THE THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF ELECTRICALLY CONDUCTIVE FABRICS

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ABSTRACT

The thermal conductivities and electrical resistivities of seven electrically conductive fabrics and one electrically insulative fabric were measured. The following fabrics were tested: a 100% spun nylon, which was electrically insulative; four electrically conductive fabrics containing metal (nylon/stainless steel blend, 100% stainless steel, glass fibre/stainless steel blend, and polyester/brass blend); and three electrically conductive fabrics containing carbon ("Graphite Cloth", glass fibre/carbon blend, and olefin/carbon blend).

The thermal conductivities were measured on a guarded hot plate apparatus. The fabrics containing carbon fibres were found to have higher thermal conductivities than all other test fabrics. The quantity of metal fibre in the fabrics did not influence thermal conductivity in a uniform pattern. The conductivities of fabrics containing metal in continuous filament form were high but the fabric containing metal in staple form had a conductivity comparable to conventional fabrics.

The electrical resistivities of all test fabrics were measured using an ohmmeter and circular electrodes. Warp and weft strips of anisotropic fabrics were also measured with the ohmmeter and electrode clips. The electrical resistivities of all fabrics containing metal were lower than those of all metal-free fabrics. The resistivities of fabrics containing metal in continuous filament form were lowest.

Application of the results to design of electrically heated clothing was discussed. The quantity of electrically conductive test fabric required to maintain man's equilibrium thermal comfort was theoretically determined for a model situation based on physiological, climatic, and apparel conditions typical of those encountered in a cold environment.

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INTRODUCTION

The current development of northern trade routes and interest in improving the habitability of Arctic areas has renewed the need to consider clothing produced for cold environments. Concerned individuals and groups, particularly the military, have extensively studied cold weather clothing since World War II. Both physiological needs of the body and designs for clothing assemblies to meet these needs have been well documented by such authors as Newburgh (35), Burton and Edholm (9), Kenchington (28), Turl (46), Alexander (2), and Fourt and Hollies (16).

Safety, economy, comfort, mobility, and thermal exchange have been considered important for the design of protective clothing. These considerations often impose incompatible requirements, so that attaining maximum efficiency in one aspect is only possible with a reduction in efficiency in another. For example, optimum thermal insulation is often obtained with additional layers of clothing which may hamper bodily movement and interfere with moisture exchange between the body and the environment. As a consequence of this incompatibility, a clothing assembly that satisfies all the requirements for cold climates has not been reported in the literature.

Thermal exchange and the rate of bodily heat loss through garments are largely controlled by the thermal conductivity of the fabrics. Fabrics and clothing must allow for a comfortable rate of exchange between man and his environment, under both varying climatic conditions and degrees of activity.

One method of maintaining thermal equilibrium at any level of activity without excessive bulk would be to provide supplementary heat of electrical origin, regulated according to bodily needs. The principle was utilized in apparel designed for World War II pilots, but proved unsuccessful owing to technological inadequacies. Batteries or generators of adequate power and sufficient lightness to be carried on the body were not available. Moreover, the conducting wires in the fabrics were subject to broken connections that resulted in power failures (35).

Recent production of electrically conductive fabrics which appear to be capable of overcoming past difficulties and satisfying requirements for cold weather clothing motivated the present investigation. The use of such fabrics in heated clothing assemblies is complicated by a lack of knowledge about the thermal conductivity and the electrical resistivity of the fabrics, and the influence of the latter property on the former.

The electrical resistivity of textiles has been investigated, but methods have been designed for testing fabrics of high resistance and interest has been focused upon the dissipation of static electricity. Previous techniques are not suitable for measuring the resistivity of those electrically conductive fabrics which are capable of generating heat.

The major purpose of the present research was to measure the thermal conductivity and electrical resistivity of seven electrically conductive fabrics, four containing metal and three containing carbon, and an electrically insulative fabric. An additional objective was to apply the thermal and electrical results in a theoretical determination of the feasibility of using electrically conductive fabrics to heat clothing.

REVIEW OF LITERATURE

Study of electrically conductive fabrics in relation to their application in heated clothing involves the concept of heat generation resulting from resistance to an electric current. The fabric property associated with heat transmission in garments is thermal conductivity, and that associated with electrical conduction is electrical resistivity. The literature review therefore considers: (1) electrically conductive fabrics, (2) measurement of fabric thermal conductivity, and (3) measurement of fabric electrical resistivity.

Because investigators have used varying terminology, the following definitions explain terms relevant both to the literature review and the present work.

Thermal Conductivity. The rate of heat flow across unit area of a material under unit temperature gradient is referred to as the thermal conductivity (53). This term refers to heat transmission through fabrics by conduction, and is numerically equal to the fabric thickness divided by its thermal resistance.

Thermal Resistance. The ratio of the temperature difference across a thermal path to the rate of heat flow along that path defines thermal resistance (39). The thermal resistance of a flat, homogeneous material is inversely proportional to its thermal conductivity (11). The effectiveness of a fabric in preventing heat transmission from an uncovered object is referred to as the thermal insulation of the fabric (31).

Electrical Resistance. The electrical resistance of a material is defined by Ohm's Law as:

$$R = \frac{V}{I} \qquad \ldots 1$$

where R is the resistance, V is the voltage applied, and I is the current that flows (26).

Electrical Resistivity. For a material of cross-sectional area A and length L, resistivity is defined mathematically as:

$$\rho = \frac{RA}{L} \text{ ohm-metres (26).} \qquad \ldots 2$$

For the special case of a square fabric of thickness d, the resistance (R') may be expressed in ohms per square. Since:

$$A = Ld$$

$$R' = \frac{\rho L}{A}$$

$$R' = \frac{\rho L}{Ld}$$

$$\text{and} \quad R' = \frac{\rho}{d} \qquad \ldots 3$$

Electrically Conductive Fabrics

Electrically heated clothing may offer a practicable solution to the problems encountered with conventional cold climate clothing for two reasons: (1) an internal heat source reduces the need for thick and cumbersome garments, and (2) the heat can be adjusted to be compatible with the rate of bodily heat loss. Field trials with electrically heated wire gloves have demonstrated additionally that:

1. Supplementary heat permits a longer tolerance to cold and contributes to dexterity.

2. When the body is adequately heated less insulation is required on the extremities.

3. The most efficient way to maintain comfort in the hands is to supply heat not to them but to the body.

4. The possibilities of supplying heat to the body should be investigated (43).

For use as resistance heating units in garments, electrically conductive fabrics containing conducting fibres have superior performance characteristics relative to electrically wired fabrics. Fabrics containing wires are necessarily inflexible and unreliable as a heat source because breakage of one wire arrests current flow. Flexibility, formability, sewability, and a relatively soft hand may be retained in fabrics which contain conducting fibres. The fibres are distributed either as continuous filaments in a conducting yarn or as staple fibres in a fabric blend. The resultant distribution patterns provide alternate pathways for an electrical current and loss of a single carbon or metal yarn reduces performance only imperceptibly (21). The magnitude of current which the fabrics can accommodate is controlled by varying such fabric structure factors as fibre content and weave pattern. Carbon fabrics, for example, have been constructed to have resistivities ranging from 0.2 to 30 ohms per square (21). Conductive fabrics are readily fitted with electrical connections for use with a power supply. Metal-containing fabrics can be soldered, and light clamping pressure can be applied to carbon-containing fabrics (21, 13). The electrical performance of conductive fabrics is consistently good because their properties do not change appreciably over time or under varying conditions. Metal fibres have a high oxidative and corrosive resistance and carbon fibres are chemically inert (17, 25, 21).

The advantages of electrically conductive fabrics are realized, then, in fabrics containing either metal or carbon as the conducting material.

Fabrics Containing Metal Fibres

The information related to metal-containing fabrics is largely in the form of descriptive advertising literature. It specifies neither the thermal conductivity or electrical resistivity of the fabrics, nor the manner in which the fabrics could be used in heated garments.

The Ryujin Company of Japan has produced electrically conductive fabrics, designated as either sheet or cloth heaters (15). The sheet heater consists of metal yarns woven with glass or synthetic fibre yarns. The resultant fabric is coated with an unidentified conducting material. The cloth heater contains both metal and insulated yarns in the warp direction. The weft yarns are impregnated with an unidentified conducting material. The manufacturer claims that both heaters are flexible and are intended for use with low voltage electrical supplies. Technical literature referring to their use in clothing assemblies was not available.

Both the Brunswick Corporation Metallic Fibres Division and the Hoskins Manufacturing Company have recently produced extremely fine metal fibres processible on textile machinery (48, 17, 25). Stainless steel has been found to be well suited to such production. Although stainless steel fibres were designed principally to discharge static electricity in carpets, they also have been used to generate heat because they offer moderate resistance to electric current flow (48, 7).

Metal fibres in staple and continuous filament form have been used alone or blended with other fibres (49). The fabrics produced from them possess a flexibility and drape comparable to those of conventional textiles (48, 49). The fibre and fabric properties have been used to advantage in heated seat pads, draperies, bedding, and diving suits (7).

Some experimental work has been done in using the metal-containing fabrics in heated sleeping bags and vests but unfortunately the information is proprietary (8).

Fabrics Containing Carbon

Electrically conductive fabrics have been produced containing carbon in the form of both carbon and graphite fibres. Relative to metal yarns, carbon and graphite yarns have a low abrasion resistance and flex life. As a result the scope of their application is more limited in unrigidified textile structures (50). Carbon and graphite fibres have been used mainly in reinforced composites, particularly in the aerospace industry, but they have also been used in conventional textile fabrics (41).

According to the manufacturer, the electrical resistance of graphite fibres is higher than carbon fibres, and it is moderately high compared to metals (33, 18). Since both carbon and graphite fibres conduct electricity, however, and both are capable of producing heat when traversed by an electric current, they have been used in conductive fabrics (41). Their possible influence on the thermal insulating power of the fabrics has not been described in the literature.

"Graphite Cloth"[1] is an electrically conductive

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[1] Trade name of Union Carbide Corporation Carbon Products Division.

fabric made from very pure, flexible graphite filaments of fine diameter. Its principal applications have been industrial, but as the fabric can be connected to a portable power supply utilization of it as a heating element in clothing may be possible (13).

Carbon filaments can be used in combination with non-conducting fibres to make an electrically conductive fabric and most often they have been used with glass because of similarity in the fibre properties. Although the flexibility, hand, and controlled electrical resistivity of the resulting fabrics appear to be suitable for use in heated garments, such an application has not been reported in the literature (47, 21, 14).

Information concerning the thermal conductivity and electrical resistivity of fabrics, and the effect of conducting fibres on the thermal conductivity is fundamental to using electrically conductive fabrics in the design of heated clothing. Absence of such information in the literature created a need to examine those aspects of the fabrics.

Measurement of the Thermal Conductivity of Fabrics

Marsh (30), G. J. Morris (31), and Fourt and Hollies (16) have reviewed extensively the numerous methods for measuring fabric thermal conductivity. In early investigations the greatest difficulty was found to be obtaining accurate thickness measurements (53, 31). The compressibility of fabrics requires that the position of the fabric surface be arbitrarily fixed by measuring thickness with the fabric under a definite pressure. In a recent investigation, Rowlands (42) found a marked hysteresis in the load-thickness graph of fabrics and a large variation of thickness at low pressures.

M. A. Morris (32) suggested that the accuracy of fabric thermal conductivity measurements might also be affected by inclusion of air layers. The effective thickness of fabrics with rough or irregular surfaces can be considerably increased if air is held between layers of fabric, or between fabrics and the apparatus. Because fabrics are relatively thin materials and air is an insulator, the effect of an air layer can be sufficiently large to increase the measured thermal resistance and create large errors.

Early investigators frequently failed to control heat transfer by processes other than conduction. Heat transferred in the air-filled interstices of the fabric by means of radiation or convection, or from changes in the fabric moisture content, may have influenced resulting data (39, 30).

Although there are many techniques for measuring fabric thermal conductivity, they fall essentially into one of the three following categories: rate of cooling method, constant-temperature method, and double-plate method (30, 31, 16).

Rate of Cooling Method

The rate of cooling method primarily determines the rate of heat loss from a hot cylinder, sphere, single plate, etc. through a fabric which surrounds the hot body and whose outer surface is exposed to the air. The techniques are simple, results are direct, and fabrics are tested without an applied pressure. Results may vary however, because of the lack of uniformity of fabric fit and tension over the hot body, and with the specific apparatus and temperature used (30). Furthermore, the temperature difference between the fabric surface and surrounding air can not be accurately measured. Numerous adaptations of the rate of cooling technique are described in the literature (31, 36, 37, 40).

Constant-Temperature Method

Constant-temperature methods measure thermal conductivity from the energy required to maintain a hot body at a constant temperature when it is covered with a fabric. Morris (31) preferred the techniques in this category because: (1) the experimental conditions can be more easily controlled; (2) the heat energy supplied to the body is calculated from electrical measurements, which are simpler, and more accurate than direct temperature measurements; and, (3) the situation approximates wearing conditions in that body temperature is approximately constant, the outer surface of clothing is exposed to still or moving air, and adjustable air gaps can be left between the hot body and the fabric.

In previous research heat losses from the hot body in any direction other than through the fabric were often not controlled. Lateral and downward heat flow from the hot body have been prevented in more recent constant-temperature investigations by the addition of a surrounding guard ring maintained at the same temperature as the hot plate.

The ASTM standard method for testing thermal transmission through fabrics requires the use of a guarded hot plate apparatus housed in a copper hood (3). This modification provides a controlled atmosphere, but as a result the apparatus is slow to reach steady-state conditions.

Tallent and Worner (44) measured the heat supply required to maintain a cylinder at body temperature with and without a covering sleeve of test fabric. Due to inadequate provision for unidirectional heat loss through the fabric, the results were suitable only for comparisons and could not be considered as absolute measurements (16).

Double-Plate Method

The double-plate method determines the heat flow rate through a fabric held between two metal plates maintained at different temperatures. The fabric specimen(s) may be in contact with one or both sides of the hot plate. Morris (31) has outlined the disadvantages of the method as follows:

1. Maintenance and operation of the apparatus are complicated.

2. The test period is lengthy.

3. Because the fabric is compressed between the plates and air is entrapped between each plate and the fabric, the results apply only to the particular apparatus used and the pressure under which the fabric is held.

The Cenco-Fitch apparatus is a double-plate apparatus which determines fabric thermal resistance from the rate of temperature rise of the cold plate. Relative to the single guarded hot plate it is reported to be inexpensive and easily operated, and to have a short test period. It is therefore better suited for general use in the textile industry (52). Wing and Monego (52), using a range of fabric types and thicknesses, developed an equation showing the relationship between thermal insulation data obtained on both the Cenco-Fitch and guarded hot plate apparatus.

David (12), and Clulow and Rees (11) modified the double-plate method by placing a heat transfer disc of known resistance in series with the fabric specimen with respect to heat flow between the plates. Since thermal resistance is proportional to the temperature difference across a resistor, and the resistance of the disc was known, the investigators were able to calculate the fabric resistance. The technique was rapid and accurate (16).

Measurement of the Electrical Resistivity of Fabrics

The majority of studies pertaining to electrical resistivity of textiles have focused upon measurement of the electrical resistivity of fibres and yarns. Hearle (19) reviewed the few studies reporting measurement of fabric electrical resistance. He pointed out that the data is difficult to interpret because the path of the electrical current is complicated and dependent upon the area of contact between neighbouring fibres and between the fibres and electrodes.

Researchers investigating fabric properties have been concerned with the ability of the fabric to accumulate and hold an electrostatic charge. Fabric resistance data resulting from both the circular and parallel electrode systems has been discussed in the literature (29, 45, 22, 38, 23, 51, 6). Both AATCC (1) and ASTM (5) have published standard test methods for measuring fabric resistance, the former requiring parallel electrodes, and the latter, suitable for use with either electrode arrangement. While circular electrodes give a measure of average resistivity in a radial direction, parallel electrodes measure the resistivity in a single direction.

Previous methods have been designed for testing conventional fabrics of very high resistance. The resistance range of the instruments used is too high to be suitable for measuring the electrical resistance of conductive fabrics.

METHOD OF STUDY

The thermal conductivity and electrical resistivity of seven electrically conductive fabrics and one electrically insulative fabric were measured.

Fabrics Studied and Measurement of Basic Properties

The test fabrics and their characteristics are described in Table 1. Seven fabrics were selected as representative of the commercial or experimental electrically conductive fabrics available in Fall, 1969. Four contained metal and three contained carbon as the conducting materials. One electrically insulative fabric, a 100% nylon (fabric 1), was chosen for comparison with the electrically conductive fabrics. It was similar in weight and fibre content to one of the conductive fabrics, 90% nylon/10% stainless steel blend (fabric 2). The fabric suppliers and their addresses are listed in Appendix A.

The quantities of conducting fibre differed in the warp and weft directions of fabrics 4, 5, 7, and 8 (glass fibre/stainless steel blend, polyester/brass blend, glass fibre/carbon blend, olefin/carbon blend); thus, electrical properties would differ according to the direction of measurement. In contrast to these anisotropic fabrics, the remaining fabrics were isotropic and the fibre content was

Table 1. Test Fabrics and their Characteristics

Fabric Number	Fibre Content	Construction	Weight (g./cm.^{2})	Thickness at 0.50 psi (cm.)	Packing Fraction
1.	100% Spun Nylon	Plain weave, staple fibre yarns	0.014	0.038	0.313
2.	90% Nylon/10% Stainless Steel	Satin weave, staple fibre yarns	0.017	0.061	0.226
3.	100% Stainless Steel	Twill weave, filament fibre yarns	0.050	0.025	0.257
4.	Glass Fibre with Stainless Steel Yarns	Plain weave with 1 metal yarn between every 50 picks and every 65 ends, filament fibre yarns	0.021	0.051	0.168
5.	Polyester with Brass Covered Yarns	Basket weave with 6 metal covered yarns between every 190 picks, filament fibre yarns	0.018	0.051	0.249
6.	Graphite	Plain weave, filament fibre yarns	0.008	0.028	0.195
7.	Glass Fibre with Carbon Yarns	Plain weave with 1 carbon yarn between every 12 ends, filament fibre yarns	0.044	0.038	0.466
8.	Olefin with Carbon Yarns	Plain weave with 1 carbon yarn between every 2 ends, filament fibre yarns	0.026	0.061	0.401

identical in both warp and weft directions.

Fabric quantity was limited but allowed for one pair of thermal conductivity test specimens for all test fabrics with the exception of fabrics 3, 7, and 8 (100% stainless steel, glass fibre/carbon blend, olefin/carbon blend) for which the method was modified. The thermal conductivity specimens were all of adequate size for the electrical resistivity measurements. The small number of specimens per fabric was considered to be adequate for the present study since interest in making inter-fabric comparisons was greater than in obtaining absolute values.

Prior to all measurements and testing, the specimens were pressed lightly with a cool iron to remove surface wrinkles and folds. They were then conditioned according to CGSB standards (10).

Weights and thicknesses were measured for all fabrics and were used to calculate packing fraction, thermal conductivity, and electrical resistivity.

The fabric characteristics were determined as follows:

1. Weight per unit area: A die cut circle with a diameter of 5.08 cm. and an area of 21.25 cm.^{2} was weighed to an accuracy of ±0.00001 g. on a Sartorious digital analytical balance. Weight was expressed in grams per square centimetre.

2. Thickness: A Frazier Compressometer with an anvil 2.54 cm. in diameter was used to measure thickness according to the CGSB recommended procedure (10). A pressure of 0.50 psi was selected to approximate the pressure of the thermal conductivity apparatus. The results are expressed as an average of ten measurements, to an accuracy of ±0.003 cm.

The method was modified slightly to measure thickness of fabrics containing carbon yarns (7 and 8) because the test fabrics were available only in narrow strips (10.2 cm. wide). As it was necessary to have larger specimens for determining both thickness and thermal conductivity, three strips of a fabric, at least 32 cm. long, were placed adjacent to one another and held together at the ends with masking tape. This modified specimen allowed for a measure of the selvedges as well as the central portion of the fabric. Therefore, out of the total ten thickness readings, five were taken on the selvedges of the fabric, and five on the central portion when selvedges had been cut off. A mean was calculated for each area. The average thickness of the test specimen was then determined by the relationship:

$$d_F = P_s d_s + P_c d_c$$

where d_F = average test specimen thickness (cm.)

P_s = proportion of test specimen constituting selvedge

d_s = thickness of selvedge (cm.)

P_c = remaining proportion of test specimen

d_c = thickness of central portion (cm.).

3. Packing Fraction: The packing fraction, defined as the proportion of the fabric's volume occupied by fibre, was determined from fabric thickness and weight according to the following formulae (26):

For homogeneous fabrics,

$$\phi = \frac{m}{A} \cdot \frac{1}{\rho_f d_F}$$

and for binary blends,

$$\phi = \frac{m}{A} \cdot \frac{1}{d_F} \left\{ \frac{P_1}{\rho_1} + \frac{P_2}{\rho_2} \right\}$$

where ϕ = packing fraction

$\frac{m}{A}$ = fabric weight per unit area (g./cm.^{2})

d_F = fabric thickness (cm.)

ρ_1 and ρ_2 = densities of fibres 1 and 2 respectively (g./cm.^{3})

P_1 and P_2 = proportions by weight of fibres 1 and 2 respectively.

Measurement of Thermal Conductivity

Apparatus

A guarded double-plate apparatus for measuring thermal insulation was used to determine the thermal conductivity of the test fabrics. It was similar to the "National Research Council, Automatically Controlled, 12 Inch, Simplified Guarded Hot Plate Apparatus" and met ASTM requirements (4, 34). A photograph of the apparatus (Figure 1) includes:

1. An automatic self-contained control system for the cold plate temperatures (extreme left).
2. A manual balancing potentiometer (upper left centre) from which the hot plate temperature was determined.
3. Two direct digital voltmeters (lower left centre) from which the potential difference and cold plate temperature were determined.
4. The plate assembly consisting of a central hot plate between two cold plates (right centre and figure 3).
5. The control system for the hot plate (extreme right).

The guarded double-plate apparatus used had been designed for use with insulating materials and it was adapted for textiles in the following manner. In order to obtain a more precise determination of air gaps in the thickness of the plate and fabric assembly, metal pins were inserted in and protruded from the top external corners of each cold plate. A micrometer, having an accuracy of ±0.001 in. (0.003 cm.), was used to measure the thickness of the

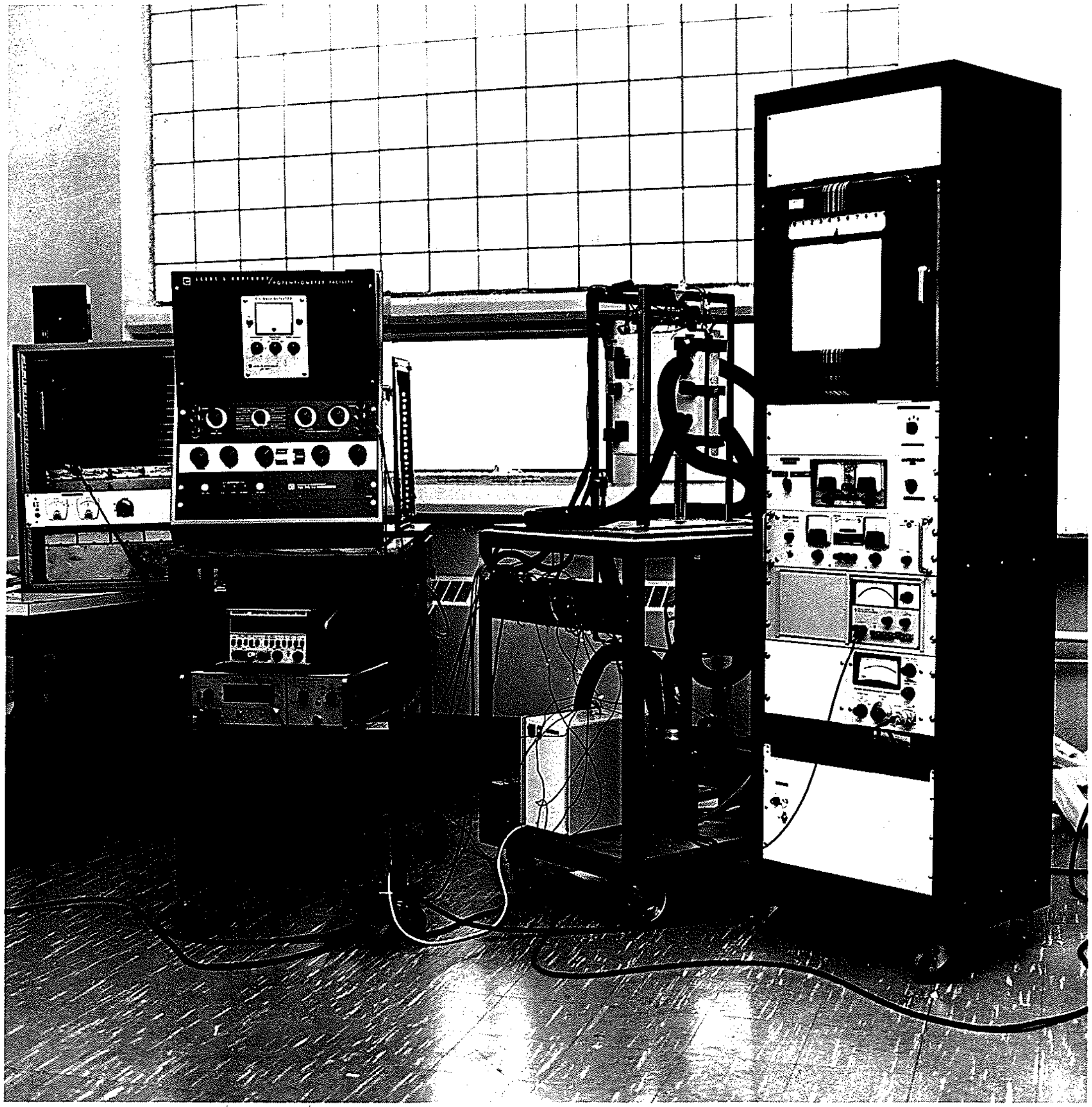


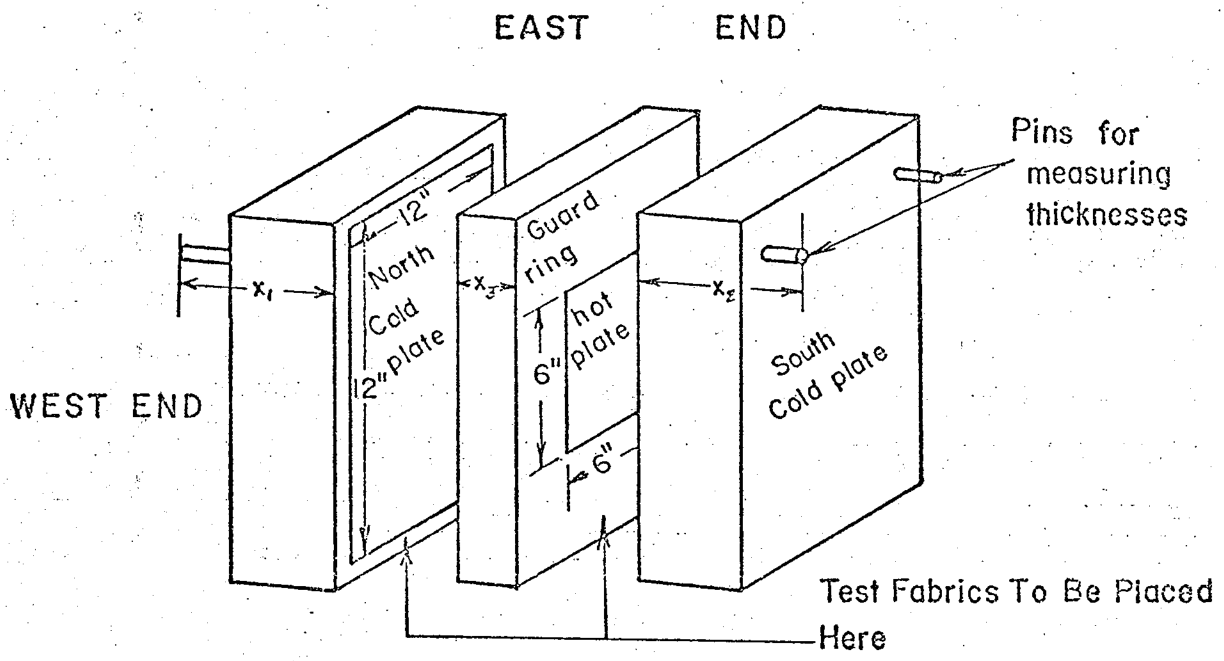
Figure 1. N.R.C. Guarded Hot Plate

plate assembly between the outer ends of the pins.

Basic thickness of the entire plate assembly was determined from ten measurements of the component parts at each end of the apparatus, i.e. central hot plate and each cold plate (Figure 2). The mean basic thickness for the East end of the assembly was 5.356 in. (13.604 cm.) and 5.409 in. (13.739 cm.) for the West end.

Six coil springs were used to hold the cold plate-fabric-hot plate assembly together during testing. The following method was used to approximate the pressure of the springs and plate assembly. Blocks of wood were held to a bathroom scale by means of the six springs and the entire unit, representing the thickness of the plate assembly, was held in a vertical position while the force in pounds was read directly from the scale. The force per unit area was then calculated. The resulting value was close to 0.50 psi, the pressure therefore selected in determining fabric thickness with the Compressometer.

The central hot plate, a six inch square (15.24 cm.), was calibrated over a temperature range of -10°C. to 50°C. This temperature was then referenced to a direct reading manual balancing thermocouple potentiometer accurate to $\pm 2\ \mu$v. The temperature of the water-cooled cold plates was controlled to $\pm 0.02^{\circ}$C. and was referenced to a direct reading digital voltmeter accurate to $\pm 3\ \mu$v. Using calibration



x_1 = thickness of the north cold plate

x_2 = thickness of the south cold plate

x_3 = thickness of the hot plate and guard ring

$\sum_{i=1}^{3} x_i$ = basic thickness of the apparatus without test specimens in place

Figure 2. Determination of the Basic Thickness of the Guarded Hot Plate Apparatus

graphs and the output in millivolts read from these instruments, the temperatures were determined with an accuracy of $\pm 0.2^{\circ}C$. The guard ring temperature was controlled automatically by means of thermocouples to have the same temperature as the central hot plate and provide unidirectional heat flow.

The potential difference across the central heater was read directly from a digital voltmeter accurate to ±0.01 volts. Since the resistance of the central heater was exactly 6.000 ohms, the power and heat flow rate were determined from the relationships:

$$P = \frac{V^2}{R}$$

and $$Q = \frac{P}{J}$$

where P = power (watts)

V = potential difference (volts)

R = resistance (ohms)

Q = heat flow rate (cal./sec.)

J = Joule's mechanical equivalent of heat (4.2 joules/cal.).

Preparation of Specimens

Two specimens, each a 29 cm. square with two small tabs extending from one edge, were cut from all the test fabrics with the exception of fabrics 3, 7, and 8 (100% stainless steel, glass fibre/carbon blend, olefin/carbon blend). Only one specimen was cut from fabric 3 due to a limited fabric quantity. This was paired with a specimen of fabric 1 (100% nylon) for testing since their thicknesses were similar. Specimen preparation for fabrics 7 and 8 has been previously discussed in reference to thickness measurements (page 20). The thermal conductivity specimens consisted of both selvedges and central portions of fabrics 7 and 8.

Procedure for Measuring Thermal Conductivity

Thermal conductivity measurements were obtained at room temperature and humidity. The specimens were not in hygroscopic equilibrium with the room when tested. One test specimen was placed on each side of the hot plate and secured in place at the top by means of masking tape and the fabric tab extensions. The cold plates were then eased towards the specimens until contact was made. Three heavy coil springs were positioned on each end of the total assembly to hold it together. Figure 3 illustrates placement of the springs on the assembly and the position of the guarded hot plate between the two water-cooled cold plates. For each test, precautions were taken to:

1. Place the coil springs in the same position, between pencil markings on the outer surfaces of the cold plate insulation material.

2. Allow the cold plates and hot plate to hang

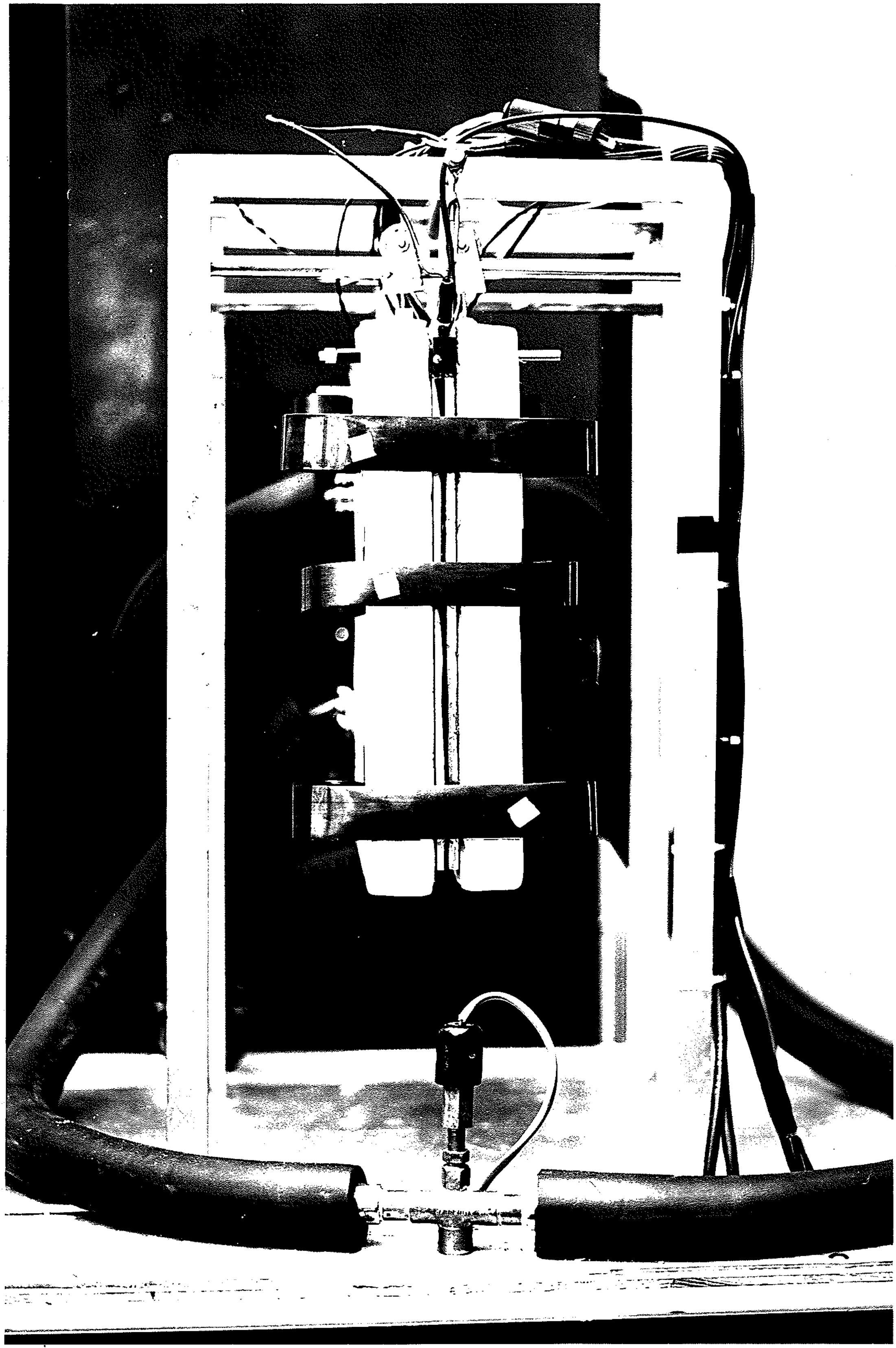


Figure 3. Plate Assembly with Test Fabrics in Place

freely from the supporting rods and therefore to remain in the same position.

3. Ensure the absence of dust or foreign matter on the pins, plates, and micrometer shafts.

4. Ensure that no properties of the plates (eg. rough edges) or of the test specimens (eg. irregularities and creases) interfered with the contact of the fabric specimens and plates. The specimen dimensions were 1.5 cm. less than the plate dimensions to allow for possible roughness at the outer edges of the plates.

With the fabric specimens in place the assembly was brought to the steady-state operating conditions. The temperature difference between the plates was kept as large as possible. The aim was to approach a hot plate temperature of 33°C. (man's average skin temperature), and a cold plate temperature of 20°C. (room temperature). In no case, however, was the hot plate temperature greater than 26.70°C. or the cold plate temperature less than 15.83°C. The potential difference required to maintain the temperature difference was read directly from the digital voltmeter and recorded. In order to randomize any effect of differences in the test specimens or air gaps, the test specimens were interchanged and placed on opposite sides of the hot plate and the procedure was repeated.

Procedure for Measuring Thickness

Thickness measurements of the total assembly with fabric specimens in place were made between the outer edges of the pins at each end of the plates when steady-state conditions had been attained. With the exception of 100% stainless steel (fabric 3), five thickness readings were made with a micrometer both when the specimens were in the first position with respect to the hot plate, and when the specimens were interchanged. The mean of each set of five measurements was calculated. Prior to each measurement the springs were removed; the specimens and plates were adjusted and repositioned; and the springs were replaced. The aim of this procedure was to minimize the effect of systematic and operator differences. With each reading, care was taken to obtain flat contact between the micrometer shafts and the ends of the pins. Problems with fabric 3, permanent creases and strong tendencies to ravel and to curl, interfered with smooth placement of the specimen between the plates. It was therefore not possible to obtain more than one thickness measurement for each specimen arrangement.

The overall thickness (measured with the micrometer from pin to pin at both East and West end pins) consisted of the following: (1) the thickness of both cold plates and of the central hot plate, (2) the thickness of both fabric specimens, and (3) the thickness of any air gaps between the hot plate, the specimens, and the cold plates. The difference between the overall thickness and the sum of the basic thickness plus the specimen thicknesses was attributed to air gaps. The air gap on each side of the hot plate was taken as half this difference. The thermal conductivity of the air layer, at a temperature equal to the mean of the hot and cold plate temperatures, was then determined from constants reported by Kaye and Laby (27). The thermal resistance of the air gaps was subtracted from the total thermal resistance to obtain the value reported for the fabric.

Calculations

The known values of heat flow rate and temperature were substituted in the heat flow equation and used to calculate thermal resistance. Heat flow through the test specimens was equal to the ratio of the temperature difference across them to the thermal resistances of the fabric and air:

$$\dot{q} = \frac{T_H - T_C}{R_{F_1} + R_A} + \frac{T_H - T_C}{R_{F_2} + R_A}$$

where $\dot{q}$ = heat flow rate per unit area (cal./m.^{2}sec.)

T_H and T_C = temperature of the hot plate and cold plates respectively ($^{\circ}$C.)

R_{F_1} and R_{F_2} = fabric thermal resistance of each specimen (m.^{2}sec.$^{\circ}$C./cal.)

R_A = thermal resistance of each air gap ($m.^2 sec. ^\circ C./cal.$).

Thermal resistance per unit area is determined from the relationship:

$$R = \frac{d}{kA}$$

Therefore the conductivity was calculated from:

$$k = \frac{d}{RA}$$

where k = thermal conductivity ($cal./m.sec. ^\circ C.$)

d = thickness (m.)

R = thermal resistance ($m.^2 sec. ^\circ C./cal.$)

A = area of specimen or air layer covering the central hot plate, through which heat flows ($m.^2$).

These thermal resistances and conductivities were calculated from experimental data using an Olivetti-Underwood Programma 101 desk computer. Details of the program and operating instructions, are presented in Appendix C.

The mean of the thermal conductivity of the specimens in the first arrangement with respect to the hot plate and in the interchanged position was reported.

Measurement of Electrical Resistivity

The ring method of measuring electrical resistivity has previously been used to determine charge dissipation in a radial direction across a fabric surface. Because it is a standard method it was selected for the present investigation. It does not, however, lend itself to anisotropic fabrics and is less appropriate for measuring electrical resistivity when current can flow in only one direction, as in electrically heated fabrics. The strip method was used to measure the resistivity in the warp and weft directions of anisotropic fabrics. As it was found to be sensitive to contact between the specimen and electrodes, it was not suitable for fabrics 1, 2, 3, and 6. A vacuum-tube multimeter[2] capable of measuring resistances over the range of 0.2 to 10^9 ohms, an adequate range for testing electrically conductive fabrics, was used in both methods.

Ring Method

Apparatus. The circular electrodes illustrated in Figure 4, consist of an inner brass ring with a 1.27 cm. radius and an outer brass ring with an 8.89 cm. radius. The rings were fitted with sockets to readily accommodate the ohmmeter leads, and were joined together by means of three plexiglass rods. The lower surfaces of the rings were bevelled to a fine edge so that the weight of the rings was concentrated on the edge and improved contact between the

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[2] Model "777", manufactured by Phaostron Company, 151 Pasadena Avenue, South Pasadena, California.

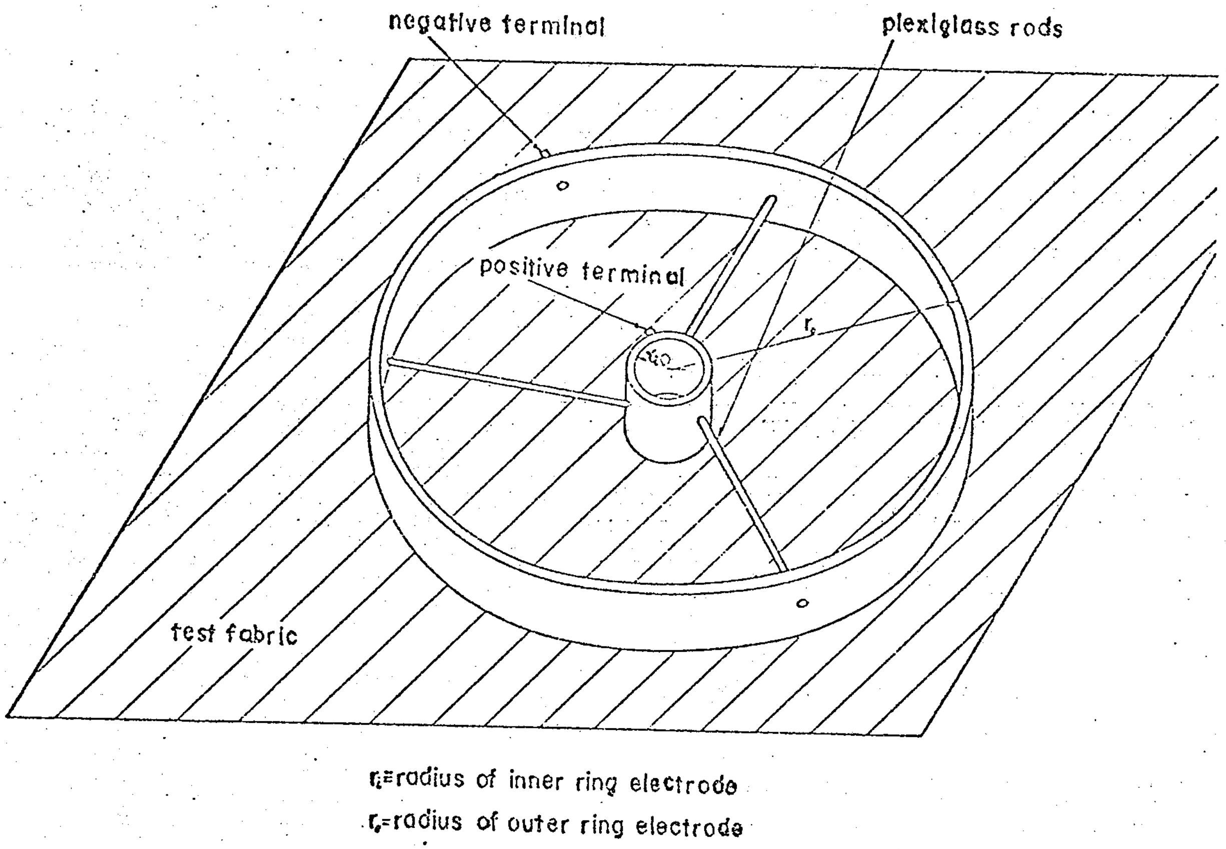

Figure 4. Circular Electrodes Used for the Determination of Fabric Resistivity

electrodes and test sample. The electrode design was developed from the circular arrangement used by Lewis (29).

Procedure. The fabric specimens measured for electrical resistivity were the same specimens as used in determining thermal conductivity. The test specimen was placed on a hard, non-conducting surface and smoothed without excessive tension. Prior to each measurement the ring electrodes were cleaned with sandpaper to remove any oxides. The rings were then placed on the specimen with the bevelled edge down. With the anisotropic fabrics the central ring was placed on at least one conducting yarn. The leads from the ohmmeter were inserted in the electrode sockets and the rings were pressed on the fabric quickly and released. After a time lapse of one minute the electrical resistance was read directly from the ohmmeter. The procedure was repeated on the face and back of both specimens of each test fabric, except fabric 3 (100% stainless steel) for which there was only one specimen. With fabric 2 (90% nylon/10% stainless steel blend), the needle of the ohmmeter fluctuated. Two different intermediary substances, silicone grease and electrode paste, were applied to the brass rings on separate trials in an attempt to obtain a constant needle deflection, but neither was effective. The resistance values were obtained, therefore, from a visual average over the period of one minute.

Calculations. The resistivity of each test fabric was calculated by averaging the resistance for face and back of both specimens and using the following formula:

$$\rho = R2\pi d_F \log_e \frac{r_o}{r_i}$$

where ρ = resistivity (ohm-metres)

R = the measured resistance (ohms)

d_F = fabric thickness (metres)

r_o = outer ring radius (metres)

r_i = inner ring radius (metres).

The resistance in ohms/square was calculated as the ratio of the resistivity to the fabric thickness (equation 3, page 5).

Strip Method

Apparatus. Small spring clips of the alligator type attached to the ohmmeter leads served as the electrodes for measuring the resistance of fabric strips.

Preparation of Specimens. A warp and weft strip of fabric of a measured length and width equal to the distance between two consecutive conducting filaments were cut from the anisotropic test fabrics (4, 5, 7, and 8). A small piece of aluminium foil was folded over both ends of the fabric strip to improve contact with the electrodes.

Procedure. A fabric strip was placed on a hard, non-conducting surface and was smoothed without excessive tension.

An electrode clip was attached to each end of the strip and the electrical resistance was read directly from the ohmmeter after a time lapse of one minute.

Calculations. The resistivity of the warp and weft direction of each anisotropic test fabric was calculated from equation 2 (page 5). The resistance in ohms/square was then calculated as the ratio of resistivity to fabric thickness (equation 3, page 5).

RESULTS AND DISCUSSION

The findings and discussion concerning the thermal conductivity and electrical resistivity of the test fabrics and the feasibility of using them to heat clothing follow.

Thermal Conductivity

Table 2 contains the mean observed values and rank orders of thermal conductivity, and the thermal resistances for the test specimens. A discussion of the results related to fabrics containing carbon follows that related to fabrics containing metal fibres.

Fabrics Containing Metal Fibres

Fabrics 2, 3, 4, and 5 (90% nylon/10% stainless steel blend, 100% stainless steel, glass fibre/stainless steel blend, polyester/brass blend) contained varying amounts of metal fibre but they did not have appreciably greater thermal conductivities than fabric 1 (100% spun nylon) which did not contain metal fibres. Thus, the quantity of metal fibre in these fabrics did not appear to influence the thermal conductivities.

The observed thermal conductivity of fabric 3 is not reported because the observed resistance is believed to be largely a reflection of the resistance of large air gaps. The difficulties in manipulating the test

Table 2. Thermal Conductivity

Fabric Number and Fibre Content	Temperature Difference $\Delta T=T_H-T_C$ (°C.)	Mean Temperature $\bar{T}=\frac{T_H+T_C}{2}$ (°C.)	Thermal Resistance $\frac{m.^2 sec. ^oC.}{cal.}$	Observed Thermal Conductivity $k_F \times 10^{-4}$ $\frac{cal.}{cm. sec. ^oC.}$	Rank Order
1. 100% Nylon	9.13	21.91	0.031	1.21	2.5
2. 90% Nylon/10% Stainless Steel	10.04	21.38	0.061	1.00	1
3. 100% Stainless Steel	8.48	22.36	0.029	--	--
4. Glass Fibre/ Stainless Steel	9.93	20.93	0.039	1.30	4
5. Polyester/ Brass	9.43	21.44	0.042	1.21	2.5
6. Graphite	5.48	23.64	0.009	3.04	7
7. Glass Fibre/ Carbon	8.21	22.48	0.009	1.67	6
8. Olefin/Carbon	8.15	22.32	0.035	1.35	5

specimen[3] were responsible for the influence of the air gaps.

Comparison of the thermal conductivity of fabric 2 with fabrics 4 and 5 indicated that the fabric containing intimately blended staple metal fibres (fabric 2) had a lower conductivity than the fabrics containing continuous filament metal fibres (4 and 5).

Earlier investigators have reported that for any given thickness, less dense fabrics have lower thermal conductivities (31). Fabric 1, with a larger packing fraction (greater density) than fabric 5, might therefore be expected to have the greater value of thermal conductivity. The measured conductivity of the fabrics proved to be identical; thus, the presence of metal may have augmented the conductivity of fabric 5.

Although fabrics 4 and 5 were of equal thickness and the packing fractions indicated that fabric 4 was not as dense as fabric 5, fabric 5 was found to have the lower thermal conductivity. Continuous filament metal yarns formed a narrow conducting strip in fabric 5. The strip appeared to be thinner and may have had a lower degree of contact with the plates than the rest of the fabric.

Fabrics Containing Carbon

The presence of carbon in fabrics 6, 7, and 8

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[3] Described in the Method, page 30.

("Graphite Cloth", glass fibre/carbon blend, olefin/carbon blend) increased their thermal conductivities over those of all test fabrics not containing carbon. Both fabrics 7 and 8 were found to conduct well, owing to their high packing fractions relative to other fabrics and the presence of carbon.

The observed thermal conductivity of fabric 6 was relatively high. The total thermal resistance was very low and therefore it was not possible to maintain a very large temperature difference between the plates during testing. The influence of air gaps was greater with fabric 6 because it was of low thickness, and the thickness of air gaps represented a larger proportion of total thickness.

Electrical Resistivity

The mean electrical resistivity values of the test fabrics as obtained with the circular electrodes are presented in Table 3 and those obtained on strips of fabric are presented in Table 4. The rank order and range of each resistivity value is tabulated for the ring method. Reference to variation in the results, the effect of tension, and the effect of fabric anisotropy on the results precedes a discussion of the findings.

Variation was observed in the ring method resistivity values between specimens of the same test fabrics. The

Table 3. Electrical Resistivity-Ring Method

Fabric Number	Fibre Content	Resistivity (ohm-metres)	Rank Order	Range (ohm-metres)	Resistivity (ohms/square)
1.	100% Nylon	$>4.6 \times 10^{6*}$	8	--	$>120 \times 10^{8*}$
2.	90% Nylon/10% Stainless Steel	5.9×10^{-3}	5	0.20×10^{-3}	9.7
3.	100% Stainless Steel	$<3.1 \times 10^{-3*}$	1.5	--	$<12^{*}$
4. face	Glass Fibre/ Stainless Steel	0.26×10^{-3}	3	0.06×10^{-3}	0.51
4. back		1.6×10^{-3}		0.20×10^{-3}	3.1
5.	Polyester/Brass	$<1.2 \times 10^{-3*}$	1.5	--	$<2.4^{*}$
6.	Graphite	2.3×10^{-3}	4	--	8.2
7.	Glass Fibre/Carbon	0.52	7	0.30	1400
8.	Olefin/Carbon	30×10^{-3}	6	20×10^{-3}	49

[*] These values were calculated from off-scale measurements and include the contribution of fabric thickness and cross-sectional area

Table 4. Electrical Resistivity-Strip Method

Fabric Number	Resistivity			
	Warp Direction		Weft Direction	
	(ohm-metres)	(ohms/square)	(ohm-metres)	(ohms/square)
4.	2.0×10^{-3}	3.9	0.39×10^{-3}	0.76
5.	25×10^{-6}	0.05	$>0.5 \times 10^{6*}$	$>9.8 \times 10^{8*}$
7.	11×10^{-3}	30.	$>0.4 \times 10^{6*}$	$>7.8 \times 10^{8*}$
8.	0.36×10^{-3}	0.59	$>0.6 \times 10^{6*}$	$>12 \times 10^{8*}$

*These values were calculated from off-scale measurements and include the contribution of fabric thickness and cross-sectional area exceptions were fabrics 1, 3, 5, and 6. Fabrics 1, 3, and 5 (100% nylon, 100% stainless steel, polyester/brass blend) had a very high or very low electrical resistivity and differences between specimens were not detectable. Fabric 6 ("Graphite Cloth") was isotropic. Hersh and Montgomery (23) also experienced variation between specimens and suggested that the disparity was due to unevenness in yarn structure and to differences in fibre-to-fibre contact. A similar effect is believed to be operative in the present results.

Fabric 2 (90% nylon/10% stainless steel blend) was sensitive to tension applied across the fabric. The electrical resistivity decreased as tension was applied owing to intermittent contact between the staple metal fibres. No other fabrics showed the same effect. Hearle (20) found a tendency for yarn resistance to decrease or increase with increasing tension depending on fibre content, but the effect was very small.

The nature of the electrodes and their contact with the test specimens prevented exact duplication of the results given by the ring and strip methods. The strip method showed that electrical conductivity was negligible in the weft direction of those anisotropic fabrics that contained conducting yarns only in the warp direction (fabrics 5, 7, and 8). The electrical resistivity in the warp direction of fabric 4 (glass fibre/stainless steel blend) was greater than that in the weft direction because there were fewer stainless steel filaments in the warp direction.

A discussion of the results as related to metal-containing fabrics, carbon-containing fabrics, and the electrically insulative fabric follows.

Fabrics Containing Metal Fibres

Fabrics 3, 4, and 5 (100% stainless steel, glass fibre/stainless steel blend, and polyester/brass blend) contained metal in continuous filament form. Fabric 2 (90% nylon/10% stainless steel blend) contained staple metal fibres.

Fabric 3 did not offer any detectable resistance to current flow between the circular electrodes and that of fabric 5 was very low. A strip of fabric 5 had a negligible electrical resistivity in the warp direction. In both fabrics the metal in continuous filament form provided a direct path for the current. The resistivity of fabric 5 in the warp direction was very low and it was off-scale when measured by the ring method. Because there were no conducting yarns in the weft direction and its electrical resistivity was great, all the current flowed through the brass yarns in the warp direction irrespective of the geometry of the electrode arrangement used to measure it. Both arrangements measured the same unidirectional current flow.

Because the conducting yarns in fabric 4 were at the surface only infrequently on the back of the fabric, mean electrical resistivity values obtained by the ring method were reported for both surfaces. The face of the fabric exhibited a lower resistivity than the back.

The electrical resistivity of fabric 5 was lower than that of the face of fabric 4 with both measuring techniques. Although both specimens contained continuous filament metal yarns, those in fabric 4 provided a greater number of possible current pathways because of the intersection of metal yarns from both the warp and weft directions. These pathways were broken when fabric 4 was cut into strips so that its resistivity was slightly higher when measured by the strip method. For the face of fabric 4 the resistivity obtained from the ring method was more similar to the weft direction strip resistivity than to the higher warp direction resistivity. This indicates that the circular electrodes were capable of measuring the lower resistivity.

The electrical resistivity of fabric 2 which contained staple metal fibres was higher than that of all the fabrics containing metal in continuous filament form. In the latter fabrics the pathways provided for the electrical current were therefore more direct. Fabric 2 had a lower resistivity than fabric 1. These fabrics were alike in fibre content except for the presence of stainless steel fibres in fabric 2. The metal resulted in a greatly reduced resistivity in fabric 2.

Fabrics Containing Carbon

Fabrics 7 (glass fibre/carbon blend) and 8 (olefin/carbon blend) contained electrically conductive carbon yarns. Fabric 6 ("Graphite Cloth") consisted of graphite filaments assaying greater than 99% carbon (18).

The electrical resistivity of fabric 6 was found to be lower than that of fabrics 7 and 8. It was higher than the resistivities of all the fabrics containing continuous filament metal fibres and lower than the fabric containing staple metal fibres.

Fabric 8 was woven with a carbon yarn between every two ends of olefin. It therefore had a much lower electrical resistivity than fabric 7 which was woven with a carbon yarn between every 12 ends of glass fibre. The ratio of the resistivities, fabric 7 to fabric 8, as given by the ring method was 17:1, and by the strip method in the warp direction it was 31:1. Since the circular electrodes measured the resistance to current flowing simultaneously in all directions, the flow in any single direction was decreased, and the electrical resistivity of that direction increased. With the strip method, the current flowed only in the warp direction because the resistivity in the weft direction of these fabrics approached infinity. Consequently the difference in the resistivity of fabrics 7 and 8 averaged over all directions (ring method) was less pronounced than the difference in the warp directions (strip method).

The electrical resistivities of the specimens containing carbon yarns were higher than the resistivities of all the metal-containing specimens. The fabrics containing continuous filament metal fibres had lower resistivities than all three carbon-containing fabrics.

Electrically Insulative Fabric

Fabric 1 (100% nylon) was found to have the highest resistivity. It was beyond the range of the ohmmeter, and relative to the resistivity of test fabrics containing conducting carbon or metal fibres, it was considered to be infinite.

Feasibility of Using Electrically Conductive Fabrics to Heat Garments

The quantity of each test fabric required to produce a given amount of heat in a given situation can be determined theoretically from the metabolic output and the ambient conditions. The rate of heat loss depends upon the rate of body heat generation, the temperature difference between the skin and the environment, and the resistance to heat loss offered by clothing. Heat loss in excess of heat generated is equivalent to the extra heat required to maintain the body temperature, and it can be supplied by proper selection of a power source and an electrically conductive fabric.

The following physiological, environmental, and apparel conditions, typical of those encountered in a cold climate, will be referred to in determining the thermal requirements for heated garments:

Physiological[4]. A man engaged in light activity generates heat at the rate of 20 cal./cm.^{2}sec. At equilibrium thermal comfort his average skin temperature is 33°C. The total surface heat transfer coefficient at his body surface is 5.0×10^{-4} cal./cm.^{2}sec.°C. The surface area of his body is 1.7×10^4 cm.^{2}.

Environmental[5]. With a light wind and a cloudy day the ambient temperature is −10°C.

Apparel. The average thickness of conventional cold climate clothing is 1.5 cm., and its thermal conductivity is 1.0×10^{-4} cal./cm . sec.°C.[6] Absence of any other thermal resistance between the skin and the clothing was assumed. The power source is a 12-volt battery.[7]

From the preceding data, the total heat flow was calculated as 25.3×10^{-4} cal./cm.^{2}sec. (Appendix B). While

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[4] Values based on information given in references 35 and 53.

[5] Selected arbitrarily as representative conditions.

[6] *supra*, footnote 4.

[7] *supra*, footnote 5.

the thermal resistance of the test fabrics is very small relative to the clothing and surface resistances, the effect of these electrically conductive fabrics on the total resistance is not accurately known. Since heat was generated at 20 cal./cm.^{2}sec., the heat debt was 5.3×10^{-4} cal./cm.^{2}sec. and for the entire body surface area it was 9.0 cal./sec., or 37.8 watts. The resistance required to produce 37.8 watts with a 12-volt battery is 3.8 ohms. The typical lengths and widths of electrically conductive fabric strips capable of supplying 3.8 ohms of resistance are presented in Table 5.

The electrically conductive fabrics most useful for supplying heat to clothing would be those which could provide the required resistance from a piece of fabric having appropriate dimensions for use in garments. The fabric dimensions must not exceed those of the garment nor concentrate the heat in too small an area. To meet these requirements, the fabric must have a moderate electrical resistivity. Fabric 1 (100% nylon) was found to have a very high electrical resistivity and was not feasible for use in heating apparel. In addition to a moderate electrical resistivity, a low thermal conductivity which would not increase heat loss would be desirable. The present results indicate that fabric 2 (90% nylon/10% stainless steel blend) best fulfills the requirements. Fabric 3 (100% stainless steel)

Table 5. Quantity of Electrically Conductive Fabric
Required to Provide 3.8 Ohms Resistance

Fabric Number	Fibre Content	Resistivity (ohm-metres)	Dimensions of Strip (centimetres)	
			Length	Width
1.	100% Nylon	$>4.6 \times 10^{6*}$	$<31 \times 10^{-11}$	10
2.	90% Nylon/10% Stainless Steel	$5.9 \times 10^{-3*}$	20	50
3.	100% Stainless Steel	$<3.1 \times 10^{-3*}$	3.1	>100
4. warp	Glass Fibre/ Stainless Steel	2.0×10^{-3}	27	30
4. weft		0.39×10^{-3}	50	10
5. warp	Polyester/Brass	25×10^{-6}	78	1
6.	Graphite	$2.3 \times 10^{-3*}$	25	50
7. warp	Glass Fibre/Carbon	11×10^{-3}	13	100
8. warp	Olefin/Carbon	0.36×10^{-3}	64	10

*These values were obtained by the ring method. The remaining values were obtained by the strip method was not suitable due to its weight and tendency to curl. In practice, strips or squares of the remaining test fabrics could be connected in parallel in a garment to provide the required heat, either distributed evenly across the garment, or concentrated in specific areas.

SUMMARY

The thermal conductivity and electrical resistivity of seven currently available electrically conductive fabrics (three containing carbon and four containing metal fibres), and one electrically insulative fabric were measured.

Thermal conductivity was measured on a double-plate apparatus consisting of a guarded hot plate between two cold plates. An ohmmeter was used with circular electrodes to measure the electrical resistivity of all fabrics. While the circular electrode arrangement was required to accurately measure the resistivity of uniformly conducting fabrics, a parallel arrangement was required to accurately measure the resistivity of anisotropic fabrics. The ohmmeter was therefore used to determine the resistivity of warp and weft direction strips of anisotropic fabrics.

The three fabrics containing carbon were found to have higher thermal conductivities than all others. The quantity of metal fibre in the fabrics did not appear to influence thermal conductivity in a uniform pattern. However, fabrics containing metal in continuous filament form were found to have higher thermal conductivities than the fabric containing intimately blended staple metal fibres.

The fabric which contained neither metal nor carbon was found to have the highest electrical resistivity. Fabrics containing metal in continuous filament form were found

to have the lowest resistivity. The electrical resistivity of fabrics containing metal in either continuous filament or staple form was lower than the resistivity of all metal-free fabrics.

The results were applied in a theoretical determination of the quantity of electrically conductive fabric required in a heated garment to maintain thermal comfort under a typical set of physiological and climatic conditions. The test fabric containing intimately blended staple metal fibres was well suited for use as a resistance heating unit in clothing because it had a moderate electrical resistivity and a low thermal conductivity. The electrically insulative fabric and the 100% stainless steel fabric were not found to be feasible choices for use in clothing because the resistivities were too high and too low respectively.

The guarded hot plate was originally designed for use with thick materials of high insulation. When testing thin fabrics of high conductivity for the present work, the critical variable was found to be measurement of fabric and air gap thicknesses. For future research, a scaling down of the plate assembly to correspond to the lower thickness of fabrics is recommended. Since errors in thickness measurements would be reduced in proportion to the number of fabric layers tested, and further, the effect of air gaps between fabric layers in garments would be simulated, use of the guarded hot plate to measure the thermal conductivity of test specimens consisting of layers of fabrics is also recommended.

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APPENDIX

APPENDIX A

Source of Test Fabrics

The test fabrics were obtained from the following sources:

1. 100% spun nylon, Type 200, purchased from Testfabrics Incorporated, 55 Vandam Street, New York, New York, 10013, U.S.A.
2. 90% nylon/10% stainless steel staple blend, glass fibre/stainless steel blend, and 100% stainless steel, supplied by Brunswick Corporation, Technical Products Division, 69 West Washington Street, Chicago, Illinois, 60602, U.S.A.
3. Polyester/brass blend, purchased from Ryujin Company Limited, C.P.O. Box 1714, Tokyo, Japan.
4. "Graphite Cloth", Grade WCJ; "Ucar" Electrically Conductive Cloth, Style 9967 (glass fibre/carbon blend); and "Ucar" Electrically Conductive Cloth, Style 9962A (olefin/carbon blend) purchased from Union Carbide Canada Limited, Metals and Carbon Department, 123 Eglinton Avenue East, Toronto 12, Canada.

APPENDIX B

Equations Used in Calculation of the Quantity of Electrically Conductive Fabric Required to Maintain Thermal Equilibrium

The resistance per unit area of clothing to heat transfer is determined from the relationship:

$$R = \frac{d}{k}$$

where R = resistance (m.^{2}sec.$^\circ$C./cal.)

d = thickness (m.)

k = conductivity (cal./m. sec.$^\circ$C.).

The surface resistance to heat transfer is given by the relationship:

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

where R_s = surface resistance (m.^{2}sec.$^\circ$C./cal.)

U = total surface heat transfer coefficient (cal./m.^{2}sec.$^\circ$C.).

The sum of these resistances gives total resistance to heat transfer.

The rate of heat flow from the man to the environment is determined as follows:

$$Q = \frac{T_s - T_\infty}{R_T}$$

where Q = heat flow rate (cal./m.^{2}sec.)

T_∞ = ambient temperature ($^\circ$C.)

T_s = skin temperature ($^{\circ}$C.)

R_T = total resistance to heat transfer ($m.^2 sec. ^{\circ}C./cal.$).

Joule's mechanical equivalent of heat is used to convert heat flow to power, thus:

$$P = Q \times J$$

where P = power (watts)

Q = heat flow rate (cal./sec.)

J = Joule's equivalent (4.2 joules/cal.).

Hence, the resistance required to produce the power is given by the relationship:

$$R = \frac{V^2}{P}$$

where R = resistance (ohms)

V = potential difference (volts)

P = power (watts).

The quantity of fabric required to provide the resistance for a strip of fabric is calculated from the relationship:

$$R = \frac{\rho L}{A}$$

Hence $$L = \frac{RA}{\rho}$$

where R = resistance (ohms)

ρ = fabric resistivity (ohm-metres)

L = fabric length (m.)

A = fabric cross-sectional area, the product of width and thickness (m.^{2}).

The resistance per square is determined from the relationship:

$$R' = \frac{\rho}{d_F}$$

where R' = resistance (ohms/square)

ρ = resistivity (ohm-metres)

d_F = fabric thickness (m.)

since the resistance in ohms/square is the same irrespective of the size of the square.

APPENDIX C

Program for Olivetti-Underwood Programma 101 and Typical Values Used in the Calculation of Thermal Conductivity

Program Instructions	Operation Instructions	Typical Values
A V	Press V	
S	Enter potential difference (volts)	13.08
↓		
A X		
a ↑		
σ X		
÷		
S	Enter temperature difference ($^{\circ}$C.)	10.02
÷		
a ↑		
R ↑		
R ÷		
R ×		
R S		
σ S		
÷		
B ↓		
S	Enter air gap thickness (cm.)	0.006
↓		
A W	If same fabric on both sides, press W	
S	Enter thermal conductivity of air (cal./cm.sec.$^{\circ}$C.)($\times 10^{-4}$)	0.61
÷		
C ↓		
a ↑		
σ ↑		
↓		
B ÷		
C −		
A ◊	Print fabric resistance (m.^{2}sec.$^{\circ}$C./cal.)	0.058
S	Enter fabric thickness (cm.)	0.061
↑		

Program Instructions	Operation Instructions	Typical Values
÷		
A ◊	Print fabric thermal conductivity (cal./cm. sec. °C.) (x10^{-4})	1.04
/ ◊		
V		
A Y	If different fabric on each side, press Y	
S	Enter thermal conductivity of air (cal./cm. sec. °C.) (x10^{-4})	
÷		
C ↑		
S	Enter thermal resistance of known fabric (m.^{2}sec. °C./cal.)	
↓		
C ⋄		
E ↕		
a ↑		
d ↓		
↓		
E ÷		
B ↑		
B -		
a ↑		
σ ↓		
↕		
÷		
C ∘		
A ◊	Print unknown fabric thermal resistance (m.^{2}sec. °C./cal.)	
S	Enter fabric thickness (cm.)	
↑		
÷		
A ◊	Print unknown fabric thermal conductivity (cal./cm. sec. °C.) (x10^{-4})	
/ ◊		
V		