To the Graduate Council:

I am submitting herewith a dissertation written by Kay Sanders Grise entitled "Thermal Comfort Characteristics of Textile Apparel Fabrics." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Home Economics.

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Kay Sanders Grise

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DEDICATED TO

MY HUSBAND, LARRY

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ABSTRACT

The purpose of this study was to investigate the properties of selected textile apparel fabrics that are relevant to thermal comfort. The fabrics were commercially-available textile materials that would normally be worn during the winter months by persons while at home with sedentary to moderate activity levels.

Nine fabrics of various fiber content and construction were investigated. Seven of the fabrics represented materials that could be used for an indoor jacket and two fabrics represented materials that could be used for a shirt or blouse.

Fabric physical properties were measured according to standard textile testing procedures. The insulation value of the fabrics was measured using the heat flow and mass transfer apparatus which was designed and fabricated at the USDA Textiles and Clothing Laboratory, Knoxville, Tennessee.

The experiments were conducted with the fabrics in spatial configurations of single fabrics, jacket and shirt fabric touching, jacket and shirt spaced 0.125" apart, jacket and shirt fabric spaced 0.250" apart.

Each test was made at three different combinations of temperature and relative humidity to simulate conditions next to the skin and in the ambient environment. Saturated salt solutions were used to maintain a constant relative humidity.

Results of the study indicate that the layering of the fabrics is the most significant factor in thermal insulation for the fabrics under investigation; insulation increases with an increase in air space. The temperature-relative humidity was also a significant factor in providing insulation.

Fabric thickness was found to be the only statistically significant physical property under the prescribed conditions. A quantitative analysis of fabric surface indicated that the surface hairiness could possibly be a contributing factor to insulation value; the fabrics with the most protruding surface hairs gave the highest insulation values.

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CHAPTER I

INTRODUCTION

Until the energy crisis, there were few restraints on the use of energy for home heating and cooling; energy supplies were plentiful and costs were low. However, the United States is now finding that the supply of energy derived from fossil fuels is not infinite—it is based on unrenewable resources.

Due to the present high cost and limited supply of energy, consumers are changing thermostat settings to save money and conserve energy, either voluntarily or because they cannot afford the cost. The Federal Energy Administration predicts that setting air conditioning thermostats no lower than 78°F could result in reductions of home cooling costs up to 47%. Generally, a reduction in the thermostat setting for heating results in a savings of approximately 3% for each degree; increasing the setting for cooling results in a savings of approximately 5% for each degree (22).

Thermal comfort has been defined by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) standard 55-66 as "that condition of mind which expresses satisfaction with the thermal environment" (23). The variables which influence the condition of thermal comfort have been defined by Fanger as: (1) activity level (heat production), (2) thermal resistance of clothing (clo value), (3) air temperature, (4) mean radiant temperature, (5) relative air velocity, (6) water vapor pressure in the ambient air.

In terms of comfort, the purpose of clothing is to serve as thermal insulation which allows controlled heat loss from the body. Clothing interacts with the air and heat flow in the ambient environment. Heat loss is either impeded or enhanced by the presence of clothing, depending on the thermal properties of the clothing (16, 79).

Heat may be exchanged between man and his environment by four physical modes—conduction, convection, radiation, and liquid-vapor transformations. Heat will be exchanged by conduction between the surface of the body and any material in contact with it which is at a different temperature. If the contacting substance is at a lower temperature than the skin, heat will be lost; if the contacting substance is at a higher temperature, heat will be gained (51).

Clothing has little effect on internal body temperature under ordinary conditions (15). However, when the conditions become unfavorable, clothing interacts with the air and heat flow in the ambient environment.

Historically, this ability of clothing to protect the wearer from heat or cold has been a factor in clothing selection. However, as the use of controlled heating and cooling has become widespread, the importance of this function has decreased. As the indoor climate is changed to less-than-comfortable temperatures in an effort to reduce energy expenditures, clothing again becomes important in maintaining thermal comfort.

Thermal insulation of clothing is comprised of the insulation of the fabrics and that of the layers of air trapped between them and between the inner layer and the skin (47). The effect of clothing on thermal comfort depends mainly on such factors as: physical properties of the fabric, air spaces between the body and the fabric (or between the fabrics themselves), and characteristics of the ambient environment.

Several studies reported in the literature are primarily concerned with the thermal aspect as a component of comfort of clothing. However, many of these studies are investigations under extreme conditions of heat or vigorous exercise rather than conditions of rest or daily routine tasks performed in the home environment. Much work needs to be done to understand how outer clothing and layered systems of clothing affect human comfort under the latter conditions.

The overall purpose of this study was to investigate some selected textile apparel fabrics that would normally be worn by persons while at home with sedentary to moderate activity levels. If there are any differences found in the insulation values of the fabrics, it can be assumed that those fabrics with higher insulation values will make a greater contribution to a person's feelings of thermal comfort when the room temperature is lowered. However, it must be borne in mind that the results will apply only to the fabrics tested and to similar environmental conditions.

The willingness of consumers to purchase clothing that will more efficiently provide thermal comfort will depend on the cost versus the marginal benefits of the clothing in relation to the cost of energy. Something more than a national conservation program is needed to create a change in clothing consumption (64).

Only if consumers can increase the utility of their clothing dollar, and at the same time be comfortable, will they be willing to purchase fabrics which may be expensive comparatively. They must feel they are realizing a savings.

I. OBJECTIVES

The objectives of this investigation were:

1. To determine the thermal insulation of single and double layers of textile apparel fabrics under varying conditions of temperature and relative humidity.

2. To determine the effect of layering on the thermal insulation capacity of the fabrics.

3. To understand the relationship between the physical characteristics of the fabrics and their thermal insulation properties.

4. To develop guidelines for consumers to use when buying clothing for cooler-than-comfortable indoor temperatures.

II. HYPOTHESES

The following hypotheses were tested in this investigation:

1. There will be a significant difference between the insulation values of the fabrics when tested as single layers.

2. There will be a significant difference between the insulation values of the fabrics when tested as double layers as compared to the insulation values of the single fabrics.

3. There will be a significant difference between the insulation values of the fabrics when tested in double layers at three different spatial separations.

4. There will be a significant difference between the insulation values of the fabrics when tested under three different combinations of temperature and relative humidity.

III. ASSUMPTIONS

In conducting this study, the following assumptions have been made:

1. Little information is available concerning thermal comfort under conditions of sedentary activity in the home environment.

2. Separation of more than one-fourth of an inch (0.63 cm) is not applicable to the prescribed conditions of the study.

3. The fabrics selected for the study are typical of what consumers would wear while at home.

4. Based on previous investigations, data collected from all instruments are valid and reproducible.

IV. LIMITATIONS

The following limitations apply to this study:

1. Environmental conditions were limited to three temperature-relative humidity combinations.

2. The spatial configurations were limited to two layers with three separations.

3. The fabrics selected for study were confined to shirt and jacket weights.

4. Time limitations prevented complete replications of all aspects of the study.

V. DEFINITIONS

Several physical characteristics were determined in order to correlate these properties with the insulation values. The definitions of these properties are (1):

Fabric weight is mass per unit area expressed in oz/yd^2 (g/m^2). Fabric count is the number (counted units) of warp yarns (ends) and filling yarns (picks) per inch and the number of wales and courses counted per inch in a knitted fabric. Yarn crimp is the difference in distance between two points in a yarn as it lies in a fabric and the same two points when the yarn has been removed from the fabric and straightened under specified tension, expressed as a percentage of the distance between two points as the yarn lies in the fabric.

Yarn twist is the number of turns about the axis of a yarn per unit of length, expressed in turns per inch. Yarn size is the fineness of the yarn. Cover factor (K) refers to the openness of a weave as determined by the fabric count and yarn count. It is the surface area composed of yarns in the plane of the fabric. Porosity is the ratio of the volume of air or void contained within the boundaries of the material to the total volume expressed as a percentage.

Fabric thickness is the distance between the upper and lower surfaces of the material, measured under a specified pressure. Pressure is the force or load per unit area, measured in pounds per square inch (psi) or kg/cm^2. Air permeability is the rate of air flow through a material under a differential pressure between the two fabric surfaces.

Compressibility is the proportional reduction in thickness of a material under prescribed conditions of increased pressure or compressive loading. Resilience is the degree to which a material recovers from compressive deformation. Hairiness refers to the projecting surface hairs on a fabric.

Moisture regain is the amount of moisture in a material determined under prescribed conditions and expressed as a percentage of the mass of the moisture-free specimen. Moisture content is defined as the amount of moisture in a material determined under prescribed conditions and expressed as a percentage of the mass of the dry specimen plus any moisture present.

The standard atmosphere for testing textiles is air maintained at a relative humidity of 65 ± 2% and a temperature of 70 ± 2°F (21 ± 1°C). The conditioning room is a room having equipment for maintaining the standard atmosphere for testing textiles throughout the room with the standard tolerance, and including facilities for circulating the air over the exposed sample or specimen.

The following definitions refer to measurement of the thermal insulation values of the fabrics:

Thermal insulation of a fabric is its resistance to heat flow. Clo unit is the amount of insulation necessary to maintain comfort for a sitting-resting subject in a normally ventilated room (air movement 20 ft/min or 10 cm/sec) at a temperature of 70°F (21°C) and a humidity less than 50% (30, 50, 59). Resistance (R) is a measure of the resistance to heat flow through the fabrics.

Layered assemblies are comprised of two or more fabrics covering the same area. The fabric spatial separation is the relative arrangement of an outer layer and an inner layer of fabric as indicated by the amount of space between them when mounted on the heat and mass transfer apparatus. Relative humidity is the ratio of the actual pressure of existing water vapor to maximum possible (equilibrium saturation) pressure of water vapor in the atmosphere at the same temperature, expressed as a percentage.

The heat flow and mass transfer tester (HMT) is an instrument designed and fabricated by C. Hassenboehler at the USDA Textiles and Clothing Laboratory in Knoxville. The instrument measures the BTU/hr ft^{2} ^{0}F transmitted through a material when placed over the instrument. A detailed description of the instrument is given in Chapter III. A sample consists of two 20" × 20" (50.8 × 50.8 cm) fabric specimens.

CHAPTER II

REVIEW OF LITERATURE

I. THEORY OF HEAT TRANSFER THROUGH CLOTHING

ASHRAE defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." This psychological determination interacts with a number of physiological conditions which have to be maintained if the human body is to remain in a state of well-being (70). According to Fanger (24), the reason for creating thermal comfort is to satisfy man's desire to feel thermally comfortable, in line with his desire for comfort in other directions. Studies have indicated, also, that a person's intellectual, manual, and perceptual performance is in general highest when he is in thermal comfort.

Fanger identifies six variables which influence the condition of thermal comfort. The four primary variables are: air temperature, mean radiant temperature, relative air velocity, and water vapor pressure in the ambient air. Of secondary importance are activity level (heat production) and thermal resistance of clothing (clo). Thermal comfort can be achieved by many different combinations of these variables.

Under conditions of favorable environmental temperature, the body as a whole is capable of maintaining the constancy of internal temperature even into advanced old age. The naked body will remain in temperature equilibrium with air at 81-83°, while a warmly clad body will remain in equilibrium at 59-60°F (9). Heat tends to be shared over the whole body and, within limits, it is the total heat loss from the body which counts (78).

Addition of clothing substitutes a certain thickness of virtually dead air for the ambient air formerly in contact with it. The rate of heat transfer will depend on the rate at which heat can pass across the space between the skin and the clothing and through the barrier presented by the clothing (51). Textile fibers incorporated in a fabric have two positive functions—they prevent air movement and they provide a shield against radiant heat loss.

Clothing tends to produce even temperature distribution over the covered surfaces of the skin which is not in accord with the great variation of naked skin temperature, nor with the distribution of thermal receptors in "normal" relations with environmental factors (4).

Total thermal resistance of a clothed body to heat transfer from the body to surrounding air was considered to be the sum of three properties:

1. thermal resistance of the textile
2. thermal resistance to heat transfer at the textile surface
3. thermal resistance of the air interlayer (84).

Thermal conductivity of a textile fabric refers to the thermal conductivity of a disperse system consisting of textile fibers and air and not that of a solid substance. Thermal insulation of clothing comprises the insulation of the fabrics and that of the layers of air trapped between them and between the inner layer and the skin (42). The effect of clothing on thermal comfort depends mainly on such factors as: physical properties of the fabric, air spaces between the body and the fabric (or between the fabrics themselves), and characteristics of the ambient environment.

Woodcock (88) has suggested an expression which gives the rate of dry heat loss as a function of ratios of difference between skin temperature and air temperature to the insulative value of clothing:

$$H_d = \frac{T_s - T_a}{I}$$

where: H_d = rate of dry heat loss per unit area

T_s = skin temperature

T_a = ambient temperature

I = insulation in clo units (thermal resistance of clothing plus overlying air layers).

A psychometric range of a particular system has been reported by Mecheels and Umbach (56), and is given by the following expression:

$$T_a = T_{a_{max}} - T_{a_{min}}$$

where: $T_{a_{max}}$ = maximum ambient temperature at which the body/clothing regulatory system will keep the core temperature constant under not-quite-comfortable but bearable conditions

$T_{a_{min}}$ = minimum ambient temperature at which a person with a defined minimum heat production will not yet feel cold.

The insulative measure of clothing is expressed by a term called "clo." The clo value is defined as the amount of insulation necessary to maintain comfort in a normally ventilated room with air movements less than 10 ft/min, at a temperature of 70°F (21°C) and a relative humidity less than 50% while the subject is resting in a sitting position (50, 59).

The clos needed for any given temperature can be computed by using the following relationship: (59)

$$I = \frac{3.1(T_s - T_a)}{3/4\ M}$$

where: T_s = average temperature of skin (33°C or 91.4°F)

T_a = temperature of air

M = metabolism (50 kcal/m^2/hr, resting)

I = insulation in clo units.

The upper limit for convenient and comfortable indoor clothing appears to be 3 clo. Although it is not convenient to wear clothing that has a maximum clo of 4 to 5, when fuel is very scarce, the most economical arrangement would be to add more clothing (59).

A clothing system possesses the greatest heat insulation as it is worn when the wind is still and there is not any body movement—that is, when sitting or standing still (56); about 25% of the total heat loss from the body under ordinary resting conditions is from insensible perspiration, which is produced continuously even when the body is quite inactive (15, 68). The rest of the heat loss is from the surface of the clothing.

Morris (60) has surveyed the literature from 1930-1950 and reported the available physical data on the thermal properties of textiles. Since that time, other studies have been conducted to measure the relationship between clothing and thermal comfort; both tactile and insulation properties have been found to be important.

II. MOISTURE

In addition to heat transfer, water-absorbing properties play an important role in comfort and warmth. The absorption or release of water from the material plays an important role in the adjustment of body temperature to variations in temperature and humidity of the surrounding atmosphere (24). One of the ways the body loses heat to its surroundings is by the evaporation of water from the skin and lungs. Even when the body is quite inactive, it is continuously producing insensible perspiration which accounts for about 25% of total heat loss from the body under ordinary resting conditions, 16% of which is from the skin (68).

For undergarments, a structure of low density is desirable. Traditional materials such as wool and cotton are capable of absorbing large amounts of water. Both fibers satisfy the basic requirements for comfort as does viscose rayon (83).

Mecheels (55) expressed the mechanisms of moisture transfer through clothing as being:

1. penetration of the air spaces between the fibers according to the laws of diffusion (determined by porosity and thickness);

2. absorption by the fiber material, transfer within fibers and desorption to the outside (natural fibers);

3. transfer of liquid water through capillary interstices of the yarns (influenced by dimensions of capillaries which can be influenced

by spinning and weaving or knitting) and by wettability of fiber surfaces (influenced by finishing processes) (synthetic fibers);

4. migration of water on fiber surfaces.

Transfer of moisture through clothing assemblies can be expressed in terms of the resistance of individual layers and between the outer surfaces in the surrounding temperatures (79, 83). The values of the resistance to water vapor transfer between the outer surface of the clothing assembly and the atmosphere vary with wind velocity in very much the same way as the resistance to heat transfer by conduction and convection. In still air, the value of the resistance to water vapor transfer between the outer surface of the clothing and the atmosphere is reduced due to convection.

Moisture transfer properties of the clothing represent the variable factor of its influence on the temperature regulation range of the body-clothing-climate system. The thermal insulation of certain clothing is approximately constant.

If the clothing becomes wet, the insulating ability of the fabric may be lowered. Water is held either within the fiber or its surface and contributes to the overall conductance as a group of conducting elements in parallel with the fibers already present (10).

Studies by previous investigators (10, 12) have shown that the thermal conductivity of fabrics increases linearly with an increase in regain until it approximates the thermal conductivity of water at about 110% regain.

The specific thermal conductivity of many types of fabrics containing moisture can be calculated quantitatively from the expression: (11)

$$k_3 = (1-v_w)k+v_wk_w$$

where: k_3 = specific conductivity of fiber-air-water mixture

v_w = volume fraction of water

k = specific conductivity of the dry air

k_w = effective specific conductivity of water = 1.98 cal.in/m^2secC^o

Mecheels et al. (56) gives the expression as:

$$H = H_d + H_e$$

where: H = total heat flow

H_d = "dry" heat flow, controlled by the thermal insulation of the clothing

H_e = thermal heat flow caused by the evaporation of water

and
$$H_e = H_d + H_l + \Delta H_m$$

where: H_l = heat of evaporation of water penetrating clothing

ΔH_m = change in heat flow due to wetting of clothing.

When considering the relationship between moisture and thermal insulation, the fabric must allow moisture to be removed from the skin. As the same time, it must have a slow rate of passage to the outside environment to avoid cooling. A low resistance to the passage of water vapor is required so that the perspiration produced by the skin when not sweating will not accumulate and condense under the clothing. The fabric must also have a high water-holding capacity so that when sweating does occur, the liquid water does not remain on the skin surface (48). The drying rate of fabrics cannot be used as a factor but total water uptake is important.

A major determinant of the moisture absorption by a textile fabric is the relative humidity of the ambient environment and the air next to the skin. When a man at rest or engaged in light activity is physiologically comfortable, the RH at skin level is about 35%, while the RH of the ambient environment is about 50% to 60% because of a lower ambient temperature (70). This comfortable state can only be maintained if the clothing is adequately permeable to water vapor. If water vapor cannot escape sufficiently quickly through the clothing, the RH of skin level will increase.

The following expression of water vapor resistance shows that it is a function of thermal resistance:

$$W = (f)R$$

where: W = resistance to water vapor

R = thermal resistance.

The rate of evaporation of moisture from a surface is determined not by the difference in RH between the surface and the ambient air but by the difference in water vapor pressure between them. Hygroscopic textile materials develop an equilibrium water vapor pressure which depends upon their regain and temperature and in steady state conditions, they reach an equilibrium regain which is determined by the temperature and water vapor pressure. When the material is brought in contact with air containing water vapor at high vapor pressure, water is absorbed by the clothing material and the latent heat liberated by the absorbed water raises the temperature of the material and the surrounding air until equilibrium is reached between the temperature and water vapor pressure of the air and regain of the material (80).

The immediate effect of an increase in water vapor pressure is a rise in the temperature of the clothing coupled with a gradual increase in its regain until equilibrium is reached between the temperature and water vapor pressure of the air and regain of the material (79).

Gagge, Nishi, and Nevins (32) at ASHRAE found that temperature rather than high humidity affects significantly the clothing required for comfort. Only about 0.1 clo was needed to be added to clothing when ambient environment RH changed from 20-40% to 50%. Sørensen and Høg (77) found that for a given garment ensemble, the moisture retain and temperature changes are primarily dependent on the temperature of the surrounding atmosphere and the physical activity of the person.

III. AIR PERMEABILITY

Air permeability refers to the ability of air to pass through the material. ASTM defines air permeability as "the rate of air flow through a material under a differential pressure between the two fabric surfaces" (1).

The air permeability of apparel fabrics influences the comfort of clothing by controlling convective heat loss and moisture evaporation. The number, depth, and size of fabric pores determine the air permeability of a textile fabric; these three determinants are governed by the characteristics of the individual components of the fabric.

Two primary methods of measuring the air permeability of textile fabrics were developed during early research, the Gurley Denseometer and the Frazier Air Permeometer (41). The Gurley method allows air permeability values to be obtained by noting the number of seconds required for a determined volume of air to pass through the fabric which is placed over an orifice of 0.1 or 1.0 square inch diameter. In contrast, the Frazier machine determines the volume of air which passes through a certain area of the fabric per unit of time.

Air permeability of a fabric is related to but not necessarily predicted by its porosity. Porosity is defined as the total volume of void space contained within its boundaries (13). Scheidigger (74) relates permeability to the "pore structure" indicating that the permeability of a material is influenced by the capillary pressure curves and the internal surface of the pores within the material, rather than the volume of the open space.

The number, depth, and size of fabric pores determine the air permeability of a textile fabric. These determinants are governed by the characteristics of the individual components of the fabric. The interrelated factors which ultimately affect air permeability of the textile fabric include fabric structure, fiber fineness, yarn size, yarn twist, yarn crimp, yarn count, and fabric finish.

Dhingra and Postle (21) found that the basic fabric structure is the major factor influencing air permeability. A direct correlation was found between air permeability and mechanical extension. Woven structures are least extensible and least permeable to air; double-knit fabrics are the most extensible and tend to have the highest values of air permeability. Synthetic warp knits were found to be intermediate in both extensibility and air permeability. As a fabric becomes more extensible, it allows the structure to become more open, thus increasing porosity and air permeability.

Hollies and Hall (42) found that knits tend to have a lower cover factor than their woven counterparts. However, for wovens, plain weaves are less permeable than other types, while weaves having long floats are more permeable. Sateens are the most permeable, followed in order by herringbone twill, oxford, and plain (5).

Air permeability was found to vary with number of picks/inch and filling yarn size (17). The yarn count largely determines the degree of closure of a fabric.

The cover factor, K, is determined as the "ratio of fabric surface covered to the whole surface." The cover factor is reduced when yarn twist is increased because the fiber bundles are compacted (17, 44).

As yarn crimp increases, as in highly textured yarns, the extensibility of the yarn increases, permitting the fabric to open, thus increasing air permeability in much the same way that the extensibility of knitted structure allows greater air flow through the fabric.

Fabric finishing may also affect air permeability, either by reducing extensibility of the yarns, by coating the fabric (resulting in increased closure of pores), or by flattening the yarns (as in calendering), which also results in increased closure (6).

Resistance to air flow increases in proportion to the number of fabric layers (26, 33, 52, 67). In a study of wind penetration in clothing systems, Fonseca and Breckenridge (26) found that two moderately permeable fabrics with a space between could provide protection from wind penetration equal to or greater than a single windbreak of low permeability. Air which penetrates the outer clothing layer does not necessarily penetrate the underlying fabric because the layer of air between the fabric provides resistance to air flow.

Lord (52) found that spacing between the fabric layers had no effect on the assembly's resistance to air passage. He did, however, find that the resistance to air flow of multiple layers of fabrics were generally additive, except for closely woven fabrics, in which the resistance to air flow of several superimposed layers was greater than the sum of individual resistances.

Goodings (33) found a synergistic effect with increasing layers of closely constructed fabrics. "Air" passing through one layer will very likely have its kinetic energy destroyed on striking the face of the next layer.

IV. COMPRESSION AND RESILIENCE

Goswami (35) defines compressibility as the proportional reduction in thickness of a material under prescribed conditions of increased pressure or compressive loading. Resilience is the degree to which a material recovers from compressive deformation.

The efficiency of a fabric as a thermal insulator during wear depends upon its resistance to compression and its resilience. If these are high, the still air is retained and the fabric continues to provide good thermal insulation (35, 46, 60).

As the yarn structure flattens when being compressed, changes occur in the size and shape of the interstices, in the fiber orientation at the yarn surface, and in the area of contact between fabric and skin. Changes can occur in values for thermal insulation, cool or warm feel, and other important comfort parameters—possibly quite different from values for apparel fabrics in an uncompressed condition (35, 45, 60).

When a loose, fibrous material is compressed, its thermal conductivity falls, passes through a minimum, and then rises. The falling phase is explained as due to the gradual suppression of convection in the air within the sample. The rising phase is explained by the fact that the fibers are better conductors than air. The squeezing out of the air raises the conductivity, once the mechanism of convection is suppressed.

Several attempts have been made to deal with compression and recovery, especially at high and low pressures. Bogaty et al. (6) examined the compressibility of a wide variety of wool blends using the expression:

$$b = (p + c)(t - a)$$

where: b = equivalent to an energy or work (compressibility energy)

p = pressure

c = force of attraction between fibers and between yarns which holds them together

t = measured thickness

a = thickness at high pressure

a, b, c are constants.

Kaswell, Barrish, and Lermond (46) gave the following expression for compressibility:

$$\% \text{ Compression} = \frac{\text{thickness at 0.1 psi} - \text{thickness at 1.0 psi}}{\text{thickness at 0.1 psi}} \times 100$$

Resilience was expressed by Bogaty et al. (12), in a study to assess the relative suitability of blended serges for cold weather use, as:

$$\% \text{ resilience} = \frac{z - y}{x - y} \times 100$$

where: x = original fabric thickness

y = compressed thickness

z = recovered thickness.

Spinning twist is an important factor in compression and resilience (27, 62). In addition, yarn structure can determine the compression and resilience (35). The twisted filament yarn can withstand more compression without flattening than with stretch or untwisted filament yarns. Lack of fiber entanglement in stretch textured filament yarns prohibits maintenance of bulkiness.

Depending on the fiber content of the yarn, blending may or may not affect the thermal properties of a yarn. Fourt and Hollies (28) found that very little synthetic fiber is required to produce thin lean yarns when used in a wool shirting structure. The fabrics were not nearly as warm as those made from 100% wool.

Results of another study (12) using acrylics (Dynel, Acrilon, and Orlon) blended with wool showed that with increase in synthetic content the yarn number had to be increased to maintain the yarn diameter and "cover" constant.

V. SURFACE CONTENT

Thermal character and skin contact sensations are related to thermal comfort. Surface hairiness of the yarns and fabrics themselves have a profound effect on the comfort factors of insulation and loss of body moisture. Surface fibers contribute substantially to fabric thickness, and therefore, to changes in insulation. Also, projecting surface fibers separate the fabric from moist skin to keep it from clinging in next-to-skin garments and causing feelings of discomfort (35).

Surface contact is important in providing a feeling of thermal comfort. A yarn that makes actual contact with the skin provides the "warm" or "cold" feel on the skin (35).

The warmth of a fabric surface is not the same as the "cold feel." "Cold feel" is that property which is assessed by the initial reaction of an observer on making contact with the fabric (60). The rougher and fuzzier a cloth is, the warmer it feels; and the smoother it is, the colder it feels (19, 37).

Texture, softness, thickness, and bulkiness provide a contact with the skin that generates a warm feeling (10, 35, 49, 81). Generally, synthetic filament yarns lack these properties, while staple yarns of natural or synthetic fibers are inherently warmer (10, 35, 46, 49, 69). Staple yarns give a fuzzy surface which, on contact with the skin, makes the fabric feel warm. In addition, they provide an insulating air space. Filament yarns produce smooth fabrics which produce a cool sensation.

Rees (69) measured the "cold feel" (or chilling effect) by observing the drop in temperature when certain fabrics were applied over a hot plate apparatus. He found that wool and cotton blankets had no chilling effect. The greatest "cold feel" was produced by a blend of acetate and silk. Silk, bleached cotton, and linen produced less of a "cold feel."

In a test conducted by Andreen, Gibson, and Wetmore (2), surface texture was found to contribute to subjective comfort of clothing. Five commercial shirting materials were evaluated with the result that the fuzzy textures were much warmer than smooth textures.

VI. YARN STRUCTURE

Yarn structure affects many of the tactile aesthetics of fabrics. Fabrics composed of yarns with high twist levels have higher bending stiffness, less compressibility, less fiber mobility, lower surface friction, less bulkiness, and less potential contact with the skin than yarns with less twist (35). There is less surface friction and potential surface contact because of less yarn flattening under low levels of compressive loading. Increased twist reduces softness, covering power, bulkiness, and hairiness.

Increased twist also shortens the length within the yarn and makes each yarn more nearly a monofilament of large radius than an assembly of parallel individual filaments of small radius (29). The hand and skin are very sensitive to these effects, which are basic to the skin contact aspects of comfort.

The extent to which yarns are deformed as they yield to the stresses from bending and compressing has a major effect on fabric properties such as coverage, permeability, and hand (75). Deformation of yarn cross section under lateral pressure can be considered a measure of softness (percent of increase in yarn width when a 4mm length of yarn is pressed laterally between two parallel plane surfaces under an applied force of 3.1 lbs.).

Softness may be dependent upon such parameters as fiber fineness, twist multiplier, number of plies, and yarn number. Skau, Honold, and Boudreau (75) used a group of 31/2 cotton yarns to show the effect of single and ply twist multipliers on deformability or softness. The softness-twist multiplier pattern was compared with the pattern relating skein breaking strength and twist multiplier in order to illustrate a means of choosing an optimum yarn construction for a specific purpose.

Softness became less as the twist multiplier in ply yarns increased. With low twist and under lateral pressure, the yarns increase considerably in width because the fibers are free to move sideways and perpendicularly to pressure. As twist is inserted in the yarn, the movement of fibers is more restricted when pressure is applied.

The softest yarns should give more coverage than the hardest yarns in similarly constructed fabrics. Both yarn softness and original yarn diameter must be considered in predicting the possible coverage to be expected in the woven fabric. If a hard and soft yarn are both woven into a similar fabric of a given thread count, considerably more coverage should be expected from the softer yarn, especially in view of its greater original diameter, than in the fabric from the harder yarn of smaller diameter (35, 75).

Thermal insulation of fabrics has been found to be proportional to the thickness of the fabrics (10, 23, 24, 49, 61, 69, 70, 81). The heat loss through a fabric is greater than through an equal thickness of air, conduction through the fibers being a contributing factor (69). Fabrics of low density have a smaller heat loss and fabrics of high density have a greater heat loss than the average. With the dense fabrics, the heat loss by conduction through the fibers will make a greater contribution to the total heat loss (69, 70).

Texture, softness, and bulkiness in a fabric are achieved by three basic yarn structural features: (a) low degree of fiber orientation with respect to the yarn axis, (b) a great amount of fiber protrusion from the yarn surface, and (c) low fiber packing density in the yarn structure (35).

The arrangement of fibers in the yarn can affect a number of fabric properties—hand, coolness to touch, and so forth (11, 28, 49). In 1930, an experiment by Finck demonstrated in a series of experiments with flax, glass wool, hair felt, and others, that when the fibers are arranged parallel to the direction of heat flow, the conductivity was 2-3 times greater than when fibers were arranged perpendicular to the direction of heat flow. In a perpendicular arrangement, there is a layer of air between each fiber that restricts heat transfer (11).

Detailed thermal resistance measurements of acrylic/wool blends revealed that fiber arrangements, rather than fiber type, affected thickness, thermal resistance, and surface hairiness (28).

Closely packed yarns, as in continuous filament yarns, are close-packed and the yarn surface is all that is available to hold air (44). More loosely packed yarns, as in wool (which has a unique resistance to packing) have a greater area of fiber surface available to hold air. The most densely packed form of wool is 69% air/49% wool. Many cotton yarns are 80% cotton/20% air.

Thermal character and skin contact sensations are improved when yarn bulk and the randomness of fiber positions are increased. Fabric constructions providing maximum cover for winter wear, and maximum permeability for summer wear, reduce the undesirable thermal sensations associated with synthetics (49).

Bulking and texturing of yarns of man-made fibers usually produce a gain in softness and fabric covering power (28). Bulking acrylic fiber yarns was found to increase the thickness index by about 70% (76). Increased thickness in this case provided air spaces between the fibers allowing for better insulation.

Textured filament yarns provide a great amount of bulk and covering power due to a high degree of fiber linearity and, at the same time, low fiber packing density. The yarns are soft and compressible. On the other hand, untextured filament yarns have high fiber linearity and high packing density, thus a smooth yarn (35).

In general, products made of textured yarns can be said to feature: (66)

(a) greater bulk, thus entrapping greater amounts of air

(b) higher thermal insulating power

(c) higher covering power.

Kaswell, Barish, and Lermond (46) found that the undesirable comfort characteristics of filament fiber woven fabrics could be changed by modifying the filament yarns by crimping, curling, or otherwise disrupting their uniformity and parallelism in order to produce a randomness approaching that of a staple yarn. The result was bulked-filament yarns with properties similar to staple yarns. The bulked yarns provided small points of contact with the skin. In the use of staple yarns, the most effective randomizing effects can be achieved by twist variations, by bulking, and in the case of wool blends, by fulling after blending (28).

Surface hairiness of the yarns and fabrics themselves have a profound effect on the comfort factors of insulation and loss of body moisture. Surface fibers contribute substantially to fabric thickness, and therefore, to changes in insulation. Also, projecting surface hairs separate the fabric from moist skin to keep it from clinging to next-to-skin garments and causing feelings of discomfort (16, 39).

There are three classifications of yarn hairiness: (6, 60)

(a) fiber ends project from yarn core

(b) fibers form loops where they pass through the outer layers of the yarn

(c) wild fibers have one or both ends lightly attached to yarn core.

Yarn hairiness is inversely related to yarn twist (6, 7, 8, 10, 34, 65). Experiments conducted by Barella (6) indicate that with cotton yarns of the same count, hairiness diminishes with increase of twist. An increase of twist from 650 t/m to 1400 t/m was significant at $\alpha = .01$. An increase of 800 t/m to 1400 t/m was significant at $\alpha = .05$.

According to Pillay (65), the number of loops in cotton yarns shows a steady decrease with increase in twist but the number of protruding fiber ends does not show any systematic change, only the length changes. This can be explained due to higher migration of fibers in the yarn which takes up the longer lengths of the fibers in the body of the yarn (34).

The decrease in yarn hairiness due to increasing twist can be explained by assuming the twist in the yarn will run close to the nip of the front rollers, resulting in an improved control over emerging fibers. Thus, longer lengths of fibers will have a greater chance of being bound up into the body of the yarn and shorter lengths will protrude (35).

Experiments by Morton and Yen related fiber migration and hairiness (6). Their experiments were carried out with a worsted yarn count of 23 tex with an initial twist of 550 t/m. The projecting fibers were counted after successive increments of additional twist of 100 t/m.

The results were in concurrence with Pillay (65) in that the loops projecting from the surface decreased more than did the fiber ends or wild fibers and that the total number of projecting fibers did decrease.

VII. LAYERING OF FABRICS

Layered assemblies of garments trap thin layers of air which increase the thermal insulating properties of the fabrics. This increase may be greater than the sum of the values for single materials. Enough air can possibly be enclosed between the layers to cause a significant increase in thermal insulation without causing a measurable change in thickness (61).

Welfers (87) found that a visible drop in heat transmission was observed with increasing number of layers. The amount of liquid transmitted and wind velocity also decreased.

Linear regression lines, representing the relationship between thermal insulation and other properties, give lower estimated values for the single fabrics than do those for multiple layers. The volume of air per unit area was found by Morris (61) to be more closely associated with variations in thermal insulation than with porosity or density.

VIII. TESTING AND INSTRUMENTATION

For many years, various techniques and instruments have been utilized for measuring thermophysical properties of textiles. Early experiments were done by three basic methods: (9)

1. Methods depending on the rate of cooling or on the cooling power of a source of heat clothed with the fabric.

2. Methods in which the sample of fabric rests on a heated plate. The transmission of heat through the fabric to air is measured by the amount of electrical energy supplied, as heat, to the plate.

3. Methods in which the sample is placed between a heating and cooling element. The transmission of heat is determined by the electrical energy supplied to the heating element.

Method No. 1 compares the thermal resistance and cooling powers of the fabrics. Methods Nos. 2 and 3 measure cloth conductivity. Many experiments have been adaptations of these methods. One of the earliest was by Krieger (9) who measured the time it took a water-filled cast iron cylinder to fall in temperature from 60° to 10°C after it was covered with fabric.

"Sweating" copper manikins have been used extensively (23, 83) to determine the heat transfer properties of fabrics. The clothing insulation value or resistance (clo) and evaporative heat transfer from the skin are measured and related to the overall protection the garments can afford.

In an experiment at ASHRAE, a heated manikin in thermal equilibrium with surroundings was used to measure thermal insulation values for typical indoor clothing assemblies (71). Welfers (87) measured the heating power for evaporation by use of a copper cylinder covered with the test fabric. A copper cylinder was first covered with a fabric impregnated with water, then a test fabric was placed over it.

The guarded hot plate is a standard instrument for measuring the relative thermal resistance of textiles as heat flows from a heated plate in contact with the textile and dissipates into still air at a lower ambient temperature via radiation, conduction, and convection (84).

Latham (48) measured thermal insulation by use of a hot plate apparatus. Total heat loss was measured by the rise in temperature caused by a fabric placed over the hot plate. Other investigators (36, 61, 79) have found the hot plate method to be successful in determining heat flow through fabrics.

Two experimental arrangements were used by David (20) to measure the insulative value of wool fabrics during the process of sorption or desorption by the fabric. An aluminum plate, insulated by polyurethane foam, is heated electrically from below. A heat flow meter is attached to measure the temperature difference across a fabric placed over it.

An aluminum tube 4" in diameter by 6" long is clothed with the fabric. The cylinder is heated and the energy output required to heat is recorded. The fabric sample is weighed and then transferred to a high humidity compartment. Recording of the data starts when the measuring device is transferred from the low humidity to the high humidity. When steady state is again reached, the fabric is again weighed. Heat flow through the fabric and temperature difference across it is obtained.

Welfers (87) employed a climatic test cabinet designed by Hoechst to measure moisture transmission through the textile and the temperature variation of the textile. Both sides of the textile were subjected to different climates.

Clulow and Rees (18) developed a new thermal transmission apparatus that works on the principle that for conductors in series with respect to direction of heat flow, the ratio of the temperature drop across them equals the ratio of their thermal resistances, and the only measurements involved are those of temperature in the equilibrium state. The instrument can measure thermal transmission properties of textile materials up to at least one inch thick.

A rather innovative method for measuring dry heat loss from a person in thermal comfort in the given surroundings and wearing the clothing as adjusted on the instrument is the Comfy Test EQ-21 (54). This instrument, developed at the Thermal Insulation Laboratory of Technical University of Denmark, monitors ambient environmental conditions and predicts the percentage of people who would be uncomfortable in the given conditions.

CHAPTER III

PROCEDURE

This investigation has attempted to quantify the thermal insulating characteristics of selected textile apparel fabrics and to determine any significant differences between them. In addition, a correlation between physical properties of the fabrics and the thermal insulation values was made to identify fabric characteristics that contribute to thermal comfort in cooler-than-comfortable conditions.

I. MATERIALS

Nine fabrics of various fiber content and construction were chosen for the study after a local market search was conducted to determine the types of fabrics being used in ready-to-wear garments. Seven fabrics were chosen to represent the type of materials that would be used for an indoor jacket or blazer and two fabrics represented materials used for a shirt. A description of the fabrics is given in Table 1.

Fabrics were purchased at Jackie's Fabrics in Knoxville, Tennessee. Prior to testing, they were conditioned at 65 ± 2% relative humidity and 70 ± 2°F (21°C) according to ASTM D1776-64 (1). Ten percent (10%) of the fabric was trimmed from each selvage edge.

II. FABRIC

Physical characteristics of weight, thread count, yarn size, yarn twist, percent yarn crimp, cover factor, thickness, air permeability,

TABLE 1

DESCRIPTION OF FABRICS

Fabric	Fiber Content	Fabric Structure	Yarn Structure	Fabric Yarn Count Yarns/Inch
A	100% wool	2 × 2 right hand twill	S, single staple	w 38 f 34
B	100% wool	1 × 1 plain weave	S, 2-ply staple	w 60 f 55
C	70% wool 30% nylon	2 × 1 right hand twill	S, single staple	w 37 f 26
D	50% wool 50% polyester	1 × 1 plain weave	Z, single staple	w 28 f 26
E	wool blend	1 × 1 plain weave	S, single staple, filament	w 48 f 40
F	100% cotton	3 × 1 left hand	Z, single staple	w 66 f 44
G	100% polyester	double knit	Z, single filament	c 34
X	65% polyester 35% cotton	1 × 1 plain weave	Z, single staple, filament	w 85 f 61
Y	100% Qiana nylon	warp knit	Z, single filament	w 46

percent compression, percent resilience, percent porosity, and percent moisture regain were measured using standard textile testing procedures according to the American Society for Testing and Materials (1). The physical properties of the fabrics are given in Table 2.

Fabric weight was determined according to ASTM D1910-64 using a Mettler balance. The weights of five randomly selected 2" × 2" (5.08cm × 5.08 cm) specimens from each fabric were recorded. The mean weight was converted to oz/yd^2 by the following formula:

$$\text{wt oz/yd}^2 = \frac{\text{weight of specimen,g} \times 45.72}{\text{length of specimen,in} \times \text{width of specimen,in}}$$

Ounces per square yard were converted to g/m^2 by the following formula:

$$\text{g/m}^2 = \text{oz/yd}^2 \times 33.906$$

Thread count, which partially determines cover, was determined according to ASTM D1910-64. Five specimens were randomly taken across the width of the fabric. The ends and picks per inch were counted using a pick glass and the mean count was recorded for each direction.

Fabric thickness, which contributes significantly to thermal insulation, was measured according to ASTM D1777-64 using the Electric Low Pressure Thickness Tester by Custom Scientific Instruments, Inc. Measurements were made to the nearest 0.001 inch five seconds after the load was applied. The pressure applied was a weight of 4.387g and a pressure foot of 1.16 cm (7/16") diameter. The mean thickness was recorded from ten randomly selected specimens for each fabric.

TABLE 2

PHYSICAL PROPERTIES OF FABRICS

Fabric	Yarn Size (g/9000m)	Yarn Twist (tpi)	Yarn Crimp (%)	Weight (oz/yd^2)	Weight (g/m^2)	Thickness 0.001"	Thickness cm	Compression (%)	Resilience (%)	Cover (%)	Permeability (ft^3/min/ft^2)	Moisture Regain (%)	Porosity (%)
A	w 698.03 f 315.354	w 8 f 9	w 7.9 f 9.4	7.85	266.162	0.063	0.160	33.57	83.3	22	105	11.3	87.3
B	w 379.134 f 467.72	w 12 f 11	w 7.1 f 5.5	6.26	212.252	0.023	0.0584	27.27	30.3	32	126	10.9	72.3
C	w 747.638 f 853.937	w 7 f 6	w 5 f 14.2	7.78	263.789	0.045	0.1143	25.00	38.9	24	80	7.7	81.7
D	w 861.024 f 1006.299	w 6 f 6	w 4.9 f 5.9	7.69	260.737	0.042	0.167	26.67	83.3	22	195	6.5	81.7
E	w 761.811 f 616.535	w 8 f 8	w 3.5 w 9.4	8.38	284.132	0.030	0.0762	6.98	57.1	32	90	4.2	70.6
F	w 733.465 f 917.716	w 8 f 7	w 11.0 f 7.9	13.60	461.122	0.039	0.099	28.72	53.8	42	< 1	6.3	70.2
G	162.992	12	60.2	8.51	288.540	0.043	0.1092	14.9	42.8	12	155	0.5	80.9
X	w 127.559 f 138.189	w 12 f 12	w 4.3 f 7.1	3.20	108.499	0.013	0.033	30.77	40.0	23	265	2.9	77.3
Y	70.866	9	98.3	4.00	135.624	0.019	0.483	13.95	20.0	10	375	3.2	75.5

Air permeability, which influences clothing comfort by controlling convective heat loss and moisture evaporation, was determined according to ASTM D737-75 (1) using the Gurley Permeometer. The Gurley Permeometer measures air flow from less than one to about 350 cubic feet of air per minute per square foot at a pressure drop equal to 0.5 inches of water.

Six specimens were selected randomly from each fabric and the mean rate of air flow was recorded in $ft^3/ft^2 \cdot min$ and converted to $cm^3/cm^2 \cdot s$ by the formula:

$$cm^3/cm^2 \cdot s = ft^3/ft^2 \cdot min \times 0.508.$$

The percentage porosity, which is related to permeability, was determined using the measured weight and thickness of the fabric from the following formula:

$$P_y = 100(1 - d_a/d_f)$$

where: P_y = % porosity of fabric

d_a = specific gravity of fabric, taken as the ratio of fabric weight (g/cm^2) to the thickness (cm)

d_f = specific gravity of the fabric.

The cover factor (K), which determines the amount of surface area covered by the fabric, was calculated using the number of threads in the warp and fill as determined in the thread count. The following formulae were used:

$$K_w = \frac{N_w}{\sqrt{CC_w}} \qquad K_f = \frac{N_f}{\sqrt{CC_f}} \qquad K_{fabric} = K_w + K_f$$

where: N = number of threads, warp (w) or fill (f)

CC = cotton count, warp or fill.

Cotton count was determined from denier using ASTM D2260. The theoretical value for total cover in which yarns are just touching is 28. Values higher than 28 may occur as yarns become flattened and fill in spaces.

Compression and resilience can reduce insulation value if the fabric can be easily compressed and does not recover from the deformation. The still air layer is destroyed, leaving only the fabric surface area which conducts heat. Expressed as a percentage, compression and resilience were calculated using the Custom Scientific Compressometer to measure thickness at each 0.1 lb/in^2 (psi) in a stepwise loading and unloading procedure at 10 second intervals. Readings were made until the maximum pressure was applied. The percent compression and resilience were determined according to the formulae:

$$\%\ \text{compression} = \frac{\text{thickness at 0.1 psi} - \text{thickness at 1.0 psi}}{\text{thickness at 0.1 psi}} \times 100 \quad (46)$$

$$\%\ \text{resilience} = \frac{z - y}{x - y} \times 100 \quad (12)$$

where: x = original fabric thickness

y = compressed fabric thickness

z = recovered fabric thickness.

The amount of twist in the yarns influences the amount of surface contact. High twist reduces softness, covering power, and hairiness.

Yarn twist, expressed in turns per inch (tpi) was measured using the Suter Twist Tester according to ASTM D1423-71 with a yarn tension of 0.25 ± 0.05 gf/tex. The mean of ten 3" specimens per fabric was recorded for warp and fill. Yarn crimp was determined according to ASTM D1910 using the Shirley Crimp Tester. The percentage crimp in warp and fill was calculated from the mean value for ten specimens using the following formula:

$$\%\ \text{crimp} = [(D_2 - D_1)] \times 100\ /D_1 \qquad (1)$$

where: D_1 = distance in inches (cm) between marks on the fabric

D_2 = distance in inches (cm) between marks on straightened yarn.

Yarn size, which partially determines cover, was determined in the warp and fill direction. Ten yarns 24.5 cm long were removed from each direction and weighed on a Mettler balance. The average weight was recorded. The crimp was removed by the Shirley Crimp Tester before weighing. Linear density was determined using the following formula:

$$\text{Linear density} = \frac{\text{wt,g} \times 9000}{.254} \qquad (1)$$

ASTM D2260-64 was used to determine tex and cotton count.

The amount of moisture regain (MR) determines how the body adjusts to variations in temperature and relative humidity of the ambient environment. Moisture absorbed into the clothing can reduce the relative humidity next to the skin and create a cooling effect by evaporation. MR, expressed as a percentage, was obtained according to ASTM D2654. Two specimens from each fabric were dried and weighed. The specimens were then placed in a previously-weighed and dried covered container and cooled in a desiccator containing phosphorus pentoxide (P_2O_5). The specimen and container were then weighed. The specimens were conditioned for 24 hours and weighed. Moisture regain was calculated according to the formula:

$$\text{\% moisture regain} = \frac{[(L - D)]}{D} \times 100$$

where: L = weight of conditioned specimen,g

D = oven-dry weight of specimen.

Surface hairiness, which determines the feeling of warmth or coolness upon contact with the skin, was measured qualitatively from the use of photographs taken of the fabric surface. The photographs were taken with a Bausch & Lomb stereo microscope and Kodak Colorsnap 35 camera at 30× magnification.

III. RESISTANCE TO HEAT FLOW

The measurement of heat transfer depends upon the instrument measuring the heat flow, control of the environmental conditions, and control of spatial separations in layering. These parameters are described as follows:

Heat transfer (heat flow) was measured by the heat flow and mass transfer tester (HMT) which was designed and fabricated by Charles Hassenboehler at the USDA Textiles & Clothing Laboratory, Knoxville. The apparatus has two chambers: the bottom chamber consists of a hot plate and a 6" × 6" transducer. The top chamber consists of a cold plate and a 6" × 6" transducer. The textile fabric is the barrier between the chambers. A diagram showing the position of the hot and cold plates and the fabric specimen is shown in Figure 1.

Heat transfer—measured in BTU/h ft^2 °F—air temperature, and relative humidity are measured and displayed on a real time basis using the micropr●ssor which converts changes in millivolts to the above parameters.

Matching heat source and heat sink units are constructed on 1/2" aluminum plates (16-inch squares) having a continuous grid of parallel copper tubing liquid conductors fastened to the plate with high conductivity epoxy as sketched in Figure 2.

An insulating fence encloses the test region and perimeter of the heat source plate. Another insulating wall rests on the perimeter of the heat source plate. The specimen is placed between the matching heat source and sink units. The inner fence impedes nonperpendicular heat flow while the extended plate area surrounding the transducer duplicates the thermal gradient on the interior test region, thus all heat flowing through the transducer also flows through the test fabric interface, and is not lost to the sides.

A desk-top computer fully controls a multiplexer and digital multimeter that reads the output from each transducer. The computer is programmed to manipulate the data and graphically plot the results, according to the program developed for the test (see Appendix). The instrument and computer are shown in Figure 3.

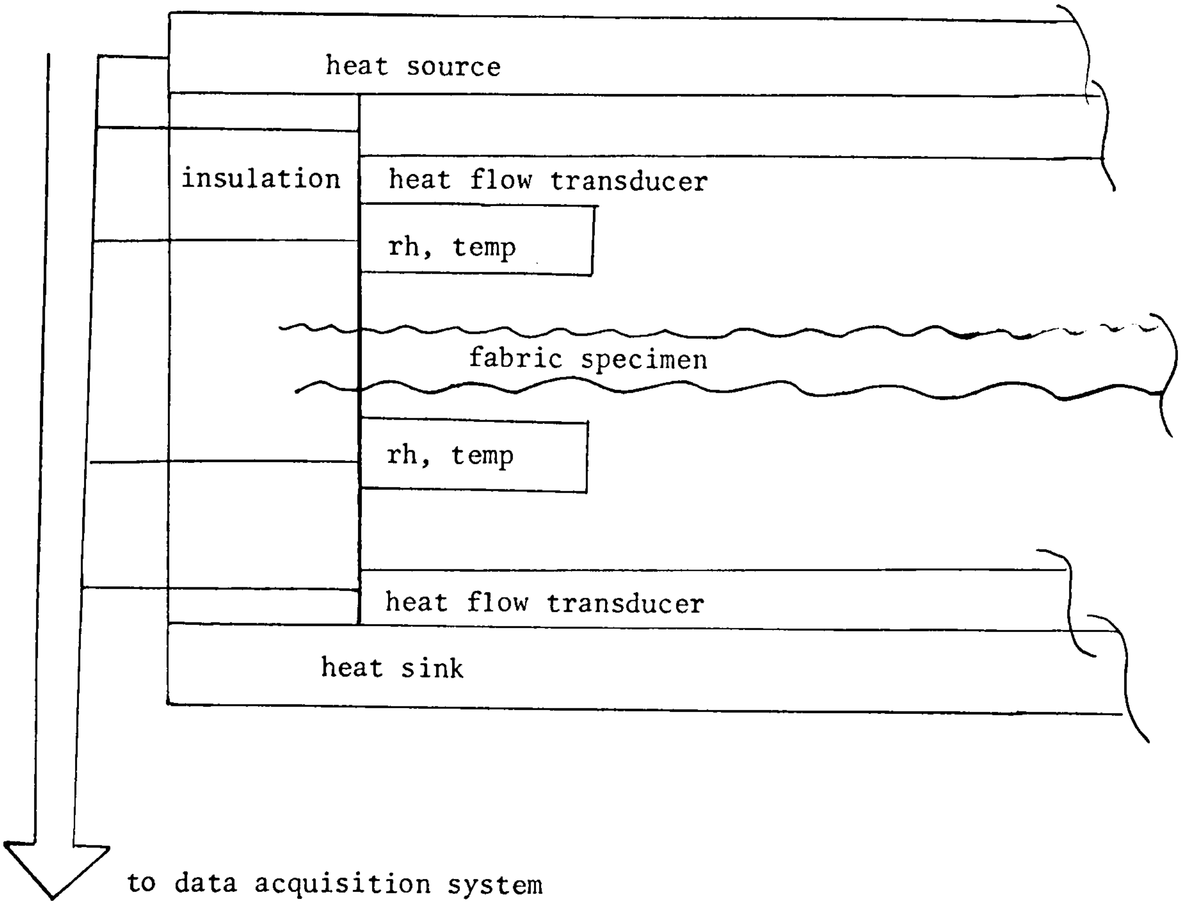


Figure 1. Device for thermal conductivity/mass transfer.

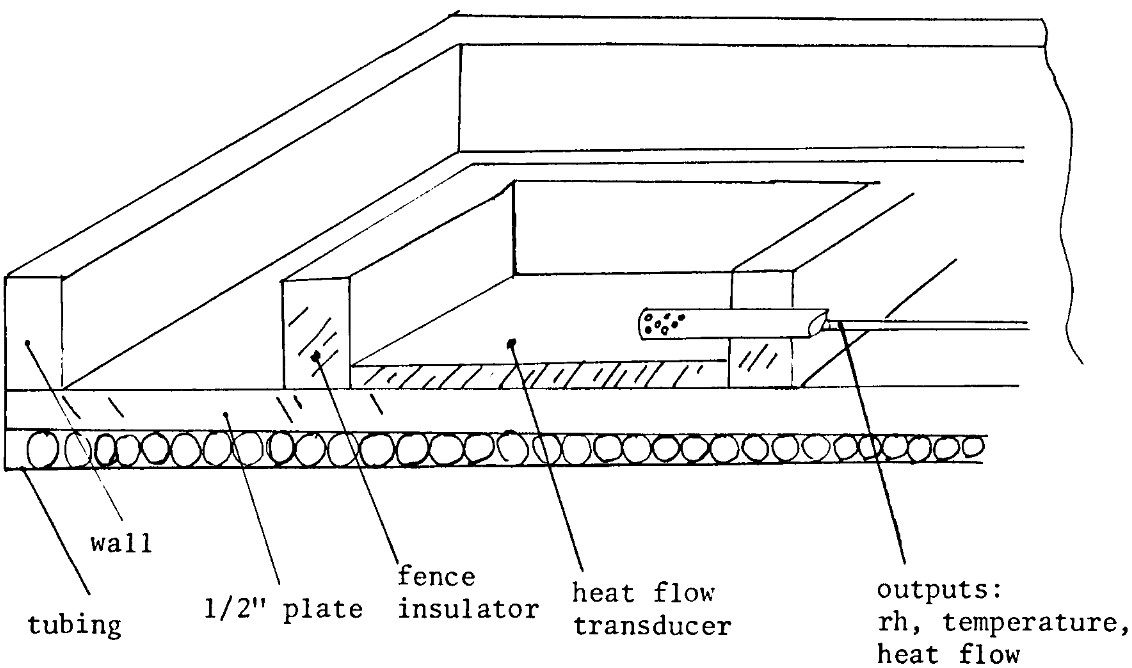


Figure 2. Schematic of heat transfer half.

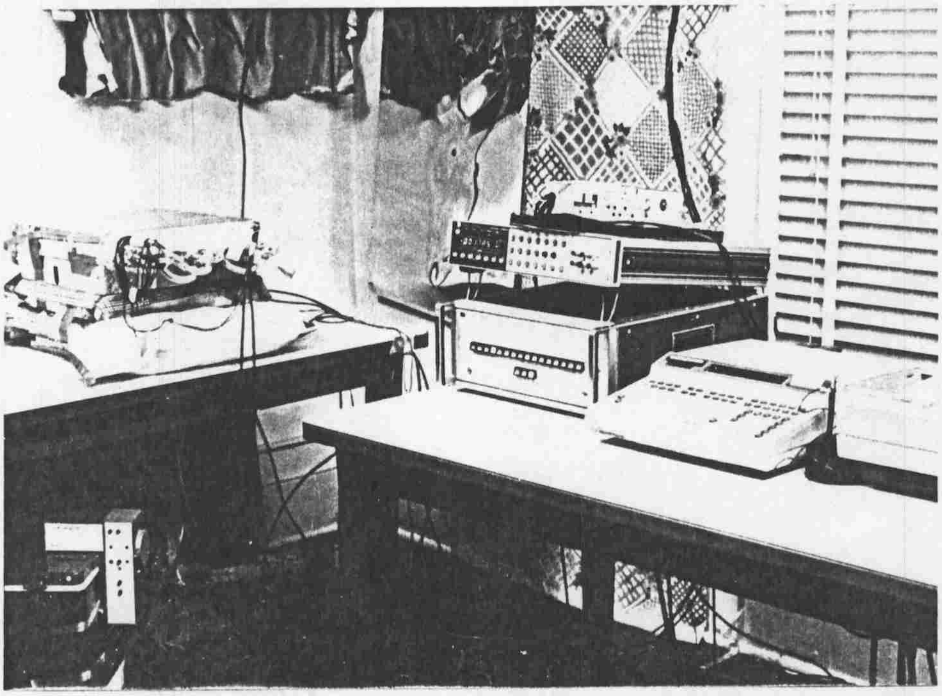


Figure 3. Heat and mass transfer tester with computer and plotter.

For each fabric and each combination of fabrics under each set of environmental conditions, the BTU/hr ft^2 °F were recorded after equilibfium was reached. Four readings were taken at six-minute intervals. The amount of heat transmitted was calculated by the following formula:

$$U_f = \frac{1}{\frac{1}{U_t} - \frac{1}{U_o}} \qquad (3)$$

where: U_f = heat transmission of fabric

U_t = total heat transmission of instrument and fabric

U_o = heat transmission of instrument without fabric barrier.

In order to express the heat flow in terms of insulation, the U_f was changed to a resistance (R) value:

$$R_f = \frac{1}{U_f}$$

where: R_f = resistance of fabric to heat transfer.

Resistance values were converted to clo units according to the formula:

1 clo = 0.88 (°F hr ft^2/BTU) or 1 clo = 0.88 (R) (27)

Environmental Control

In order to provide three temperature-relative humidity combinations which would simulate possible next-to-skin and ambient conditions, saturated salt solutions were used to produce various humidity levels. No salts were used for one set of conditions, producing RH levels of 36 ± 2%, 94 ± 2°F and 50 ± 2%, 69 ± 2°F. In a second test, an aqueous solution of $CaCl_26H_2O$ was used in the hot chamber with a constant RH of 42 ± 2% and temperature of 94 ± 2°F. Magnesium acetate [$MG(C_2H_3O_2)4H_2O$] was used in the upper (cold) chamber to give an RH of 68 ± 2% with a temperature of 70 ± 2°F. The investigator could not establish the estimated values of RH for these two salts of 32.9% and 65%, respectively (86).

In a third test, the established RH levels were 32 ± 2% for the hot chamber with a temperature of 94 ± 2°F, and the ambient air RH and temperature were used instead of the cold chamber. These conditions varied from 45-50% RH and from 70-75°F. $CaCl_26H_2O$ was used to maintain the RH in the hot chamber. With the open system, the calcium chloride maintained a lower RH than with the closed system.

Spatial Separation

Three spatial separations were tested to determine any change in insulation value with the addition of air layers. The fabrics were placed on the HMT in single and double layers. The double layers consisted of each of the seven outerwear fabrics placed over each of the shirting fabrics in configurations of 0.000", 0.125" separation, and 0.250" separation. Spacers fabricated of balsa wood with cross pieces for support provided the air layers.

IV. EXPERIMENTAL DESIGN

The independent variables for the study included the seven outer fabrics, the two shirt fabrics, and three spatial separations, and the three temperature-RH combinations. The dependent variable was heat transfer (converted to resistance to heat transfer). The complete design is given in Figure 4. Due to time required for each measurement, only random replications were made to check reproducibility of data.

V. STATISTICAL ANALYSIS

A four-way analysis of variance was used to test for differences in the factors of outer fabric, shirt fabric, spatial separation, and temperature-relative humidity combination. Physical properties of the fabrics were added as covariates to determine any significant effect caused by factors other than the main effects.

Pearson-product-moment correlation and multiple regression analysis were used to determine the correlation coefficients and linear relationship between the physical properties and resistance values of the fabrics. For all data analysis, levels of significance were set at 0.05.

The Statistical Analysis System (SAS) software package and the Wang 700 Series were used for computer analysis of data (72).

<table>
<tr><td>I</td><td colspan="21">A-G</td><td colspan="3">N</td></tr>
<tr><td>II</td><td colspan="9">X</td><td colspan="9">Y</td><td colspan="3">0</td><td>X</td><td colspan="2">Y</td></tr>
<tr><td>III</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">1</td><td colspan="3">2</td><td colspan="3">3</td><td colspan="3">0</td><td colspan="3">0</td></tr>
<tr><td>IV</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td><td>r</td><td>s</td><td>t</td></tr>
</table>

I. Outer fabric
   A. 100% wool
   B. 100% wool
   C. 70% wool/30% nylon
   D. 50% wool/50% polyester
   E. wool/acrylic
   F. 100% cotton denim
   G. 100% polyester double knit
   N. No outer fabric.

II. Shirt fabric
   X. 65% polyester/35% cotton
   Y. 100% Qiana nylon
   0. No shirt fabric

III. Spatial configuration
   1. 0.000" separation
   2. 0.125" separation
   3. 0.250" separation
   0. Single layer

IV. Temperature-relative humidity combination
   r. 94 ± 2°F, 36 ± 2%; 69 ± 2°F, 50 ± 2%
   s. 94 ± 2°F, 42 ± 2%; 70 ± 2°F, 68 ± 2%
   t. 94 ± 2°F, 32 ± 2%; 70 ± 2°F, 45 ± 2%

Figure 4

Research Design

CHAPTER IV

RESULTS AND DISCUSSION

I. INTRODUCTION

Included in this chapter is a discussion of the results obtained from the investigation of resistance to heat flow properties of nine apparel fabrics, seven of which are classified as outer fabrics and two shirting fabrics. The resistance values represent the ability of the fabric to provide insulation and to keep the wearer thermally comfortable.

The conditions specified for the investigation were to simulate environmental parameters in the home. The activity level of the wearer was assumed to be moderate to low. The instrument used to measure the heat flow through the fabrics was adjusted to simulate temperature and relative humidity next to the skin and temperature and relative humidity of the ambient environment.

The fabrics were tested as single components and as assemblies of outer fabric layered over shirt fabric at three different spatial separations. The spacing was used to determine the effect, if any, of the air space between fabric layers.

In addition, the investigation was carried out under three combinations of temperature and relative humidity. The change in resistance to heat flow at different temperature-relative combinations was measured.

The results of the investigation are presented as follows:

The resistance to heat transfer for each of the single fabric components is given in Section II, and a comparison has been made between the fabrics indicating which fabrics are the best insulators.

The experimental test results and statistical analysis with the fabrics in assemblies of outer fabric layered over shirt fabric is given in Section III. Separate discussions are given for the outer fabrics and the shirt fabrics as they contribute to the resistance to heat flow in double layers. In addition, the interaction of outer fabric and shirt fabric as a combination is discussed.

The effect of the spacing between the fabrics in double layers and the interaction of the spacing with the factors of outer fabric, shirt fabric, and temperature-relative humidity combination are also included in Section III.

Section IV deals with a comparison of the resistance to heat flow for single and double layers of fabrics. The resistance values for each combination of outer fabric and shirt fabric are compared with the resistance values for the single layer components.

The effect of temperature and relative humidity on the resistance to heat flow of the fabrics and the assemblies is given in Section V. Of the conditions used in the experiment, the combination that provided the best environmental conditions for increasing insulation is given.

The discussion in Section VI pertains to the physical properties of the fabrics and the relationship of the physical properties to the resistance values for fabrics as single layers and in assemblies.

The conversion of the resistance values to clo units is included in Section VII. The purpose for converting the resistance values to clo units was to make the results useable by consumers and other workers in the field familiar with the latter terminology. ASHRAE and other research institutions refer to clo units when presenting research results that can be interpreted by consumers.

II. FABRICS IN SINGLE LAYERS

Each of the nine fabrics was tested as a single component for resistance to heat flow at each temperature-relative humidity combination. The outer fabrics and shirt fabrics were considered to be two separate groups.

Both the highest and lowest resistance values were exhibited by outer fabrics made of 100% wool (fabrics A and B, respectively). Generally, the fabrics with a hairy surface having a large area available to hold air were the same fabrics which had higher resistance values. For example, fabrics E, C, and D show a hairy surface and resemble fabric A in resistance. On the other hand, fabrics G, F, and B have smooth surfaces and thus have the lowest resistance values. A plot of the values for the single fabrics is given in Figure 5.

When analyzed statistically using a priori contrasts, the fabrics in single layers were not significantly different from each other.

A three-way analysis of variance indicates that the outer fabric, shirt fabric, and temperature-relative humidity combination are significant at 0.01 in contributing to resistance to heat flow. However, when the physical properties of the fabrics were added as covariates, the

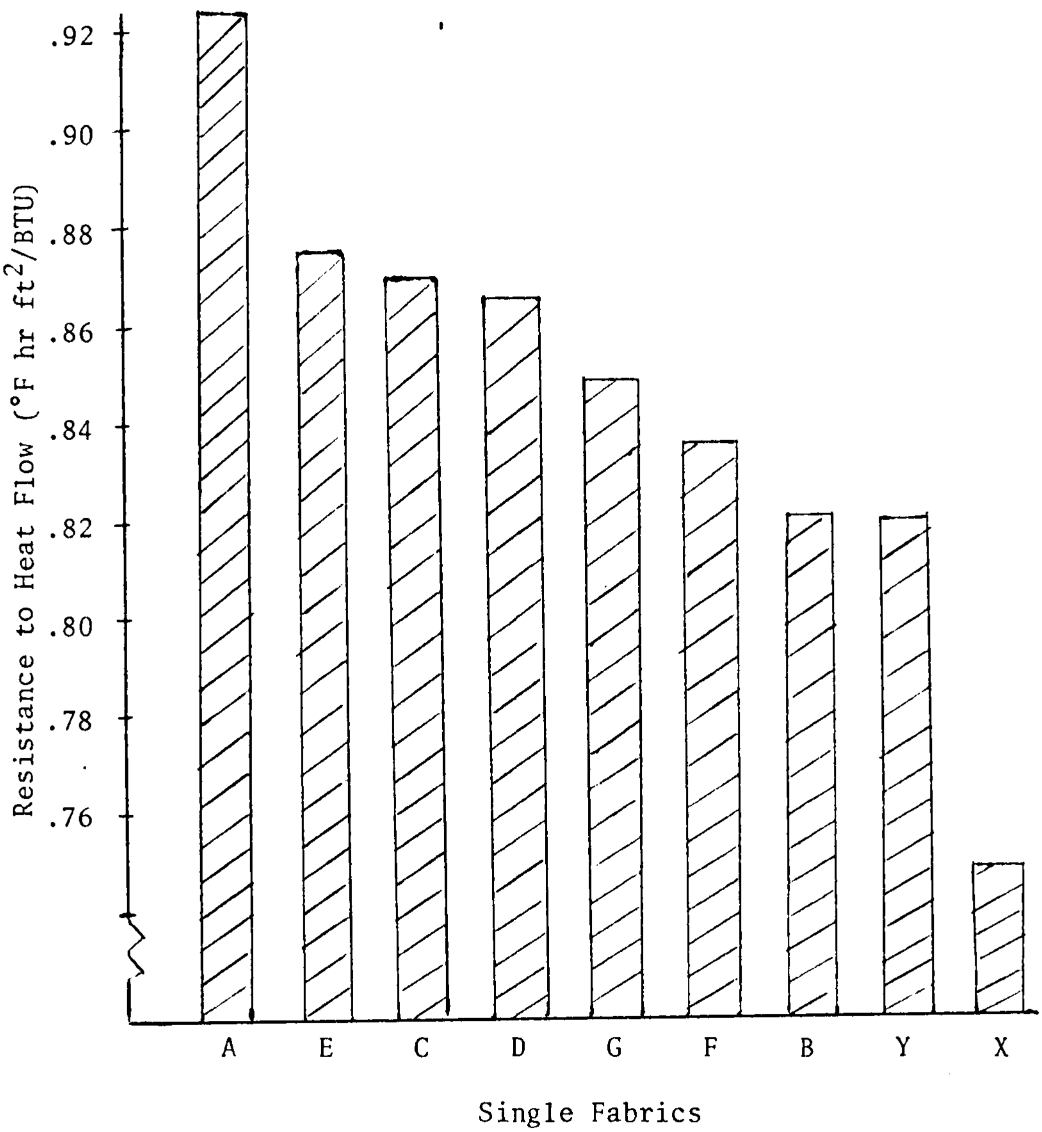


Figure 5. Resistance values of fabrics in single layers.

outer fabric and the shirt fabric were found to be no longer significant and the thickness replaced them as a significant factor. Table 3 shows the analysis of variance and analysis of covariance for the single fabrics.

For the two shirt fabrics, the 100% Qiana nylon (fabric Y) consistently gave a higher resistance value than did fabric X (65% polyester/35% cotton). Each fabric is presented separately in the following discussion.

Outer Fabric A. Outer fabric A exhibited the highest resistance to heat flow of all the fabrics (0.926). Made of 100% wool, it has a very hairy surface and the highest thickness measurement (0.063"). In addition, fabric A consistently gave the highest resistance values when measured in double layers.

Outer Fabric B. The lowest resistance to heat flow of the outer fabrics was exhibited by fabric B (0.842), a 100% worsted wool fabric having the lowest thickness. When layered with the shirt fabrics, the resistance was consistently lower than that for all outer fabrics. Although made of staple yarns, the fabric surface was rather smooth and closely woven.

Outer Fabric C. Fabric C, very similar in structure to fabric A, had the third highest resistance in a single layer. The difference in resistance between C and A can possibly be explained due to the fact that the thickness and resilience are less for C than for A and the addition of filament yarns in C (70% wool/30% nylon) makes the surface less hairy.

Outer Fabric D. Fabric D (50% wool/50% polyester) had the fourth highest resistance value. The thickness of this fabric is slightly less

TABLE 3

ANALYSIS OF VARIANCE AND COVARIANCE FOR FABRICS IN SINGLE LAYERS

Source	DF	MS	F[a]
Analysis of Variance for Main Effects			
Outer Fabric	7	.0061	6.91**
Shirt Fabric	1	.0078	8.82**
Temperature-Relative Humidity	2	.0478	54.23**
Analysis of Covariance			
Thickness	1	0.0363	41.21**
Temperature-Relative Humidity	2	0.0478	54.23**
Compression	1	0.0029	24.67**

[a]**Indicates significance at 0.01.

than that of fabric C. However, the addition of 50% filament fiber creates a surface that is smooth and, consequently, does not trap and hold a still air layer.

Outer Fabric E. Fabric E (wool/acrylic) gave inconsistent results throughout the investigation. The thickness and surface area were not closely similar to the other fabrics which gave high resistance values. However, the measurements were sometimes high.

Outer Fabric F. Outer fabric F (100% cotton denim) exhibited the second lowest resistance to heat flow of the outer fabrics. This can possibly be explained due to the fact that fabric F is a tightly woven structure with little air space within the fabric. Because of the tightness of the structure, one can expect that the surface of the fabric will have fewer protruding fibers, hence a much thinner still air layer; therefore, it is ineffective in containing the heat flow.

Outer Fabric G. Fabric G was approximately 0.001" thicker than fabric D. The resistance value, however, was found to be slightly lower. This could perhaps be attributed to the smooth surface texture, lower cover factor, and lower resilience of this fabric. The 100% polyester filament yarns are smooth, and thus allow little entrapment of air due to close surface contact.

Shirt Fabric X. Shirt fabric X (65% polyester/35% cotton) was found to have the lowest resistance of all the fabrics examined in this study. In addition, this fabric also had the lowest thickness value (0.013"), as was expected. Consequently, the closely woven structure and smooth surface limited the amount of air that could be entrapped by the fabric.

Shirt Fabric Y. Shirt fabric Y (100% Qiana nylon, single knit) had a mean resistance value higher than that for fabric X and very similar to the outer fabric B. The lower thickness (0.019") and the smooth filament yarns could perhaps be the factors that contribute to the low resistance values as compared to the outer fabrics.

III. DOUBLE-LAYER FABRIC ASSEMBLIES

Previous investigators have shown that layering of fabrics is more efficient in providing resistance to heat flow than a single fabric. The findings of the present study are in agreement with the previous results. When outer fabrics were combined in layered form over shirt fabrics, the resistance values were found to be higher than those of each of the single fabrics.

Results obtained with these experimental fabrics indicate that thickness of the outer fabrics, spatial separation between fabric layers, and the temperature-relative humidity combination have a significant effect on the fabric insulation properties. As with the single layers, the highest and lowest resistance values were exhibited by fabrics A and B, respectively. Both A and B are made of 100% wool.

Also, the fabrics with a hairy surface tended to produce the higher resistances, as was the case with the single fabrics. Thickness of the outer fabrics was found to be the significant factor in the analysis of covariance.

Each factor involved in the investigation and analysis is given in the following discussion. A four-way analysis of variance was used to test for differences in the main effects and interactions of the four factors: outer fabric, shirt fabric, spatial separation, and temperature-relative humidity combination. Physical characteristics were added as covariates to determine their contribution to the resistance to heat flow. Results of the analyses are given in Table 4. Means for the factor main effects are given in Table 5.

Outer Fabrics

The seven outer fabrics had a highly significant effect on the resistance values of the fabrics when tested in double layers. The 100% wool material (fabric A) exhibited the highest value for resistance to heat flow while the 100% worsted wool material (fabric B) showed the lowest resistance. The means for the fabrics are plotted in Figure 6 in rank order from outer fabric with the highest resistance to the outer fabric having the lowest resistance.

The data suggest that the important factor in the resistance to heat flow is something other than fiber content, since the highest and the lowest values were obtained with fabrics made of 100% wool. Analysis of covariance indicates that thickness is the contributing factor rather than fiber content or other physical properties examined in this study (see Table 6).

The outer fabric was determined as nonsignificant when thickness was introduced as a variable. The probability of F for the outer fabric changed from 0.003 to 0.9, while the F value for thickness was at a probability level less than 0.001.

When the thickness values are compared to resistance values, there is a proportional relationship. This finding is in agreement with

TABLE 4

ANALYSIS OF VARIANCE FOR RESISTANCE VALUES OF DOUBLE-LAYER FABRIC ASSEMBLIES

Source	DF	MS	F[a]
Outer Fabric	6	0.0148	5.27**
Shirt Fabric	1	0.0549	19.53**
Outer Fabric × Shirt Fabric	6	0.0033	1.17
Spatial Separation	2	0.9071	322.44**
Outer Fabric × Spatial Separation	12	0.0452	1.61
Shirt Fabric × Spatial Separation	2	0.0005	0.20
Temperature-Relative Humidity	2	0.2491	88.56**
Outer Fabric × Temperature-Relative Humidity	12	0.0029	1.06
Shirt Fabric × Temperature-Relative Humidity	2	0.0050	1.79
Spatial Separation × Temperature-Relative Humidity	4	0.0089	3.20*
Outer Fabric × Shirt Fabric × Temperature-Relative Humidity	12	0.0017	0.62
Outer Fabric × Spatial Separation × Temperature-Relative Humidity	12	0.0031	1.12
Shirt Fabric × Spatial Separation × Temperature-Relative Humidity	4	0.0029	1.04
Model	77	0.0348	12.39**
Residual	48	0.0028	
Total	125		

[a] *Indicates significance at 0.05; **Indicates significance at 0.01.

TABLE 5

MEANS OF FACTOR MAIN EFFECTS FOR DOUBLE-LAYER ASSEMBLIES

Factors	Resistance (°F hr ft^2/BTU)[a]
Outer Fabric Layered with Shirt Fabric	
A	1.248
B	1.154
C	1.199
D	1.196
E	1.174
F	1.188
G	1.202
Shirt Fabric Layered with Outer Fabric	
X (65% polyester/35% cotton)	1.206
Y (100% Qiana nylon)	1.245
Spatial Separation	
0.000"	1.090
0.125"	1.267
0.250"	1.381
Temperature-Relative Humidity	
TR1 (94°-36%, 70°-50%)	1.198
TR2 (94°-42%, 70°-68%)	1.241
TR3 (94°-32%, 70°-45%)	1.097

[a]Rounded to nearest 0.001.

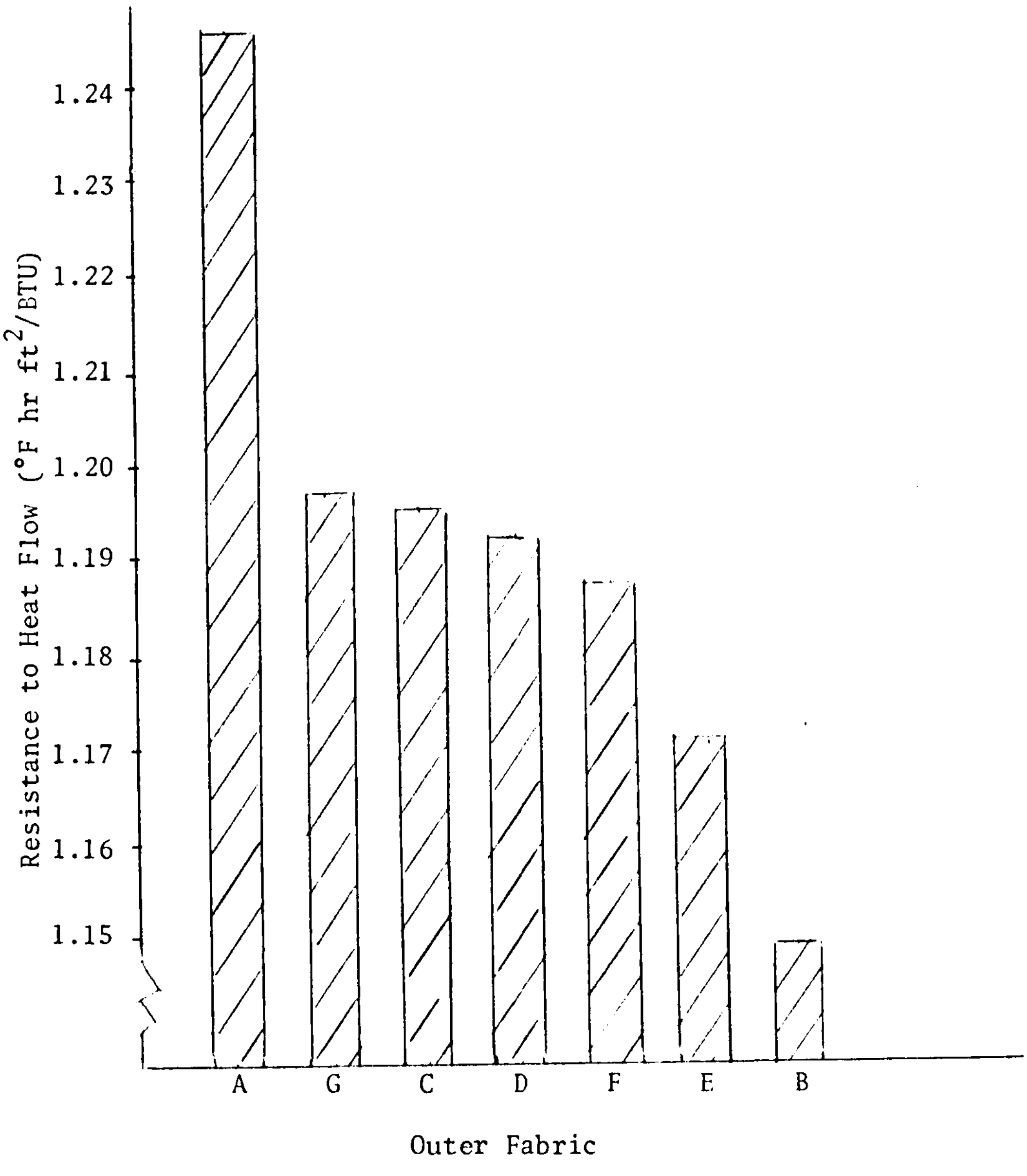


Figure 6. Means for resistance of outer fabrics in double-layer assemblies.

TABLE 6

ANALYSIS OF COVARIANCE FOR PHYSICAL PROPERTIES OF FABRICS IN DOUBLE LAYERS

Source[a]	DF	MS	F[b]
Thickness	1	0.0985	28.83**
Weight	1	0.0000	0.01
Porosity	1	0.0000	0.01
Moisture Regain	1	0.0000	0.01
Compression	1	0.0018	0.00
Resilience	1	0.0000	0.00
Air Permeability	1	0.0000	0.00
Cover	1	0.0000	0.00
Outer Fabric	2	0.0002	0.08
Shirt Fabric	1	0.0440	13.21**
Spatial Separation	2	0.9007	263.65**
Temperature-Relative Humidity	2	0.2315	67.75**
Thickness × Spatial Separation	2	0.0115	3.39*

[a]Only interactions significant at 0.05 are listed.

[b]**Indicates significance at 0.01; *Indicates significance at 0.05.

previous investigators (9, 22, 23, 27, 47, 59, 67, 68, 79). The thicker the fabric, the greater is the air drag, and thus, an increase in the thermal insulation. The relationship of thickness and resistance of outer fabrics is shown in Figure 7.

Fabric thickness was the only physical property that had a significant correlation with R when tested using Pearson product moment correlation (P = 0.0359). Other physical properties will be discussed in Section VI of this chapter.

In order to determine whether outer fabrics were significantly different from each other, a priori contrasts were made. This analysis indicated that fabric A (100% wool) was significantly different from fabric B (100% wool), fabric D (50% wool/50% polyester), fabric E (wool/acrylic), and fabric F (100% cotton denim). None of the other outer fabrics were significantly different from each other. The results are given in Table 7. As can be seen in Figure 3, page 44, fabric A has a much higher resistance as compared to the other fabrics although it was not statistically significantly different from fabrics C and G in the measurement of resistance to heat flow.

Shirt Fabrics

The two shirt fabrics were highly significant in their contribution to resistance to heat flow in double-layer assemblies. Shirt fabric Y (100% nylon) was found to have a higher resistance than that of fabric X. When contrasts were made between the shirt fabrics, a significant difference between the value of X and Y was observed at a significance

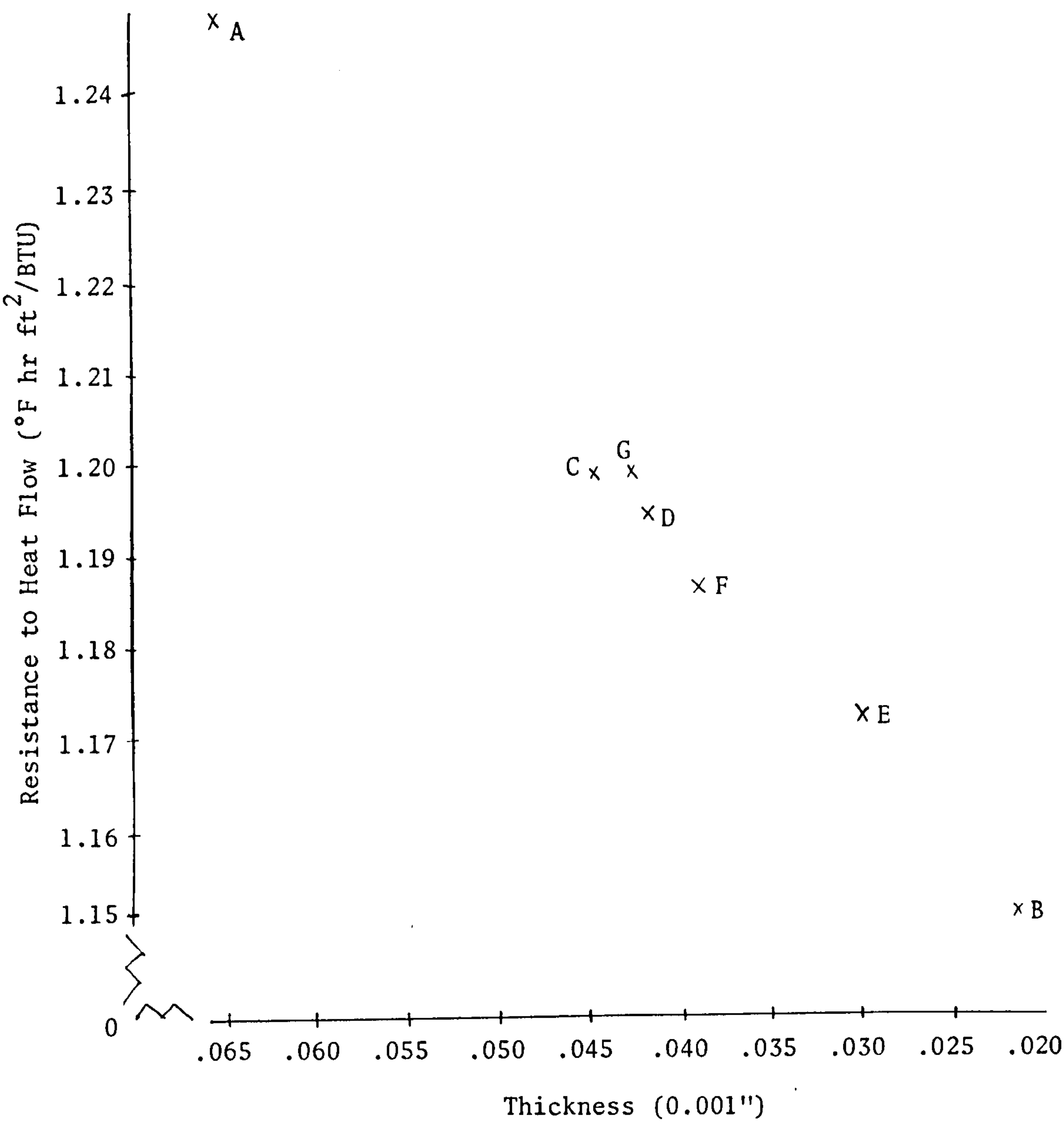


Figure 7. Thermal resistance and thickness of outer fabrics.

TABLE 7

CONTRASTS OF RESISTANCE OF OUTER FABRIC IN DOUBLE-LAYER ASSEMBLIES

Contrast[a]	SS	F[b]
Fabric A Contrasted with Fabric B	0.0833	11.13**
Fabric A Contrasted with Fabric C	0.0242	3.24
Fabric A Contrasted with Fabric D	0.0273	3.65*
Fabric A Contrasted with Fabric E	0.0606	8.09*
Fabric A Contrasted with Fabric F	0.3080	4.11*
Fabric A Contrasted with Fabric G	0.0196	2.62
Fabric B Contrasted with Fabric C	0.0177	2.36
Fabric B Contrasted with Fabric D	0.0152	2.03
Fabric B Contrasted with Fabric E	0.0018	0.24
Fabric B Contrasted with Fabric F	0.0128	1.71
Fabric B Contrasted with Fabric G	0.0221	2.95
Fabric C Contrasted with Fabric D	0.0001	0.01
Fabric C Contrasted with Fabric E	0.0082	1.09
Fabric C Contrasted with Fabric F	0.0004	0.05
Fabric C Contrasted with Fabric G	0.0002	0.03
Fabric D Contrasted with Fabric E	0.0065	0.87
Fabric D Contrasted with Fabric F	0.0001	0.01
Fabric D Contrasted with Fabric G	0.0006	0.09
Fabric E Contrasted with Fabric F	0.0049	0.67
Fabric E Contrasted with Fabric G	0.0113	1.51

TABLE 7 (continued)

Contrast[a]	SS	F[b]
Fabric F Contrasted with Fabric G	0.0013	0.17

[a]Each contrast is made using the means of the outer fabrics layered with shirt fabric X and shirt fabric Y.

[b]*Indicates significance at 0.05; **Indicates significance at 0.01.

level of 0.01. The means for the fabrics in double layers are given in Table 5, page 59.

The thickness of the shirting fabrics studied is, as expected, less than that for the outer fabrics. However, when thickness was introduced as a covariate, the shirt fabric remained significant, indicating that for these experimental fabrics, thickness is found not to be a major property of the shirt fabric in determining resistance when layered with an outer fabric.

Outer Fabrics × Shirt Fabrics

The interaction of the outer fabrics and the shirt fabrics was found not to be significant when subjected to the analysis of variance against all the main effects and interactions. The means of the factor interactions are given in Table 8.

When the outer fabrics were layered with shirt fabric Y (100% nylon), the resistance was higher than when outer fabrics were layered with shirt fabric X (65% polyester/35% cotton) with the exception of outer fabric F (100% cotton denim). The outer fabric A (100% wool) layered over shirt fabric Y yielded the highest resistance value (1.3341) while the outer fabric B (100% wool) layered with shirt fabric X yielded the lowest resistance (1.188) of all the fabric combinations.

The remaining resistance values from highest to lowest for outer fabric over shirt fabric Y were as follows: G (1.288), C (1.274), D (1.257), F (1.240), E (1.236), and B (1.223). For rhe outer fabric layered with shirt fabric X, the resistance values were found to be: A (1.269), F (1.236), D (1.236), C (1.222), G (1.222), and E (1.203).

TABLE 8

MEANS OF OUTER FABRIC AND SHIRT FABRIC INTERACTIONS FOR DOUBLE-LAYERED ASSEMBLIES

Fabric Assemblies	Resistance (°F hr ft^2/BTU)[a]
Outer Fabric × Shirt Fabric	
A Layered with X	1.269
A Layered with Y	1.334
B Layered with X	1.188
B Layered with Y	1.223
C Layered with X	1.222
C Layered with Y	1.274
D Layered with X	1.236
D Layered with Y	1.257
E Layered with X	1.203
E Layered with Y	1.236
F Layered with X	1.246
F Layered with Y	1.240
G Layered with X	1.222
G Layered with Y	1.288

[a]Rounded to nearest 0.001.

The rank order of the means for the resistance values for interactions of the outer fabric layered with shirt fabric Y remained consistent with the means of the outer fabrics in double layer assemblies (see Figure 8). However, layering of the outer fabrics with shirt fabric X did not produce a rank order of resistance consistent with that of fabric Y; the fabrics in layers ranked in the following order were F, D, C, and G.

Spatial Separation

The spatial separation of the fabrics in double layer assemblies was a highly significant factor (F = 322.44) in the resistance to heat flow. The spacing between the fabrics created additional layers of warm air which were absent in the case of single layers.

The resistance increased significantly as the spacing was increased from practically no spacing (0.000") to 0.125" to 0.250" as shown in Table 9.

TABLE 9

CONTRASTS BETWEEN SPATIAL SEPARATIONS

Contrast	SS	F^a
0.000" Contrasted with 0.125"	0.6537	83.23**
0.000" Contrasted with 0.250"	1.7745	225.95**
0.125" Contrasted with 0.250"	0.2742	34.91**

[a]**Indicates significance at 0.01.

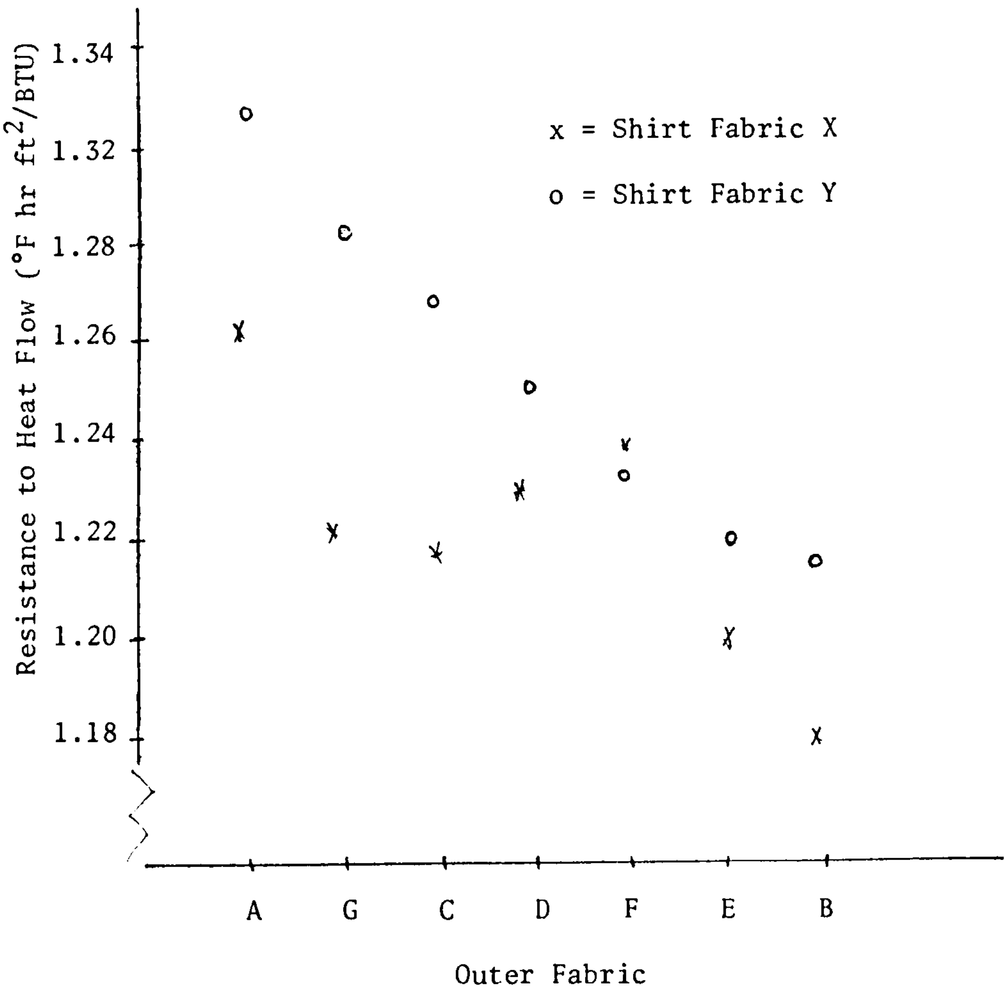


Figure 8. Resistance of outer fabrics layered with shirt fabrics.

These findings are in agreement with Morris (61) and Welfers (87); they found a significant increase in resistance with increase in air layers. Figure 9 shows the increase in resistance with increased separation between fabric layers. The means for outer fabric and shirt fabric at each separation are given in Table 10.

When a Pearson product moment correlation was used to determine a correlation between spatial separation and resistance, the correlation r was found to be greater than 0.8 as each fabric was layered with each shirt fabric. The probability was significant in each case except for the combination of outer fabric A and shirt fabric X (see Table 11).

Outer Fabric × Spatial Separation

The interaction of the outer fabric with the spatial separation was found to be not significant (see Table 4, page 58). However, when thickness was added as a covariate, the interaction of thickness and spatial separation was observed to be significant at a level of 0.05. Adding the thickness as a covariate caused the outer fabric to be nonsignificant. This suggests that the thickness of the outer fabric and the spatial separation have a dominant effect in determining the resistance.

There was an increase in resistance as the thickness of the air layer was increased; however, the magnitude of increase of additional spatial separation to gain the equivalent increase in resistance was different for different fabrics as shown in Figure 10. As the spacing increased to 0.250", there was little difference in the resistance of outer fabrics. This observation suggests that the trapped air appears

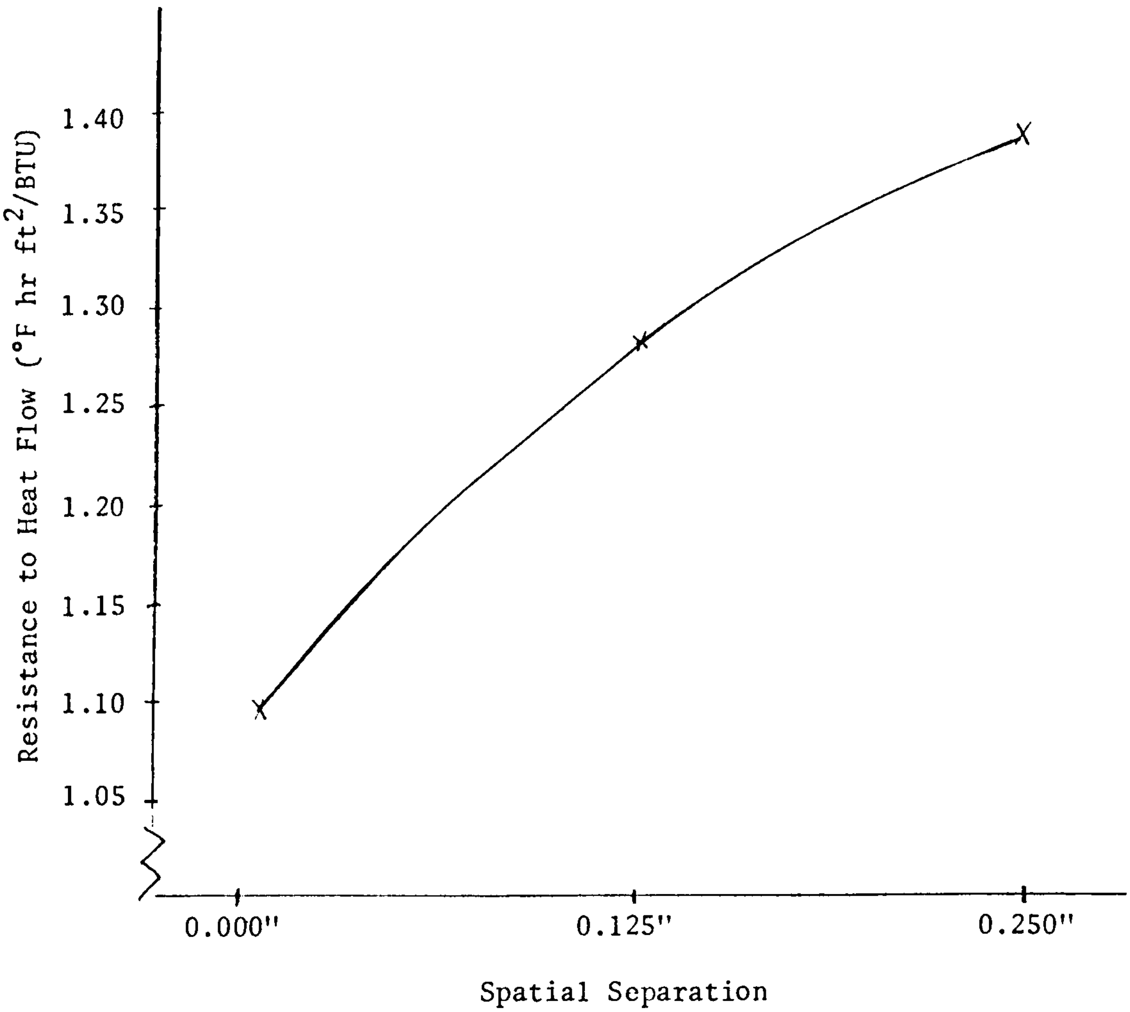


Figure 9. Influence of spatial separation on resistance for double-layered assemblies.

TABLE 10

MEANS OF RESISTANCE OF OUTER FABRICS AND SHIRT FABRICS WITH SPATIAL SEPARATIONS

Fabric Layers	Resistance to Heat Flow (°F hr ft²/BTU)[a] 0.000" Separation	0.125" Separation	0.250" Separation
Outer Fabrics Layered with Shirt Fabrics			
A	1.138	1.368	1.399
B	1.034	1.227	1.355
C	1.074	1.297	1.378
D	1.114	1.249	1.377
E	1.089	1.207	1.363
F	1.114	1.240	1.375
G	1.069	1.277	1.418
Shirt Fabrics Layered with Outer Fabrics			
X	1.065	1.223	1.363
Y	1.115	1.280	1.398

[a]Rounded to nearest 0.001.

TABLE 11

CORRELATION OF SPATIAL SEPARATION AND RESISTANCE FOR COMBINATIONS OF OUTER FABRIC AND SHIRT FABRIC

Fabric Combination	Resistance (°F hr ft^2/BTU)[a]	r[b]
A and X	1.283	0.805
A and Y	1.366	0.897*
B and X	1.222	0.951**
B and Y	1.256	0.949**
C and X	1.258	0.894**
C and Y	1.331	0.964**
D and X	1.272	0.962**
D and Y	1.324	0.936**
E and X	1.274	0.941**
E and Y	1.319	0.912**
F and X	1.258	0.969**
F and Y	1.301	0.950**
G and X	1.252	0.922**
G and Y	1.320	0.936**

[a]Rounded to nearest 0.001.

[b]r = Pearson product moment correlation.

*Indicates probability |r| under Ho:rHo = 0 at 0.05.

**Indicates probability |r| under Ho:rHo = 0 at 0.01.

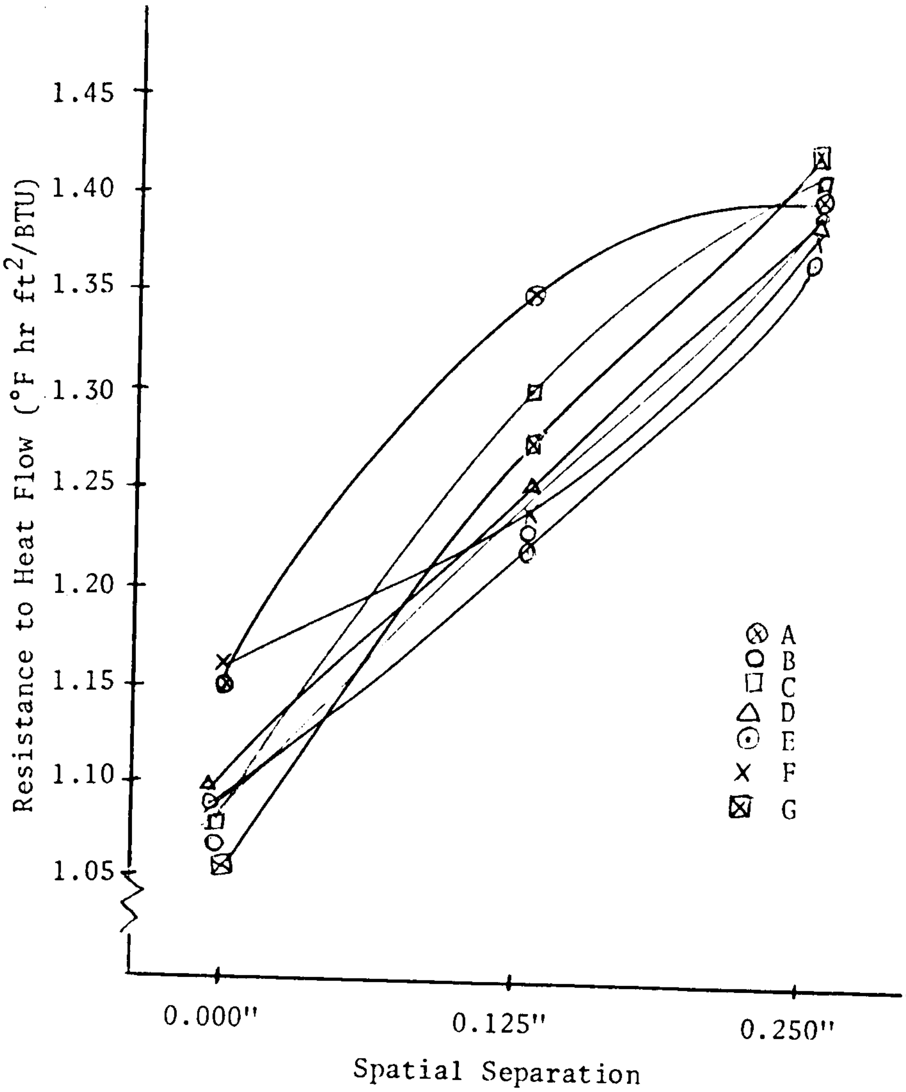


Figure 10. Effect of spatial separation on resistance of outer fabrics in double-layer assemblies.

to be the primary insulator rather than the fabrics, which supports the earlier findings.

Shirt Fabric × Spatial Separation

The interaction of the shirt fabric and the spatial separation was not significant (see Table 4, page 58). However, there was an increase in the mean resistance of the shirt fabrics in layered assemblies as the spacing between the layers was increased (see Figure 11). The difference in resistance of the shirt fabrics decreased at the highest spacing (0.250") indicating that the spatial separation is an important factor, more so than the combination of fabrics as was observed for outer fabrics.

Outer Fabric × Shirt Fabric × Spatial Separation

The three-way interaction of outer fabric with shirt fabric and spatial separation was not significant (see Table 4, page 58). The means for the outer fabric and shirt fabric at each spatial separation are given in Table 12.

When an outer fabric was layered with a shirt fabric, the amount of heat transmitted through the fabric decreased as the spatial separation increased, as shown in Figures 12 through 18. This was found to be similar in all combinations of outer fabric and shirt fabric. Since the decrease in transmitted heat is inversely related to resistance, the resistance increased for each layered assembly with each increase in spatial separation. With the exception of outer fabrics D and F, the heat transmission of outer fabric layered over shirt fabric X was always higher than with outer fabric layered over shirt fabric Y.

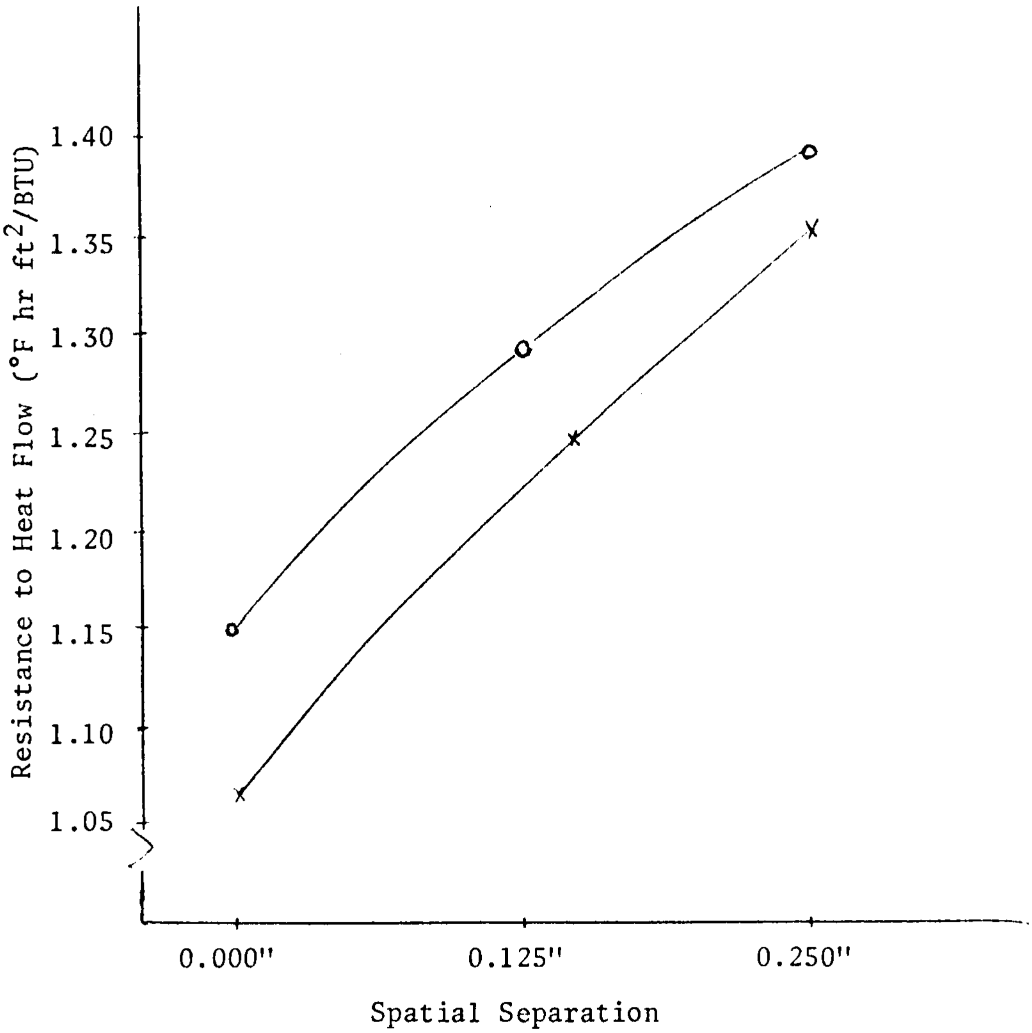


Figure 11. Effect of spatial separation on mean resistance of shirt fabrics in double-layer assemblies.

TABLE 12

MEANS OF RESISTANCE FOR EACH OUTER FABRIC LAYERED WITH EACH SHIRT FABRIC AT EACH SPATIAL SEPARATION

Fabric Assemblies	Resistance to Heat Flow (°F hr ft^2/BTU)[a] 0.000" Separation	0.125" Separation	0.250" Separation
Outer Fabric Layered with Shirt Fabric			
A and X	1.114	1.339	1.355
A and Y	1.161	1.398	1.444
B and X	1.008	1.226	1.319
B and Y	1.051	1.228	1.391
C and X	1.045	1.268	1.362
C and Y	1.103	1.327	1.394
D and X	1.076	1.236	1.397
D and Y	1.151	1.262	1.357
E and X	1.056	1.227	1.327
E and Y	1.122	1.187	1.399
F and X	1.105	1.251	1.383
F and Y	1.123	1.229	1.368
G and X	1.044	1.223	1.400
G and Y	1.094	1.332	1.437

[a]Values are rounded to nearest 0.001.

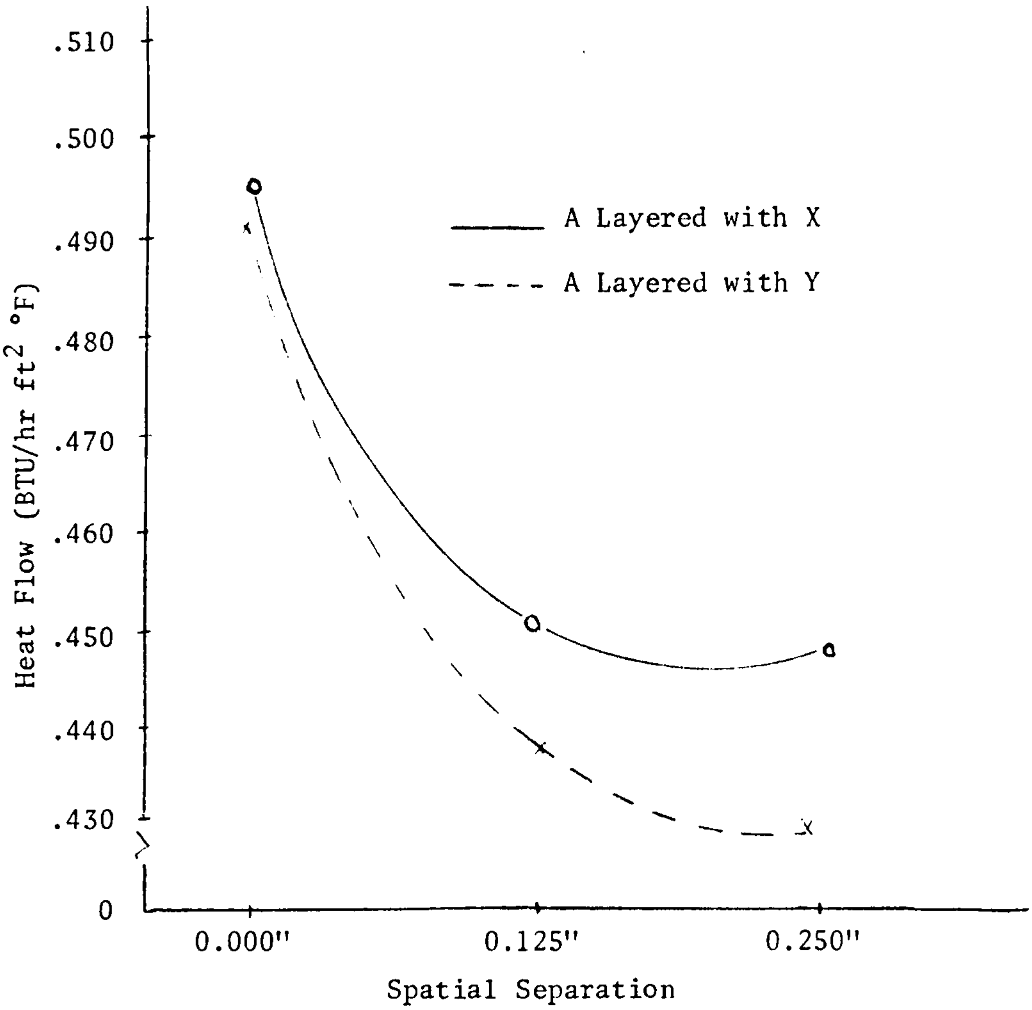


Figure 12. Mean heat transmission of outer fabric A layered with shirt fabrics X and Y at each spatial separation.

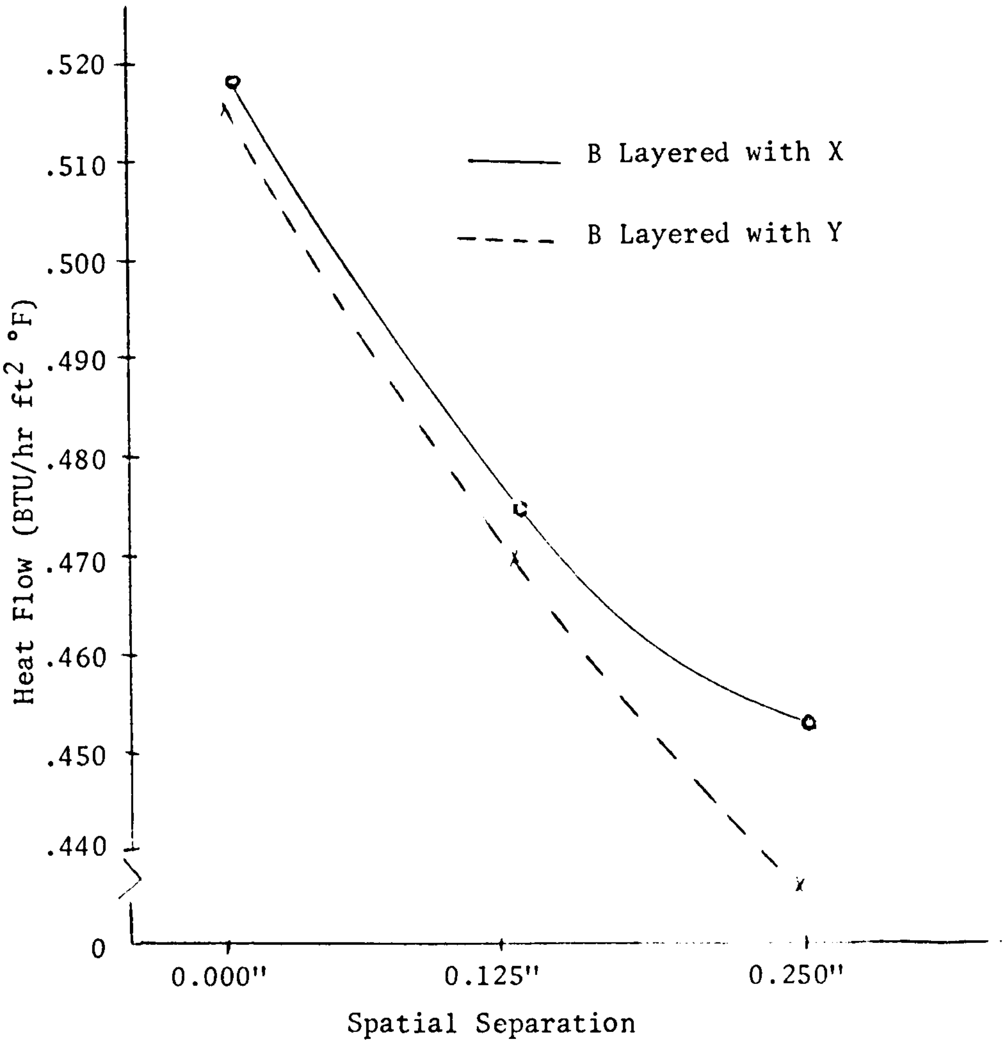


Figure 13. Mean heat transmission of outer fabric B layered with shirt fabrics X and Y at each spatial separation.

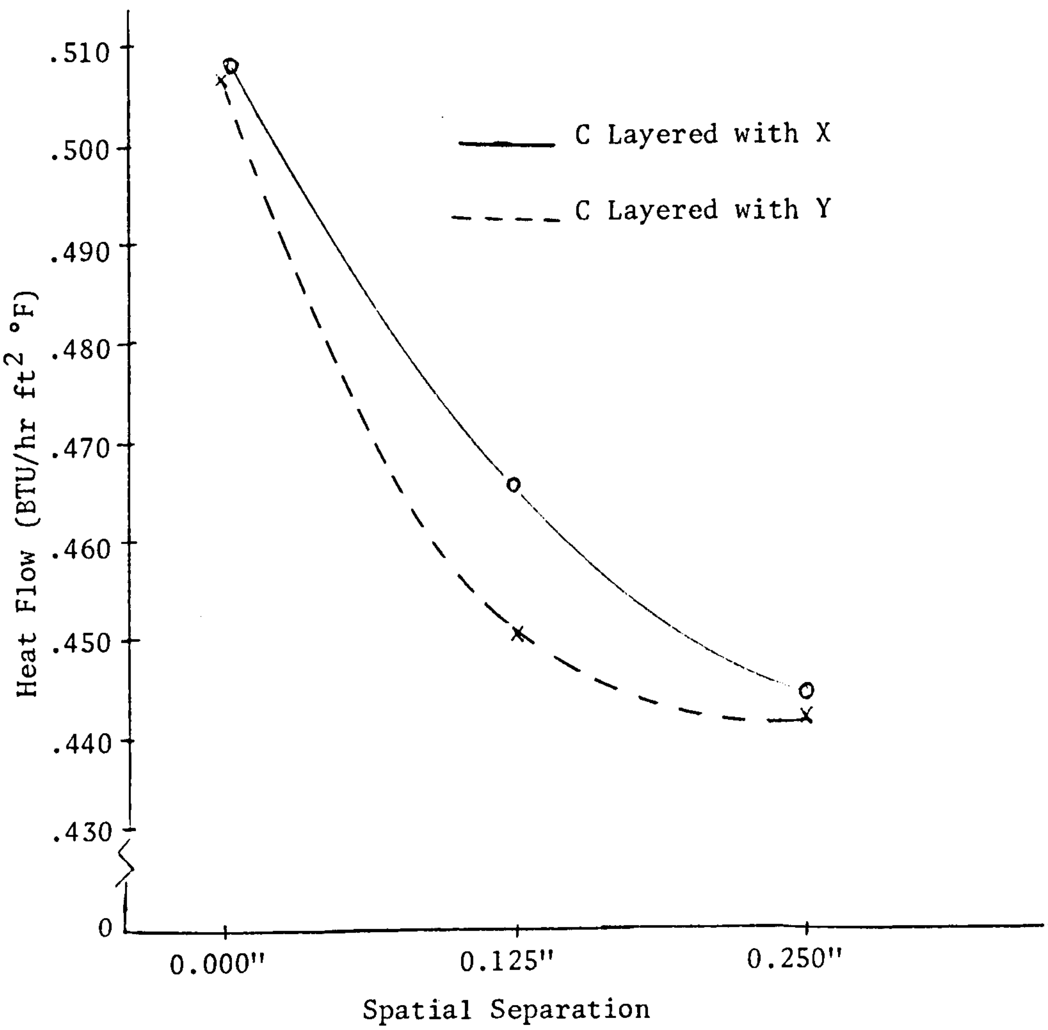


Figure 14. Mean heat transmission of outer fabric C layered with shirt fabrics X and Y at each spatial separation.

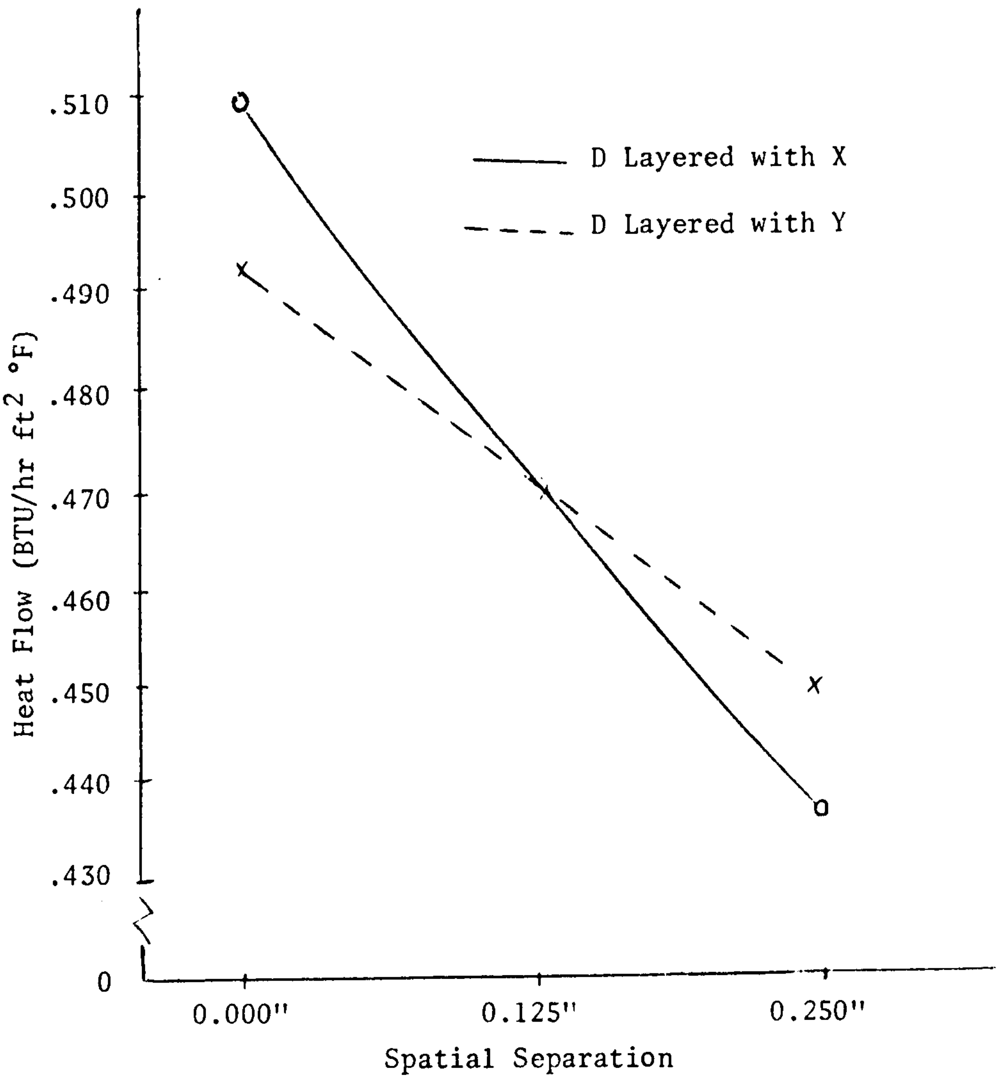


Figure 15. Mean heat transmission of outer fabric D layered with shirt fabrics X and Y at each spatial separation.

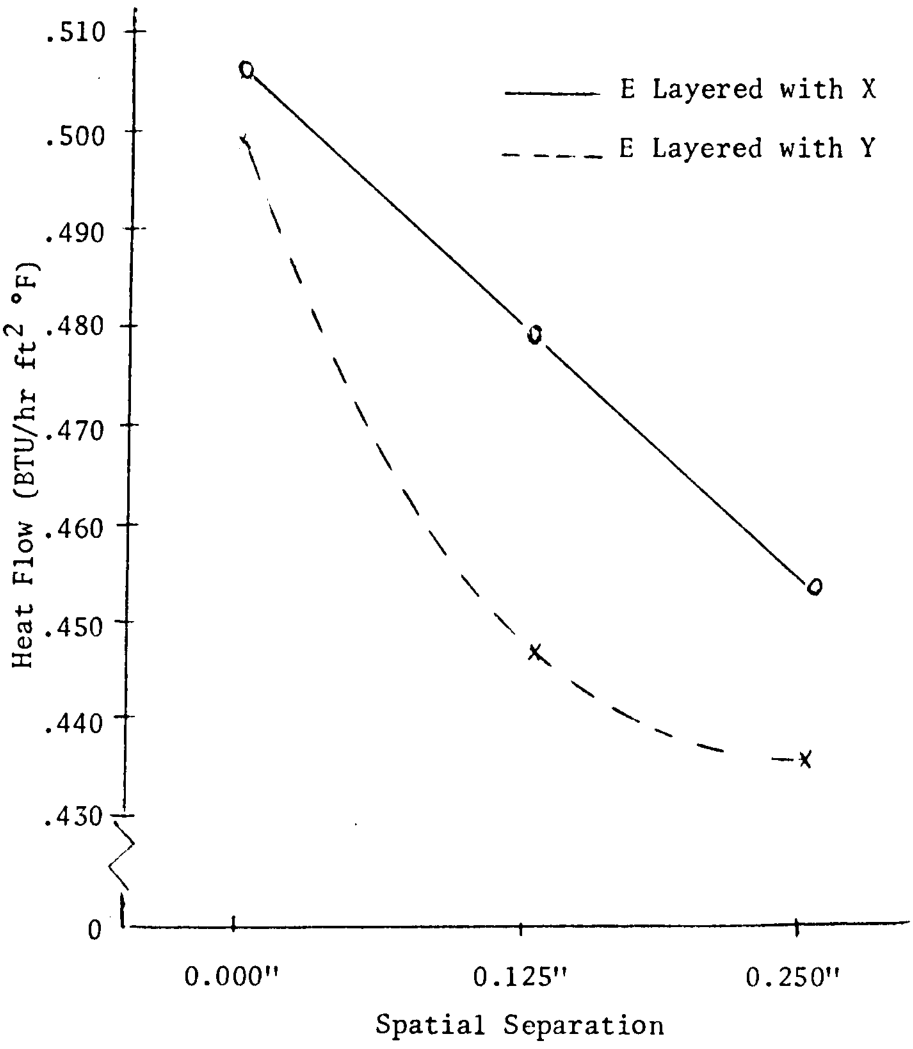


Figure 16. Mean heat transmission of outer fabric E layered with shirt fabrics X and Y at each spatial separation.

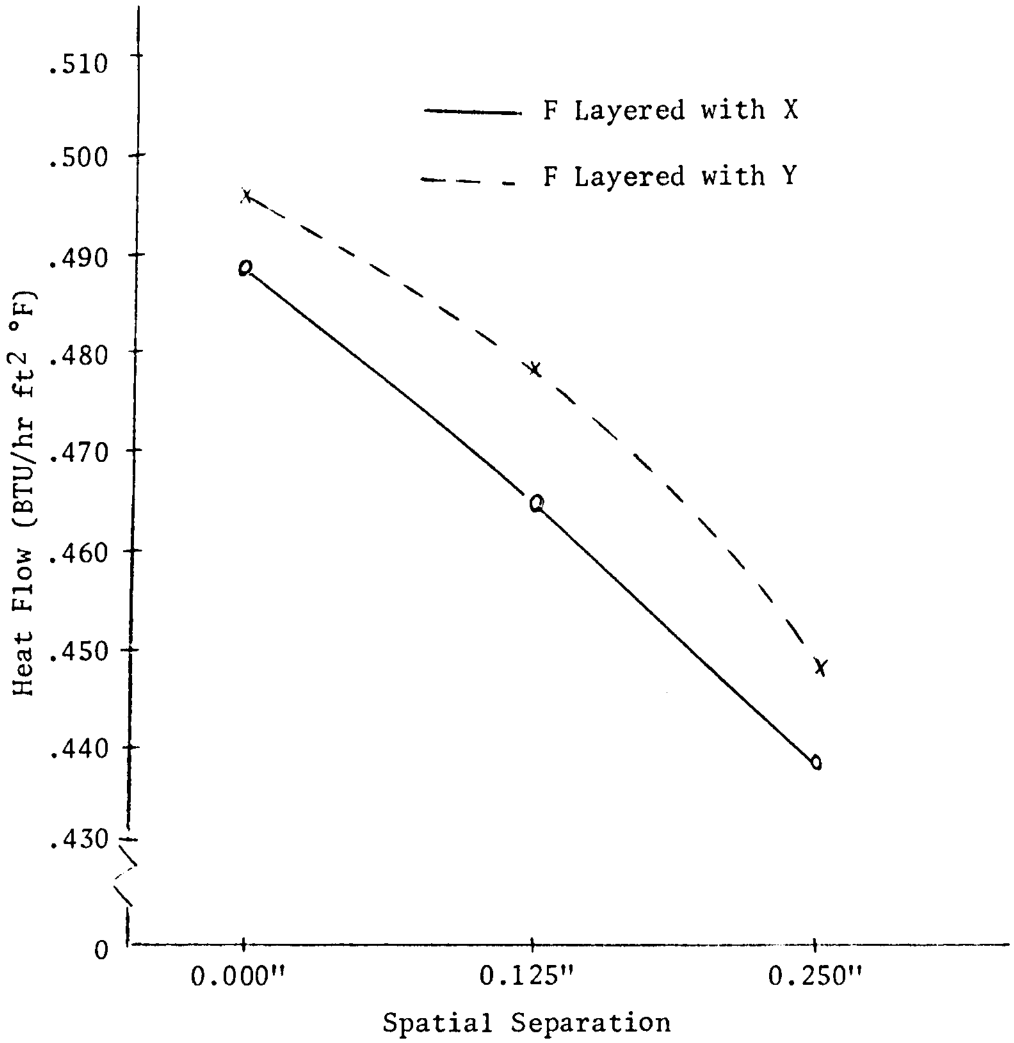


Figure 17. Mean heat transmission of outer fabric F layered with shirt fabrics X and Y at each spatial separation.

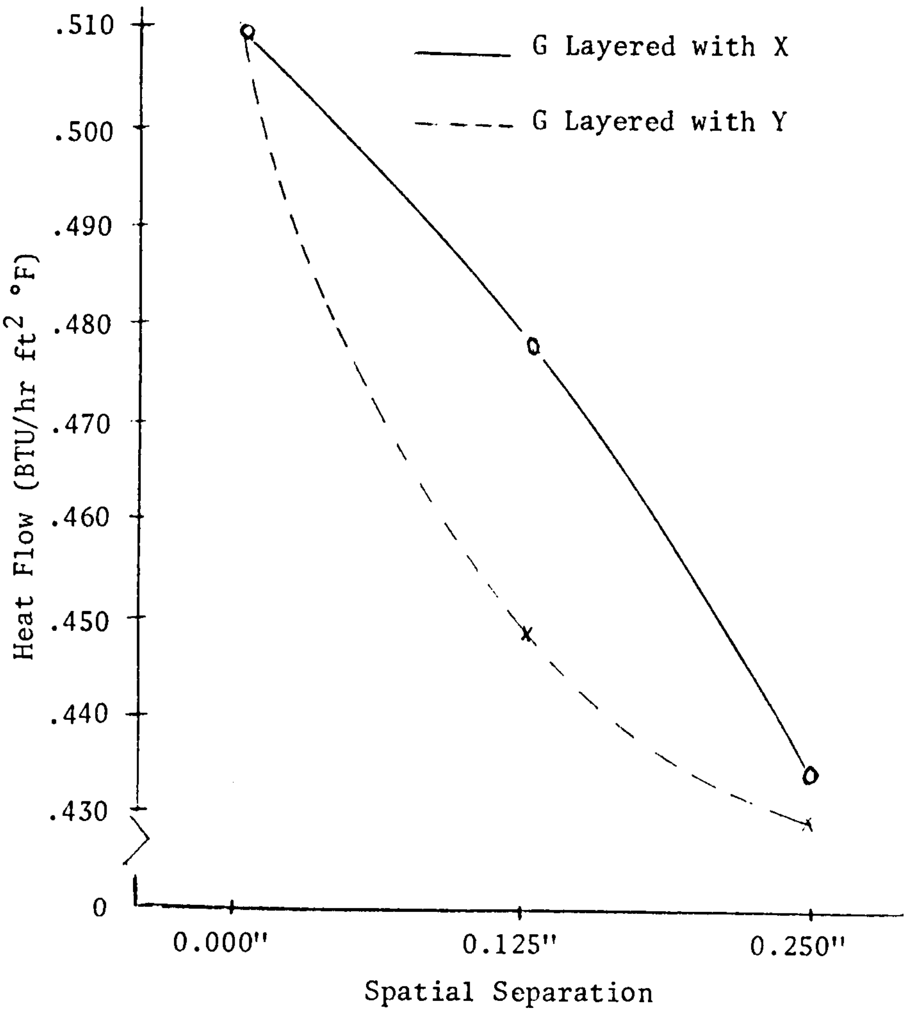


Figure 18. Mean heat transmission of outer fabric G layered with shirt fabrics X and Y at each spatial separation.

IV. RESISTANCE TO HEAT FLOW OF SINGLE VERSUS DOUBLE LAYERS

Each of the single fabrics exhibited lower resistance to heat flow than did the assemblies of outer fabric and shirt fabric. A comparison of the means for the resistances of the single layers and the means of the resistances calculated for the fabrics as they are in assemblies of outer fabric and shirt fabric are given in Table 13.

For both single and double layers, results of the analysis of variance indicate that the outer fabric, the shirt fabric, and the temperature-relative humidity were significant factors at a level of 0.01 in determining resistance to heat flow through fabrics. In addition, in the analysis of covariance, fabric thickness replaced the outer fabric as contributing significantly to the resistance when the fabrics were tested in assemblies. For the analysis of single layers, thickness replaced both the outer and shirt fabrics as significant factors. This can perhaps be expected since the outer fabrics and shirt fabrics have a wide range of measurements of thickness.

Contrasts between the resistances of double layers compared to single layers were found to be significant in each case at a level of 0.01 as shown in Table 14. The total heat transfer of the assemblies was lower than that for any of the single layer components tested individually, resulting in a higher resistance. Figures 19 through 32 show the increase in resistance caused by layering the shirt and outer fabrics. Even though the intervals between humidities are not uniform, the plotting of results in this manner should not negate the trend.

TABLE 13

COMPARISON OF MEANS FOR RESISTANCE OF FABRICS IN SINGLE AND DOUBLE LAYERS

Fabric	Resistance to Heat Flow (°F hr ft^2/BTU)[a] Single	Double
Outer Fabrics		
A	0.926	1.248
B	0.842	1.154
C	0.894	1.199
D	0.889	1.196
E	0.899	1.174
F	0.854	1.188
G	0.882	1.202
Shirt Fabrics		
X	0.770	1.206
Y	0.842	1.245

[a]Rounded to nearest 0.001.

TABLE 14

CONTRASTS OF DOUBLE-LAYER ASSEMBLIES AND SINGLE LAYER COMPONENTS

Contrasts[a]	SS	F
A Over X Contrasted with A + X		
0.000" Spatial Separation	0.1419	47.08**
0.125" Spatial Separation	0.4282	160.01**
0.250" Spatial Separation	0.5134	170.38**
A Over Y Contrasted with A + Y		
0.000" Spatial Separation	0.1534	50.93**
0.125" Spatial Separation	0.5277	175.12**
0.250" Spatial Separation	0.6264	207.89**
B Over X Contrasted with B + X		
0.000" Spatial Separation	0.0899	29.83**
0.125" Spatial Separation	0.3534	117.26**
0.250" Spatial Separation	0.5256	174.44**
B Over Y Contrasted with B + Y		
0.000" Spatial Separation	0.0871	28.90**
0.125" Spatial Separation	0.2985	99.06**
0.250" Spatial Separation	0.6028	200.04**
C Over X Contrasted with C + X		
0.000" Spatial Separation	0.9102	30.21**
0.125" Spatial Separation	0.3796	125.98**
0.250" Spatial Separation	0.5625	186.67**
C Over Y Contrasted with C + Y		
0.000" Spatial Separation	0.1104	36.65**
0.125" Spatial Separation	0.4214	139.83**
0.250" Spatial Separation	0.5526	180.40**
D Over X Contrasted with D + X		
0.000" Spatial Separation	0.1214	40.27**
0.125" Spatial Separation	0.3296	109.40**
0.250" Spatial Separation	0.6445	213.88**
D Over Y Contrasted with D + Y		
0.000" Spatial Separation	0.1628	54.04**
0.125" Spatial Separation	0.3147	104.43**
0.250" Spatial Separation	0.4835	160.44**

TABLE 14 (continued)

Contrasts[a]	SS	F
E Over X Contrasted with E + X		
0.000" Spatial Separation	0.0977	32.42**
0.125" Spatial Separation	0.3084	102.34**
0.250" Spatial Separation	0.4854	161.10**
E Over Y Contrasted with E + Y		
0.000" Spatial Separation	0.1267	42.04**
0.125" Spatial Separation	0.1997	66.28**
0.250" Spatial Separation	0.5576	185.03**
F Over X Contrasted with F + X		
0.000" Spatial Separation	0.1715	56.91**
0.125" Spatial Separation	0.3851	127.81**
0.250" Spatial Separation	0.6525	216.52**
F Over Y Contrasted with F + Y		
0.000" Spatial Separation	0.1514	50.25**
0.125" Spatial Separation	0.2901	96.26**
0.250" Spatial Separation	0.5398	179.12**
G Over X Contrasted with G + Y		
0.000" Spatial Separation	0.0949	31.49**
0.125" Spatial Separation	0.3155	104.69**
0.250" Spatial Separation	0.6586	218.55**
G Over Y Contrasted with G + Y		
0.000" Spatial Separation	0.1072	35.57**
0.125" Spatial Separation	0.4415	146.51**
0.250" Spatial Separation	0.6616	219.57**

[a]A-G = outer fabrics; X-Y = shirt fabrics.

[b]**Indicates significance at 0.01.

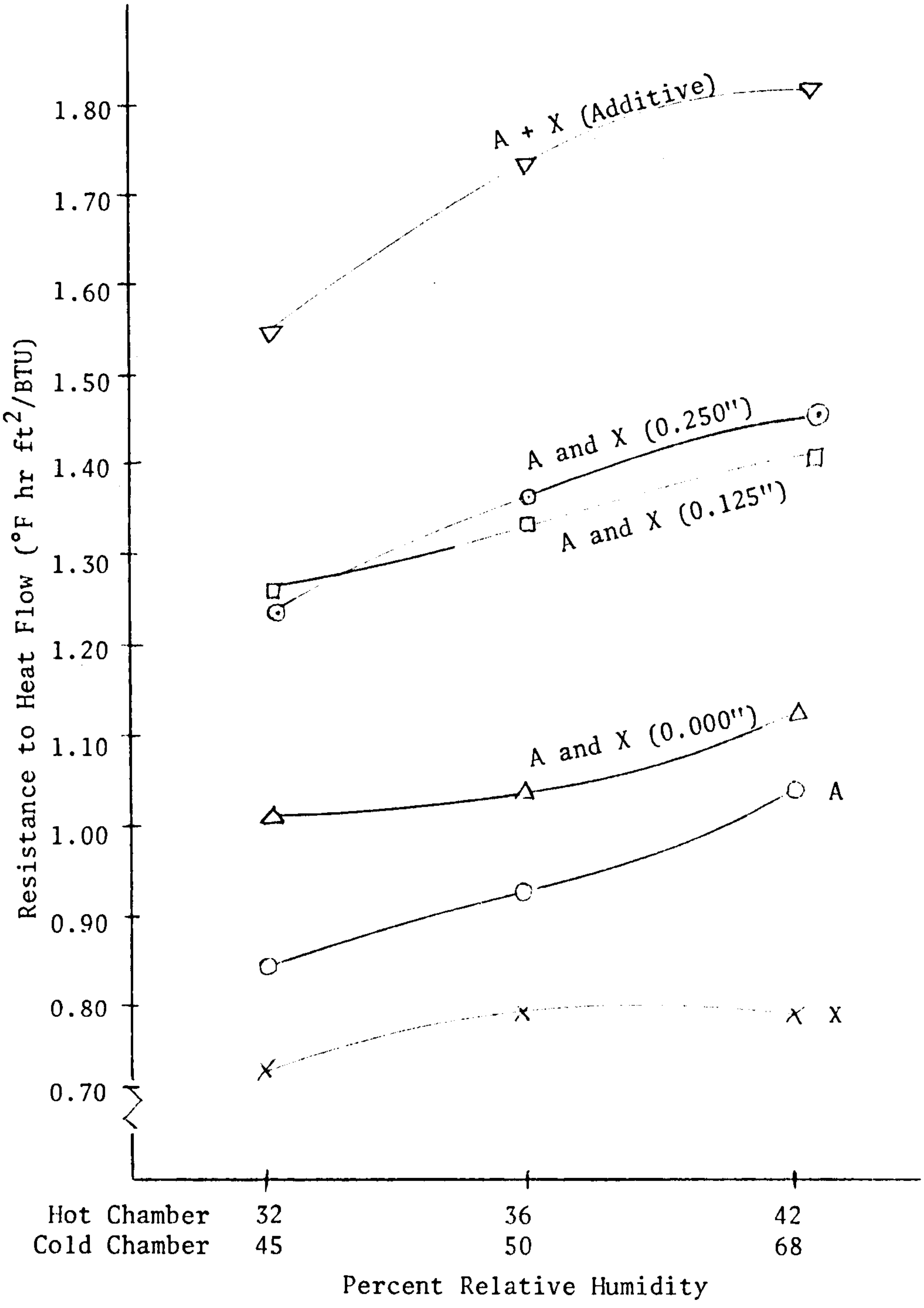


Figure 19. Changes in resistance when outer fabric A is layered with shirt fabric X.

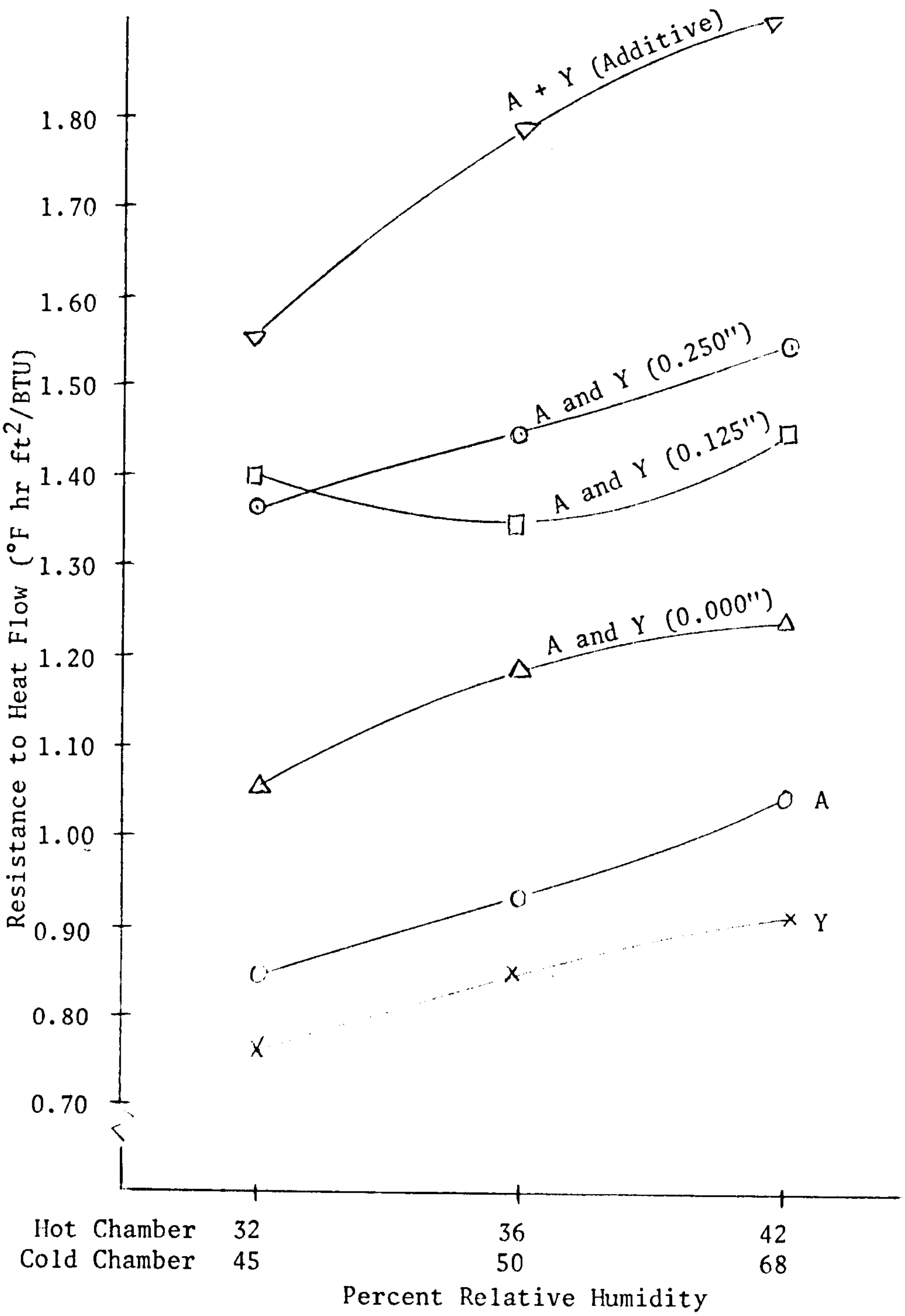


Figure 20. Changes in resistance when outer fabric A is layered with shirt fabric Y.

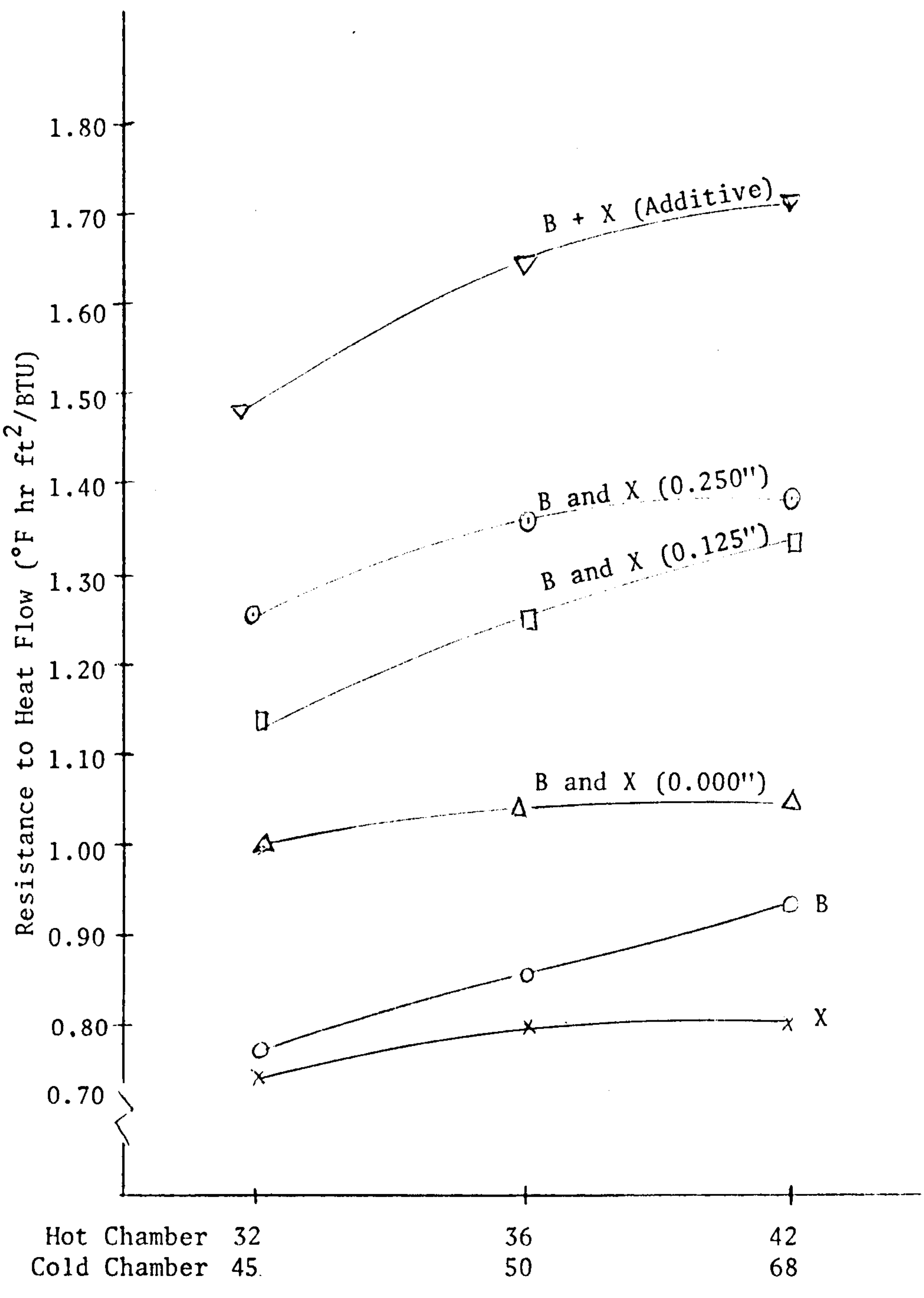


Figure 21. Changes in resistance when outer fabric B is layered with shirt fabric X.

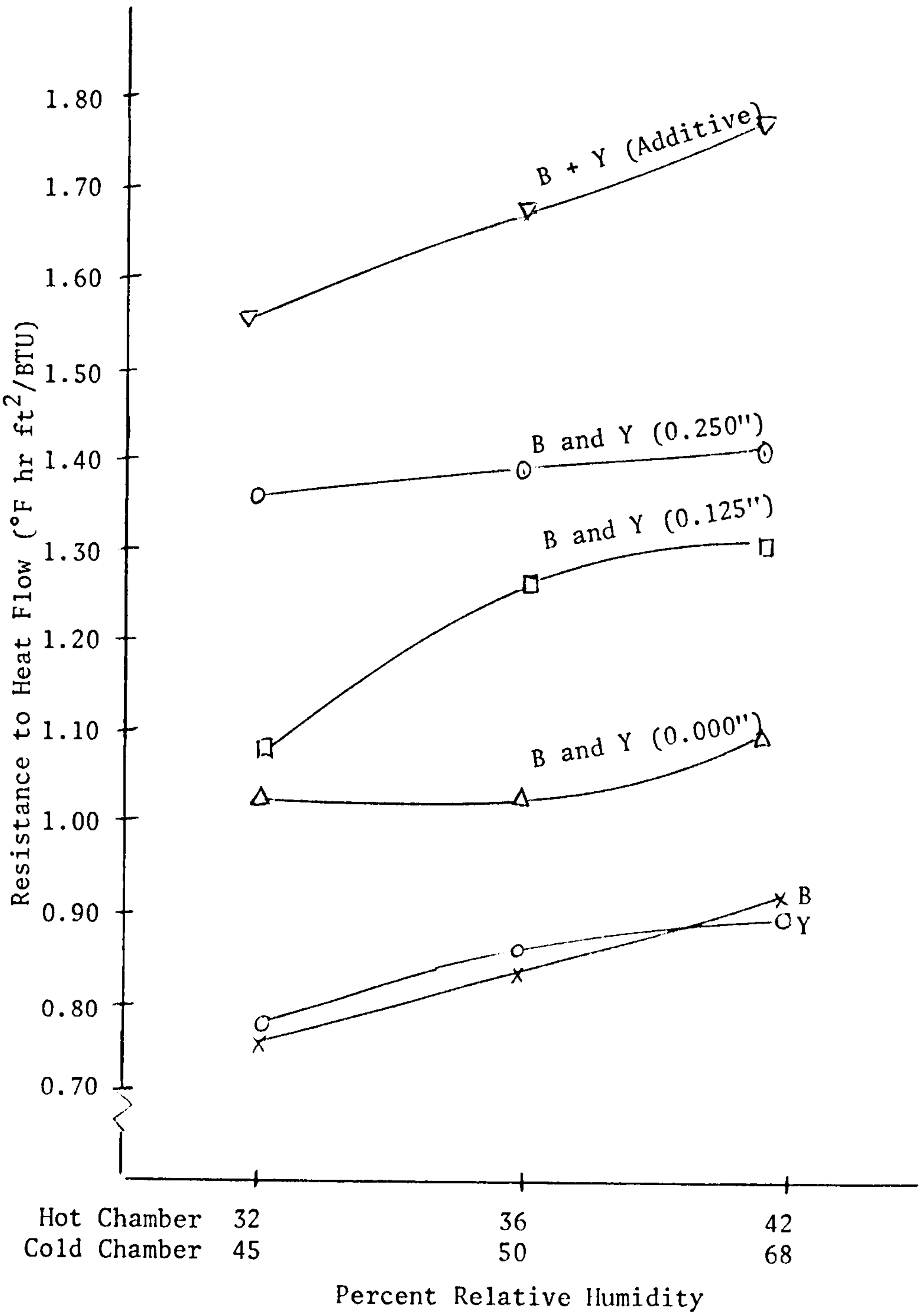


Figure 22. Changes in resistance when outer fabric B is layered with shirt fabric Y.

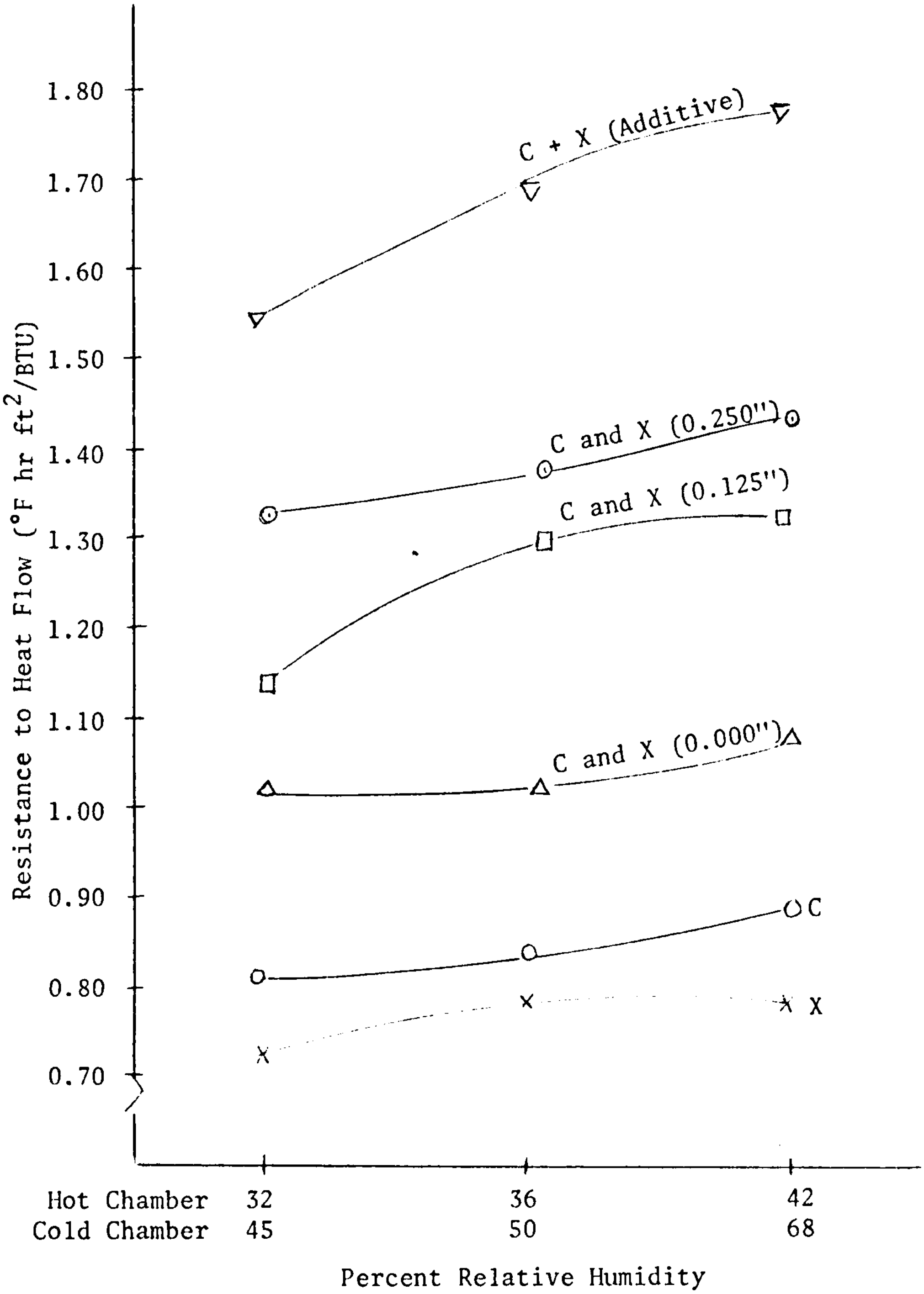


Figure 23. Changes in resistance when outer fabric C is layered with shirt fabric X.

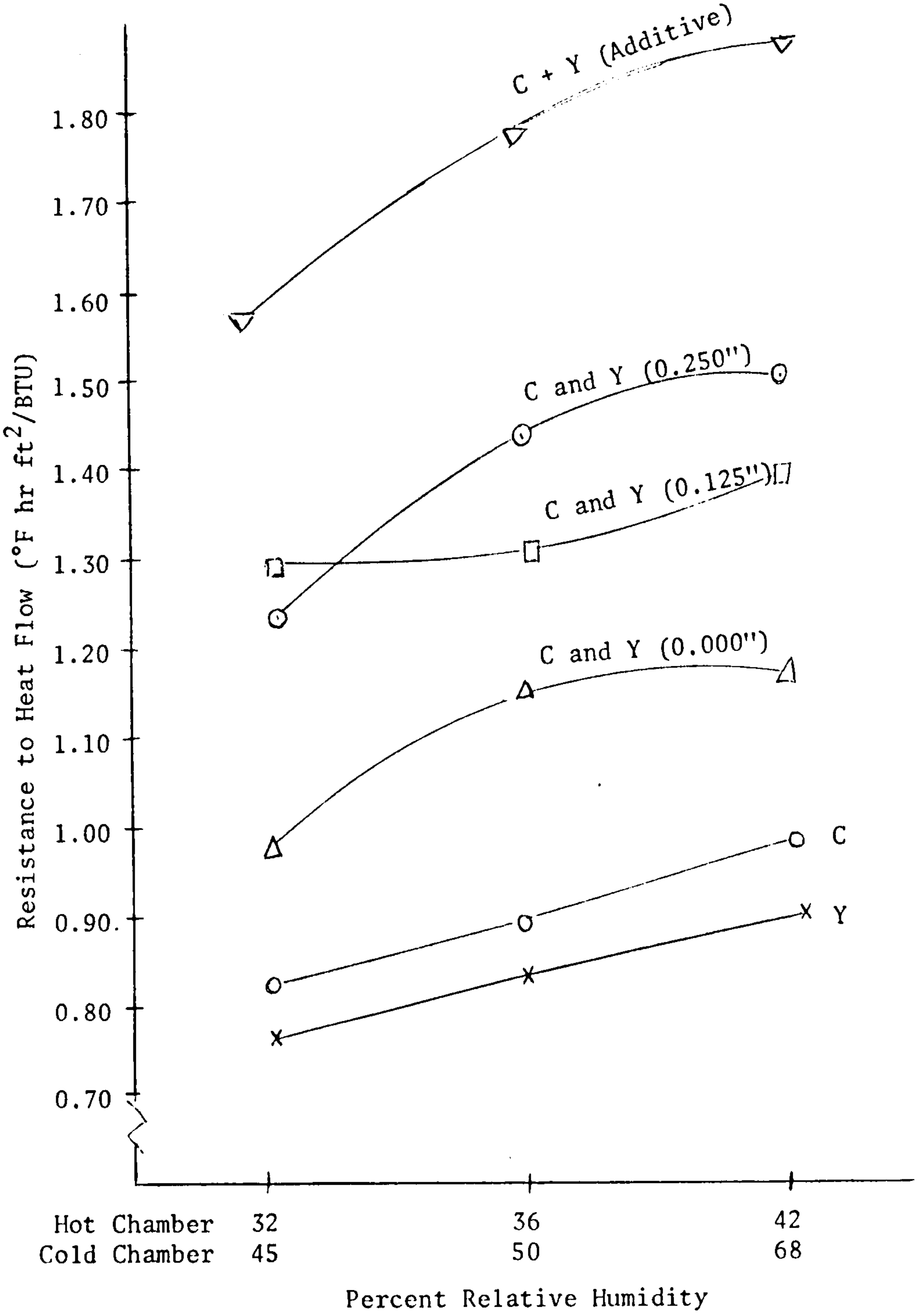


Figure 24. Changes in resistance when outer fabric C is layered with shirt fabric Y.

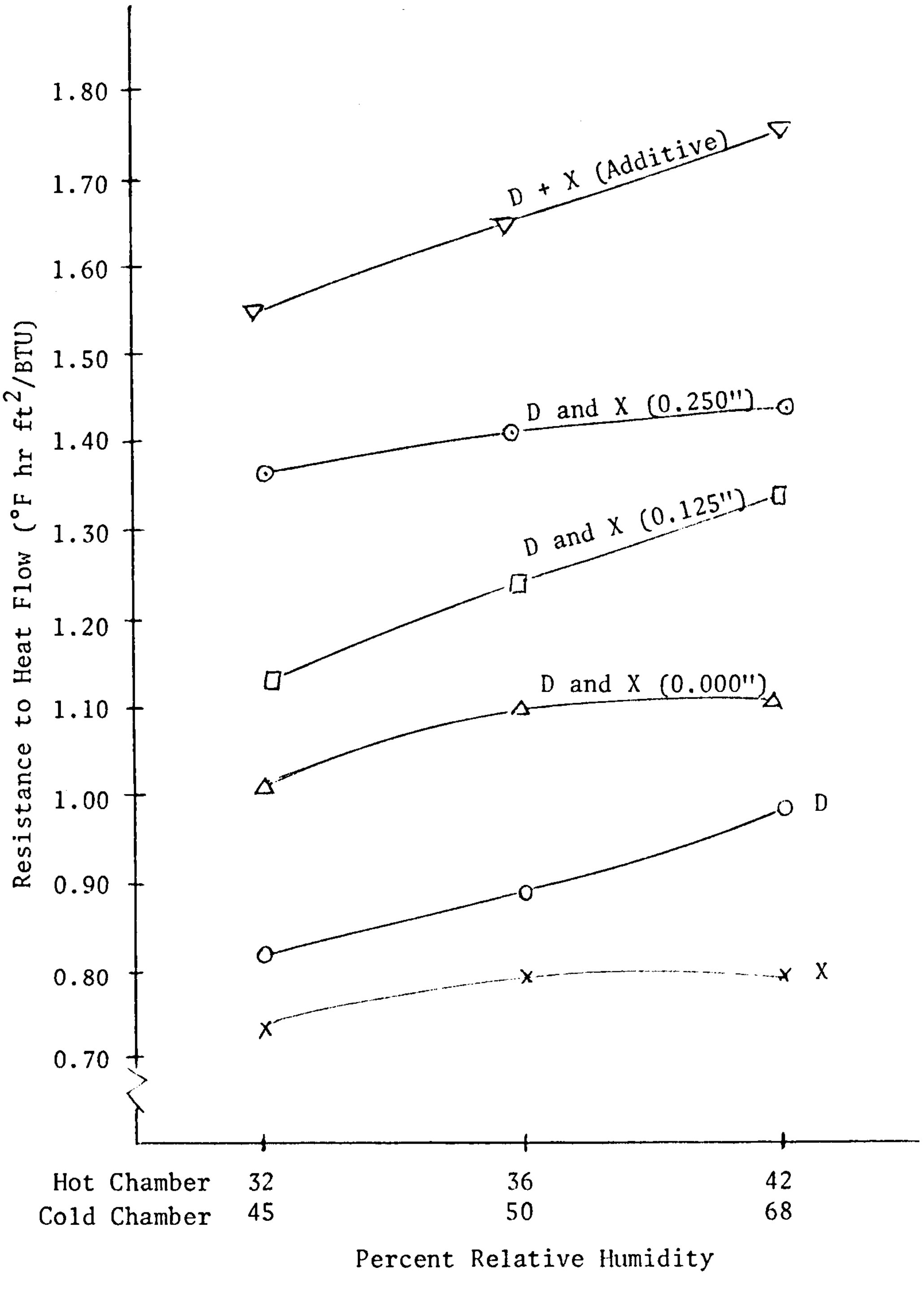


Figure 25. Changes in resistance when outer fabric D is layered with shirt fabric X.

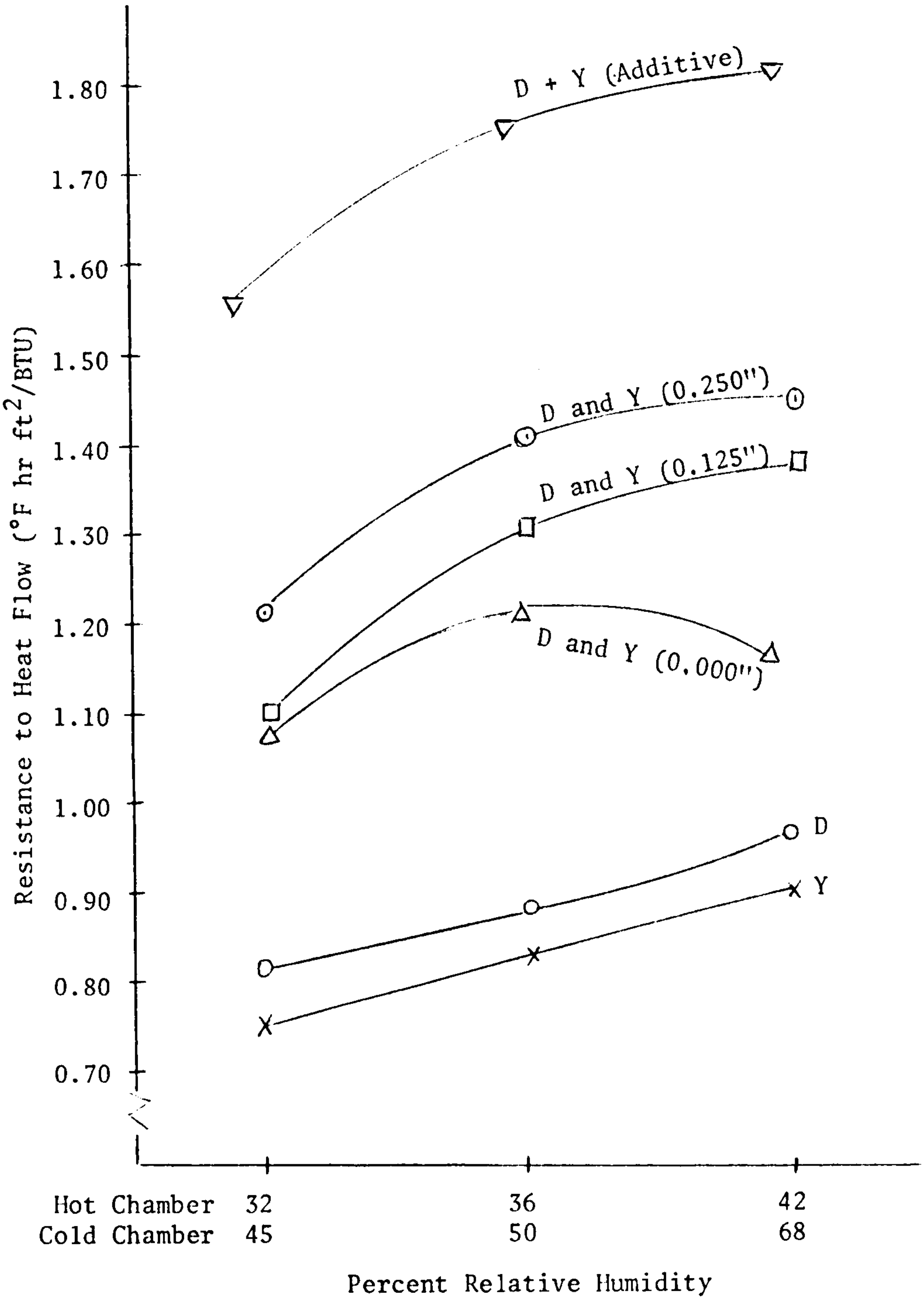


Figure 26. Changes in resistance when outer fabric D is layered with shirt fabric Y.

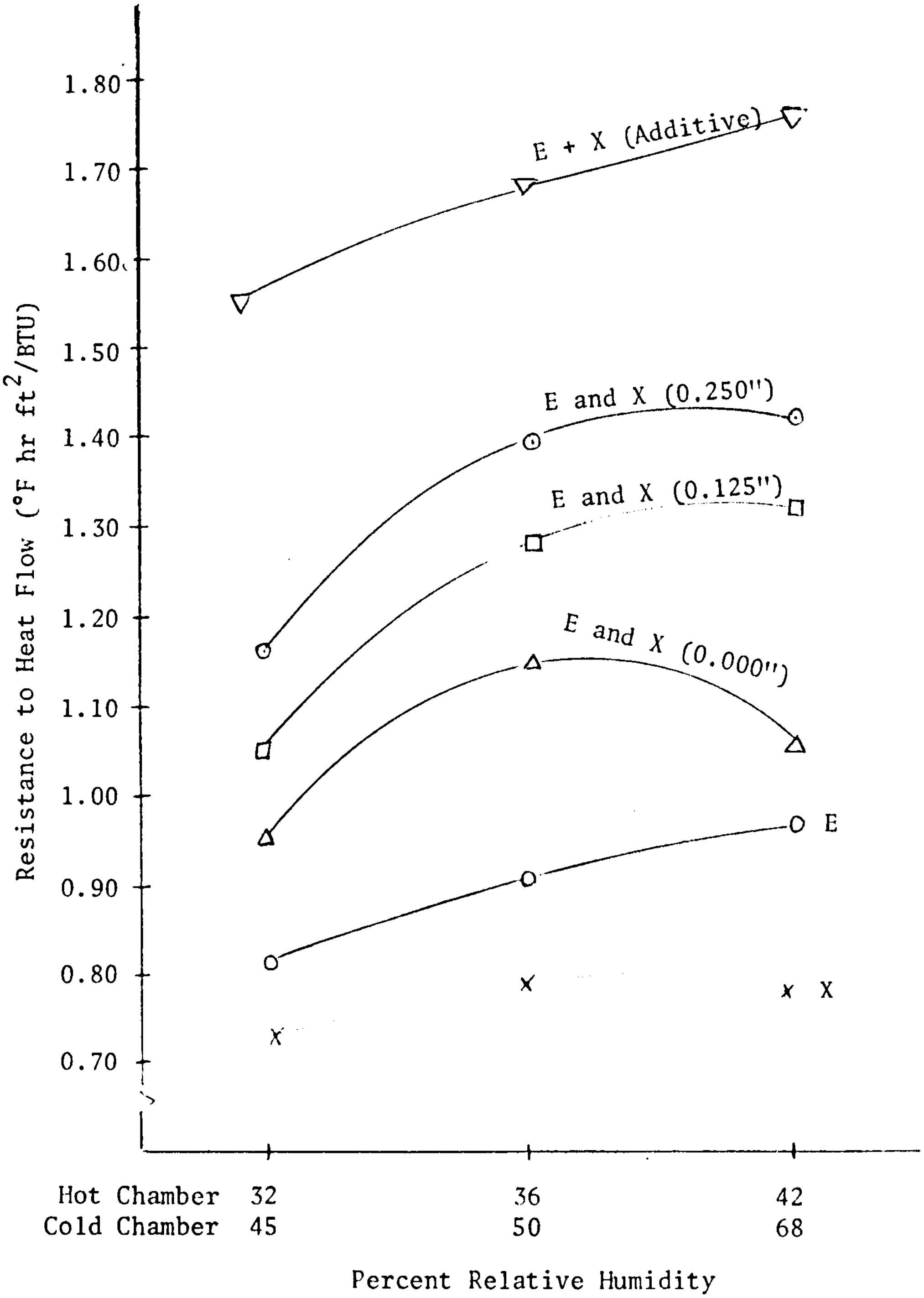


Figure 27. Changes in resistance when outer fabric E is layered with shirt fabric X.

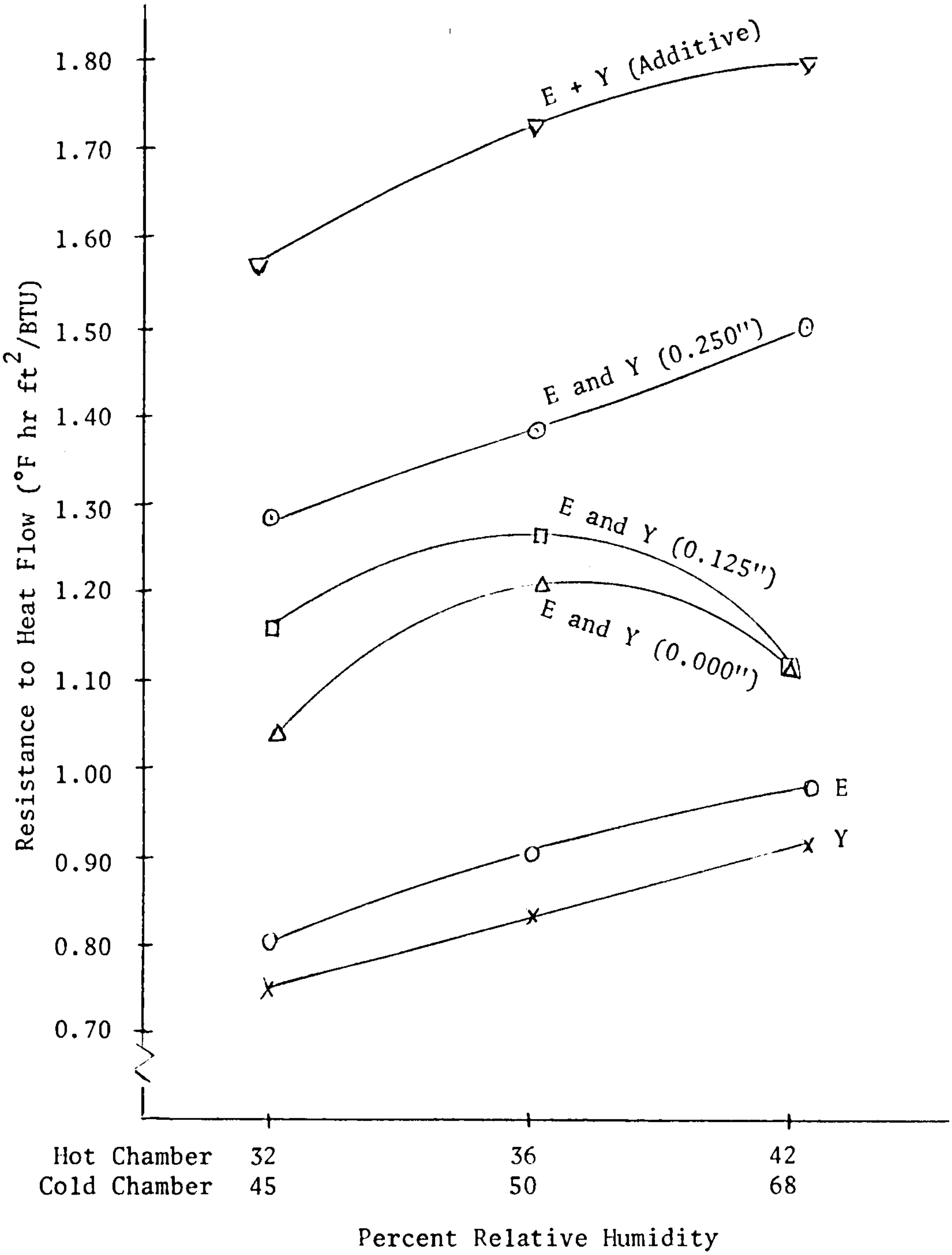


Figure 28. Changes in resistance when outer fabric E is layered with shirt fabric Y.

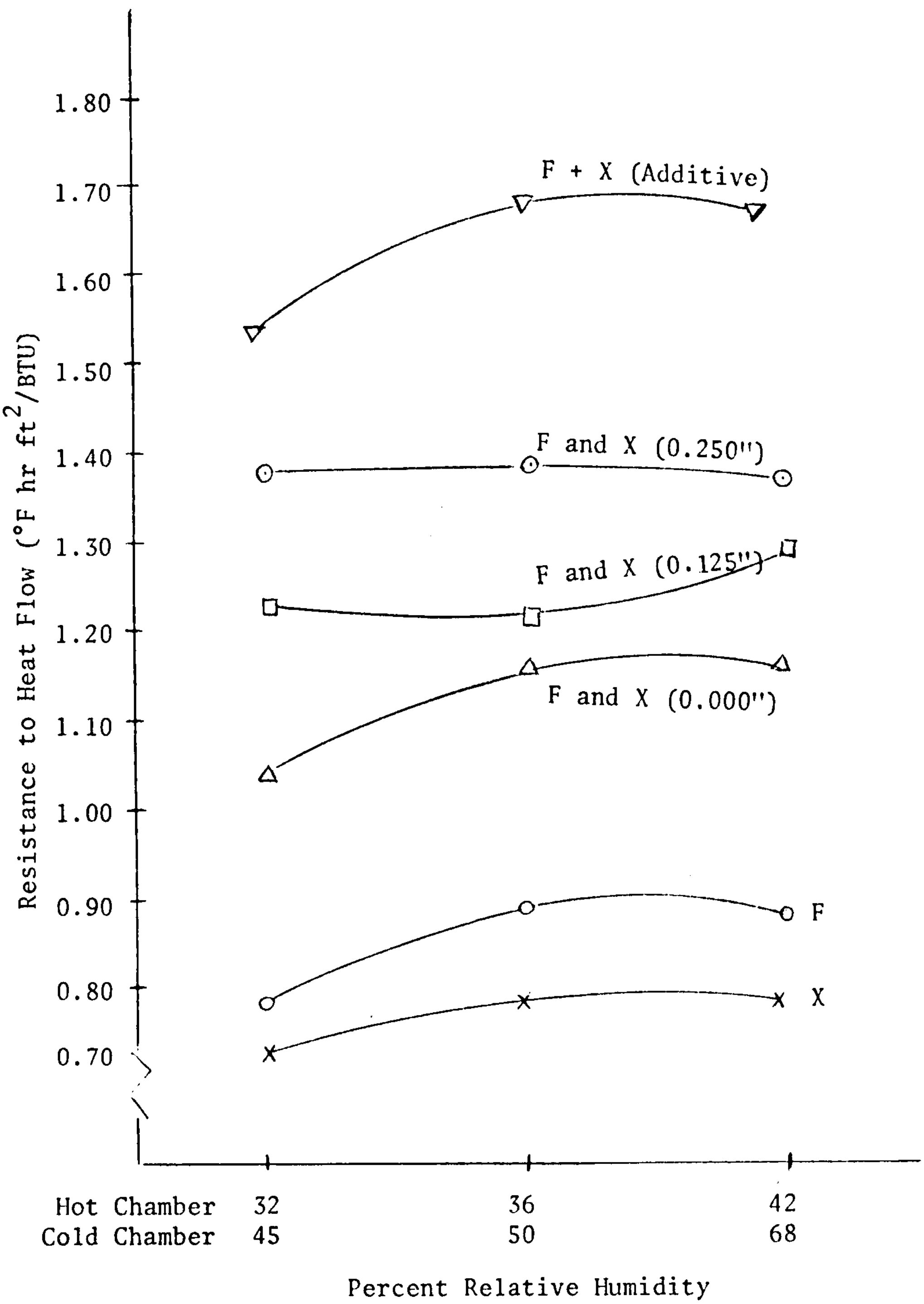


Figure 29. Changes in resistance when outer fabric F is layered with shirt fabric X.

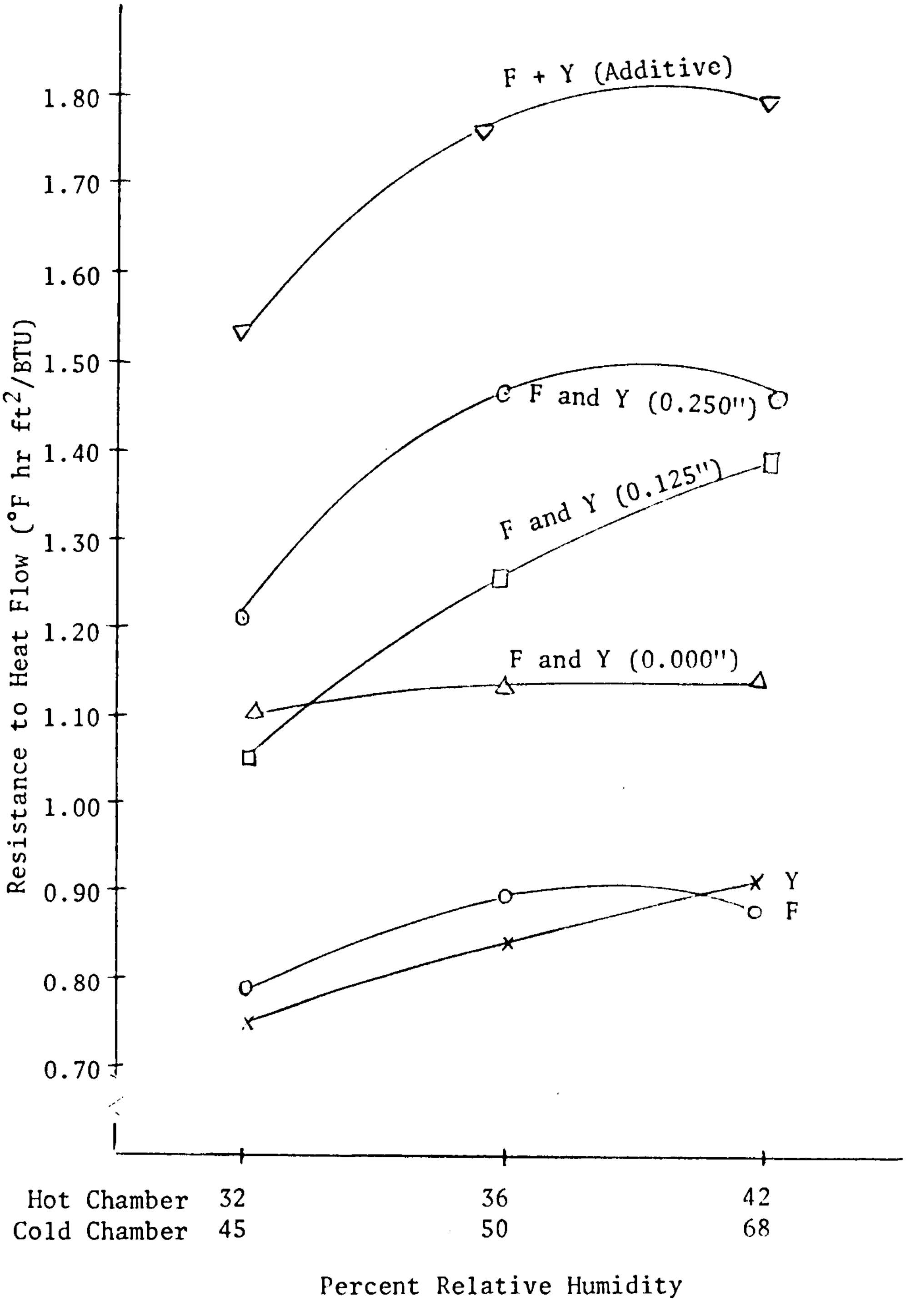


Figure 30. Changes in resistance when outer fabric F is layered with shirt fabric Y.

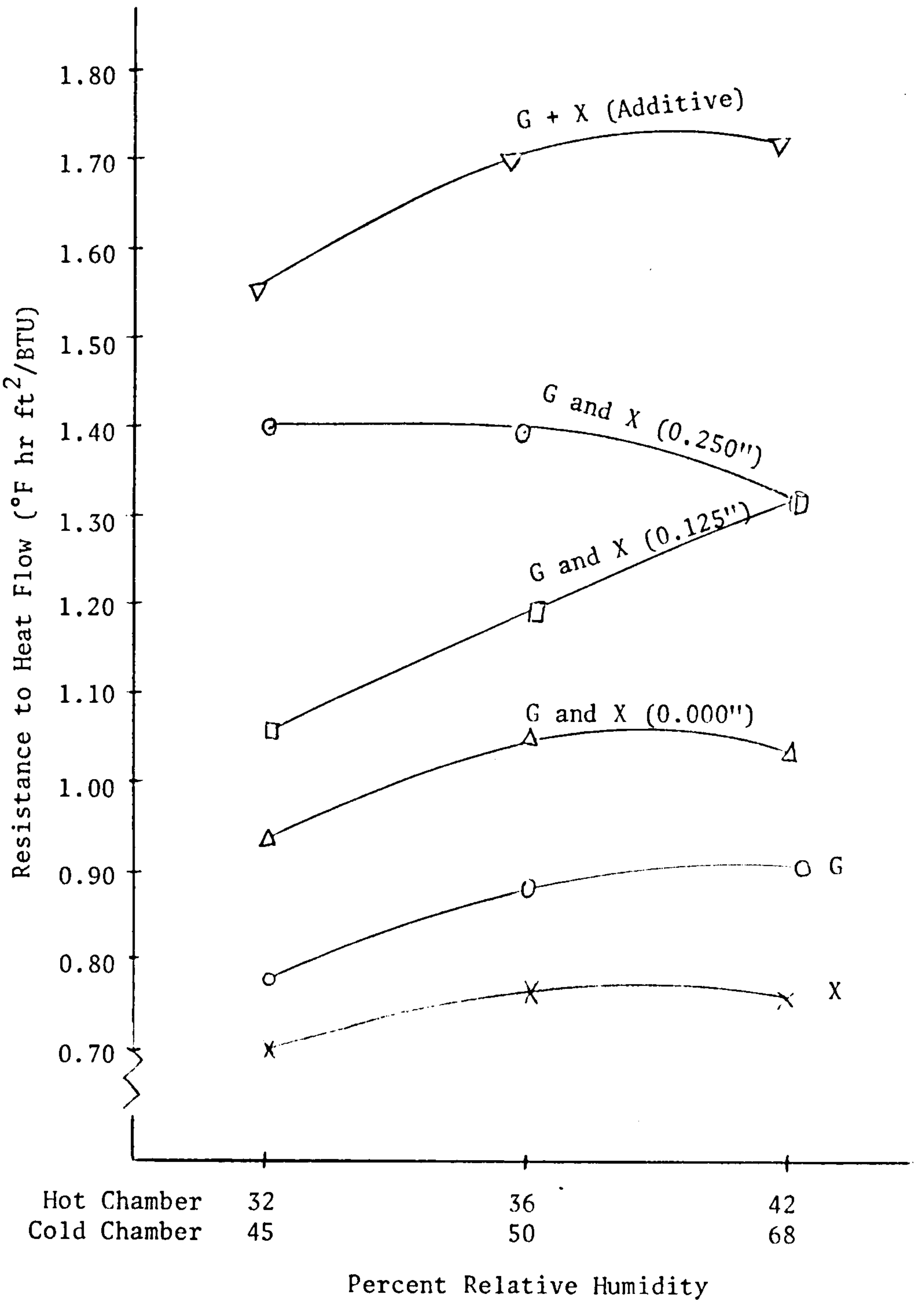


Figure 31. Changes in resistance when outer fabric G is layered with shirt fabric X.

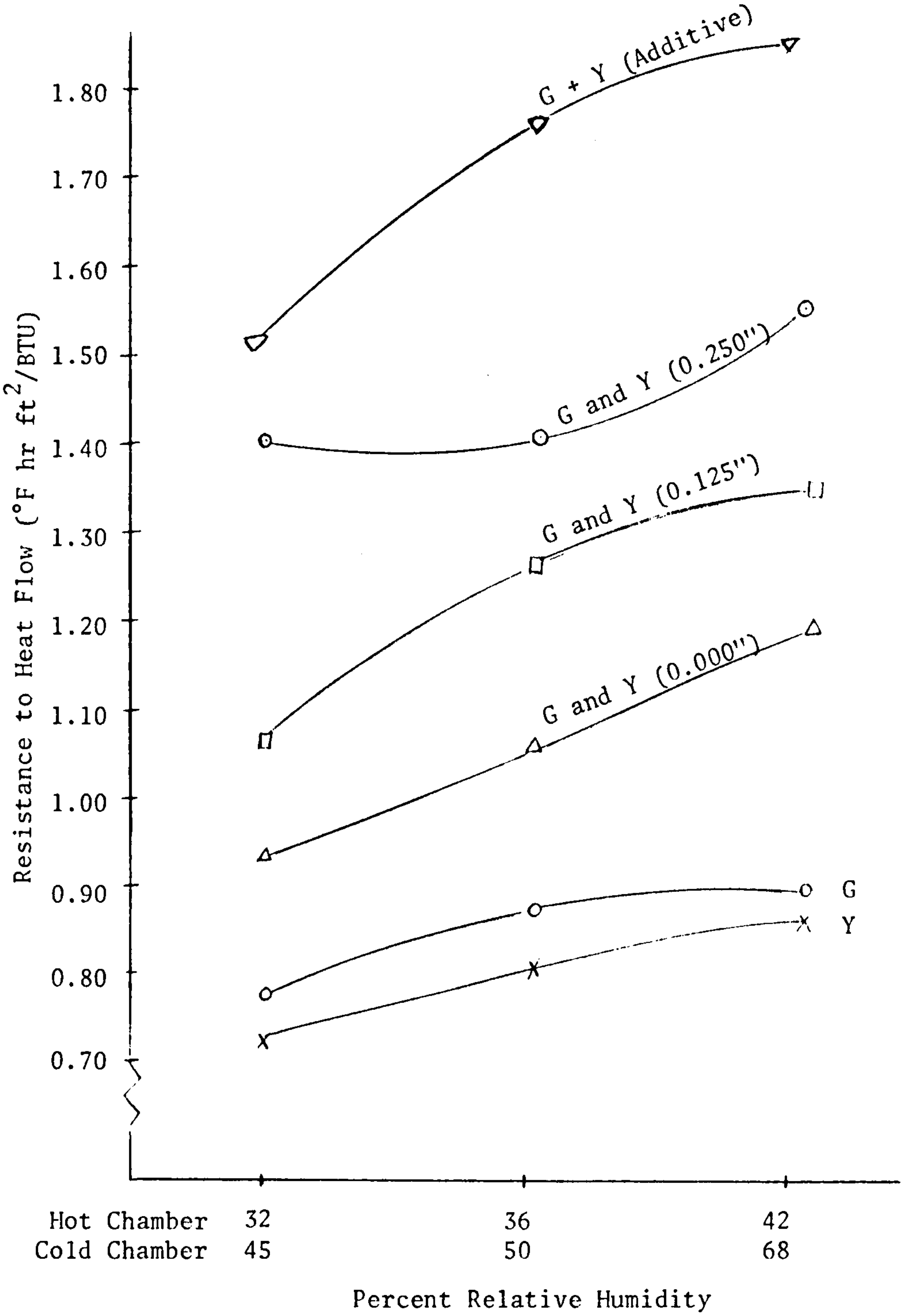


Figure 32. Changes in resistance when outer fabric G is layered with shirt fabric Y.

Regression analysis of thickness and resistance, using the measured thickness of the combination of outer fabric and shirt fabric at 0.000" separation, indicates that a given unit increase in the thickness of the double layers is associated with a greater increase in resistance (2.63) than is the case for single layers (2.39). This finding is in agreement with findings reported by Morris (61); she reported that the "increasing thickness of multiple layers of fabrics is associated with larger concomitant increases in the total amount of air held within the structure than would be the case for single fabrics."

Although the resistance values of the double layers were higher than those for the individual fabric components, the increase did not show an additive relationship which was found by other investigators (34, 61). However, the differences in the expected and the measured values are explained as follows.

Mechanism of the Instrument

The heat and mass transfer tester (HMT) is specifically designed to provide for measurement of environmental parameters between the heat source and the specimen. Therefore, the space between the heat source and the fabric must be large enough to accommodate a sensor. This volume (6" × 6" × 2 5/8") allows convection to take place before the heat reaches the fabric.

In comparison, many of the instruments used in other studies (such as the guarded hot plate and heated mannikins) have very little convective effect due to the limited air space between the heat source and the fabric. Consequently, very little heat is lost due to the convective action under the fabric or fabrics.

Gardner, Grady, and Mohamed (32) report that a weakness of the guarded hot plate and previously used heat flow meter for "measuring thermal conductivity is that they do not allow for free air circulation around the samples as that would occur in actual use. The presence of air currents alters the heat flow and thus affects the thermal conductivity."

Fabric Thickness

It has been discussed previously that thickness is the best predictor of resistance to heat flow for the fabrics under investigation. In order to determine if the change in resistance could be predicted by the change in thickness, measurements of the thickness of the outer fabric layered with each shirt fabric at 0.000" separation were made. The thickness of combined layers was compared with the sum of the individual thickness values of fabrics under investigation.

The results show that the combined measured values of thickness are found to be lower than the additive values. At the same time, the measured values of resistance of the double layers are generally lower than the additive values. Therefore, it appears that the differences in thickness may account for the differences in the resistance. Table 15 shows the differences in the measured and additive values of thickness and resistance.

TABLE 15

COMPARISON OF MEASURED AND ADDITIVE THICKNESS AND RESISTANCE MEASUREMENTS OF FABRICS IN DOUBLE LAYERS

Fabric Combination[a]	Thickness, Inches		Resistance (°F hr ft^2/BTU)[b]	
	Measured	Additive	Measured	Additive
A and X	0.070	0.076	1.114	1.696
A and Y	0.075	0.082	1.161	1.768
B and X	0.030	0.036	1.018	1.610
B and Y	0.038	0.042	1.051	1.684
C and X	0.049	0.058	1.045	1.664
C and Y	0.055	0.064	1.103	1.736
D and X	0.047	0.055	1.076	1.659
D and Y	0.054	0.061	1.151	1.731
E and X	0.039	0.043	1.056	1.669
E and Y	0.047	0.049	1.122	1.741
F and X	0.043	0.052	1.105	1.624
F and Y	0.055	0.058	1.123	1.696
G and X	0.052	0.056	1.044	1.652
G and Y	0.058	0.062	1.094	1.724

[a]Fabric combination is outer fabric layered over shirt fabric at 0.000" separation.

[b]Rounded to nearest 0.001.

V. TEMPERATURE-RELATIVE HUMIDITY AND RESISTANCE TO HEAT FLOW

The three different combinations of temperature and relative humidity investigated were found to be significantly different from each other in providing resistance to heat flow, as shown in the contrasts in Table 16. Figure 33 shows the change in resistance with the change in relative humidity. Throughout the experimental investigation, the temperature was held constant at 94 ± 2°F in the hot chamber and 69 ± 2°F in the cold chamber.

As the relative humidity increased in each chamber, the resistance to heat flow increased. This can possibly be explained on the basis of moisture transport, swelling of yarns, and the system used to measure the heat flow. The results can be generalized only for the same conditions under which this experiment was conducted.

The least difference in resistance was found between the measurements made at 36 ± 2% RH in the hot chamber, 50 ± 2% RH in the cold chamber, and 42 ± 2% RH in the hot chamber with 68 ± 2% RH in the cold chamber. The largest differences observed were found between the experimental conditions of 42 ± 2% RH in the hot chamber, 68 ± 2% RH in the cold chamber, and 32 ± 2% RH in the hot chamber with 45 ± 2% RH in the cold chamber. The means for the resistance measurements are given in Table 17.

In still air, the value of the resistance to water vapor transfer between the outer surface of the clothing and the atmosphere is reduced due to lack of convection. The higher resistance values were possibly caused by the lack of moisture transported due to lack of convection in the air spaces of the fabrics.

TABLE 16

CONTRASTS FOR TEMPERATURE-RELATIVE HUMIDITY COMBINATION AND RESISTANCE

Contrasts[a]	SS	F[b]
TR1—TR2	0.047667	15.51**
TR1—TR3	0.259520	84.46**
TR2—TR3	0.529632	172.38**

[a]TR1 = 94 ± 2°F, 36 ± 2% (hot chamber);
69 ± 2°F, 50 ± 2% (cold chamber).

TR2 = 94 ± 2°F, 42 ± 2% (hot chamber);
70 ± 2°F, 68 ± 2% (cold chamber).

TR3 = 94 ± 2°F, 32 ± 2% (hot chamber);
70 ± 2°F, 45 ± 2% (cold chamber).

[b]**Indicates significance at 0.01.

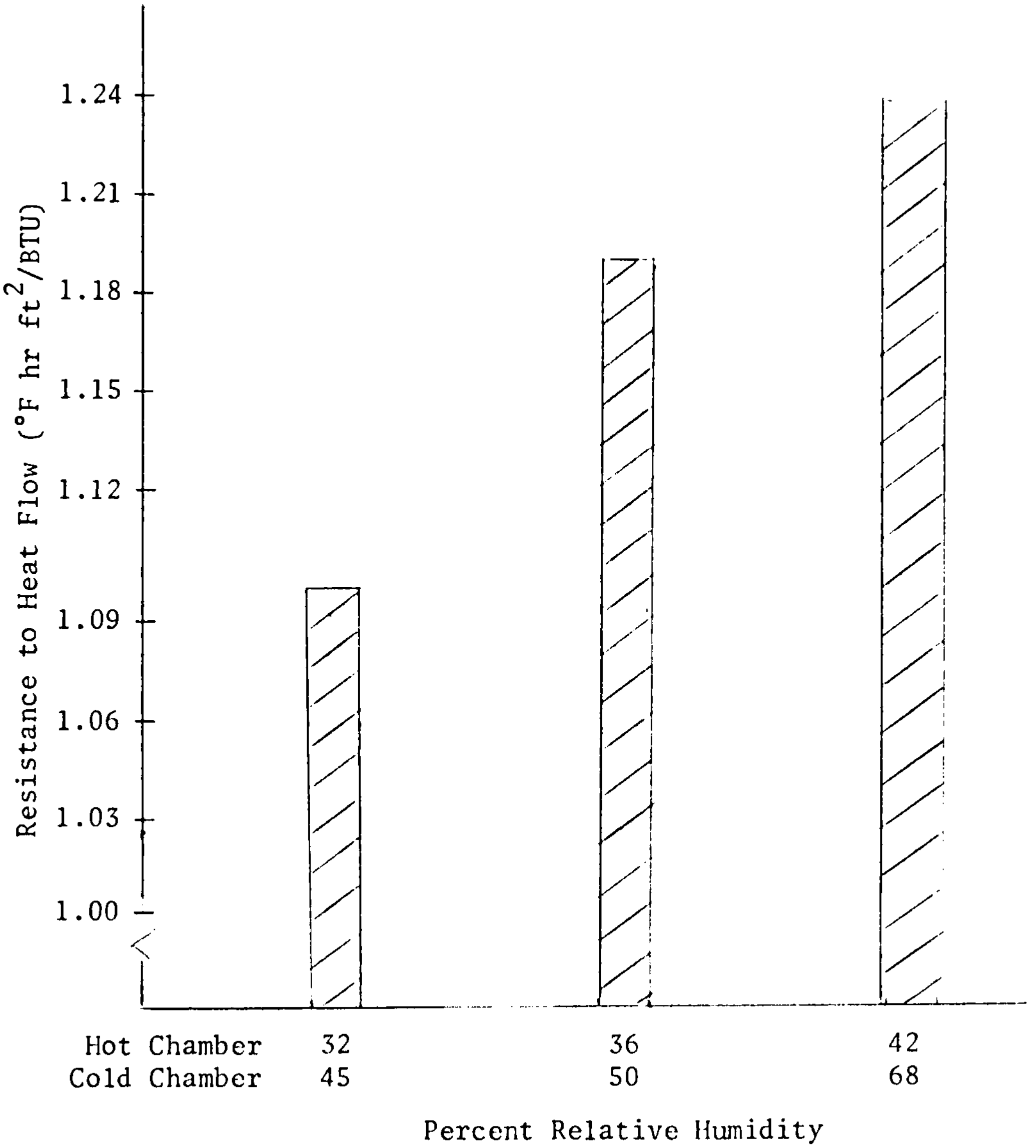


Figure 33. Change in resistance with change in relative humidity.

TABLE 17

MEANS OF RESISTANCE VALUES FOR SINGLE AND DOUBLE-LAYER FABRIC ASSEMBLIES AT EACH COMBINATION OF TEMPERATURE-RELATIVE HUMIDITY

Fabric Assemblies	Resistance (°F hr ft^2/BTU)[a]		
	TR1	TR2	TR3
Single Fabrics			
A	0.933	1.041	0.804
B	0.841	0.921	0.764
C	0.898	0.975	0.809
D	0.887	0.975	0.806
E	0.905	0.975	0.818
F	0.899	0.877	0.787
G	0.917	0.922	0.808
X	0.789	0.789	0.732
Y	0.844	0.916	0.766
Double-Layer			
A and X	1.275	1.351	1.182
A and Y	1.320	1.413	1.269
B and X	1.208	1.235	1.119
B and Y	1.222	1.289	1.158
C and X	1.220	1.296	1.159
C and Y	1.304	1.358	1.162
D and X	1.247	1.297	1.164
D and Y	1.309	1.340	1.122
E and X	1.267	1.281	1.062
E and Y	1.300	1.246	1.161
F and X	1.257	1.259	1.224
F and Y	1.280	1.321	1.119
G and X	1.245	1.258	1.164
G and Y	1.277	1.362	1.224

[a]Rounded to nearest 0.001.

TR1 = 94°F, 36% (hot chamber);
69°F, 50% (cold chamber).

TR2 = 94°F, 42% (hot chamber);
70°F, 68% (cold chamber).

TR3 = 94°F, 32% (hot chamber);
70°F, 45% (cold chamber).

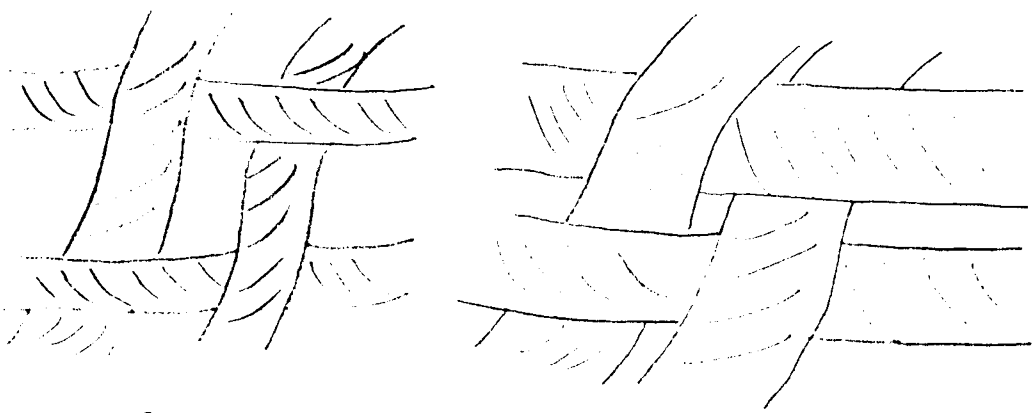
Due to swelling of the structure, the air spaces fill up as the moisture is absorbed from the hot chamber, as shown in Figure 34. When the ambient relative humidity is higher than the moisture content of the fabric, little evaporation from the fabric takes place. The higher the RH, the less likely the moisture in the fabric will evaporate. More heat is required from the hot chamber (or the skin) to keep the moisture warm. Therefore, since the moisture evaporates slowly, the resistance to heat flow is higher.

Depending on the fabric and its ability to absorb moisture, the RH at the skin surface may become high, causing discomfort. However, this phenomenon was not studied in the present investigation. The relative humidity in the hot chamber was controlled to simulate real life conditions.

VI. PHYSICAL PROPERTIES OF THE FABRICS AND RESISTANCE TO HEAT FLOW OF FABRICS IN SINGLE AND DOUBLE LAYERS

Physical properties of the fabrics were determined and included in the statistical analysis in order to determine their effect on the resistance values of the fabrics. The analysis indicates that fabric thickness is a significant factor in contributing to resistance for both single and double layers. Fabric compressibility was a significant factor in the case of single layers only. Each of the physical properties is discussed in terms of its contribution to the insulation value of the fabrics.

The following physical properties of the experimental fabrics were measured according to the procedures given in Chapter III: fabric



Before

After

Figure 34. Comparison of air spaces between yarns before and after moisture is introduced into the fabric.

weight, fabric thickness, yarn count, yarn size, yarn twist, percent yarn crimp, percent fabric compression, percent fabric resilience, fabric cover factor, fabric air permeability, fabric porosity, and fabric moisture regain. Yarn count, yarn size, yarn twist, and yarn crimp were not used in the analysis as they are determinants of cover factor and air permeability. The resulting effect of the physical properties on the resistance to heat flow for both single and double layers is discussed as follows.

Fabric thickness was statistically significant in its contribution to resistance to heat transfer when used as a covariate in the analysis of variance for double and single layers. Other than compressibility of fabric single layers, thickness was the only physical property to be significant.

In addition, thickness was the only property found to be significant ($P < 0.05$) when tested using Pearson product moment correlation and multiple regression analysis ($P < 0.01$). Figure 35 shows the relationship between thickness and resistance to heat flow of the experimental fabrics.

Thick fabrics provide a larger surface area for holding still air, especially if the density is low. Consequently, the flow of heat is impeded due to the poor conductive property of still air (60).

Fabric weight was found to show no particular relationship to heat flow of the experimental fabrics. Even though fabrics G, F, and E are heavier than fabric A, fabric A showed a significantly higher resistance to heat flow than either fabric E or F. Furthermore, fabric E, which is heavier than fabrics C and D, gave a lower resistance. Figure 36 shows the relationship between fabric weight and resistance.

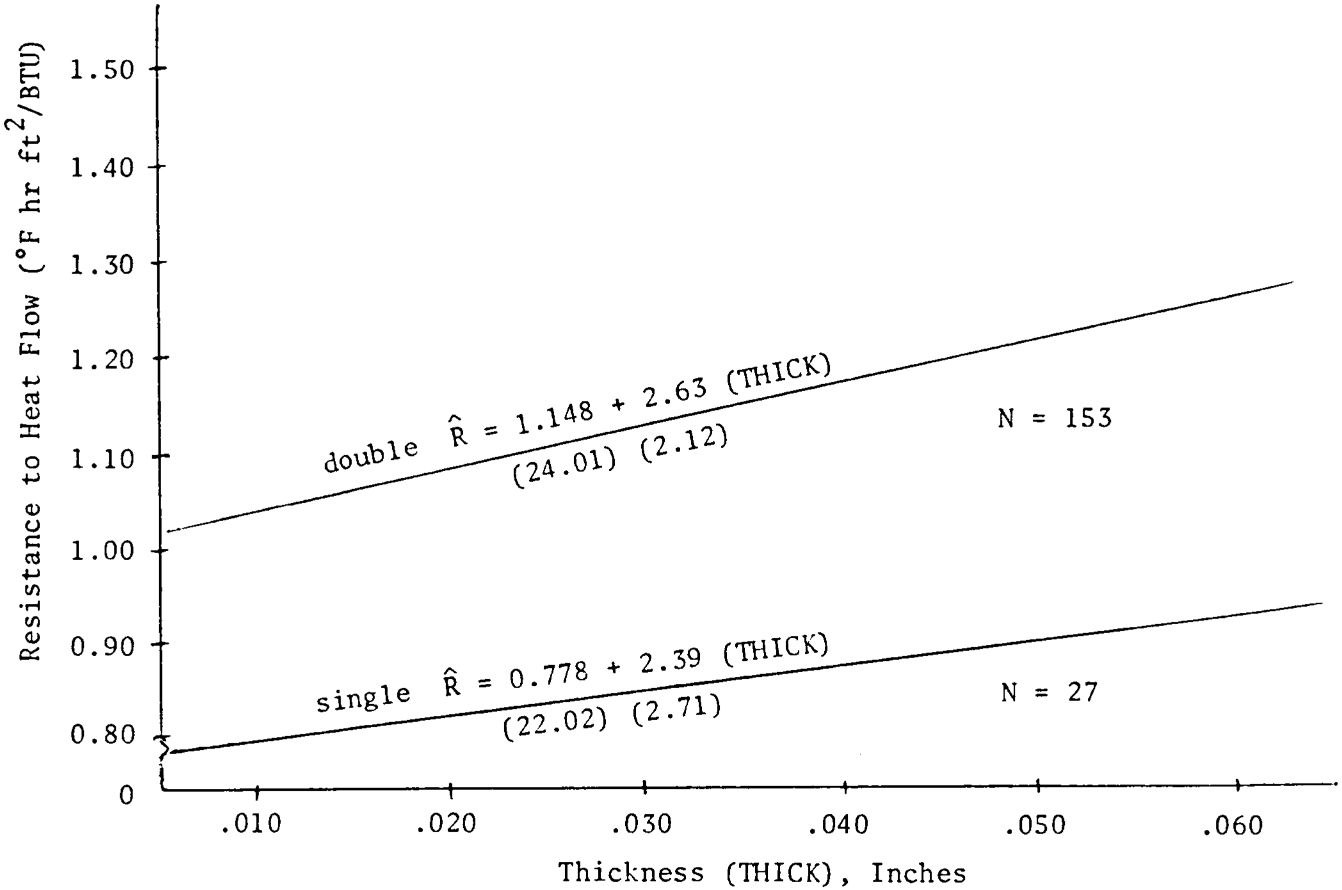


Figure 35. Fabric thickness versus resistance of single and double layers. (t in parentheses.)

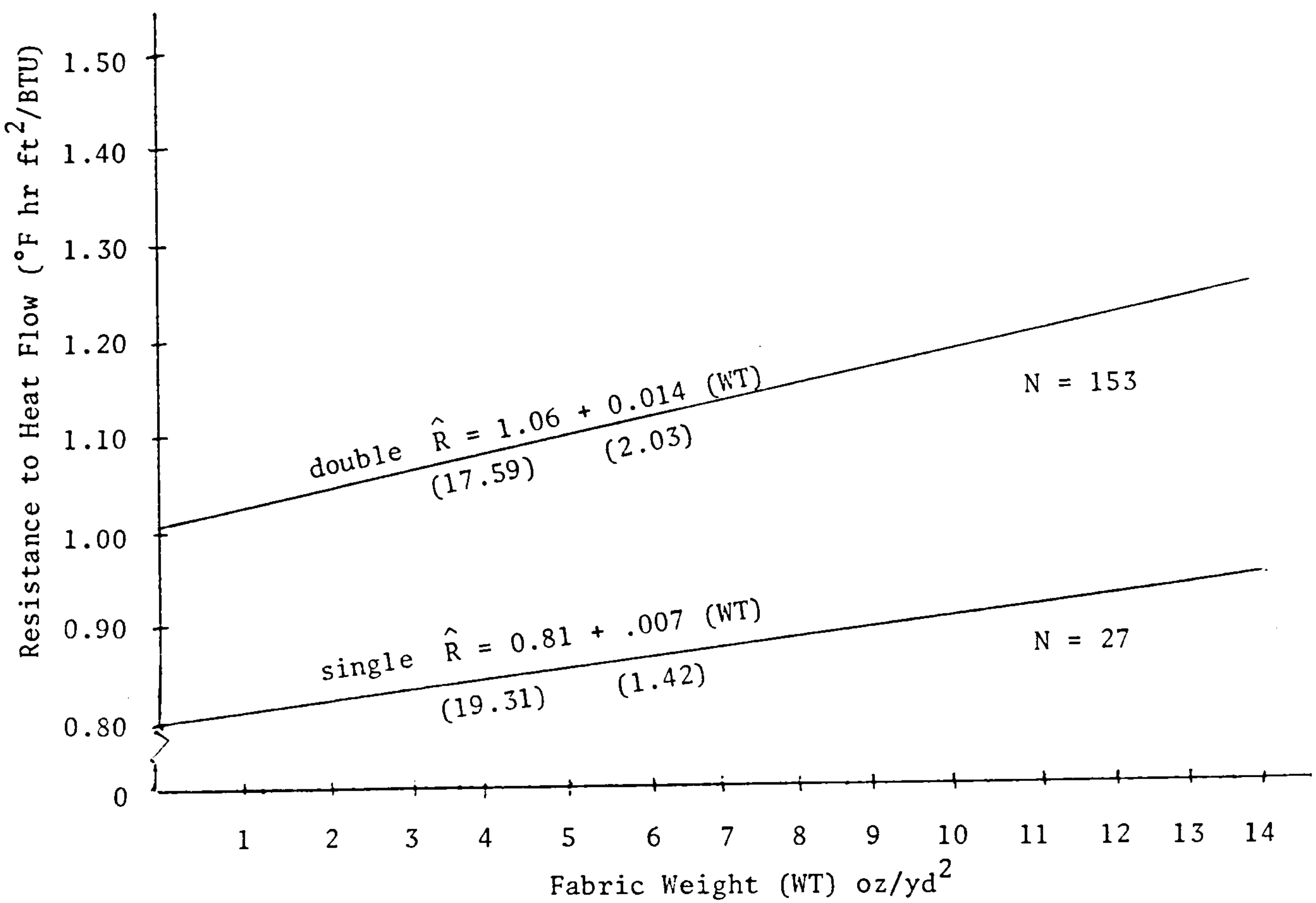


Figure 36. Fabric weight versus resistance of single and double layers. (t in parentheses.)

It can be seen that the increase of resistance with a unit increase in weight is greater with layered fabrics than with the single fabrics. This finding is essentially similar to the finding observed for the relationship between fabric thickness and resistance.

Air permeability of the fabrics was found not to be a significant factor in resistance. The air velocity was assumed to be zero; therefore, on the basis of the present investigation, it is difficult to comment regarding the influence of fabric air permeability on the resistance to heat flow.

In the present investigation, the rating of the fabrics on the basis of air permeability from highest to lowest was found to be D, G, B, A, E, C, and F, while the rank order on the basis of resistance from highest to lowest was observed to be A, G, C, D, F, E, and B. Figure 37 shows the relationship between air permeability and thermal resistance. The regression line has a slight negative slope indicating that, although there is little correlation between the two parameters, the relationship is negative.

Fabric compression, which is generally inversely related to resistance, was found to be a significant factor in determining resistance for single layers only. The relationship was a negative one, producing a negative slope of the regression line as shown in Figure 38. The double layers, on the other hand, exhibited a positive slope.

The fabric resilience (recovery to the uncompressed condition) was greater for the double than single layers (see Figure 39), although neither showed a significant trend or pattern in the relationship between resilience and resistance.

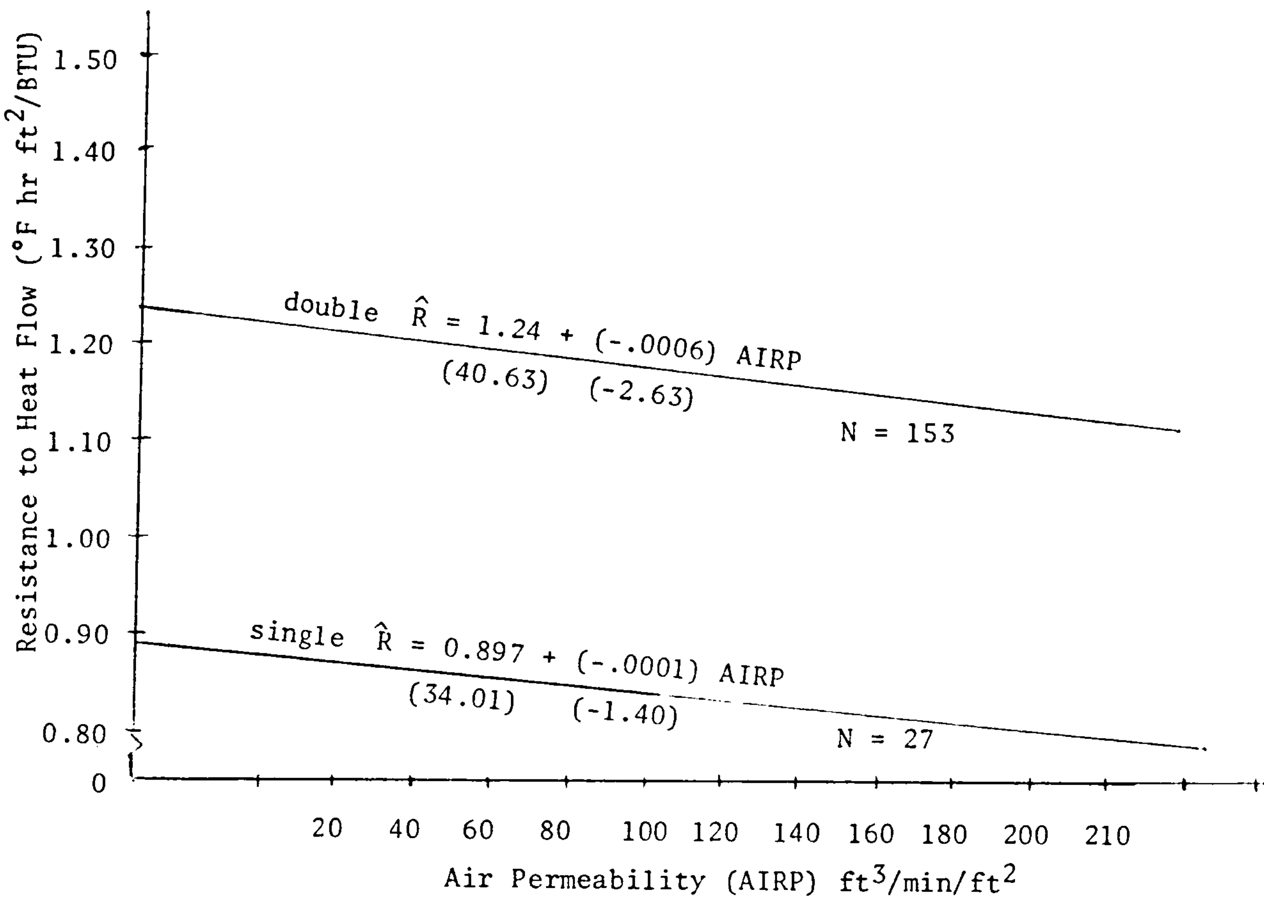


Figure 37. Fabric air permeability versus resistance of single and double layers. (t in parentheses)

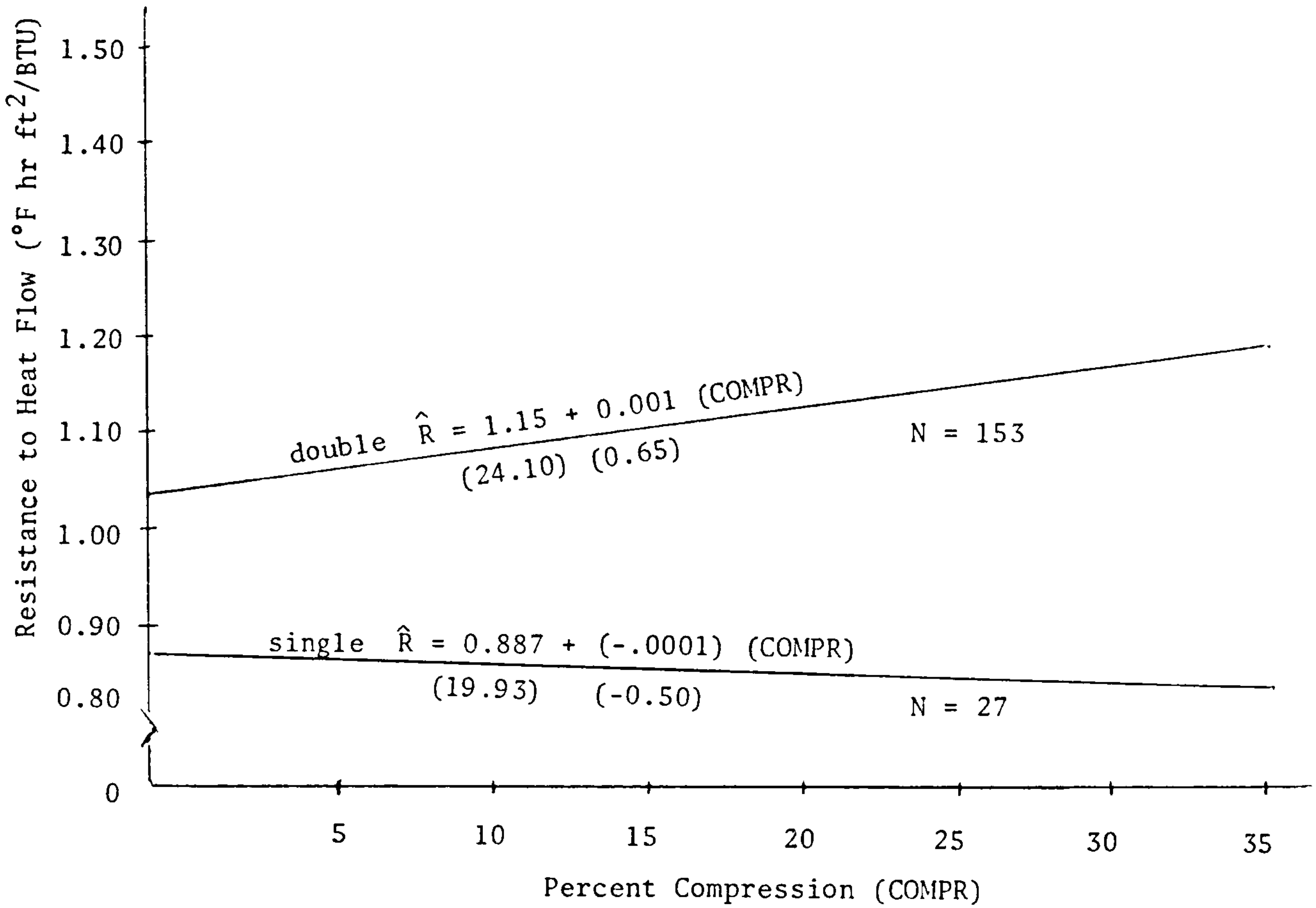


Figure 38. Fabric compression versus resistance of single and double layers. (t in parentheses.)

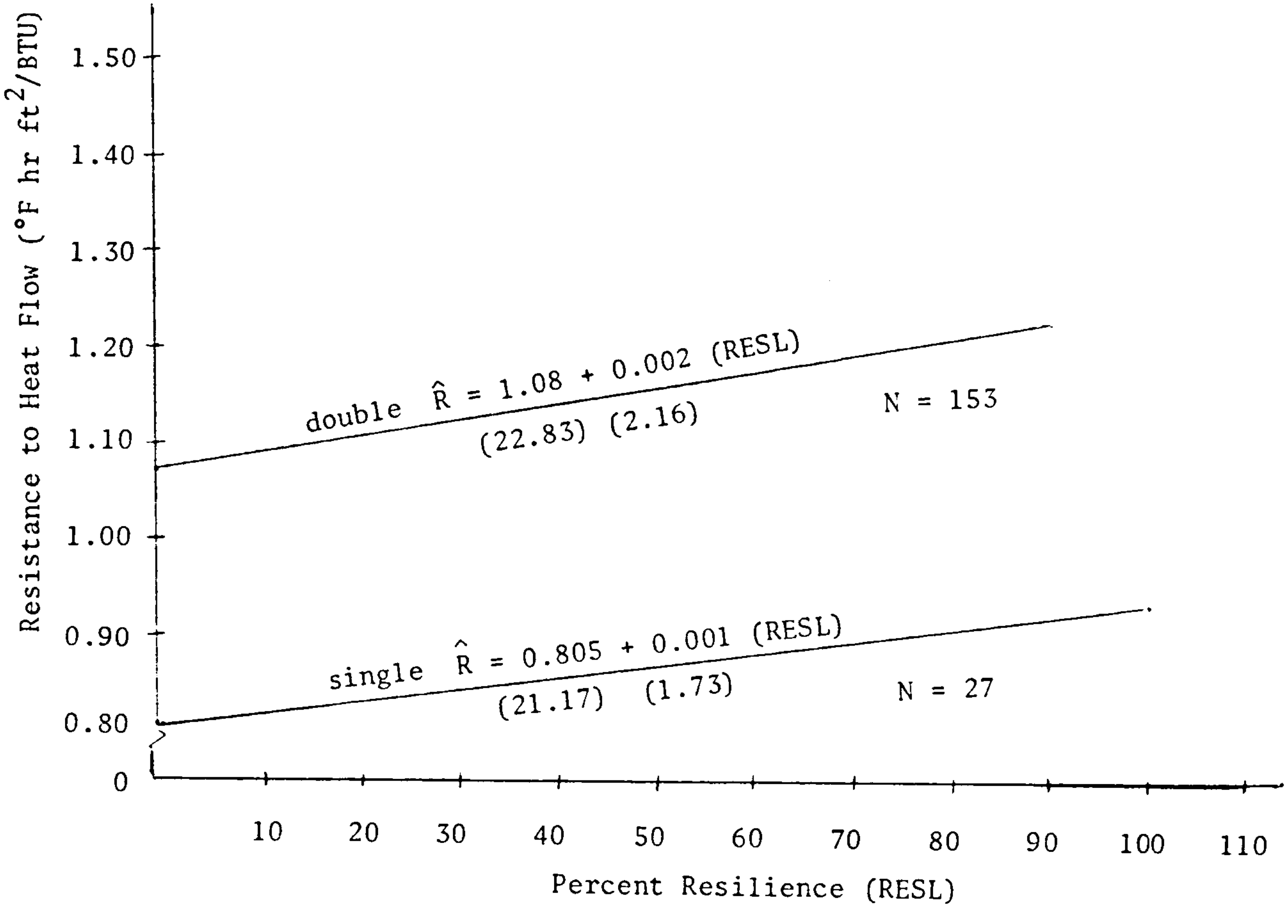


Figure 39. Fabric resilience versus resistance of single and double layers. (t in parentheses.)

Fabric porosity exhibited a positive correlation with resistance, although it was not found to be statistically significant. The effect of porosity on resistance was greater for double layers than for single layers as shown in Figure 40.

Fabric cover factor was found to have no discernible correlation with resistance, as shown in Figure 41. However, even though fabrics B, E, and F exhibited the highest cover factor, their resistance measurements were low.

Fabric moisture regain (expressed as a percentage) was found not to be a statistically significant factor in affecting resistance to heat flow. There was not a pattern established that could exhibit either a strong positive or negative relationship. Figure 42 shows almost no correlation with both single and double layers.

Moisture regain could possibly be accounted for in this experiment due to fiber content (although the moisture regain of fibers was not measured), while the resistance could possibly be related to the fabric structure and thickness, thus accounting for the lack of correlation. Fabrics A and B (both 100% wool) exhibited the higher moisture regain but were the highest and lowest, respectively, in resistance for double layers. Fabric G (100% polyester) with the lowest moisture regain, exhibited the second highest resistance. The rank order from highest to lowest for moisture regain was A, B, C, D, F, E, G, while the resistance was ranked as A, G, C, D, F, E, and B. These results are, however, inconsistent with the fact that the higher RH produced the greatest resistance values.

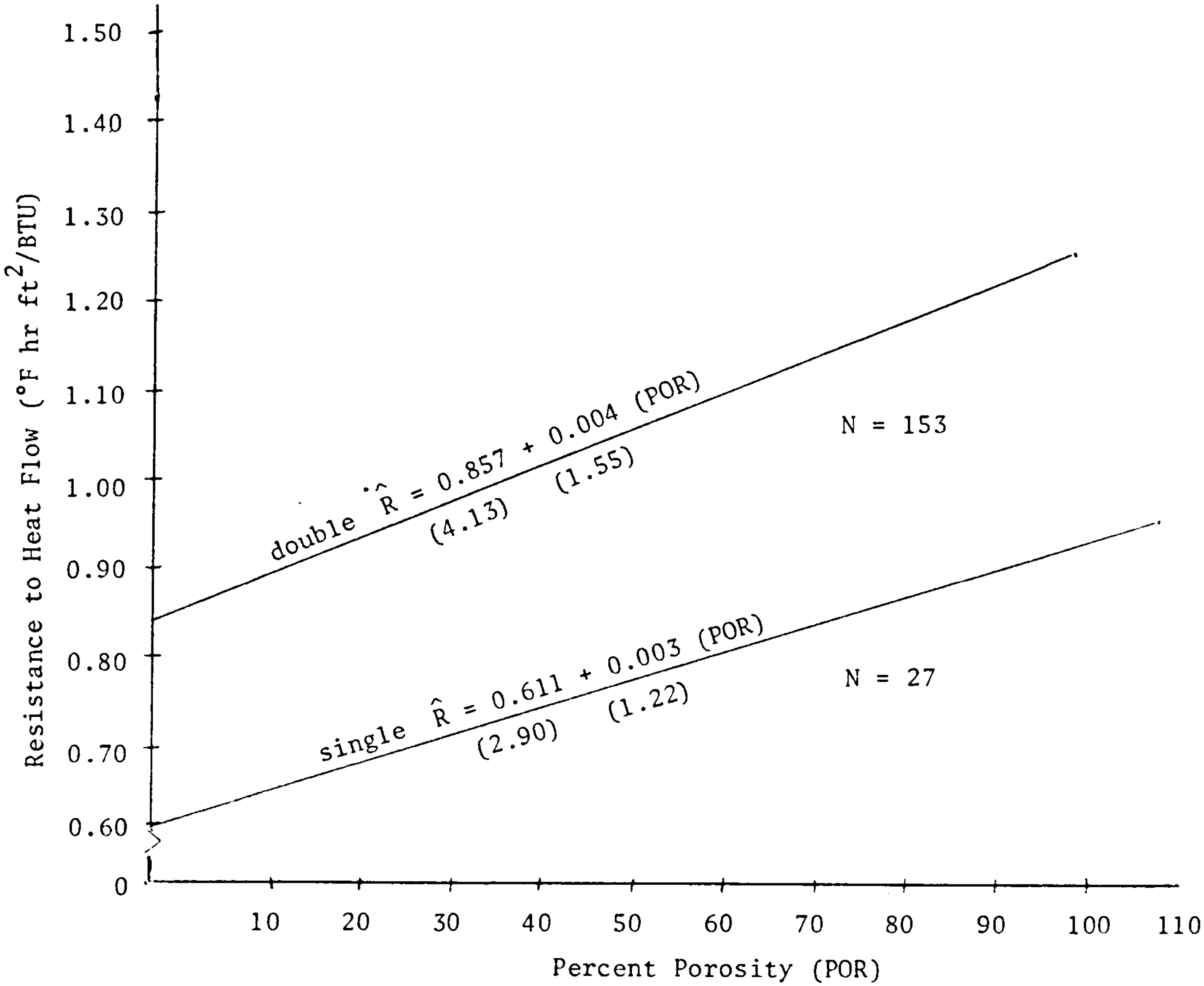


Figure 40. Fabric porosity versus resistance of single and double layers. (t in parentheses.)

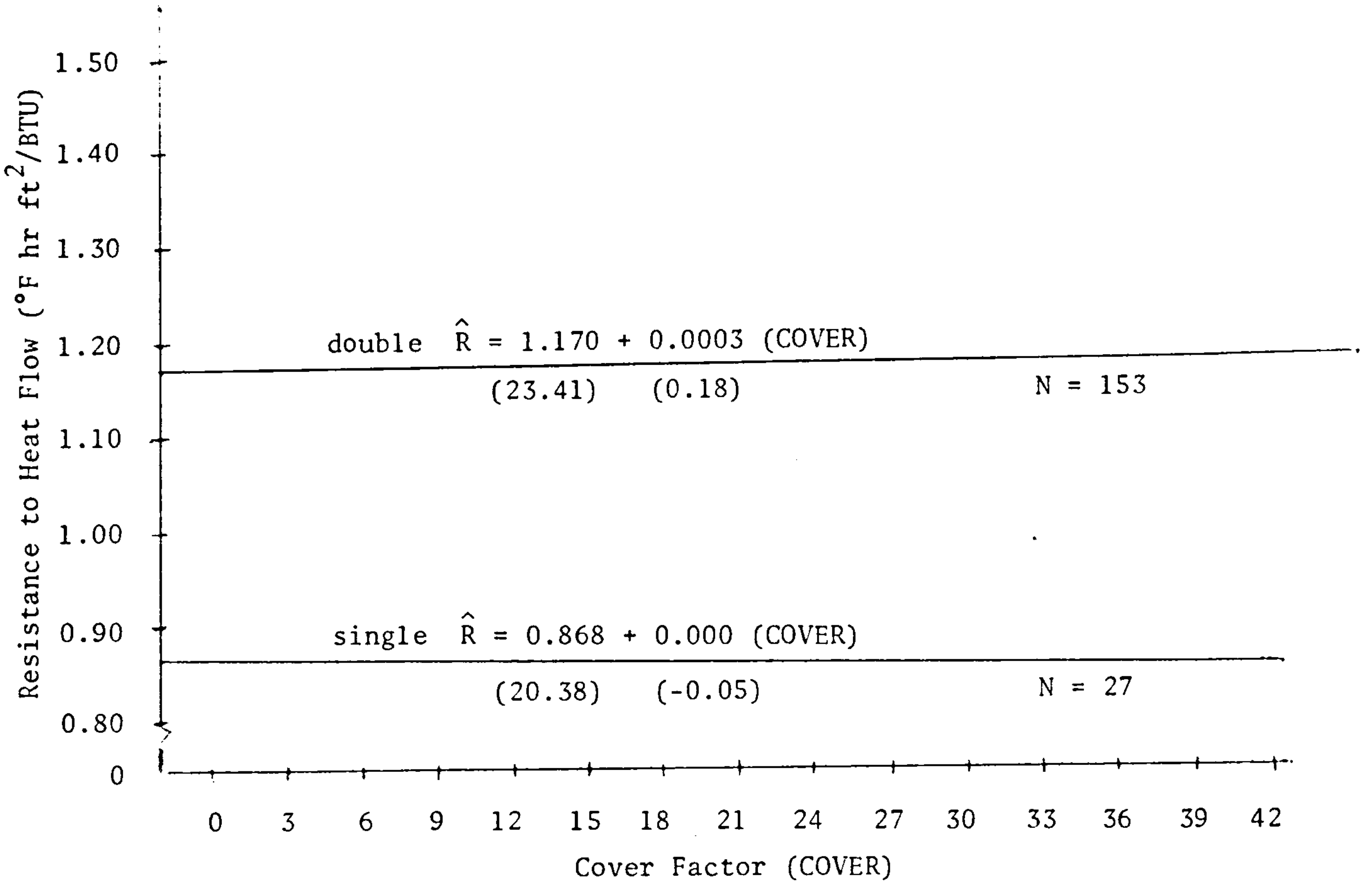


Figure 41. Fabric cover factor versus resistance of single and double layers. (t in parentheses.)

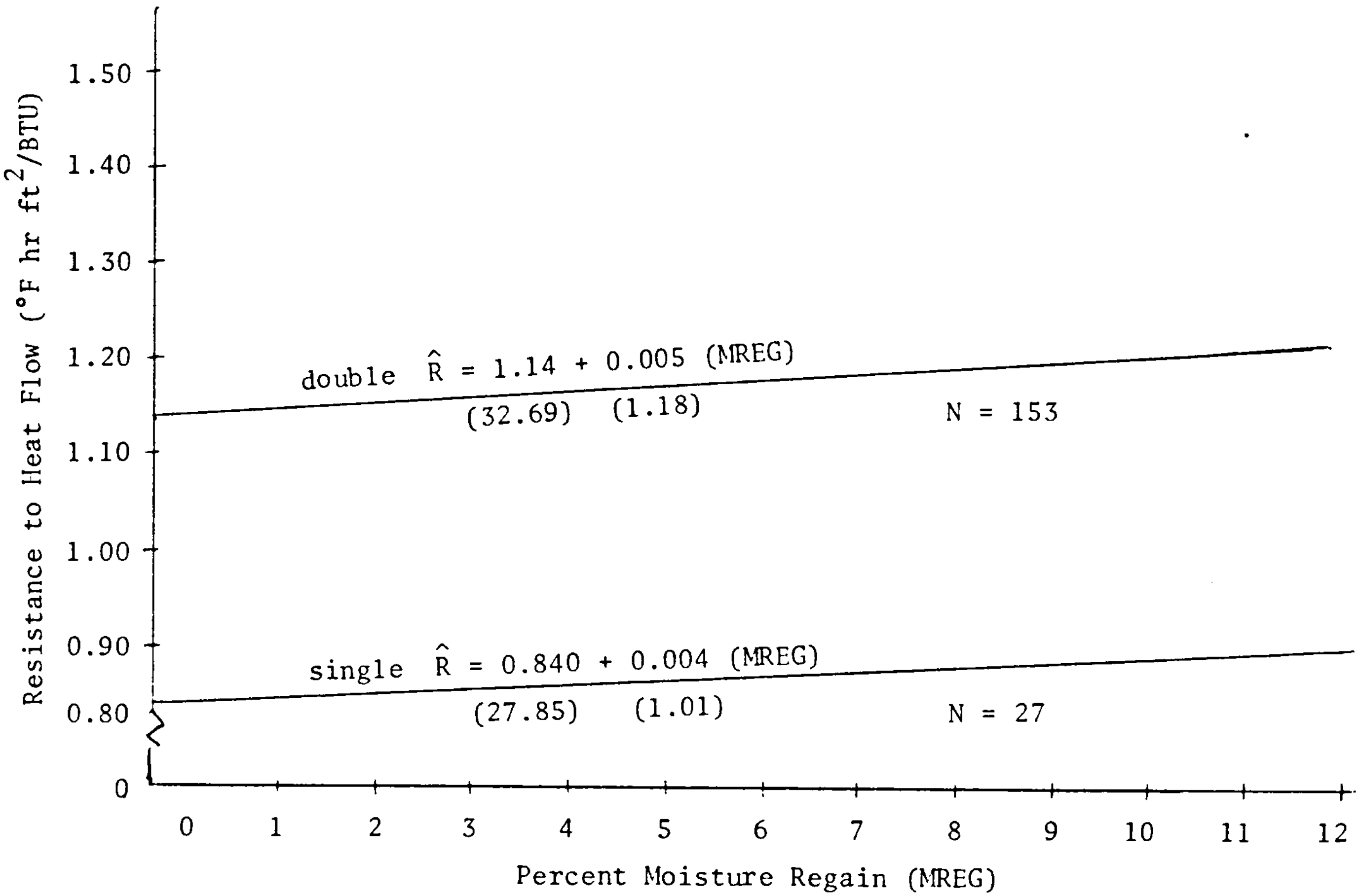


Figure 42. Fabric moisture regain versus resistance of single and double layers. (t in parentheses.)

The smoothness or hairiness of a fabric, a qualitative measure, was judged from the fabric surface photographs as shown in Figures 43 through 51. The fabrics which appeared to have more protruding surface hairs (A, D, C) also exhibited the highest resistance values, with one exception; fabric G gave a high resistance value although it had smooth filament yarns. However, the thickness of fabric G (0.043") is significantly high enough to possibly account for the higher resistance value.

VII. CLO UNITS FOR EXPERIMENTAL FABRICS

In order to make a comparison with the studies reported in the literature and to make recommendations to consumers, the resistance values were converted to clo units. A "clo" unit is defined as the amount of insulation necessary to maintain comfort for a sitting-resting subject in a normally ventilated room (air movement 20 ft/min or 10 cm/sec) at a temperature of 70°F (21°C) and a humidity less than 50% (30, 50, 59).

The clo units were calculated from resistance units according to the formula: 1 clo = 0.88 ($°F\ hr\ ft^2/BTU$) = 0.88 (resistance). The clo units for each single fabric and for each layered assembly are given in Table 18. The clo units were used in Chapter VI for presenting guidelines concerning the best choice of fabric for providing warmth. It must be kept in mind that the fabrics tested are piece goods and the values given are for flat fabric samples and not for constructed garments.

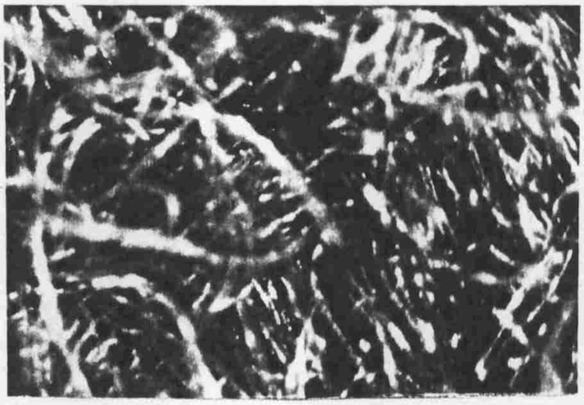


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Figure 43. Fabric A (100% wool), 30×, 4 sec.

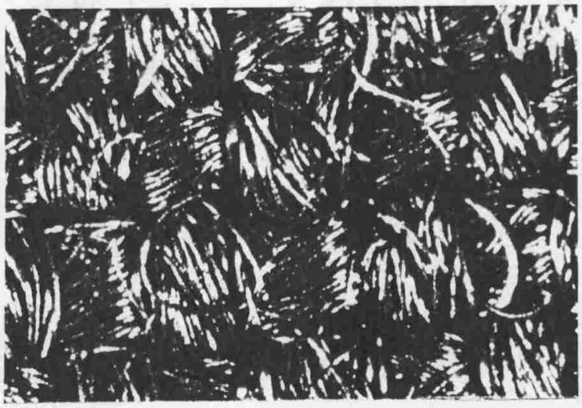

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Figure 44. Fabric B (100% wool), 30×, 10 sec.

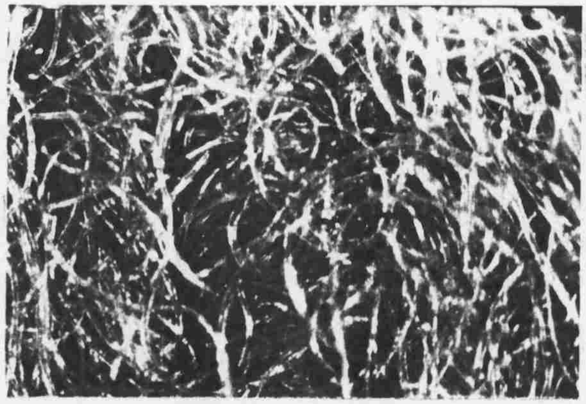

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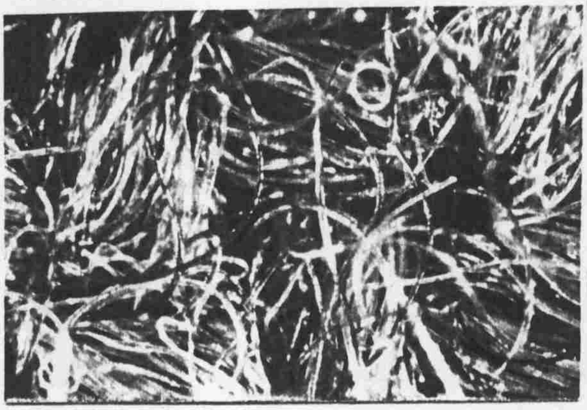
Figure 45. Fabric C (70% wool/30% nylon), 30×, 4 sec.



↑ W ↓

Figure 46. Fabric D (50% wool/50% polyester), 30×, 2 sec.

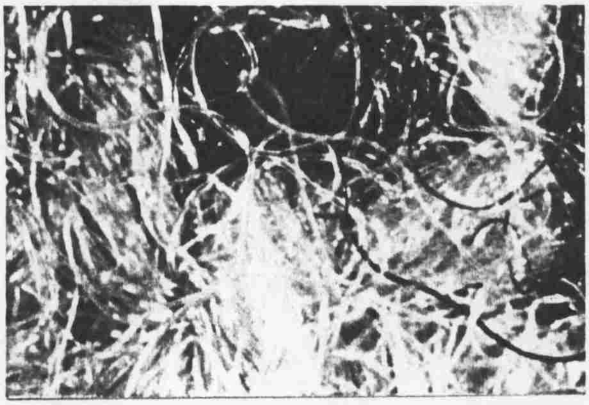


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Figure 47. Fabric E (wool/acrylic), 30×, 4 sec.

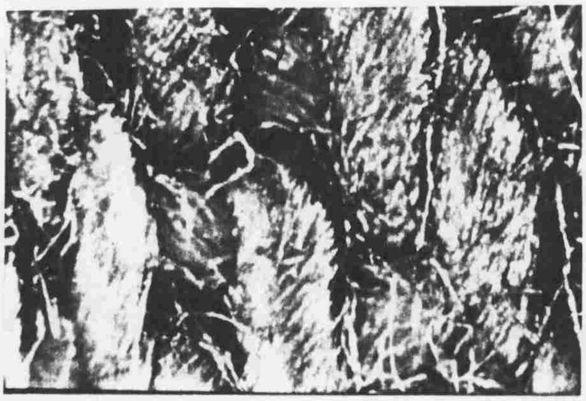

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Figure 48. Fabric F (100% cotton denim), 30×, 4 sec.

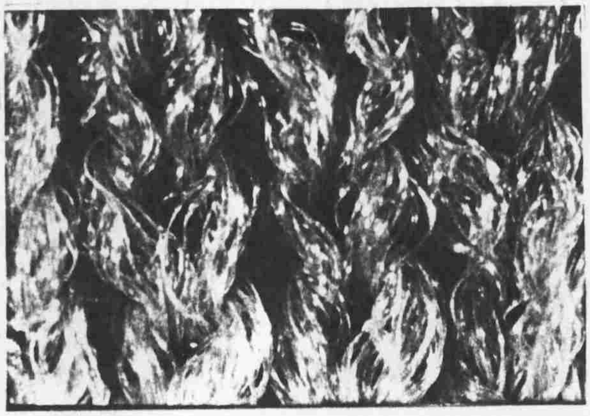

Figure 49. Fabric G (100% polyester double knit), 30×, 4 sec.

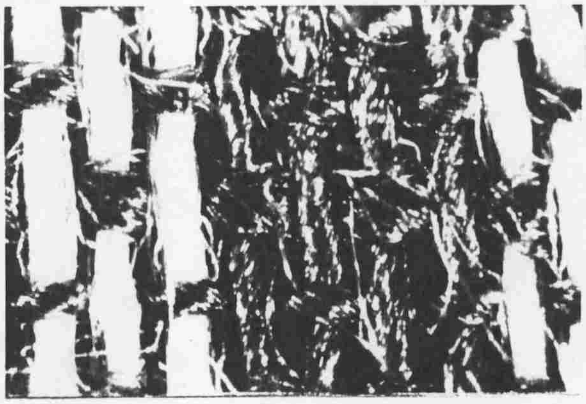

Figure 50. Fabric X (65% polyester/35% cotton), 30×, 4 sec.

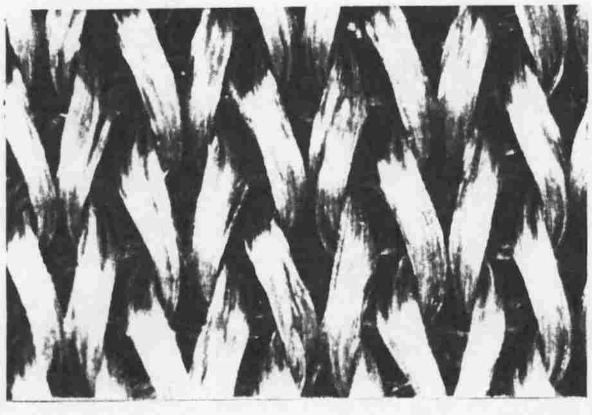

Figure 51. Fabric Y (100% Qiana nylon), 30×, 4 sec.

TABLE 18

CLO UNITS FOR SINGLE AND DOUBLE-LAYER FABRIC ASSEMBLIES AT EACH SPATIAL SEPARATION

	Clo Units[a]		
Fabric Assemblies	0.000" Separation	0.125" Separation	0.250" Separation
Single Fabrics			
A	0.815		
B	0.741		
C	0.787		
D	0.782		
E	0.791		
F	0.752		
G	0.776		
X	0.678		
Y	0.741		
Double-Layer Assemblies			
A and X	0.980	1.180	1.192
A and Y	1.022	1.230	1.271
B and X	0.887	1.079	1.161
B and Y	0.925	1.081	1.224
C and X	0.919	1.116	1.198
C and Y	0.971	1.168	1.227

TABLE 18 (continued)

Fabric Assemblies	Clo Units[a]		
	0.000" Separation	0.125" Separation	0.250" Separation
Double-Layer Assemblies			
D and X	0.947	1.088	1.229
D and Y	1.029	1.106	1.194
E and X	0.973	1.080	1.168
E and Y	0.987	1.044	1.231
F and X	0.972	1.101	1.217
F and Y	0.988	1.082	1.204
G and X	0.919	1.076	1.232
G and Y	0.963	1.172	1.264

[a]Rounded to nearest 0.001.

VIII. SUMMARY

The results obtained in this study apply only to those fabrics investigated and under similar environmental conditions. The conditions of the investigation were set as being a home environment with low to moderate activity level; consequently, no attempt can be made to apply the results to other settings or activity levels.

The theory that layering of fabrics provides a greater amount of insulation than do the single layers was supported by the study (Hypothesis 2). The entrapment of warm air plays a major role in insulation value.

In addition, it was found that fabric construction, particularly fabric thickness, rather than fabric type was a major factor in determining resistance to heat flow. Two fabrics of 100% wool provided a wide range of resistance values, including the highest and the lowest values.

The surface of the fabric, although judged qualitatively, appeared to be a major factor. The fabrics with a soft, hairy surface provided the highest insulation.

Spatial separation, ranging from a theoretical 0.000" to 0.250", caused a positive relationship between the amount of spacing and resistance (Hypothesis 3). The greater the spacing, the higher was the resistance.

Relative humidity played a major role in the determination of the resistance of fabrics (Hypothesis 4). The highest resistances were present with the higher ambient and next-to-skin relative humidities, while the lowest resistances were present with the lower ambient humidity and lower next-to-skin humidities.

Hypothesis 1 was not supported by the study since there was not a significant difference between the insulation values of the fabrics tested as single layers.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

I. SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate selected thermal characteristics of textile apparel fabrics which contribute to the resistance to heat flow (insulation value) of the fabrics. The conditions for the study were established as being the home environment during the winter with the wearer having a sedentary to moderate activity level.

The materials investigated were representative of materials used in the manufacture of commercially available ready-to-wear apparel. The fabrics were purchased from a local (Knoxville, Tennessee) fabric store.

The experiment was designed to study the effects of (a) jacket fabrics, (b) shirt fabrics, (c) layering of the fabrics, (d) spatial separation of the fabrics, (e) temperature-relative humidity combinations, and (f) physical properties of the fabrics.

The fabrics tested were: two woven fabrics of 100% wool, three woven wool and synthetic fiber blends, one 100% cotton denim fabric, and one 100% polyester double knit fabric. The shirting fabrics consisted of a 65% polyester/35% cotton woven fabric and a 100% nylon single knit.

The fabrics were layered with three spatial separations of 0.000", 0.125", and 0.250" with the jacket fabric being layered over the shirt fabric. Each single fabric and each assembly was tested at three different temperature-relative humidity combinations used as test conditions were: 94 ± 2°F, 36 ± 2% and 69 ± 2°F, 50 ± 2%; 94 ± 2°F, 42 ± 2%, and 70 ± 2°F, 68 ± 2%; 94 ± 2°F, 32 ± 2% and 70 ± 2°F, 45 ± 2%.

The fabric physical properties that were measured and analyzed for their effect in providing resistance to heat flow were thickness, weight, compression, resilience, cover, porosity, moisture regain, and air permeability.

The layering of fabrics proved to be the most significant factor contributing to insulation value (resistance) for the fabrics in this investigation. Each of the assemblies produced a greater resistance than did any of the single layer components. In addition, the insulation value increased as spacing increased due to the greater volume of air trapped between the fabrics.

The temperature-relative humidity combination was a significant factor in this study with the greatest resistance values generally being exhibited by the combination of 94°F-42% for the simulation of next-to-skin conditions and 69°F-68% for the simulation of ambient environmental conditions.

With the temperature being held constant for each test, the increase in relative humidity caused an increase in resistance. This phenomenon can possibly be explained due to the test conditions—relatively little air movement and slow evaporation from the fabrics tested. The heat source must produce more heat to maintain the temperature, thus causing a greater resistance to heat flow.

Statistical analysis indicates that the outer (jacket) fabrics contributed significantly to the insulation values found, with the structure and surface characteristics being more significant than the fiber type. Both the highest and lowest values of resistance of the jacket fabrics were exhibited by woven fabrics of 100% wool. The next highest values observed were those for the fabrics composed of wool blends with synthetic fibers. The polyester double knit and cotton denim were lower in resistance than all the jacket fabrics except for a fabric of 100% worsted wool.

The highest insulation values were detected for the fabrics with a hairy surface. The fabrics with the greatest numbers of protruding surface hairs had a large percentage of wool, a staple fiber with a rough, scaly surface. As the amount of smooth, filament fiber increased, the insulation value decreased. The outer fabric with the lowest resistance was 100% wool, a worsted fabric with smooth, closely woven yarns, producing a smooth surface.

Of the two shirt fabrics, the greatest insulation value was exhibited by the nylon single knit. The 65% polyester/35% cotton woven fabric exhibited the lowest resistance of all the fabrics tested.

Fabric thickness was found to be the only statistically significant physical property for determining insulation value. Thickness rather than fiber type determined the resistance, as was shown by the two fabrics of 100% wool. The highest and lowest outer fabric insulation values and largest and smallest thickness measurements were exhibited by the two wool fabrics.

Other physical properties measured—such as weight, cover factor, air permeability, moisture regain, porosity, compression, and resilience—were found not to be significant factors contributing to the insulation value of the fabrics in this investigation. Previous studies on the thermal characteristics (insulation) of textile fabrics have found that most of the above-mentioned physical properties have a significant influence on the thermal insulation. However, the disagreement can possibly be explained due to the differences in environmental conditions studied, including the greater activity levels, extreme temperatures, and wind velocities that are greater than would be found in the home environment.

II. RECOMMENDATIONS FOR FURTHER STUDY

The types of fabrics and conditions for this study were limited due to financial and time restraints. However, there are several parameters which are worthy of further study.

Other fabrics should be investigated in order to have a wide variety of fiber and construction types that can be compared for their insulation characteristics. In addition to shirt and jacket fabrics, lining and underwear materials should be included in the investigation, as they are often an integral part of winter attire.

The materials under investigation were fabric samples 20" × 20" square, subject to the instrument parameters without regard to garment design and fit to a human body. Another type of instrument which would simulate body proportions with constructed garments would represent actual wearing conditions.

In this investigation, the relative humidity was varied while the temperature was held constant. Further study should include a variety of temperatures, especially temperatures lower than what is normally considered in the comfort range (70-72°F).

The effect of fabric color should be investigated as a factor of fabric insulation, as the fabric's ability to radiate heat is a function of color and texture. Fabric color was not a variable in the present study.

A follow-up should be conducted to include people wear-testing garments made from the same or similar materials to give a subjective evaluation of the thermal comfort provided by the fabrics under similar conditions. The wear test should include a subjective assessment of thermal tactile sensations produced by the fabrics.

CHAPTER VI

INFORMATION FOR EDUCATORS AND CONSUMERS TO ASSIST IN CHOOSING CLOTHING TO MAINTAIN THERMAL COMFORT DURING THE WINTER

Due to the rising cost and limited supply of energy resources, many consumers are finding that they can save money by practicing energy conservation in the home. Their strategies may include lowering thermostat settings, adding insulation in the walls, ceiling and floors, or changing the structure of the dwelling. Many new housing structures are designed to maximize the efficiency of the energy source.

Structural changes are not always feasible or possible. Textile products at the windows, on the floors and walls, and on furniture provide a means of reducing heat loss.

Instead of, or in addition to, the aforementioned ways to reduce energy consumption yet be thermally comfortable, a person can use clothing as a principle means of keeping warm. The careful selection and combination of clothing articles can provide a feeling of being thermally comfortable.

Based on the findings of the present investigation, the following information is provided to assist in the selection and use of clothing to provide thermal comfort. Educators, retailers and any others who might influence the clothing selection decisions of consumers may find this information useful.

It must be kept in mind that the study included fabrics only, rather than garments. The styling of the garment could increase or decrease the ability of the fabric to provide thermal comfort. The ability of the fabric to provide thermal comfort is discussed in terms of insulation values as determined by the clo value of the fabric. The clo value was determined from the measurements of heat flow through the fabrics.

I. RESEARCH RESULTS

Very little information is available in the literature concerning previous research to determine insulation values of clothing fabrics under the same or similar conditions and the same or similar fabrics as were used in the present study. Therefore, few comparisons can be made to be able to make judgments concerning the use of materials other than those in the present study for achieving thermal comfort. However, some characteristics of the fabrics (thickness, surface character) seem to be consistent in providing good insulating properties.

According to the results of previous studies, fabrics that have a soft, fuzzy surface are warmer to the touch than fabrics with hard, smooth surfaces (2, 10, 19, 35, 37, 46, 49, 60, 69, 81). In addition, the fuzzy surfaces trap and hold warm air to provide insulation. In the present study, the fabrics which provided the highest insulation values were a fuzzy fabric of 100% wool and three other fabrics which were 70% wool/30% nylon, 50% wool/50% polyester and a wool/acrylic blend. The least insulation values were provided by fabrics of 100% polyester double knit, 100% cotton denim, and a worsted 100% wool fabric which had a tightly woven, smooth surface.

In addition to having a fuzzy surface, the fabric should be thick. This investigation supports findings of previous studies in that thick fabrics provide greater insulation than do thin fabrics. Thickness seems to be a more important characteristic than does fiber type, as shown by the two fabrics of 100% wool with the highest and lowest insulation values and the corresponding highest and lowest thicknesses.

Combining more than one fabric into layers provides a greater amount of insulation than wearing one fabric only. Layering the fabrics provides air spaces between the fabrics to hold warm air. The warm air layer reduces penetration of cold air and helps keep the body warm. The greatest insulation value for the fabrics in the present study was provided by a combination of 100% wool (fuzzy surface) and a single knit nylon. The layered combination which provided the least amount of insulation was provided by a 100% worsted wool over a shirt fabric of 65% polyester/35% cotton.

II. COMPARING COST AND BENEFIT

Although research results show that certain fabrics and certain layered combinations of fabrics provide better insulation than other fabrics and combinations, the consumer must ultimately decide what to buy in terms of the cost of the clothing and the amount of money saved on energy used for heating. The benefits derived (energy saved) must be equal to or greater than the cost of the clothing.

The Federal Energy Administration estimates that a reduction in the thermostat setting for heat generally results in a savings of approximately 3% for each degree (22). This estimate can be used to compare the energy savings and clothing costs in terms of thermal comfort provided.

The fabric prices and amounts of insulation (clo) provided by each fabric as measured in the present study in order of highest to lowest insulation values are provided in Table 19.

The fabrics that provide the least insulation are thin and smooth while the thick, fuzzy fabrics provide the most insulation. The price range varies for the fabrics with the highest insulation value, giving the consumer an opportunity to choose warm fabrics without buying the most expensive fabrics.

TABLE 19

PRICE AND INSULATION PROVIDED BY FABRICS INVESTIGATED

Fabrics[a]	Price/Linear Yard	Insulation (Clo Units)	Cost/Clo Unit	Clo/Dollar
100% Wool (thick, fuzzy)	$11.98	0.815	$14.70	0.07
Wool/Acrylic	7.50	0.787	9.53	0.10
70% Wool/30% Nylon	11.98	0.791	15.14	0.07
50% Wool/50% Polyester	6.98	0.782	8.92	0.11
100% Polyester Double Knit	3.98	0.776	5.13	0.19
100% Cotton Denim	2.98	0.752	3.96	0.25
100% Wool (thin, smooth)	10.98	0.741	14.82	0.07
100% Nylon Single Knit	3.88	0.741	5.24	0.19
65% Polyester/35% Cotton	2.98	0.678	4.39	0.23

[a]Purchased at Jackie's Fabrics, Knoxville, TN, November 1979.

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APPENDIX

COMPUTER PROGRAM FOR HEAT TRANSFER

```
0: spc;prt"
 HEAT FLOW WITH
 MASS TRANSPORT"
 ;spc ;moct
1: prt "connect
 relay   0→TO;
 1 T1;2 HF0"
2: prt "3→HF1;
 4→t;5 RH
3: prt "DRAPES:
 Tu=6;T153=7;
 HF153=8;HF152=9
 ;HF158=10"
4: dim M$[16]
5: ent "Enter
 date,initials,
 press CONT.",M$
6: prt "Date=",
 M$
7: dim A$[16]
8: ent "ENTER
 EXP # & sample
 info",A$;spc 1
9: prt A$
10: gsb 73
11: enp "SAMPLIN
 G RATE? min.",Q
12: fxd 1;ent
 "ENTER AMBIENT
 TEMP,F",R;prt
 "Tamb/ F = ",R
13: fxd 2;ent
 "ENTER MIL.
 TIME",X;prt
 "TIME",X;X-frc(
 X)+frc(X)/.6→X
14: prt "dectime
 =",X;X-(Q+.3)/
 60→E
15: dsp "Waiting
  for sensor
 equilibrium";
 wait 140
16: dsp "  JESU
 S  LIVES ";wait
  10;dsp "";wait
  100
17: dps " RA!
 RA! RA!,-T-$
 C";wait 25;dsp
 ""
18: wrt 722,"F1R
 7A0H0M3T1"
19: for K=4 to 5
20: moct;wtb 9,
 170040,10000,
 10000+dto(2↑K)
21: gsb "DMM"
22: if K=4;prt
 "t/0,F=",20S→Z
23: if K=5;pen#
 2
24: if K=5;lbl
 "";20S→S;prt
 "RH/0/52",'RH/
 0/52'→S
25: if K=5;plt
 X,.01S;pen;time
 9000
26: next K
27: for L=0 to 5
28: if L<6;moct;
 wtb 9, 14000,
 14000+dto(2↑L)
29: gsb "DMM"
30: lbl ""
31: if L=0;pen#
 2;45000S→T; prt
 "dT0 = ',T;abs1T
 )→T;plt X,.01T;
 pen;time 5000
32: if L=1;45000
 S→U;prt "dt/
 1=",U;abs(U)→U
33: if L=1;plt
 X,.01U;pen;time
  9000
34: if L=2;381S/
 (T+U)→Y
35: if L=2;prt
 "BTU/0=",Y;pen#
  2;plt X,10S;
 pen;time 4000
36; if L=2;if
 G#0;plt E,G;
 time 5000
37; if L=2;plt
X,Y→G,=1;time
 5000
38: if L=3;392S/
 (U+T)→Y
39: if L=3; prt
 "BTU/1=",Y;plt
 X,10S;pen;time
 5000
40: if L=3;if
 H#0;plt E,H;
 time 9000
41: if L=3;plt
 X,Y→H;pen;time
 5000
42: if L=3;if
 I#0;plt E,I;
 time 9000
43: if L=4;prt
 "/1,F=",20S;
 abs(20S-Z)→Z
44: if L=4;plt
X,.01Z;pen;time
 5000
45: if L=5;20S→S
 ;prt "RH/51",
 'RH/51'→S
46: if L =5;plt
 X,.01S,-1;time
 5000
47: if L=5;pen#
 0;plt 20,0,-1
48: if L=5;moct;
 wtb 9,10000
49: next L
50: spc
51: wrt 722,"T2"
52: if Q=0;gto
 12
53: for P=1 to
.2Q-3dsp Q1.5-
 .5P,"min to
 test";wait 3000
 0;next P
```

```
54: Q/60+X→X;
 gto 14
55: "DMM":wait
 5500
56: fxd 4;0→S;
 for M=1 to 50;
 red 722,A;dsp
 1000A;S+A→S
57: if A>.00000;
 if abs((S/M-A)/
 (S/M))>.05;prt
 "noise";jmp -1
58: next M
59; fxd 3;ret
 .02S S
60: "HFmf":ret
 1.108386*.99869
 48↑T→F
61: "RH/0/52":gt
 o 62;if S>4;
 gto 63;if S>23;
 gto 64;if S>62;
 gto 65;if S>96
62: 0→S;ret S
63: ret 36.36026
 7*1.0109256↑S→S
64: ret 9.817541
 *S↑.5018653→S
65: ret 8.905783
 7*S↑.5278797→S
66: "RH/51":gto
 68; if S>22;gto
 69; if S>38; gto
 70; if S>55; gto
 71
67: gto 71;if
 S>87;gto 72
68: ret 21.8989→
 1.01577476↑S→S
69: ret 18.82454
 *1.02422015↑S→S
70: ret 4.994013
 *S↑.61742276→S
71: 435 35.78852
 34+1.009184↑S
72: set 28.15047
 77*1.012057↑S→S
73: pclr;lbl "";
 wrt 705,"lp670,
 27,14896,10418
 ";pen#1;scl 6,
 20,0,1
74: fxd 0
75: lbl "";xax
 .1,.25,7,20,4
76: lbl "";fxd
 2;xax 7,.05,.1,
 1,2;plt 10,0;
 lbl "DeciTIME,
 h."
77: pclr;lbl "";
 csiz 1,1.5,8/
 10.90
78: dim D$[20]
79: "TRANS.,BTU/
 h↑ft 2 F,"→D$
80: lbl "";plt
 5.8,.2;lbl D$,
A$,M$
81: ret
*3095
```

VITA

Kay Sanders Grise was born on March 25, 1947. She lived on a farm near Wickliffe, Kentucky, attended Wickliffe Elementary School, and was graduated from Ballard Memorial High School in 1965.

In 1969, she received a Bachelor of Science degree in Home Economics from Murray State University in Murray, Kentucky. In June 1969, she accepted a position with the University of Kentucky Cooperative Extension Service in Muhlenberg County, Kentucky. In 1977, Mrs. Grise received a Master of Science degree from Western Kentucky University in Clothing and Textiles. While at WKU, she was a graduate assistant and received a graduate student research grant.

She taught Vocational Home Economics for one year and then entered the Interdisciplinary Doctoral Program in Home Economics at The University of Tennessee, Knoxville. While at UT, Mrs. Grise was a graduate teaching assistant in the Department of Textiles and Clothing and a graduate research assistant, funded by the United States Department of Agriculture Textiles & Clothing Laboratory, Knoxville.

During her graduate study, the author was invited to present research papers at the 1977 and 1980 national meetings of the Association of College Professors of Textiles and Clothing and the 1980 annual meeting of the Tennessee Home Economics Association.

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In August 1980, Mrs. Grise began employment on the faculty at Southern Illinois University in the Division of Comprehensive Planning and Design, Clothing and Textiles. She is a member of the American Home Economics Association, Association of College Professors of Textiles and Clothing, American Association of Textile Chemists and Colorists, Phi Kappa Phi, and Kappa Omicron Phi.

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