THERMAL RESISTANCE OF FABRIC-BATT ASSEMBLIES

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ABSTRACT

Thermal resistance is an important property of a textile assembly formed for use as a cold-weather outergarment. It is useful, therefore, to measure the thermal resistance of textile materials which can be used successfully to form such an assembly. The present research was so designed to study thermal resistance of single-, double-, and triple-layers of cotton-, wool-, polyester-, and multifiber-batts. A guarded hot-plate apparatus was used following a modification of ASTM Method D:1518. Thermal conductivity measurements were made on batt layers alone and on batt layers sandwiched between nylon- and cotton-Testfabric, under 7 g/cm^2, 14 g/cm^2, and 21 g/cm^2 pressure levels of compression. Data were statistically analyzed as two - 3 X 4 X 3 analyses of variance. One analysis was made on batt layers alone and the second on the fabrics and batts in combination. Significant main effects were obtained on both analyses for the three factors - multiple layers of batts, fiber type of batts, and pressure levels of compression. The two-way interactions between these factors were also found significant indicating a need to consider factors as they interrelate to obtain optimum thermal resistance. A t-test showed no significant difference between mean thermal resistance values for batt layers and fabrics and batt layers in combination. The results were correlated with and explained in view of previous research findings. Correlation coefficients and multiple regression equation constants were calculated and discussed to reinforce both statistical and non-statistical inferences given.

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INTRODUCTION

Cold-weather outerwear is concerned basically with minimizing thermal stresses imposed on man by the environment. Insulating ability is therefore of prime consideration for assemblies of textile materials to be used in cold-climate outerwear. Since parts of Canada are subjected to these cold extremes in temperature it is useful to measure the thermal resistance of single- and multiple-layers of textile materials that can be used to form such an assembly in order to find the best possible combination of textiles useful as an insulator in cold weather.

Traditionally, protection against the cold environment has been provided by garments made from fabrics of great thickness and heavy weight giving rise to considerable discomfort to the wearer. The modern trend is to use lightweight fabrics to provide adequate warmth.

The goal of achieving warmth without weight has been difficult in the past. However, today, fibrous batts, made from loose fiber stock, tend to serve the dual requirements of providing warmth and low weight. Batts are used successfully as insulation fillers because they are low in density and therefore provide low thermal conductivity. However, the stress-strain properties of batts are such that they cannot be used alone for many textile applications in which mechanical properties are important. Hence the need for sandwiching batts between fabrics.

The problems of improving thermal resistance in outerwear have been investigated. Belding (5), Fourt and Hollies (13), Monego et al (20), and Morris (22) considered the thermal resistance of fabrics, foams and laminates, and fabric assemblies. Baxter and Cassie (4), Bogaty et al (6), Frederick (11), and Weiner and Shah (30) studied the thermal resistance of single layers of fibrous batts. However, studies which specifically examined thermal resistance of multiple layers of fibrous batts or of assemblies containing both fabric- and batt-layers were not found in the published literature. Since a cold-climate garment, today, contains a combination of fabric- and batt-layers it may be relevant and indeed worthwhile to investigate thermal conductivity of assemblies that resemble such a garment. In addition, it may be worthwhile to examine whether theories documented for fabrics, foams and laminates, and single batt layers apply similarly in the study of fabric-batt assemblies.

Purpose of Study

The purpose of this study was to gain an insight into the influence of the physical properties such as thickness, pressure, and fiber type on thermal resistance of selected fabric-batt assemblies, and to determine which of these properties are most significant in terms of thermal insulation of an outerwear garment.

The specific objectives of this research were:

1. To determine the effect of three layer-combinations of batts on thermal resistance for selected fabric-batt assemblies.

2. To determine the effect of four different fiber types of batts on thermal resistance for selected fabric-batt assemblies.

3. To determine the effect of three different pressure levels of compression on thermal resistance for selected fabric-batt assemblies.

4. To determine the interaction effect of these factors - multiple layers, fiber type, and pressure level, on thermal resistance for selected fabric-batt assemblies.

5. To gain an understanding, based on the results of the study, to recommend an effective fabric-batt assembly for cold weather.

Limitations

The best design for this study was to obtain batts with similar characteristics - weight, density, packing factor, porosity; for each of the fiber types used in the batt construction. Due to the inherent differences in fiber properties, however, it was not possible to obtain batts with these specifications. Manufacturer practices involve keeping one property of the fibrous batt a constant, e.g. weight or density. The other properties will vary according to the fiber type contained in the batt. Generally speaking, the cotton-, wool-, and polyester-batts had similar characteristics while the multifiber batt differed.

Definition of Terms Used

For the purpose of this study terms relating to the fabric-batt assemblies and thermal- and air-holding properties of the textile materials were defined.

> The first two terms describe the make-up of the cold-climate garment, and the next five terms describe the heat transmitting properties, while the last term describes an air-containing property of a textile material.

Batt Layer-Combination. An assembly formed from either one-, two-, or three-layers of batts made from any one fiber type.

Outerwear. An assembly composed of either single- or multiple-layers of batts sandwiched between a nylon outer-fabric and a cotton lining-fabric.

Conduction. The power to transport heat from molecule to molecule by collision wherein the molecules exchange their kinetic energy- the flow of heat through a medium without actual physical transfer of material (15).

Thermal Conductivity. The rate of heat flow across a unit area of a material, through a unit thickness, under unit temperature gradient - heat transfer through materials by conduction (2).

Thermal Insulation. That property by virtue of which a material can resist heat flow (2).

Thermal Resistance. The ratio of temperature difference across a thermal path to the rate of heat flow along that path, under steady-state conditions of heat flow (2).

Optimum Thermal Resistance. The maximum thermal resistance value obtainable with the use of an insulating material.

Porosity. The ratio of the volume of air or void contained within the boundaries of a material to the total volume, expressed as a percentage (17).

Chapter 2

REVIEW OF LITERATURE

Previous researchers have identified a number of factors which effect thermal resistance of a given textile assembly. Among these factors are the still air held within the assembly, the thickness of the fabrics contained within the assembly, pressure exerted on the assembly, and, the influence of the constituent fibers of the assembly. The effect of each of these factors on thermal resistance of a given textile assembly is reviewed in this chapter.

Effect of Air on the Thermal Conductivity of a Textile Assembly

Air held by the constituent fibers and the air layers formed between the fabric layers will effect the thermal conductivity of a textile assembly.

Air Held by Fibers of a Textile Material

Thermal resistance of clothing fabrics can be attributed to the amount of immobilized air contained within the fabric structure. Fourt and Hollies (13) and Rees (25) explained that fabrics are a mixture of air and fibers in which the fiber dominates by weight and visibility, but the air dominates by volume. At least two-thirds of the volume of all clothing fabric is air.

Fibers in a fabric entrap air because fibers have enormous total surface and air clings to a solid surface (17). A fabric composed of many thousands of fibers will therefore act to slow down air movement and heat transfer by convection. The amount of entrapped air will depend on how closely packed the fibers are in the fabric. Carded-cotton fibers, and wool fibers, because of their natural crimp, provide an open-structured yarn while silk and continuous filament man-made fibers automatically produce tightly packed yarn. In the latter, only the yarn surface is available for imposing drag on air movement. Kaswell (17) reported the most densely packed wool fabric contains 60% air and 40% wool, while the most densely packed cotton fabric contains 20% air and 80% cotton.

Thermal conductivity of fibers in comparison to immobilized air has been investigated (5,8,9,15,25,28). Rees (25) pointed out thermal conductivity of clothing fabrics is one and one-half-to two-times greater than still air. Thermal conductivity of all textile fibers was found ten-to twenty-times greater than still air. Crow (9) reported thermal conductivity of a fibrous pad with density equal to 0.5 g/cm^3 was six times greater than still air.

The recognition of the role of still air in providing the best thermal insulation in clothing fabric was important to the study and development of thermal resistance in clothing. The thermal resistance of a textile material was found to improve by simultaneously increasing its thickness and decreasing its bulk density in order to increase the volume of air that can be contained in the material (6,8,9,21,25).

Pierce and Rees (24) established thermal resistance of a low-density fibrous mass used as an insulation filler in outerwear to be similar to that for still air. They found that either a decrease or an increase in density of such a fibrous mass causes a decrease in thermal resistance. This decrease in thermal resistance was found to be by different mechanisms. By reducing the density of the mass increased convection within and radiation through the mass of fibers decreased its thermal resistance. With an increase in density thermal resistance of the fibrous mass was again reduced due to increased transfer of heat by conduction through the fibers.

Air Layers Formed Between Fabric Layers of a Textile Assembly

Studies have shown that the accuracy of thermal resistance measurements for textile assemblies is affected by the amount of immobilized air contained between the fabric layers. Siple (28) reported optimum thermal resistance of an assembly was reached when the air layers were 0.67 mm thick. Burton and Edholm (8) gave the value to be 12.7 mm. Beyond this point, Burton and Edholm found there was no more gain in thermal resistance for the assembly. This was credited to the development of convective currents which move more freely as the air space between the fabric layers becomes wider.

Morris (22) found a great amount of air was held within a textile assembly in which poor contact was made between fabrics due to rough or irregular surfaces. The reverse was found for assemblies made of fabrics with smooth surfaces. Morris concluded accurate estimates of thermal resistance of textile assemblies could be obtained by adding the values for the individual layers only if they have smooth surfaces. Accuracy of thermal resistance values for assemblies of fabrics possessing rough or irregular surfaces would depend on measuring the thermal resistance of the textile assembly as a whole. These results may suggest perhaps the volume of air per unit area provides a better basis for estimating thermal resistance for a multiple of fabric layers.

Thickness of Textile Materials

Fanger (10) pointed out thermal resistance of a given textile assembly intended for clothing purposes is dependent upon thickness and porosity of the individual fabric layers forming the assembly. Since variation in porosity is found only moderate in textile materials intended for clothing purposes, thickness was established as the more important property. Aelion and Brown (1), Frederick (11), Horn (15), Morris, G.J. (21), Morris, M.A. (22), and Weiner and Shah (30) are in agreement with Fanger. Fourt and Hollies (13) believe, however, weight of the textile material at a given thickness, retention of thickness under pressure, and recovery of thickness on release of applied pressure, in ways needed for clothing, are properties which are perhaps more important to the understanding of thermal insulation of textile materials than is the thickness - thermal resistance property alone.

Many investigators have observed that there is a linear relationship between thermal resistance and thickness of textile materials, whether the variation in thickness is obtained by testing a range of fabrics with varying thicknesses (1,13,21,25,29), by adding successive layers of fabric (13,22,28), or by altering the thickness of the textile material by changing the pressure per unit area (6,10,12,17,18,30).

Speakman and Chamberlain (29) reported an increase in thermal resistance with an increase in thickness of textile fabrics they tested to thicknesses of 1.4 mm. Baxter and Cassie (4) gave the value to be 9.9 mm. Beyond this thickness measurement Baxter and Cassie found the slope of the thickness - thermal resistance curve fell off to become horizontally asymptotic (Figure 1).

Aelion and Brown (1) found good correlation between thickness and thermal resistance. These researchers found the relationship between heat loss and thickness of textile fabrics tested could be expressed by a hyperbolic-shaped curve as shown in Figure 2.

These studies might suggest that a linear relationship may exist between thickness and thermal resistance measurements for textile fabric layers and textile assemblies, however, this relationship cannot be assumed beyond limits of thickness measurements recorded for textile systems tested.

Pressure Applied to Textile Materials

A textile fabric has no clearly defined surface, and consequently, measurements of thickness must be taken under a definite pressure, ideally the pressure to which the fabric would be subjected to in use. Researchers (6,11,12,17,30) have accepted the fact that thickness of a textile material is a function of applied pressure and have suggested that pressure level be specified whenever discussing thickness. This interdependence between thickness and pressure level was found true not only at relatively high pressure levels required to compress the textile material to a thickness of 2.5 mm but also at lower pressure levels, as found by Rowlands (27).

Larose (18) considered what takes place when a fabric is being compressed. When fibers in a textile fabric are subjected to pressure they must taken on new positions and in doing so slip past other fibers

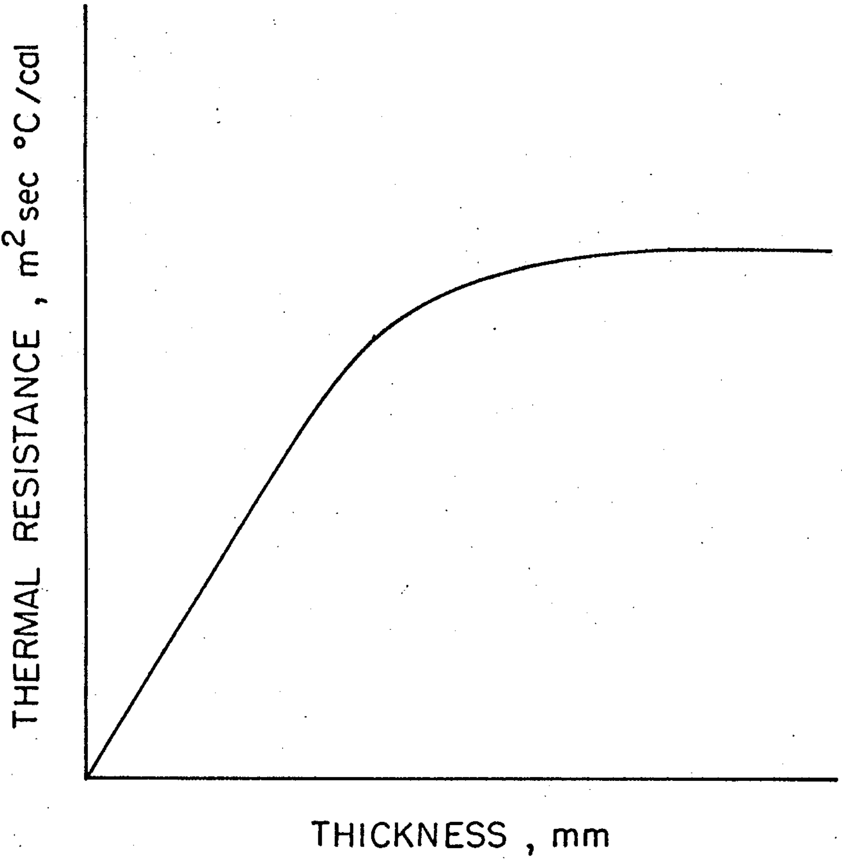

Figure 1. Relationship Between Thickness and Thermal Resistance Falls Off to Become Horizontally Asymptotic.

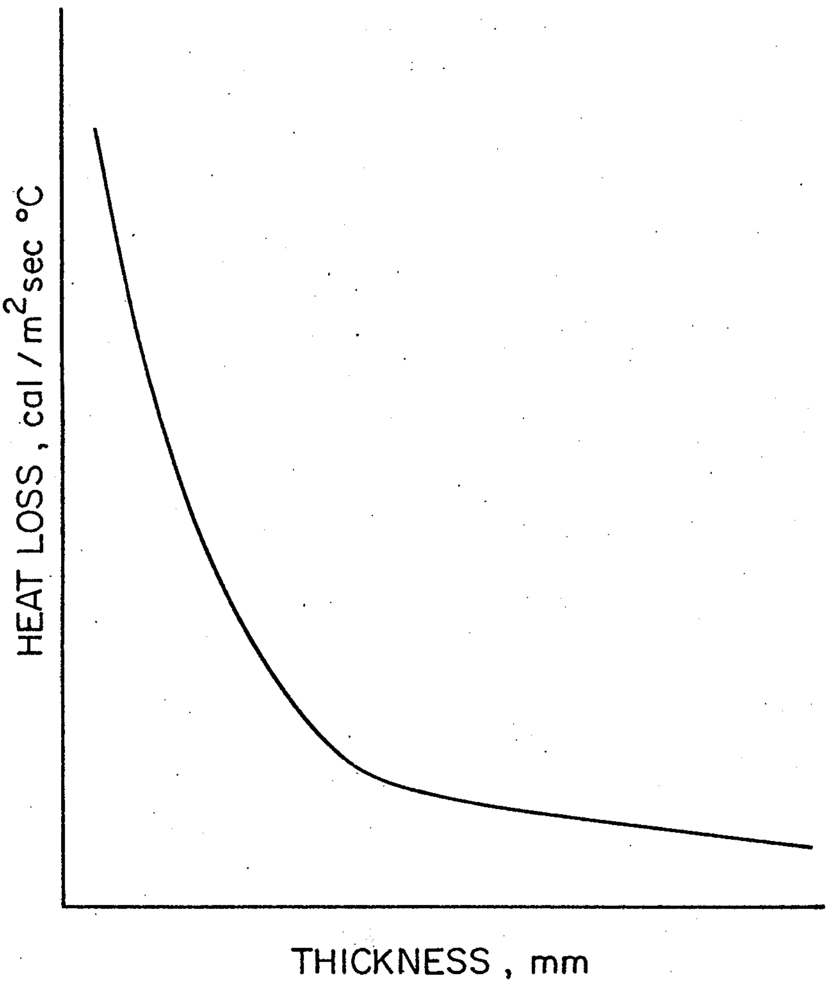

Figure 2. Relationship Between Thickness and Heat Loss Expressed as a Hyperbolic-Shaped Curve.

at certain points of contact. This gives rise to frictional effects. The number of such contacts and effort required to overcome the frictional force will increase as the fabric becomes denser.

For fuzzy fabrics of wool-like character the decrease in thermal resistance with pressure is counterbalanced by a change in the arrangement of the fibers in the fabric (6). The overall thermal resistance will remain essentially unaltered, therefore, even at high pressure levels. Decreases in thermal resistance with pressure is appreciable for smooth fabrics of combed cotton-or synthetic-fibers, however, since fiber arrangement in the fabric undergoes only minor changes.

Researchers have examined the effects of applied pressure on thermal resistance of textile fabric- and batt-constructions. Frederick (11), Fourt and Harris (12), and Weiner and Shah (30) found imposed pressure reduced the thickness of these textile constructions, which in turn, reduced their thermal resistance. Severe wear and excessive constant compression applied can also frequently lead to appreciable temporary or permanent reduction in thickness.

The ability to withstand compression, therefore, is a major criterion for the selection of fabrics and fibrous batts for use in an effective cold-weather outergarment. A number of researchers (6,11,14, 20,21,24,30) recognized since batts are more compressible than conventional textile structures, and since thermal resistance of fibrous batts is more or less proportional to thickness, batt thermal resistance could be reduced under certain use-conditions. Also, these researchers recognized that batts made from one fiber type could provide better thermal resistance than batts made from another fiber type due to inherent differences in stress-strain characteristics for different fibers.

Constituent Fibers of Textile Materials

Several researchers (6,9,10,11,17,24,25,30,31) have demonstrated the thermal conductivities of different types of fibers are basically the same. They concluded, therefore, that fabric- and batt-thermal resistance is largely independent of the chemical nature of the constituent fiber. Fiber arrangement and fiber-form are two aspects of fibers described in the literature as influencing thermal resistance values.

Bogaty and co-workers (6) showed thermal resistance of a fibrous batt was governed by fiber arrangement as well as by thickness. Further, researchers established thermal resistance of a batt is dependent on the randomness (7,30,31) and direction (6,9,11) of the fiber arrangement.

In the above studies, a parallel fiber arrangement gave a higher thermal resistance value than did a disoriented fiber arrangement. Also, fibers oriented in a direction parallel, rather than perpendicular, to the direction of the batt surface produced improved thermal resistance. This was credited to the fact that alternate layers of fibers and air could be maintained with the parallel fiber arrangement.

Frederick (11) discussed the importance of the influence of the fiber-form on thermal resistance of fibrous-batt constructions. Both fiber diameter and fiber shape were identified in effecting the compressional resilience of the batt construction, and hence thermal resistance values.

Improvements have been made by increasing the size of the fiber diameter in order to reduce the ability of the fiber to bend. Also, fibers in a batt construction should be oriented in a direction parallel to the direction of the applied compressive force to obtain optimum compressional resilience.

Frederick (11) considered the use of helix-shaped fibers in improving loftiness of batt constructions. Also, he demonstrated the value of crimped staple-fibers over straight filament-fibers explaining that a low coefficient of thermal conductivity of a batt construction could be obtained by blending a mixture of highly-crimped staple fibers.

Frederick (11), Kaswell (17), and Rees (25) examined compressional resilience of some natural-, regenerated-, and totally synthetic-fibers. Throughout their examinations, wool fiber possessed the greatest loftiness and greatest ability to retain loftiness. This was attributed to the natural crimp of the wool fiber. Regenerated- and totally synthetic-fibers, since they are more uniform along their length, fitted closer together and therefore produced a less lofty fibrous mass.

Morton and Hearle (23) found a wool fiber-mass possessed a higher percentage resilience than a polyester fiber-mass, after severe pressure conditions. In addition, these researchers noticed the polyester fiber-mass maintained a peculiar crushed appearance after the compressive force was removed. They believed this to be a result of straining the polyester fibers beyond elastic limits at points where the fibers crossed one another.

The above studies suggest that differences in thermal resistance values for textile fabrics and batts could be attributed to the mechanical properties of the constituent fiber, in particular, to their resiliency.

The studies discussed in this literature review have provided the information that immobilized air entrapped in a textile system, thickness of a textile system, pressure applied to a textile system, and, the fiber contained in a textile system, each can exhibit restraints on thermal resistance of the textile system. Further, and perhaps most important, these studies have shown that interactions between the above factors need to be considered and understood when meeting requirements for optimum thermal resistance.

Chapter 3

EXPERIMENTAL PROCEDURE

The present research investigated thermal resistance values of fabric-batt assemblies containing single- and multiple-layers of batts sandwiched between a nylon outer-fabric and a cotton lining-fabric. The thermal resistance values of the single- and multiple-layers of batts were also studied. The factors investigated were four fiber types of batts, three pressure levels of compression on fabric and batts, single- and multiple-layers of batts, and some physical properties of batts. Batt- and fabric-batt-assemblies were mounted between a hot- and cold-plate until thermal equilibrium of the samples was attained at which time thermal conductivity was measured. Information about the batts and fabrics, preparation of test specimens, apparatus and procedure, and analysis of results follow. All testing was conducted in a testing atmosphere of 25 ± 2°C and 42 ± 4% RH.

Selection of Textile Materials

Batts

Three batt types each containing either cotton-, wool-, or polyester-fibers and one containing a mixture of various fibers were chosen for this study. The selection was considered representative of those batts available for use in the make-up of cold-weather garments. The batt suppliers and their addresses are listed in Appendix "A". Batts were selected on the basis of almost similar porosity.

Fabrics

Nylon 'Antron Taffeta', style #316, and cotton 'Print Cloth', bleached, 80X80, style #400, were obtained through Testfabric Incorporated, New Jersey, and were used as outer- and lining-fabrics, respectively, during this study. Testfabrics were chosen since no specifications exist for the selection of outer- and lining-fabric for use in cold-weather garment construction. Also, Testfabrics are free from special finishes which might effect results of the study.

Preparation of Textile Specimens for Experimental Use

Seventy-two 254 mm X 254 mm samples were cut from each of the cotton-, wool-, polyester-, and multifiber-batts. Since it was necessary to place equivalent assemblies of one-, two-, or three-layers of batts on either side of the guarded hot-plate for any one test, each assembly being held between a cold plate and the hot plate, these assemblies were classified as pairs and acted as one test specimen throughout the study. Randomly chosen samples of each fibrous batt were arranged into three sets for testing.

1. Twelve batt-layers were divided into three groups containing four batt-layers each. Each group of four batt-layers was assigned to one of 7 g/cm^2, 14 g/cm^2, or 21 g/cm^2 pressure. The four batts of each group were divided into assemblies containing one batt-layer each. Each batt layer was measured for thickness at the given pressure, weight per unit area, density, packing factor, and porosity. Two assemblies were classified as one pair.

2. Twenty-four batt-layers were divided into three groups containing eight batt-layers each. Each group of eight batt-layers was assigned to one of 7 g/cm^2, 14 g/cm^2, or 21 g/cm^2 pressure. The eight batt-layers of each group were divided into four assemblies containing two batt-layers each. The two batt-layers were measured as one for thickness at the given pressure, weight per unit area, density, packing factor, and porosity. Two assemblies were classified as one pair.

3. Thirty-six batt-layers were divided into three groups containing twelve batt-layers each. Each group of twelve batt-layers was assigned to one of 7 g/cm^2, 14 g/cm^2, or 21 g/cm^2 pressure. The twelve batt-layers of each group were divided into four assemblies containing three batt-layers each. The three batt-layers were measured as one for thickness at the given pressure, weight per unit area, density, packing factor, and porosity. Two assemblies were classified as one pair.

The fabrics were pressed lightly with a cool iron to obtain a flat surface. One-hundred and thirty-two 254 mm X 254 mm samples were cut from the nylon- and cotton-Testfabrics. These samples were chosen at random, were measured for thickness at the given pressure, weight per unit area, density, packing factor, and porosity, and were coded. The coded nylon outer-fabric and the cotton lining-fabric were then paired and placed on either side of each established batt assembly to form a fabric-batt assembly.

Pressures exerted on the fibrous batt assemblies and outer- and lining-fabrics, in this study, were selected in accordance with ASTM D:1777, 1970 requirements. Actual test-size of the specimens was 152.4 mm X 152.4 mm. Due to the nature of the measurements of physical properties required for the batt- and fabric-samples, however, it was necessary to cut the test specimens 254 mm X 254 mm. After measurements of thickness at the given pressures, weight per unit area, density, packing factor, and porosity fibrous batts and Testfabrics were cut 152.4 mm X 152.4 mm.

Determination of Physical Properties of Textile Specimens

The procedures used to measure batt- and fabric-characteristics are enumerated below.

1. Thickness at a given pressure was determined according to

ASTM (1970) Designation: D1777. A Custom Scientific Instrument Low Pressure Gage, with a 19 mm diameter anvil and a 76.2 mm diameter pressure foot under 7 g/cm^2, 14 g/cm^2, and 21 g/cm^2 pressure was used. Four thickness measurements were taken for each batt assembly and for each nylon- and cotton-fabric layer. In order that these four thickness measurements did not overlap, on any one test sample, fabrics and batts were cut to a size larger than actual test-size.

2. Batt- and fabric-weights, in g/m^2, were determined according to CGSB (1971) 4-GP-2 Method 5.A-1958. Single- and multiple-layer assemblies of batts and each layer of nylon- and cotton-fabric, cut 254 mm^2, were weighed on a Sartorius Automatic Preweighing Balance.

3. Batt density was determined (17) following the relationship:

$$\text{Batt Density, g/cm}^3 = \frac{\text{Batt Weight, g}}{\text{Batt Thickness, cm X 10,000}}$$

4. Fabric density was determined (17) following the relationship:

$$\text{Fabric Density, g/cm}^3 = \frac{\text{Fabric Weight, g}}{\text{Fabric Thickness, cm X 10,000}}$$

5. Batt packing factor was determined (17) following the relationship:

$$\text{Batt Packing Factor} = \frac{\text{Batt Density}}{\text{Fiber Density}}$$

6. Fabric packing factor was determined (17) following the relationship:

$$\text{Fabric Packing Factor} = \frac{\text{Fabric Density}}{\text{Fiber Density}}$$

7. Batt porosity was determined (17) following the relationship:

$$\text{Batt Porosity} = 1 - \frac{\text{Batt Density}}{\text{Fiber Density}}$$

8. Fabric porosity was determined (17) following the relationship:

$$\text{Fabric Porosity} = 1 - \frac{\text{Fabric Density}}{\text{Fiber Density}}$$

Tables 1 and 2 provide the results of the measurements of thickness, weight, density, packing factor, and porosity of the selected fibrous batts and Testfabrics.

Description of the Guarded Hot-Plate Apparatus

A guarded hot-plate apparatus for measuring thermal resistance was used to determine thermal conductivity of the batt- and fabric-batt-assemblies. The guarded hot-plate was originally designed for use with thick materials of high thermal resistance and was thus similar to the 'National Research Council of Canada, Automatically Controlled, 12-Inch, Simplified Guarded Hot-Plate Apparatus'. The apparatus was adapted for textile use by scaling down the plate assembly from 12-inches to 6-inches to correspond to the lower thicknesses of the batt- and fabric-batt-assemblies. Tests were carried out according to modified method ASTM (1972) Designation: D1518 equipped with the 6-inch hot plate designed specifically for textile use. A photograph of the apparatus (Plate 1) includes:

1. An automatic self-contained control system for the cold-plate temperatures (extreme left-A).

2. The main control system for the hot plate (center-B); also known as the central heater.

3. The plate assembly consisting of a central hot-plate and guard plate between two cold-plates (upper right-C). An enlarged view of the plate assembly is shown in Plates 2 and 3.

Table 1. Descriptive Analysis of Fibrous Batts*

Fiber Type	Batt Layers	Pressure g/cm^2	Thickness mm	Weight g/m^2	Density g/cm^3	Packing Factor	Porosity
Cotton	1	7	4.928	279.007	0.057	0.037	0.953
		14	4.243	269.351	0.064	0.042	0.958
		21	3.489	247.806	0.071	0.046	0.954
	2	7	10.283	576.521	0.056	0.037	0.963
		14	8.414	571.367	0.068	0.044	0.955
		21	7.553	551.218	0.073	0.048	0.952
	3	7	15.211	855.598	0.058	0.038	0.962
		14	12.657	840.718	0.059	0.039	0.961
		21	11.053	799.023	0.072	0.047	0.953
Wool	1	7	4.202	171.778	0.041	0.031	0.968
		14	3.174	164.261	0.052	0.039	0.960
		21	2.879	183.713	0.065	0.049	0.950
	2	7	8.886	347.393	0.039	0.030	0.970
		14	6.595	364.404	0.057	0.043	0.957
		21	5.189	338.171	0.065	0.049	0.950
	3	7	13.765	581.597	0.042	0.032	0.968
		14	11.123	584.155	0.053	0.040	0.960
		21	8.002	518.784	0.065	0.049	0.951
Polyester	1	7	4.775	115.862	0.024	0.018	0.982
		14	2.758	107.725	0.039	0.028	0.972
		21	2.479	126.363	0.051	0.037	0.958
	2	7	8.771	214.674	0.024	0.018	0.982
		14	5.248	210.024	0.040	0.029	0.971
		21	4.906	248.619	0.051	0.037	0.963
	3	7	14.097	350.066	0.025	0.018	0.982
		14	9.121	356.150	0.039	0.028	0.972
		21	6.886	354.304	0.051	0.037	0.963
Multi-fiber	1	7	1.968	117.838	0.059	0.043	0.957
		14	1.775	131.982	0.074	0.053	0.947
		21	1.646	122.721	0.074	0.053	0.946
	2	7	3.576	229.283	0.064	0.046	0.954
		14	3.430	254.122	0.073	0.053	0.947
		21	3.059	247.961	0.081	0.058	0.942
	3	7	5.379	349.602	0.065	0.047	0.953
		14	4.803	358.282	0.075	0.054	0.946
		21	4.011	340.612	0.085	0.061	0.939

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* Based on an average of four measurements

Table 2. Descriptive Analysis of Fabrics*

Fabric	Pressure g/cm^2	Thickness mm	Weight g/m^2	Density g/cm^3	Packing Factor	Porosity
Nylon	7	.117	70.086	0.604	0.530	0.470
	14	.111	69.685	0.627	0.549	0.451
	21	.112	69.117	0.612	0.537	0.439
Cotton	7	.337	104.915	0.311	0.203	0.797
	14	.313	105.703	0.338	0.221	0.779
	21	.297	104.586	0.351	0.229	0.770

* Based on an average of twelve measurements

Plate 1. Guarded Hot-Plate Apparatus.

Plate 2. Central Hot-Plate and Guard Plate Between Two Cold-Plates with Plexiglas Spacer Mounted at Upper Section of Guard Plate.

Plate 3. Plate Assembly with Three-Layer Multifiber Batt-Assembly, Plexiglas Spacers, and Coil Spring in Place.

4. A manual balancing digital voltmeter (lower right-D) from which the hot- and cold-plate temperatures were determined.

Two coil springs were used to hold the cold plate-fabric-hot plate-fabric-cold plate assembly together during testing. Plexiglas spacers (Plate 3) were used to separate the cold- and hot-plates at a precalculated distance from each other. This enabled the plates to exert a predetermined pressure on the fabric-batt assemblies held between them.

Figure 3 illustrates the dimensions of the plates and the temperatures at which the plates were maintained during testing. The central hot-plate, a 101.6 mm square, was maintained at a temperature of 33°C. This temperature was referenced to a direct reading automatic balancing thermocouple potentiometer accurate to ± 2µv. The temperature of the water-cooled cold-plates, each a 152.4 mm square, was maintained at 11°C during testing, and was controlled by an automatic self-contained system accurate to ± 3µv. Using calibration charts (Tables 5 and 6, Appendix "B") and output in millivolts, read from the manual balancing voltmeter, the temperatures were determined with an accuracy of ± 0.2°C. The guard-heater temperature was automatically controlled by means of thermocouples to maintain the same temperature as the central hot-plate and, thus, provide unidirectional heat flow across the system.

Design and Use of Plexiglas Spacers

Thickness measurements at a given pressure were determined for the batt assemblies and for each of the outer- and lining-fabrics. Plexiglas spacers were cut to an accuracy of ± .02 mm from the values

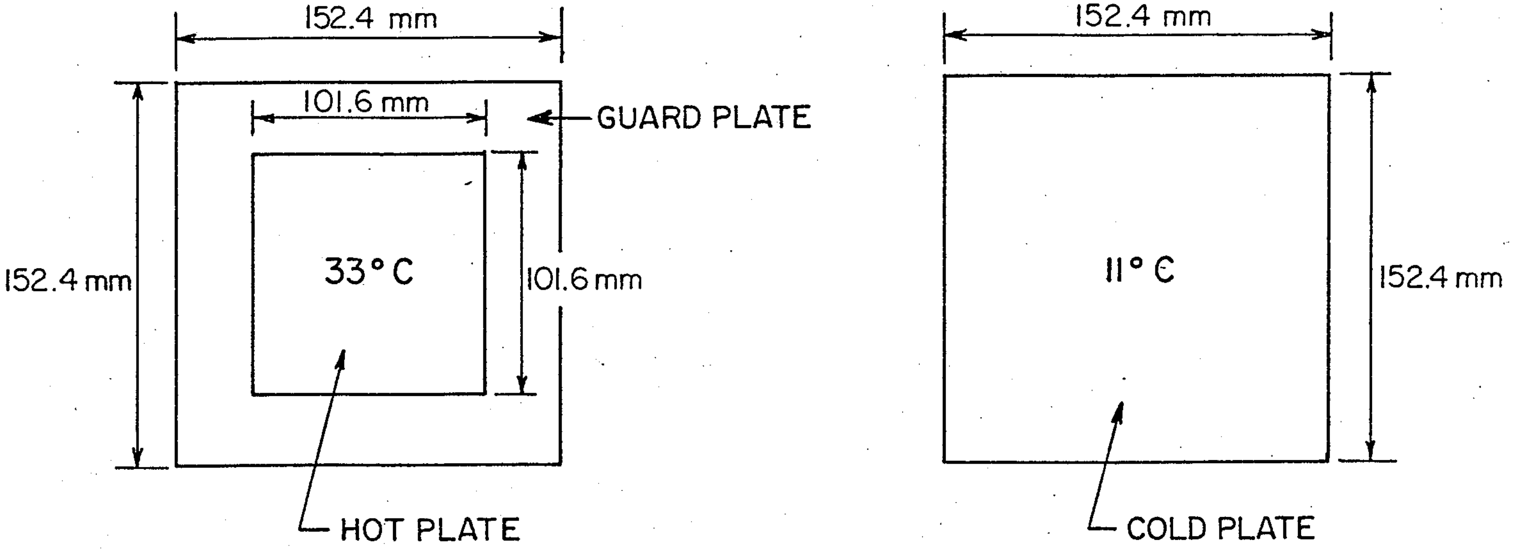

Figure 3. Plate Dimensions and Plate Temperatures Maintained at During Testing.

obtained for the thickness measurement of the batt assemblies and the fabric-batt assemblies. Eight spacers were cut for each thickness measurement. Four of these spacers were placed at each corner of one side of the guard plate and the remaining four were placed at each corner of the other side of the guard plate (Plate 3). Spacers were held in place by a silicone dielectric '4-Compound' - Dow Corning. The precision-cut spacers were used to separate the hot- and cold-plates during testing. This resulted in a specific pressure being exerted on the test specimens. It was under such pressures that the thermal conductivities of the various combinations of textile assemblies were measured.

Plexiglas was selected as the spacer material, in this study, for its versatility. Plexiglas can easily be precision-cut to size and can easily be mounted on either side of the guard plate. In addition, plexiglas was readily available, relatively inexpensive, and, in itself, acted as a heat insulator. It therefore did not conduct heat from the hot plate to the cold plates.

Procedure for Measuring Heat Flow

Thermal conductivity measurements were obtained at ambient temperature and humidity ($25 \pm 2^{o}C$ and $42 \pm 4\%$ RH). The specimens were conditioned for a minimum of 72-hours and were therefore in hygroscopic equilibrium with the room conditions when tested. Plexiglas spacers were attached at each corner on either side of the guard plate. One-half of the pair of the batt- or fabric-batt-assemblies were placed on either side of the hot plate. The test specimens were held in position by hand and the cold plates were eased towards the specimens until they made contact with the plexiglas spacers. One coil spring was then positioned at each side of the total cold plate-fabric-hot plate-fabric-cold plate assembly to hold the assembly together. Plate 3 illustrates placement of the plexiglas spacers, batt assemblies, and springs, and the position of the guarded hot-plate between the two water-cooled cold-plates. Throughout the study the nylon outer-fabric was placed in contact with the cold plates and the cotton lining-fabric in contact with the hot plate. To make room for plexiglas spacers during testing each specimen was clipped away at an angle at each corner (Figure 4).

With the assemblies in place the total system was brought to steady-state operating conditions. The temperature difference between the plates was kept as large as possible to a maximum of 5^{o}C. The aim was to approach a hot-plate temperature of 33^{o}C-man's average skin temperature, and a cold-plate temperature of 11^{o}C-average temperature of a fall season day. Under no circumstances was the hot-plate temperature allowed to go above 33.6^{o}C and the cold-plate temperature allowed to go below 10.3^{o}C. The potential difference required to maintain the temperature difference between the plates was calculated manually noting the difference between the temperature of the cold plates from that of the hot plate. The resistance of the central hot-plate was determined at 6.0217 ohms.

Computation of Thermal Conductivity and Thermal Resistance

Thermal conductivity measurements of the batt assemblies, outer- and lining-fabrics, and fabric-batt assemblies were calculated manually from the relationship:

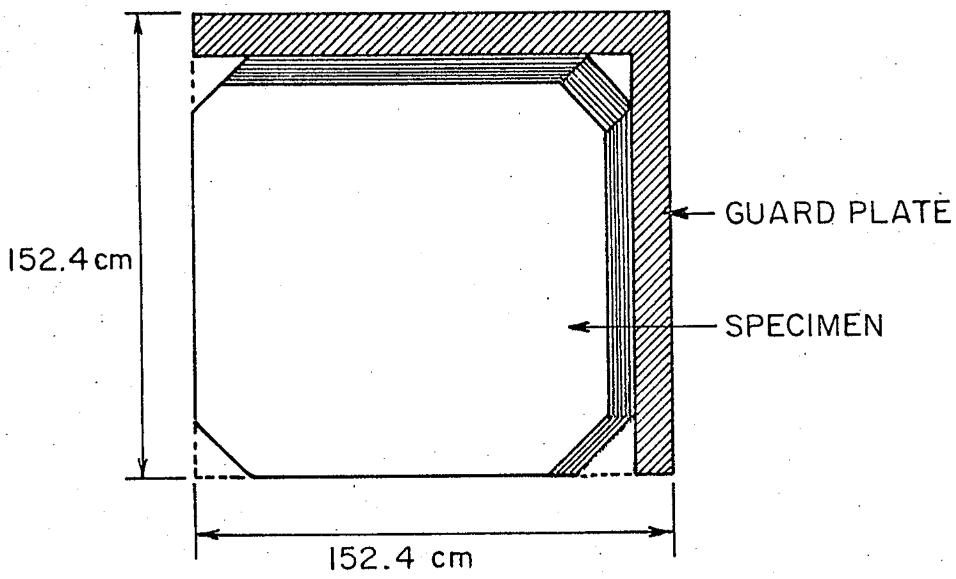

Figure 4. Specimens Clipped at an Angle at Each Corner.

$$K = \frac{q\ L}{\Delta t\ A}$$

and

$$q = \frac{V^2}{R} \times 3.41443$$

where K = thermal conductivity (cal/m sec °C)

q = heat flow rate (cal/m^2 sec)

L = thickness (m)

Δt = temperature gradient (T hot - T cold, °C)

A = area of specimen covering central hot-plate through which heat flows (m^2)

V = main heater voltage (volts)

R = resistance of central hot-plate (6.0217 ohms)

The guarded hot-plate apparatus was not capable of measuring the thermal conductivity of one layer of either of the nylon-or cotton-Testfabrics. Uniform heat flow could not be obtained when testing a single layer of the Testfabrics because these fabrics were too thin. Since the relationship between thickness and thermal resistance is understood to be more or less linear, the thermal conductivity of a number of layers of each of the Testfabrics was measured.

Four separate thermal conductivity measurements were conducted for each of the nylon- and cotton-Testfabrics in decreasing order using eighteen-, sixteen-, fourteen-, and then twelve-layers of fabric. These four measurements were converted to thermal resistance values and plotted on a thermal resistance-thickness graph. Extrapolation was utilized to estimate the thermal resistance values for one layer of each of the nylon- and cotton-fabrics. The use of extrapolation was considered to be a more accurate method of finding the thermal resistance of single layers of Testfabrics.

The known values for assembly thickness, thermal conductivity, and test-section area were applied in the following relationship to calculate thermal resistance per unit area:

$$R = \frac{L}{KA}$$

where R = thermal resistance (m^2 sec ^{o}C/cal)
L = thickness (m)
K = thermal conductivity (cal / m sec ^{o}C)
A = area of specimen covering central hot-plate through which heat flows (m^2)

The thermal conductivities and thermal resistivities were calculated manually using a compact portable Digi-matic D-8 Electronic Calculator.

Statistical Analysis

Thermal resistances of batt assemblies and fabric-batt assemblies were analyzed as factorial experiments with three factors - multiple layers, fiber type, and pressure level, within a completely randomized design. A t-test was conducted to test the difference between mean thermal resistance values for batt- and fabric-batt-assemblies. Correlation coefficients and multiple regression equation constants were calculated to show the relationship between thickness, pressure, and thermal resistance values for the batt- and fabric-batt-assemblies. All calculations were made on an Olivetti-Underwood Programma 603 desk computer.

Chapter 4

DISCUSSION OF RESULTS

A series of graphs and tables have been prepared to present thermal resistance values for the batt- and fabric-batt-assemblies and to show the relationship of these values with the main factors - multiple layers, fiber type, and pressure level. Figures 6, 7, and 8 show the relationship between the thermal resistance of the fabric-batt assemblies and the main factors. The relationship between thermal resistance of the assemblies and the two-way interactions of the main factors are depicted in Figures 9,12, and 15. Simpler views of the relationships between thermal resistance of the assemblies and the interrelationships are illustrated in Figures 10 and 11, 13 and 14, and 16 and 17. The thermal resistance values and corresponding thickness measurements of the batt assemblies and fabric-batt assemblies, under each of 7 g/cm^2, 14 g/cm^2, and 21 g/cm^2 pressure level are recorded in Table 3. Table 8 (Appendix "C") provides the results of percentage changes in thermal resistance between that for batt assemblies and that for fabric-batt assemblies. Table 9 of Appendix "C" contains the mean thermal resistance values of the assemblies as a function of the number of batt layers, fiber type, and pressure level, while Table 10 (Appendix "C") contains the mean thermal resistance values of the assemblies as a function of the interrelationships of these factors. The analyses of variance for thermal resistance of batt assemblies and fabric-batt assemblies are presented in Appendix "D" (Table 13). Table 15 (Appendix "D") contains the correlation coefficients and multiple regression equation constants which show the relationship between pressure, thickness, and thermal resistance for the assemblies.

It should be noted that separate analyses of the thermal resistance values were made for batt assemblies and fabric-batt assemblies. The relationship between these separate analyses is considered first to provide a foundation for discussion of the main factors in the experiment.

Thermal Resistance of Batt Assemblies and Fabric-Batt Assemblies

The mean thermal resistance values for the batt assemblies and fabric-batt assemblies were 3.29 m^2sec °C/cal and 3.40 m^2sec °C/cal, respectively. A simple t-test indicated, with 99% confidence, that there was no significant difference between the mean thermal resistance values.

Thermal resistance and thickness measurements of the nylon- and cotton-Testfabrics were measured. Figure 5 illustrates the relationship between thermal resistance values and thickness measurements of the Testfabrics. These values are recorded in Table 7, Appendix "C". The thermal resistance of one layer of each of the nylon- and cotton-fabrics has been estimated by means of extrapolation, given by the broken lines in Figure 5. Thermal resistance values for a single layer of nylon and cotton (Table 7, Appendix "C") were found quite small in relation to that for batt layers (Table 3), probably falling within the error region of the thermal resistance measurements for the batt layers. The addition of the nylon- and cotton-fabrics did not substantially increase the thickness measurements for the fabric-batt assemblies from that for the

Table 3. Measured Values of Thermal Resistance for Batt- and Fabric-Batt-Assemblies of Various Fiber Types*

Pressure Level g/cm^2	Number of Batt Layers	Fiber Type	Batt Assemblies Thermal Resistance m^2 sec ^oC/cal	Batt Assemblies Thickness mm	Fabric-Batt Assemblies Thermal Resistance m^2 sec ^oC/cal	Fabric-Batt Assemblies Thickness mm
7	1	Cotton	2.39	4.93	2.63	5.34
		Wool	2.33	4.20	2.41	4.71
		Polyester	2.55	4.77	2.51	5.25
		Multifiber	1.24	1.97	1.28	2.43
	2	Cotton	5.41	10.28	5.11	10.74
		Wool	4.74	8.89	4.84	9.34
		Polyester	4.20	8.77	3.99	9.22
		Multifiber	1.99	3.51	2.09	4.03
	3	Cotton	7.78	17.24	8.13	17.70
		Wool	6.83	13.76	7.05	14.21
		Polyester	6.58	14.09	6.35	14.53
		Multifiber	2.95	5.38	2.97	5.82
14	1	Cotton	2.09	4.24	2.22	4.67
		Wool	1.81	3.17	1.84	3.60
		Polyester	1.61	2.76	1.69	3.19
		Multifiber	1.19	1.77	1.30	2.21
	2	Cotton	3.92	8.41	4.17	8.83
		Wool	3.57	6.59	3.70	7.01
		Polyester	2.89	5.25	2.82	5.67
		Multifiber	1.89	3.43	2.15	3.86
	3	Cotton	5.95	14.48	6.79	14.93
		Wool	5.38	11.12	6.05	11.54
		Polyester	4.42	9.12	4.57	9.53
		Multifiber	2.64	4.80	2.74	5.22
21	1	Cotton	1.60	3.49	1.84	3.91
		Wool	1.63	2.88	1.78	3.31
		Polyester	1.36	2.48	1.49	2.89
		Multifiber	1.23	1.65	1.04	2.06
	2	Cotton	3.49	7.55	3.81	7.97
		Wool	3.12	5.19	3.01	5.60
		Polyester	2.81	4.91	2.76	5.31
		Multifiber	1.71	3.06	1.72	3.46
	3	Cotton	4.80	11.03	5.31	11.43
		Wool	4.50	8.00	4.40	8.40
		Polyester	3.68	6.88	3.64	7.29
		Multifiber	2.19	4.01	2.39	4.42

* Based on an average of two thermal resistance measurements.

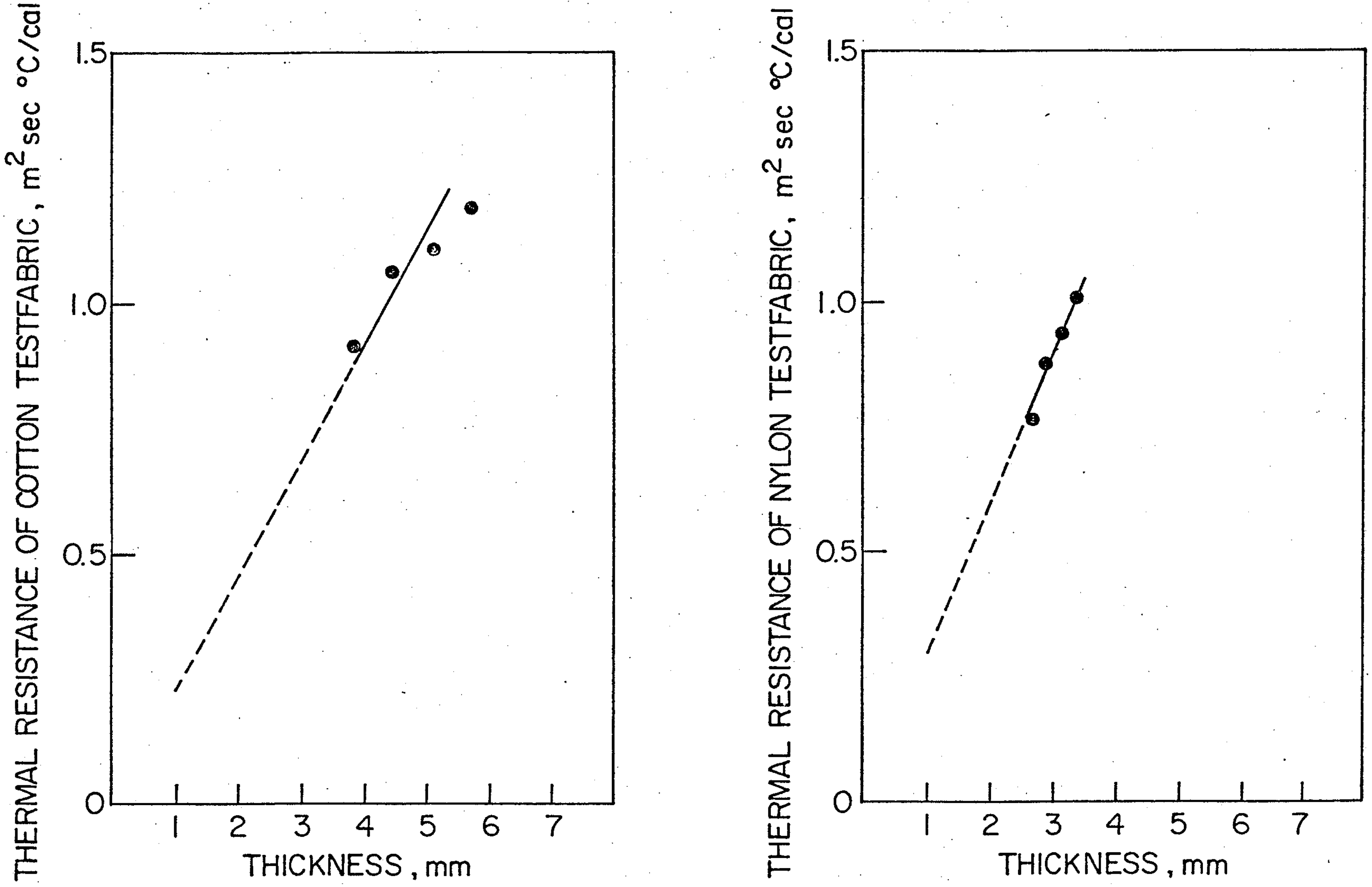

Figure 5. Relationship Between Thickness and Thermal Resistance of Cotton- and Nylon-Testfabrics.

batt assemblies. This is probably due to the fact that thickness of the Testfabrics was insignificant in comparison to that of the batt layers.

The addition of the Testfabrics produced larger thermal resistance values, in general, for assemblies of wool-, cotton-, and multifiber-batts (Table 8, Appendix "C"). However, in six out of nine cases the thermal resistance for polyester batt assemblies was greater than that for polyester fabric-batt assemblies. It is possible that the nylon- and cotton-Testfabrics reacted with the polyester batt to a much greater extent than with the other fibrous batts effecting an increase in thermal conductivity through the assembly by altering the still air components of the batt. Further, the surface of a fibrous batt is less uniform than that of a woven textile fabric. Therefore, when a fabric layer is added to a batt layer a thin air-film can be entrapped between them, held in the void spaces created by the roughness of the batt surface. This layer of air can act as an insulator if convection can be avoided. Since wool- and cotton- fiber masses produce batts possessing rather irregular surfaces, it is quite likely that a thin film of air could have been entrapped between the nylon- and cotton-fabric layers and these batt layers, in the present study, to improve thermal resistance values for the wool- and cotton- batt assemblies. Since thermal resistance values for polyester fabric-batt assemblies were less than that for polyester batt assemblies the development of air layers between the fabric- and batt-layers appears to be negligible. This could suggest that the polyester batt had a more uniform surface than did the wool- or cotton-batts. Since the thermal resistance values for the nylon-and cotton-Testfabrics were quite small in comparison to that for the batt layers, and if little or no air was held between the fabric- and batt-layers, then the thermal resistance of the polyester fabric-batt assemblies would be similar to that for the polyester batt assemblies.

It has been established by statistical analysis that the thermal resistance values for the batt assemblies and fabric-batt assemblies are similar. Thus, in the following section, in which factors which have influenced the thermal resistance values are considered, discussions of the thermal resistance of the assemblies will be considered together.

Factors Considered in the Thermal Resistance Study

The different factors - multiple layers, fiber type, pressure level, and the two-way interactions between these factors - multiple layers by fiber type, multiple layers by pressure level, and pressure level by fiber type, significantly effected thermal resistance values for the assemblies considered in this study. Each was significant at the .01 level. Discussion of the factors and interaction of these factors will be confined to consideration of the above significant main factors and interrelationships.

It should be recalled from the outline of the experimental procedure that three of the fibrous batts - cotton, wool, and polyester maintained similar porosity under applied pressure while the porosity of the multifiber batt differed from these three. Because of this fundamental difference in the multifiber batt it was not compared with the other batts unless warranted by the nature of the results.

Multiple Layers of Batts

The statistical analysis (Table 13, Appendix "D") indicates thermal resistance values for the assemblies were effected by the number of batt layers, significant at the .01 level. Figure 6 illustrates the relationship between thermal resistance and the number of batt layers. This illustration shows as the number of batt layers were increased, from one- to two- to three-layers, the thermal resistance values increased. However, Table 3 indicates that thermal resistance values did not double as the batts were increased from one- to two-layers, nor did they increase three-fold when the batts were increased from one- to three-layers. The corresponding thickness measurements for the assemblies followed a similar trend. This phenomenon was more pronounced for polyester- and multifiber-batt assemblies.

As mentioned in the 'Experimental Procedure' the fibrous batts were cut and chosen at random to be placed into layer-combinations to form an assembly. It is possible that one batt-layer of the layer-combination was not identical in thickness to the next. This would account for the deviation in thickness measurement as the number of batt layers were increased from one- to two-layers and from one- to three-layers. Further, most fibrous batt surfaces are irregular possessing a random 'hills and valleys' configuration. It is quite likely, when batt layers are placed on top of one another the surface fibers suffer displacement allowing the hills and valleys to interlock, to a certain extent. The result of this interlocking would be a reduction in the maximum height one batt-layer could be held away from the next batt layer. By interlocking

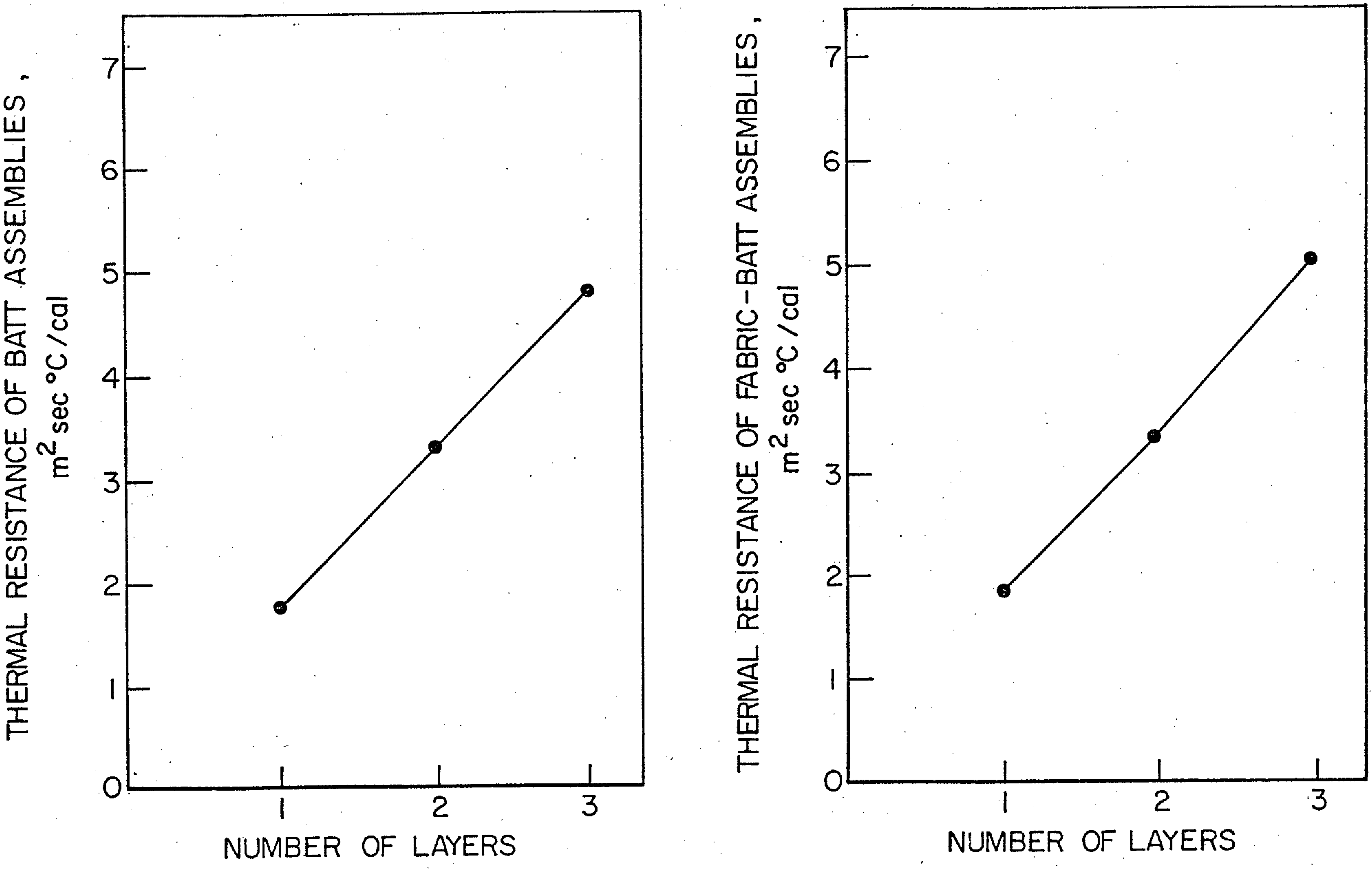

Figure 6. Relationship Between Batt Layer(s) and Thermal Resistance for Batt- and Fabric-Batt-Assemblies.

of the hills and valleys air that would normally be held in the void spaces of the irregular batt surface would be forced out displaced by fibers which possess a higher thermal conductivity than air. The result would be not only a reduction of the maximum thickness but also a reduction of the maximum thermal resistance for each batt layer in the assembly. If this occurs thickness and thermal resistance measurements for the batt assembly would not be an additive factor from those for the single batt-layer. During actual testing the fibrous batt-layers were difficult to distinguish between when in the assembly. Also, upon separation it was evident that surface fibers of one batt-layer had interlocked with surface fibers of a second batt-layer.

The calculated F-values given in Table 13, Appendix "D" show the number of batt layers had the most pronounced effect of the main factors and interactions of these factors on changes in thermal resistance of the assemblies. A number of researchers (1,10,28,30) found that increasing thickness was the most important property governing the increase in thermal resistance of fabric- and batt-constructions. The result of increased thermal resistance with an increase in number of batt layers, found in the present study, correlates with findings of these researchers.

Fiber Type

The statistical analysis given in Table 13 (Appendix "D") shows that a change in fiber type had an effect on thermal resistance values of the batt- and fabric-batt-assemblies, significant at a level of .01. In addition, the calculated F-values indicate fiber type was second in importance in effecting thermal resistance of the assemblies.

Figure 7 illustrates a downward sloping line showing the relationship between fiber type and thermal resistance. The cotton batt produced the largest thermal resistance values. This result appears reasonable in view of the thickness measurements of each of the batt fiber-types (Table 1). It was expected thermal resistance of assemblies of multifiber batt would be lower than that of assemblies of cotton-, wool-, and polyester-batts, since thickness measurements of the multifiber batt were less than that for the other fibrous batts. Figure 7 gives evidence to support this suggestion.

Pressure Level of Compression

Thermal resistance values for the batt-and fabric-batt-assemblies were measured under 7 g/cm^2, 14 g/cm^2, and 21 g/cm^2 pressure. Figure 8 illustrates as pressure level was increased the thermal resistance values for the assemblies decreased. The statistical analysis given in Table 13, Appendix "D" indicates pressure level was significant at a level of .01 in effecting thermal resistance of the assemblies.

Researchers have investigated effects of applied pressure on thermal resistance of single fabric-layers, fabric assemblies, and single batt-layers. Frederick (11), Fourt and Harris (12), and Weiner and Shah (30) found imposed pressure reduced the thickness of these textile constructions, which in turn, reduced their thermal resistance. It was expected the pressure imposed altered the thickness of the air layers between the fabric layers of the fabric assembly, as well as reducing the air components of the batt layers. Results of decreases in thermal resistance for the assemblies as pressure level was increased, in

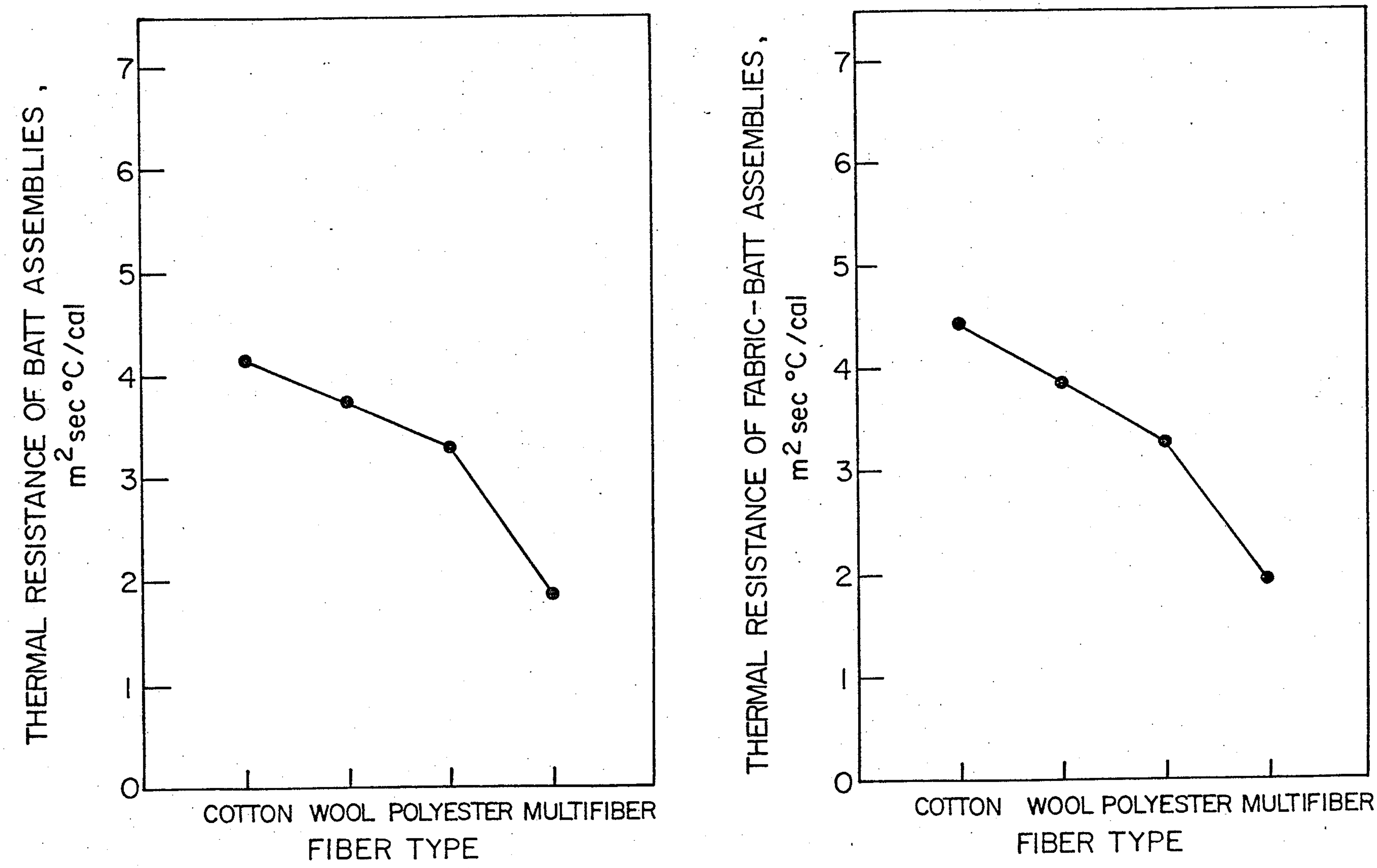

Figure 7. Relationship Between Fiber Type and Thermal Resistance for Batt- and Fabric-Batt-Assemblies.

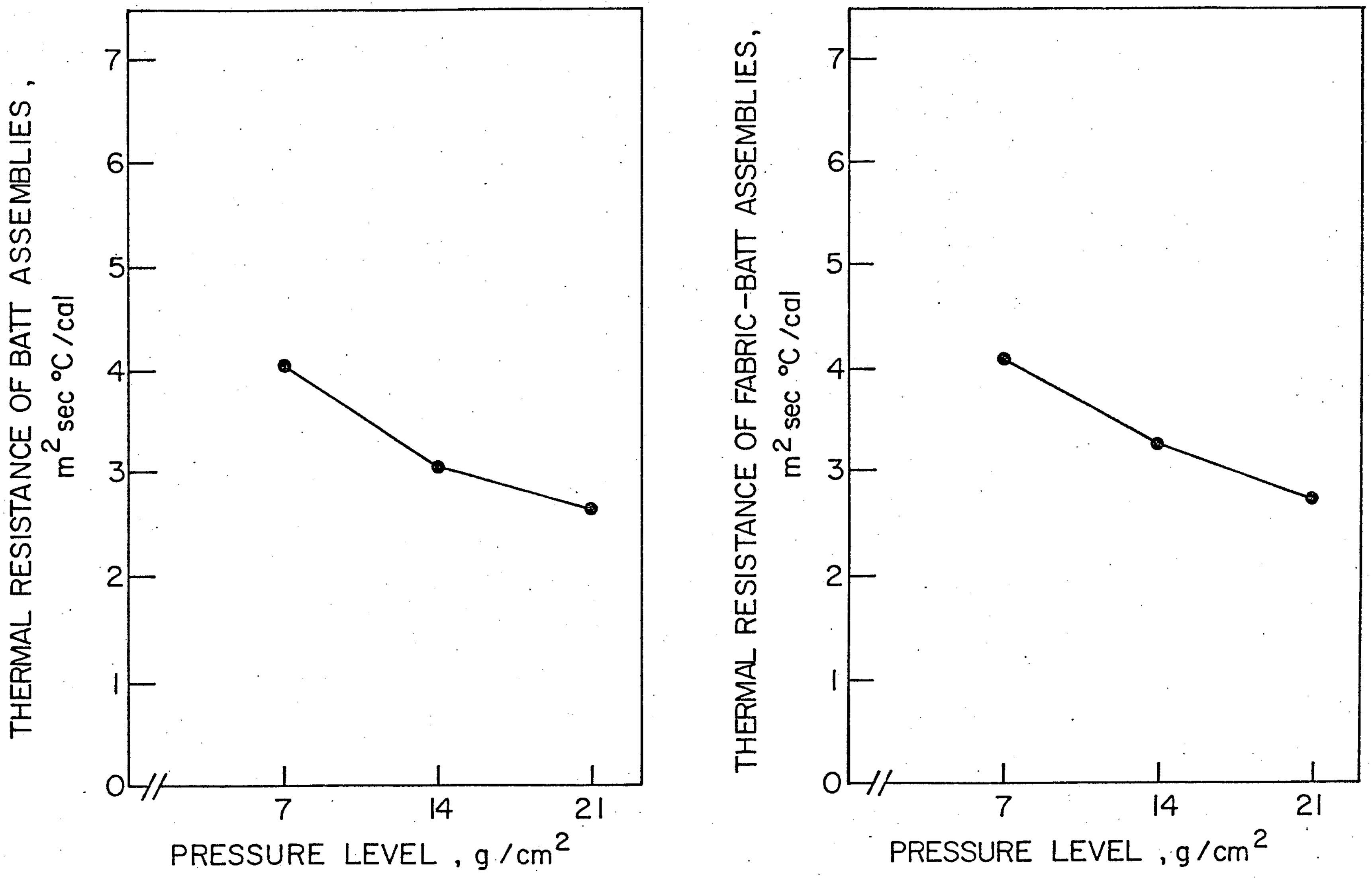

Figure 8. Relationship Between Pressure Level and Thermal Resistance for Batt- and Fabric-Batt-Assemblies.

the present study, corresponds with results found for fabric assemblies and single batt-layers.

When pressure level was increased from 7 g/cm^2 to 14 g/cm^2 thickness of assemblies of polyester batts was compressed by a greater percentage than was thickness of assemblies of wool- or cotton-batts (Table 3). This same trend occurred with thermal resistance values for assemblies of polyester batt. This compression effect on the polyester batt, under 14 g/cm^2 pressure, could be effecting the slope of the line in Figure 8. Morton and Hearle's (23) research was considered to support this theory. After compressing different staple fiber-masses under a known pressure the wool fiber-mass was found to have a higher compressional resilience than the polyester fiber-mass. Further, Morton and Hearle noticed that the polyester fiber-mass maintained a particular crushed appearance after the compression. They believed this appearance to be the result of compressing the fibers beyond elastic limits at points where the fibers crossed one another. The result is a reduction in the air-holding capabilities of these fibers which would decrease the thermal resistance of the mass. The reduced thermal resistance for assemblies of polyester batt, in the present study, may also be attributed to compressing the fibers to their elastic limits.

Interaction of Multiple Layers by Fiber Type

The two-way multiple layers by fiber type interrelationship was significant at a level of .01 in effecting the thermal resistance of the assemblies. Figure 9 illustrates as the number of batt layers of the assemblies were increased, assemblies composed of each of the

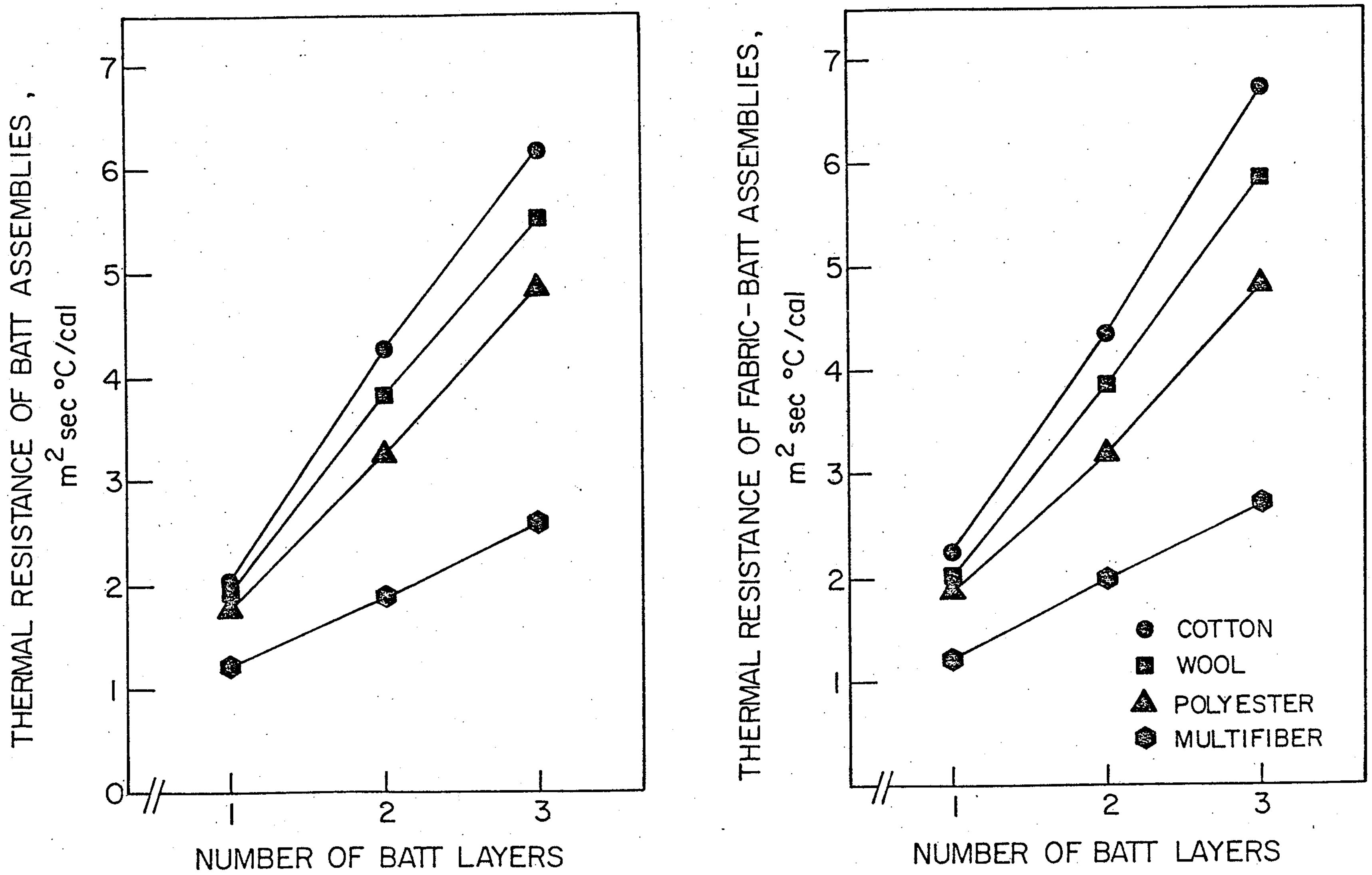

Figure 9. Thermal Resistance for Batt Assemblies and Fabric-Batt Assemblies as a Function of Batt Layer(s) and Fiber Type.

fibrous batts, the thermal resistance values increased. The slope of the lines in Figure 9 appear similar to the slope of the lines shown in Figure 6, for the cotton-, wool-, and polyester-batts. It is suspected the number of batt layers had a more pronounced effect than did the chemical nature of the fiber on thermal resistance of the assemblies.

Thermal resistance values of single layers of cotton-, wool-, and polyester-batts were similar (Figure 9). When the batt layers were increased from one- to two-layers and from one- to three-layers, however, assemblies of cotton produced higher thermal resistance values. Table 1 indicates cotton batt-layers were initially thicker than wool- or polyester-batt-layers. As batt layers were added together to form an assembly there was a higher percentage increase in thickness for assemblies of cotton than for assemblies of wool and polyester. This would explain the increase in distance between the lines illustrated in Figure 9.

Simpler graphs illustrating relationships between thermal resistance as a function of fiber type and number of batt layers, under each of the three pressure levels, are depicted in Figures 10 and 11. Cotton fabric-batt assemblies produced the largest thermal resistance values of the selected fabric-batt assemblies (Figure 11). As mentioned previously, this was expected since the cotton batt maintained the largest thickness measurements of the fibrous batts tested, under the three pressure levels. This trend was not found with thermal resistance values for batt assemblies (Figure 10). Single batt-layers of cotton, wool, and polyester had similar effects on thermal resistance under 7 g/cm^2 pressure, whereas single batt-layers of wool and

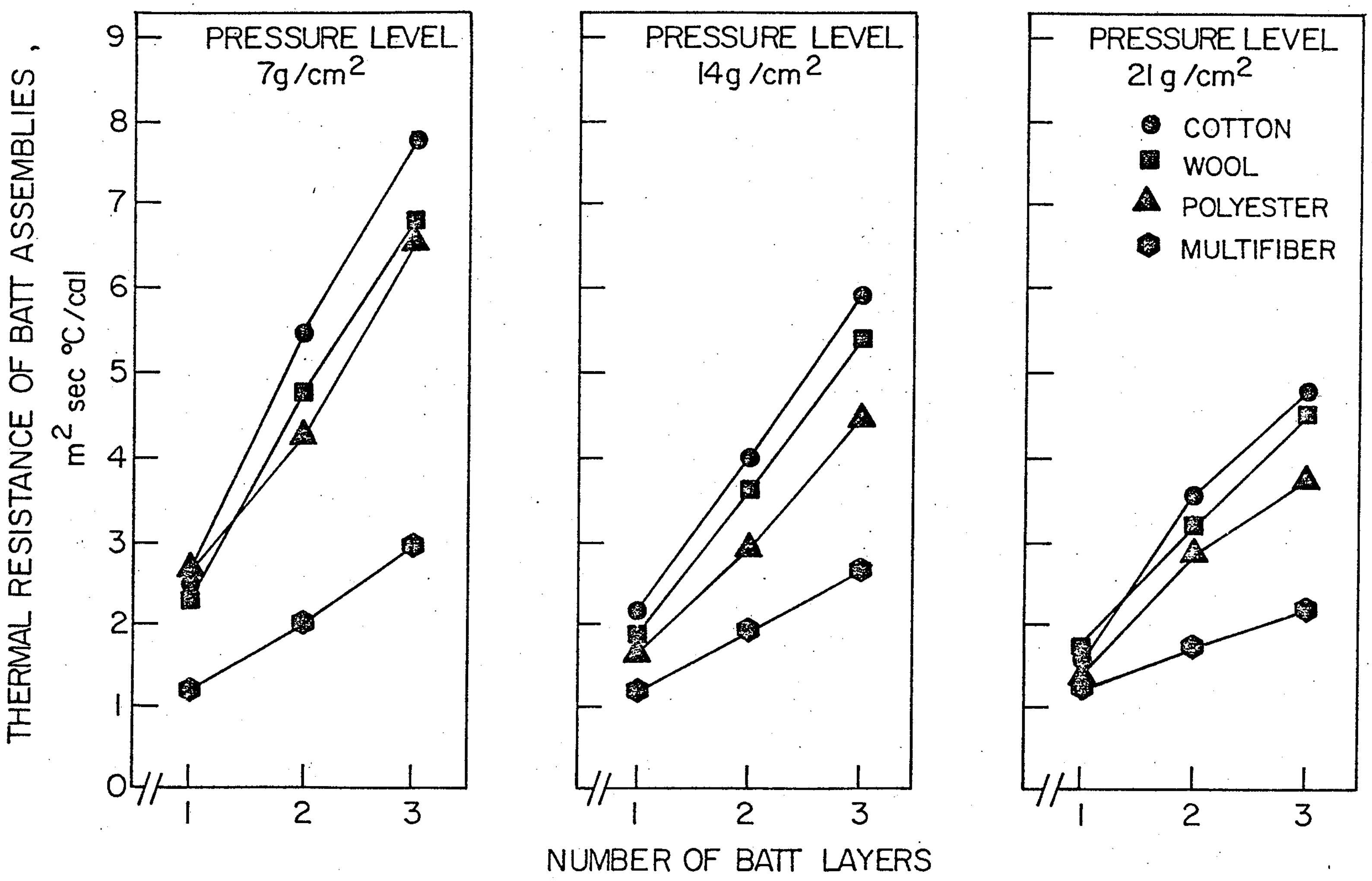

Figure 10. Thermal Resistance for Batt Assemblies Under Each of 7g/cm^2, 14g/cm^2, and 21g/cm^2 Pressure as a Function of Batt Layer(s) and Fiber Type.

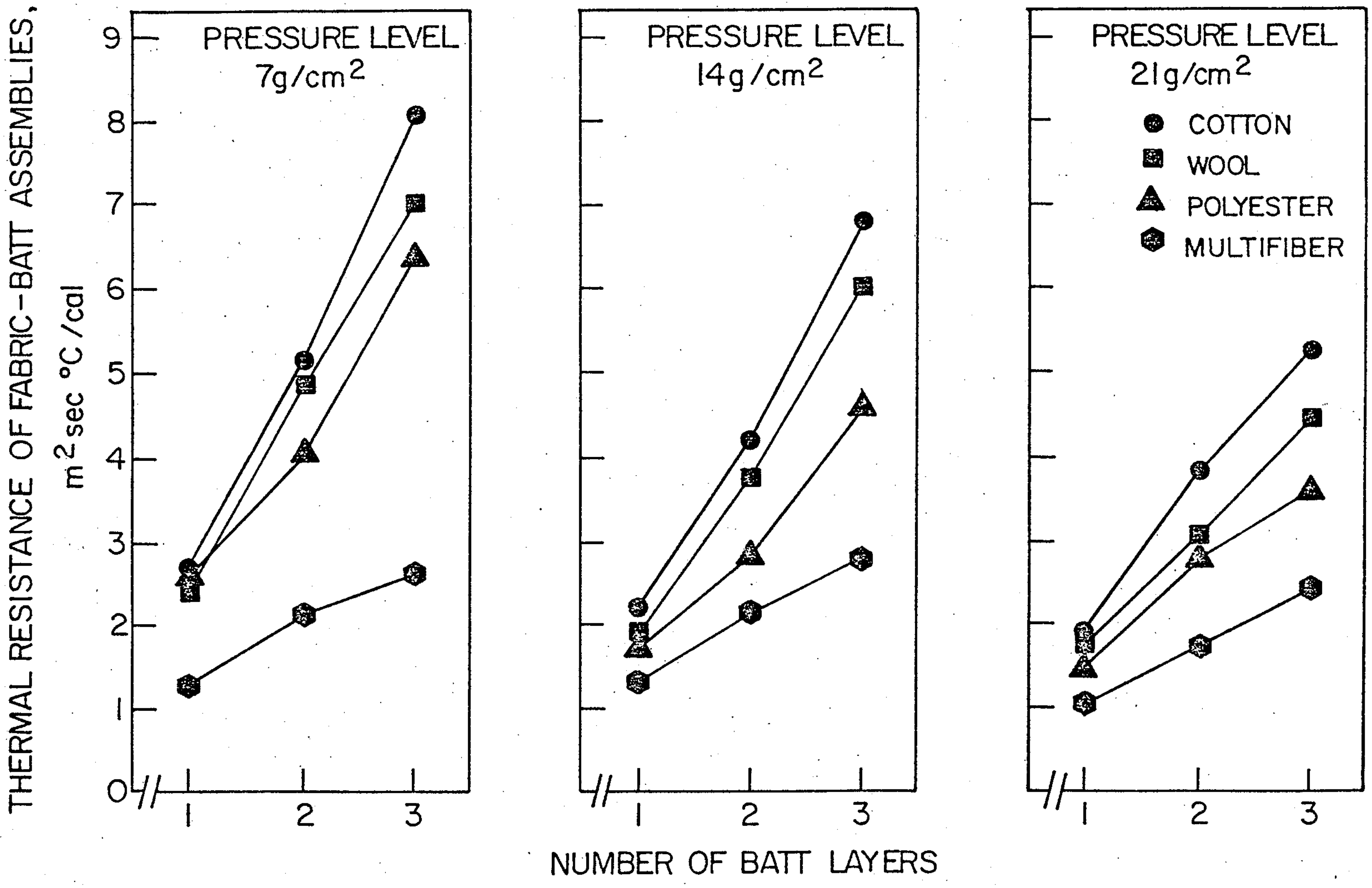

Figure 11. Thermal Resistance for Fabric-Batt Assemblies Under Each of 7g/cm^2, 14g/cm^2, and 21g/cm^2 Pressure as a Function of Batt Layer(s) and Fiber Type.

cotton had similar effects under 21 g/cm^2 pressure. Thermal resistance values for assemblies of two- and three-layers of cotton were greater, however, than thermal resistance values for assemblies of two- and three-layers of wool and polyester, under the three pressure levels. These results might suggest that a fibrous batt of given thermal resistance value could be constructed from any textile fiber by making the batt sufficiently thick.

Interaction of Multiple Layers by Pressure Level

The analysis of variance table (Table 13, Appendix "D") shows the two-way multiple layer by pressure level interaction was significant at the .01 level in effecting thermal resistance of the assemblies. Figure 12 illustrates as pressure level was increased, for each batt layer-combination, the thermal resistance for the assemblies decreased. Mean thermal resistance values from which the illustrations in Figure 12 were derived are given in Table 10, Appendix "C".

Simpler graphs depicting the relationship between thermal resistance as a function of the interaction effect between multiple layers and pressure level, for each of the fibrous batts, are provided in Figures 13 and 14. A single batt-layer of polyester produced larger thermal resistance values than single layers of the other fibrous batts, under 7 g/cm^2 pressure. A single batt-layer of wool gave higher thermal resistance readings than single layers of the other fibrous batts, under 21 g/cm^2 pressure (Figure 13). Fabric-batt assemblies with one-, two-, and three-layers of cotton batt (Figure 14) produced the largest thermal resistance values of the selected fabric-batt assemblies.

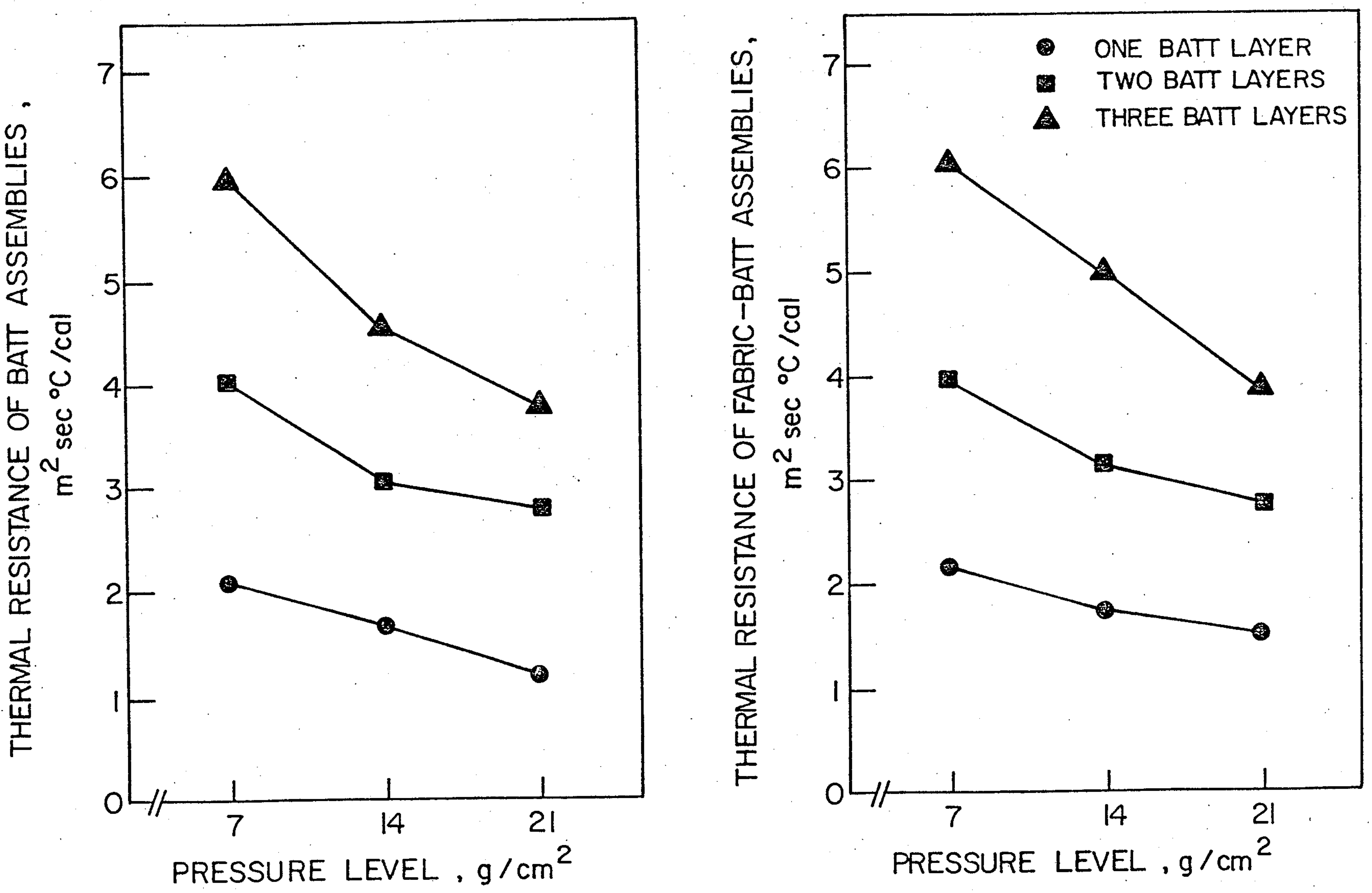

Figure 12. Thermal Resistance for Batt Assemblies and Fabric-Batt Assemblies as a Function of Pressure Level and Batt Layer(s).

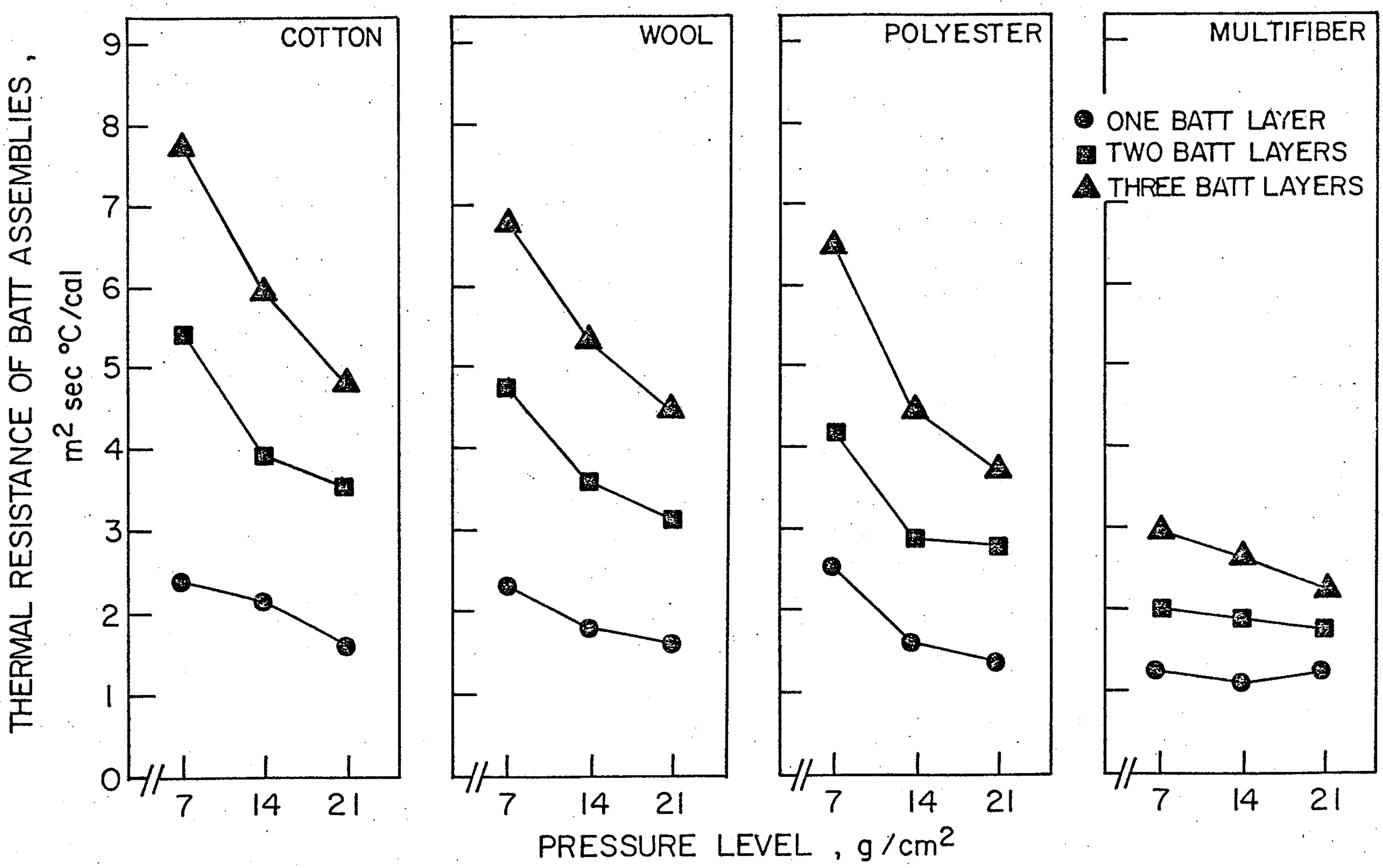

Figure 13. Thermal Resistance for Batt Assemblies of Each of the Cotton-, Wool-, Polyester- and Multifiber-Batts as a Function of Pressure Level and Batt Layer(s).

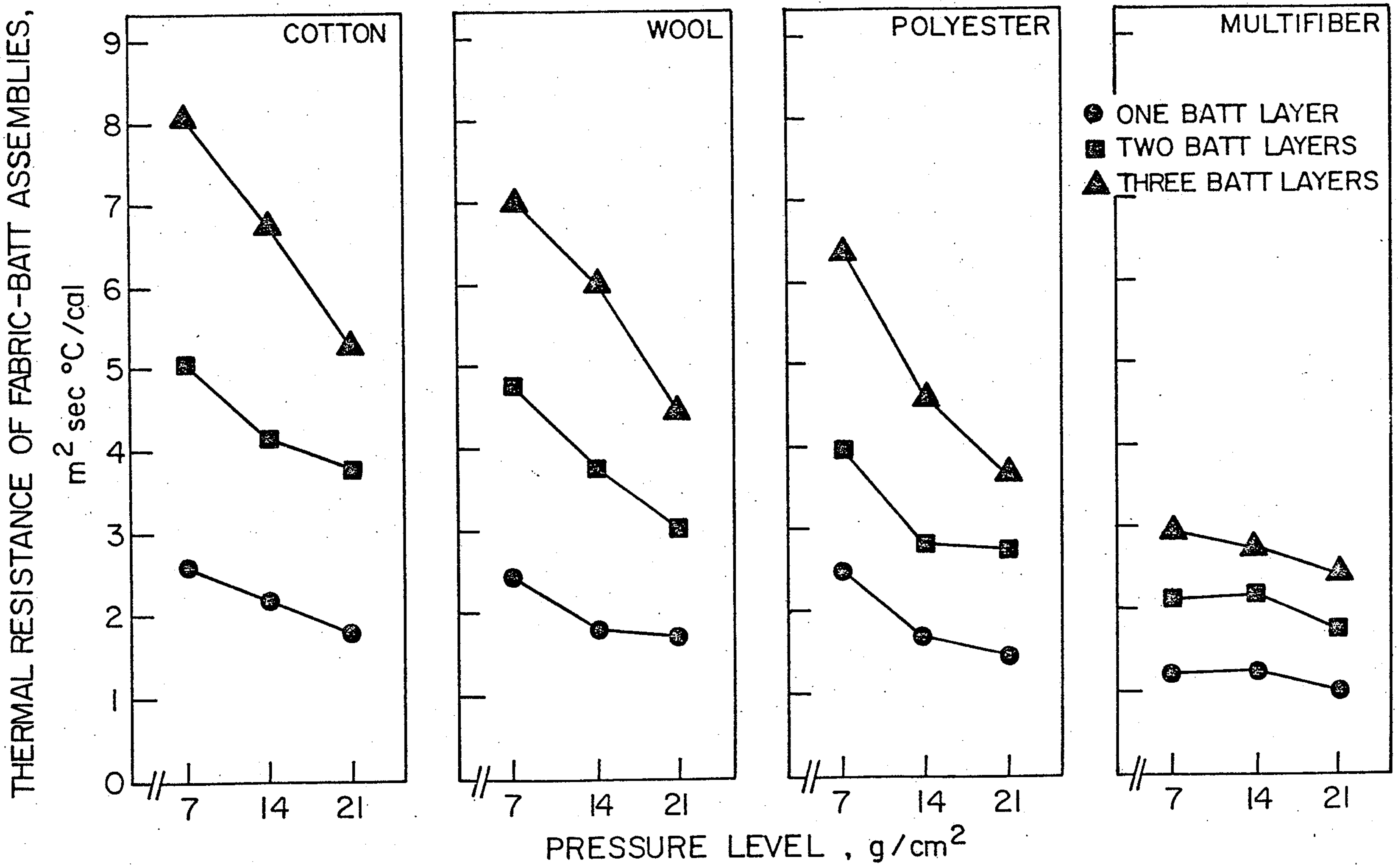

Figure 14. Thermal Resistance for Fabric-Batt Assemblies of Each of the Cotton-, Wool-, Polyester-, and Multifiber-Batts as a Function of Pressure Level and Batt Layer(s).

Frederick (11), Pierce and Rees (24), and Weiner and Shah (30) found thermal resistance of fabric assemblies and of single batt-layers to be effected by the mechanical properties of the constituent fiber. These researchers recognized that batts made from one fiber type could provide better thermal resistance than batts made from another fiber type due to inherent variations in stress-response characteristics of different fibers. Fibrous batts that produce higher thermal resistance should therefore maintain greater thickness under equivalent pressure conditions.

Kaswell (17), Morton and Hearle (23), and Rees (25) commented on the compressional resilience of different fibers. They found wool to have the greatest loftiness and greatest ability to retain loftiness of the cotton-, wool-, and cellulose acetate-fiber masses they tested. Morton and Hearle found wool staple-fiber mass to possess higher percentage compressional resilience than polyester staple-fiber mass, under severe pressure conditions. Perhaps the difference in thermal resistance for assemblies of wool-, cotton-, and polyester-fibers, in the present study, might also be attributed to the mechanical properties of the fiber, especially to their compressional resilience.

Interaction of Pressure Level by Fiber Type

Figure 15 illustrates a series of downward sloping lines. These lines indicate as pressure level was increased from 7 g/cm^2 to 14 g/cm^2 to 21 g/cm^2 the thermal resistance for the assemblies decreased. The slope of these lines in Figure 15, for the cotton-, wool-, and polyester-batts, are similar to those depicted in Figure 8. This might suggest

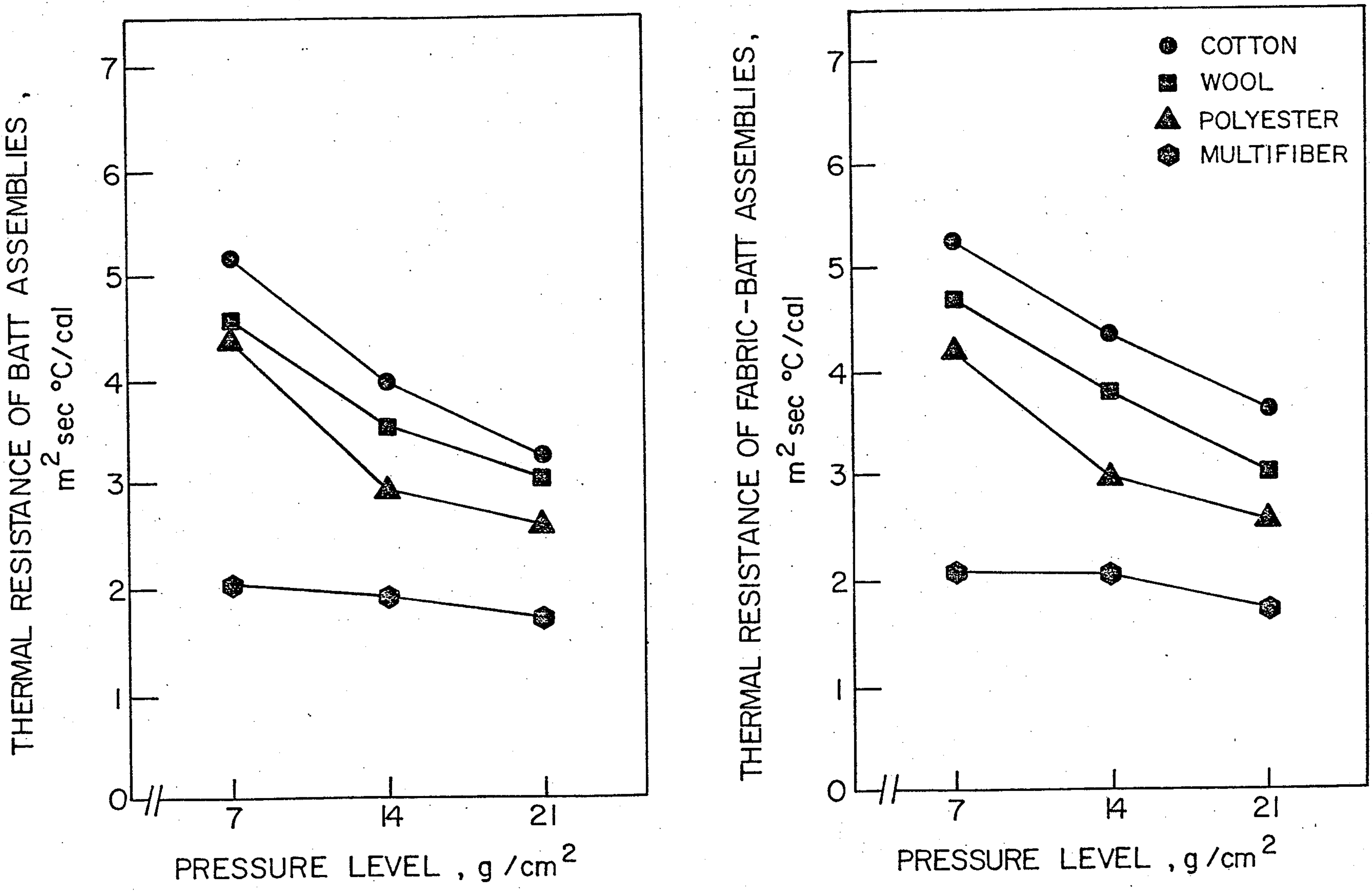

Figure 15. Thermal Resistance for Batt Assemblies and Fabric-Batt Assemblies as a Function of Pressure Level and Fiber Type.

that pressure level was exhibiting the most pronounced effect on the thermal resistance of the assemblies, and, that the chemical nature of the fiber was not having an appreciable effect. The thickness maintained by the particular fibrous batt, under applied pressure, is suspected of effecting the thermal resistance values.

Decreases in thermal resistance values for assemblies of wool- and cotton-batts were similar as pressure level was increased (Figure 15). Assemblies of polyester batt reacted differently, however, especially under 14 g/cm^2 pressure. Under this pressure level the wool- and cotton-batts maintained greater thickness than did the polyester batt (Table 3). Further, the decrease in thickness for the polyester batt was by a greater percentage than that for the cotton- and wool-batts. The slope of the lines for polyester assemblies, illustrated in Figure 15, are suspected of being a result of this sharper decrease in thickness exhibited. The compressional resilience of the polyester fiber appears to have been more severely altered, under 14 g/cm^2 pressure, to a point where the fiber became less resilient than the wool- or cotton-fibers. This theory is in keeping with Frederick's (11), Pierce and Rees's (24), and Weiner and Shah's (30) concept on the compressional resilience of different fibers.

Aelion and Brown (1), Burton and Edholm (8), Fanger (10), and Kaswell (17) pointed out that thermal conductivities of different fibers are similar. They concluded from this that fabric thermal resistance is independent of fiber chemistry. The suggestion, in this chapter, that chemical make-up of the fiber did not alter the thermal resistance of the assemblies is in line with these researcher's findings.

Further, the points corresponding to each of the cotton-, wool-, polyester-, and multi-fibers in Figure 15 moved closer together as pressure level was increased to a maximum of 21 g/cm^2. It is reasonable to expect that if pressure level was increased still further these points would continue to move closer together until they eventually overlapped. This would give evidence to conclude that chemical make-up of different fibers is not important in determining thermal resistance of textile fabrics.

Figures 16 and 17 illustrate simpler views of the relationship between thermal resistance of the assemblies as a function of the interaction effect between pressure level and fiber type. A single batt-layer of polyester produced larger thermal resistance values than did single layers of the other fibrous batts, under 7 g/cm^2 pressure. However, under 14 g/cm^2 pressure, single batt-layers of wool and cotton produced larger thermal resistance values. The compression effect on polyester became apparent under the 14 g/cm^2 pressure level. Similar trends were found with thermal resistance values of fabric-batt assemblies (Figure 17). These findings indicate further, with the application of pressure, differences in thermal resistance are given for assemblies which differ in fiber content. These results correlate with findings of Frederick (11), Fourt and Harris (12), Kaswell (17), and Weiner and Shah (30), which have been discussed previously.

Figure 17 shows thermal resistance values for fabric-batt assemblies containing one- and two-layers of multifiber batt increased as pressure level was increased from 7 g/cm^2 to 14 g/cm^2. These increases

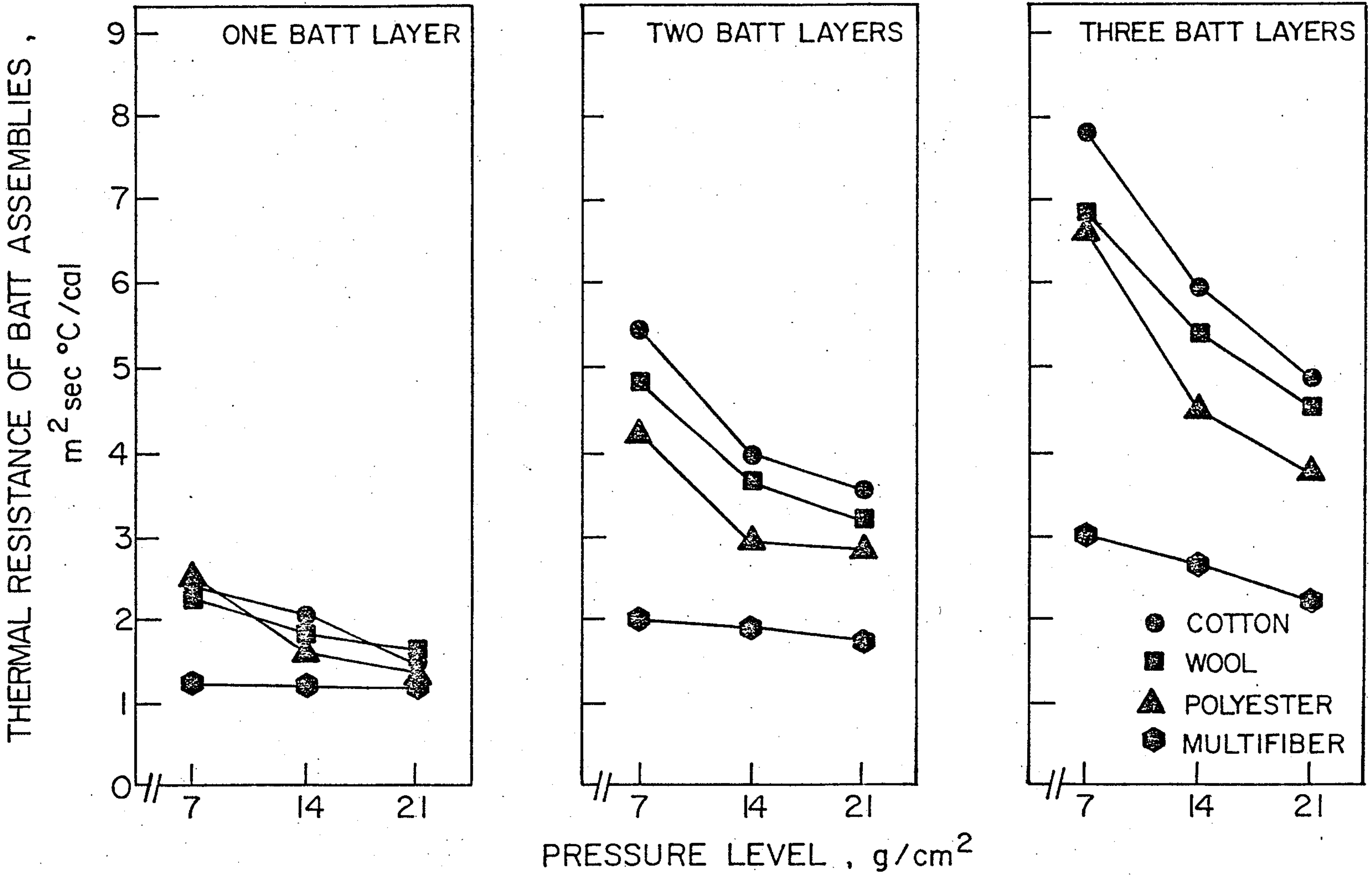

Figure 16. Thermal Resistance for Batt Assemblies Composed of One-, Two-, and Three-Batt Layer-Combinations as a Function of Pressure Level and Fiber Type.

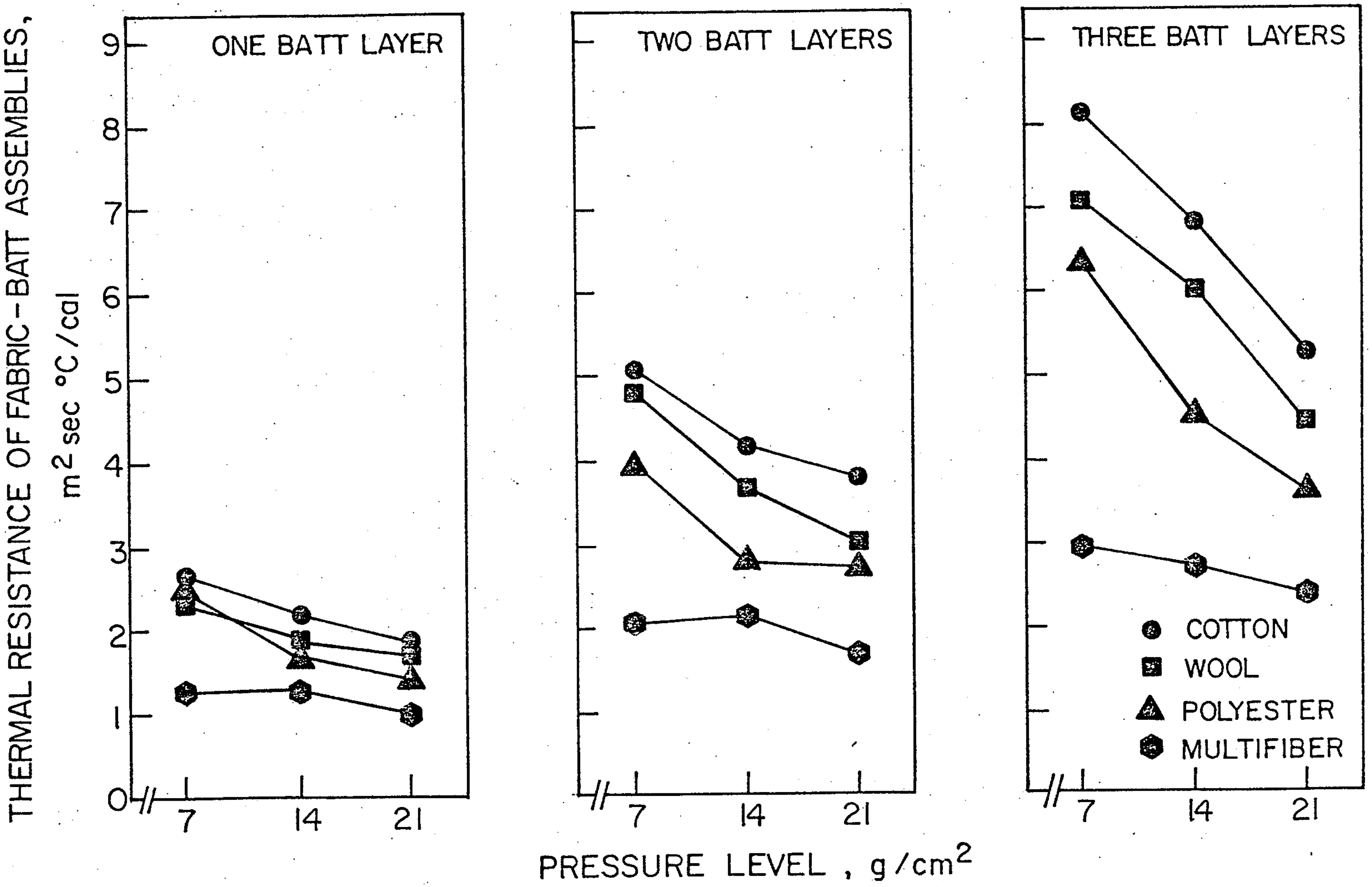

Figure 17. Thermal Resistance for Fabric-Batt Assemblies Composed of One-, Two-, and Three-Batt Layer-Combinations as a Function of Pressure Level and Fiber Type.

were 1.6% and 2.9%, respectively (Table 12, Appendix "C"). It is likely that initial thickness of the multifiber batt was too small to be substantially influenced by a pressure increase of this magnitude. Also, a film of air could have been entrapped between fabric- and batt-layers when the nylon- and cotton-Testfabrics were added. The overall result would be an increase in the thermal resistance for these assemblies.

Regression Analysis for Thickness, Pressure, and Thermal Resistance of the Assemblies

Correlation coefficients and multiple regression equation constants were calculated in an attempt to reinforce the statistical and non-statistical inferences given in this study. These values are recorded in Table 15, Appendix "D". The correlation coefficients for the assemblies show an extremely low correlation between the effects of thickness and pressure on thermal resistance values. As has been discussed in the previous sections, the calculated F-values (Table 13, Appendix "D") indicates that the number of batt layers of the assembly had the most pronounced effect while pressure level exhibited the least pronounced effect on the thermal resistance values of the assemblies. The higher correlation coefficient values recorded for polyester reinforces the suggestion that the polyester batt was more sensitive to pressure than were the other three fibrous batts tested.

The correlation coefficients indicate that the thickness of the assemblies is in inverse relationship with pressure exerted on the assemblies. It was found, in this study, as pressure applied to the assembly was increased the thickness of the assembly decreased. This trend was outlined in Table 3 and illustrated in Figures 8 and 12. The regression line constant for thickness, b2, indicates that the slope of the regression lines for cotton-, wool-, and polyester-batts were similar. The slopes were displaced progressively up the Y-axis (as the 'a' value increases) from each other with increasing order from polyester to wool to cotton. Figure 9 illustrates this trend pointing out that the slopes were not parallel. This was consistent with results of thickness measurements for the selected fibrous batts presented in Table 3.

Chapter 5

SUMMARY AND RECOMMENDATIONS

The present research investigated thermal resistance values of textile assemblies formed in a manner to resemble a cold-climate outer-garment. Thermal resistance of single- and multiple-layers of different fibrous batts was measured using a guarded hot-plate apparatus equipped with a 6-inch guarded hot-plate designed specifically for textile use, following modified ASTM Method D:1518. Test specimens were mounted between a hot- and cold-plate until thermal equilibrium was attained at which time thermal conductivity was measured. Thermal conductivity values were made for batt layers alone and for batt layers held between layers of nylon- and cotton-Testfabrics, under imposed pressure conditions, in a testing atmosphere of 25 ± 2°C and 42 ± 4% RH.

Thermal resistance values for the textile assemblies were statistically analyzed as two - 3 X 4 X 3 analyses of variance. The first analysis considered thermal resistance for the batt layers while the second analysis considered thermal resistance for fabrics and batt layers in combination. Factors considered in the analyses of data were: three batt layer-combinations - single-, double-, and triple-layers of batts; four fiber types of batts - cotton, wool, polyester, and a multi-fiber mixture; and three pressure levels of compression - 7 g/cm^2, 14 g/cm^2, and 21 g/cm^2. Significant main effects were obtained on both analyses for these factors, each significant at the .01 level.

The number of batt layers was the most important factor effecting thermal resistance values. Results indicated as the number of batt layers of the assemblies were increased the thermal resistance values for the assemblies increased. The thermal resistance values did not double when batts were increased from one- to two-layers nor did the values increase three-fold when batts were increased from one- to three layers. The fact that batts were cut and chosen at random such that thickness measurement of one batt-layer was not identical to the next may be a partial explanation of this phenomenon. One layer of each of the cotton-, wool-, and polyester-batts produced similar thermal resistance values. As the number of batt layers were increased, however, the cotton batt produced the largest values. The present study was not designed to consider number of batt layers necessary for optimum thermal resistance for the assemblies. Thus, a recommendation for future research would be to consider the amount of batt layers needed to produce optimum thermal resistance in such assemblies.

Results indicated Testfabric layers effected thermal resistance values for the assemblies. It might be worthwhile, therefore, to consider the thermal resistance of other fabrics suitable as outer- and lining-fabrics for use in cold-climate outerwear, in order to gain information on thermal resistance of a selection of textile fabrics. The present study was not designed to determine if an interaction effect exists between the fabric layers and other variables considered, on thermal resistance values. A recommendation for further study, therefore, would be to establish if this interaction effect exists, possibly by considering the Testfabric layers, as well as other suitable fabric layers, as a fourth factor in the analyses of variance.

Fiber type had an effect on thermal resistance for the assemblies but to a lesser extent than did the number of batt layers. It was suspected the chemical nature of the fiber type was not having a pronounced effect on thermal resistance values. Instead, the thickness maintained by the particular fiber, under applied pressure, was explained as effecting thermal resistance values. In order of increasing thermal resistance fiber types were: multifiber; polyester; wool; and cotton. This was reasonable in view of thickness measurements presented in Table 1. The present study was limited due to differences in physical properties of the selected fibrous batts. A suggestion for future study would be to obtain different fibrous batts possessing physical characteristics even more similar than those considered, possibly each having an identical physical property. This would enable a better basis for comparing thermal resistance values of different fibrous batts.

The attainment of thermal resistance values of other fiber types available for use in batt make-up for cold-weather outerwear would be another recommendation for further study. This would provide a range of information on changes in thermal resistance with fiber type. Also, the study of thermal resistance with different fiber types could provide more extensive information on the effects of compressional resilience of these different fibers.

Pressure level had less of an effect on thermal resistance for the assemblies than did the number of batt layers or fiber type. Results showed as pressure level was increased to a maximum of 21 g/cm^2 the thermal resistance for the assemblies decreased. The polyester batt was found to be more sensitive to pressure than were the other fibrous batts tested. Higher percentage compression of the polyester batt was possibly due to compressing the polyester fiber to the elastic limit. A recommendation for future study would be to examine the pressure effect on polyester fiber, specifically, in order to validate results of the present study and to determine the reason for this pressure effect. Also, since pressure level had an effect on thermal resistance values it appears reasonable to consider pressure levels higher than the 21 g/cm^2, possibly to 35 g/cm^2, as given in the standard testing procedures. Considering more than three pressure levels in any one study would be a suggestion for future research since this would provide more direct information into effects of pressure on thermal resistance values.

Batts made from one fiber type have been found to provide better thermal resistance than batts made from another fiber type due to inherent stress-response variations for different fibers. In the present study, the cotton batt produced the largest thermal resistance values. However, this study was not designed to measure thermal resistance of the textile assemblies after pressure had been applied continuously, over time, as would happen with a cold-climate outergarment in use. Therefore, the cotton batt should not be considered specifically, as the better fibrous batt of those selected in this study, in terms of high thermal resistance. A recommendation for future study would be to investigate thermal resistance for different fibrous batts as pressure is imposed on a continuous basis, over a period of time. This might provide information for the recommendation of a fiber type which maintains a high compressional resilience and thus high thermal resistance.

The two-way interactions between the factors were found to significantly influence thermal resistance for the assemblies. Each was significant at the .01 level. This indicated the importance of considering the number of batt layers, fiber type of batt, and pressure level of compression, as they interrelate, to obtain optimum thermal resistance. Results showed the multiple layers by fiber type interaction had the most pronounced effect of the significant interactions, on thermal resistance values. This was reasonable in view of the significant main effects for factors -multiple layers and fiber type. Results gave evidence to suggest that thickness of the assemblies and pressure applied to the assemblies effected a change in thermal resistance, while the chemical nature of different fibers did not have a pronounced effect on the values.

A t-test, significant at the .01 level, showed no difference between thermal resistance for batt layers alone and for fabrics and batts in combination. Thermal resistance values of one layer of each of the Testfabrics were found quite small in comparison to that for the batt layers.

Results of the present study were correlated with and examined in view of previous research findings. Correlation coefficients and multiple regression equation constants showing the relationship between pressure, thickness, and thermal resistance for the assemblies were calculated and used to reinforce findings from the present research. Results of the analysis suggested further that thickness of the assemblies exhibited the most pronounced effect on thermal resistance values while pressure level exhibited the least pronounced effect. The analysis gave evidence to suggest interdependence between thickness measurements and pressure applied to the assemblies. Also, results of the analysis provided information suggesting sensitivity of the polyester batt to pressure.

Based on results of the present study, improved thermal resistance of a fabric-batt assembly used for cold-weather conditions could be achieved by increasing the number of batt layers between the outer- and lining-fabrics of the assembly, until optimum thermal resistance is obtained. However, the increase in thermal resistance, for all fiber types, with an increase in batt-layer number, in the present study, was found to be modified by the specific fiber type involved, as well as by the degree to which the batts were compressed. Fiber type of batt, therefore, should be selected on the basis of its ability to withstand compression, since maintenance of thickness is important to the attainment of high thermal resistance.

The present study dealt only with new textile materials and therefore the effects of wear on thermal resistance was not determined. In order to obtain additional information on thermal resistance of cold-weather outergarments it might be worthwhile to introduce a study to consider thermal resistance with wear, and perhaps with some refurbishing processes such as laundering or dry cleaning. These suggestions appear reasonable since it is necessary to maintain the thermal resistance of a cold-climate outergarment with use, over time.

Throughout the present study, thermal resistance has been established as an important consideration for textile assemblies used to form a cold-weather outergarment. The goal has been to obtain an outergarment which provides adequate warmth without heavy weight. The present research considered the effects of some important variables on textile assemblies which have been formed in a manner similar to such outergarments. The recommendations for further study, in this chapter, are expected to provide additional information into thermal resistance of cold-climate outerwear.

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APPENDICES

APPENDIX "A"

TEST FABRIC

Table 4. Source of Test Fabric

Fabrics	Supplier
Nylon	Test fabric Incorporated, New Jersey, New York, U.S.A.
Cotton	Test fabric Incorporated, New Jersey, New York, U.S.A.

Batts	Supplier
Cotton	Toronto Quilting and Embroidery, Winnipeg, Manitoba, Canada
Multifiber	Toronto Quilting and Embroidery, Winnipeg, Manitoba, Canada
Wool	"Metav"-Brandon Mills, Brandon, Manitoba, Canada
Polyester	"Metav"-Brandon Mills, Brandon, Manitoba, Canada

APPENDIX "B"

CALIBRATION CHARTS

Table 5. Calibration Chart for Cold Plates

Millivolt Reading	Temperature °C	Millivolt Reading	Temperature °C
.486	10.0066	.510	11.0859
.487	10.0516	.511	11.1308
.488	10.0965	.512	11.1758
.489	10.1415	.513	11.2208
.490	10.1865	.514	11.2657
.491	10.2314	.515	11.3107
.492	10.2764	.516	11.3557
.493	10.3214	.517	11.4007
.494	10.3663	.518	11.4456
.495	10.4113	.519	11.4906
.496	10.4563	.520	11.5356
.497	10.5012	.521	11.5806
.498	10.5462	.522	11.6255
.499	10.5912	.523	11.6705
.500	10.6361	.524	11.7155
.501	10.6811	.525	11.7604
.502	10.7261	.526	11.8054
.503	10.7711	.527	11.8504
.504	10.8160	.528	11.8954
.505	10.8610	.529	11.9403
.506	10.9060	.530	11.9853
.507	10.9510	.531	12.0303
.508	10.9959	.532	12.0752
.509	11.0409	.533	12.1202

Table 6. Calibration Chart for Hot Plate

Millivolt Reading	Temperature °C	Millivolt Reading	Temperature °C
1.384	31.9846	1.408	33.0441
1.385	32.0288	1.409	33.0882
1.386	32.0729	1.410	33.1324
1.387	32.1171	1.411	33.1765
1.388	32.1612	1.412	33.2206
1.389	32.2054	1.413	33.2648
1.390	32.2495	1.414	33.3089
1.391	32.2936	1.415	33.3531
1.392	32.3378	1.416	33.3972
1.393	32.3819	1.417	33.4413
1.394	32.4261	1.418	33.4855
1.395	32.4702	1.419	33.5296
1.396	32.5144	1.420	33.5738
1.397	32.5585	1.421	33.6179
1.398	32.6026	1.422	33.6621
1.399	32.6468	1.423	33.7062
1.400	32.6909	1.424	33.7504
1.401	32.7351	1.425	33.7945
1.402	32.7792	1.426	33.8386
1.403	32.8233	1.427	33.8828
1.404	32.8675	1.428	33.9269
1.405	32.9116	1.429	33.9711
1.406	32.9558	1.430	34.0152
1.407	32.9999	1.431	34.0593

APPENDIX "C"

EXPERIMENTAL RESULTS

Table 7. Measured Values of Thermal Resistance for Cotton and Nylon Testfabrics*

Number of Fabric Layers	Cotton Thermal Resistance $m^2 sec\ ^oC/cal$	Cotton Thickness mm	Nylon Thermal Resistance $m^2 sec\ ^oC/cal$	Nylon Thickness mm
18	1.19	5.71	1.01	3.35
16	1.10	5.08	0.94	3.12
14	1.05	4.44	0.88	2.89
12	0.91	3.81	0.79	2.69

* Based on an average of two thermal resistance measurements; thickness measurements calculated at $7g/cm^2$ pressure level.

Table 8. Percent Change in Thermal Resistance Values Between Batt- and Fabric-Batt-Assemblies

Number of Batt Layers	Fiber Type	Percent Change in Thermal Resistance Value(%)* 7g/cm^2 pressure	14g/cm^2 pressure	21g/cm^2 pressure
1	Cotton	+10.0	+ 6.2	+15.0
	Wool	+ 3.4	+ 1.7	+ 9.2
	Polyester	- 1.6	+ 4.9	+ 9.6
	Multifiber	+ 3.2	+ 9.2	-18.3
2	Cotton	- 5.9	+ 6.4	+ 9.2
	Wool	+ 2.1	+ 3.6	- 3.6
	Polyester	- 5.3	- 2.5	- 1.8
	Multifiber	+ 5.0	+13.7	+ 0.6
3	Cotton	+ 4.5	+14.1	+10.6
	Wool	+ 3.2	+12.4	- 2.3
	Polyester	- 3.6	+ 3.4	- 1.1
	Multifiber	+ 0.7	+ 3.8	+ 9.1

* Based on an average of two thermal resistance measurements.

$$\%\ \text{change} = \left[\frac{\text{Thermal Resistance of Fabric-Batt Assemblies} - \text{Thermal Resistance of Batt Assemblies}}{\text{Thermal Resistance of Batt Assemblies}}\right] \times 100$$

Table 9. Mean Thermal Resistance for Batt- and Fabric-Batt-Assemblies as as Function of the Main Factors

	Batt Assemblies		Fabric-Batt Assemblies	
	Mean Thermal Resistance $m^2 sec\ ^oC/cal$	SD	Mean Thermal Resistance $m^2 sec\ ^oC/cal$	SD
Number of Batt Layers*				
1	1.75	0.48	1.84	0.52
2	3.31	1.15	3.35	1.09
3	4.81	1.76	5.03	1.87
Fiber Type**				
Cotton	4.16	2.02	4.44	2.11
Wool	3.77	1.75	3.90	1.85
Polyester	3.34	1.60	3.31	1.52
Multifiber	1.89	0.63	1.96	0.68
Pressure Level, g/cm^2*				
7	4.08	2.17	4.11	2.18
14	3.11	1.54	3.34	1.76
21	2.68	1.24	2.77	1.30

* Based on an average of twenty-four thermal resistance measurements.

** Based on an average of eighteen thermal resistance measurements.

Table 10. Mean Thermal Resistance for Batt- and Fabric-Batt Assemblies as a Function of Interaction Effects of the Main Factors

				Batt Assemblies		Fabric-Batt Assemblies	
Interaction	Number of Batt Layers	Fiber Type	Pressure Level g/cm^2	Mean Thermal Resistance m^2sec °C/cal	SD	Mean Thermal Resistance m^2sec °C/cal	SD
Multiple Layers X Fiber Type**	1	Cotton	-	2.03	0.40	2.23	0.39
	2		-	4.27	1.01	4.36	0.67
	3		-	6.18	1.50	6.74	1.41
	1	Wool	-	1.92	0.36	1.63	0.31
	2		-	3.81	0.84	3.85	0.92
	3		-	5.57	1.18	5.83	1.34
	1	Polyester	-	1.84	0.63	1.90	0.54
	2		-	3.30	0.78	3.19	0.69
	3		-	4.89	1.51	4.85	1.38
	1	Multifiber	-	1.22	0.03	1.21	0.14
	2		-	1.86	0.14	1.99	0.23
	3		-	2.59	0.38	2.70	0.29
Pressure Level X Multiple Layers**	1	—	7	2.13	0.60	2.21	0.62
		—	14	1.67	0.38	1.76	0.38
		—	21	1.45	0.19	1.54	0.36
	2	—	7	4.08	1.48	4.01	1.36
		—	14	3.07	0.89	3.21	0.90
		—	21	2.78	0.77	2.82	0.86
	3	—	7	6.03	2.12	6.12	2.23
		—	14	4.60	1.45	5.04	1.79
		—	21	3.79	1.17	3.93	1.24
Pressure Level X Fiber Type**	-	Cotton	7	5.19	2.70	5.29	2.75
	-		14	3.99	1.93	4.39	2.29
	-		21	3.30	1.61	3.65	1.74
	-	Wool	7	4.63	2.25	4.77	2.32
	-		14	3.59	1.78	3.86	2.11
	-		21	3.08	1.43	3.06	1.31
	-	Polyester	7	4.44	2.03	4.28	1.94
	-		14	2.97	1.41	3.03	1.45
	-		21	2.62	1.17	2.63	1.08
	-	Multifiber	7	2.06	0.86	2.11	0.84
	-		14	1.91	0.72	2.06	0.72
	-		21	1.71	0.48	1.72	0.67

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* Based on an average of eight thermal resistance measurements.

** Based on an average of six thermal resistance measurements.

Table 11. Percent Increase in Thermal Resistance for Batt- and Fabric-Batt-Assemblies as the Number of Batts are Increased from One- to Two-Layers and from One- to Three-Layers

Pressure Level g/cm^2	Number of Batt Layers	Fiber Type	Percent Increase of Thermal Resistance Value (%)*	
			Batt Assemblies	Fabric-Batt Assemblies
7	2	Cotton	+126.4	+ 94.3
		Wool	+103.4	+100.8
		Polyester	+ 64.7	+ 59.0
		Multifiber	+ 60.5	+ 63.3
	3	Cotton	+225.5	+209.1
		Wool	+193.1	+192.5
		Polyester	+158.0	+152.9
		Multifiber	+137.9	+132.0
14	2	Cotton	+ 87.6	+ 87.8
		Wool	+ 97.2	+101.1
		Polyester	+ 79.5	+ 66.9
		Multifiber	+ 58.8	+ 65.4
	3	Cotton	+184.7	+205.9
		Wool	+198.2	+228.8
		Polyester	+174.5	+170.4
		Multifiber	+121.8	+110.8
21	2	Cotton	+118.1	+107.1
		Wool	+ 91.4	+ 69.1
		Polyester	+106.6	+ 85.2
		Multifiber	+ 38.0	+ 65.4
	3	Cotton	+200.0	+188.6
		Wool	+176.1	+147.2
		Polyester	+170.1	+144.3
		Multifiber	+ 78.0	+129.8

* Based on an average of two readings using measured thermal resistance values for one batt layer as control.

Table 12. Percent Change in Thermal Resistance for Batt- and Fabric-Batt-Assemblies as Pressure Level is Increased from 7g/cm^2 to 14g/cm^2 and from 7g/cm^2 to 21g/cm^2

Number of Batt Layers	Pressure Level g/cm^2	Fiber Type	Percent Change of Thermal Resistance Value (%)*	
			Batt Assemblies	Fabric-Batt Assemblies
1	14	Cotton	-14.3	-18.5
		Wool	-28.7	-30.9
		Polyester	-58.4	-48.5
		Multifiber	- 4.2	+ 1.6
	21	Cotton	-49.4	-42.9
		Wool	-42.9	-35.4
		Polyester	-87.5	-68.5
		Multifiber	- 0.8	-23.1
2	14	Cotton	-38.0	-22.5
		Wool	-32.8	-30.8
		Polyester	-45.3	-41.5
		Multifiber	- 5.3	+ 2.9
	21	Cotton	-55.0	-34.1
		Wool	-51.9	-60.8
		Polyester	-49.5	-44.6
		Multifiber	-16.4	-21.5
3	14	Cotton	-30.8	-19.7
		Wool	-26.9	-16.5
		Polyester	-48.9	-38.9
		Multifiber	-11.7	- 8.4
	21	Cotton	-62.1	-53.1
		Wool	-51.8	-60.2
		Polyester	-78.8	-74.4
		Multifiber	-34.7	-24.3

* Based on an average of two readings using measured thermal resistance values at 7g/cm^2 pressure level as control.

APPENDIX "D"

STATISTICAL ANALYSIS

Table 13. Analyses of Variance of Thermal Resistance for Batt- and Fabric-Batt-Assemblies

Item	Multiple Layers (A)	Fiber Type (B)	Pressure Level (C)	AXB	AXC	BXC	AXBXC	Residual	Total
Batt Assemblies									
df	2	3	2	6	4	6	12	36	71
SS	205.80	97.15	45.61	24.35	9.56	9.71	1.82	3.30	397.31
MS	102.90	32.38	22.81	4.06	2.39	1.62	0.15	0.09	-
F.01	5.20	4.41	5.20	3.35	3.91	3.35	2.74	-	-
F	1123.74*	353.64*	249.07*	44.33*	26.11*	17.67*	1.66	-	-
Fabric-Batt Assemblies									
df	2	3	2	6	4	6	12	36	71
SS	225.52	112.73	40.33	28.20	8.98	7.93	2.96	5.75	432.39
MS	112.76	35.58	20.16	4.70	2.24	1.32	0.25	0.16	-
F.01	5.20	4.41	5.20	3.35	3.91	3.35	2.74	-	-
F	706.06*	222.77*	126.26*	29.43*	14.06*	8.27*	1.54	-	-

* Significant at the .01 level

Table 14. Comparison of Mean Thermal Resistance Values for Batt- and Fabric-Batt-Assemblies

Type of Assembly	Number of Samples	Mean Thermal Resistance m^2sec ^{o}C/cal	SD	t
Batt	36	3.29	1.73	0.2717
Fabric-Batt	36	3.40	1.80	

* Significant at .01 level (t = 2.648).

Table 15. Correlation Coefficients and Multiple Regression Constants Showing Relationship Between Pressure, Thickness, and Thermal Resistance for Batt- and Fabric-Batt-Assemblies

Type of Assembly	Fiber Type	Pressure g/cm^2	Thickness mm	Thermal Resistance $m^2 sec\ ^oC/cal$	Correlation Coefficient	Regression Line Constants		
						a	b_1	b_2
Batt	Cotton	X_1	X_2	Y	-0.08	0.48	-1.69	15.73
	Wool	X_1	X_2	Y	-0.42	0.05	0.61	17.26
	Polyester	X_1	X_2	Y	-0.53	-0.02	1.92	15.06
	Multifiber	X_1	X_2	Y	-0.25	0.14	-0.09	17.47
Fabric-Batt	Cotton	X_1	X_2	Y	-0.26	1.41	-5.18	15.01
	Wool	X_1	X_2	Y	-0.42	0.28	0.92	16.75
	Polyester	X_1	X_2	Y	-0.53	0.27	1.33	15.46
	Multifiber	X_1	X_2	Y	-0.26	0.32	-0.43	17.50