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THERMAL INSULATION CHARACTERISTICS OF TEXTILE DRAPERY FABRICS

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Helen Heins Epps

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ABSTRACT

The purpose of this study was to determine what fiber, fabric and constructional properties of draperies are associated with high thermal insulation values at different levels of relative humidity. Four factors associated with the drapery fabrics (fiber type, color, fabric openness and lining type) and three factors related to the drapery design (drapery fullness, lining fullness, and spatial configuration) were investigated. An eighth independent variable, relative humidity, was also included. The dependent variable was the heat flow through the drapery at a temperature differential of approximately 25°F.

Transmittances of drapery models representing selected levels of the eight independent variables were measured on a standard window equipped with a heat sensor device connected to a computer.

The physical properties of moisture regain, reflectance, thickness, weight, air permeability, porosity and drape of each of the fabrics were measured in order to determine relationships between these properties and the heat transmittance of the drapery.

Single thicknesses of eight drapery fabrics and two lining fabrics were tested for insulation value at two relative humidity levels, 45% and 65%. Analysis of variance showed the following factors to be significant: fiber type, weave openness and relative humidity. Color was not significant.

The four light colored drapery fabrics were tested in layered combinations with a lining fabric at the two relative humidity levels.

Two levels of drapery fullness (50% and 100%), three levels of lining fullness (flat, 50% and 100%) and three levels of lining-drapery spatial separations (touching, 1/4 inch and 1/2 inch) were tested. Fabric, lining fullness, drapery fullness, spatial configuration and relative humidity were found to be significant.

Additional analysis revealed several regression models for predicting the insulation value of the draperies. Although many of the factors were found to be significant, variables were eliminated from the models in a stepwise procedure. Analysis showed that 98% of the variation in transmittance in the single layer fabrics could be predicted by relative humidity and air permeability, and that 92% of the variation in transmittance of the multiple fabric configurations could be predicted by relative humidity, air permeability and lining fullness.

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CHAPTER I

INTRODUCTION

Decreasing energy supplies and consumer concern over energy costs have resulted in a need for increased research effort in the area of energy conservation. Energy conservation in buildings involves maintenance of thermal comfort at decreased levels of energy use and is achieved in part by minimizing heat flow between the indoor and outdoor environments. There have been few studies of the role of household textile items in home energy conservation. Although well-insulated windows have been found to reduce heat transfer between the indoor and outdoor environment, the contribution of draperies to window insulation, particularly as it relates to alterations in indoor relative humidity, have not been studied in detail.

Five percent of our total national energy consumption is lost through architectural windows (71). Home energy conservation techniques currently being used are less effective in reducing energy loss through windows than through walls, ceilings and floors. Although the total energy loss from a home decreases as it is better insulated, the actual percentage of heat loss through windows increases (44). Certain types of window designs are effective in reducing energy loss; however, this reduction does not yet equal the reduction in energy loss through well-insulated walls.

If effectively managed, window draperies can aid in reducing heat loss through windows. They also have the additional advantage of

flexibility, in that they can be easily opened to allow maximum benefit from solar heat gain or closed to reduce heat loss (12).

Draperies can influence energy conservation by reducing winter heat loss and summer heat gain (16). Studies have shown that the ability of window shading devices to block air flow is the single most important characteristic in influencing the overall insulation value (16, 18). However, if draperies are designed with an effective, functional drape-to-wall seal so as to control convective heat loss, the importance of other fiber, fabric and constructional characteristics come into play. While several isolated studies have focused on various insulative properties of draperies and other shading devices, the relative importance of each of these factors has not been determined.

Indoor relative humidities vary seasonally. Depending on the type of heating system used, very low relative humidities are possible during winter. However, advances in building technology stemming from the current emphasis on energy efficiency have resulted in reduced infiltration and ventilation rates in buildings. As well as adversely affecting indoor air quality (38), another situation which can result from a combination of reduced infiltration and lowered indoor temperatures is an increase in the indoor relative humidity, often to the point of condensation within the building. Further compounding the problem, increases in indoor relative humidity, through the use of mechanical humidifiers, are recommended as protection against winter colds (31).

Whether due to reduced infiltration, lowered indoor temperatures, or the use of mechanical humidifiers, alterations of the indoor

relative humidity will influence the insulative properties of drapery fabrics.

The relationship between the moisture sorption characteristics of a fiber and its insulative properties at various levels of relative humidity has not been explained. While it might be expected that draperies constructed from hydrophilic fibers will show more response to changes in relative humidity than will those composed of hydrophobic fibers, the influence of this response on the insulative properties of the drapery has not been reported in the literature.

Identification of the optimum energy conserving characteristics of draperies is necessary in order to develop draperies which, when used in combination with well-insulated windows, will reduce window energy loss to the point of approximating energy loss through walls, while maximizing the desirable benefits of draperies and windows, including flexibility, visibility and solar heating when desired, and esthetics.

This project focuses on the relationships among heat transfer, relative humidity and several fiber, fabric and constructional characteristics of draperies. The independent variables include fiber type (hydrophilic or hydrophobic), color, fabric construction (openness of weave), fullness of the drapery face fabric and lining fabric, and spacing between the lining and drapery face fabric. The dependent variable is the thermal transmittance value of the drapery plus the window. The transmittance values of drapery models representing combinations of different levels of each of the variables were measured at two different relative humidity levels.

I. OBJECTIVES

The overall objectives of this investigation were:

1. To determine the role of humidity and fiber hydrophilicity in heat flow through textile drapery and lining material systems.

2. To study the effect of the drapery system geometry (flat versus fully pleated lining and drapery fabrics, and spatial separation between the lining and drapery fabrics) on heat flow.

A corollary to this objective was to investigate the influence of fabric geometry (weave openness) and various physical properties on heat flow.

3. To determine the influence of the combined window and drapery system on heat flow.

II. HYPOTHESES

The following hypotheses were tested in this investigation:

1. There will be a significant difference between the transmittance values of the ten fabrics when tested in single layered, flat configurations.

2. There will be a significant difference between the transmittance values of the hydrophilic fabrics and the transmittance values of the hydrophobic fabrics.

3. There will be a significant difference between the transmittance values of the light colored fabrics and the dark colored fabrics.

4. There will be a significant difference between the transmittance values of the open-weave fabrics and the tightly woven fabrics.

5. There will be a significant difference between the transmittance values of the draperies tested at low relative humidity and those tested at high relative humidity.

6. There will be a significant difference between the transmittance values of the four light colored fabrics when tested in layered configurations with the lining fabric.

7. There will be a significant difference between the transmittance values of the draperies which represent different levels of drapery fullness.

8. There will be a significant difference between the transmittance values of the draperies which represent different levels of lining fullness.

9. There will be a significant difference between the transmittance values of the draperies which represent different levels of spatial separation between the lining fabric and drapery fabric.

III. ASSUMPTIONS

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

1. Fabrics selected for the study are representative of the extremes available in moisture sorption properties, color and fabric weave openness.

2. The test window, the design of the simulated drapery, and the temperature and relative humidities used for the test are typical of those found in residential settings.

3. Data from all of the techniques used are valid and reproducible.

IV. LIMITATIONS

The following limitations apply to this study:

1. The fabrics selected for the study represent only 100% content of a single fiber. No fiber blends were used.

2. The drapery models were evaluated at only two indoor relative humidity levels, one indoor temperature level, and one indoor-outdoor temperature differential.

3. The spatial configurations were limited to three levels of spacing between the lining and drapery fabrics and only one level between the lining and window glass.

4. Only two levels of drapery fullness were included, and only two levels of lining fullness with each level of drapery fullness were evaluated.

5. Only one type of lining fabric was studied in the double layer configurations.

6. During testing the draperies were completely sealed to the window at the top, bottom and two sides. The findings of this study are not directly applicable to drapery-window systems which are not constructed with a tight drapery-to-wall seal.

7. There were only two replications of each of the tests.

V. DEFINITIONS

In order to obtain numerical measures of each of the independent variables, several of the definitions used within this study differ from the generally accepted definitions. These specifically defined

terms include hydrophilicity, color, fabric openness, fabric weight, fabric thickness, relative humidity, standard atmospheric conditions, conditioning room, thermal insulation, thermal transmittance and fullness.

The hydrophilic or hydrophobic nature of a fiber generally refers to the capacity of the fiber for attracting water. For the purpose of this study, hydrophilicity has the same definition as moisture regain, which is defined by ASTM as "the amount of water in a material determined under prescribed conditions and expressed as a percentage of the mass of the water-free specimen" (1).

Color refers to the lightness or darkness as determined by an average of five readings of the L value on the Hunterlab Color Difference Meter (Model D25D2), where an L reading of 100 is absolute white and an L reading of zero is absolute black.

Fabric openness is generally a subjective judgment which may be related to the ability of the fabric to allow light to pass through, the fabric porosity, or the air permeability. However, within the context of this study, fabric openness will have the same definition as air permeability, which is defined by ASTM as the rate of air flow through a material under a pressure differential between the two fabric surfaces (1).

Fabric weight is mass per unit area expressed in oz/yd^2 (g/m^2). Fabric thickness is the distance between the upper and lower surfaces of the fabric, measured under a specific pressure.

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. Standard atmospheric conditions consist of a relative humidity of 65 ± 2% and a temperature of 70 ± 2°F (21 ± 1°C). A conditioning room is a room equipped to maintain standard atmospheric conditions with the standard tolerance.

Thermal transmittance is a direct measure of heat flow through a material, reported as Btu/hr/ft^2/°F. Thermal transmittance is often referred to as "U value." Thermal insulation of a fabric is a measure of its resistance to heat flow, expressed as its R value. The R value is the inverse of the U value.

Fullness is the width of fabric used to fill the width of window, expressed as a percentage. One hundred percent fullness is twice the width of fabric required to fill the space covered by the closed drapery, while 50% fullness is one and one-half times the width of fabric required to fill the space covered by the closed drapery. At zero percent fullness, the width of fabric covering the window is the same as the width of window, therefore the fabric is flat.

CHAPTER II

REVIEW OF LITERATURE

I. ENERGY CONSERVATION

Increasing energy costs have resulted in intensified consumer interest in the energy issue. Energy conservation can save more energy than new energy sources can produce, per dollar invested (17). Whether thermostats are maintained at recommended conservative temperature levels is dependent upon the thermal comfort of individuals in their homes. ASHRAE has defined thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (21).

Approximately 40% of residential energy is used for space heating (36). For this reason, a major energy conservation effort is being aimed at reducing the amount of fuel used for space heating and cooling.

Energy conservation in buildings involves maintenance of thermal comfort at decreased levels of energy use, and is achieved in part by minimizing heat flow between the indoor and outdoor environments. Heat is defined as energy in transient form (47). A temperature gradient between two environments causes heat to transfer from the higher temperature environment to the lower temperature environment. In order to maintain thermal comfort at conservative levels of energy use, both winter heat loss and summer heat gain must be minimized.

According to the Department of Energy, 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 (19).

Voluntary energy conservation is directly related to knowledge about how to conserve and how to maintain comfort at reduced levels of energy consumption. If energy conservation efforts are to be effective, pleas for energy conservation must be accompanied by specific information on how to conserve energy without sacrificing thermal comfort (65).

II. THEORY OF HEAT TRANSFER

Energy conservation in buildings is dependent upon heat transfer into or from the building. Methods of general heat transfer are presented followed by details of heat transfer associated with windows, textile fabrics and draperies.

Applying the principle of heat transfer to energy conservation in buildings, the goal is to minimize both outward heat flow in winter and inward heat flow in summer. Heat transfer occurs primarily by three modes: conduction, radiation and convection. Conduction is heat transfer by physical contact, either within a body or between two touching bodies, while radiation involves heat transfer through space. Convection involves heat being transferred in a moving gas or liquid mass. Energy conservation techniques may focus on one or more of these modes of heat transfer.

Heat transfer is expressed by the following fundamental equation for steady state heat conduction:

$$q = -k\ A \frac{dt}{dx}$$

where

q = heat flow rate, BTU per hour,

k = thermal conductivity, BTU per (hour) (square foot) (°F per foot),

A = cross-sectional area normal to flow, square feet, and

$\frac{dt}{dx}$ = temperature gradient, °F per foot.

Since more than one mode of heat transfer may be involved simultaneously, an overall coefficient of heat transfer, U, is used to represent heat transfer by convection, conduction and radiation. The overall heat transfer coefficient, U, is defined by the following equation:

$$U = \frac{q}{A\ T}$$

where

q = heat transfer, BTU per hour,

A = area, ft^2, and

T = temperature differential, °F per foot (2).

The more commonly used term, R value, represents the resistance to heat transfer. The relationship between U and R is indicated by the formula:

$$U = \frac{1}{R}$$

III. WINDOW ORIENTATION AND DESIGN

The term "building envelope" has been used to describe the barrier between the inside and outside of a building (9). The structure of the building envelope directly influences heat flow into or out of the building. Fenestration, or openings in the building envelope, including windows, account for substantial amounts of heat loss or gain to the building. The design and location of fenestration further influences heat loss or gain. Since the relative significance of draperies in reducing overall heat transfer depends on the types and locations of the windows with which they are used, a discussion of window design and location is included.

Window orientation to the sun is related to solar heat gain. Generally, windows oriented toward the south allow for greater solar radiation heat gain than do other orientations, while windows oriented toward the north receive the least amount of direct sunlight. According to Burberry, if unobstructed southerly oriented windows are curtained at night, the solar radiation gained during the heating season will exceed convective heat losses through the window (9). A double-glazed window not exposed to sunlight can lose ten times as much heat as an equal area of well-insulated wall, while 20 times as much heat is lost if the window is single-glazed (70).

The type of window is an important factor in heat transfer. Windows allow for radiant heat transfer, usually in the form of solar heat gain. Window glass is also a vehicle of conductive heat transfer. Internal air spaces in building components provide a resistance to heat

flow. Heat transfer across the thin air space takes place by radiation from the warmer to the colder surface, by conduction across the still air layer, and by convection currents in the enclosed air (26). When there is an air space between two layers of glass, heat transfer through the air space is less efficient than heat transfer through glass; therefore, a thin air layer actually serves as insulation which minimizes heat transfer by breaking the conduction path of the glass. The design of double-glazed, triple-glazed and storm windows is based on this principle. The rate of conductive heat flow is less through windows consisting of two layers of glass separated by an air space than through a single layer of glass. Three layers of glass separated by air layers further minimizes conductive heat transfer (34). According to Langdon (44), adding storm windows or double panes to windows will generally be as effective as adding two inches of insulation to the walls and ceiling of a small, reasonably well-sealed home.

Heat absorbing tinted glass also minimizes heat transfer. Metallic oxide added to the glass during its manufacture causes it to absorb heat which is then radiated and convected to the cooler side of the glass. Windows which have heat absorbing tinted glass can reduce solar heat gain in the summer, however, when the building is air conditioned the glass directs more heat into the room because the indoor temperature is lower than that of the outside environment.

Some of the heat loss associated with windows is due to heat transfer by convection or air leakage which occurs where the wall and sash meet the window frame or where window panes meet the frame.

Weatherstripping and caulking can aid in reducing this convective heat loss (18).

While caulking, weatherstripping and use of double-glazed, triple-glazed or storm windows can aid in energy conservation, even well-insulated windows account for a large amount of heat loss in buildings. The amount of heat loss from a building will decrease as wall and ceiling insulation is increased and single paned windows are replaced with double-paned or storm windows. However, as the home becomes better insulated, the percentage of heat loss through windows will increase as much as 10%, although the total heat loss decreases (44). This indicates a need for additional methods of reducing heat transfer through windows.

IV. FIBER, YARN AND FABRIC PROPERTIES

Certain characteristics of textile fibers, yarns and fabrics are associated with thermal insulation properties. Yarn and fabric color are measured in terms of light reflectance. Because radiant heat is also reflected or absorbed, color can be associated with radiant and conductive heat transfer in textiles. Light colored fabrics reflect heat, while darker colors absorb heat.

Bulky yarns and fabrics containing air spaces which serve as insulation can contribute to reduced heat transfer. Thick, fluffy fabrics and those with rough or irregular surface textures may also tend to modify conductive and radiant heat flow. Smooth yarns and tightly woven fabrics with high thread counts are associated with low air permeability and will help prevent convective heat loss (25).

Yarn structure directly influences fabric softness and bulkiness. High degrees of bulk and softness are achieved by three yarn structural features:

1. a low degree of fiber orientation with respect to the yarn axis;
2. a great amount of fiber protrusion from the yarn surface, and
3. low fiber packing density in the yarn structure (29).

Generally, synthetic filament yarns are associated with low overall thermal insulation because they often lack the qualities of softness, thickness and bulkiness. On the other hand, staple yarns, regardless of fiber type, are associated with higher thermal insulation values (6, 29, 39, 45, 61). Staple yarns typically contain more air space than filament yarns. However, texturizing can greatly increase the amount of air space in filament yarns. Texturizing effects an increase in softness and covering power as well as insulating power (25, 29, 59).

Yarn twist is also related to thermal insulation, in that the amount of twist influences yarn softness and bulkiness (69). With increased twist, the softness, covering power and bulk decrease, as the yarn begins to resemble a monofilament of large radius rather than an assembly of smaller, parallel filaments (25).

Fiber arrangement within the yarn is related to insulation value. In early research, Finck demonstrated that the conductivity of fibers arranged parallel to the direction of heat flow was two to three times greater than that of fibers arranged perpendicular to the direction of heat flow (7).

Both fabric thickness and layering of fabrics have been shown to be directly related to thermal insulation (6, 20, 21, 32, 43, 50, 52, 61, 62, 72, 75). This relationship is due to the increased amount of air space which serves as insulation. Increases in thermal resistance for layers of fabrics have been found to be greater than the sum of individual values for the single layers (32, 50). This is attributed to the added insulation of the air layer between the fabric surfaces.

V. AIR PERMEABILITY AND POROSITY

The air permeability of a material can be defined simply as the degree to which the material is penetrable by air, or 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).

Two primary methods of measuring the air permeability of textile fabrics were developed during the early research, the Gurley Densometer and the Frazier Air Permeometer (39). The Gurley method allows air permeability values to be obtained by noting the time 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 minute. Landsberg and Winston (43) found a curvilinear relationship between the Frazier and Gurley measurements, and recommended the Gurley method for measuring the air permeability of fabrics of low porosity and the Frazier method for materials of high porosity.

Based on work using the Shirley Air Permeability Tester, which is designed to measure the rate of passage of air being drawn through the fabric by a suction pump, Oxtoby (53) has suggested that for fabrics which permit a high rate of air flow, the air permeability measurement should be made from multiple layers of fabric. The permeability of a single layer could then be estimated by extrapolation from a logarithmic plot of the results. Oxtoby maintains that this method is particularly applicable to knitted fabrics.

"Porosity" is defined as "the ratio of the projected geometrical area of the opening across the material to the total area of the material" (35), or the ratio of void to total volume (67). Porosity is the complement of solidity, which is the ratio of the area of solid parts of the material to the total area of the material. Fabric porosity can be classified into three components: (1) intrafiber porosity, defined as the void space within the fiber walls; (2) interfiber porosity, or the void space between fibers in the yarns, and (3) interyarn porosity, or the void volume between yarns (10, 25).

Relationship between Air Permeability and Porosity

Many of the early researchers used the terms air permeability and porosity interchangeably. Robertson (64) and Hoerner (35) used a wire mesh screen as a simple model of a fabric, stating that textile fabrics show practically the same aerodynamic properties as screens, if the dimensions are identical. Although this model is useful in describing the porosity of open-weave fabrics, it assumes that there is a close

relationship between porosity and air permeability, and obviously does not take into consideration the geometry of the fabric pores in determining air permeability of the fabric structure.

In reality, the permeability of a material cannot be predicted from its porosity. Porosity of a textile fabric is the total volume of void space contained within its boundaries, while permeability is the accessability of that void space to the flow of a gas or a liquid. According to Scheidegger (67), a general correlation between porosity and permeability cannot exist. Instead, Scheidegger relates permeability to the rather arbitrary term, "pore structure," indicating that the permeability of a material is influenced by the capillary pressure curves and the internal surface area of the pores within the material, rather than the actual volume of the open space.

Porosity and Fabric Geometry

Although there is no specific relationship between porosity and permeability, the geometric factors which influence air permeability of textile fabrics are related to porosity. Defining textile fabrics as structures consisting of a "lattice work of threads," Clayton (11) explained the relationship between the fabric structure and the geometry of fabric pores, stating that "most fabrics can be looked upon as a series of holes held together by threads. Any variation in the position of the threads or of their size or shape will cause a variation in the area and the shape of the holes" (11). Clayton considered air permeability in terms of three factors related to the pores in the fabrics: (1) cross-sectional area of each pore; (2) depth of each pore,

or the thickness of the fabric; and (3) the number of pores per unit area. According to Backer (3), both fabric thickness (pore depth) and the number of pores in a given area can be easily determined, but pore size is difficult to analyze.

Burleigh (10) found a direct correlation between interfiber pore spaces and air permeability using a mercury intrusion method of studying pore size distribution. Wakeham (74) used a similar method of mercury intrusion into fabric pores to study interfiber and interyarn pore spaces in 14 fabrics. The data obtained were used to explain differences in air permeability among the fabrics. The volume and diameter of interfiber pores were found to have a high correlation with air permeability.

The measurement of fabric pores has been quite limited, and the geometry of textile fabric interstices cannot be easily characterized. Nevertheless, a theoretical model of open fabric structures can be useful in understanding the mechanism of air permeability. Backer (4) idealized the threads of open fabric structures as flexible, inextensible, circular cylinders which are relatively impermeable to air passage. Although the cross section of a particular pore might vary through the thickness of the fabric, the parameter which influences air flow to the greatest extent is the minimum cross-sectional area of the pore. While it would be difficult to define the total cross-sectional area of a pore, the point at which the cross-section area is the smallest can be determined and this minimum cross-section area can be used to determine relationships between the fabric pores and air permeability, assuming

that the smallest effective pore area is parallel to the plane of the fabric, which may not be the case.

The minimum cross sectional area is used to describe the effective porosity of various interstice types, determined by the type of weave. However, the actual cross-sectional area of the interstices varies through the thickness of the fabric. The concept of minimum cross-sectional area is helpful in explaining air permeability, but is limited in usefulness because it is based on the assumption that texture, yarn count and crimp are completely balanced. The theory assumes that yarns are solid flexible cylinders. The model is not particularly applicable to closely woven structures in which the tension of the interlaced yarns results in great distortion (flattening) of the cylindrical yarn. In many closely woven fabrics, the yarn must crimp sideways as well as up and down (49). Backer admits that the assumptions of the idealized theory are more often violated than obeyed.

Because of yarn interlacing, the sides of a pore are staggered relative to one another in the direction of the pore length. Air cannot flow directly through such pores; the pore geometry often dictates a very irregular path in which there are changes in the direction of air flow. Two pores of equal area may show different levels of air permeability because of differences in the form of the pores. Goodings (28) reports that air flow through a hole drilled straight through a cylinder was greater than the air flow through a hole of equal area which was not straight, but had two right angles. The specimen in which the air path was angular in form required a higher differential pressure to produce

the same rate of flow through it as through the specimen with the cylindrical air path. The angular air path would be similar to the irregular air path in textile fabric interstices.

Goodings (28) studied the relationship between differential pressure and air flow through ten fabrics representing a wide range of air permeability given by very tight to very open fabrics. Results showed that a linear relationship between pressure and flow exists only in fabrics having very low or extremely high air permeabilities. In the majority of the fabrics studied, the rate of acceleration of air flow was slowed as the pressure was increased. Departure from a linear relationship between pressure and air flow, especially at low pressure, is partially attributable to turbulence which results because of the lack of uniformity of pore size within the fabric being tested.

While 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. The interrelated factors which ultimately affect air permeability of the textile fabric include fabric structure, fiber fineness, yarn size, twist, crimp, yarn count, and fabric finish.

Dhingra and Postle (15) concluded that fabric structure is the major factor influencing air permeability of outerwear fabrics. This study showed a correlation between air permeability and extensibility. Woven structures, which are generally least extensible, were found to be least permeable while double knit fabrics, which are most extensible, were found 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.

Fabric thickness determines the depth of fabric pores. When other factors are held constant, air permeability decreases with increasing fabric thickness (40). Clayton (11) used the term "sectional permeability," P_s, to express the permeability of a fabric of unit thickness. Sectional permeability is determined by the expression:

$$P_s \approx P \times d \quad ,$$

where d represents fabric thickness in millimeters. Use of the sectional permeability allows comparison of fabrics which have different thicknesses.

Fabric and Yarn Factors Related to Air Permeability

The air permeability of plain weave fabrics was found to vary with the number of picks per inch and the filling yarn size. As the number of threads per inch was increased from 35 to 65, the air permeability decreased, but beyond 65 threads per inch the air permeability decreased at a much lower rate, as the fabric approached complete closure. The permeability was also found to increase as the filling yarns were increased in size (11).

In Clayton's studies which showed a decrease in air permeability as filling count was increased, all the other factors were held constant.

However, in studies on the permeability of parachute cloths, Goglia (27) found that as the filling thread count was increased, the porosity and air permeability decreased, regardless of the weave type, yarn size or warp thread count.

The degree of closure of a fabric is determined largely by the yarn count. The cover factor, K is defined as the ratio of threads per unit length to the square root of the count (58), or the ratio of fabric surface covered by material to the whole surface (39). A constant cover factor can be obtained by adjusting the filling yarn size and the number of picks per inch.

Yarn twist has a profound effect on porosity and air permeability. As twist increases, permeability increases (11, 39), when other factors are held constant. Generally, increasing twist results in increased yarn circularity and density, which reduces the yarn diameter by consolidating the fiber bundle, thus reducing the cover factor of the fabric. However, because high twist increases yarn density, fabrics consisting of highly twisted yarns may be constructed with a higher yarn count, thus reducing air permeability.

In fabrics made of low twist yarns, the interfiber porosity influences air permeability, as air is permitted to pass through the yarns, but when high twist yarns are used, air flow is restricted to the fabric pores, or interyarn pores (28). In this case, it is assumed that air leaves the fabric in a free turbulent stream (76).

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 structures allows greater air flow through the fabric. In a study of nonwoven air filters, it was found that as fiber crimp frequency is increased, the permeability of the filter increases (42).

The compressibility of a yarn or fabric indirectly influences air permeability. As a yarn is compressed, the structure flattens out, thereby changing the pore geometry, resulting in increased fabric closure, or reduced permeability. However, the ability of yarns to be compressed is related to twist. Low twist yarns, which contribute to interfiber (as opposed to interyarn) permeability, are generally more compressible than highly twisted yarns. Compression and the resulting loss of permeability due to flattening of the yarns may occur during wear over a long period of time.

Multiple Layers of Fabric

Resistance to air flow has been shown to increase in proportion to the number of fabric layers (23, 28, 46, 60). In a study of wind penetration in clothing systems, Fonseca and Breckenridge (23) found that two moderately permeable fabrics with a space between them could provide protection from wind penetration equal to or greater than a single windbreaker of low permeability.

In contrast to the findings of Fonseca and Breckenridge, Lord (46) found that spacing between the fabric layers had no effect on the assembly's resistance to air passage. Lord did, however, find that the resistances to air flow of multiple layers of fabric were generally

additive, except for closely woven fabric, in which the resistance to air flow of several superimposed layers was somewhat greater than the sum of the individual values. Systems consisting of up to five layers of fabrics were tested.

Goodings (28), who also found a synergestic effect with increasing layers of closely constructed fabrics, explains that air passing through one layer will have its kinetic energy dissipated on striking the surface of the next layer. Goodings has stated that successive layers of fabric are not equivalent to one thick fabric. Nonalignment of the pores in the various layers resulting in loss of kinetic energy reduces the air permeability of the system.

VI. MOISTURE

Moisture transfer is presumed to be closely related to heat transfer. The thermal conductivity of a textile fabric refers to the thermal conductivity of a disperse system consisting of textile fibers and air rather than a single solid substance. Thermal insulation of fabrics includes both the insulation value of the fibers and the insulation value of the air entrapped between them (37). As moisture content of the air increases, the overall thermal insulation decreases. Similarly, as a fabric becomes moist, its insulating value decreases. Water held either within the fiber or in the air entrapped within the fabric structure contributes to the overall conductance of the system, thereby reducing the insulation capacity of the fabric (6).

The specific thermal conductivity of a fabric containing moisture can be calculated from the expression:

$$k_3 = (1 - V_w)\ k + V_w k_w$$

where:

k_3 = specific conductivity of the fiber, air, and water mixture,

V_w = volume fraction of water,

k = specific conductivity of the dry air, and

k_w = effective specific conductivity of water (1.98) (7).

Thermal conductivity of fabrics has been shown to increase linearly with an increase in regain, until it approximates the thermal conductivity of water at about 110% regain (6, 8).

Since thermal insulation is influenced by the amount of moisture in the fabric system, the actual moisture absorption capacity of a fiber will influence its thermal insulation value. The usual reaction of a fiber to atmospheric changes is an immediate attempt to modify the atmosphere until equilibrium is reached. As moisture is introduced, there is an initial increase in temperature, resulting in reduced relative humidity. However, as additional moisture is introduced, it begins to diffuse into the fiber (13). The amount of diffusion possible will depend on the capacity of the fiber to attract water molecules.

Mecheels (48) has attributed moisture transfer through fabrics to four possible mechanisms:

1. penetration of the air spaces between the fibers according to laws of diffusion;
2. absorption by the fiber material, transfer within fibers and desorption to the outside;

3. transfer of liquid water through capillary interstices of the yarns;
4. migration of water on the fiber surfaces.

The transfer of water vapor, and therefore, the first and second of these mechanisms, is primarily related to insulation at varying levels of relative humidity. The first mechanism is governed largely by fabric porosity and thickness. The second mechanism relates primarily to natural, hydrophilic fibers. The third mechanism, transfer through yarn interstices, relates primarily to synthetic hydrophobic fibers and is influenced by the dimensions of the yarn interstices and the wettability of the fiber surfaces.

VII. DRAPERIES AND OTHER WINDOW INSULATION DEVICES

Draperies can aid in reducing heat loss through windows. They may also have the additional advantage of flexibility, in that they can be easily opened to allow maximum benefit from solar heat gain or closed to reduce convective or conductive heat loss. This flexibility is an important factor in energy conservation, as heat transfer through windows varies throughout the day and night, as well as seasonally.

In an analysis of fenestration tests completed in Phoenix, after studying several window and shading combinations at different orientations, Yellott, Schuyler and Timmons concluded that reflectance is the most significant property of a fabric in reducing total heat gain. In this analysis, tightly woven shades with a high reflectance were found to be the only type of shade which gave adequate protection from afternoon sun on a western exposure (78).

Properties of window roller shades which have been identified as having a significant effect on heat flow are the position of the shade and the type of material used (54). Transmittance values for a fully drawn aluminum foil roller shade were shown to be lower than those for fabric roller shades. These measurements were made with the apparatus hung so as to have a one-half inch opening on all sides of the shade. Sealing the edges of the roller shade to the window frame resulted in even lower transmittance values. A fabric roller shade with sealed edges was slightly more effective than the aluminum foil shade with unattached edges. By attaching the edges, the aluminum shades were found to have even lower transmittance values. The reduced transmittance can be attributed to less circulation of room air between the roller shade and the window glass, thus minimizing convective heat losses. This study also showed that the transmittance value of a window with a half drawn shade was equal to the average of the transmittance values for a fully drawn shade and a window without a shade.

Ozisik and Schutrum also studied the effectiveness of draperies in reducing solar heat gain through windows with regular and heat absorbing glass (55). After testing a variety of draperies of different fibers, fabric weights, yarn counts and colors, they concluded that the reflectance of the drapery on the glass side largely determines the amount of solar heat gain. Fabric with a high solar reflectance on the glass side excludes more solar heat than a fabric with a low reflectance.

In a study of solar heat gain through insulated and heat absorbing glass combined with light and medium colored draperies, absorptance,

reflectance, and transmittance characteristics of the draperies were identified as factors in determining total heat gain (57). In this study, reflectance and absorptance measured on the flat fabrics did not agree with measures taken on the hanging draperies, because of the complexity of the drapery folds. Although color was the primary drapery variable in this study, the researchers state that the properties of absorptance, reflectance, and transmittance are also functions of other characteristics, including the weave, luster and weight.

In a study of shading coefficients, Morrison, Wheeler, and Farber studied three drapery fabrics classified by color and weave in combination with different types of glass. The study showed that as the transmittance of the glass decreased, the solar optical properties of the draperies have less effect on the shading coefficient of the drapery-glass combination. However, the drapery materials were found to have a significant effect on the shading coefficient for insulating reflective glass panels (51).

Yellott (77) and Keyes (41) studied the openness factor of drapery fabrics. Yellott concluded that solar reflectance is the factor which determines shading coefficients for tightly woven fabrics while solar transmission is the most important property for fabrics which have more open weaves. Keyes explained that very different fabrics can have the same transmittance level, indicating that both fabric weave and color influence the amount of shading provided by draperies. Radiation may be transmitted either through fabric or through openings in the fabric. Transmittance through the fabric depends on color or yarn reflectance,

while the amount of transmittance through openings in the fabric is dependent upon the openness of the fabric weave. Keyes categorized drapery fabrics according to their openness factor, yarn reflectance and color. The nine resulting classifications were recommended as a basis for selecting draperies according to their shading properties.

Dix and Lavan (16) conducted studies to measure the influence of draperies and other indoor shading devices on thermal transmission under simulated winter and summer conditions. Using thermistors located near test windows in environmentally controlled chambers, they evaluated a variety of devices. A white, opaque roller shade hung inside the window recess with a one-fourth inch opening at the edges was found to provide a 28% reduction in heat loss through the window. In the same study, a plastic-backed fabric drapery provided a 6% reduction while a Venetian blind produced a similar reduction of 7%. The low values were attributed to the inability of these devices to restrict air flow. The louvers of the Venetian blind could not be shut tightly, and the drapery which hung outside the casement allowed air to flow vertically along its pleats. The roller shade hung outside the window casement produced only a 12% reduction in heat loss.

On comparing winter heat losses with summer heat gains, Dix and Lavan found that a medium colored drapery with a white plastic backing reduced conductive heat loss under winter conditions by 6 to 7% and conductive and radiant heat gains under summer conditions by 33%, respectively. Shades inside casements were found to reduce heat loss under winter conditions by 24 to 31% and radiant heat gain under summer

conditions by 47 to 54%. Dix and Lavan concluded that the ability of shading devices to block air flow was more important than other properties in influencing thermal transmittance.

Grasso and Buchanan (30) examined the influence of fabric properties on the effectiveness of window roller shade treatments. The study listed Sunshed, Vinyl Exlite, and Fiberglas as being the most effective in reducing heat losses among traditional shade fabrics. More effective results were obtained from a wooden shade which produced a 34% reduction in heat loss. The most effective reduction in heat loss was provided by a Mylar coated vinyl, which reduced heat loss by 45%. The effectiveness of the three traditional fabrics was attributed to the fact that they were slightly thicker than other typical shade fabrics tested. The ability of a fabric to resist conduction increases as its thickness increases. The Mylar film, which was similar in thickness to the other shade fabrics, also contributed to reduction of heat transfer through radiation. When investigating the importance of the distance between the window shade and glass, the researchers found that energy efficiency was greater when the shade was closer to the window. This was explained by the fact that less air was able to move between the shade and the window, resulting in lower transmittance values. This particular study also showed that multiple layers of fabric in window shade systems provided an improvement over single layer systems within each fabric type. This is due to the additional insulation provided by each extra layer.

Pennington, Morrison and Ingley (56) analyzed various types of double-draped window configurations and found that the lowered U value

resulting from such a layered configuration is valuable in minimizing winter heat losses and summer heat gains. According to this research, the flexibility resulting from double draping is of prime importance, in that it allows control of light and outward vision. Also, a system of double draping can be used to either lower or raise solar heat gains, depending on the properties of the drapery materials and the arrangement. Draperies can also improve indoor comfort conditions because the fabric temperatures are more nearly that of the occupied space.

Feather (22) studied the insulation characteristics of eleven different lined and unlined draperies custom constructed to fit a test window. The fabrics, which also varied in weave openness, included various fiber types: 100% polyester, a 50/50 cotton/polyester blend, a 65/35 rayon/acetate blend, and 100% cotton. The draperies were constructed to contain a fabric width of 2.8 times the width of the window, with the exception of a sheer sample, which contained 3.5 times the width of the window. The draperies, which had a 3-inch pinch-pleated heading and a 3-inch hem, were hung on an end-curved rod placed under a 4-inch cornice which extended 4-3/4 inches beyond the window edge. The draperies hung to within 1/2 inch of the floor. Findings of the study showed no significant relationship between fabric weight and insulation value. Fiber type was also found to be less important than fabric construction.

A self-lined (laminated) drapery was found to provide better insulation than the traditional unlined samples, but less than those samples with separate linings.

A white roller shade constructed of finely woven cotton impregnated with vinyl was tested independently and in combination with the draperies. The roller shade alone provided greater insulation than all of the lined and unlined drapery samples. However, the greatest reduction in heat loss was realized when the shade was used in combination with the draperies.

The configuration of the drapery on the window was a major factor of consideration by Hassenboehler and Donoghue (33). A conventional drapery was compared with a configuration in which the lower edge of the drapery was folded under and sealed to the bottom of the test window, forming a "bag" configuration. Additionally, a flat screen of open-weave sheer fabric sealed to the window on all four sides was tested. The screen was also tested in combination with the conventional drapery and the bag configuration.

The samples were tested in combination with materials chosen to represent idealized draping elements. Aluminized kraft paper was used to represent idealized radiation control and a 0.75-inch polyurethane foam board was used as the ideal conduction control. Combined radiation and conduction control was provided by a 0.75-inch polyurethane foam board with aluminized kraft paper on either side.

Under tests which simulated both summer and winter conditions, both the screen and bag configurations were found to impede the transport of the window-drape air mass. On a seasonal basis, the bag and screen configurations reduced transmittance through the window by approximately 33%, while the screen and bag combination produced a 44% reduction when

used with the traditional drapery fabric components. Results were similar when the bag and screen configuration was tested with the idealized radiation and conduction control devices.

Selkowitz (68) has summarized the issues related to various types of insulating window systems. Potential problem areas associated with movable insulating devices such as draperies include condensation, infiltration, and air leakage.

A major source of energy loss in buildings is infiltration through poorly fitted windows. This loss can be minimized through the use of tight fitting insulation devices. However, as air leakage around the device increases, the insulating efficiency decreases. Achieving effective seals which prevent air leakage presents a critical design problem, particularly for movable insulating devices such as draperies.

Draperies and other interior insulating devices will reduce glass temperatures and increase the likelihood of condensation. As the tightness of the window itself is increased, and as air leakage around the insulating device is reduced, the likelihood of condensation is increased.

As air leakage is reduced, causing interior surface temperatures to rise, the thermal comfort of individuals in the vicinity of the window will be increased. In the absence of drafts, thermal comfort can be achieved at lower air temperatures. Therefore, the use of draperies or other insulating devices which prevent drafts can result in energy savings due to the reduction in temperature required for maintenance of thermal comfort.

According to Selkowitz, one of the most critical factors influencing the energy efficiency of draperies and other devices is user responsibility. In order for potential savings to be fully realized, the user must conscientiously open and close the draperies as needed to maximize the benefits of solar heat gain and to minimize energy losses. Selkowitz maintains that the best approach for guaranteeing effective operation is to couple the insulating function with a function that is already familiar and routine to the user, such as closing a drapery at night for privacy.

Based on studies using a large building energy analysis computer program, Selkowitz notes that movable insulating devices (which can include draperies) used in conjunction with either single or double glazed windows can reduce thermal losses to a level comparable to that of a well-insulated wall. However, as a window becomes insulated, the potential benefit from additional insulation decreases. As the R-value of the window-drapery system is increased from R5 to R10, the incremental savings is only marginal. It is within this region that the cost of providing additional insulation might outweigh the benefit (68).

VIII. INSTRUMENTATION

Various instruments that have been used to measure insulation properties of textile fabrics have been reported in the literature. Three include:

1. Methods that depend on the rate of cooling of a source of heat covered by the fabric.

2. Methods in which the sample rests on a heated plate. The heat transmitted through the fabric to the 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 a cooling element. Heat transmittance is determined by the amount of electrical energy supplied to the heating element (5).

The first of these three methods is used to compare fabrics on the basis of thermal resistance and cooling power. The second and third methods measure conductivity of the fabric.

There have been many innovative adaptations of these methods. A British instrument called the togmeter measures the overall thermal resistance of a fabric placed between two flat plates. The instrument measures the steady state conduction plus the radiation and conduction through the entrapped air (52).

The guarded hot plate has become a standard instrument for measuring the relative thermal resistance of textile fabrics in this country. Heat flows from a heated plate placed in contact with the experimental fabric and then dissipates into the still air at a lower ambient temperature. Thermal resistance is determined from the rise in temperature which results when a fabric is placed over the hot plate (73).

Various researchers have developed their own instrumentation for specifically testing thermal transmittance of draperies. This instrumentation usually involves a cold chamber and a warm or hot chamber. The drapery sample is typically placed between the two

chambers and its resistance is calculated from the heat flow from the warmer chamber, through the window and drapery to the cold chamber.

Hassenboehler and Donoghue (33) modified a refrigerator chamber by covering the freezing compartment with a model window. Draperies were then tested on the window. Heat flow through the window-drapery system was monitored through sensors by a computer.

The guarded hot box test, specified by ASTM Standard C236 is used to determine the thermal transmittance of various building sections and components, including windows (63). A test sample of the particular building component is placed in a divided box on which one side of the test panel is exposed to a cold condition (cold box) and the other side to a warm condition (guard box), representing the interior and exterior environments of a typical building. A metering box is then placed over the test sample. The metering box contains an electrical heating apparatus which controls the energy input. By measuring the energy input into the metering box and minimizing the temperature difference between the inside of the metering box and the inside of the guard box, the amount of energy flowing through the test sample is measured. The U value of the test specimen can be calculated from the temperatures of the cold box, the guard box and the metering box.

CHAPTER III

PROCEDURE

The purpose of this investigation has been to identify characteristics of textile drapery fabrics and drapery configurations which contribute to low heat transmittance and to determine any significant differences between these characteristics.

I. FABRICS

Ten fabrics were chosen for the study after a local market search was conducted to determine the availability of fabrics being used for draperies. Eight drapery fabrics were chosen to represent selected fiber and fabric characteristics determined by the three experimental factors of fiber type, color, and fabric openness. Four fabrics composed of a hydrophilic type fiber, such as rayon or cotton, and four fabrics composed of a hydrophobic type fiber, polyester, were selected. Within each fiber category, two light colored fabrics and two darker colored fabrics were chosen. The third criterion for fabrics was that they vary in openness. Therefore, within each category of color, an open weave fabric and a tightly woven fabric were selected. This yielded a total of eight different combinations of the three factors, as shown in Figure 1.

Two lining fabrics were also selected to represent both hydrophilic and hydrophobic fiber types. Specifically, a medium weight cotton lining fabric and a sheer polyester fabric were chosen.

FIBER	hydrophilic				hydrophobic			
COLOR	light		dark		light		dark	
WEAVE	tight	open	tight	open	tight	open	tight	open

Figure 1. Fabric factors.

The fiber content of each of the ten fabrics was verified using chemical solubility and microscopic techniques.

II. FABRIC CHARACTERISTICS

Physical characteristics including fabric weight, thread count, yarn crimp, yarn linear density, fabric cover factor, fabric thickness, fabric reflectance, air permeability, porosity, moisture regain and drape coefficient were determined using standard textile testing procedures according to the American Society for Testing and Materials (1). The physical properties of the experimental fabrics are shown in Table 1.

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

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

TABLE 1

PHYSICAL PROPERTIES OF FABRICS

Fabric	Fiber	Yarn Tex	Yarn Crimp (%)	Thread Count	Weight (oz/yd^2)	Weight (g/m^2)	Thickness (inches)	Thickness (cm)	Porosity (%)	Air Permeability ($ft^3/min/ft^2$)	Cover	Reflectance	Drape Coefficient	Moisture Regain (%)
A	100% cotton	W 41.82 F 68.13	W 3.3 F 7.1	W 86 F 35	7.29	247.14	.0231	.0587	72.3	42	34.8	75.0	54.0	8.13
B	100% cotton	W 39.99 F 75.16	W 6.0 F 8.3	W 89 F 37	8.07	193.00	.0278	.0706	82.0	32	36.4	31.4	55.1	8.57
C	100% rayon	W 58.29 F 128.67	W 2.0 F 8.7	W 27 F 22	5.33	180.67	.0240	.0610	80.2	340	18.8	71.6	70.9	10.64
D	100% rayon	W 58.31 F 144.71	W 1.9 F 5.6	W 26 F 22	5.51	186.87	.0268	.0681	81.7	245	19.1	54.1	60.9	10.62
E	100% polyester	W 38.27 F 37.87	W 20.4 F 17.9	W 65 F 59	6.48	219.78	.0340	.0864	81.7	80	31.4	87.0	35.6	0.27
F	100% polyester	W 39.33 F 39.87	W 9.9 F 24.3	W 73 F 58	7.12	241.40	.0262	.0665	73.9	80	33.9	13.9	36.8	0.45
G	100% polyester	W 7.26 F 109.44	W 6.1 F 2.2	W 23 F 17	2.68	90.84	.0298	.0757	91.4	701	9.9	77.9	34.9	0.27
H	100% polyester	W 7.31 F 119.02	W 6.0 F 2.1	W 23 F 17	2.73	92.74	.0304	.0772	91.4	701	10.2	54.1	40.1	0.23
X	100% cotton	W 18.6 F 15.4	W 1.7 F 2.5	W 82 F 73	3.32	112.74	.0168	.0427	82.7	120	26.3	85.2	45.9	7.33
Y	100% polyester	W 5.44 F 21.95	W 2.2 F 1.5	W 102 F 50	1.76	59.72	.0098	.0249	82.9	342	19.4	79.9	47.8	0.21

The weights in ounces per square yard were converted to g/m^2 by the following formula:

$$g/m^2 = oz/yd^2 \times 33.906 \quad .$$

Thread count was determined according to ASTM D1910-64. Five 2" × 2" specimens were randomly taken from each fabric. The ends and picks were counted using a pick glass and the mean count per inch was recorded for each direction, warp and filling.

Yarn crimp was determined according to ASTM D1910 using the Shirley Crimp Tester. The percentage crimp in warp and filling yarns was calculated from the mean value for five specimens using the following formula:

$$\text{Percent crimp} = \frac{(D_2 - D_1) \times 100}{D_1}$$

where:

D_1 = distance between marks on the fabric, prior to removal of yarns, and

D_2 = distance between marks on the straightened yarn.

Yarn linear density was determined according to ASTM D2260 at the same time that yarn crimp was measured. While the yarn was under tension in the Shirley Crimp tester it was cut to a length of 90 cm, removed and weighed. Denier (g/9000 m) was calculated and then converted to tex by the following formula:

$$\text{tex} = \frac{\text{denier}}{9}$$

Denier was also converted to cotton count by the following formula:

$$\text{cotton count} = \frac{5314.87}{\text{denier}}$$

The cover factor (K), which determines the amount of surface area covered by the fabric, was calculated using the warp and filling thread count and cotton count, according to the following formulas:

$$K_w = \frac{N_w}{\sqrt{CC_w}}$$

$$K_f = \frac{N_f}{\sqrt{CC_f}}$$

$$K_{fabric} = K_w + K_f$$

where:

N = thread count, warp (w) or filling (f), and

CC = cotton count, warp (w) or filling (f).

The theoretical value for total cover in which yarns are just touching is 28.

Fabric thickness 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. A weight of 1.1326 g and a presser foot with area of 1 cm^2 were applied. The mean thickness was recorded from five randomly selected specimens for each fabric.

Fabric reflectance was determined using the Hunterlab Color Difference Meter (Model D25D2). The means of five readings per fabric of the L value (black-white scale) were recorded.

Air permeability was determined according to ASTM D737-75 (1) using the Gurley Permeometer. Five randomly selected specimens from each fabric were measured and the mean rate of air flow was recorded in $ft^3/min/ft^2$ and converted to $cm^3/sec/cm^2$ by the formula:

$$cm^3/sec/cm^2 = ft^3/min/ft^2 \times 0.508 \quad .$$

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, and is the recommended instrument for measuring air permeability of more tightly woven fabrics.

Two of the open weave fabrics included in this study could not be evaluated directly using the Gurley Permeometer because their air permeabilities were beyond the range of the instrument. The air permeabilities of these fabrics were determined indirectly by testing multiple layers of fabric. Readings were obtained from successive numbers of fabric layers, ranging from four (the fewest number of layers from which a reading could be obtained) to twenty (the maximum number of layers which could be accommodated between the jaws of the instrument. A plot of air permeability versus number of fabric layers indicated a curvilinear relationship between the two factors, as shown in Figure 2. A nonlinear regression analysis (66) of the data provided the following model for predicting the air permeability of the fabric:

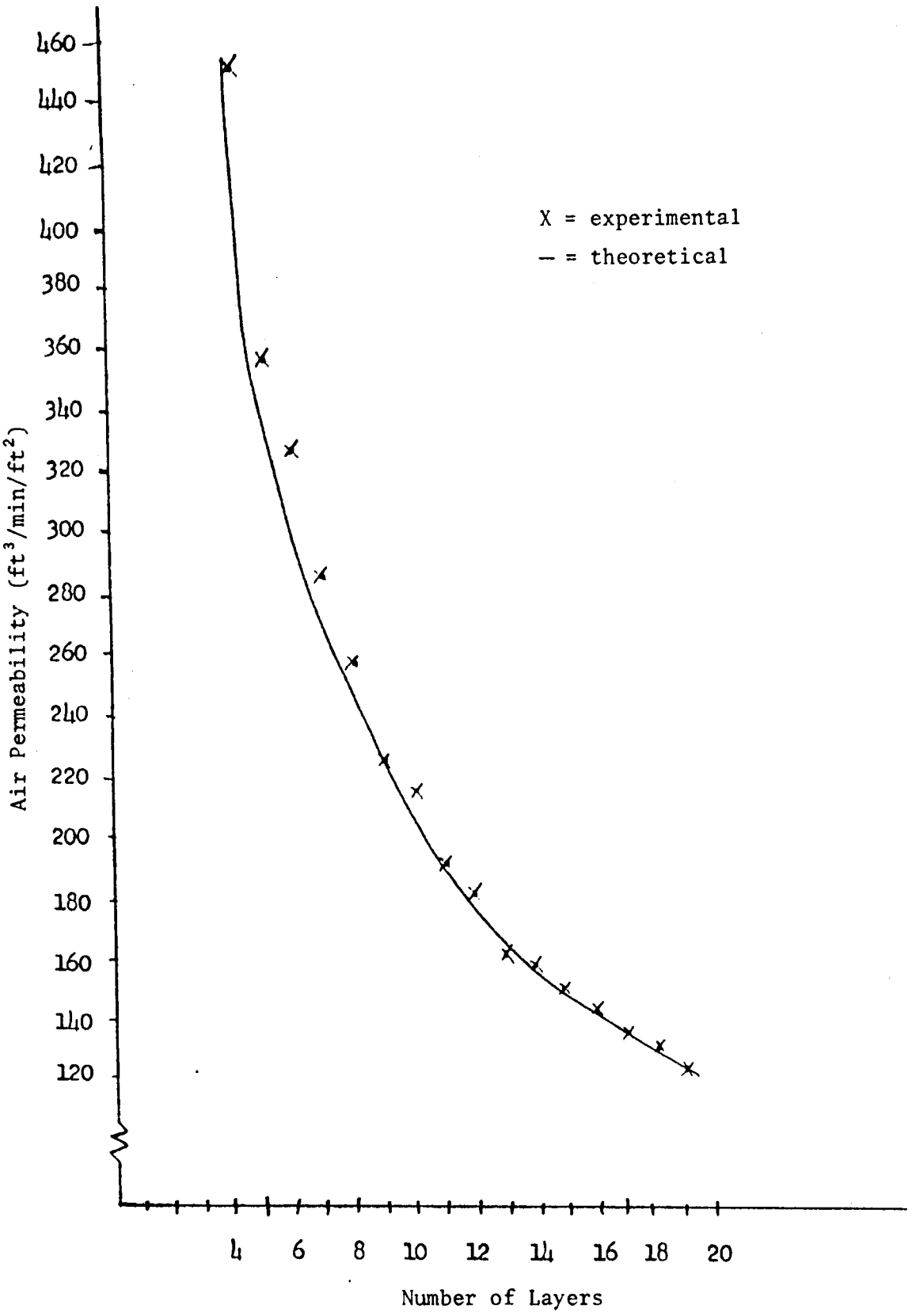


Figure 2. Air permeability of successive layers of fabric G.

$$\text{Permeability} = 107.39 + 724.76 \times e^{-0.19944 \times \text{layers}}$$

An R-square of .9508 indicated good fit of the model to the data. The single layer air permeabilities of the two very open weave fabrics were predicted from this equation.

In order to assess the accuracy of this method, the air permeabilities of successive fabric layers were measured for three of the other test fabrics, a tightly woven drapery fabric, an open weave drapery fabric, and the sheer lining fabric. The number of layers tested ranged from one to the maximum which could be accommodated between the jaws of the instrument (14 layers of fabric B, 16 layers of fabric C, and 56 layers of fabric y). Similar curvilinear relationships between air permeability and fabric layers were indicated for each of these fabrics and high R-square values for the nonlinear regression equations indicated excellent fit of the models to the data.

The percentage porosity was determined using the measured weight and thickness of the fabric and the specific gravity of the fibers by the following formula:

$$P_y = 100\ (1 - da/df)$$

where:

P_y = percent porosity of the fabric,

da = density of the fabric, taken as the ratio of fabric weight (g/cm^2) to fabric thickness (cm), and

df = density of the fiber.

The following densities of the respective fibers were used in the evaluation of fabric porosity:

cotton = 1.52 g/cm^3

rayon = 1.49 g/cm^3

polyester = 1.39 g/cm^3

Moisture regain, expressed as a percentage, was determined according to ASTM D2654. Three 8" × 8" samples of each fabric were conditioned for 24 hours. Each conditioned specimen was weighed in a previously weighed container, dried in an oven at 105 ± 2°C for thirty minutes, cooled for thirty minutes in a dessicator containing phosphorus pentoxide (P_2O_5) and reweighed. This procedure was repeated until a constant weight was obtained. The percent moisture content was calculated according to the following formula:

$$\text{Percent moisture content} = \frac{W_1 - W_2}{W_1} \times 100$$

where:

W_1 = initial weight of the specimen, and

W_2 = final weight of the specimen after drying to constant weight.

After the moisture content was determined, each specimen was conditioned for 24 hours and reweighed. This procedure was repeated until a constant weight was obtained. The percent moisture regain was then calculated according to the following formula:

$$\text{Percent percent moisture regain} = \frac{W_3 - W_2}{W_2} \times 100$$

where:

W_3 (regain weight) = weight of the specimen after conditioning to constant weight, and

W_2 (final weight) = weight of the specimen after drying to constant weight.

The drape coefficient for each fabric was determined using the Fabric Research Laboratory Drapemeter. Three 10-inch diameter circular specimens of each fabric were tested on both sides. The drape coefficient was calculated according to the following formula:

$$F = \frac{A_3 - A_2}{A_1 - A_2} \times 100$$

where:

F = drape coefficient,

A_1 = weight of a 10" paper ring, representing the flat fabric,

A_2 = weight of a 4" paper ring, representing the platform from which the fabric is draped, and

A_3 = weight of the projected fabric image, cut from the paper used to obtain A_1.

III. GEOMETRIC CONFIGURATION OF THE DRAPERIES

Three experimental variables related to drapery configuration were included in the study: drapery fabric fullness, lining fullness, and spatial separation between the lining and drapery. Two levels of drapery fabric fullness were tested: 50% and 100%. Within each of the categories of drapery fullness, two levels of lining fullness were

tested: zero percent (flat), and the same fullness as the drapery fullness (50% lining fullness with 50% drapery fullness and 100% lining fullness with 100% drapery fullness). Three levels of spacing between the lining and drapery were tested: touching, 1/4 inch and 1/2 inch. A total of twelve different combinations of the three configuration factors were tested, as indicated in Figure 3.

Drapery fullness	50%						100%					
Lining fullness	flat			50%			flat			100%		
Spacing—Lining to Drapery (inches)	0	$\frac{1}{4}$	$\frac{1}{2}$	0	$\frac{1}{4}$	$\frac{1}{2}$	0	$\frac{1}{4}$	$\frac{1}{2}$	0	$\frac{1}{4}$	$\frac{1}{2}$

Figure 3. Configuration factors.

To maintain the desired drapery and lining fullness and spatial configuration, spacers cut from rigid styrofoam were used at the top and bottom of the window frame. The spacers were designed to simulate the pleats in a hanging drapery. For both fullness levels, an amplitude of three inches was selected, to represent the depth of pleats in a hanging drapery. The technique of constructing an arc to represent 50% fullness is illustrated in Figure 4. In this procedure arc length B was determined to be 1.5 times the period A. Depth C represents the selected amplitude, or simulated pleat depth, and is equal to three inches. To construct the spacer for 50% fullness, half-circles with

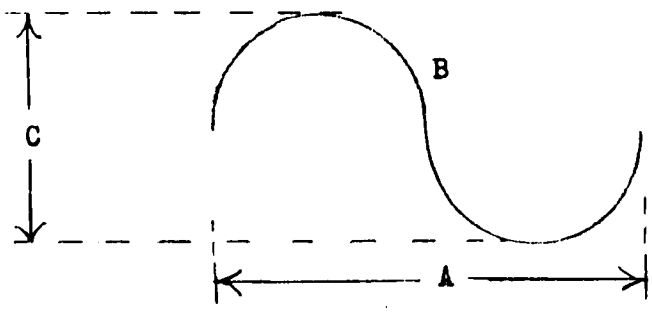


Figure 4. Fifty percent fullness.

radii of 1.6 inches and centers .1 inch above and below the centerline of the spacer were constructed as illustrated in Figure 5, which represents a segment of the total arc. The procedure and derivation for determining the arc are illustrated in Figure 6.

In Figure 6, which represents the calculations for one section of the total arc, the radius C of the arc then equals 1.5 inches, which is half the desired amplitude (3") and provides 50% fullness and,

$G = 1.6$ inches

$I = 0.1$ inch

$f = G = 1.6$ inches

whereas,

$\cos\theta = d/f = .1/1.6 = .063$

$\cos^{-1}(.063) = 86.417°$

$\sin(86.417°) = .998$

$e = f \sin\theta = (1.6)(.998) = 1.597$

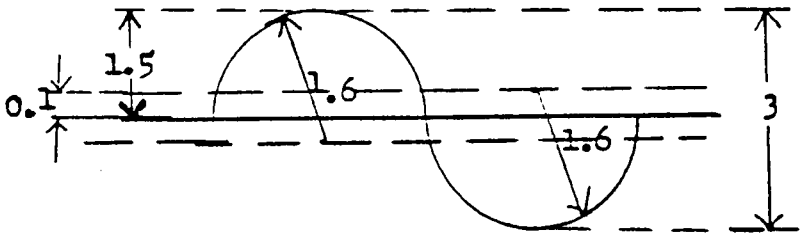


Figure 5. Construction of arc representing 50% fullness.

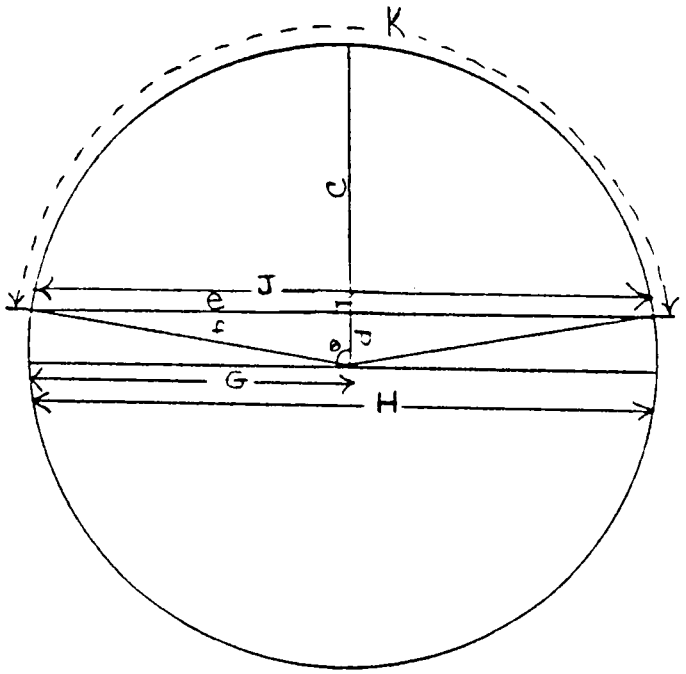


Figure 6. Determination of 50% fullness.

$J = 2e = 3.194$

$K = \phi r$ where $\phi = 2\theta$ in radians

therefore,

$$K = (2\theta)\left(\frac{\text{rad}}{180^\circ}\right)(r) = (172.834^\circ)\left(\frac{\pi}{180^\circ}\right)(1.6) = 4.826$$

and,

$$\frac{K}{2e} = \frac{K}{J} = \frac{4.826}{3.194} = 1.51 \text{ inches} \quad .$$

For 100% fullness, arclength B was required to be twice the period A, as illustrated in Figure 7. Distance C is 3 inches, representing the desired amplitude, or simulated pleat depth.

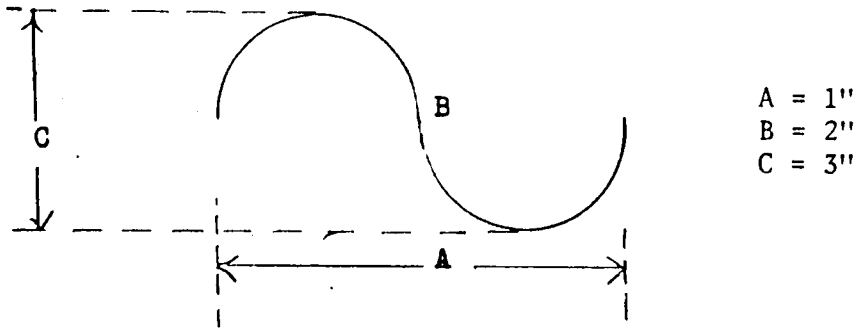


Figure 7. One hundred percent fullness.

To construct the spacers for 100% fullness, half circles with radii equal to one inch and centers 0.5 inches away from the centerline were constructed, as illustrated in Figure 8, which represents one segment of the total arclength. The half circles were then connected with straight lines (ab).

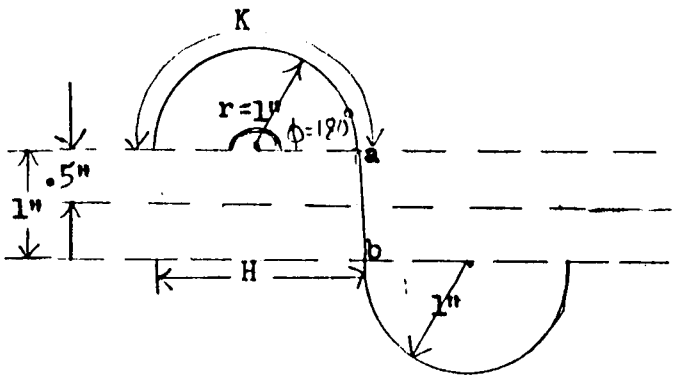


Figure 8. Construction of arc representing 100% fullness.

The arclength of the spacer representing 100% fullness is twice the length of the baseline, as explained by the following calculations:

arclength $K = \phi r$

and,

$$K = (180°)\left(\frac{\pi \text{rad}}{180°}\right)(1")$$

$K = 3.142$ inches

$2K = 6.283$ inches

$2K + 4\ (.5) = 6.283 + 2 = 8.283$ inches

whereas,

$H = 2r = 2$ inches

therefore,

$2H = 4$ inches

and,

$$\frac{2K + 4\ (.5)}{2H} = \frac{8.283}{4} = 2.07 \text{ inches} \quad .$$

For lining fullnesses of 50% and 100%, spacers were constructed so that the lining would be positioned 3/4 inch away from the window frame, as illustrated in Figure 9. The arcs for each spacer were constructed according to the steps previously presented.

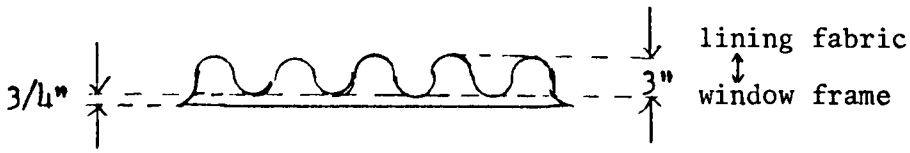


Figure 9. Lining spacer.

For configurations representing pleated linings and pleated draperies with spatial separations between the lining and drapery fabrics, secondary spacers were used, as illustrated in Figure 10.

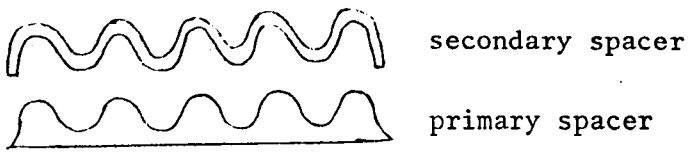


Figure 10. Primary and secondary spacers.

The flat surface of the primary spacer is attached to the window frame. The lining fabric is attached to the curved surface of the primary

spacer. The secondary spacer is placed over the lining fabric, and the drapery fabric is attached to the secondary spacer.

Figures 40-51 (in the Appendix) represent the 12 drapery-lining-spatial configurations which were included in the investigation.

Patterns for each of the spacers were first constructed on paper and transferred to sheets of two-inch thick styrofoam. The spacers were then cut using an electric hot wire. Two identical spacers were constructed for each configuration under investigation, one for the top of the window and one for the bottom.

Wooden fabric stretcher strips were used to construct 36" × 40" frames. The spacers were attached tightly to the frames using masking tape. Fabrics were pinned onto the spacers and sealed at the sides with additional wooden strips placed on top of the fabric. The entire assembly was then mounted onto the test window and held in place by metal clamps.

A tight seal on all four sides of the window allowed maintenance of a constant volume of air between the window and lining and the lining and drapery. The volume of the air spaces for each of the twelve configurations was calculated.

Determination of Spacer Area

Using the basic formula that volume equals length times width times depth, or area times length, the area represented by the basic spacers (50% fullness or 100% fullness) was first calculated geometrically. The area of the spacers was then used in calculating volume of the air spaces within the drapery system.

For the 50% fullness spacer, individual arcs in the spacer are represented by two basic forms, A_1 and A_2, as shown in Figure 11.

Figure 12 illustrates calculation of the area of segment A_1 of the 50% fullness spacer. Segment A_1 is subdivided into parts a, b, and c. The area of the two parts, a and b, is represented as a semicircle of radius 1.6, with angle = 172.83°, or 3.017 radians. The area of this semicircle is calculated by the formula:

$$A = \frac{\phi}{2} r^2$$

Using this formula,

$$A = \frac{3.017}{2} \times (1.6)^2 = 3.861 \text{ in}^2$$

The area of the two parts, b and c, is represented by a rectangle whose height = 1.6 - .1 = 1.5, and length = 3.194 (from Figure 6). The area of this rectangle is (1.5) × (3.194) = 4.791 in^2.

The area of the triangle which represents part b is 1/2 base × height, where the base is 3.194 and the height is .1, or

$$(1/2)\ (3.194)\ (.1) = .1597 \text{ in}^2 \quad .$$

The area of segment A_1 = area of (a + b) + area of (b + c) - area of (b), or, A_1 = 3.861 + 4.791 - .1597 = 8.492 in^2.

In Figure 12, the area represented by b plus c equals the area represented by a, plus the area of A_2 (Figure 11). The total area of b + c is 4.791 in^2. Therefore, the total area of a + b + c + A_2 is

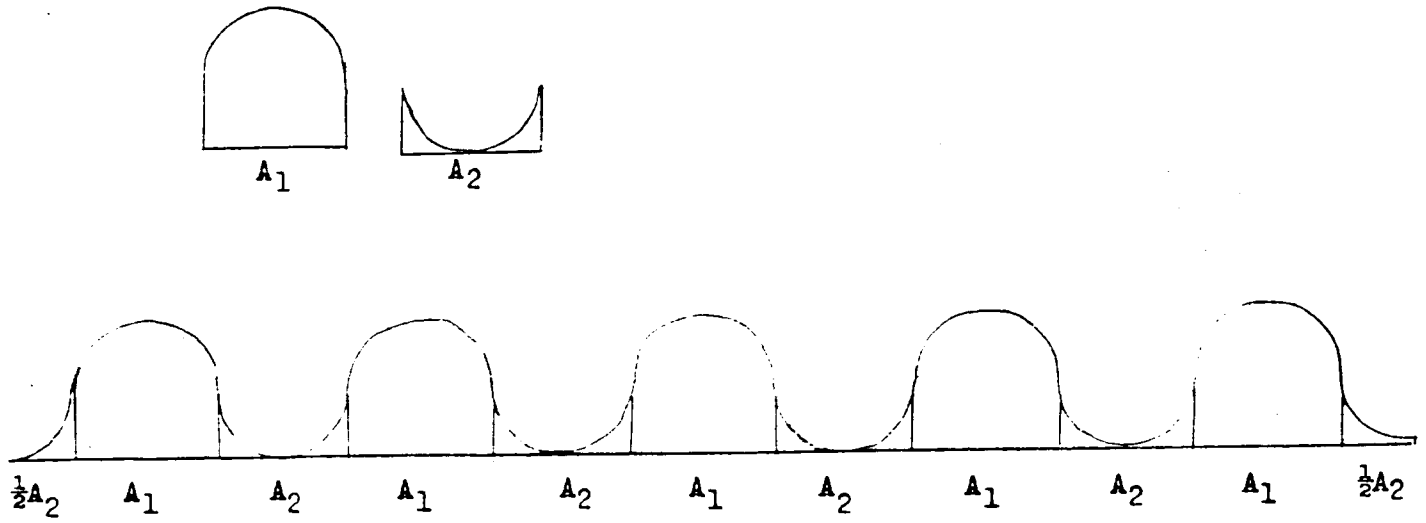


Figure 11. Geometry of the spacer representing 50% fullness.

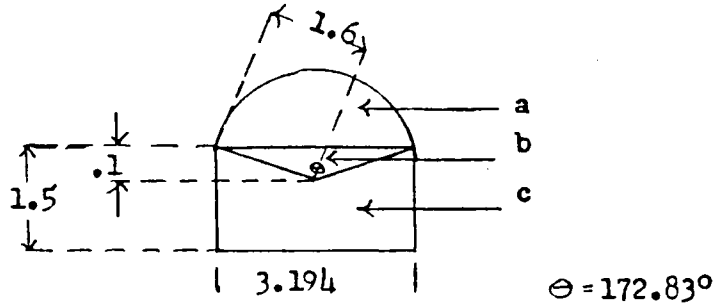


Figure 12. Segment A_1 of 50% fullness spacer.

$2(4.791) = 9.582$ in^2. The area A_2 (Figure 11) = total area of the rectangle shown in Figure 12 = area a - area b - A_1, or

$$9.582 - 8.492 = 1.090 \text{ in}^2 \quad .$$

As shown in Figure 9, the basic 50% fullness spacer includes five A_1 segments, four A_2 segments, and two 1/2 A_2 segments. Therefore, the total area of the basic 50% fullness spacer is 5 (8.492) + 4 (1.090) + 2 (.5) (1.090) = 47.91 in^2.

The calculation of the area of the basic 100% fullness spacer is similar to that of the 50% fullness spacer, although somewhat less complicated.

Individual arcs in the 100% fullness spacer are represented by two basic forms, A_1 and A_2, as illustrated in Figure 13.

Segment A_1 of the 100% fullness spacer is subdivided into parts a and b, as illustrated in Figure 14. The segment a represents a half-circle with radius equal to 1" (from Figure 6, p. 50). The area of segment a equals 1/2 πr^2, or, (1/2) (π) $(1)^2 = 1.571$ in^2.

Segment b is then a square, of 2" sides, and its area is 4 square inches. The total area of A_1 = area a + area b is

$$1.571 \text{ in}^2 + 4 \text{ in}^2 = 5.571 \text{ in}^2 \quad .$$

The rectangle B in Figure 15 represents the desired area, A_2 (shaded), plus the area a, a half-circle with radius 1. The area of part a

$$= 1/2\ \pi r^2 = (1/2)\ (\pi)\ (1)^2 = 1.571 \text{ in}^2 \quad .$$

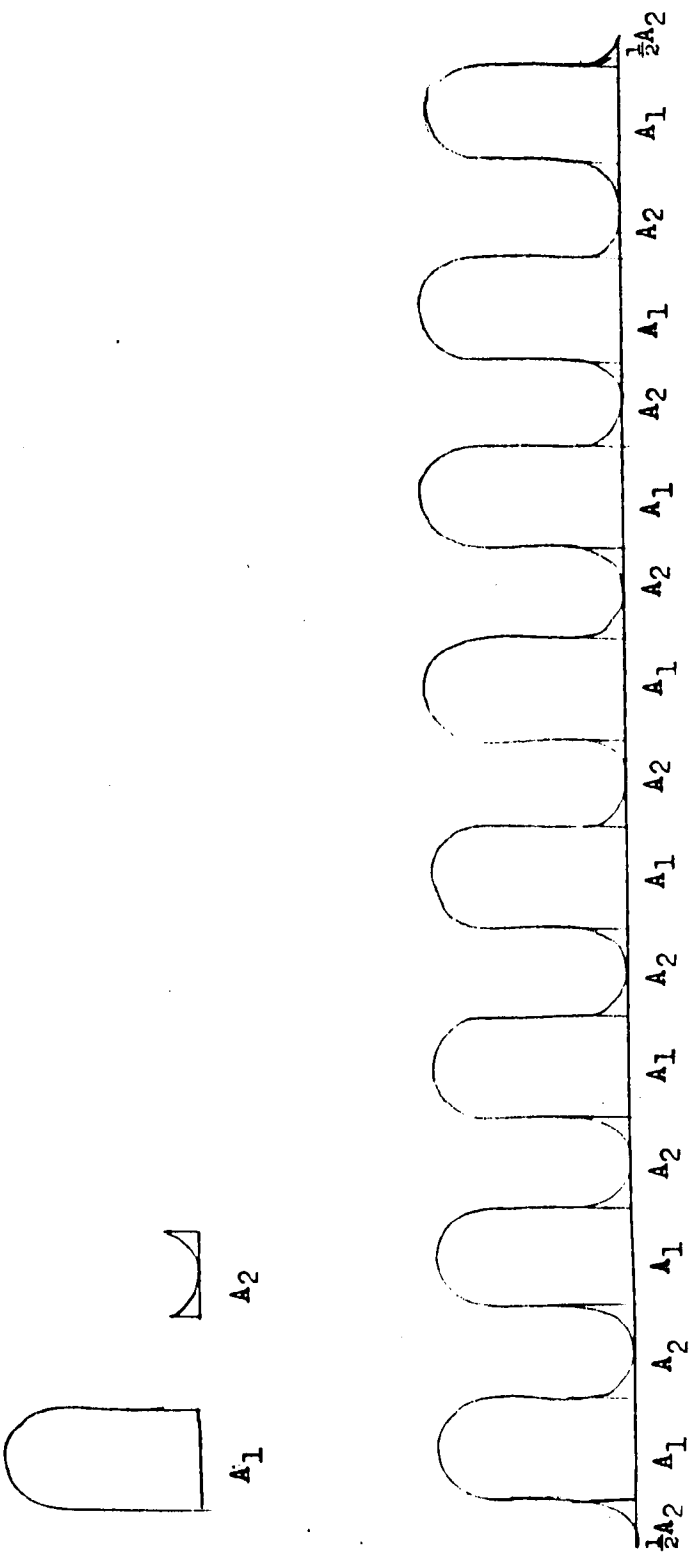


Figure 13. Geometry of the spacer representing 100% fullness.

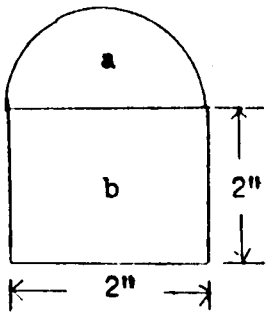


Figure 14. Segment A_1 of 100% fullness spacer.

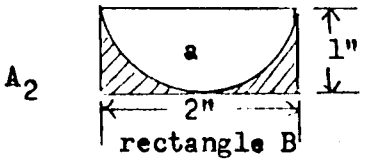


Figure 15. Segment A_2 of 100% fullness spacer.

The total area B in Figure 15 is a rectangle, 1" × 2". Therefore, the area of B = 1 × 2 = 2". The desired area, A_2 = area B minus area a, or 2 - 1.571 = .429 in^2.

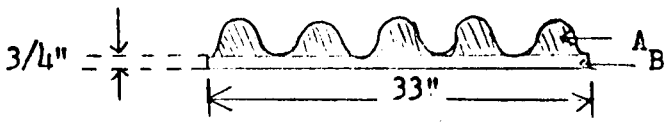
As shown in Figure 13, the basic 100% fullness spacer includes eight A_1 segments, seven A_2 segments and two 1/2 A_2 segments. Therefore, the total area of the basic 100% fullness spacer

$$= 7\ (5.571) + 7\ (.429) + 2\ (1/2)\ (.429)$$

$$= 48\ in^2.$$

The area of a basic 50% fullness spacer is 47.91 in^2, and the area of a basic 100% fullness spacer is 48 in^2. This represents the shaded (A) portions of each of the spacers in Figures 16 through 23. The

areas of the rectangles (B) which form the remaining portions of each of the spacers are calculated by the formula A = length × width.



area A = 47.91
area B = (.75) (33)
= 24.75
Total area of spacer
= 72.66 in^2

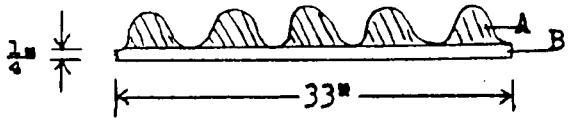
Figure 16. Spacer used for 50% lining fullness



area A = 47.91

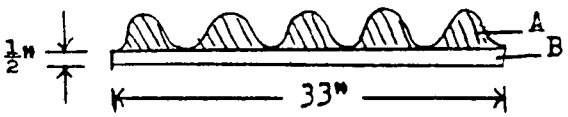
Total area of spacer
= 47.91 in^2

Figure 17. Spacer used for 50% drapery fullness with flat lining, zero spacing.



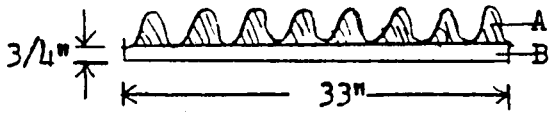
area A = 47.91
area B = (.25) (33)
= 8.25
Total area of spacer
= 56.16 in^2

Figure 18. Spacer used for 50% drapery fullness with flat lining, 1/4" spacing.



area A = 47.91
area B = (.5) (33)
= 16.5
Total area of spacer
= 64.41 in^2

Figure 19. Spacer used for 50% drapery fullness with flat lining, 1/2" spacing.



area A = 48
area B = (.75) (33)
= 24.75
Total area of spacer
= 72.75 in^2

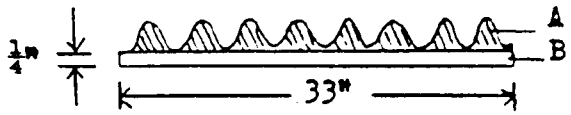
Figure 20. Spacer used for 100% lining fullness.



area A = 48

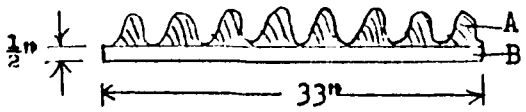
Total area of spacer
= 48 in^2

Figure 21. Spacer used for 100% drapery fullness with flat lining, zero spacing.



area A = 48
area B = (.25) (33)
= 8.25
Total area of spacer
= 56.25 in^2

Figure 22. Spacer used for 100% drapery fullness with flat lining, 1/4" spacing.



area A = 48
area B = (.5) (33)
= 16.5
Total area of spacer
= 64.5 in^2

Figure 23. Spacer used for 100% drapery fullness with flat lining, 1/2" spacing.

For lining fullnesses of 50% or 100%, the areas of the spacers used between the lining fabric and drapery fabric are calculated differently.

A portion of this type of spacer (for 50% fullness) is illustrated in Figure 24. The curve of line A is identical to that of the 50% spacer in Figure 11 (page 56). The area of the spacer is calculated by the length of the centerline (c) times the width of the spacer (1/4" or 1/2").

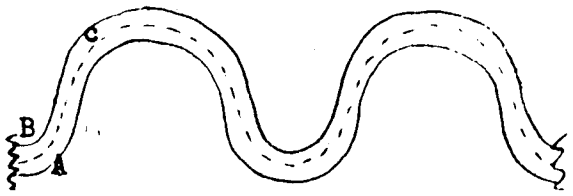


Figure 24. Spacer for identical levels of drapery fullness and lining fullness.

The total length of the centerline, c, is determined by the length of the two different sizes of arcs contained in the spacer, as shown in Figure 25.

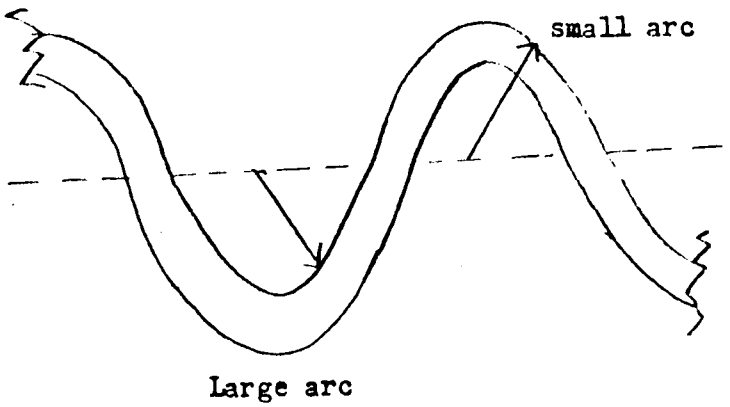


Figure 25. Arcs of spacer used for identical levels of drapery fullness and lining fullness.

The formula for arclength = θ (in radians) $\times$ radius. As indicated in previous calculations for the 50% fullness spacer, $\theta = 3.017$. For a 1/2" spacer, the radius for the large arc = 1.6 + .25, and the radius for the small arc = 1.6 - .25. Therefore, for a 1/2" spacer, the length of the large arc = (3.017) $\times$ (1.6 + .25) = 5.581 and the length of the small arc = (3.017) $\times$ (1.6 - .25) = 4.073.

In a 50% spacer, there are a total of five large arcs and five small arcs, so the total arclength of a 1/2-inch, 50% spacer = 5 (5.581) + 5 (4.073) = 48.27 in. The width of the spacer = .5 in. Therefore, the area = length $\times$ width = 48.27 $\times$ .5 = 24.135 in^2.

Similarly, for a 50% fullness, 1/4-inch spacer, the radius for the large arc = 1.6 + .125 and the radius for the small arc = 1.6 - .125. Therefore, for a 1/4-inch spacer, the length of the large arc = (3.017) $\times$ (1.6 + .125) = 5.204 in. and the length of the small arc = (3.017) $\times$ (1.6 - .125) = 4.450075 in.

The total arclength of a 1/4-inch, 50% fullness spacer is 5 (5.2043) + 5 (4.450075) = 48.272 in.

The width of the spacer is .25 in. Therefore, the area = length $\times$ width, or (48.2772) $\times$ (.25) = 12.068 in^2.

A portion of the 100% fullness spacer to be used between a 100% fullness lining and drapery is illustrated in Figure 26. The arclength of the 100% fullness spacer is determined by the lengths of the large arcs and small arcs, plus the length of the straight segments which connect the two types of arcs.

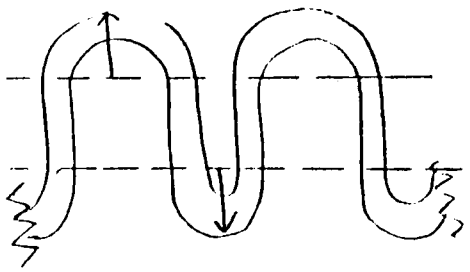


Figure 26. Arcs of 100% fullness spacer.

The arclength of the half-circles = πr. As shown in the previous calculations, the radius of the half-circles in the 100% spacer is 1 inch. For a 1/2-inch, 100% fullness spacer, the radius of the large arc = 1 + .25 inches, and the radius of the small arc, 1 - .25 inches. Using the formula, arclength = πr, the length of the large arc = $\pi(1.25)$ = 3.927 and the length of the small arc = $\pi(.75)$ = 2.356. The length of the straight portions = 1 inch. Therefore, the arclength of a 1/2-inch, 100% fullness spacer = 8 large arcs + 8 small arcs + 16 straight segments, or 8 (3.927) + 8 (2.356) + 16 (1) = 66.264 inches. The area of the spacer = length × width = (66.264) × (.5) = 33.132 in^2.

Similarly, for a 1/4-inch, 100% fullness spacer, the radius of the large arc = 1 + .125 inches and the radius of the small arc = 1 - .125 inches. Using the formula, arclength = πr, the length of the large arc = $\pi(1.125)$ = 3.534 inches and the length of the small arc = $\pi(.875)$ = 2.749 inches. The length of the straight portions = 1 inch. The total arclength of a 1/4-inch, 100% fullness spacer equals 8 large arcs + 8 small arcs + 16 straight segments, or 8 (3.534) + 8 (2.749) + 16 (1) = 66.264. The area of the spacer = length × width = (66.264) × (.25) = 16.566 in^2.

For configurations having flat linings, the area of the spacer used between the window frame and lining fabric was determined by width and thickness. The width was 33 inches, which equals the width of the frame opening, and the spacer was 3/4-inch thick, therefore, the area of the spacer was calculated to be $33 \times .75 = 24.75$ in^2.

Determination of Volume

The volume of the air space between the lining and drapery fabrics and the window glass and lining fabric was calculated by multiplying the area of the spacer by the height of the window frame opening. The height of the window frame opening was 36.25 inches.

Also, for the window to lining volume, the area represented by the distance from the window glass to the edge of the styrofoam spacer was determined. The distance from the window glass to the outside edge of the permanent window frame was 3 inches, and the thickness of the portable frame (onto which the styrofoam was mounted) was .75 inches. The width of the window frame opening was 33 inches. Therefore, the area of the plane between the window glass and styrofoam spacer is calculated as follows: Area $(3.00 + .75) \times (33) = 123.75$ in^2.

The magnitude of volumes between window glass and lining fabric and between lining fabric and drapery fabric for the various configurations studied are given in Tables 2 and 3. Table 4 lists the calculated volumes by configuration. These calculations are based on the assumption that there is no space between the drapery and lining fabrics; the air space which naturally results from minimal fabric separation due to protruding fibers from each of the two fabric surfaces is not considered.

TABLE 2

DETERMINATION OF VOLUME BETWEEN WINDOW GLASS AND LINING FABRIC

Lining Fullness (%)	Area of Spacer (A) in^2	Area of Plane between Glass and Spacer (B) in^2	Height of Window Frame Opening (C) in	Volume between Glass and Lining [(A + B) × C] in^3
flat	24.75	123.75	36.25	5383.125
50	72.66	123.75	36.25	7119.8625
100	72.75	123.75	36.25	7123.125

TABLE 3

DETERMINATION OF VOLUME BETWEEN LINING FABRIC AND DRAPERY FABRIC

Configuration for Which Spacer Is Used			Area of Spacer (A) in^2	Height of Window Opening (B) in	Volume between Lining and Drapery (A × B) in^3
DF[a]	LF[b]	SP[c]			
50	0	0	47.91	36.25	1736.74
50	0	1/4	56.16	36.25	2035.80
50	0	1/2	64.41	36.25	2334.86
100	0	0	48.00	36.25	1740.00
100	0	1/4	56.25	36.25	2039.06
100	0	1/2	64.50	36.25	2338.13
50	50	1/4	12.068	36.25	437.47
50	50	1/2	24.135	36.25	874.89
100	100	1/4	16.566	36.25	600.52
100	100	1/2	33.132	36.25	1201.04

[a]DF = drapery fullness, %.

[b]LF = lining fullness, %.

[c]SP = lining to drapery spatial separation, inches.

TABLE 4

VOLUME BY CONFIGURATION

Configuration DF[a]	LF[b]	SP[c]	$Volume_1$ (window to lining) (in^3)	$Volume_2$ (lining to drapery) (in^3)
50	0	0	5383.13	1736.74
50	0	1/4	5383.13	2035.80
50	0	1/2	5383.13	2334.86
50	50	0	7132.91	0
50	50	1/4	7132.91	437.47
50	50	1/2	7132.91	874.89
100	0	0	5383.13	1740.00
100	0	1/4	5383.13	2039.06
100	0	1/2	5383.13	2338.13
100	100	0	7123.13	0
100	100	1/4	7123.13	600.52
100	100	1/2	7123.13	1201.04

[a] DF = drapery fullness, %.

[b] LF = lining fullness, %.

[c] SP = lining to drapery spatial separation, inches.

Fabric Surface Area

The fabric surface area for each of the three fullness levels was also determined. This was calculated by multiplying the height of the window opening by the width of the fabric required to fit the spacer placed over the window opening. The results are shown in Table 5. A summary of fabric surface areas by configurations is shown in Table 6.

TABLE 5

FABRIC SURFACE AREA

Fullness	Area (in^2)
flat	1196
50%	1794
100%	2392

TABLE 6

FABRIC SURFACE AREA BY CONFIGURATION

Configuration DF[a]	Configuration LF[b]	Lining Surface Area (in^2)	Drapery Surface Area (in^2)	Total Fabric Surface Area (in^2)
50	0	1196	1794	2990
50	50	1794	1794	3588
100	0	1196	2392	3588
100	100	2392	2392	4784

[a] DF = drapery fullness, %.

[b] LF = lining fullness, %.

IV. HEAT TRANSFER

The instrumentation used for measuring heat transfer was designed and fabricated by Charles Hassenboehler at the USDA Textiles and Clothing Laboratory, Knoxville.

The thermal transmittance of each model drapery was measured on a standard 36" × 40" window built into the wall of a conditioning room. On one side of the window is a closed chamber cooled by an air conditioning unit designed to simulate cold outdoor temperature levels and to allow variation in temperature between the two sides of the window. The window is equipped with three transducers which measure the heat flowing from the warmer side of the window (inside the conditioning room) to the cool side. The combination of window and drapery serves as a barrier between the cold chamber and the warm chamber (the conditioning room). The test window is illustrated in Figure 27.

A desk-top computer fully controls a multiplexer and digital multimeter that reads the output from each transducer. The computer monitors the window temperature, room temperature and the room relative humidity and is programmed to manipulate the data and graphically plot, at three minute intervals, the difference in temperature between the two sides of the window (delta T), the room temperature, the room relative humidity, and the transmittance ($Btu/hr/ft^2/°F$) according to the program developed for the test (see Appendix).

Draperies were left on the window approximately one hour, or until five readings were made after equilibrium was reached, as indicated by

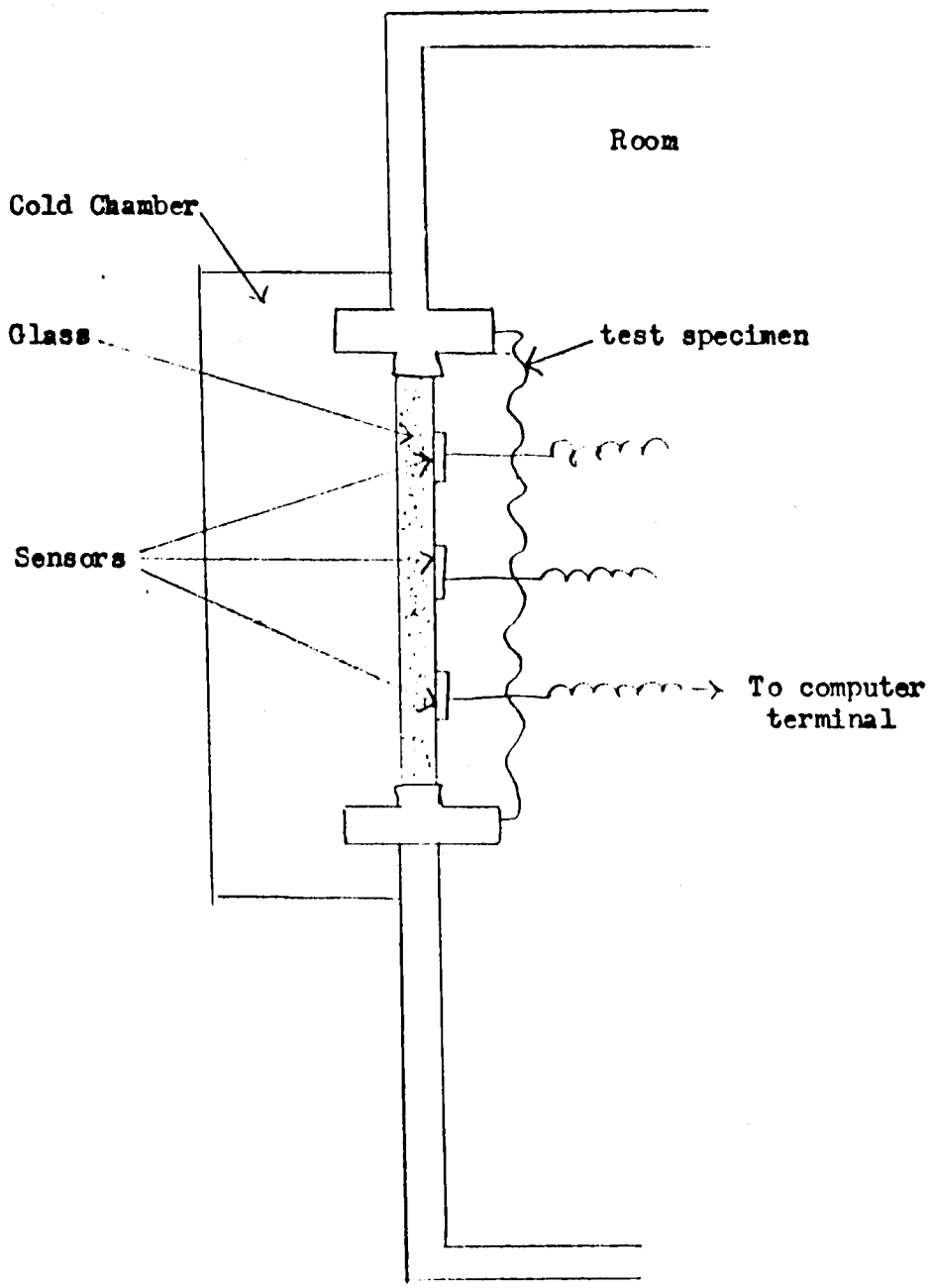


Figure 27. Test window.

a horizontal graph of the transmittance reading. The mean of five readings was recorded for each test.

The temperature inside the conditioning room was maintained at 70 ± 2°F. To avoid changes in temperature due to on-off cycling of the air conditioner, two space heaters were used in the room. This caused the air conditioner to remain on throughout the testing.

The relative humidity of the conditioning room was controlled by the use of portable humidifiers adjusted to maintain the relative humidity at the two selected test levels (45% and 68%). The combination of air conditioning, space heating and humidifiers provided constant temperature and relative humidity.

V. EXPERIMENTAL DESIGN

The eight independent variables for the study included the two fiber types, two fabric colors, two levels of fabric openness, two lining fabric types, two drapery fullnesses, three lining fullnesses, three spatial configurations and two levels of relative humidity. The dependent variable was heat transmittance.

The study was divided into two phases. Phase one consisted of testing each of the eight drapery fabrics and two lining fabrics in a single, flat configuration. Phase two testing included each of the four light-colored drapery fabrics in double-layered configurations with the cotton lining fabric. The complete research design is given in Figures 28 and 29.

Fiber	hydrophilic								hydrophobic							
Color	light				dark				light				dark			
Weave	open		tight		open		tight		open		tight		open		tight	
RH	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low

Lining	hydrophilic	hydrophobic

Figure 28. Research design—phase one.

Drapery Fullness				50						100					
Lining Fullness				0			50			0			100		
Spacing				0	¼	½	0	¼	½	0	¼	½	0	¼	½
Fiber	Weave	Relative Humidity													
hydrophobic	tight	low													
		high													
	open	low													
		high													
hydrophilic	tight	low													
		high													
	open	low													
		high													

Figure 29. Research design—phase two.

Two replications of each test were made. The research schedule was randomized in order to minimize error. Using a table of random numbers, one of the two relative humidity levels was chosen for each of sixteen days, until each relative humidity level had been chosen eight times. After the relative humidity level for each test day was chosen, then each of the 48 prenumbered experimental cells, representing each combination of the experimental factors, was randomly selected until 12 cells per day were chosen and until each cell was chosen twice for each humidity level. This yielded a total of 32 single layer tests and 192 multilayer tests.

VI. STATISTICAL ANALYSIS

For the single layer fabrics, a two-way analysis of variance was used to test for differences in the factors of fabric and relative humidity. Additionally, a four-way analysis of variance tested for differences in the factors fiber type, weave openness, color, and relative humidity. A priori statistical contrasts provided comparisons of the various levels of each factor.

For the multilayer tests, a six-way analysis of variance using a general linear models (GLM) procedure was used to test for differences in the factors of fiber, fabric openness, relative humidity, drapery fullness, lining fullness and spatial configuration. Additionally, the fabric factors were combined and a five-way analysis of variance using a GLM procedure was used to test for differences in the factors of fabric, relative humidity, drapery fullness, lining fullness and spatial

configuration. A priori statistical contrasts were used to further explore the differences among the variables.

Additional analysis included the physical factors plus each of the main experimental factors as continuous variables in multiple regression analysis to determine relationships between the variables and the heat transmittance of the draperies. Regression models were developed for predicting heat transmittance.

For all data analysis, levels of significance were set at 0.05. The Statistical Analysis System (SAS) software package was used for computer analysis of the data.

CHAPTER IV

RESULTS AND DISCUSSION

I. INTRODUCTION

This chapter includes presentation and explanation of the results obtained from the investigation of heat transmittance of fabrics used in draperies in single and double layered models of various geometric configurations.

Drapery models were tested under conditions which simulate those in a home environment. Tests were conducted on a standard window of the type which might be used in a typical home. The temperature behind the test window was altered to simulate winter conditions. The difference in temperature between the two sides of the window was maintained at approximately 25°F throughout each test. The temperature inside the test room was maintained at 70 ± 2°F to simulate actual indoor conditions. Tests were conducted at two levels of relative humidity inside the test room, 45 ± 2% and 68 ± 2%.

The drapery models were mounted on a wooden and styrofoam frame which was then attached to the window so that the model had complete contact with the window frame. The drapery was sealed tightly at the top, bottom and both sides to eliminate air leakage and heat loss around the window. Because heat loss due to air leakage was eliminated as much as possible, the transmittance measured by the instrument represents the actual heat loss through the drapery fabric and window.

Eight drapery fabrics and two lining fabrics were tested as single components in a flat configuration. Four of the drapery fabrics (all light colors) were then tested in assemblies with one of the lining fabrics at two levels of drapery fullness, three levels of lining fullness, and three levels of spatial separation between the lining and drapery fabrics. Two replications of each combination of these factors were tested. Values reported throughout the study are the means of the two replications.

The results of the investigation are presented as follows: The heat transmittance (U value) for each of the single fabrics on the window in a flat configuration is presented in Section II. Comparisons between the fabrics and between tests conducted at the two relative humidity levels are discussed.

Results of the double layered models are presented in Section III. Each of the experimental factors associated with the double layered tests is discussed: drapery fullness, lining fullness and spatial separation between the lining and drapery fabrics. Additionally, results are discussed as they relate to the calculated values of drapery fabric and lining fabric surface area and the calculated volumes of the window glass to lining air space and the lining fabric to drapery fabric air space.

Section IV includes discussion of the relationships between the physical properties of the fabrics and the transmittance values of the fabrics obtained on the window. Linear regression models for predicting transmittance from the experimental factors and physical properties are presented for the single layer and double layer tests.

II. TRANSMITTANCE OF SINGLE LAYERS

Each of the eight drapery fabrics and two lining fabrics was tested twice for heat transmittance on the test window at the two relative humidity levels (45% and 68%). For each test the room temperature was maintained at 70 ± 2°F and the temperature differential (ΔT) was maintained at 25 ± 2°F. Fabrics were tested singly, in a flat configuration, with the drapery sealed to the window frame at the top, bottom and both sides.

The highest transmittance values were exhibited by the most open-weave fabrics, as expected, while the more tightly woven fabrics were found to have the lowest transmittance values, indicating that tightly woven fabrics which have the capacity to limit the flow of air are better insulators.

Fabric A (Table 1, p. 40) was found to have one of the lower heat transmittance values of the experimental fabrics. This 100% cotton, twill weave fabric has an off-white color. For the purposes of analysis, fabric A has been classified as a hydrophilic, tight weave, light colored fabric.

Fabric B exhibited essentially similar, but slightly lower heat transmittance. The 100% cotton, twill weave, rust colored fabric is similar to fabric A in every respect except color. It was classified as a hydrophilic, tight weave, dark colored fabric.

Fabric C was found to have the fourth highest heat transmittance value. This fabric is made from 100% rayon, and has a plain, open

weave and light green color. Fabric C was classified as a hydrophilic, open weave, light colored fabric.

Fabric D was found to have the fifth highest heat transmittance readings. The 100% rayon, olive green colored fabric has a plain open weave, but it is slightly more tightly woven than fabric C, as indicated by its air permeability (Table 1, p. 40). Fabric D was classified as a hydrophilic, open weave, dark colored fabric.

Fabric E exhibited the lowest heat transmittance readings of all the experimental fabrics, indicating that it is the best insulator of the fabrics tested. The 100% polyester white fabric has a tight twill weave and is made from textured yarns. This fabric was classified as hydrophobic, tight weave, and light color.

Fabric F was found to have heat transmittance values only slightly higher than fabric E. It is identical to fabric E except for its color, black. Fabric F was classified as hydrophobic, tight weave and dark color.

Fabric G showed the second highest transmittance readings. This off-white, 100% polyester fabric has a very open, plain weave. It is made from novelty yarns. Fabric G was classified as a hydrophobic, open weave, light colored fabric.

Fabric H was found to have the highest transmittance values of all the experimental fabrics, indicating that it is the poorest insulator of all fabrics tested. Fabric H is a medium green color, but is identical to fabric G in other respects. For purposes of this study it was classified as hydrophobic, open weave and dark colored.

Fabric X is a white, 100% cotton, moderately tightly woven plain weave fabric used as a lining fabric. It exhibited the fifth from the lowest transmittance readings. This fabric was classified as hydrophilic, tight weave and light colored.

Fabric Y, also used as a lining fabric, is an off-white, 100% polyester, thin, sheer fabric. It was found to have the third highest transmittance, probably due to its relatively low thickness. Fabric Y was classified as hydrophobic, tight weave, and light colored.

Table 7 shows the transmittance values of the experimental fabrics and Figure 30 shows the graphic representation of the same.

TABLE 7

TRANSMITTANCE VALUES OF FABRICS
(SINGLE LAYERS, FLAT)

Fabric	Transmittance (Btu/hr/ft^2/°F)
A	.5538
B	.5509
C	.6856
D	.6224
E	.5384
F	.5405
G	.8530
H	.8568
X	.5642
Y	.7053

Each fabric exhibited a higher transmittance at the higher level of relative humidity.

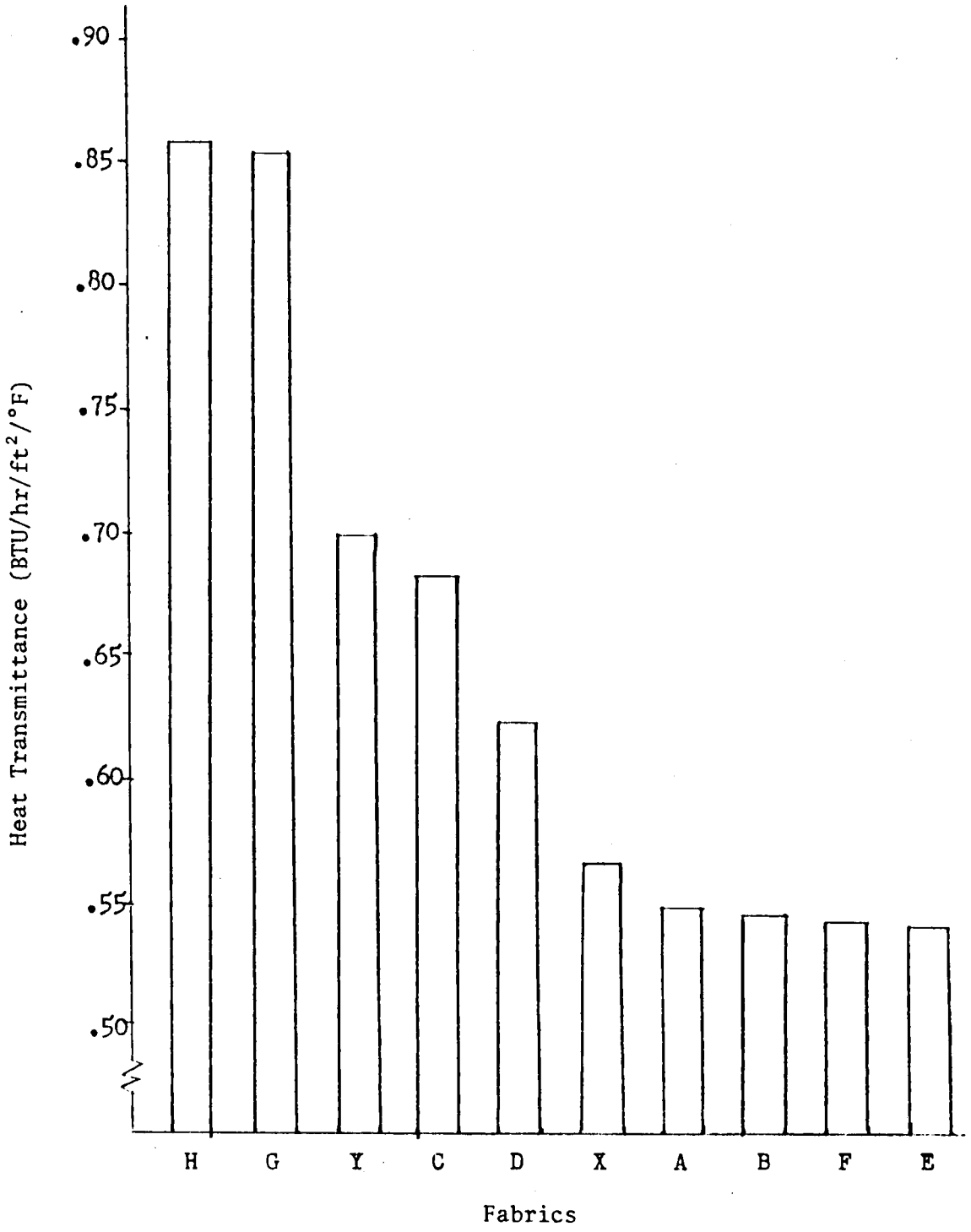


Figure 30. Heat transmittance of single layer fabrics.

Table 8 shows the mean transmittance at each relative humidity level calculated from the pool of all the experimental data. Table 9 lists the transmittances of each experimental fabric at each relative humidity level. Figure 31 shows the differences in fabric transmittance values at the two relative humidity levels.

A two way analysis of variance indicated that both fabric and relative humidity are significant at the .0001 level in contributing to heat transmittance. A summary of the analysis is shown in Table 10.

The fabric related variables (fiber type, weave openness and color) were also analyzed as separate factors in a four-way analysis of variance which also included relative humidity. The results of the analysis given in Table 11 show that fiber type was significant at the .01 level, weave openness at the .0005 level, and relative humidity at the .005 level. Color was not significant.

The transmittance values of fabrics by fiber type are shown in Table 12. The fabrics composed of hydrophobic fibers showed higher transmittance values than those of hydrophilic fibers, indicating that hydrophilic fibers are significantly better insulators.

Because both fiber type and relative humidity were found to be significant, a comparison was made between the two fiber types at each relative humidity level. Mean transmittance values by fiber type and relative humidity are shown in Table 13 and differences in transmittance by hydrophilic and hydrophobic fibers at the two relative humidity levels are shown graphically in Figure 32. The percentage difference in transmittance between the two humidity levels is slightly higher (21.9%)

TABLE 8

TRANSMITTANCE BY RELATIVE HUMIDITY

Relative Humidity	Transmittance (Btu/hr/ft²/°F)
45 ± 2%	.5816
68 ± 2%	.7126

TABLE 9

TRANSMITTANCE OF FABRICS AT DIFFERENT RELATIVE HUMIDITIES

Fabric	Relative Humidity (%)	Transmittance (Btu/hr/ft²/°F)
A	45	.5022
	68	.6054
B	45	.4950
	68	.6068
C	45	.6031
	68	.7682
D	45	.5475
	68	.6973
E	45	.4903
	68	.5865
F	45	.4893
	68	.5917
G	45	.7763
	68	.9297
H	45	.7801
	68	.9335
X	45	.4992
	68	.6292
Y	45	.6327
	68	.7779

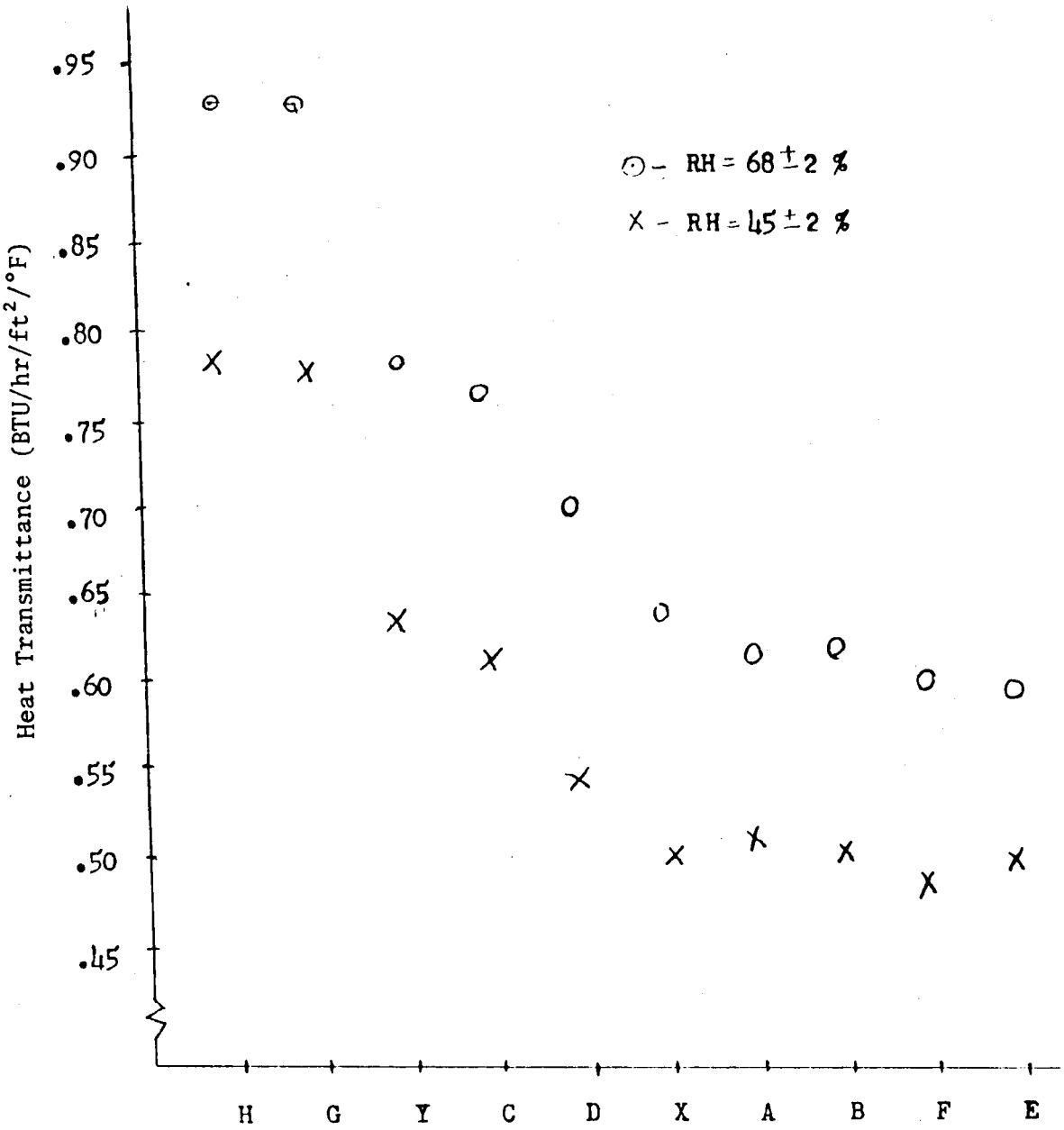


Figure 31. Heat transmittance of single fabrics at different relative humidity levels.

TABLE 10

TWO FACTOR ANALYSIS OF VARIANCE FOR FABRICS
IN SINGLE LAYERS

Source	DF	MS	F
Fabric	9	.2797	94.94*
Relative humidity	1	.0859	262.30*

*Significant at the 0.0001 level.

TABLE 11

FOUR FACTOR ANALYSIS OF VARIANCE FOR FABRICS
IN SINGLE LAYERS

Source	DF	MS	F
Fiber type	1	.0534	8.86*
Weave openness	1	.1365	22.62***
Color	1	.0021	0.35
Relative humidity	1	.0859	14.22**

*Significant at the .01 level.

**Significant at the .005 level.

***Significant at the .0005 level.

TABLE 12

MEAN TRANSMITTANCES BY FIBER TYPE

Fiber Type	Transmittance (Btu/hr/ft²/°F)
Hydrophilic[a]	.6031
Hydrophobic[b]	.6971

[a]Fabrics A, B, C, D, and X.

[b]Fabrics E, F, G, H, and Y.

TABLE 13

TRANSMITTANCES BY FIBER TYPE AND RELATIVE HUMIDITY

Fiber Type	Relative Humidity	Transmittance (Btu/hr/ft²/°F)
Hydrophilic	45 ± 2%	.5369
Hydrophilic	68 ± 2%	.6694
Hydrophobic	45 ± 2%	.6340
Hydrophobic	68 ± 2%	.7603

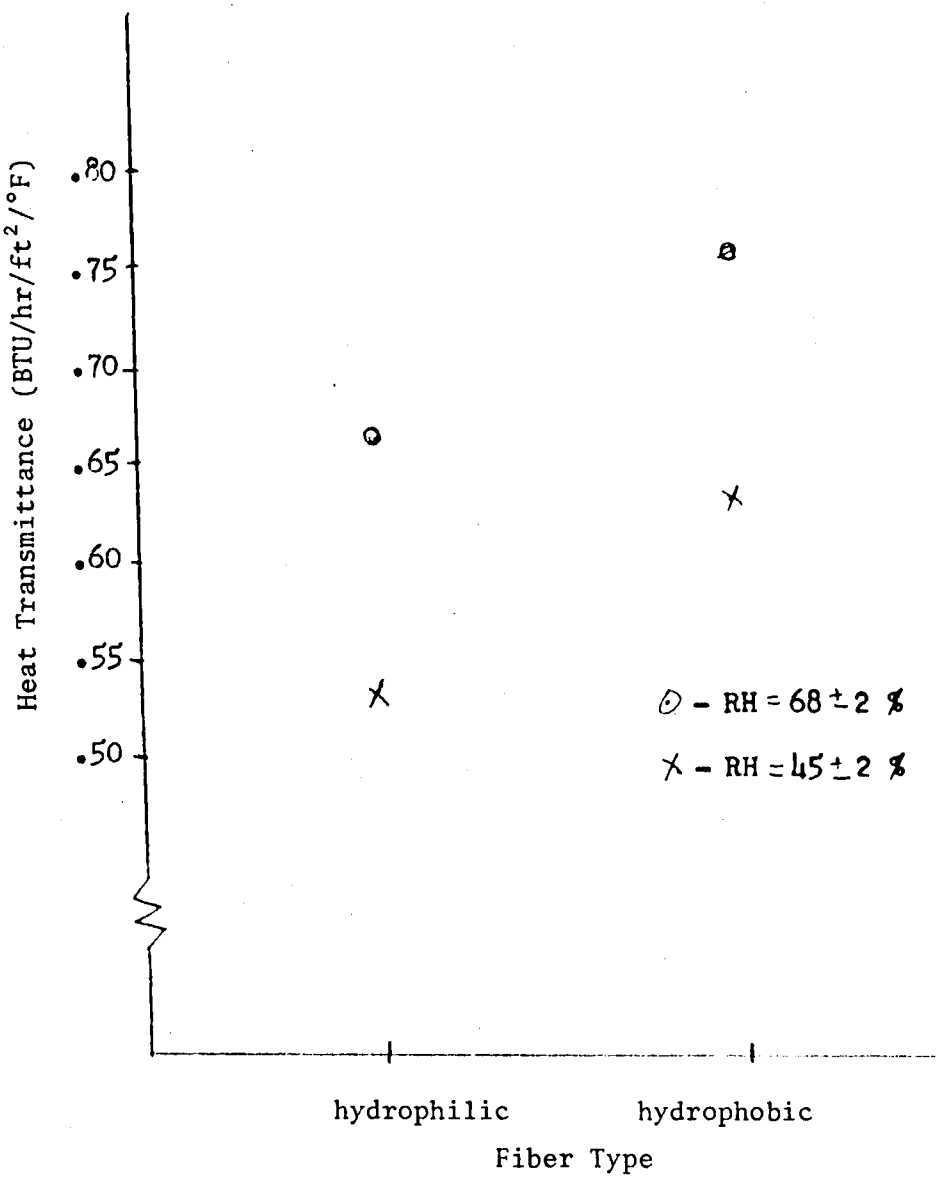


Figure 32. Transmittance of fiber types by relative humidity levels.

for the hydrophilic fabrics than for the hydrophobic fabrics (18.1%). However, the difference between the two fiber types is negligible. As indicated in Table 13 and Figure 32, both fiber types showed similar increases in transmittance corresponding to an increase in relative humidity. Increased transmittance at the higher relative humidity level can perhaps be attributed to loss of heat which is required for evaporation of moisture. A second possible explanation for increased transmittance at higher relative humidity levels is that conductivity of the fabric is altered by the presence of moisture, possibly resulting in increased heat loss through conduction. Additionally, condensation associated with high relative humidity levels could alter the reflective properties of the fabrics, causing increased heat transmittance.

Weave openness was found to be the most significant factor attributing to transmittance by the single layer fabrics. Mean values shown in Table 14 indicate that the open weave fabrics exhibit higher transmittance values than the tightly woven fabrics. Mean transmittance values by weave openness and relative humidity, shown in Table 15, indicate that the transmittance values of open-weave and tight weave fabrics respond essentially in a similar manner to changes in relative humidity.

TABLE 14

TRANSMITTANCES BY WEAVE OPENNESS

Weave Openness	Transmittance ($Btu/hr/ft^2/°F$)
Open	.7544
Tight	.5459

TABLE 15

TRANSMITTANCES BY WEAVE OPENNESS AND RELATIVE HUMIDITY

Weave Openness	Relative Humidity	Transmittance (Btu/hr/ft^2/°F)
open	45 ± 2%	.6767
open	68 ± 2%	.8322
tight	45 ± 2%	.4942
tight	68 ± 2%	.5976

Table 16 shows the mean transmittance values based on fabric color. Although the factor was not significant, the light colored fabrics showed slightly higher transmittance values than the dark colored fabrics.

TABLE 16

TRANSMITTANCES BY COLOR

Color	Transmittance (Btu/hr/ft^2/°F)
light[a]	.6500
dark[b]	.6426

[a]Fabrics A, C, E, G, X, and Y.

[b]Fabrics B, D, F, and H.

In an effort to identify the sources contributing to significance of the overall fabric factor in the two-way analysis of variance, fabric data were further analyzed statistically using a priori contrasts. Individual contrasts were made which compared the fabrics according to

three characteristics: fiber type, weave openness, and color. These three categories of contrasts will be discussed separately.

Contrasts Based on Fiber Type

Four contrasts were made which compared the eight drapery fabrics according to fiber type. The contrasts of fabric A with fabric E, fabric B with fabric F, and fabric C with fabric G were found not to be significant, indicating that differences in heat transmittance between the fabrics cannot be attributed to fiber type. However, the contrast of fabric D with fabric H was significant at the .03 level. Observation of the fabrics indicated that these two fabrics are less similar in fabric openness than the other pairs of fabrics. The difference in openness between fabrics D and H appeared to be greater than the difference in openness between fabrics C and G, for example. Therefore, it is assumed that a variable other than fiber type, namely fabric openness, is perhaps contributing to the apparent significance in the contrast between fabrics D and H.

The four-way analysis of variance showed that fiber type is significant, however, it is less significant than fabric weave openness. On the basis of these contrasts, the significance of fiber type is presumably due to differences in hdrophilicity between fabric D (hydrophilic) and fabric H (hydrophobic). It should be noted, however, that these two fabrics are also quite different in weave openness. Results of the contrasts based on fiber type are summarized in Table 17.

TABLE 17

CONTRASTS OF SINGLE LAYER FABRICS BASED ON FIBER TYPE

Contrast	SS	F
Fabric A contrasted with fabric E	.0002	0.03
Fabric B contrasted with fabric F	.0001	0.01
Fabric C contrasted with fabric G	.0280	3.15
Fabric D contrasted with fabric H	.0549	6.19*

*Significant at .05 level.

Contrasts Based on Weave Openness

The eight drapery fabrics were compared according to weave openness on the basis of four contrasts. The contrasts of fabric A with fabric C and fabric B with fabric D were not significant, indicating that the relationship between fabric openness and heat transmittance is not significant for these fabrics. However, the contrasts of fabric E with G and fabric F with H were both significant at the .007 level, indicating that differences in heat transmittance between these fabrics are perhaps related to fabric openness.

Consideration of the definition of fabric openness provides an explanation for these findings which might initially appear to be contradictory. For the purpose of this study the fabrics were classified as either open or tight weaves. This classification was quite useful in planning the investigation; however, categorization according to this ordinal scale is by no means exact. Although fabrics C, D, G and H were all categorized as open weaves, fabrics C and D are much less open than

fabrics G and H. Because of this difference, contrasts of fabrics C and D with tightly woven fabrics are less likely to be significant than contrasts of fabrics G and H with tightly woven fabrics. Examination of the significance levels of each of the four contrasts shows that the magnitude of significance increases as the difference in fabric openness between the contrasted fabrics increases, indicating that fabric openness is indeed a significant contributor to difference in heat transmittance among the fabrics included in this investigation.

Table 18 summarizes the contrasts based on fabric weave openness.

TABLE 18

CONTRASTS OF SINGLE LAYER FABRICS BASED ON WEAVE OPENNESS

Contrast	SS	F
Fabric A contrasted with fabric C	.0173	1.96
Fabric B contrasted with fabric D	.0051	0.58
Fabric E contrasted with fabric G	.0989	11.14*
Fabric F contrasted with fabric H	.1000	11.26*

*Significant at the .01 level.

Contrasts Based on Fabric Color

Four contrasts provided comparison of the drapery fabrics on the basis of color: fabric A with B, fabric C with D, fabric E with F, and fabric G with H. None of the contrasts were found to be significant. Interestingly, fabric pairs which were chosen for the study specifically because of their similarities in every respect except color, namely

fabrics A and B, C and D and G and H, showed very low significance levels (.97, .98 and .96, respectively), indicating that fabric differences in heat transmittance, as determined by this technique, are not related to fabric color.

The contrasts based on fabric color are summarized in Table 19.

TABLE 19

CONTRASTS OF SINGLE LAYER FABRICS BASED ON COLOR

Contrast	SS	F	Significance Level
Fabric A contrasted with fabric B	.000008	.00[a]	.9761
Fabric C contrasted with fabric D	.004000	.45	.5173
Fabric E contrasted with fabric F	.000004	.00[a]	.9827
Fabric G contrasted with fabric H	.000014	.00[a]	.9686

[a]Value of .00 indicates that the F value is smaller than the number of significant figures printed by the computer.

III. DOUBLE LAYER TESTS

The four light colored drapery fabrics (A, C, E, and G) and the cotton lining fabric (X) were used for the multilayer tests. Two levels of drapery fullness (50% and 100%), three levels of lining fullness (flat and 50% with the 50% drapery fullness and flat and 100% with the 100% drapery fullness) and three levels of spatial separation between lining and drapery fabrics (zero spacing, 1/4 inch, and 1/2 inch), were tested at two relative humidity levels (45 ± 2% and 68 ± 2%). Two replications were made of each experimental cell, yielding a total of 192 observations.

For each test the room temperature was maintained at 70 ± 2°F and the ΔT was maintained at 25 ± 2°F.

The mean transmittance values by each factor category are listed in Table 20.

Results in Table 20 indicate that the open weave drapery fabric with the lining has the highest transmittance. This is also shown graphically in Figure 33. The trend is very similar to that observed for single layer fabrics, except that the positions of fabrics E and A are reversed (Table 7, p. 80 and Figure 30, p. 81); however, in both cases, there is little difference in transmittance values between these two fabrics.

The effect of the lining fabric is to reduce the magnitude of difference between the various fabrics, as evidenced by the fact that the range of mean transmittance values is smaller for the multilayer system than for the single fabrics. In other words, the addition of lining greatly reduces heat transmittance, but also reduces the degree of variation in transmittance among the drapery fabrics.

A five-way analysis of variance indicated that all five of the experimental factors were significant. Fabric, lining fullness and relative humidity were significant at the .0001 level, drapery fullness was significant at the .001 level, and spacing was significant at the .05 level.

All possible two-way interactions were also included in the model. The interaction of lining fullness with spacing was significant at the .05 level. The other interactions were not significant. Results of the analysis are summarized in Table 21.

TABLE 20

MEANS OF FACTOR MAIN EFFECTS FOR MULTILAYER MODELS

Factors	Transmittance (Btu/hr/ft²/°F)	
Drapery Fabric	without lining	with lining
A	.5538	.4605
C	.6856	.4841
E	.5384	.4664
G	.8530	.5250
Drapery Fullness		
50%		.4753
100%		.4927
Lining Fullness		
flat		.4497
50%		.5025
100%		.5342
Spatial Separation		
0.00"		.4912
0.25"		.4830
0.50"		.4779
Relative Humidity		
45%		.4435
68%		.5245

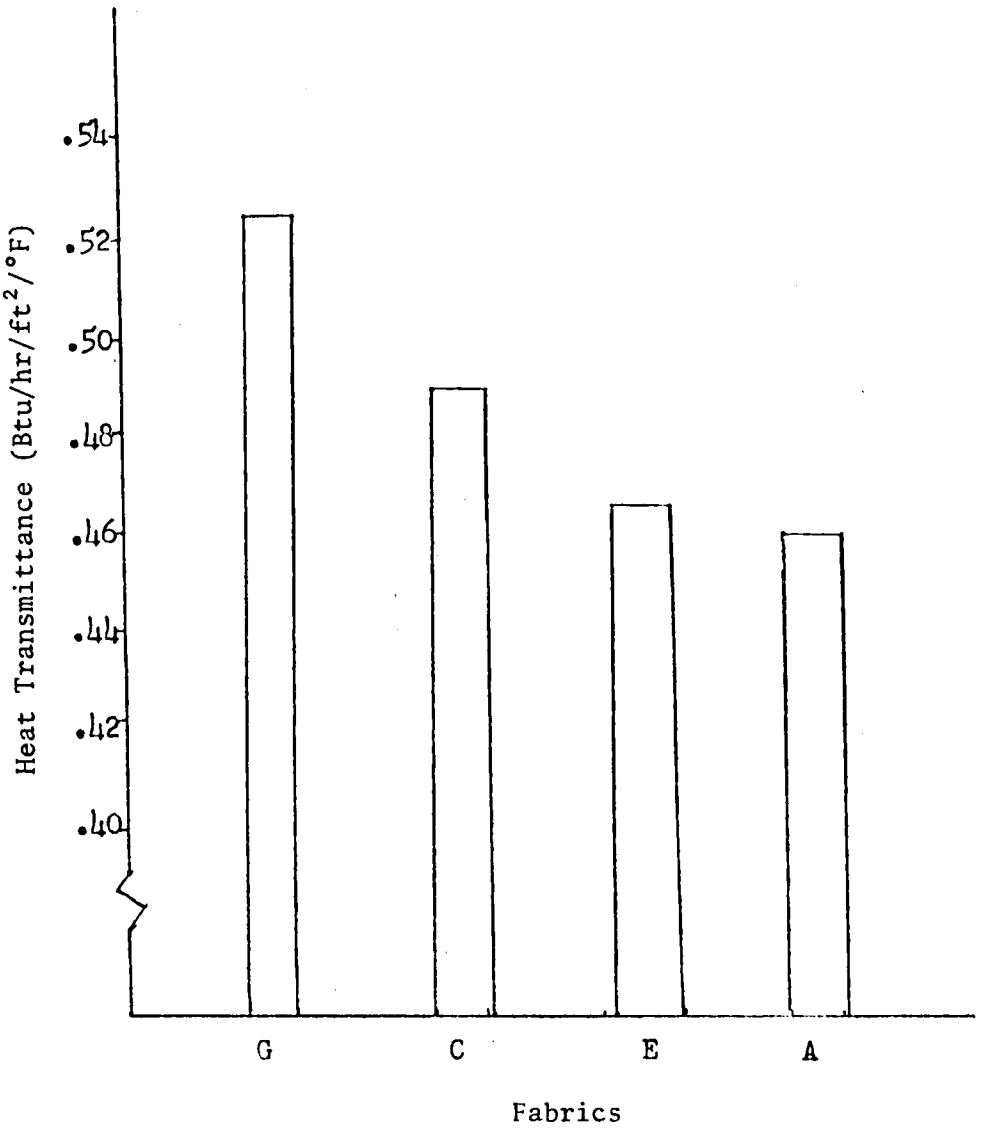


Figure 33. Transmittance of drapery fabrics layered with lining fabric.

TABLE 21

ANALYSIS OF VARIANCE FOR LAYERED FABRICS

Source	DF	MS	F
Fabric	1	.037058	65.14***
Drapery fullness	1	.007214	12.68**
Lining fullness	1	.116367	204.55***
Spacing	1	.002830	4.97*
Relative humidity	1	.157172	276.28***
Fabric * Drapery fullness	1	.000002	.00[a]
Fabric * Lining fullness	1	.000263	.46
Fabric * Spacing	1	.000409	.72
Fabric * Relative humidity	1	.000174	3.06
Drapery fullness * Lining fullness	1	.001570	2.76
Drapery fullness * Spacing	1	.000002	.00
Drapery fullness * Relative humidity	1	.000411	.72
Lining fullness * Spacing	1	.003109	5.47*
Lining fullness * Relative humidity	1	.005734	1.08
Spacing * Relative humidity	1	.000179	.32

*Significant at the .05 level.

**Significant at the .001 level.

***Significant at the .0001 level.

[a]Values of .00 indicate F values smaller than the number of significant figures calculated by the computer.

A priori statistical contrasts provided more specific characterization of the sources contributing to significance of the fabric, lining fullness and spacing factors. Individual contrasts were made which compared the four fabrics, the three levels of lining fullness and the three spatial separations. The contrasts are summarized in Table 22.

The means of factor main effects (Table 20), the means by combined factors (Tables 23-30), and the statistical contrasts (Table 22) each provide information to explain the findings which are also shown graphically in Figures 34-39. Based on these data, each of the factors will be discussed separately.

Fabric Type

Each of the four drapery fabrics was tested in a layered combination with lining fabric X. The most open weave fabric, G, exhibited the highest transmittance, followed by fabric C, a moderately open weave. The lowest transmittances were shown by fabrics E and A.

Contrasts between fabrics indicate that all of the fabrics exhibited significantly different heat transmittance values, with the exception of fabrics A and E. All contrasts with fabric G, the most open weave of the four fabrics, were significant at the .0001 level. The contrast between fabric C, a moderately open weave fabric, and fabric E, a tightly woven fabric, was significant at the .005 level. The contrast between fabrics A and E, which were similar in weave openness, was not significant. This pattern indicates that differences in transmittance between fabrics are due to differences in fabric openness.

TABLE 22

CONTRASTS OF MULTILAYER DRAPERIES

Contrast	SS	F
Fabric A contrasted with fabric C	.0067	18.95***
Fabric A contrasted with fabric E	.0004	1.18
Fabric A contrasted with fabric G	.0499	140.92***
Fabric C contrasted with fabric E	.0038	10.67**
Fabric C contrasted with fabric G	.0200	56.52***
Fabric E contrasted with fabric G	.0412	116.29***
Zero LF[a] contrasted with 50% LF	.0169	59.16***
Zero LF contrasted with 100% LF	.0476	166.42***
50% LF contrasted with 100% LF	.0058	20.35***
Zero SP[b] contrasted with 1/4" SP	.0017	6.11*
Zero SP contrasted with 1/2" SP	.0047	16.48***
1/4" SP contrasted with 1/2" SP	.0007	2.52

*Significant at the .01 level.

**Significant at the .005 level.

***Significant at the .0001 level.

[a]Lining fullness.

[b]Spacing.

TABLE 23

TRANSMITTANCE VALUES BY DRAPERY FULLNESS AND LINING FULLNESS

DF[a] (%)	LF[b] (%)	Lining Surface Area (in^2)	Drapery Surface Area (in^2)	Total Fabric Surface Area (in^2)	Transmittance[c] ($Btu/hr/ft^2/°F$)
flat	no lining	0	1196	1196	.6577
50	flat	1196	1794	2990	.4482
50	50	1794	1794	3588	.5025
100	flat	1196	2392	3588	.4512
100	100	2392	2392	4784	.5341

[a]Drapery fullness.

[b]Lining fullness.

[c]Mean transmittance of fabrics A, C, E and G.

TABLE 24

TRANSMITTANCE VALUES BY DRAPERY FULLNESS, LINING FULLNESS AND SPACING

DF[a] (%)	LF[b] (%)	SP[c] (in)	Volume—Window Glass to Lining (in^3)	Volume—Lining to Drapery Fabric (in^3)	Transmittance ($Btu/hr/ft^2/°F$)
50	flat	0	5383	1737	.4467
50	flat	1/4	5383	2036	.4492
50	flat	1/2	5383	2335	.4486
50	50	0	7120	0[d]	.5210
50	50	1/4	7120	437	.4945
50	50	1/2	7120	875	.4919
100	flat	0	5383	1740	.4499
100	flat	1/4	5383	2039	.4524
100	flat	1/2	5383	2338	.4512
100	100	0	7123	0[d]	.5470
100	100	1/2	7123	1201	.5198

[a]Drapery fullness.

[b]Lining fullness.

[c]Spacing.

[d]Theoretical volume (actually a small amount of air volume is trapped due to separation imposed by protruding hairs and weave indentations).

TABLE 25

TRANSMITTANCE BY FABRIC AND DRAPERY FULLNESS

Fabric	Drapery Fullness (%)	Transmittance (Btu/hr/ft²/°F)
A	50	.4557
A	100	.4653
C	50	.4718
C	100	.4965
E	50	.4543
E	100	.4785
G	50	.5196
G	100	.5303

TABLE 26

TRANSMITTANCE BY FABRIC AND LINING FULLNESS

Fabric	Lining Fullness (%)	Transmittance (Btu/hr/ft²/°F)
A	0	.4335
A	50	.4809
A	100	.4905
C	0	.4433
C	50	.4973
C	100	.5526
E	0	.4310
E	50	.4822
E	100	.5215
G	0	.4909
G	50	.5496
G	100	.5685

TABLE 27

TRANSMITTANCE BY FABRIC AND SPACING

Fabric	Spacing (in)	Transmittance (Btu/hr/ft²/°F)
A	0	.4700
A	1/4	.4645
A	1/2	.4469
C	0	.4889
C	1/4	.4820
C	1/2	.4816
E	0	.4787
E	1/4	.4605
E	1/2	.4601
G	0	.5271
G	1/4	.5249
G	1/2	.5229

TABLE 28

TRANSMITTANCE BY FABRIC AND RELATIVE HUMIDITY

Fabric	Relative Humidity (%)	Transmittance (Btu/hr/ft²/°F)
A	45	.4284
A	68	.4926
C	45	.4426
C	68	.5257
E	45	.4221
E	68	.5107
G	45	.4811
G	68	.5689

TABLE 29

TRANSMITTANCE BY VOLUME BETWEEN GLASS AND LINING

Volume (in^3)	Transmittance ($Btu/hr/ft^2/°F$)
5383.125	.4497
7119.862	.5025
7123.125	.5341

TABLE 30

TRANSMITTANCE BY VOLUME BETWEEN LINING AND DRAPERY

Volume (in^3)	Transmittance ($Btu/hr/ft^2/°F$)
0	.5340
437	.4945
600	.5356
875	.4919
1201	.5198
1737	.4467
1740	.4499
2036	.4492
2039	.4524
2335	.4486
2338	.4512

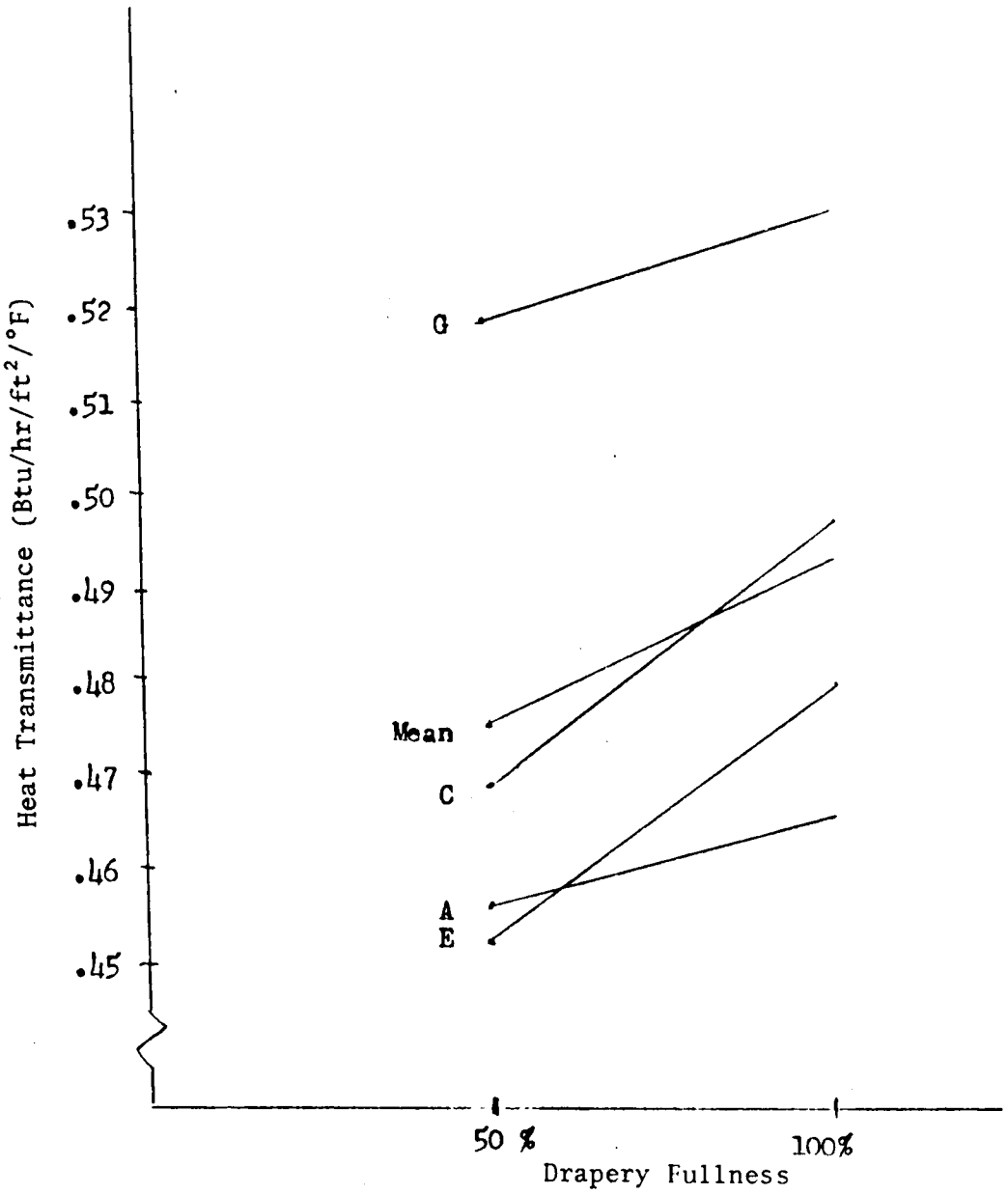


Figure 34. Differences in transmittance between fabrics by drapery fullness.

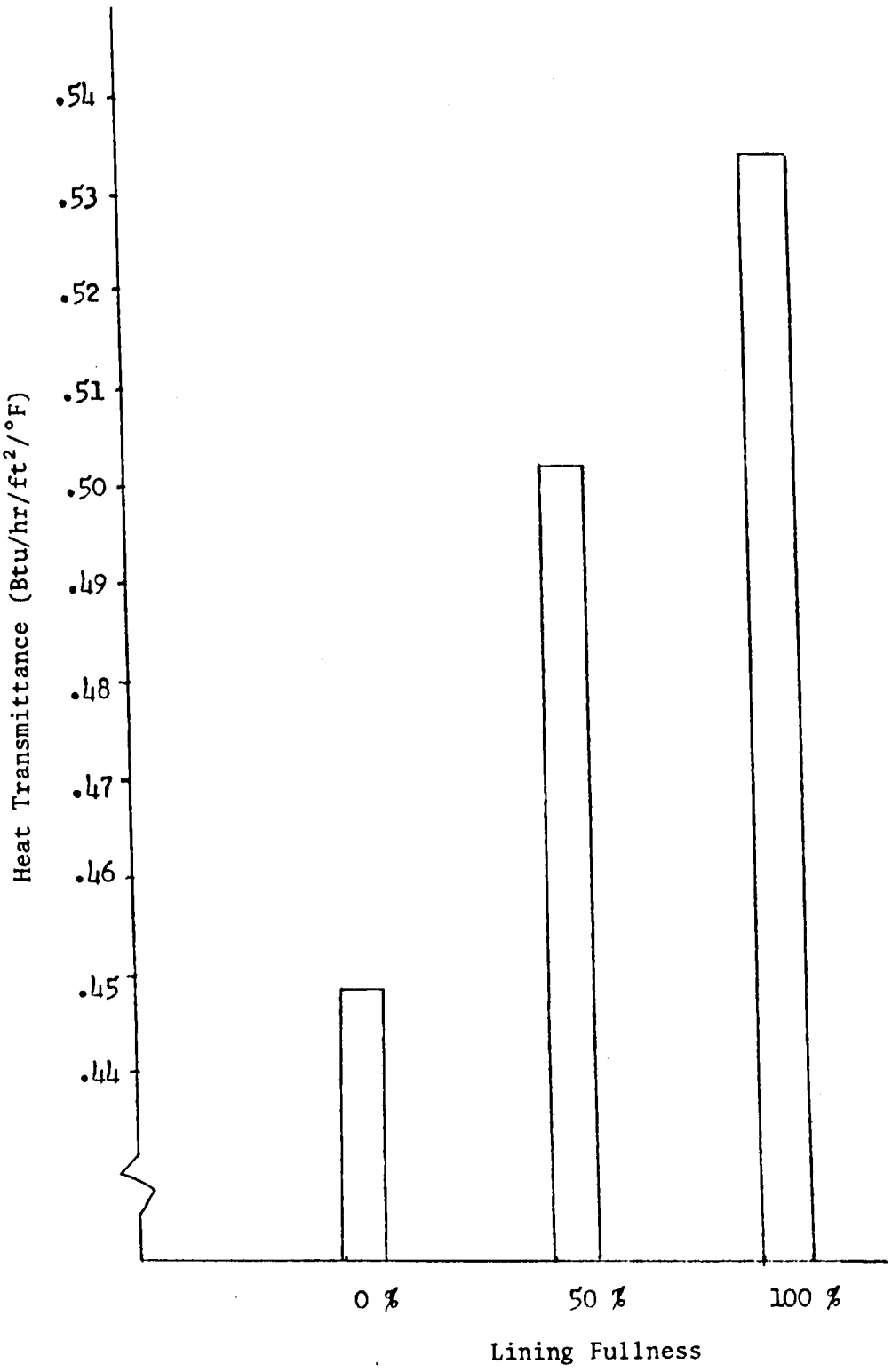


Figure 35. Effect of lining fullness on transmittance.

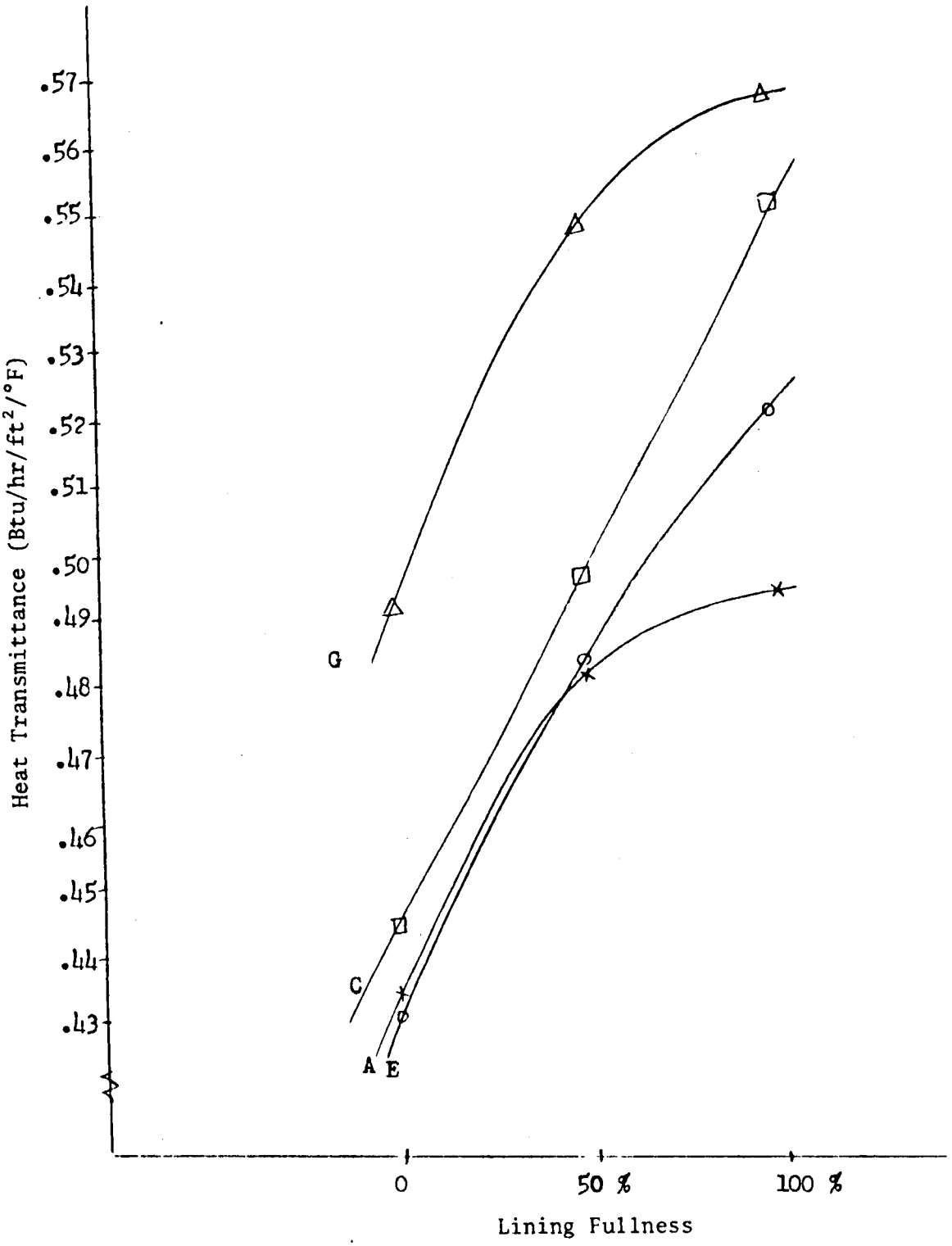


Figure 36. Effect of lining fullness on transmittance of various drapery fabrics.

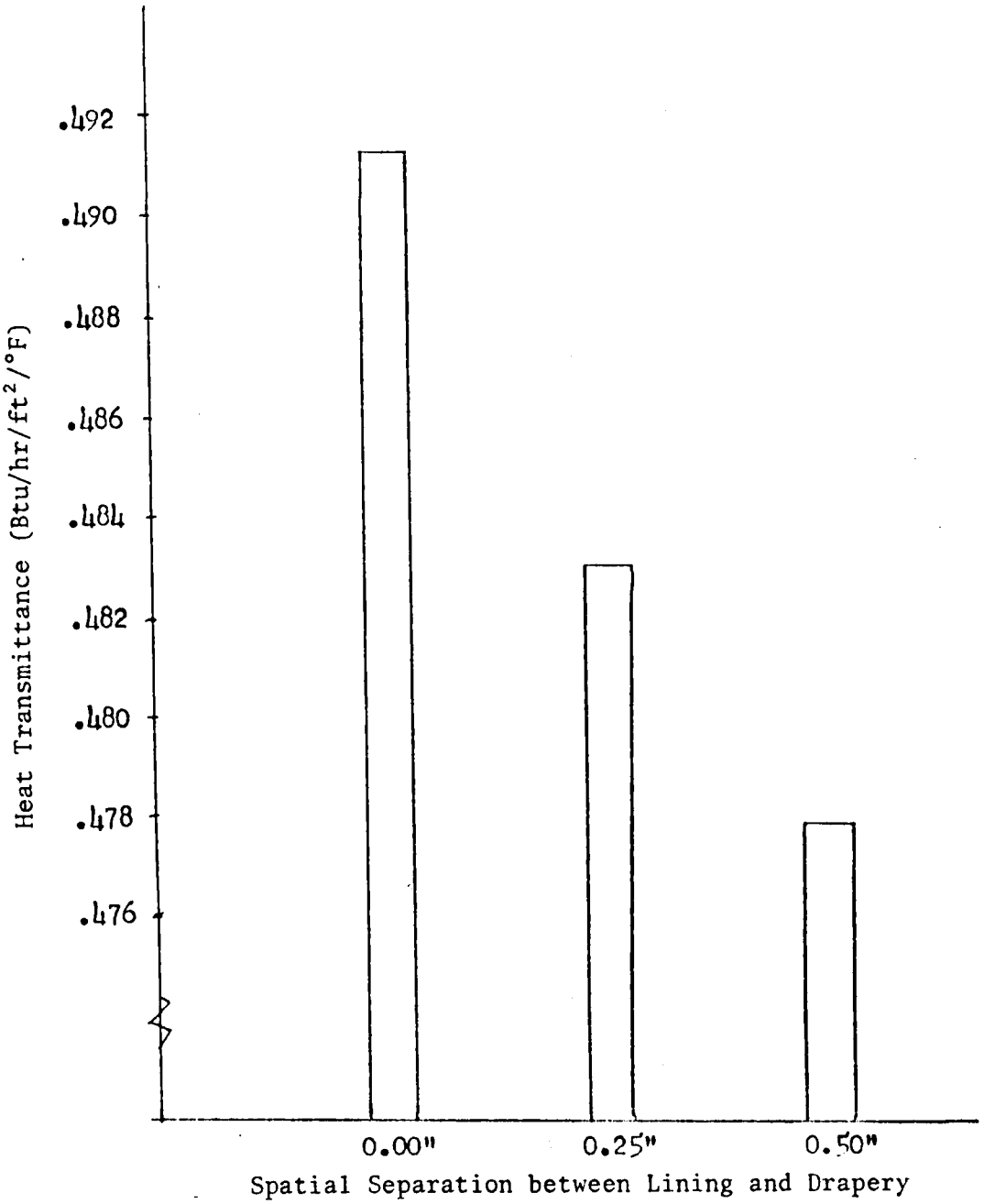


Figure 37. Transmittance of draperies by spacing.

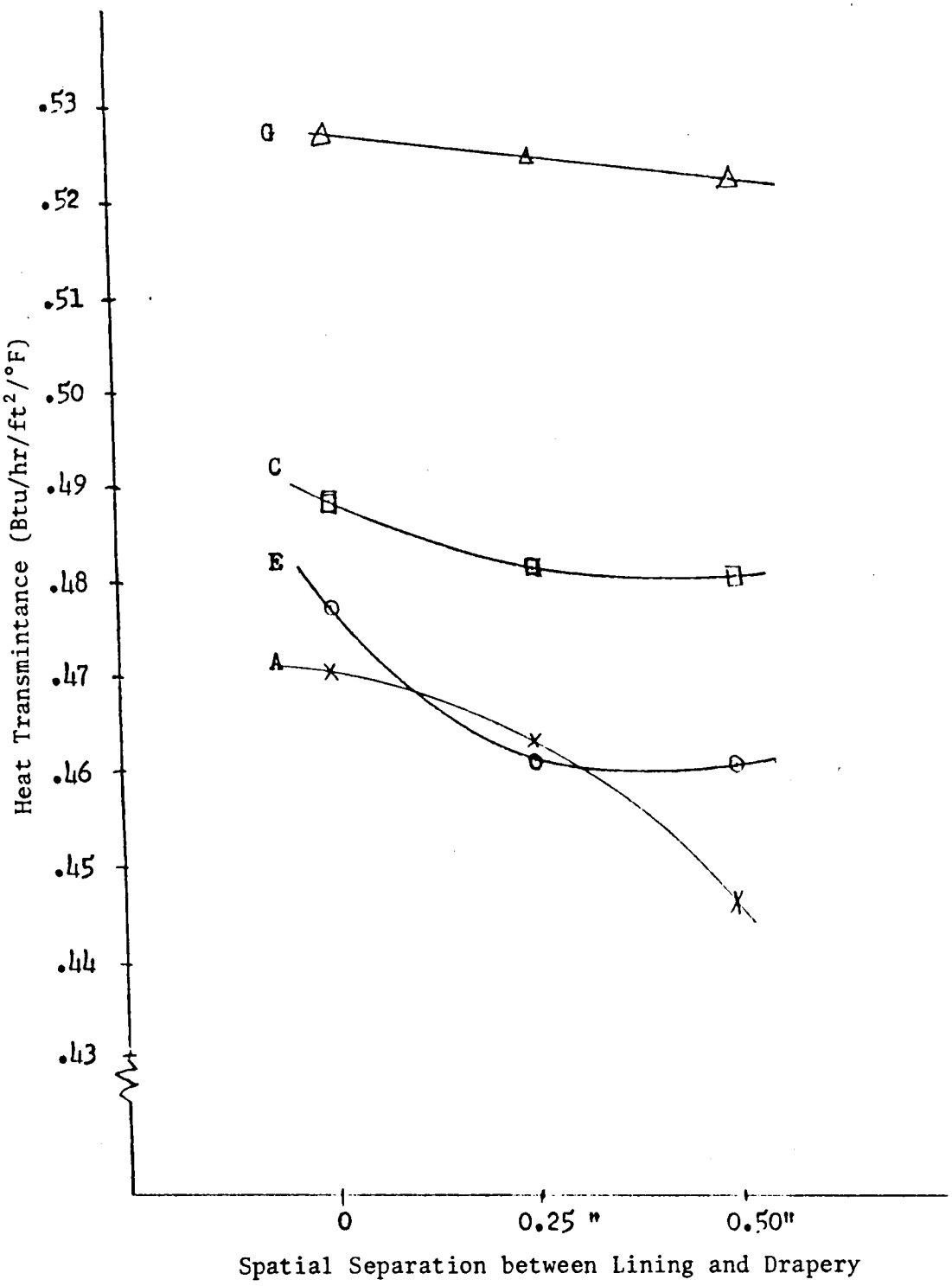


Figure 38. Effect of spacing between fabrics on transmittance.

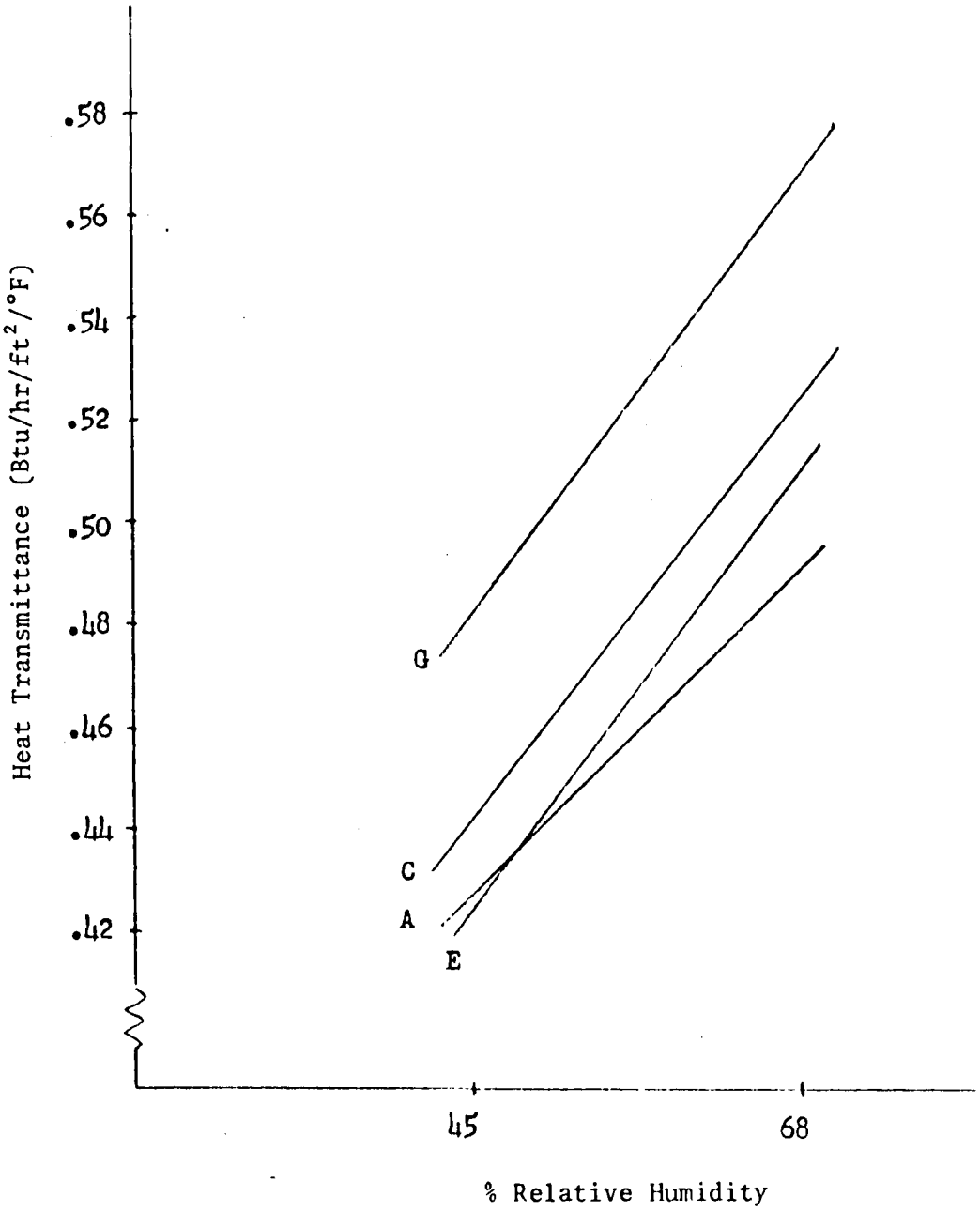


Figure 39. Differences in transmittance between fabrics by relative humidity.

Nonsignificance of the contrast between the hydrophobic fabric A and hydrophilic fabric E indicates that differences in heat transmittance are probably not attributable to fiber type. Significance of the contrasts between hydrophilic fabric C and hydrophobic fabric E and between hydrophilic fabric C and hydrophobic fabric G can perhaps be attributed to differences in weave openness rather than differences in fiber type.

Drapery Fullness

The 100% drapery fullness level showed a significantly higher transmittance level than the 50% fullness level. The total surface area of the drapery fabric is greater for the 100% fullness than for the 50% fullness.

The fact that weave openness was found to be the most significant of the fabric factors is important as it relates to drapery fullness. Significance of weave openness indicates significance of the fabric's ability to slow the flow of air. Since the fabric geometry is a major influence on transmittance, it follows that the amount of fabric surface area would also be important.

Lining Fullness

The overall significance of lining fullness was .0001. As with drapery fullness, transmittance increased as lining fullness increased, or as the total surface area of the fabric increased.

The three contrasts between the various levels of lining fullness were each significant at the .0001 level. Lining fullness influences

the overall geometry of the drapery by altering both the volume and the configuration of the air space between the lining fabric and the drapery fabric. Significance of the contrasts between lining fullnesses indicates that the configuration and volume of the two air spaces, as well as the total fabric surface area, influence heat transmittance of draperies.

Spatial Separation

Three levels of spatial separation between lining fabric and drapery fabric were tested. The data indicate that there is an inverse relationship between spacing and transmittance; transmittance increases as the level of spacing is reduced. When other factors are held constant (drapery fullness and lining fullness), the effect of spacing is evident. The dead air space between the lining and drapery fabrics serves to increase the insulation capacity of the drapery.

Contrasts were made between the levels of spatial separation between the lining fabric and drapery fabric. The contrast between zero spacing and 1/2-inch spacing was significant at the .0001 level. The other two spatial contrasts allow a closer examination of the variable. Zero spacing contrasted with 1/4-inch spacing was significant at the .01 level, while the contrast between 1/4-inch and 1/2-inch spacing was not significant. Therefore, although transmittance decreases as spacing increases from 1/4-inch to 1/2-inch, the influence of spacing on transmittance becomes less significant.

Combination of Drapery Fullness and Lining Fullness

The combination of the two factors drapery fullness and lining fullness influences both the volume of air space between the window glass and lining fabric and between the lining fabric and drapery fabric and the total surface area of the lining and drapery fabrics. Each of these factors, volume of the air space and surface area of the drapery components, is related to the heat transmittance value of the drapery.

Total transmittance of the combined factors of lining fullness and drapery fullness indicate that as the surface area of the fabric increases, the transmittance also increases. This may be due to direct heat loss through the fabric or to convective heat loss resulting from air movement within the simulated pleats of those systems with higher levels of fabric fullness.

The lowest transmittance was exhibited by the combination of flat lining and 50% drapery fullness, which represented the lowest total fabric surface area tested, only 2990 square inches. Low levels of heat loss can possibly be attributed to less fabric surface area through which heat is lost directly, or to reduced convection within the system because of low levels of pleating.

The combination of 100% lining fullness and 100% drapery fullness, which represented the highest total fabric surface area in the study (4784 square inches), showed the highest transmittance value. In other words, as heat is lost directly through fabric interstices, as the total number of interstices increases (amount of fabric surface area increases) heat loss also increases.

The intermediate level of total fabric surface area, 3588 square inches, was represented by the two following combinations: 50% drapery fullness with 50% lining fullness and 100% drapery fullness with a flat lining. Although these two combinations were identical in the total area of fabric surface incorporated in the drapery, their transmittance values were different, indicating that fabric surface area alone does not account for the differences in transmittance. It should be noted that, even when the factor of spacing is held constant, the volume of the air space between the lining and drapery fabrics is quite different for these two models. Regardless of the spacing factor, the model representing 100% drapery fullness and a flat lining will always have a larger volume of air between the fabrics than will the model in which the drapery and lining fabrics are equal in fullness. Therefore, the difference between the two models can be attributed to the difference in volume of the air space. The combination of 100% drapery fullness with a flat lining, which has the higher volume of air enclosed between the lining and drapery fabrics, has the lower transmittance value, while the 50% drapery fullness, 50% lining fullness combination, representing a smaller volume between the two fabrics, has the higher transmittance value of the two models. This trend is in agreement with the findings related to the spacing factor, which show that as the spatial separation between the lining fabric and drapery fabric increases, the trnasmittance value decreases, or resistance to heat flow increases.

Combination of Drapery Fullness, Lining Fullness and Spacing

When combined, the three configuration factors (drapery fullness, lining fullness and spacing) allow comparison of the models on the basis of volume of air space within the drapery model. Specifically, the volume between the window glass and lining fabric (V_1) and the volume between the lining fabric and drapery fabric (V_2) are determined by these three factors.

Based on the findings related to spatial separation alone, it might be expected that as either enclosed volume$_1$ or volume$_2$ increases, transmittance would also increase. However, as indicated in Table 24, p. 101, there is no definite trend in transmittance values corresponding to either of the volume calculations. This indicates that the volume of air within the drapery model has less influence on heat transmittance than does the total area of fabric surface.

In the analysis of variance, the interaction of lining fullness and spacing was found to be significant at the .05 level. Table 24 provides clues to the significance of this interaction. When lining fullness and spacing are considered as separate factors, the findings are easily interpreted. As lining fullness increases, transmittance increases, and as spacing increases, transmittance decreases. However, when the configuration factors are considered as a combination, the interaction is obvious. For the 50% and 100% lining fullnesses, transmittance does indeed increase as the spatial separation decreases, but, for the flat linings, this trend is not followed. For both the 50% drapery-flat lining combination and the 100% drapery-flat lining

combination, transmittance increases as the spatial separation increases from 0.00 to 0.25 inches, and is maintained at approximately the same level as the spatial separation is increased from 0.25 to 0.50 inches.

The differences in V_2 (lining fabric to drapery fabric) between those models with flat linings and those with either 50% or 100% linings is used to explain the interaction of lining fullness and spacing. At relatively low volumes (up to approximately 1200 cubic inches), transmittance does decrease as volume increases, or as spatial separation increases. However, as the volume is increased to greater levels (2035 cubic inches and higher), transmittance increases. Relatively small increases in volume of the air space provide increased insulation, but as the volume becomes larger, there is likely to be increased air circulation within the space. Such air movement increases convective heat loss, resulting in an overall decrease in insulation value (increase in transmittance).

Relative Humidity

As in the single layer tests, relative humidity of the surrounding room air was found to be quite significant. Measurements carried out at 68% relative humidity showed higher transmittance values than those made at 45% relative humidity for all drapery materials and drapery combinations. As the air became more saturated, the ability of the drapery to insulate against heat loss was inhibited. This was found to be true for both hydrophilic and hydrophobic fibers. As was suggested in a previous section, water condensation perhaps influences the heat loss in the system which is evident from lower transmittance values.

Summary of Multilayer Results

Analysis of the data for the multilayer drapery models based on comparisons between means for each factor and combination of factors plus analysis of variance and a priori statistical contrasts indicates that fabric openness, total area of fabric surface, and volume of the air space within the drapery model each are related to the heat transmittance values of the multilayer draperies. Also, the relative humidity of the surrounding room air significantly influences the transmittance values of the draperies.

IV. PHYSICAL PROPERTIES

The following physical properties for each of the fabrics were included in the statistical analysis: fabric weight, thickness, porosity, air permeability, reflectance, drape coefficient, moisture regain and specific heat. Each of these properties was measured according to the methods indicated in Chapter III, with the exception of specific heat. The factor of specific heat of the particular fiber was added to the analysis procedure after testing had been completed.

Regression models using all of the physical factors plus the factors used in the initial analysis of variance models were developed for the single layer data and the multilayer data. The regression models for the two groups of data will be presented separately.

Single Layer Models

A statistical model which included each of the factors was analyzed. The analysis of variance table for this model is included in Table 31.

TABLE 31

REGRESSION ANALYSIS FOR FABRICS IN SINGLE LAYERS, MODEL 1

Source	DF	MS	F
Fabric	1	.2797	94.94**
Relative hunidity	1	.0859	262.30**
Weight	1	.0000	0.05
Thickness	1	.0262	80.14**
Porosity	1	.0009	2.80
Air Permeability	1	.0604	184.45**
Fabric reflectance	1	.0000	0.15
Drapeability	1	.0000	0.00
Cover factor	1	.0016	5.05*
Moisture regain	1	.0001	0.53
Specific heat	1	.0013	4.12

*Significant at .05 level.

**Significant at .0001 level.

Fabric, relative humidity, fabric thickness, and air permeability were found to be significant at the .0001 level. Cover factor was significant at the .05 level. The other factors were not significant. The R^2 value for the model was .992, indicating excellent fit of the model to the data. The possible range of R^2 is zero to one. As the value approaches one, the significance of the model as a predictor of the dependent variable increases. The R^2 value of .992 indicates that 99.2% of the variation in transmittance can be predicted by the model.

In order to find the best model for predicting transmittance, a stepwise procedure was used. The goal of this process is to arrive at a model with the fewest possible variables without sacrificing the overall predictive capacity of the model, or, to eliminate variables

without greatly reducing the R^2 value. Although several of the variables were found to be significant, from a practical perspective, it would be of great value to be able to predict the transmittance of a fabric from the fewest possible number of variables.

Fabric was replaced by weave openness as a factor in the second model, since weave openness is itself a single variable while the term fabric represented several different variables. Weave openness was chosen because it was found to be highly significant in the earlier analysis of variance. All of the variables which were not significant in the initial regression model, plus cover factor, which was significant at only the .05 level, were eliminated from the second model. The resulting model, which included weave openness, air permeability, relative humidity and thickness, had an R^2 value of .9862. In this model, weave, air permeability and relative humidity were significant at the .0001 level and thickness was significant at the .05 level. The results of this model are presented in Table 32.

TABLE 32

REGRESSION ANALYSIS FOR FABRICS IN SINGLE LAYERS, MODEL 2

Source	DF	MS	F
Weave openness	1	.1365	404.21**
Air permeability	1	.1392	412.35**
Relative humidity	1	.0859	254.21**
Thickness	1	.0018	5.26*

*Significant at the .05 level.

**Significant at the .0001 level.

In a third regression model, the same four variables were included, but the order of the variables was changed. Air permeability was entered as the first variable, since its F value was the highest on the previous model. This model showed nonsignificance of the weave openness variable, as indicated in Table 33. This was caused by the close relationship between weave openness and air permeability, indicating that these two variables are reflecting nearly the same measurements, and therefore both variables are not needed in the model. The R^2 value for this model was also .9862.

TABLE 33

REGRESSION ANALYSIS FOR FABRICS IN SINGLE LAYERS, MODEL 3

Source	DF	MS	F
Air permeability	1	.2758	816.53**
Weave openness	1	.0000	.02
Relative humidity	1	.0859	254.21**
Thickness	1	.0018	5.26*

*Significant at the .05 level.

**Significant at the .0001 level.

Since weave openness was not found to be significant, it was eliminated from the model. A fourth regression model included the three factors, air permeability, relative humidity and thickness. In this model only air permeability and relative humidity were significant, each at the .0001 level. Thickness was not significant. The R^2 value of the model was .9839. Results of the analysis are shown in Table 34.

TABLE 34

REGRESSION ANALYSIS FOR FABRICS IN SINGLE LAYERS, MODEL 4

Source	DF	MS	F
Air permeability	1	.2758	746.01*
Relative humidity	1	.0859	232.25*
Thickness	1	.0009	2.53

*Significant at the .0001 level.

Because thickness was not significant in model 4, it was eliminated from the fifth model, leaving only the two factors, air permeability and relative humidity. In this model, both variables were significant at the .0001 level, and the R^2 value of the model was .9814, indicating that 98.14% of the variation in transmittance between the fabrics tested can be predicted by these two factors alone. The actual model is: Transmittance = .45155 + .00232 (relative humidity) + .00048526 (air permeability). Results of the analysis are summarized in Table 35.

TABLE 35

REGRESSION ANALYSIS FOR FABRICS IN SINGLE LAYERS, MODEL 5

Source	DF	MS	F
Relative humidity	1	.0859	213.06*
Air permeability	1	.2758	684.35*

*Significant at the .0001 level.

Separate regression models for relative humidity and air permeability were also tested. However, the R^2 for the model which included only air permeability was .7484, and the R^2 for the model which included only relative humidity was only .2330, indicating that neither of the two variables should be used alone to predict transmittance.

Multilayer Models

In order to find the most suitable model with the least number of variables for predicting the transmittance value of the multilayer drapery models, the results of the single layer stepwise elimination procedure were used. Those physical property variables which were found to be significant in the single layer models were used in the initial multilayer model, in addition to the three configuration factors including drapery fullness, lining fullness and spacing.

The first multilayer model tested included relative humidity, air permeability, lining fullness, drapery fullness and spacing. Relative humidity, air permeability and lining fullness were each significant at the .0001 level and spacing was significant at the .01 level. Drapery fullness was not significant. The R^2 value for the multilayer models was expected to be somewhat lower than those of the single layer models, since R^2 always decreases as the number of observations increases. There were 40 observations in the single layer data and 192 in the multilayer data. Table 36 summarizes the results of the analysis.

Since drapery fullness was not significant, it was eliminated from the second model. In this model, relative humidity, lining fullness and air permeability were each significant at the .0001 level. Spacing

TABLE 36

REGRESSION ANALYSIS FOR MULTILAYER DRAPERIES, MODEL 1

Source	DF	MS	F
Relative humidity	1	.0172	396.02**
Air permeability	1	.0603	151.87**
Lining fullness	1	.1231	310.18**
Drapery fullness	1	.0005	1.21
Spacing	1	.0028	7.13*

*Significant at the .01 level.

**Significant at the .0001 level.

was significant at the .01 level. The R^2 for the model was .9046. Results of the regression analysis for the second model are shown in Table 37.

TABLE 37

REGRESSION ANALYSIS FOR MULTILAYER DRAPERIES, MODEL 2

Source	DF	MS	F
Relative humidity	1	.1572	395.13**
Lining fullness	1	.1231	309.48**
Air permeability	1	.0603	151.53**
Spacing	1	.0028	7.12*

*Significant at the .01 level.

**Significant at the .0001 level.

The least significant variable, spacing, was eliminated from the third model. In this model, relative humidity, lining fullness, and air permeability were each significant at the .0001 level. The R^2 value for the model was .9023, indicating that the elimination of the spacing factor did not significantly alter the predictive capacity of the model. Table 38 includes a summary of the analysis of this model.

TABLE 38

REGRESSION ANALYSIS FOR MULTILAYER DRAPERIES, MODEL 3

Source	DF	MS	F
Relative humidity	1	.1572	370.50*
Lining fullness	1	.1231	290.19*
Air permeability	1	.0603	142.00*

*Significant at the .0001 level.

The analysis showed that 90.23% of the variation in transmittance could be predicted by the following model: Transmittance = 0.3403 + .00095 (relative humidity) + .043188 (lining fullness) + 0.000639 (air permeability).

Two additional regression models were tested, neither of which can be recommended because of their low R^2 values. A model which consisted of relative humidity and air permeability was found to have an R^2 of .5729, and a model which included only lining fullness had an R^2 value of .3294.

Individual Physical Properties

Individual regression models were developed for each of the physical factors for the single layered tests. Graphs for each of these models are shown in the appendix (Figures 52-60). The purpose of this section is only to show the relationship between each physical factor and the transmittance value of the drapery on the window. Because of their extremely low R^2 values the models should not be used to predict transmittance, or to indicate significance of the relationship between the physical factor and transmittance.

As indicated by the graphs, the factors of fabric thickness, porosity, air permeability, reflectance, drape coefficient, moisture regain and specific heat were found to have direct relationships with transmittance, while fabric weight and cover factors were inversely related to heat transmittance. In previous studies (32), fabric thickness was found to be inversely related to transmittance, that is, transmittance was found to decrease as fabric thickness increased. It should be noted that the two fabrics with very open weaves had relatively high thickness measurements. Although these fabrics were quite thick, their transmittance values were very high, due to the openness of the fabric weave. The researcher therefore concludes that fabric openness contributed to the apparent direct relationship between thickness and transmittance. If tests had included a wider range of fabric thicknesses, and if the fabrics had been similar in other respects, particularly weave openness, the findings would probably have agreed more closely with those of previous studies.

V. SUMMARY

The results of this study are applicable only to those specific fabrics and configurations investigated.

Hypothesis 1 can be accepted. There were significant differences between the transmittance values of the ten fabrics when tested in single, flat configurations.

Hypothesis 2 cannot be accepted. Although analysis of variance showed significant differences between hydrophilic and hydrophobic fibers, statistical contrasts between individual fabrics indicated that the differences were due to fabric weave openness rather than fiber type.

Hypothesis 3 cannot be accepted. There were no significant differences in transmittance values between the light colored and dark colored fabrics.

Hypothesis 4 is accepted. Analysis of variance and statistical contrasts between fabrics supported the hypothesis that there are significant differences in transmittance values between the open-weave and tightly woven fabrics.

Hypothesis 5 is accepted. All fabrics and all configurations showed significantly higher transmittance values at the higher relative humidity level than at the low level.

Hypothesis 6 is accepted. Based on analysis of variance, there were significant differences between the transmittance values of the fabrics which were tested in layered configurations with the lining fabrics. Individual statistical contrasts between fabrics indicated only fabrics A and E were not significantly different. These two fabrics are similar

in weave openness but different in hydrophilicity, which confirms that weave openness is a significant factor while fiber type is not.

Hypothesis 7 and 8 are both accepted. Transmittance increased significantly as both lining fullness and drapery fullness increased, or as the total surface area of fabric in the drapery increased. Lining fullness was more significant than drapery fullness, probably because the investigation included a wider range of lining fullness than drapery fullness.

Hypothesis 9 is accepted. Spatial separation was found to be a significant factor in contributing to thermal transmittance values. Generally, transmittance decreased as spatial separation increased. However, there were differences among the various drapery models, depending on the total volume of air space between the lining fabric and drapery fabric created by the spacing factor and the lining fullness and drapery fullness factors. At lower volume levels, transmittance decreased as spacing increased, but as the total volume increased, transmittance increased as the spatial separation increased. This finding indicates that up to a certain volume, increased spatial separation provides air entrapment, which serves as insulation, but beyond that optimum volume of air space, increased spatial separation results in air circulation within the space, causing convective heat loss.

Analysis of the physical properties of the fabrics showed fabric thickness, air permeability and cover factor to be significantly related to fabric transmittance. Fabric weight, porosity, reflectance

drape coefficient, moisture regain and specific heat were not significant, according to the multiple regression analysis.

A stepwise elimination procedure resulted in several models for predicting the thermal transmittance values of the fabrics and draperies. Analysis showed that 98% of the variation in transmittance of single fabrics in a flat configuration can be predicted from the relative humidity of the indoor environment and the air permeability of the fabric. Further analysis showed that 90% of the variation in double layered drapery models can be predicted from the indoor relative humidity, air permeability of the fabric, and the lining fullness of the drapery.

Tables 39 and 40 summarize the mean transmittance values of two replications for each of the experimental factors included in the investigation.

TABLE 39

TRANSMITTANCE VALUES—PHASE ONE (SINGLE LAYERS)

Fiber	hydrophilic								hydrophobic												
Color	light				dark				light				dark								
Weave	open (C)		tight (A)		open (D)		tight (B)		open (G)		tight (E)		open (H)		tight (F)		Lining	hydrophilic (X)		hydrophobic (Y)	
RH	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	RH	high	low	high	low
	.7682	.6031	.6054	.5022	.6973	.5475	.6068	.4950	.9297	.7763	.5865	.4903	.9335	.7801	.5971	.4893		.6292	.4992	.7779	.6327

Transmittance (Btu/hr/ft²/°F)

TABLE 40

TRANSMITTANCE VALUES—PHASE TWO (DOUBLE LAYERS)

Fiber	hydrophilic				hydrophobic				Spacing (inches)	Lining Fullness (%)	Drapery Fullness (%)
Weave	open (Fabric C)		tight (Fabric A)		open (Fabric G)		tight (Fabric E)				
Relative Humidity	high	low	high	low	high	low	high	low			
	.4815	.4080	.4466	.3924	.5155	.4674	.4727	.3900	0	0	50
	.4729	.4168	.4754	.4012	.5379	.4520	.4431	.3946	¼		
	.4946	.4038	.4629	.4042	.5162	.4493	.4638	.3942	½		
	.5521	.4937	.5326	.4767	.6037	.5062	.5667	.4364	0	50	
	.5290	.4361	.5172	.4460	.5866	.5038	.5138	.4238	¼		
	.5362	.4365	.4835	.4293	.6001	.4970	.5251	.4274	½		
	.4588	.4037	.4718	.4035	.5198	.4625	.4806	.4015	0	0	100
	.4724	.4261	.4800	.3977	.5113	.4579	.4759	.3985	¼		
	.4904	.3943	.4621	.4046	.5482	.4535	.4379	.4188	½		
	.6020	.5141	.5569	.4798	.6300	.5120	.6008	.4808	0	100	
	.6105	.4923	.5387	.4598	.6265	.5234	.5646	.4694	¼		
	.6110	.4858	.4835	.4456	.6306	.4884	.5838	.4296	½		

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

I. SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate relationships among thermal transmittance and various fiber, fabric and geometrical variables of window draperies and to identify physical characteristics of fabrics which contribute to low heat transmittance of draperies made from those fabrics.

Draperies were tested at an indoor temperature of 70 ± 2°F and at two relative humidity levels, 45 ± 2% and 68 ± 2%. The temperature differential between the two sides of the test window was maintained at approximately 25°, with the conditions behind the window set to simulate cold winter conditions.

In phase one, each of the eight drapery fabrics and two lining fabrics were tested for heat transmittance on the test window in a flat configuration. Although initial analysis of variance for phase one showed that each of the experimental factors was significant (with the exception of color), statistical contrasts designed to compare the various levels within each factor type showed that the apparent significance of fiber type was actually due to weave openness.

In phase two, four of the drapery fabrics, representing light colors, were tested in layered combinations with the cotton lining fabric in various configurations determined by drapery fullness, lining fullness and spatial separation between the lining fabric and drapery fabric.

Each of the variables (fabric, drapery fullness, lining fullness, spacing and relative humidity) was significant. Based on specific statistical contrasts, fabric significance was attributed to weave openness. Significance of each of the configuration factors indicated the importance of both the fabric surface area and the volume of air space within the drapery. The interaction of lining fullness and spacing was also found to be significant. Examination of the data showed that increased spatial separation at low volume levels results in decreased transmittance, but when the total volume of air enclosed in the drapery system is significantly increased (by altering fabric fullness), the increased spatial separation between the lining fabric and drapery fabric results in increased transmittance, which is likely due to free air movement within the relatively large volume of air space.

Investigation of relationships between physical characteristics of the fabrics and heat transmittance using regression analysis showed that air permeability is the single most important fabric characteristic related to transmittance. Fabric thickness and cover factor were also found to be significant; fabric weight, porosity, reflectance, drapeability, moisture regain and specific heat were not. The relationship between air permeability and transmittance was direct; as air permeability increased, transmittance increased. Inverse relationships between cover factor and transmittance and between thickness and transmittance were indicated. As cover factor increases, or as the degree of fabric closure increases, transmittance decreases.

In contrast with the findings of previous studies, transmittance was found to increase with increasing fabric thickness. However, closer

examination of the data lead the researcher to conclude that apparent differences due to fabric thickness were actually due to differences in weave openness; two of the fabrics which had relatively high thickness measurements were also very open in weave.

A stepwise linear regression procedure resulted in several models for predicting thermal transmittance. Analysis showed that 98% of the variation in heat transmittance of single flat fabrics can be predicted from air permeability and relative humidity, and that 90% of the variation in transmittance of multilayer draperies can be predicted from air permeability, lining fullness and relative humidity.

The findings of the study indicate that thermal transmittance is significantly decreased (insulation value is improved) if drapery fabrics are tightly woven and if the total amount of fabric used in the drapery is reduced. Two general conclusions about the mechanism of heat loss can be drawn from the study:

1. Heat is lost through fabric interstices.
2. Heat loss increases as the number of fabric interstices increases (as the total fabric surface area increases).

A third major conclusion is that increased relative humidity impedes the insulation capacity of draperies. Heat is required to evaporate excess moisture associated with high relative humidity, resulting in greater overall heat loss. Moisture may also alter the conductivity of the fabric system, possibly resulting in increased heat loss through conduction.

II. RECOMMENDATIONS

The selection of fabrics for the study was somewhat limited by the requirement that they represent extremes of hydrophilicity and that they consist of 100% of a single fiber. Since fiber type is apparently not a very significant factor in determining transmittance, the selection of fabrics on the basis of fiber type should not be a requirement in future studies. This will permit a wider range of fabric choice, more representative of those fabrics presently used in draperies, including fiber blends.

Different types of lining fabrics should be tested. A major limitation of this study was that only one lining fabric was used for the multilayer tests. Since both lining fullness and air permeability were found to be extremely significant, further investigations should focus on the relative significance of lining fullness as the air permeability of the lining fabric is varied. Double layers of fabrics (drapery fabric plus lining fabric) were used in this study. Triple layers should also be investigated. For example, the traditional use of fabric sheers in combination with lined draperies should also be examined. Various configurations, including a flat lining and a flat drapery, should be included in further study.

Relative humidity was a significant factor in both phases of this study. Since relative humidity greatly influences the insulation capacity of draperies, other relative humidity levels should also be tested. Additionally, the mode of heat loss at increased levels of relative humidity should be determined.

Throughout the investigation, the fabrics were completely sealed to the window frame. This control over convective heat loss allowed closer examination of fabric factors than would have been possible with traditional, free hanging draperies. However, the functionality of draperies completely sealed to the window frame must be considered. Two research questions related to this point should be investigated:

1. As the drape-to-window seal is decreased, to what extent do the fabric and configuration factors decrease in significance?
2. In terms of functional design, how can draperies be designed so that the window-drapery seal is maintained without sacrificing functionality and consumer acceptance?

Draperies with high levels of fabric fullness are valued aesthetically, and are generally believed to be associated with increased thermal insulation. However, this study shows that low levels of fullness are associated with low transmittance, or increased insulation. This indicates a need for consumer education related to this finding.

The fact that several different regression models were developed is important in terms of both research and education. Researchers might use the more precise measure of fabric air permeability in predicting transmittance, while consumer educational recommendations might be made on the basis of the more general term, "weave openness." Degress of weave openness could easily be judged by relatively untrained consumers, while skilled researchers might rely on the more scientific measurements of air permeability or cover factor. Similarly, calculations of fabric

surface area and volume of air spaces within the drapery would be useful in research, while the comparable "amount of pleating" or "fullness" would be more meaningful to consumers.

The maximum energy efficiency of draperies will not be realized without effective management by the consumer. Consumer education is a prerequisite for effective management. Educational efforts should be directed toward the specifics of how to use draperies to improve window insulation as well as toward the broader issue of using textiles to maintain thermal comfort while reducing energy use.

Consumer education information based on this study should include the following points:

1. Although energy efficiency can be improved by sealing the drapery to the window frame, aesthetics and functionality may suffer.
2. Sealing the drapery to the window in order to reduce convective heat loss might also result in increased humidity levels and condensation between the drapery and window glass. Such increases in moisture are likely to inhibit the effectiveness of the drapery as an insulating device.
3. Tightly woven fabrics and low levels of drapery and lining fullness are associated with low thermal transmittance, or high insulation values.

In addition to traditional methods of consumer education, this information might also be communicated to consumers through retailers or manufacturers.

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APPENDIX

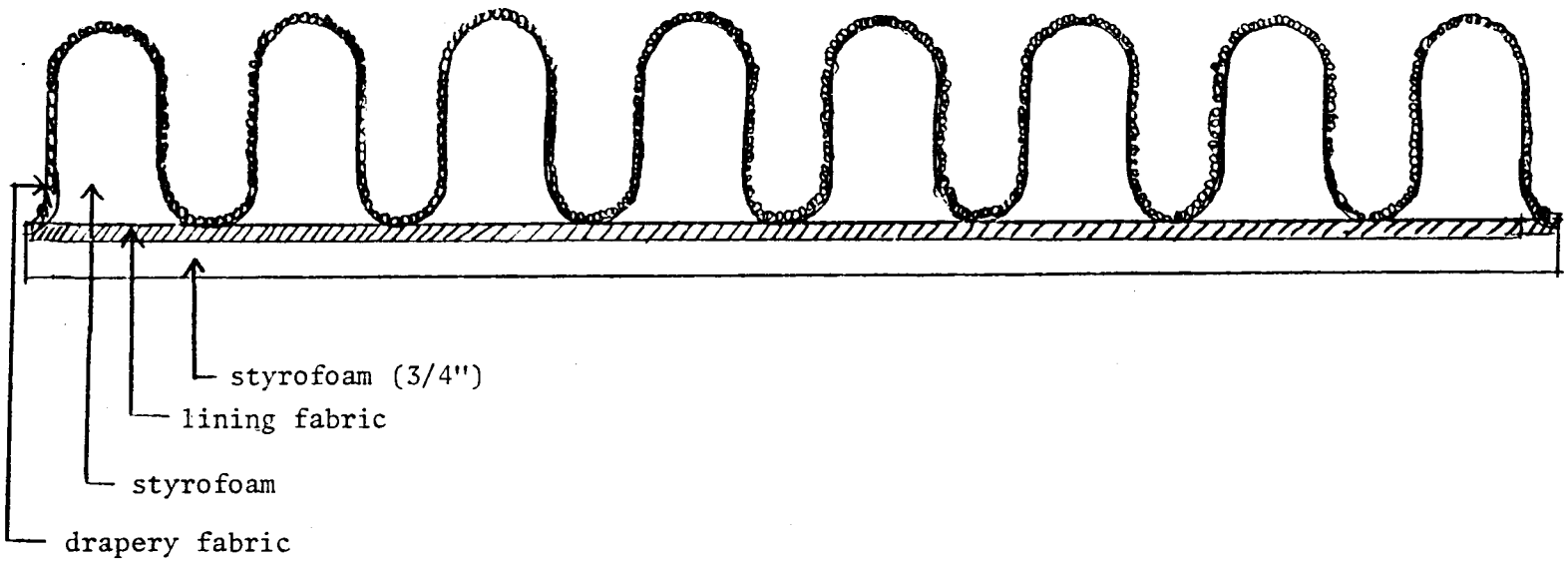


Figure 40. Spacer/fabric configuration for 100% drapery fullness, flat lining, zero spacing.

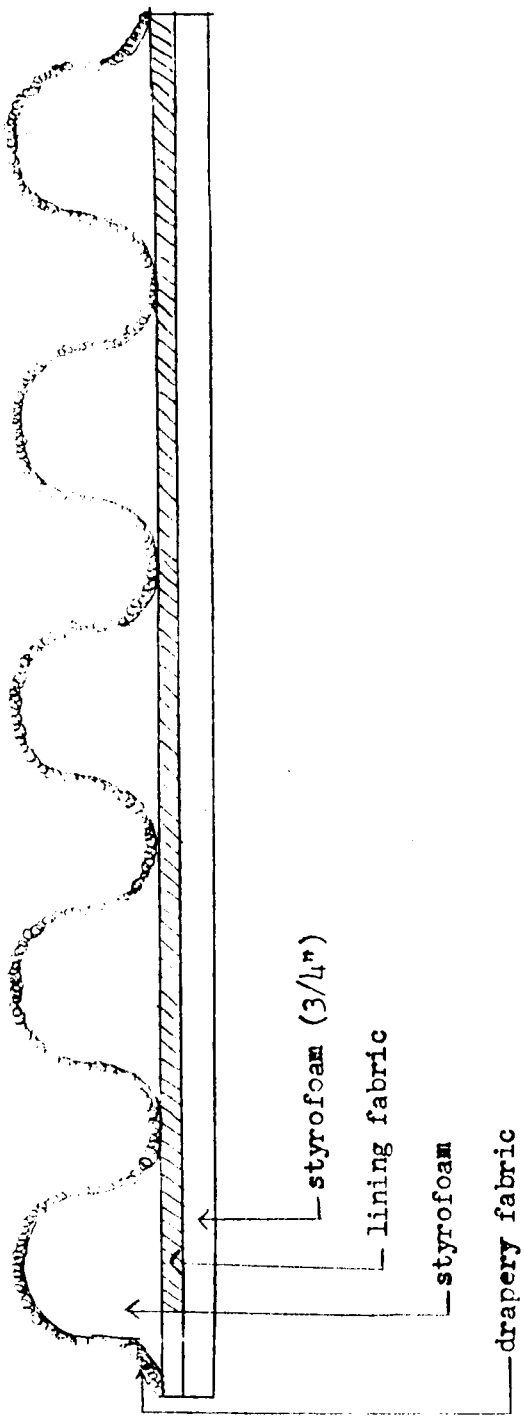


Figure 41. Spacer/fabric configuration for 50% drapery fullness, flat lining, zero spacing.

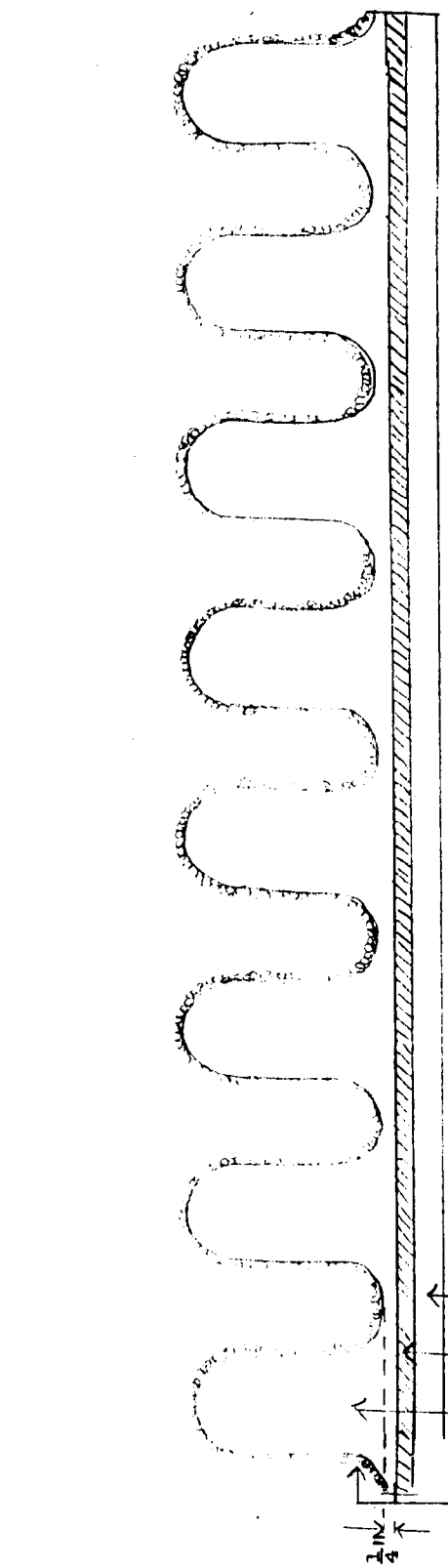


Figure 42. Spacer/fabric configuration for 100% drapery fullness, flat lining, 1/4-inch spacing.

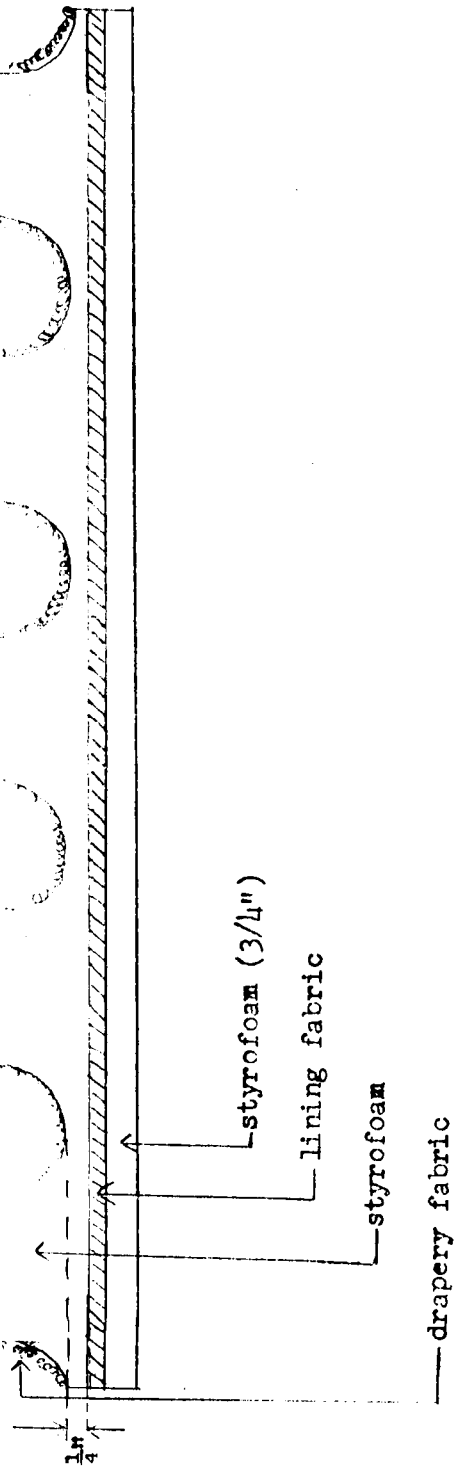


Figure 43. Spacer/fabric configuration for 50% drapery fullness, flat lining, 1/4-inch spacing.

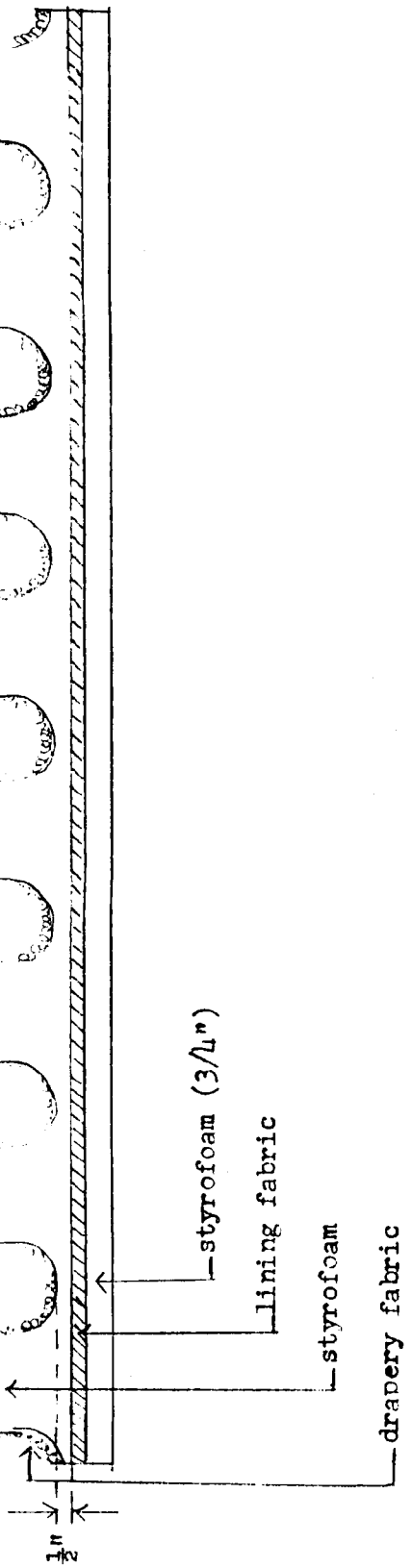


Figure 44. Spacer/fabric configuration for 100% drapery fullness, flat lining, 1/2-inch spacing.

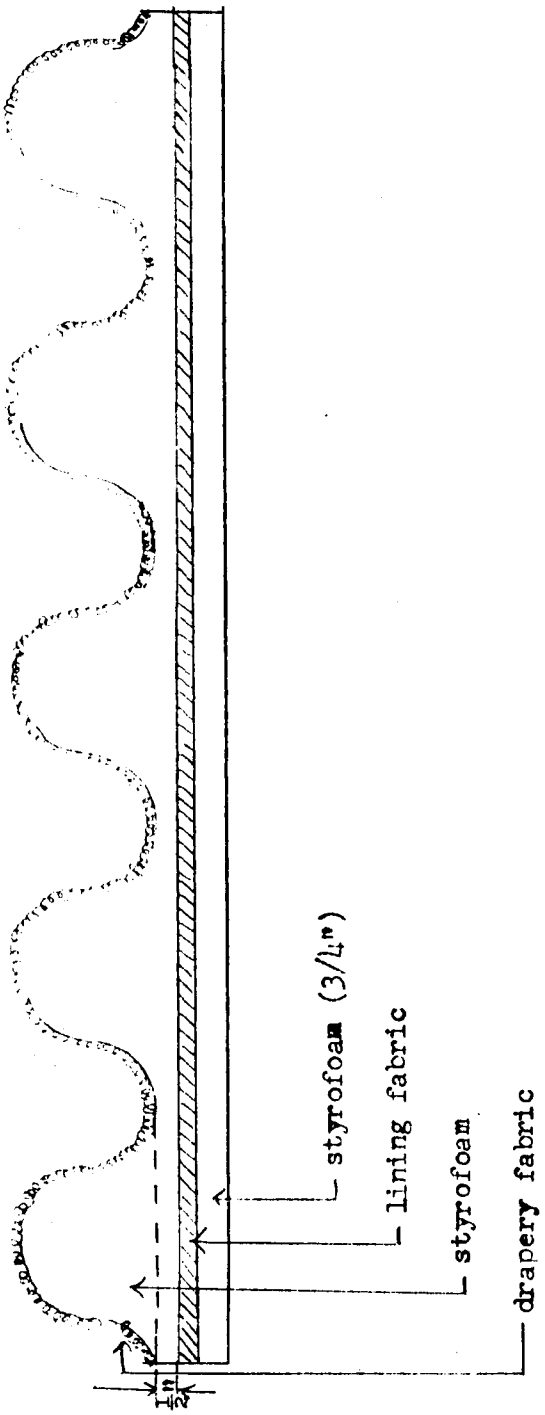


Figure 45. Spacer/fabric configuration for 50% drapery fullness, flat lining, 1/2-inch spacing.

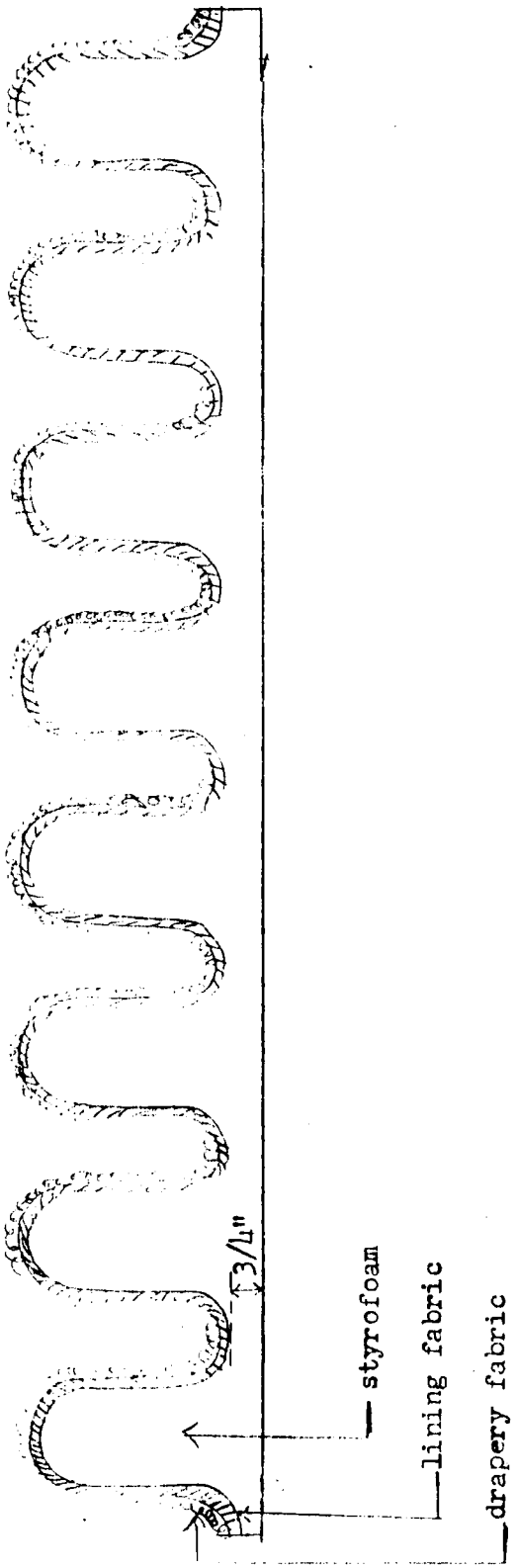


Figure 46. Spacer/fabric configuration for 100% drapery fullness, 100% lining fullness, zero spacing.

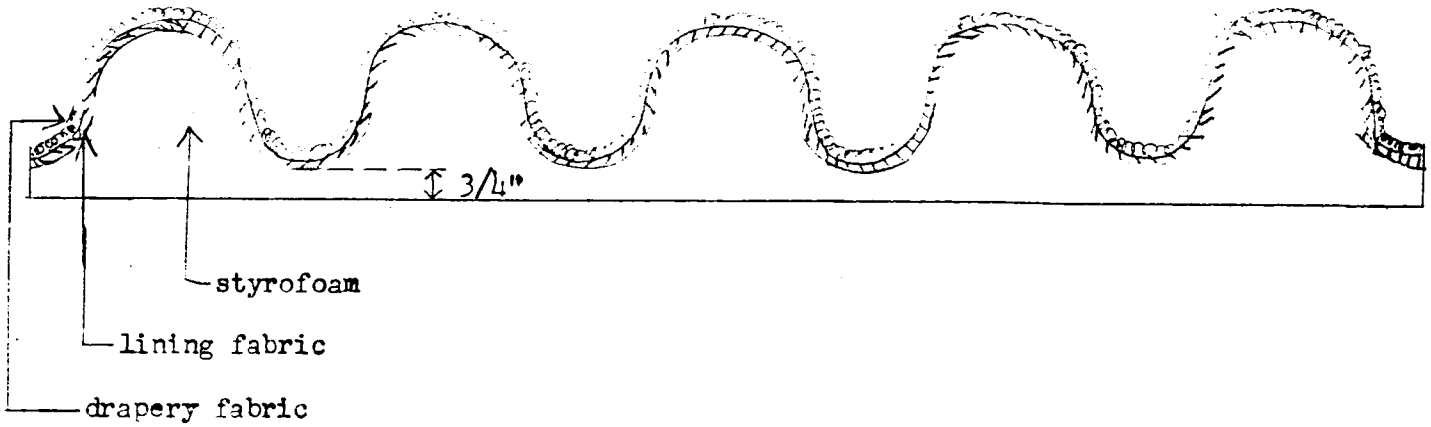


Figure 47. Spacer/fabric configuration for 50% drapery fullness, 50% lining fullness, zero spacing.

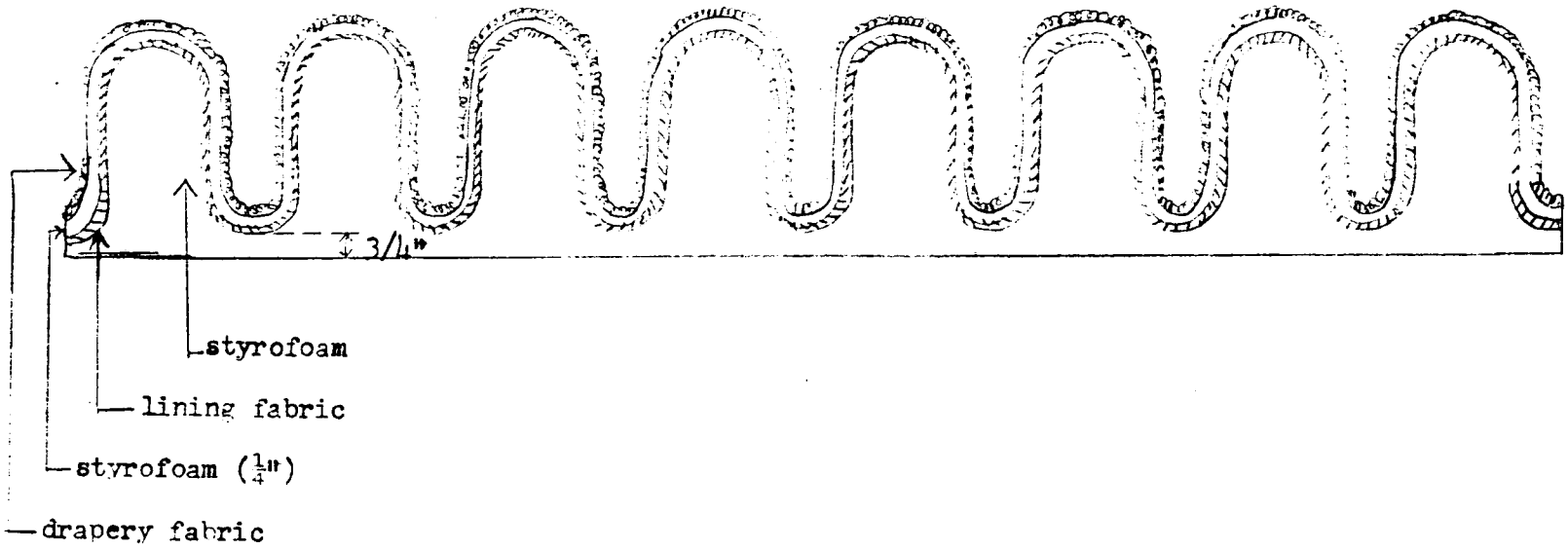


Figure 48. Spacer/fabric configuration for 100% drapery fullness, 100% lining fullness, 1/4-inch spacing.

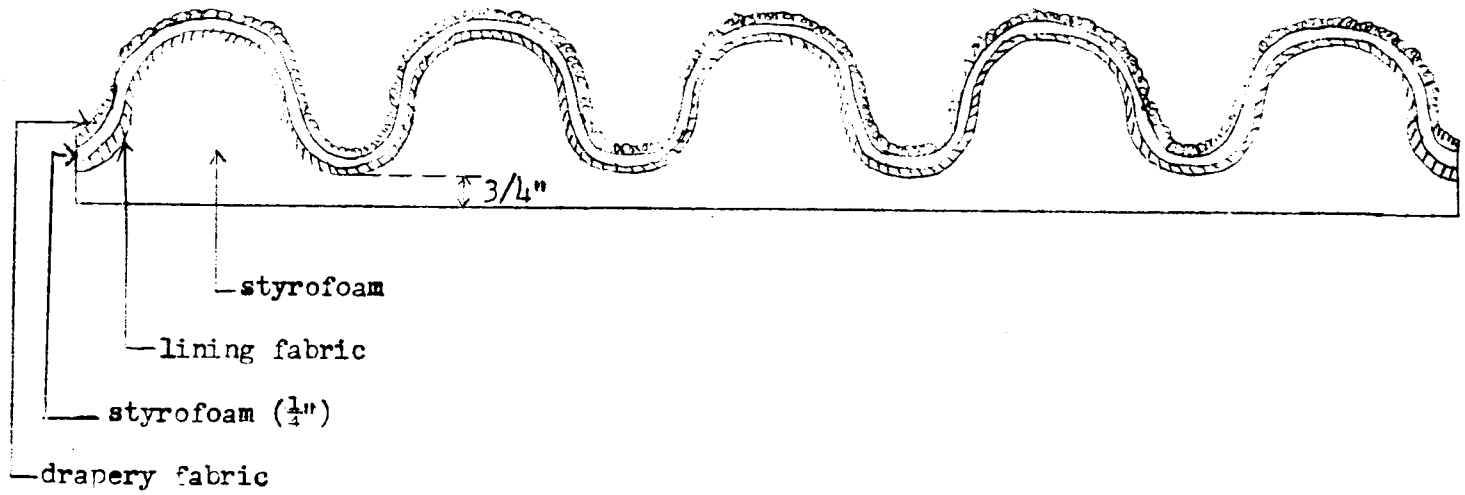


Figure 49. Spacer/fabric configuration for 50% drapery fullness, 50% lining fullness, 1/4-inch spacing.

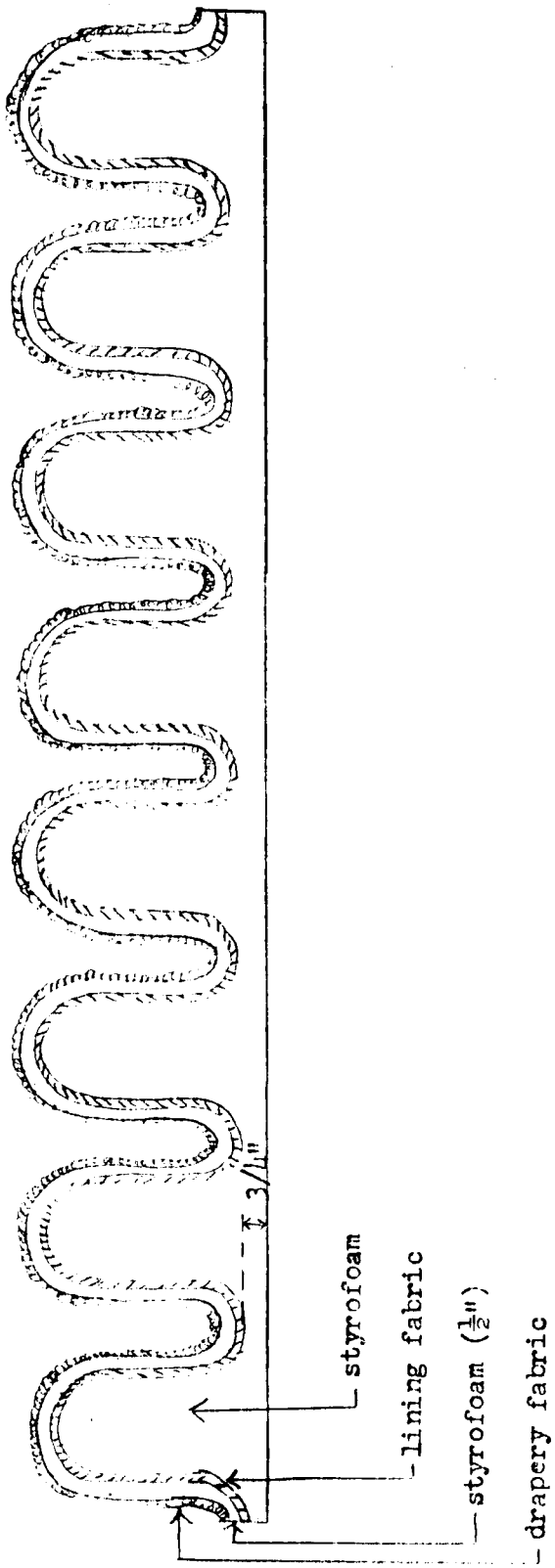


Figure 50. Spacer/fabric configuration for 100% drapery fullness, 100% lining fullness, 1/2-inch spacing.

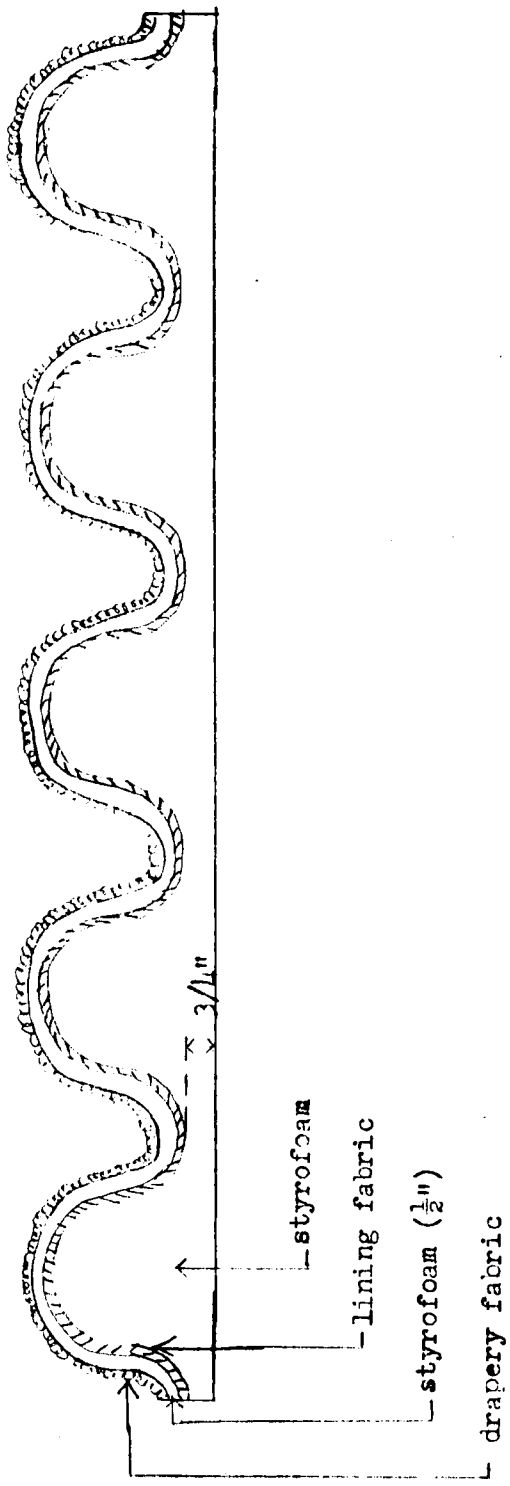


Figure 51. Spacing/fabric configuration for 50% drapery fullness, 50% lining fullness, 1/2-inch spacing.

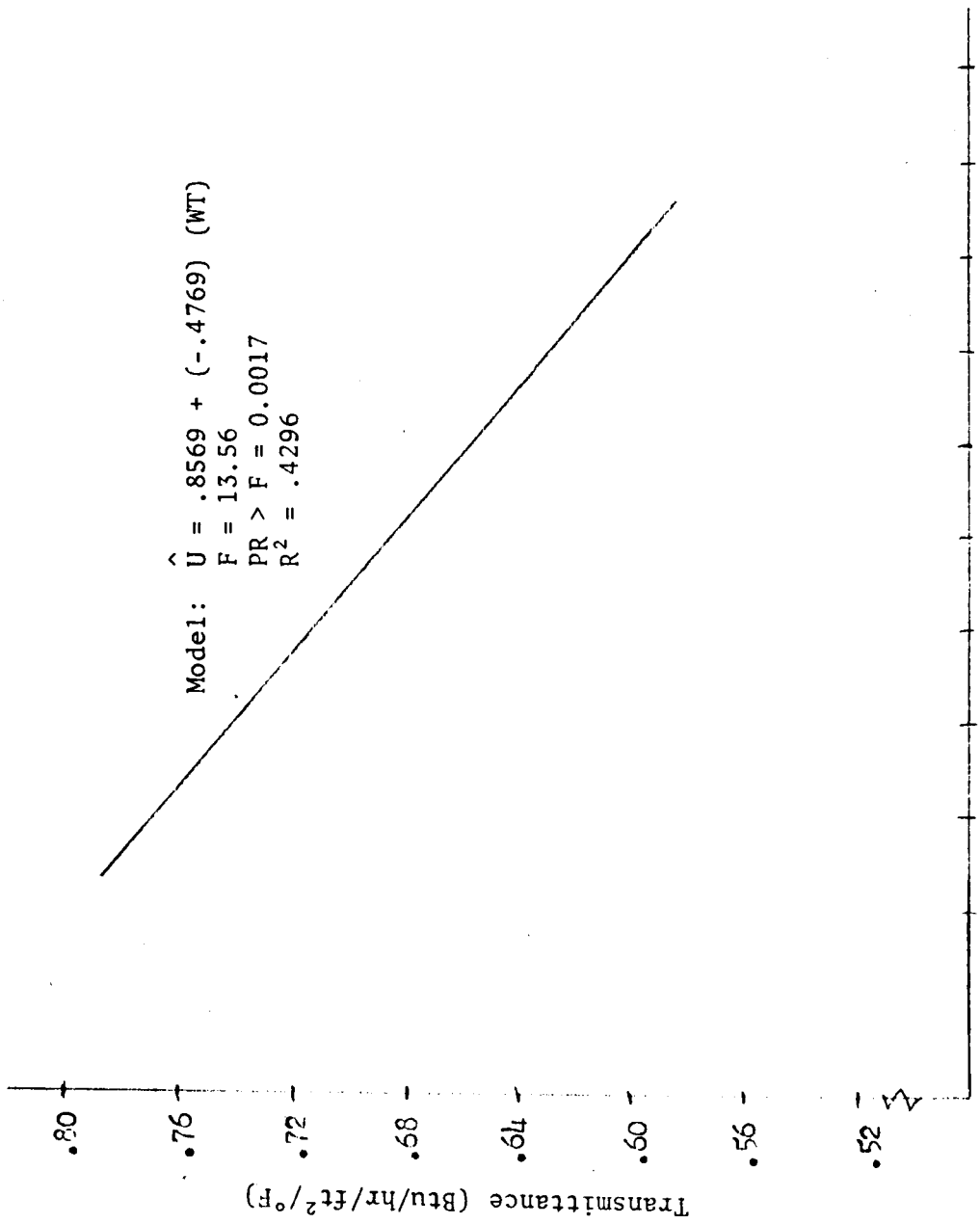


Figure 52. Fabric weight versus transmittance.

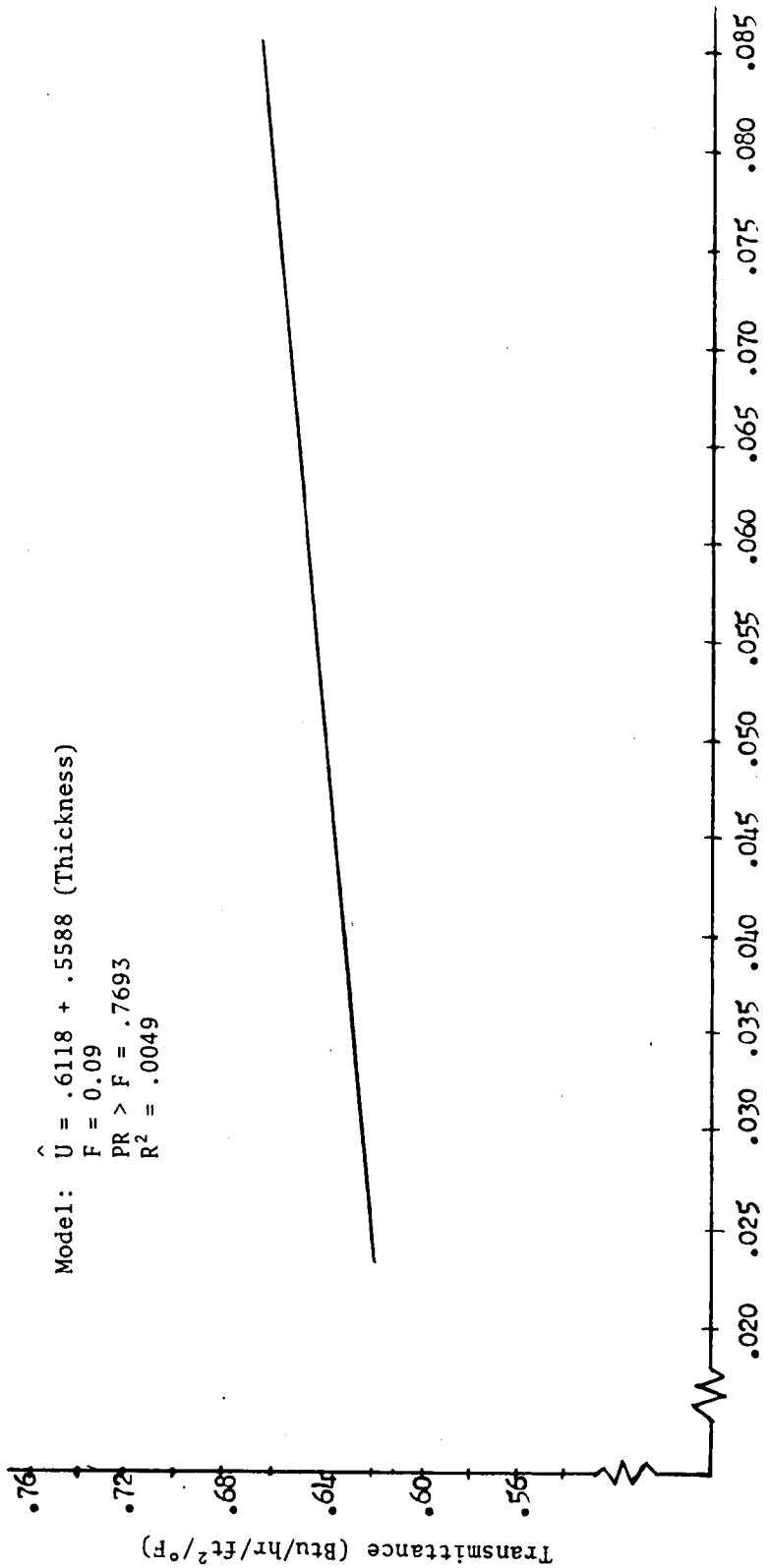


Figure 53. Fabric thickness versus transmittance.

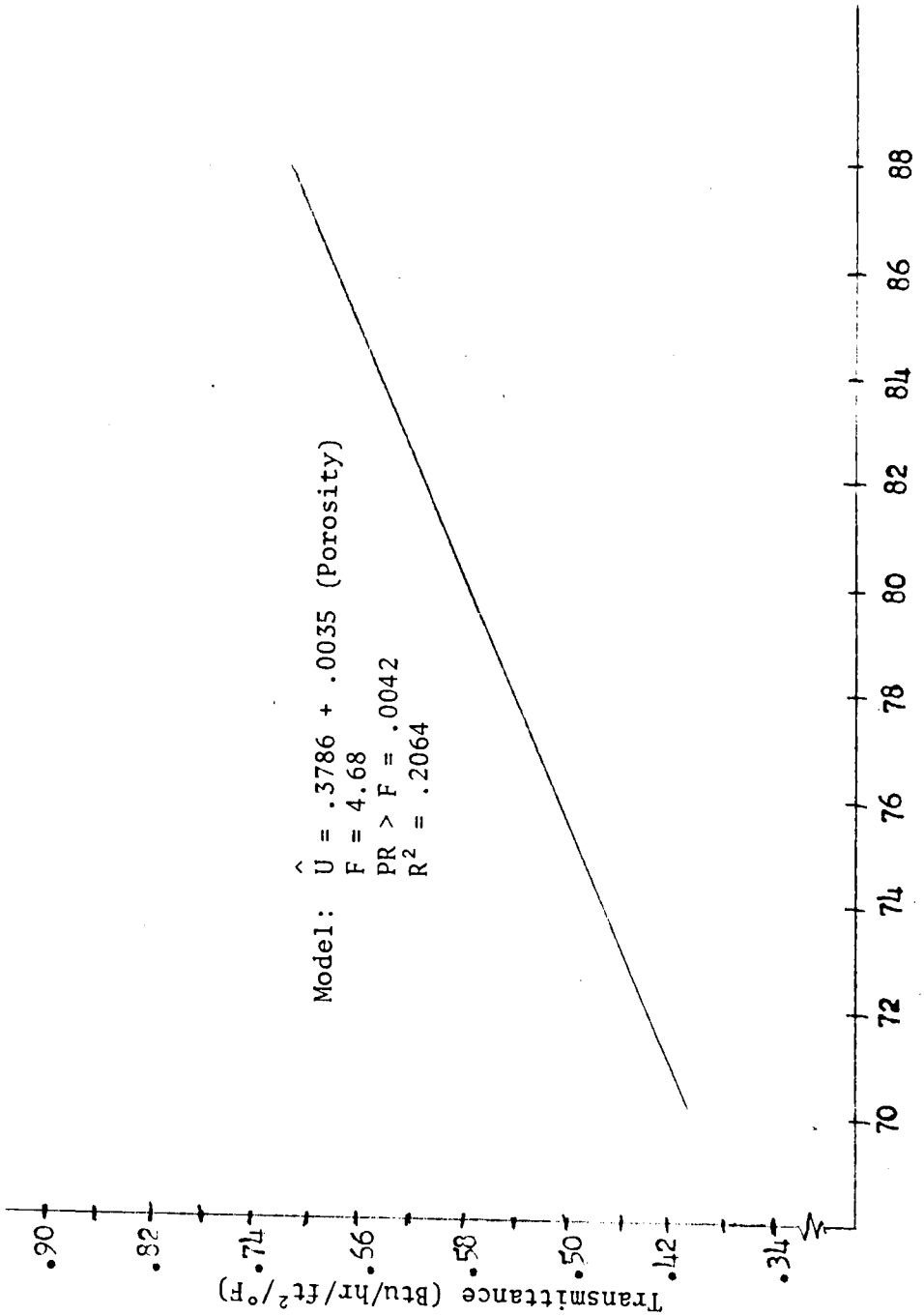


Figure 54. Fabric porosity versus transmittance.

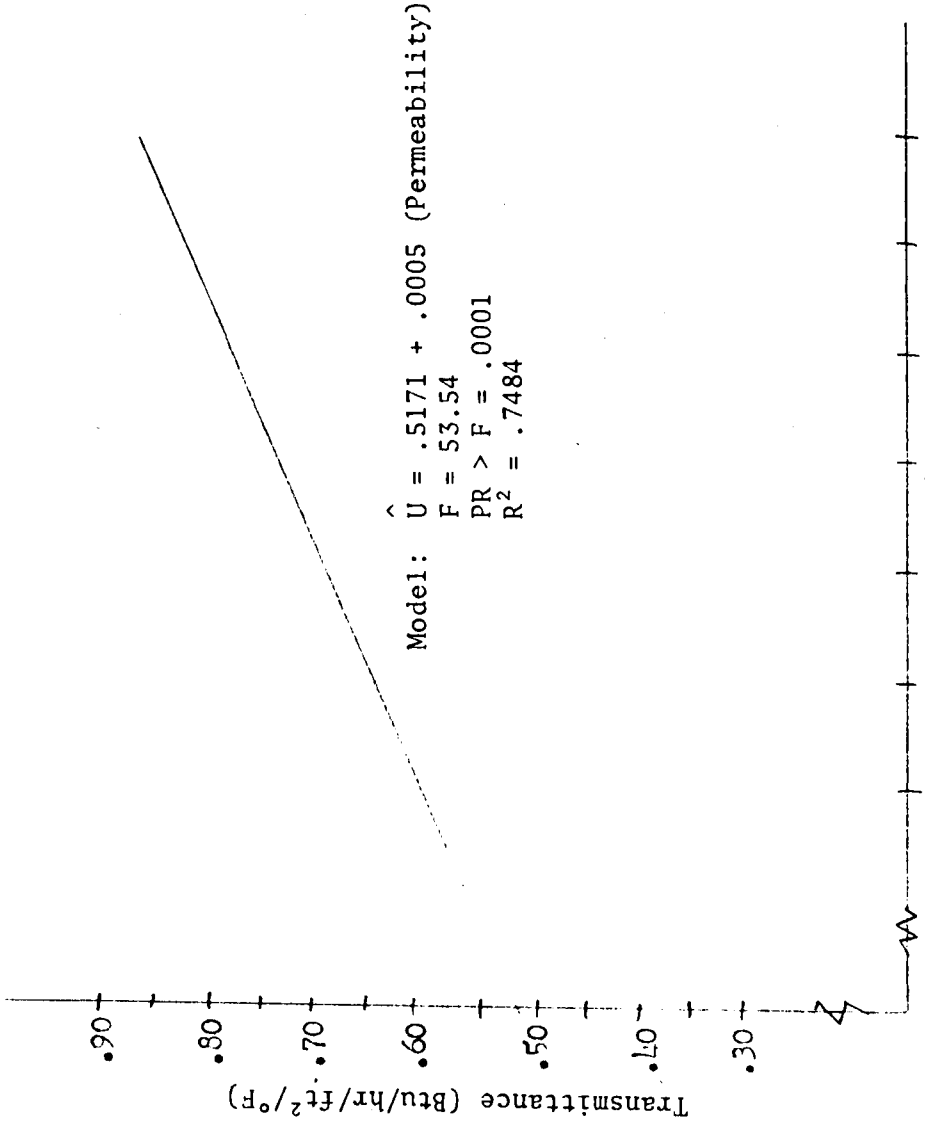


Figure 55. Fabric air permeability versus transmittance.

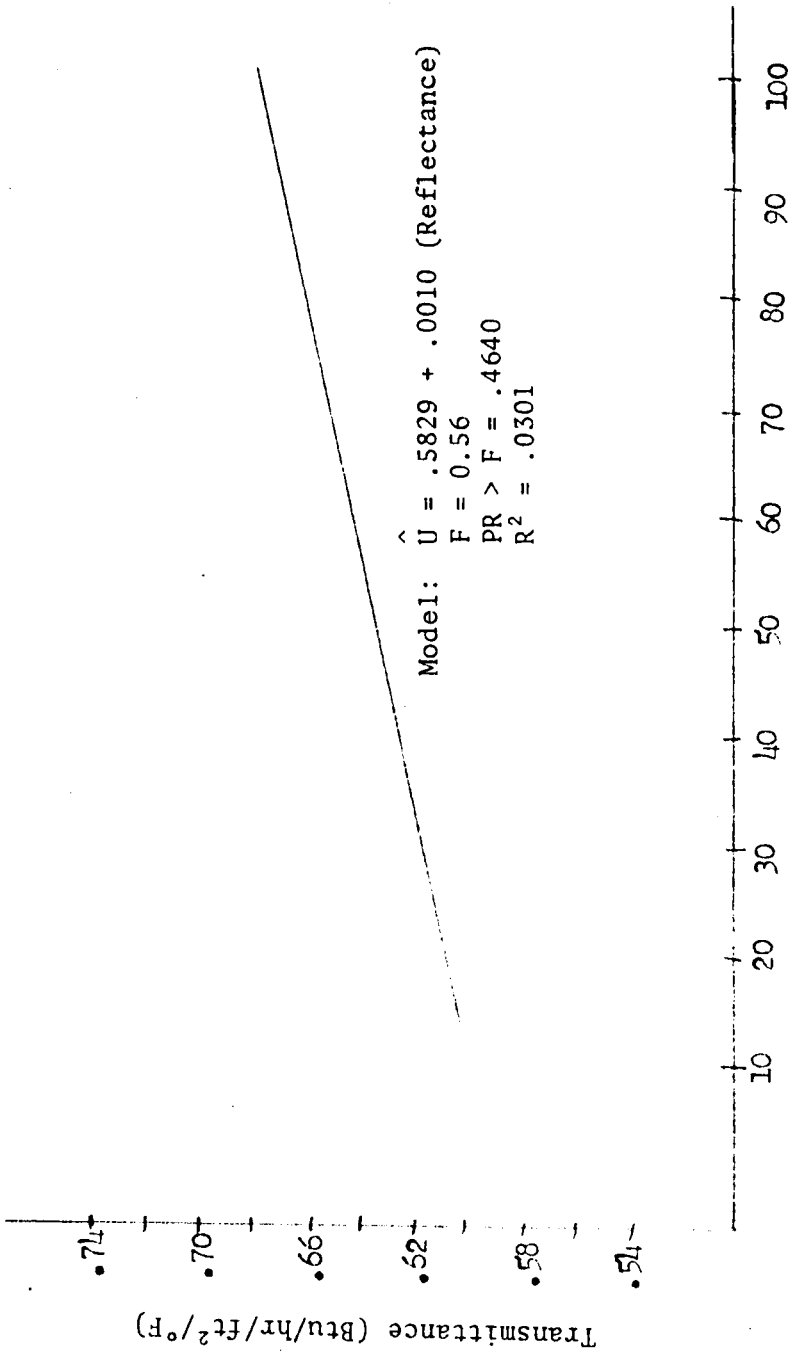


Figure 56. Fabric reflectance versus transmittance.

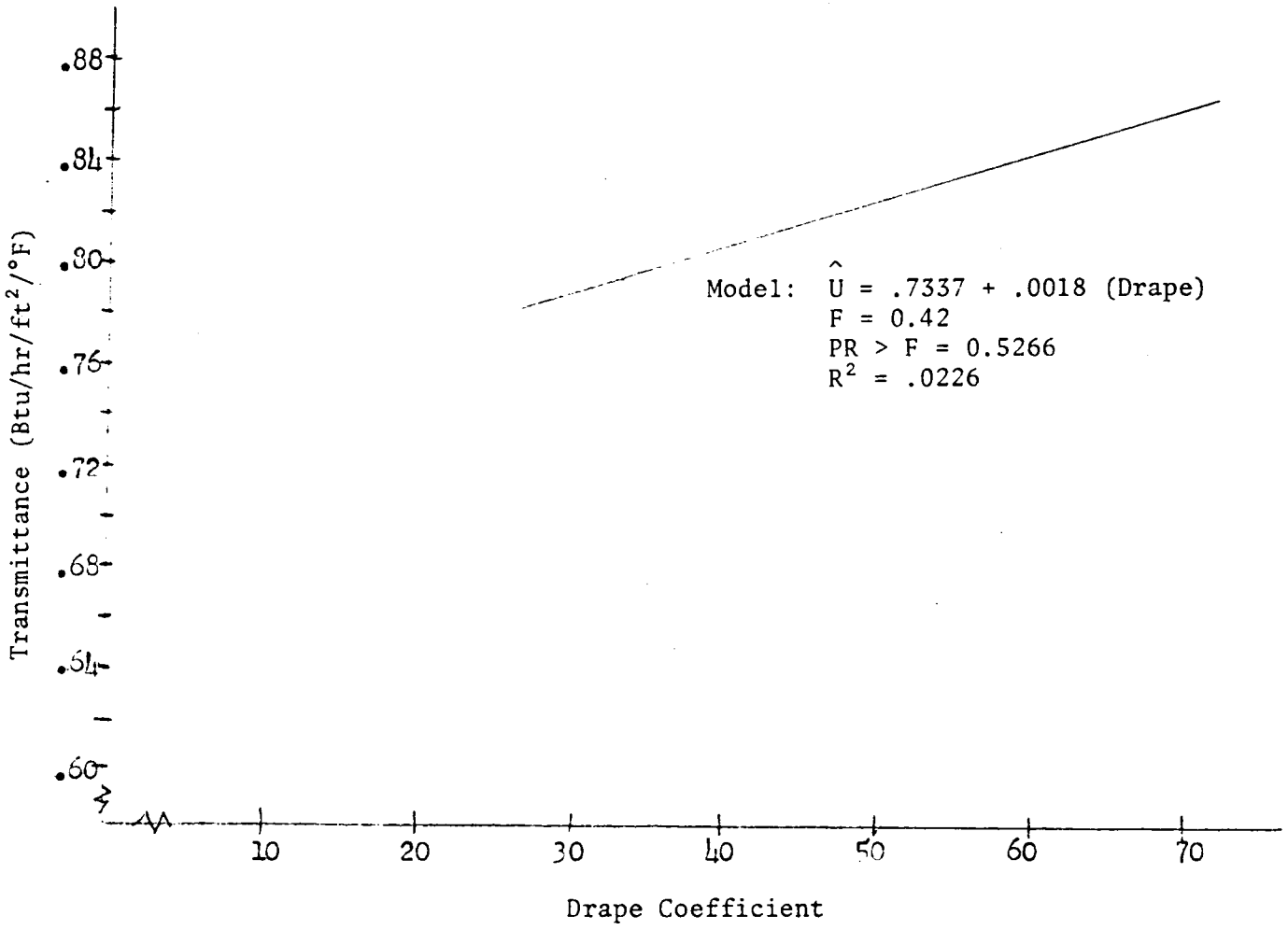


Figure 57. Fabric drapeability versus transmittance.

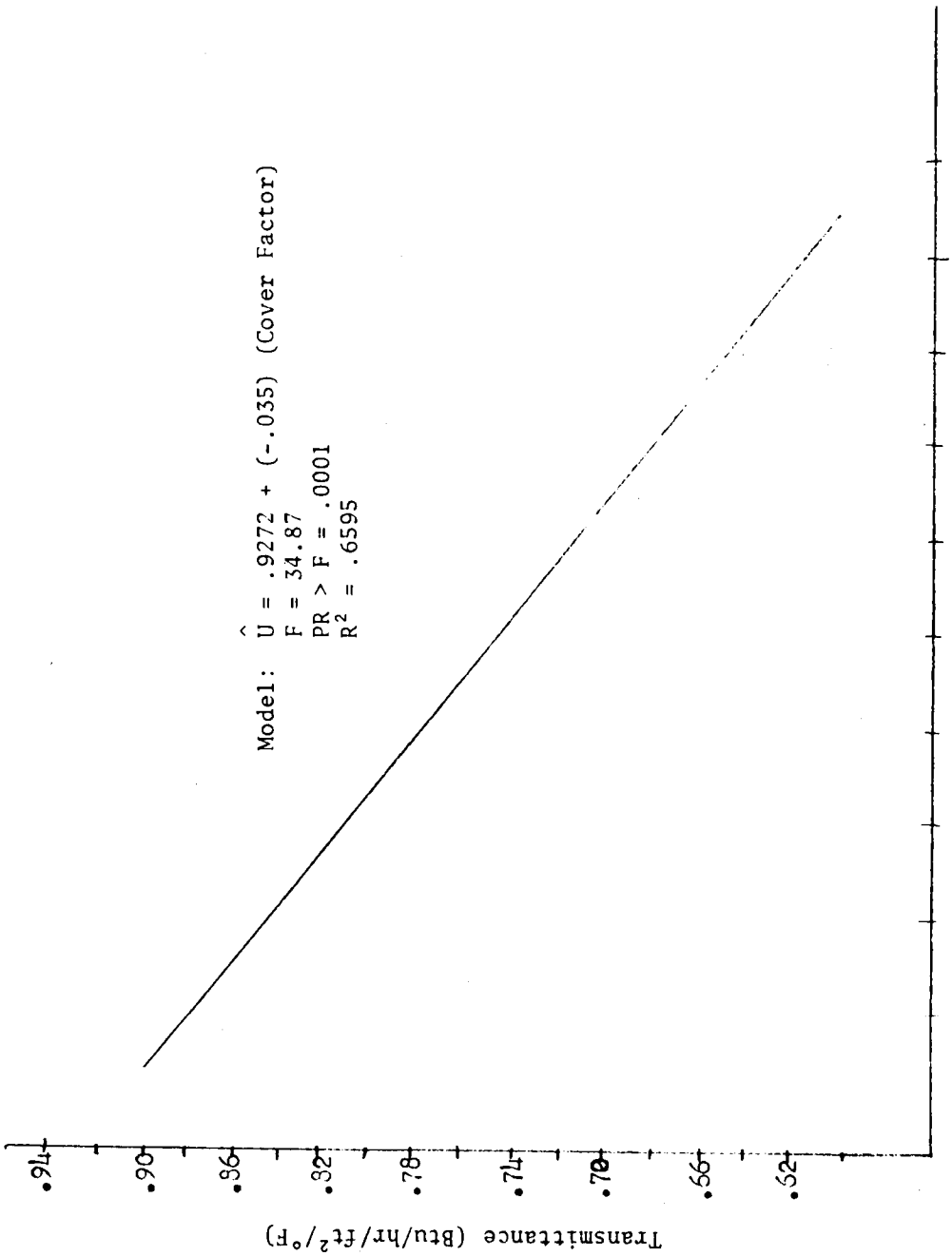


Figure 58. Fabric cover versus transmittance.

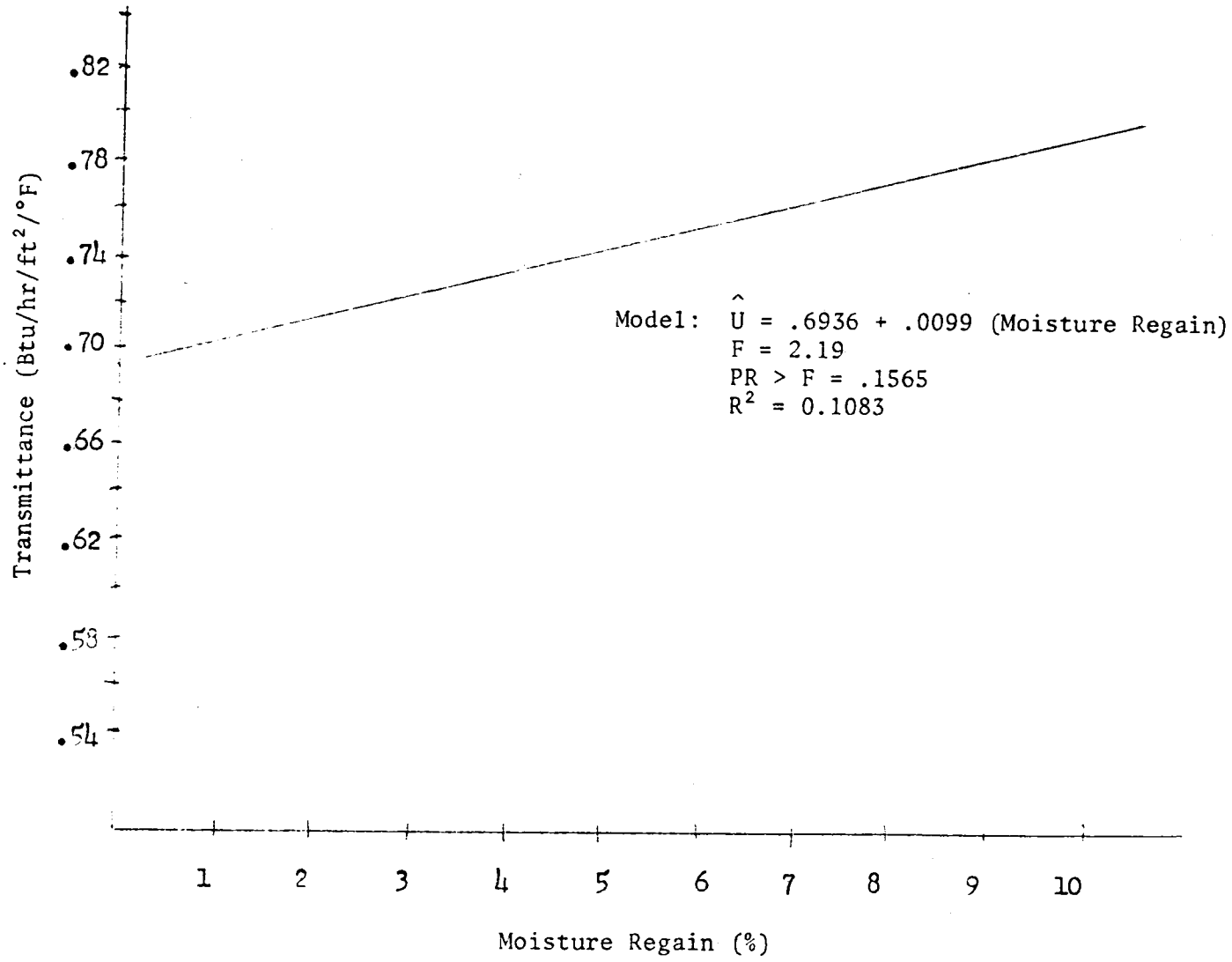


Figure 59. Fabric moisture regain versus transmittance.

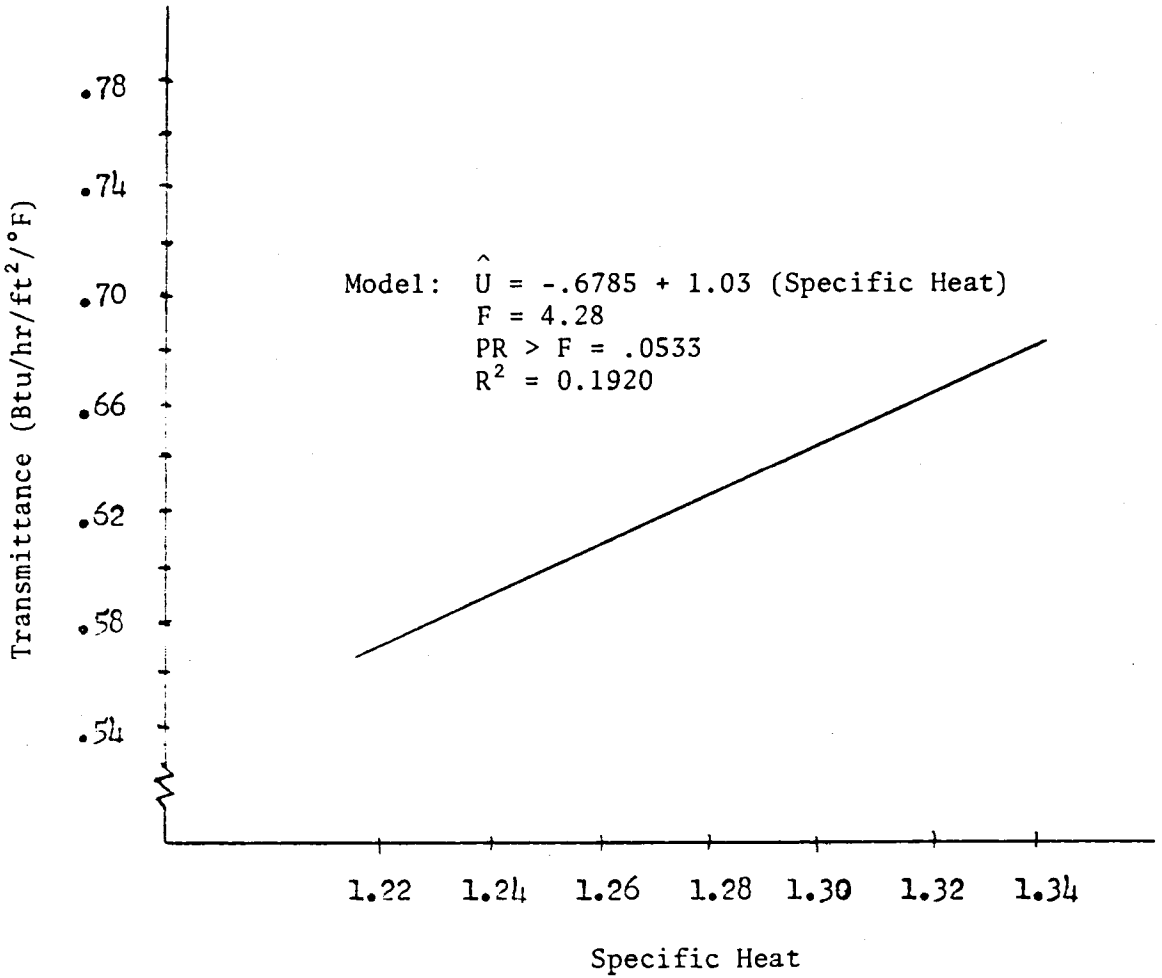


Figure 60. Fabric specific heat versus transmittance.

COMPUTER PROGRAM FOR HEAT TRANSFER OF SIMULATED DRAPERIES

```
0: prt "SIM-SOL
 DRAPES r3,r5,
 r6,";spc 'moct
1: gsb "Graph"
2: dim A$[16]
3: ent "TYPE IN
  sample info",
 A$;spc 1
4: prt A$
5: fxd 0;180000→
 I
6: jmp 2
7: fxd 0;dim
 A$[16];enp "SAM
 PLING RATE in
 msec",I;wait
 3000
8: "time":
9: dim T$[14]
10: wrt 5, "R"
11: red 5,T$
12: prt T$
13: "decitime":v
 al(T$[7,8])+
 val(T$[10,11])/
 60+val(T$[13,
 14])/3600→X
14: if A$="";
 jmp 2
15: pen# 1;csiz
 1.5,2,1,90;plt
 X-.1,.2;lbl A$,
 " @",T$
16: oni 5,"flux"
17: eir 5
18: wrt 5,"U1H/
 U1=01"
19: wrt 5,"U1P",
 I
20: wrt 5,"U1G"
21: gto 22;lke
22: gto 21;lke
23: dsp "Waiting
  for sensor
 equillibrium";
 wait 140
24: dsp "
          ";wait
  10;dsp "";wait
  100
25: dsp "  RA!
 RA! RA!, T $
 C";wait 25;dsp
 ""
26: "flux":
27: wrt 722, "FIR
 7A0H0M3T1"
28: "LLR":
29: wtb 11,17000
 0,10000
30: prt "deciTim
 e",X
31: prt "LLR
 mVolts"
32: fxd 0
33: moct;for
 B=2 to 6
34: moct;wtb 11,
 170040, 110000,
 110000+dto(2↑B)
35: gsb "DMM"
36: fxd 6;prt
 1000S→r(B+1)
37: next B
38: gto 66
39: 1.517-r1*
 1000→r1;25.6613
 r1-.61955r1↑2+
 .02218r1↑3-.000
 355r1↑4→r1
40: 1.8(37-r1)→r
 1;prt "dt",r1
41: 392*,9727r2/
 r1→Y;prt "BTU/
 l=",Y
42: if Y>1.04;
 plt X,.5Y;pen;
 wtb 11,110000;
 gto 68
43: if H#0;plt
 E,H
44: plt X,Y→H;
 pen
45: 1.517-r7*
 1000→r7;25.6613
 r7-.61955r7↑2+
 .02218r7↑3-.000
 355r7↑4→r7
46: wtb 11,11000
 0
47: gto 68
48: moct;wtb 9,
 170040,10000,
 10020
49: gsb "DMM"
50: S→T
51: wrt 722, "T2"
 ;fxd 3
52: moct;for
 J=1 to 6
53: 0→S;for M=1
 to 20
54: wtb 9,170160
 ,40000+J
55: wtb 9,170260
56: wti 0,11;
 wti 4,40000;
 rdi 4→V
57: ((otdV→V)-
 (V>2047)4096)1e
 -2→V;dsp V;S+
 V→S
58: next M
59: .059→rJ
60: next J
61: spc
62: wtb 9,170160
 ,40000
63: gsb 110
65: eir 5
65: iret
66: "Room T &
 RH":
67: wtb 11,11000
 0
68: moct;for
 K=6 to 7
```

```
69: moct;wtb 11,
 12000,12000+
 dto(2↑K)
70: gsb "DMM"
71: if K-6;20S→Z
 ;plt X,.01Z;pen
72: if K-7;20S→S
 ;'RH/51'→S
73: if K-7;plt
 X,.01S;pen
74: next K
75: wtb 11,10000
76: gto 110
77: for L=6 to 7
78: moct;wtb 11,
 16000,16000+
 dto(2↑L)
79: gsb "DMM"
80: gto 103
81: "LLA/D":wait
  5000
82: fxd 4;0→S;
 for M-1 to 20;
 red 722,A;dsp
 1000A;S+A→S
83: if A>.00003;
 if abs((S/M-A)/
 (S/M))>.05;prt
 "noise";jmp -1
84: next M
85: fxd 3;ret
 .05S→S
86: gto 97
87: if L=1;R-
 45000S→U;prt
 "Th/1=",U;abs(U
 -T)→V;U→T;cll
 'HFmf';F→J
88: if L=1;plt
 X,.01V;pen;time
  1000
89: if L=2;381FS
 /V→Y;prt "BTU/
 0=",Y;pen# 1;
 plt X,10S;pen;
 time 1000
90: if L=2;if
 G#0;plt E,G;
 time 9000
91: if L-2;plt
 X,Y→G,-1;time
 1000
92: 392Jr2/45000
 r1→Y;prt "BTU/
 1=",Y;plt X,
 10S;pen
93: if H#0;plt
 E,H
94: if L-3;plt
 X,Y→H;pen;time
 1000
95: if L-3;if
 I#0;plt E,I;
 time 9000
96: if L-3;prt
 "aveBtu",.5(G+
 H)→I;plt X,I;
 pen;time 5000
97: if K-6;prt
 "t/o,F=",20S→Z
98: if K-6;plt
 X,.01Z;pen
99: if K-7;'RH/
 0/52'→S
100: if K=7;plt
 X,.01S;pen
101: next K
102: gto 77
103: if L=6;prt
 "t/1,F=",20S→S;
 prt "dT=",abs(S
 -Z)
104: if L=7;prt
 "RH/50",'RH/0/
 52'→S
105: next L
106: wtb 11,1000
 0
107: gto 129
108: eir 5
109: iret
110: "DRAPE plot
 ":
111: pen# 2
112: prt "D-time
 ",X
113: -r7→r7
114: .789-r7→r7;
 25.6613r7-.6195
 5r7↑2+.02218r7↑
 3-.000355r7↑4→r
 7
115: 1.8(19.87-
 r7)→r7
116: prt "delta
 T =",r7→U
117: plt X,-.01U
 ;pen
118: prt "Trm,
 F=",Z
119: 1→F
120: if W#0;plt
 E,W
121: plt X,Z→W;
 pen
122: 8.28r3F/U→Z
123: 7.91r5F/
 U→S;Z+S→Z
124: 10.05r6F/
 U→S;(S+Z)/3→Z
125: prt "ave
 BTUw=",Z
126: if Y#0;plt
 E,Y
126: if Z>3.2;
 plt X,.5Z→Y;
 pen;wtb 11,1100
 00;jmp 2
128: plt X,Z→Y,-
 1;plt 20,0,1;
 wtb 11,110000
129: spc
130: wrt 722,
 "T2"
131: X→E
132: I/3600000+
 X→X
133: eir 5
134: iret
135: "DMM":
136: wait 7500
137: fxd 4;0→S;
 for M=1 to 20;
 red 722,A;dsp
 1000A;S+A→S
```

```
138: if A>.00003
 ;if abs((S/M-
 A)/(S/M))>.05;
 prt "noise";
 jmp -1
139: next M
140: fxd 3;ret
 .05S→S
141: "HFmf":ret
 1.108386*.99869
 48↑T→F
142: "RH/0/52":g
 to 143;if S>4;
 gto 144;if S>23
 ;gto 145;if
 S>62;gto 146;
 if S>96
143: .01→S;ret S
144: ret 36.3602
 67*1.0109256↑S→
 S
145: ret 9.81754
 1*S↑.5018653→S
146: ret 8.90578
 37*S↑.5278797→S
147: "RH/51":gto
 149;if S>22;
 gto 150;if S>38
 ;gto 151; if
 S>55;gto 152
148: gto 152;if
 S>87;gto 153
149: ret 21.8989
 *1.01577476↑S→S
150: ret 18.8245
 4*1.02422015↑S→
 S
151: ret 4.99401
 3*S↑.61742276→S
152: ret 35.7885
 234*1.009184↑S
153: ret 28.1504
 777*1.012057↑S→
 S
154: "Graph":pcl
 r;lbl "";wrt
 705,"ip1666,
 1306,15894,1044
 4";pen# 1
155: scl 1,25,-
 1.5,3
156: fxd 0;lbl
 "";xax 0,.2,1,
 25,5
157: fxd 1;yax
 1,.1,-2,3,5;
 plt 7,-.5;lbl
 "DeciTIME, h."
158: pclr;lbl
 "";csiz 2,1.5,
 8/10,90
159; plt -1,.45;
 lbl "TRANS.,
 BTU/h ft↑2 F,"
160: ret
*22331
```

VITA

Helen Heins Epps was born on July 20, 1949 in Kingstree, South Carolina. She lived in rural Williamsburg County, South Carolina, attended Hebron Elementary School, and graduated from Kingstree High School in 1967.

In 1970 she received a Bachelor of Science degree in Home Economics Education from Winthrop College in Rock Hill, South Carolina. In August 1970 she accepted a position with Lexington County School District Five, as Home Arts teacher at Irmo Middle School in Irmo, South Carolina. In 1972 she received a Master of Science degree in Clothing and Textiles from Winthrop College. While at Winthrop she was a graduate assistant.

In 1972 Ms. Epps accepted a position with Clemson University Cooperative Extension Service as Associate County Extension Home Economist in Georgetown County, South Carolina, and in 1975 she was promoted to Associate County Extension Leader in Chesterfield County, South Carolina.

In 1978 she enrolled in the Interdisciplinary doctoral program in Home Economics at The University of Tennessee, Knoxville. While at UT, she 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 and Clothing Laboratory, Knoxville. She also received a Grant-in-Aid from the American Society of Heating, Refrigerating and Air Conditioning Engineers.

In September 1981, Ms. Epps began employment as Assistant Professor on the faculty of the University of Georgia, Athens, in the College of

Home Economics, Department of Clothing, Textiles, Interiors and Furnishings. She is a member of the American Home Economics Association, International Federation of Home Economics, Association of College Professors of Textiles and Clothing, the American Association of Textile Chemists and Colorists, Phi Kappa Phi, Phi Upsilon Omicron, and Omicron Nu.