (1974) found the following relationship between the thermal insulation of an ensemble and the summation of values for the individual garments (ΣI_{cli}): $I_{cl} = k_1 \Sigma I_{cli} + k_2$, where k_1 was a constant less than one, and both k_1 and k_2 were dependent on sex (female or male clothings). This equation has since been simplified in ASHRAE Standard 55-81 for thermal environment: $I_{cl} = 0.82 \Sigma I_{cli}$.

This paper presents an even simpler method. Instead of describing the thermal insulation of a single garment by means of the basic thermal insulation (I_{cli}), it is proposed to use the effective thermal insulation (I_{clu}). The result of the present study is then the following relationship: $I_{cl} = \Sigma I_{clu}$.

The basic thermal insulation of a clothing ensemble is simply estimated as the sum of the effective insulation for the single garments (ΣI_{clu}). Another important advantage of using the proposed method is that when expressing the insulation of a single garment by the effective insulation it is not necedssary to perform the difficult measurement of the increased clothing area factor, f_{cl}. The proposed relationship is based on measurements of 70 clothing ensembles in the range 0.7–2.6 clo.

INTRODUCTION

The thermal insulation of the clothing worn by people is an essential parameter when predicting the influence of the thermal environment on human beings. In cold, neutral, and warm environments, the type of clothing worn will influence the heat exchange between the human body and the environment. This, in turn, influences the acceptability and stress of that environment. In warm environments, clothing is often used to provide protection against the physical environment (dust, sparks, radition) and may, in some cases, increase stress and reduce working time. However, clothing may also be used as protection against heat and increase the working time. In a neutral thermal environment, clothing has a significant influence on the preferred ambient temperature. For example, a change in thermal insulation of $\sim$ 0.2 clo will change the preferred ambient temperature by $\sim$ 1.5 ^{0}C for a seated person. In cold environments clothing is, in most cases, the only method for making the working conditions tolerable.

The thermal insulation of the clothing ensembles must be estimated when evaluating moderate thermal environments according to ASHRAE 55-81 or ISO 7730 (1984) (PMV-PPD index), when evaluating hot environments according to ISO/DIS 7933 (1983) (Required Sweat Rate Index) or ET* (Gagge et al.1972), and when evaluating cold environments according to the method (IREQ, Required Clothing Insulation) suggested by Holmér (1984). For this purpose, it is necessary to provide the user of these or similar procedures with methods for the estimation of the thermal insulation.

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The thermal insulation of a clothing ensemble is normally measured on a thermal manikin (Seppanen et al. 1972; McCullough et al. 1983b; Olesen et al. 1982). Very few thermal manikins are, however, available (Mecheels and Umbach 1976; Goldman 1974; Seppanen et al. 1972; Olesen et al. 1982), and the measurements have to be performed in a laboratory.

For practical use, therefore simplified methods that can be used in the field are necessary. The most widely used methods utilize look-up tables of clothing insulation values. One kind of table includes thermal insulation values for clothing ensembles measured on a standing thermal manikin. Another type of table includes values for the thermal insulation of individual garments also measured on a standing thermal mannequin. Based on the summation of values for individual garments (I_{cli}), it is then possible to estimate the thermal insulation of a whole ensemble (I_{cl}).

The following summation equations have been suggested in literature:

$$I_{cl} = 0.727\,\Sigma I_{cli} + 0.113 \quad \text{clo (men)} \quad \text{Sprague and Munson 1974} \tag{1}$$

$$I_{cl} = 0.770\,\Sigma I_{cli} + 0.05 \quad \text{clo (women)} \quad \text{Sprague and Munson 1974} \tag{2}$$

$$I_{cl} = 0.82\,\Sigma I_{cli} \quad \text{ASHRAE 1981} \tag{3}$$

The data for the above equations are from measurements on daily wear ensembles with a thermal insulation in the range 0.2 to 1.0 clo-value.

The purpose of this study was to verify that these methods also can be used for typical work clothing and for ensembles with thermal insulation values up to 2.6 clo.

METHOD

All the measurements presented in this paper were performed on a standing thermal manikin which has been described in details by Olesen et al. (1982). In the following paragraphs, the measuring method and experimental facilities are described.

Expressions for the Thermal Insulation of Clothing

The thermal insulation of a clothing ensemble or a single garment is expressed in this paper by the "clo" unit introduced by Gagge et al. (1941). The clo is defined in SI unit as 1 clo = 0.155 m^2K/W.

The insulation of clothing ensembles has been expressed in different ways in the literature. The clothing insulation reported by Goldman (1974), Breckenridge and Goldman (1977), Mecheels and Umbach (1976; 1979), and Holmér and Elnäs (1981) were expressed by the total insulation, I_T. The results reported by Nishi et al. (1975; 1976) were given as effective clothing insulation, I_{cle}, while Seppanen et al. (1972) and Sprague and Munson (1974) in their comprehensive clothing studies used the basic clothing insulation, I_{cl}. Recent publications by McCullough et al. (1982; 1983) and McCullough and Wyon (1983) use both total and basic insulation.

<u>Total insulation</u> (I_T) is the insulation from the skin surface to the environment, including the effect of the increased surface area (f_{cl}) and the resistance at the surface of the clothed body (I_a).

$$I_T = \frac{\bar{t}_s - t_o}{0.155\,Q} \tag{4}$$

<u>where</u>

I_T = total insulation, clo

Q = dry heat loss per m^2 skin area, W/ dm^2

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

t_o = operative temperature, °C

<u>Effective clothing insulation</u> (I_{cle}) is the insulation from the skin to the clothing surface, excluding the effect of the increased surface area of the clothed body (f_{cl}).

$$I_{cle} = I_T - I_a = \frac{\bar{t}_s - t_o}{0.155\ Q} - I_a \quad (5)$$

where

I_{cle} = effective clothing insulation, clo

I_a = resistance at the surface of the clothed body, clo

Intrinsic or basic clothing insulation (I_{cl}) is the insulation from the skin to the clothing surface:

$$I_{cl} = I_T - I_a/f_{cl} = \frac{\bar{t}_s - t_o}{0.155\ Q} - I_a/f_{cl} \quad (6)$$

where

I_{cl} = intrinsic or basic clothing insulation, clo

f_{cl} = clothing area factor.

Clothing area factor (f_{cl}) is defined as:

$$f_{cl} = A_{cl}/A_n \quad (7)$$

where

A_{cl} = surface area of the clothed body

A_n = surface area of the nude body

The following equation provides the relationship between I_{cl}, I_{cle} and I_T:

$$I_{cl} = I_{cle} + I_a(1 - 1/f_{cl}) = I_T - I_a/f_{cl} \quad (8)$$

In the literature (Fanger 1982; ASHRAE 1981) the following relationship between I_{cl} and f_{cl} has been suggested

$$f_{cl} = 1 + 0.2\ I_{cl} \quad (9)$$

When introducing this in Equation 8 and assuming I_a = 0.8 clo, the following relationship is found:

$$I_{cle} = I_{cl}\ \left(\frac{1 + 0.2\ I_{cl} - 0.16}{1 + 0.2\ I_{cl}}\right) \quad (10)$$

This means that I_{cle} always is smaller than I_{cl}, because the expression between parentheses is less than one. For I_{cl} values in the range 0.5 to 2.0 clo, Equation 10, may be approximated by:

$$I_{cle} = 0.87\ I_{cl}$$

Under the above assumption I_{cle} is then about 13% lower than I_{cl}.

The relationship is important when comparing data from different studies. Clo-values for clothing ensembles cannot be compared without specifying whether they refer to the total, the effective, or the basic clothing insulation. The drawback of I_T is that it includes in the definition the surface resistance which is influenced by the air velocity and temperature level. The same clothing ensemble may therefore have a different clo-value in different environments. The drawback of I_{cle} is that it ignores the increased surface area of the clothed body and is insufficient to provide a complete simulation of the heat transfer process. The basic insulation, I_{cl}, combined with f_{cl} provides the required data for thermally characterising clothing.

In the present study, measurements were performed enabling thermal insulation to be expressed in total (I_T), effective (I_{cle}), and basic (I_{cl}), thermal insulation. The same expressions and methods were used for the insulation of a single garment where:

I_{Ti} = total thermal insulation of an individual garment

I_{clu} = effective thermal insulation of an indiviual garment

I_{cli} = basic thermal insulation of an individual garment

MEASUREMENT

The thermal insulation of the garments and ensembles was measured on a thermal manikin, which was developed from a display manikin and consists of a fiberglass reinforced polyester shell. The manikin has joints in the shoulders, hips, and knees so it can stand up, be seated, walk, or cycle on an ergometer. The body is divided into 16 segments, each of which is supplied with its own heating and control system. To simulate a human being, the control of the manikin is arranged to maintain a surface temperature equal to the skin temperature of a person in thermal comfort at the actual activity. This is done by heating the manikin to a fixed internal temperature of 36.4 °C and providing a thermal resistance (electrical + shell) equal to 0.348 clo between the inside and surface of the manikin. This resistance corresponds approximately to the resistance between the deep body and skin of a human being during thermal comfort.

The tests reported here were performed in a climatic chamber (Kjerulf-Jensen et al. 1975) in which the whole floor is used as an air outlet. The air change was 60 h^{-1}. The air velocity was <0.05 m/s and air temperature = mean radiant temperature = operative temperature t_o. During all tests the relative humidity was ∿50%.

The total clothing insulation was measured using the thermal manikin. As the manikin is heated to a constant internal temperature, t_i, the following is valid:

$$I_T = \frac{t_i - t_o}{0.155\ Q_m} - I_s \text{ clo} \tag{11}$$

where

t_o = operative temperature, °C

t_i = internal temperature of the manikin = 36.4 °C

I_s = resistance of the manikin shell = 0.348 clo

Q_m = heat loss from the manikin W/m²

The effective and basic thermal insulation was then estimated from Equations 5 and 6. To do this, it was necessary to know the resistance at the surface between manikin and environment (I_a) and the clothing area factor (f_{cl}). The surface resistance was estimated according to Equation 9 by operating the manikin nude.

The clothing area factor (f_{cl}) was measured by a photographic technique using pictures from six directions (Olesen et al. 1982). The measuring procedures were the same for individual garments and ensembles. The resistance of the manikin shell (0.348 clo) and the internal temperature of the mannequin (36.4 °C) were constant. The operative temperature (t_o) used varied between 13 °C and 26 °C depending on the level of insulation. In this way, a heat loss from the manikin of between 40 W/m² and 80 W/m² was obtained. If the heat loss is too low, the accuracy of the heat loss measurement has too much influence on the results, while at too high a heat loss, small changes in the thermal insulation may not be measurable.

RESULTS

Measurement with the nude manikin showed that the surface resistance, I_a, was not significantly influenced by the temperature level in the climatic chamber. In all calculations of single garments and ensembles insulation, a value of I_a = 0.70 clo was used. The results of the measured thermal insulation of individual garments are shown in Appendix 1. The thermal insulation of approximately 200 garments has been measured according to the method described above, but values are only partly shown in Appendix 1. The total thermal insulation (I_{Ti}) was first measured according to Equation 11, and then the basic (I_{cli}) and the effective (I_{clu}) insulation values were estimated according to Equations 5 and 6.

The increased area factor, (f_{cl}), was measured on approximately 50 items by photographic techniques. For the other garments, f_{cl} was evaluated by means of the measured values or values reported by McCullough et al. (1983a; 1983b). The relationship between the thermal insulation of a garment and its weight was studied. Figure 1 shows the relationship between I_{clu} and weight; and in Table 1, the results of a linear regression are shown between both I_{cli}-weight and I_{clu}-weight. The results of the measured insulation values of clothing ensembles are shown in Appendix 2. The thermal insulation of approximately 70 clothing ensembles was measured using the method described earlier, but only some of the results are shown in Appendix 2. First, the total thermal insulation (I_T) was measured according to Equation 11, and then the basic (I_{cl}) insulation was estimated according to Equation 6.

The increased area factor (f_{cl}) was measured on approximately 20 ensembles using the method described earlier. For the other ensembles, f_{cl} was evaluated by means of the measured values or values reported by McCullough et al. (1983b), and McCullough and Jones (1983a). The relationship between the clothing area factor (f_{cl}) and the basic thermal insulation (I_{cl}) was studied. The data from the present study are shown in Figure 2, and the regression analysis is shown in Table 1. The relationship between the basic thermal insulation of a clothing ensemble and the total weight of the ensemble except shoes is shown in Figure 3, and the regression analysis is shown in Table 1. The relationship between basic thermal insulation I_{cl} of an ensemble and the summation of the individual effective insulation (ΣI_{clu}) and the summation of the individual basic insulation values (ΣI_{cli}) are shown in Figures 4 and 5, respectively. The results of a linear regression between I_{cl} and ΣI_{clu} or ΣI_{cli} are shown in Table 1. Both regression through the origin (0.0) and with intercept are shown.

DISCUSSION

The most important result of this study is the result of a linear regression between the basic thermal insulation of a clothing ensemble, I_{cl}, and the summation of the effective thermal insulation for the individual garments, (ΣI_{clu}). From Table 1 it can be seen that the basic insulation, I_{cl}, of an ensemble can be estimated by just adding together the effective insulation (I_{clu}) of each garment. This is a very important result, because by using this method, the thermal insulation of garments are based on the effective value (Equation 5). Thus, it is not necessary to perform the very time-consuming, and in some cases not very realistic, measurement of the clothing area factor (f_{cl}) for each garment. When estimating the basic thermal insulation for a single garment (I_{cli}), it is necessary to measure the clothing area factor. A shirt by itself will hang loose on a thermal manikin and in many cases have an unrealistic high f_{cl}-value, compared with the influence that a shirt tucked into a pair of trousers has on the f_{cl}-value for a clothing ensemble. For the human heat balance equation, knowledge of individual insulation values for each garment is not needed. The values for a garment are only used for individual comparison of different garments and for predicting the thermal insulation of a whole ensemble. It is, however, possible to compare thermal insulation of garments based on the effective insulation, (I_{clu}). In practice, it is also much easier to use a simple summation of insulation values for individual garments ($I_{cl} = \Sigma I_{clu}$) instead of an equation where it is necessary to multiply the sum of the individual values by a constant ($I_{cl} = 0.82\ \Sigma I_{cli}$).

Another advantage is when future garments have to be marked with a value for the thermal insulation. If the garments are marked with the effective thermal insulation value, I_{clu}, then it will be easy for the user just to add the values when he/she wants to estimate the thermal insulation of the whole ensemble, I_{cl}. A Nordic standard committee is now working on a standard for measuring the thermal insulation of clothing garments and ensembles. The aim of this standard is also to establish a procedure for describing the thermal properties (insulation, evaporative resistance, airtightness) of garments and how this should be indicated on the garments. In the future, it will then be possible to see the garments labelled with the thermal properties along with the size, washing instructions, and type of fabrics.

This simple relationship could be expected when looking at Equation 10. Here it is seen that I_{cle} is about 13% lower than I_{cl}. When adding I_{clu} for the single garments, this should then automatically result in a 13% lower sum than when adding I_{cli} values. When comparing relationships $I_{cl} = 0.82\ \Sigma I_{cli}$ (ASHRAE 1981) and the present result $I_{cl} = \Sigma I_{clu}$, then it seems like I_{clu} values are about 18% lower than I_{cli} values. This is not in agreement with the expected 13% from Equation 10. In this equation, however, it was assumed that the increase in f_{cl} was 0.2/clo, while the present results indicate a relationship of 0.26/clo, which can explain the difference.

From Figure 4, it can be seen that at low I_{cl} values (<1.0 clo) the regression line with intercept (I_{cl}=0.85 ΣI_{clu} + 0.25) gives a better prediction of the I_{cl} values. This is due to the fact that at lower I_{cl} values, the overlapping is less and the increase in insulation is mainly due to an increase in the body surface area covered. In this case, addition of the basic insulation values for each garment may be a better predictor. However, the question is, whether this more complicated procedure provides significantly more benefit compared with the single relationship given above. By using an equation with intercept, the standard deviation of the estimate is improved from 0.17 clo to 0.14 clo.

In future it will be much easier, and confusion with effective, intrinsic/basic or total thermal insulation can be avoided, if everybody agreed upon expressing the thermal insulation of individual garments as I_{clu} (effective) and the thermal insulation of ensembles as I_{cl} (basic).

Earlier summation formulae were based on the basic thermal insulation for each garment (I_{cli}) (Sprague and Munson 1974; ASHRAE 1981). As seen from Table 1, data from the present study result in exactly the same regression lines, I_{cl}=0.73 ΣI_{cli}+ 0.17 and I_{cl}= 0.82 ΣI_{cli} (see Equation 1 and 3).

An easy way of predicting the thermal insulation of a clothing garment or ensemble could be the weight. This is shown in Table 1 and Figures 1 and 3. For a garment, I_{clu}, the relationship has a slope of 0.48. For I_{cli} the slope is 0.59. Researchers (McCullough et al. 1983; McCullough and Jones 1983b) performed similar regressions for each type of fabric separately. They found that the relationship was much more significant with R^2= 0.9, and the slope of the relationship to I_{cli} varied between 0.45 and 1.00 depending on the type of fabric. The big difference in R^2 is due to the great variety of textiles used in the present study. The standard deviation of the prediction of I_{clu} is 0.14 clo, which is not acceptable for individual garments.

For a clothing ensemble, the relationship for I_{cl} has an inclination of 0.57, which is very similar to the value 0.59 for individual garments, I_{cli}. These results are shown in Table 1, together with results from other studies (McCullough et al. 1983; McCullough and Jones 1983b). They estimate an inclination equal to 0.19, but unfortunately, their regression line is not forced through the origin (0.0). In the ASHRAE Standard 55-81, a relationship of 0.35 clo/kg is suggested. Both are much lower than the 0.57 clo/kg found in the present study. This difference may be caused by the many ensembles, included in the present study, with high insulative materials. These ensembles will have a much higher clo/weight relationship than the fabrics used in the studies of McCullough et al. (1983) and Sprague and Munson (1974). This only emphasizes how unreliable the total ensemble weight is as predictor of the thermal insulation. The standard deviation of prediction is 0.38, which is unacceptable high.

The measurement of the increased area factor, f_{cl}, is very time consuming. Therefore a relationship between f_{cl} and I_{cl} is often used. Fanger (1982) suggested the following relationship:

$$f_{cl} = \begin{cases} 1.00 + 0.2\, I_{cl} & I_{cl} < 0.5 \\ 1.05 + 0.1\, I_{cl} & I_{cl} > 0.5 \end{cases}$$

The present study resulted in a relationship f_{cl} = 1 + 0.26 I_{cl} (Table 1) based on 19 clothing ensembles in the range of 0.7 to 2.4 clo. The relationship has a standard deviation of 0.11, which in practice may not be an acceptable prediction of the clothing area factor. A similar relationship has been studied by McCullouth and Jones (1983a) and Sprague and Munson (reported by McCullough and Jones 1983a). The accuracy of prediction based on their results was better but is based on a narrower and lower range of values. All three studies show, however, that the increase in f_{cl} per clo is greater than the 0.2/clo or 0.1/clo suggested by Fanger (1982). The regressions in Table 1 show a 24-36% increase in f_{cl} per clo.

The present study showed that I_a was independent of the ambient temperature. This may be due to the construction of the climatic chamber. As the whole floor is used as an air outlet, there is a slow air-flow from floor to ceiling in the same direction as the natural convection. This may result in a stable boundary layer around the body at low air velocities (0.05 m/s), which is not being changed by an increased Δt between body and chamber. In other climatic chambers, the temperature difference might influence I_a, so it is important to perform this test with a nude manikin before running tests with clothing. This, of course, has to be performed only once.

The present data on garment and ensemble clo-values add new information to the literature due to the many types of work clothing and the higher insulation values, which have been included.

CONCLUSIONS

A very simple relation between the thermal insulation of a clothing ensemble (I_{cl}) and the thermal insulation of the individual garments (I_{clu}) has been established.

$$I_{cl} = \Sigma I_{clu}$$

where the thermal insulation of a clothing ensemble is expressed in basic insulation and the thermal insulation of a garment in effective insulation.

This method also facilitates the measurement of thermal insulation of individual garments, I_{clu}, because measurement of the clothing area factor, f_{cl}, is avoided. This relation is based on measurement with 70 clothing ensembles in the range 0.7 to 2.6 clo.

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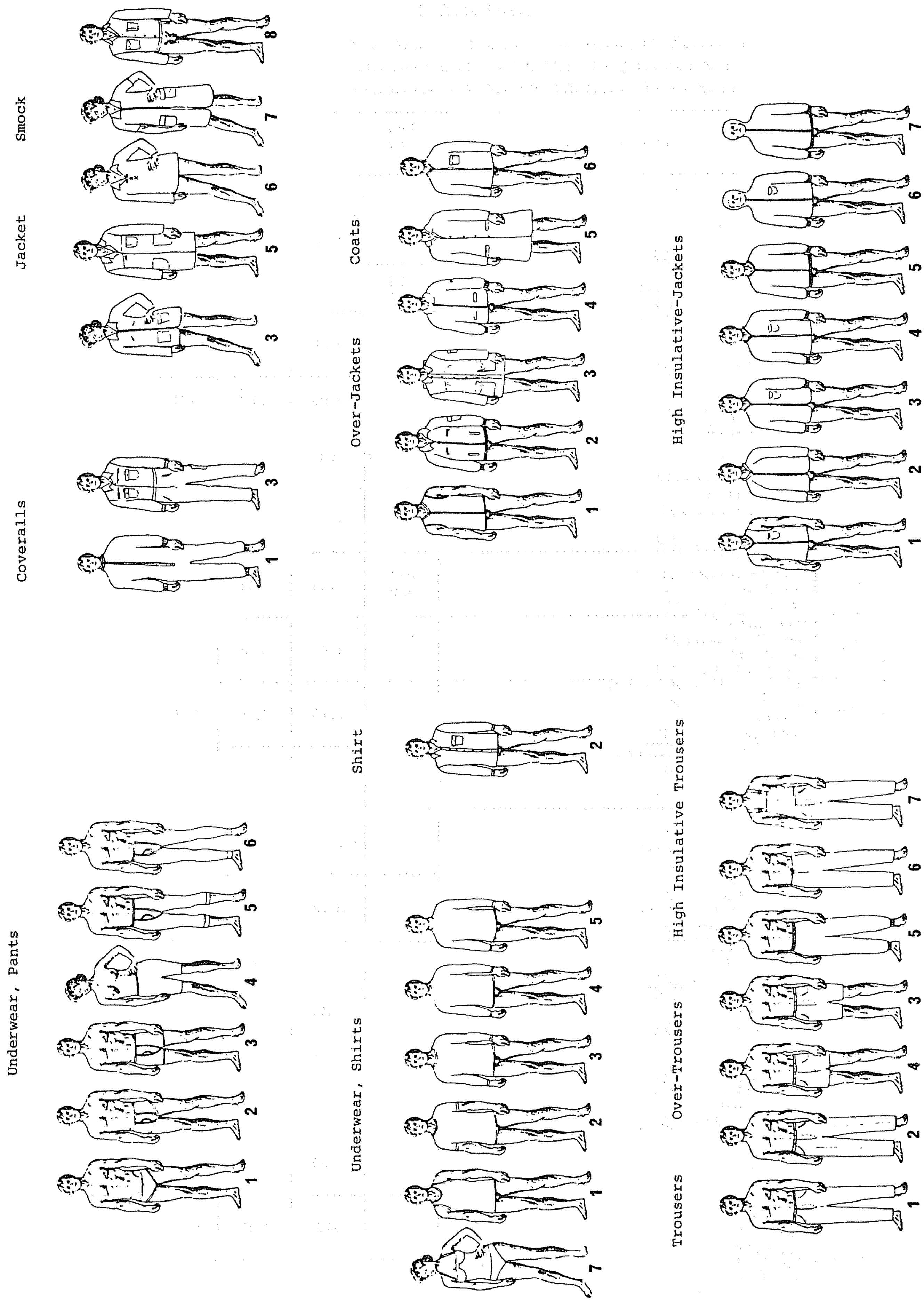
APPENDIX 1

Thermal insulation values (effective insulation, I_{clu}) for individual garments. The type No. refers to the shown figures of garment designs.

No.	Garment description	Type no.	Fabric No.	Garment weight g	Thermal insulation I_{clu} clo	Thermal insulation I_{clu} m²°C/W
	UNDERWEAR PANTS					
7	Pants, short legs	3	51	70	0,04	0,006
9	Pants, 1/2 long legs	4	51	137	0,06	0,009
10	Pants, long legs	6	51	198	0,12	0,019
20	Briefs	2	52	66	0,03	0,005
22	Pants, long legs	6	52	162	0,08	0,012
23	Briefs	2	50	80	0,04	0,006
25	Pants, 3/4 long legs	5	50	186	0,08	0,012
26	Pants, long legs	6	50	193	0,10	0,016
28	Pants, long legs	6	53	221	0,10	0,016
43	Pants, long legs	6	54	165	0,13	0,020
44	Bra and panties	7	57	87	0,04	0,006
46	Pants, long legs	6	55	270	0,22	0,034
48	Pants, long legs	6	56	155	0,07	0,011
	UNDERWEAR SHIRTS					
6	Briefs	2	51	67	0,04	0,006
13	Shirt, no arms	1	50	150	0,06	0,009
29	Shirt, no arms	1	52	106	0,05	0,008
31	T-shirt	2	50	180	0,10	0,016
33	Shirt, long arms	3	50	200	0,12	0,019
36	T-shirt	2	53	196	0,09	0,014
37	Shirt, long arms	3	53	236	0,16	0,025
42	Shirt, long arms	3	54	182	0,16	0,025
45	Shirt, long arms	3	55	360	0,25	0,039
47	Shirt, long arms	3	56	195	0,11	0,017
	SHIRTS					
70	Long sleeve, shirt collar	2	59	370	0,29	0,045
71	Long sleeve, shirt collar	2	60	360	0,21	0,033
73	Long sleeve, shirt collar	2		220	0,18	0,028
	TROUSERS					
91	Straight, loose	2	59	640	0,26	0,040
92	Straight, loose	2	60	605	0,20	0,031
93	Overalls	7	60	755	0,24	0,036
94	Overalls	7	59	910	0,28	0,043
101	Straight, loose	2	58	320	0,23	0,036
	COVERALLS					
112	Work	3	59	1260	0,52	0,081
113	Work	3	60	1140	0,49	0,076
120	Work	3		890	0,51	0,079
121	Chemical protective	3		1340	0,60	0,093
	JACKET, VEST, SMOCK					
150	Jacket, no buttons	6	60	640	0,26	0,040
151	Work jacket	8	59	652	0,26	0,040
152	Work jacket	8	60	610	0,21	0,033
154	Work smock, above knee lenght	5		547	0,34	0,053
155	Work smock, below knee length	7		575	0,36	0,056
167	Work jacket, female	3	58	400	0,24	0,037

No.	Garment description	Type No.	Fabric No.	Garment weight g	Thermal insulation I_{clu} clo	Thermal insulation I_{clu} m²°C/W
	COATS, OVER–JACKETS, OVER–TROUSERS					
180	Trousers, loose	6	60	745	0,19	0,029
181	Jacket, above knee length	3	60	942	0,28	0,043
182	Trousers, loose	6	61	452	0,46	0,071
183	Jacket, above knee length	6	61	945	0,69	0,107
184	Coat, below knee length	5		1820	0,65	0,101
185	Down-jacket	4		880	0,55	0,085
186	Down-vest	1		620	0,30	0,047
187	Coat, below knee length	5		650	0,56	0,087
188	Parca-coat, multicomponent	3		1440	0,67	0,104
189	Parca-coat, multicomponent with hat	3		1440	0,79	0,122
190	Overalls, multicomponent	7		800	0,52	0,081
191	Heat protective felt trousers	6		1300	0,33	0,051
192	Jacket, multicomponent	3		1350	0,69	0,107
193	Heat protective felt jacket	6		1620	0,42	0,065
194	Heat reflective, aluminized trousers	6		670	0,33	0,051
195	Heat reflective, Aluminized coat	6		830	0,42	0,065
196	Rainprotective trousers	6		250	0,17	0,026
197	Rainprotective jacket	6		500	0,31	0,048
198	Jacket, multicomponent	2		1000	0,36	0,056
	HIGH INSULATIVE TROUSERS					
200	Trousers, fiber-pelt	5	62	341	0,40	0,062
201	Trousers, multicomponent	5	63	322	0,30	0,047
203	Trousers, multicomponent	5	64	292	0,32	0,050
204	Trousers, multicomponent	5	—	360	0,31	0,048
205	Trousers, multicomponent	5	65	225	0,35	0,054
	HIGH INSULATIVE COVERALLS					
210	Coverall, multicomponent	1	63	615	0,80	0,124
211	Coverall, multicomponent, filling	4		1500	1,03	0,160
213	Coverall, fiber-pelt	1	62	1215	1,13	0,175
	HIGH INSULATIVE JACKETS					
220	Jacket, linnin at wrist and hip, fiber-pelt	5	62	417	0,39	0,060
221	Jacket, linning at wrists, fiber-pelt	3	62	437	0,43	0,067
222	Jacket, fiber-pelt on outside	2	62	434	0,40	0,062
224	Jacket, fiber-pelt, head covered	7	62	472	0,37	0,057
225	Jacket, multicomponent, extra back-length	4	63	370	0,39	0,060
226	Vest, multicomponent	1	63	212	0,20	0,031
227	Jacket with hat		63			
228	Jacket, multicomponent	4	64	292	0,38	0,059
229	Jacket, multicomponent	3	—	310	0,32	0,050
230	Jacket, multicomponent	3	65	225	0,37	0,057
231	Jacket, multicomponent	3	—	270	0,34	0,053
232	Jacket, multicomponent	3	—	365	0,45	0,070
233	Jacket, multicomponent	3	—	270	0,40	0,062
	SOCKS, SHOES, GLOVES, HATS ETC.					
251	Thick gloves, fiber-pelt	4	70	82	0,08	0,012
252	Thick socks, calf length, fiber-pelt	2	70	113	0,11	0,017
253	Thick socks, ankle length, fiber-pelt	1	70	77	0,05	0,008
254	Socks, ankle length	1		61	0,02	0,003
255	Suede-shoes, rubber sole	6			0,02	0,003
256	Thick socks, ankle length	1		112	0,05	0,008
257	Wooden-shoes	7			0,03	0,005
258	Shoes				0,05	0,008
259	Cap	12		100	0,01	0,002


Smock
Jacket
Coveralls
Coats
Over-Jackets
High Insulative-Jackets
Underwear, Pants
Underwear, Shirts
Shirt
High Insulative Trousers
Over-Trousers
Trousers

APPENDIX 2

Thermal insulation values (basic insulation, I_{cl}) for clothing ensembles. The numbers after each individual garment refer to Appendix 1.

No.	Clothing ensemble	Combination	Weight g	f_{cl}	I_{cl} clo	I_{cl} m^2°C/W
	WORK CLOTHING					
434	Underpants 23 Trousers 91, Shirt 70 Socks 254, Shoes 255		1105	1,24	0,75	0,116
429	Underpants 23 Shirt 70, Trousers 91, Jacket 151 Socks 254, Shoes 255	**434** 151	1803	1,29	0,87	0,135
435	Underpants 23, undershirt 31 Shirt 70, trousers 91 Jacket 151 Socks 254, shoes 244	**429** 31	1939	1,29	0,98	0,152
423	Underpants 23, Shirt 71, Trousers 92, jacket 152 Socks 254, shoes 255		1708	1,36	0,79	0,122
425	Underpants 23 Shirt 71 Coverall 113 Socks 254, shoes 255		1633	1,36	0,81	0,126
426	Underpants 23 Shirt 71, Trousers 93 Jacket 152 Socks 254, shoes 255		1858	1,30	0,87	0,135
427	Underpants 23 Shirt 70, Trousers 91 Smock 150 Socks 254, shoes 255	**434** 150	1783	1,38	0,86	0,133
424	Underpants 23 Shirt 71, trousers 92 Smock 154 Socks 254, shoes 255		1645	1,40	0,91	0,141
420	Underpants 23, undershirt 31 Shirt 70, trousers 91 Coverall 112 Socks 254, shoes 255		2573	1,31	1,18	0,183
428	Underpants 23, undershirt 31 Shirt 71, trousers 92 Coverall 113 Socks 254, shoes 255		2538	1,31	1,05	0,163
421	Underpants 23 Shirt 70, trousers 94 Jacket 151, coverall 112 Socks 254, shoes 255		3333	1,40	1,33	0,206
422	Underpants 20 Shirt 71, trousers 93 Jacket 152, coverall 113 Socks 254, shoes 255		2992	1,40	1,25	0,194
471	Underpants 23 Coverall 255 Socks 254, shoes 255		1031	1,25	0,72	0,112
470	Undershirt 33, underpants 26 Coverall 120 Socks 254, shoes 255		1344	1,25	0,84	0,130
480	Underpants 23, undershirt 31 Coverall 120 Socks 254, shoes 255		1210	1,30	0,82	0,127
481	Undershirt 47, underpants 48 Coverall 120 Socks 254, shoes 255		1300	1,30	0,84	0,130
483	Underpants 23, undershirt 31 Shirt 73 Coverall 120 Socks 254, shoes 255		1430	1,30	0,94	0,146
430	Underpants 44 Shirt 73, skirt 61 Jacket 167 Socks 258, shoes 255		976	1,28	0,79	0,122
431	Underpants 44 Shirt 73, trousers 101 Jacket 167 Socks 254, shoes 255		1088	1,26	0,90	0,140

No.	Clothing ensemble	Combination	Weight	f_{cl}	I_{cl}	
			g		clo	m²°C/W
	COLD PROTECTIVE CLOTHING					
400	Undershirt 42, Underpants 43 Coverall 115 Socks 254, shoes 255		1286	1,18	1,11	0,172
401	Undershirt 42, Underpants 43 Insulated trousers 201, insulated jacket 225 Socks 254, Shoes 255		1363	1,27	1,20	1,186
402	Undershirt 42, Underpants 43 Insulated trousers 201, insulated jacket 226 Socks 254, shoes, 255		1205	1,22	0,85	0,132
404	Undershirt 42, Underpants 43 Coverall 210 Overtrousers 182, overjacket 183 Socks 256, shoes 257		2564	1,40	0,88	0,291
405	Undershirt 42, underpants 43 Insulated trousers 201, insulated trousers 225 Overtrousers 182, overjacket 183 Socks 256, shoes 257		2641	1,42	2,13	0,330
406	Undershirt 42, underpants 43, Insulated trousers 201, insulated jacket 225 Overtrousers 182, overjacket 183 Socks 254, shoes 255		2490	1,42	2,41	0,374
407	Undershirt 42, underpants 43 Insulated trousers 200, insulated jacket 221 Socks 254, shoes 255		2449	1,22	1,40	0,217
408	Undershirt 42, underpants 43 Insulated trousers 200, insulated jacket 222 Socks 254, shoes 255		2445	1,22	1,38	0,214
409	Undershirt 42, underpants 43 Insulated trousers 200, insulated jacket 222 Overtrousers 182, overjacket 183 Socks 256, shoes 257		2631	1,42	2,22	0,344
410	Undershirt 42, underpants 43 Insulated trousers 200, insulated jacket 221 Overtrousers 182, overjacket 183 Socks 256, shoes 257		2884	1,42	2,17	0,336
411	Undershirt 42, underpants 43 Insulated trousers 201, insulated jacket 225 Overtrousers 182, overjacket 183 Socks 256, shoes 255		2566	1,42	2,16	0,335
436	Underpants 23, undershirt 31 Shirt 70, trousers 91, Jacket 151 Insulated trousers 228, insulated trousers 203 Socks 256, shoes 257		2618	1,36	1,53	0,237
438	Underpants 23, undershirt 31 Shirt 70, trousers 91, Jacket 151, thermo-j 228 Socks 256,		2326	1,30	1,18	0,183
439	Underpants 23, undershirt 31 Shirt 70, trousers 91, jacket 151 Insulated trousers 203, insulated jacket 228 Socks 256, shoes 255	**438** 203	2618	1,35	1,46	0,226
482	Undershirt 47, underpants 48 Insulated trousers 204, insulated jacket 229 Coverall 120 Socks 254, shoes 255	**481** 204 229	1970	1,32	1,43	0,222
441	Underpants 23, undershirt 31 Shirt 70, trousers 91 Jacket 151, insulated jacket 255 Socks 256, shoes 255	**~435** 225	2404	1,36	1,23	0,191
442	Underpants 23, undershirt 31 Shirt 70, trousers 91 Jacket 151, insulated jacket 225 Insulated trousers 201 Socks 256, shoes 255	**441** 201	2726	1,35	1,54	0,239
472	Underpants 23, undershirt 31 Shirt 70 Insulated jacket 228, insulated trousers 203 Overtrousers 190, overjacket 198 Socks 254, shoes 255, gloves 251, hat 259		3257	1,45	2,26	0,350
473	Underpants 23, undershirt 31 Shirt 70 Insulated jacket 228, insulated trousers 203 Overtrousers 190, overjacket 188 Socks 254, shoes 255, gloves 251, hat 259		3697	1,48	2,30	0,357

No.	Clothing ensemble	Combination	Weight g	f_{cl}	I_{cl} clo	I_{cl} m^2°C/W
	COLD PROTECTIVE CLOTHING cont.					
491	Undershirt 47, underpants 48 Coverall 120 Overjacket 188 Socks 254, shoes 255, hat 259, gloves 251	**481** 188 251 259	2920	1,43	1,63	0,253
492	Undershirt 47, underpants 48 Coverall 120, overjacket 188, overtrousers 190 Gloves 251, hat 259 Socks 259, shoes 255	**491** 190	3720	1,49	2,34	0,363
493	Undershirt 47, underpants 48 Insulated trousers 204, insulated jacket 229 Overtrousers 190, overjacket 188 Socks 254, shoes 255, hat 259, gloves 251		4390	1,48	2,55	0,395
474	Underpants 23, undershirt 31 Shirt 70 Insulated jacket 228, insulated trousers 203 Overtrousers 190, overjacket 198 Socks 254, shoes 255, gloves 251, hat 259		3697	1,49	2,48	0,384
475	Underpants 23, undershirt 31 Shirt 70, trousers 91, Jacket 151 Overtrousers 190, overjacket 189 Socks 254, shoes 255, gloves 251, hat 259		4405	1,49	2,15	0,333
476	Underpants 23, undershirt 31 Shirt 70, trousers 91, Jacket 151 Overjacket 188, overtrousers 190 Socks 254, shoes 255, gloves 251, hat 259	**477** 251 259	4405	1,48	2,03	0,315
477	Underpants 23, undershirt 31 Shirt 70, trousers 91, jacket 151 Overjacket 188, overtrousers 190 Socks 254, shoes 255		4223	1,45	1,87	0,290
484	Underpants 23, undershirt 31 Coverall 120 Insulated trousers 204, insulated jacket 229 Socks 254, shoes 255	**480** 204 229	1780	1,35	1,42	0,220
479	Underpants 23, undershirt 31 Shirt 70, trousers 91, jacket 151 Overjacket 198, overtrousers 190 Socks 254, shoes 151	**435** 190 198	3783	1,42	1,86	0,288
478	Underpants 23, undershirt 31 Shirt 70, trousers 91, jacket 151 Overjacket 198, overtrouse 190 Socks 254, shoes 151, hat 259, gloves 251	**479** 251 259	3965	1,45	2,02	0,313
	HEAT PROTECTIVE CLOTHING					
488	Underpants 23, Undershirt 31 Coverall 255 Overtrouse 194, Overjacket 195 Socks 254, Shoes 255	**480** 194 195	2710	1,45	1,48	0,229
489	Underpants 23, Undershirt 31 Coverall 120 Overtrouse 191, overjacket 193 Shoes 255, Socks 254	**480** 191 193	4630	1,50	1,55	0,240
	CHEMICAL PROTECTIVE CLOTHING					
490	Undershirt 47, underpants 48 coverall 120, coverall 121 Socks 254, shoes 255	**481** 121	2640	1,45	1,42	0,220
	RAIN PROTECTIVE CLOTHING					
487	Undershirt 47, underpants 48 Insulated trousers 204, insulated jacket 229 Overtrouse 196, overjacket 197 Socks 254, shoes 255		1830	1,45	1,57	0,243
486	Underpants 23, undershirt 31 Insulated trousers 204, insulated jacket 229 Overjacket 197, overtrouse 196 Socks 254, Shoes 255		1740	1,38	1,51	0,234
485	Underpants 23, undershirt 31 Coverall 120 Overjacket 197, overtrouse 196 Socks 254, shoes 255	**480** 196 197	1960	1,45	1,29	0,022

TABLE 1.

Results of a linear regression between clothing area factor and thermal insulation, between thermal insulation and weight, and between basic thermal insulation and summation of insulation for garments.

Data Source	Regression Equation	Number	R^2 %	Stand. Dev.	f_{cl}-range	I_{cl}-range clo	Weight-range kg
Present study	I_{clu}= 0.48 Weight (kg)	192	81	0.14		0.00-1.32	0.02-2.2
Present study	I_{cli}= 0.59 Weight (kg)	192	83	0.16		0.01-1.41	0.02-2.2
McCullough et al. 1983	I_{cli}= 0.45→1.00 Weight (kg)		80			0.1 -0.63	0.1 -1.3
Present study	f_{cl}= 1 + 0.26 I_{cl}	19	90	0.11	1.19-1.49	0.7 -2.4	
McCullough et al. 1983	f_{cl}= 1 + 0.34 I_{cl}	21	45	0.046	1.15-1.37	0.47-0.96	
Sprague & Munson 1974	f_{cl}= 1 + 0.29 I_{cl}	31		0.039	1.05-1.26	0.21-1.06	
Present study	I_{cl}= 0.57 Weight (kg)	70	94	0.38		0.7 -2.06	0.8 -4.5
McCullough et al. 1983	I_{cl}= 0.19 Weight (kg) + 0.28	21	24			0.47-0.96	1.6 -3.2
Present study	I_{cl}= 1.01 ΣI_{clu}	69	99	0.17		0.7 -2.6	
Present study	I_{cl}= 0.82 ΣI_{cli}	69	99	0.16		0.7 -2.6	
Present study	I_{cl}= 0.85 ΣI_{clu}+ 0.25	69	93	0.14		0.7 -2.6	
Present study	I_{cl}= 0.73 ΣI_{cli}+ 0.17	69	92	0.15		0.7 -2.6	
ASHRAE 55-81*	I_{cl}= 0.82 ΣI_{cli}					0.21-1.00	
Sprague & Munson 1974	I_{cl}= 0.727 ΣI_{cli}+ 0.113 (Men)			0.04		0.48-1.06	
	I_{cl}= 0.770 ΣI_{cli}+ 0.05 (Women)			0.05		0.21-0.97	

*Based on the data from Sprague & Munson 1974

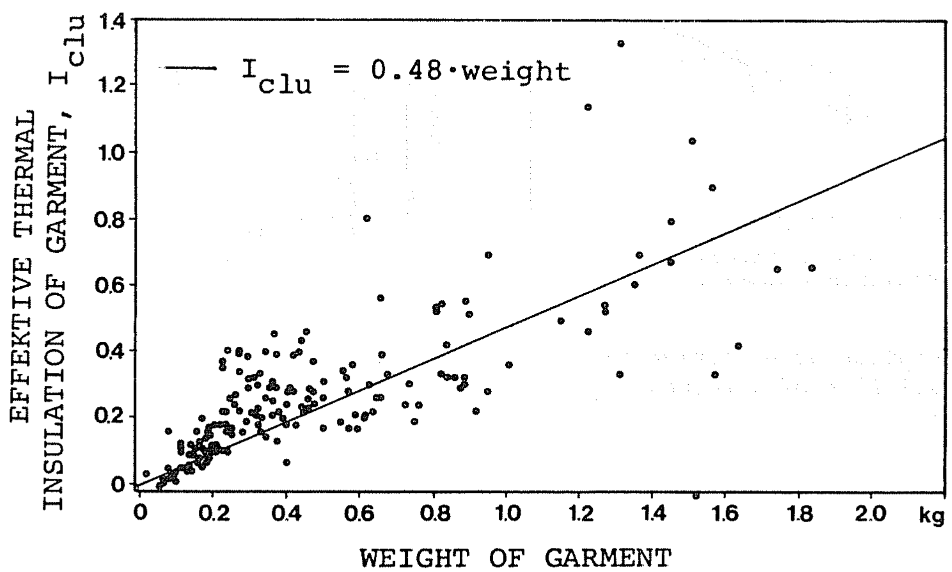


Figure 1. Weight of garment versus effective thermal insulation, I_{clu}

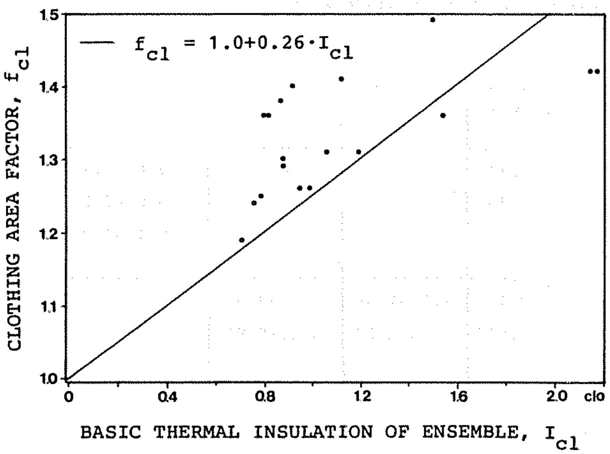


Figure 2. Basic thermal insulation of ensembles, I_{cl}, versus clothing area factor I_{cl}

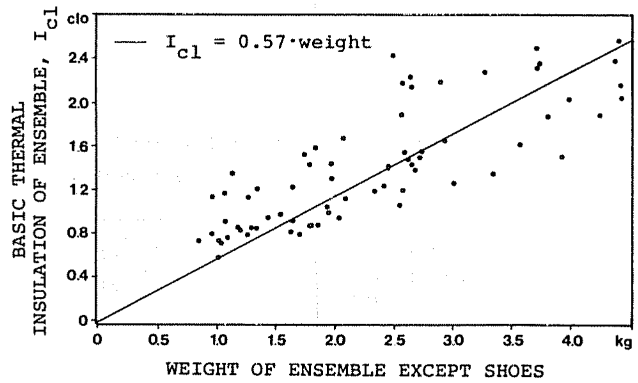


Figure 3. Weight of ensembles except shoes versus basic thermal insulation, I_{cl}

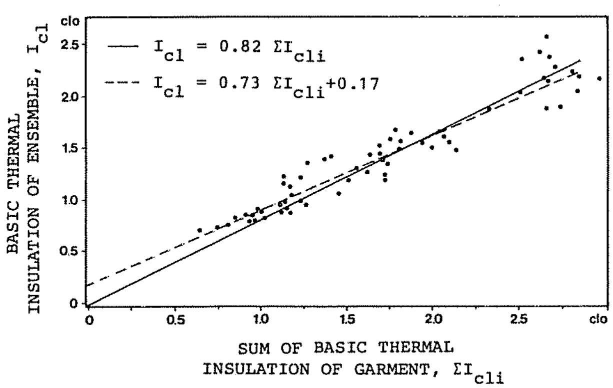


Figure 4. Summation of effective thermal insulation of garments, I_{clu}, versus thermal insulation of ensembles, I_{cl}

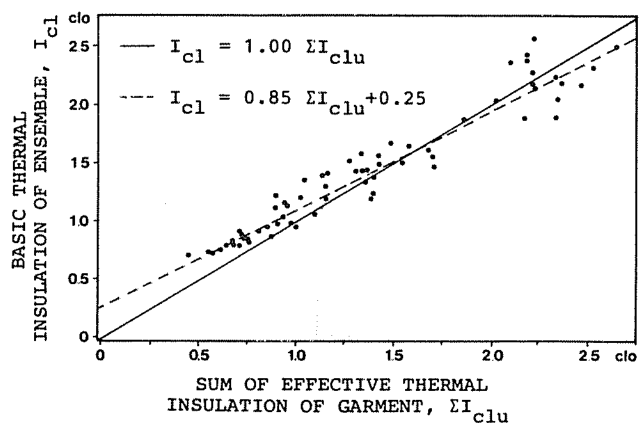


Figure 5. Summation of basic thermal insulation of garments, I_{cli}, versus the basic thermal insulation of ensembles, I_{cl}