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Simulation of Garment Layer Separation on the Human Body to Determine the Electrostatic Propensity of Thermal-Protective Fabric Systems at Low Humidities

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Simulation of Garment Layer Separation on the Human Body to Determine the Electrostatic Propensity of Thermal-Protective Fabric Systems at Low Humidities submitted by Tannis Louise Grant in partial fulfillment of the requirements for the degree of Master of Science in Textiles and Clothing.

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This thesis is dedicated
to my parents

ABSTRACT

Understanding the phenomenon of static electricity generation on clothing is essential in predicting the potential hazard associated with a garment system. A method was developed to measure the relative hazard of thermal-protective garment systems by simulating garment layer separation on the body. This method allowed for measurement of peak discharge potential from a capacitor, from which discharge energy was calculated. Correlations were conducted between data from this study and data from a previous study obtained directly from human subjects performing the activity of removing a garment layer. The method developed simulates the human-body activity under certain conditions better than under others. Humidity affected electrostatic properties differently depending on the layers within a system. As either rubbing speed or pressure are increased, both peak discharge potential and discharge energy increases. At slower speeds (25 RPM) systems with layers of the same materials have electrostatic properties similar to systems with an anti-static layer.

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Chapter 1
INTRODUCTION

Compared with the discovery of static electricity around 600 BC, concern about the problems of this phenomenon associated with clothing are relatively recent. Static electricity is generated on clothing through contact and friction with, or separation from other garments or external materials, including the human body. Under such circumstances, static electricity is generated regularly on people and their clothing during everyday wear and use. Often these charges are insignificant and go unnoticed, however, under certain conditions large amounts of charge may be generated and accumulate, leading to various problems.

The most noticeable problems of static electricity generation and build-up occur at low humidity levels, where very little moisture is available to help conduct charge away. In addition, those fibers or materials which do not absorb much moisture, even at mid-humidity levels, will also be problematic (Hayek & Chromey, 1951). It is often believed that synthetic fibers are most prone to static electricity generation, however, natural fibers at low humidity levels may behave similarly.

Unless modified, most textile materials are good insulators allowing for static electricity to accumulate on the surface, causing problems often considered to be a nuisance. Oppositely charged layers of fabric can cause clinging of garments to other articles of clothing or to the body (N. Wilson, 1987). Soiling of textiles is also a problem as dust and dirt particles from the surrounding air are attracted to charged surfaces (Morton & Hearle, 1975, p.531).

When charges on the clothing worn induce a charge onto the human body more serious problems develop. The human body acts as a capacitor with ability to store large amounts of charge which, when sufficient charge has accumulated, may result in a spark. The spark itself in this instance is the cause of concern.

Damage to static sensitive electronic equipment may occur when a person with built-up charge comes into contact with such devices (Roth, 1990). The major hazard exists when a spark discharge occurs in an environment of flammable gas fumes, vapors, or powders.

If enough energy is released in the discharge to ignite such substances, a fire or explosion may occur (Crow, 1991, p.3). In either case, the problems associated with static electricity in industry pose both financial and safety concerns. To overcome these problems, accurate methods to predict and control electrostatic behavior of textile systems are required.

Statement of Problem

Existing test methods fail to take into consideration the method of charge generation on clothing during wear and use, or on those external materials they come into contact with, the transfer of such charge to the human body, and the resulting discharge when the body comes in contact with a grounded, conductive object. In order to predict accurately the electrostatic behavior of a fabric or fabric system, these and other conditions existing in real-life situations must be identified and incorporated into small-scale test methods. In this manner, laboratory tests simulating real-life electrostatic discharges as obtained from clothed human body experiments, will allow for quick and similar results without the use of human subjects. From measured electrical potential, it will be possible to calculate the associated discharge energy, and therefore to predict the relative electrical hazard associated with various textile systems. This could lead to recommendations regarding safer garment systems for wear in hazardous environments.

Justification

The ease with which static electricity is generated on clothing makes it an everyday problem. Common activities such as walking, removing a jacket, or getting out of a vehicle allow for charge generation and the associated problems of static electricity. When charge from the clothing induces a charge on the body, potentially damaging and hazardous situations may arise. Instances of damage to sensitive electronic equipment due to spark discharges from the human body are well documented. Serious and fatal accidents involving the ignition of flammable gas from a spark are less common, however, such safety risks exist for those workers exposed to hazardous environments. Such workers need to be properly protected by both eliminating the source of ignition and protecting them in the case of an explosion. Much of the attention to date has focused on the latter, and on improving thermal-protective textiles, while often overlooking the electrostatic characteristics of these products. More research in this area is essential to facilitate control and management of the generation and accumulation of static electricity on thermal-protective clothing, and the subsequent discharge from the human body in hazardous environments. In an attempt to do this, anti-static fibers and finishes have been developed. Often, however, such techniques rely on moisture sorption from the surrounding atmosphere to reduce charge generation and improve charge decay (Crow, 1991; N. Wilson, 1987). This property limits the usefulness of such applications, especially considering that workers in many parts of the world may be exposed to very cold, dry environments during winter months.

In conducting human-body experiments (HBE's), with humans wearing thermal-protective clothing, conducted at ranges from 0% to 20% relative humidity (RH), researchers found that many thermal-protective garment systems produced discharge energies high enough to ignite certain flammable gases (Osei-Ntiri, 1992; Rizvi, Crown, Osei-Ntiri, Smy & Gonzalez, 1995; Rizvi, Crown, Gonzalez & Smy, in press). The two HBE's simulated everyday work activities of sliding across a truck seat and removal of an outer layer garment, for the consideration of charge generation on clothing. Gonzalez (1995) developed a small-scale test method to simulate the former activity, which showed high correlation with the discharge potentials from the human body. The activity of central importance to this research is that presented by Rizvi, et al. (in press), specifically the separation of garment layers on the human body.

The purpose of this study is to combine several parameters influencing charge generation during everyday activities, as identified in the second HBE, into a small-scale test method. This approach will allow for a much closer relationship between results from HBE's, what happens in real-life situations, and those results from the small-scale test method. Simulating what happens on the clothing and workers in the field will allow for more accurate predictions of the electrostatic behavior of various textiles than can be determined using current test methods.

Objectives

The objectives of this study are to:

1. develop a small-scale test method to measure the electrostatic properties of thermal-protective fabric systems to simulate the separation of garment layers on the human body;
2. determine the differences in peak discharge potential and discharge energy among various thermal-protective fabric systems as measured when following the new small-scale test method, at 0% and 20% RH, and 22°C;
3. determine the effect of rubbing speed and pressure (weight) on peak discharge potential and discharge energy; and
4. determine the relationship between both peak discharge potentials and discharge energies from the new small-scale test method and from the HBE.

Null Hypotheses

To meet objective 2, the following null hypotheses will be tested:

Ho_1. When fabric systems are tested following the newly developed method at 0% and 20% RH, there are no significant main effects of outer-layer fabric, inner-layer fabric, or relative humidity on electrostatic properties, and there are no interaction effects.

To meet objective 3, the following null hypothesis will be tested:

Ho_2. When rubbing speed and weight used for the new method are varied, there are no main effects of inner-layer fabric, rubbing speed or pressure on electrostatic properties, and there are no interaction effects.

To meet objective 4, the following null hypothesis will be tested:

Ho_3. There are no significant correlations between electrostatic properties as measured from the new small-scale test method and those obtained from the human body experiment.

Delimitations and Limitations

The delimitations of this research include:

1. The fabrics chosen for measurement of electrostatic propensity were limited to thermal-protective fabrics consisting of aramid/carbon, aramid/PBI, aramid/FR viscose, and FR cotton fibres.
2. The environmental conditions for testing were limited to 0% and 20% RH, and 22^{0}C.

The limitations include:

1. Fabrics used in construction of the garments worn in the HBE were no longer available. Limited amounts were available from the actual garments, but were only used in those experiments which were meant to simulate the HBE.

Definition of Terms

The following definitions are relevant to this research:

Electric Charge: "electric charge is an intrinsic property of protons and electrons, and only two types of charge have been discovered, positive and negative. A proton has a positive charge, and an electron has a negative charge" (Cutnell & Johnson, 1992, p.490). The unit for measuring charge is the coulomb [C].

Static Electricity: "static electricity connotes the phenomena of attraction and repulsion observed between electrically-charged bodies [as differentiated] from the effects of 'dynamic electricity' which is utilized in the generation of power or energy when it passed through a system" (Crugnola & Robinson, 1959, p.2).

Contact Electrification: refers to the generation of charge when two materials come into contact, and then separate (Greason, 1992).

Triboelectrification: is a form of contact electrification which involves a frictional force (Taylor & Secker, 1994).

Electrostatic Propensity: "the capacity of a nonconducting material to acquire and hold an electrical charge by induction (via corona discharge) or by triboelectric means (rubbing with another material)" (ASTM D4238-90 Standard Test Method for Electrostatic Propensity of Textiles, p.371).

Electric Force: the electric force of two or more charges depends on the type of charges involved. That is, those charges of opposite signs will experience an attractive force, while those of similar signs a repulsive force (Cutnell & Johnson, 1992).

Potential Energy: "energy stored in an object because of its state or position" (Zitzewitz, Neff & Davids, 1992, p.218). The unit of potential energy is the joule [J].

Electrical Potential: "when an electrical force is applied to a body, the body tends to move in the direction of the force. If the body is free and moves in the direction of the force, it loses potential energy. If, instead, the body moves against the force, work must be done to overcome it, and the body gains potential energy...the potential is therefore a measure of the electrical forces which are present in a given situation" (Crugnola & Robinson, 1959, p.2). The unit of electrical potential is the volt [V].

Surface Resistivity: " the resistance between two electrodes on the surface of an insulating material... the units are ohms per square" (Rodriguez, 1989, p.302).

Charge Decay: is the neutralization process in which the charge spreads out or is (re)combined with opposite charges to reduce the overall charge (Jonassen, 1991).

Discharge: is the process involving the ionization and breakdown of the atmosphere surrounding a charged object (Jonassen, 1991).

Dielectric: is a non-conducting, or electrically-insulative material (Cutnell & Johnson, 1992).

Capacitor: a capacitor is a device, consisting of two conductors separated by an insulative material (a dielectric), which is used to store electric charge (Zitzewitz, Neff & Davids, 1992).

Capacitance: "the capacitance of a device is a measure of its ability to store charge and electrical potential energy" (Serway, 1990, p.711). This value, expressed in farads [F], is derived from "the ratio of the magnitude of the charge on either conductor to the magnitude of the potential difference between them" (Serway, 1990, p.711), as shown in the following equation:

$$C\,[F]=Q[C]\,/V[V]$$

Dielectric Constant: "when a dielectric material is inserted between the plates of a capacitor, the capacitance increases. If the dielectric completely fills the space between the plates, the capacitance increases by a dimensionless factor, k, called the dielectric constant" (Serway, 1990, p.720).

Chapter 2
REVIEW OF LITERATURE

This literature review addresses how the basic principles of static electricity relate to textile materials. Various factors affecting charge generation and charge dissipation are considered, and methods of determining these properties are introduced.

General Principles of Static Electricity

History

The phenomenon of static electricity was first discovered around 600 BC by the Greek philosopher Thales (Cutnell & Johnson, 1992). He found that when petrified tree resin, amber, was rubbed with wool or fur, small bits of leaves and straw were attracted to it. This attraction is known to be due to electrical forces. The term electric comes from the Greek word for amber, elecktron (Serway, 1990).

Benjamin Franklin made many contributions to the study of electricity. Starting in 1741, he did much work with the generation of electricity through friction, and discovered the two types of electric charges - positive and negative (Serway, 1990; Zitzewitz, Neff & Davids, 1992). Charles Coulomb, in the late 1700's, studied the effects of magnitude of charge and separation between two point charges (Cutnell & Johnson, 1992). The relationship he discovered is known today as Coulomb's Law. For his contribution to this field of science, the unit for measuring electric charge, the Coulomb, was named after this physicist.

Charge Generation and Transfer

When two objects come in contact with each other, one acquires a negative charge while the other, a positive charge. This transfer of charge may occur via electrons, ions, or charged particles (N. Wilson, 1987; Harper, 1967). In the case of electron transfer, the object acquiring the negative charge gains an excess of electrons, while that with the positive charge loses electrons. In keeping with the law that charge is conserved, not created, the magnitude of the charges are the same, but the polarities are opposite. That is, the number of electrons removed from one surface, is equal to the number of electrons gained by the other.

Conductivity

The ability of the charge generated to distribute itself throughout an object, depends on the conductivity of the object. A good conductor has charge carriers which easily carry the electrons, and redistribute the charge throughout the entire object. Materials that trap electrons at the point of generation are called insulators, and have poor electrical conductivity. Insulators can become more highly charged than conductors because of this slow movement of electrons, allowing charge to accumulate on successive contacts.

Charging mechanisms

Electrification of an object can occur by either one of two processes: induction, or contact. Charging by induction is the "process of giving one object a net electric charge *without* touching the object to a second charged object" (Cutnell & Johnson, 1992, p.504). When a negatively charged object is brought close to a neutral conductor, the electrons are repelled from the side nearest the charged object. This results in a separation of the charges within the neutral conductor. In this example, the side nearest the charge is positive while the other side is negative. If the conductor is grounded, the electrons will flow to earth, leaving the material with a positive charge (Greason, 1992).

Charging by induction works well for conductors, but not for insulators, since electron movement is restricted (Cutnell & Johnson, 1992). Polarization of positive and negative charges within an insulator, as described above, is slow and electrons cannot flow to earth when grounded. However, a small amount of charge is created from the polarization of the molecules themselves.

Contact charging refers to the process of electrification when two materials come into contact. Depending on the initial charges of the surfaces and whether they are electron accepting or electron donating, electrons will transfer at the interface from one surface to the other. If the initial charges are zero, the amount of charge on each surface will be equal in magnitude but opposite in polarity. Contact charging will occur on all materials, both conductors and insulators, however, the charge retained depends on these properties. As conductive materials are being separated, the charge on each surface flows rapidly to the last point of contact between the surfaces, where they recombine and cancel each other out, resulting in a low residual charge (Taylor & Secker, 1994; Greason, 1992). For insulative materials, charge does not flow easily through the material and cannot recombine, resulting in greater charges upon separation.

Charge Neutralization

Charge Decay

Charge decay occurs through various means that are characterized as those "neutralization processes, which are not based on a change of the conductivity of the conducting medium" (Jonassen, 1991, p.31). Because of the high electrical resistance of air, electrons do not travel easily through this medium, and charge decay to air occurs very slowly (Crow, 1991). If a negatively charged object is connected to ground, it will lose some of its free electrons to earth and become neutral. This latter mechanism will only occur in conductive materials where electrons flow readily, either along the surface or through the bulk of the material (Teixeira & Edelstein, 1954).

Teixeira and Edelstein (1954) also identify another method of charge dissipation for insulators, which they call "self-neutralization". Insulators do not have uniformly charged surfaces, but rather areas of positive and negative charges. Under certain conditions with some conductivity occurring, the charges will combine, leaving neutral areas on the material.

Discharge

Every insulating material has a breakdown field strength which, when reached, the insulating characteristics fail, and current flows through a small gap producing a bright light with a distinguishable sound (Taylor & Secker, 1994). When the field strength of a material exceeds the breakdown strength of air, electrons are pulled off creating positive and negative ions which pair together. This is called discharge, and there are three different processes through which this may occur: corona, brush and spark. The energy in a corona discharge is much lower than that needed to ignite the most incendive gas mixture (Jonassen, 1991). A brush discharge occurs when the air around a pointed region becomes ionized, allowing for charges to be conducted to the air. The spark discharge is the most incendive discharge, and the one most commonly experienced by the body. In this case, the discharge occurs quickly through a very narrow gap. The pulling off of electrons is what causes the glow that can be seen from a spark. The flow of electrons occurs in an attempt to neutralize the conductor, which often is the body (Crow, 1991).

Static Electricity and Textiles

Fowler (1989) suggested three parameters one must consider when judging the electrostatic hazard of a material: charge generation, charge dissipation, and charge retention. Teixeira and Edelstein (1954) suggest that all mechanisms of charge generation and charge dissipation must be considered when evaluating the electrostatic behavior of textiles. Such factors include the method of charging, resistivity, peak charge, and charge decay. These factors are often interrelated, and such relationships will be discussed below.

The properties and structure of the textile itself are important factors that will affect its electrostatic characteristics, however, environmental conditions may alter these properties and thus the behavior. The two most influential environmental conditions include relative humidity and temperature, and will be discussed in association with each electrostatic property where relevant.

Charge Generation

When two insulative surfaces such as textiles are separated, the charge is localized at the area of contact only, and does not flow throughout the material, as would occur in a conductor (Hersh & Montgomery, 1956). For this reason, charge accumulation is a problem for most textiles and clothing systems, especially at low humidities (Crow, 1991; N. Wilson, 1987). Jeziorny and Urbanczyk (1973) made some connections between the molecular and fine structures of a fiber and the amount of charge generation possible. They propose that high crystallinity, high molecular weight polymers, and low orientation contribute to greater charge generation in a fiber. In support of this, Haenen (1976) explained that as crystallinity increases, the availability of holes into which electrons can be accepted, decreases. This researcher also speculates that double bonds may readily donate electrons, and that those materials with many double bonds are most likely to become positively charged upon contact with other materials.

Triboelectrification

Triboelectrification is defined as contact electrification involving some type of frictional force, and is the term usually used for electrification of textiles as it is most commonly encountered in everyday life (Chubb, 1988; Sello & Stevens, 1983). A triboelectric series can be developed from this type of charging. This is a list of materials ordered in such a way that when two materials are rubbed together, the one higher up on the list becomes positively charged, while the other negatively charged (Hersh & Montgomery, 1955).Such a series is useful to predict the electrostatic behavior, in terms of polarity, of two materials when rubbed together (Hayek & Chromey, 1951).

Justification for a triboelectric series is given by Hersh and Montgomery (1956), who state that a particular order is created because of the unique molecular structure of a material . Each fiber has its own set of electrons that is unique to its structure. Since no two surfaces are exactly alike, upon contact electrons will always flow from the surface with the most free electrons to that with the least. Ballou (1954) constructed a triboelectric series and discovered that those fibers at the positive end of the list contained amide groups, suggesting that certain molecular groups may have a tendency to lose electrons more readily than others. Gonsalves (1953) supported this idea since he found greater magnitudes of charge resulting when the two materials rubbed together were farther apart in the series. This is explained by the concept that materials near the extreme ends of a series have a greater number of electrons available to transfer between surfaces. Because of the complex factors affecting triboelectrification, several different series have been developed by different researchers (Fowler, 1988). Such factors are discussed below.

Velocity. Increasing the rubbing velocity has two effects on electrification: it decreases the amount of time for electrons to tunnel or flow to other areas, and it increases the temperature at the point of contact (Hersh & Montgomery, 1956; Hammant, Sumner &

Wyatt, 1981). The first effect means that for insulators, charge will build up since it has less time to leak away (Hersh & Montgomery, 1955; Chubb, 1988). The increase in temperature allows for increased ease of mobility for electron transfer. Frictional rubbing of two surfaces results in charge transfer between the surfaces due to temperature differences brought about by asymmetrical rubbing (Harper, 1967). As the temperature in this area increases, mobile particles will flow from the hotter surface to the colder surface (Henry, 1953).

Surface characteristics and area of contact. Fabric structure will affect the amount of contact made between two surfaces and thus, the amount of charge generated. D. Wilson (1963) stated that "friction arises from adhesion at the points of real contact (asperities)" (p.T149). This suggests that even with simple contact of fabric surfaces without any intentional rubbing, some friction will result from the intrinsic characteristics of the surfaces. Factors related to surface characteristics which will affect the contact area between two surfaces include: type of yarns (filament vs. spun yarns), type of weave, and alignment of surface fibers after repeated rubbing (D.Wilson, 1963; Carr, Posey, & Tincher, 1988; Thorndike & Varley, 1961; Ajayi, 1992).

Measurement of the area of contact is complex. Fabric surfaces are rather uneven and total surface area contact is not made when two fabrics touch (Gonsalves, 1953). Accurate measurement of the area of contact is very difficult, but it is assumed that the true area of contact is usually less than the apparent area (Hersh & Montgomery, 1955; Henry, 1953). Contact will be made at those high points which are readily accessible, and as a result, electrification will be much lower than if the two surfaces were flat and regular (Ballou, 1954). The application of pressure and slight rubbing will help to achieve closer contact between surfaces (N.Wilson, 1987), however, vigorous rubbing changes the mechanisms of charging, and incorporates additional variables which have been shown to result in an increase or decrease in charge generation, including changes in polarity in some cases (Gonsalves, 1953; Hersh & Montgomery, 1955; Lowell, 1976). Lowell (1976) offers a possible explanation for this, suggesting that repeated contacts disturb the structure of the molecules, bringing to the surface molecular groups from within which may participate in acceptance or donation of additional electrons, resulting in greater charge generation. This explanation is based on experiments involving films in contact with metals, in which very little contamination of the surfaces occurs. Hersh and Montgomery (1955) observed erratic behavior during their experiments with textile fibers, which were eliminated upon washing. Such behavior suggests that contamination of fibers could also contribute to an increase or decrease in charge generation upon successive contacts.

Dielectric constant. The dielectric constant of a non-conducting material refers to the increase in capacitance of a capacitor with this material in it. The capacitance increases since the charge cannot be conducted through the material, but rather accumulates on the material. When an electric field is applied to a material, polarization within it occurs. This can happen as dipolar molecules, such as water, align themselves in the direction of the field, or when atoms and other molecules become induced dipoles from uneven distribution of electrons within these structures (Morton & Hearle, 1975). In fibers with only directly absorbed water molecules, the dielectric constant is lower as these molecules are tightly held in place and cannot orient themselves (Hearle, 1954). This may also be a factor at low humidity levels in which the moisture content of a fiber is very low, consisting primarily of directly bound water molecules.

Textile materials with high dielectric constants tend to generate greater positive charges upon contact and separation with other materials (Ballou, 1954). Gallo and Lama (1976) relate this to the ease of ionization of materials with high dielectric constants. Electrons in the atoms found in materials with high dielectric constants tend to be less tightly bound to the nucleus, increasing the ease of removal of electrons, and allowing for such particles to become ionized. Upon contact of two materials, electron transfer occurs from the surface with the high dielectric constant, where electrons are more easily removed, to that with the lower dielectric constant, leaving the former material positively charged. Therefore, a triboelectric series is ordered in such a way that those materials at the top of the series have the highest dielectric constants; this is called Coehn's law (van Krevelen, 1976). This condition is true in some instances, however, Harper (1967) questioned the universality of this law, as the order of a triboelectric series will change when the conditions of charge generation change.

Effect of relative humidity. Hersh and Montgomery (1956) speculate that there will be no change in the order of a triboelectric series at different humidity levels. There will however, be a decrease in the magnitude of the charge generated based on the conductivity of the fiber. This decrease can be explained by the increase in conductivity at higher humidities, and will be discussed further in the section dealing with resistivity. However, since not all fibers regain the same amount of moisture at certain humidity levels, this may have an affect on the order of fibers in a triboelectric series. Due to the hysteresis effect, electrostatic charge generation on fabrics when conditioned from the dry state differ from those conditioned from the wet state, and must be considered when conditioning fabrics (Sereda & Feldman, 1964).

Evaluation of Test Methods

The proposed ASTM F23.20.05 "Standard Test Method for Evaluating Triboelectric (Static) Charge Generation on Protective Clothing Materials" (Stull & Greimel, 1996), is one method which uses triboelectrification as the charging mechanism. Friction tests are often avoided since it is thought to be difficult to reproduce consistent results (Joshi, 1996; Shah & Dweltz, 1994). This method overcomes this problem by using a mechanised rubbing wheel to generate a consistent amount of rubbing, with controlled pressure. The charge generated is measured from the rubbed surface of the material using a sensor head. This method is acceptable for use with non-homogeneous materials, and for multiple-layer fabric systems.

An alternative method to this is a modified version of proposed ASTM F23.20.05 (Gonzalez, Rizvi, Crown & Smy, 1997). This modification represents the process that occurs when charge is transferred to the human body from the clothing worn, by using a capacitor to store the transferred charge from the outside surface of the fabric system. The resulting discharge from the body which occurs upon touching a conductor is simulated by discharging the capacitor.

Charge Dissipation

Once charge is generated on the surface of a textile, the subsequent dissipation will depend on the conductivity of the fibers, the moisture content of the textile, and the humidity and other materials in the surrounding atmosphere.

Resistivity

The ability of charge to flow along a fiber depends on the resistivity, or inversely, the conductivity of the fiber. It can be thought that a fabric having high resistivity has low conductivity. The unit for measuring this property is ohms per square.

A current can be carried through a material via ions. The greater the number of free ions available to conduct this current, the lower the resistance of the material (Morton & Hearle, 1975). Hartgrove (1970) identified differences in resistivity for the same fiber type when different weave structures were used, but suggested that other factors such as yarn denier, number of filaments, and weight may differ along with the weave, contributing to differences in resistivity.

Environmental factors affecting resistivity. At high humidity levels, many textile fabrics become good electrical conductors because of moisture absorbed from the air (Crow, 1991). According to Sello and Stevens (1983) water has very low resistivity, or in other words is highly conductive, and thus will affect the resistivity of a textile material. Morton and Hearle (1975) generalized that for every 13% increase in relative humidity, the resistance of a material decreases tenfold. This is a crude generalization since each material regains moisture differently than others, and not always linearly. These researchers suggest that conduction occurs in the non-crystalline regions of a fiber only, which have a different moisture content from that of crystalline regions, which will act as insulators. Sharman, Hersh & Montgomery (1953) studied the effect of drawing on the conductivity of filament fibers, and found an inverse relationship, in that as drawing increased, the conductivity decreased. In explaining why this effect occurred, it could not be answered by considering the difference in moisture regain as it varies with drawing, suggesting that other factors must be affecting the conductivity. If crystallinity increases upon drawing, and crystalline regions are good insulators, it may be a combination of increased crystallinity and decreased moisture sorption which reduces the conductivity of the fibers.

It has been found that as temperature increases, resistivity decreases (Hersh and Montgomery, 1956). An increase in temperature results in an increase in charge carriers able to conduct any charge. Sello and Stevens (1983) suggest that since most textiles are used at room temperature, where this effect is negligible, humidity plays a more important role in determining resistivity. However, both moisture and temperature variables are important considerations for those materials used and worn outdoors which may be exposed to both cold temperatures and low humidity levels.

Relationship between resistivity and charge generation. There has been no direct correlation found between surface resistivity and charge generation, or triboelectrification (Baumgartner, 1987; Fowler, 1988). An apparent low amount of charge generated is often mistakenly thought to be caused by low resistivity, when it is really caused by a fast decay rate which may allow for charge to decay quicker than it can be measured. A large amount of charge may be generated, however, if the material has low resistivity the charge will decay quickly.

Evaluation of test methods. AATCC Test Method 76-1989 "Electrical Resistivity of Fabrics" is used to determine surface electrical resistivity (AATCC, 1989). This method cannot be used for fabrics containing anti-static finishes or conductive fibers since the equipment will measure the resistance of the conductive materials, which are much lower than the bulk of the fabric (Chubb, 1988; Crow, 1991; Scott, 1981). Teixeira and Edelstein (1954) recognize that measuring resistivity only considers charge dissipation based on direct conduction, and that anti-static agents may dissipate charge primarily through a different method of charge leakage, other than conduction. Chubb (1988) argues that the method of initial charge distribution may also affect charge migration, and thus resistivity.

Charge Decay

Onogi, Sugiura and Nakaoka (1996) suggest that charge decay occurs, in part, when adsorbed water molecules on a fiber evaporate, taking with them any charges on the surface. They found that at a certain water content level within a fiber, charge decay increases rapidly. This is related to the idea that water molecules are absorbed in two stages; initially water molecules are firmly bound to the fiber molecules, but once these sites are filled the water molecules are less firmly attracted to the first ones and are free to move and participate in evaporation. The humidity level at which each stage occurs varies, depending on the molecular and fine structures of the fiber. The affect of the color of a textile on its electrostatic properties is not well known, however, one study found that dye concentration affected charge decay in that the lighter the shade, the lower the concentration of dye, the lower the decay time (Shah & Dweltz, 1994). This may be due in part to the difference in moisture sorption, or in the availability of charge carriers.

As previously mentioned, charge decay to air occurs very slowly, however, when oppositely charged ions and particles from the atmosphere are attracted to the charged surface, some of the charges cancel out, aiding in decay (Teixeira & Edelstein, 1954; Jonassen, 1991). In addition, it has been found that charge decays differently based on the method of charge generation utilized, and the polarity of the charge. Positive and negative charges have been found to decay at different rates, due to the relative mobility of the different charge carriers (Taylor, Owen and Elias, 1987; N. Wilson, 1985). These researchers and others have found that the rate of charge decay differs depending on the method of charge generation used, applied voltage versus corona charging (Baum, Lewis & Toomer, 1977; Haenen, 1976).

<u>Conductive fibers</u>. Controlling the charge decay of a material is an important issue in the elimination of harmful discharges (Jonassen, 1991). To increase the charge dissipation of a textile material, it is necessary to increase its conductivity (Sello & Stevens, 1983). Crow (1991) identifies three methods to accomplish this: (i) use of an antistatic finish; (ii) inclusion of antistatic or conductive particles within the structure; and (iii) incorporation of metallic or conductive fibers into the yarns.

The underlying concept behind the use of many antistatic finishes is to increase the moisture sorption of fibers (Crow, 1991; N. Wilson, 1987). This method is ineffective in low humidity environments, where there is very little, or no water available for sorption to occur (Scott, 1981). In addition, such finishes are often not fast to washing, making them ineffective after laundering (Sello & Stevens, 1983).

The use of conductive particles involves either blending particles of carbon black with the textiles fibers before spinning (epitropic fibers), or using carbon as the core around which the fibers are spun (Crow, 1991). Some problems exist with this method since cotton and polyester/cotton fibers cannot be blended with carbon, and some dyeing processes damage the carbon particles. Stainless steel fibers are incorporated into fabric structures to help bleed off any charges to air (Crow, 1991). Staple lengths of metallic fibers are blended with staple fibers, into yarns. These last two methods of static control are recommended by N. Wilson (1987), since materials composed of carbon or metallic fibers are less dependent upon the moisture content of the surrounding environment for charge decay.

Relationship between resistivity and charge decay. Resistivity is only one measure which can be used to estimate the amount of charge dissipation of a material, since accumulation of electrostatic charge is influenced by resistivity (Crow, 1991; Teixeira & Edelstein, 1954). The high insulative characteristics of most fabrics contribute to high levels of resistivity, which often prevents any charge generated on the material from leaking away. Low surface resistivity is necessary in order for a fast rate of charge decay (Baumgartner, 1987), and good correlation has been found between these two characteristics (Ramer & Richards, 1968).

Evaluation of test methods. One method of measuring charge decay is the Federal Test Standard 191A Test Method 5931 (Superintendent of Documents, 1990). It is suggested, however, that any method using an electrode to charge the specimen is inadequate, since this only allows for charge to flow along the conducting features of the material, with no way of measuring the charge immobilized on the insulative features (Chubb, 1988; Owens & Klein, 1990). For this reason, a fabric may 'pass' both resistivity and charge decay tests, but still develop high triboelectrification values. This method is also not suggested for use with non-homogeneous materials, such as textiles (Chubb & Malinverni, 1993).

Static Electricity and the Human Body

The fact that the human body is a good conductor of electricity, and that often our bodies are insulated from ground, causes charges to be easily induced onto, or produced by, the body and stored until a grounded object is touched (Scott, 1981). Charging of the human body occurs by either triboelectrification or induction (Roth, 1990; Greason, 1992). Clothing worn directly against the skin can produce charges from repeated contact, friction, and separation of these two surfaces. Charges generated on clothing through contact with materials other than the body, can lead to charges induced onto the body from the garments. In either case, when the person touches a grounded conductor, because the body has become polarized, charge flows to ground in order to balance out the polarization. If this charge is large enough to produce an electric field greater than the breakdown energy of air, a spark will be created when the conductive object is touched (Crow, 1991). Conductive footwear and wrist straps when worn, are helpful in conducting any charge induced on the body to ground (Crow, 1991; O'Shea, 1996). This prevents charge from building-up and being dissipated through sparks.

Electrostatic Hazards

The amount of energy generated from the discharge process will determine the incendivity of the discharge. A spark carries with it energy which increases the temperature of the surrounding air. If the temperature rises above the critical value of the air-gas mixture, ignition may occur (N. Wilson, 1987). The critical value, known as the minimum ignition energy (MIE), is the lowest energy required to ignite a certain gas or mixture (Taylor & Secker, 1994). These are used in combination with the energies acquired from the human body, in the form of a spark discharge, to determine the potential hazard in a particular environment. Various MIE's are reported in the literature depending on the concentration of the air/gas mixtures, and on other experimental conditions. The following are examples of MIE values for various gases: methane, 0.29mJ; propane, 0.25mJ; acetylene, 0.017mJ (Bustin & Dukek, 1983); and air/natural gas, 0.30mJ

(Wilson, 1979). Very sensitive powders may have MIE's as low as a few *u*J, which may also cause damage to sensitive electronics (Taylor & Secker, 1994).

Human-Body Experiments (HBE's)

Various types of HBE's have been conducted to determine the effect of such variables as body capacitance, type of activity performed, atmospheric conditions and fiber and clothing type, on the charge induced onto the body. The speed of removing an outer layer garment has been found to influence charge generation, in that the quicker the rate of removal, the greater the charge generated (Scott, 1981; Osei-Ntiri, 1992). As well, those activities which require more body movements generate greater charges than stationary activities (Scott, 1981). A breakdown of the charge generated at various parts of a clothing system reveals that those loose areas of garments where fabric can flow easily are most susceptible to charge generation, although the effect of this on charging the body was not investigated. Veghte and Millard (1963) conducted HBE's to measure charge generation on the surface of various garments in order to calculate the amount of stored energy on the clothing. This calculation was used to determine the potential hazard of the garments, without consideration of the human body, which could potentially store much greater charges than the clothing. In addition, discharge from the surface of the textile will also be much lower than that from the body, since the charges involved in the discharge from the insulating surface will only be those in the near vicinity, not from the entire surface (Rizvi & Smy, 1992). Crugnola and Robinson (1959) suggest that a garment which can develop 3000 volts, or more, on an individual could lead to a spark with enough energy to ignite a gasoline-air mixture. The garments used in their HBE's exceeded this value at and below 35% RH. These researchers went on to develop a test method which presented results in support of those obtained from the HBE's.

Most of the HBE's to date have dealt with traditional, non-protective clothing at relatively high humidity levels (Phillips, 1982; Veghte & Millard, 1963; Wilson, 1977/78). Research at the University of Alberta, however, has been conducted into the consideration of electrostatic properties of thermal protective clothing systems. HBE's replicating common workplace activities of sliding across a truck seat and removal of an outer layer garment were carried out at low humidities (Osei-Ntiri, 1992; Rizvi, Crown, Osei-Ntiri, Smy & Gonzalez, 1995; Rizvi, Crown, Gonzalez & Smy, in press). In each case, the discharge potential from the human body, in the form of a spark, was determined after each activity was performed.

These studies demonstrate that when electrification of clothing occurred via a material external to the garment system, the outer layer of the system had the greatest influence on the charge generated. In addition, charge generation was greatest when the garment systems comprised materials of similar fiber types. On the other hand, when two layers are separated, the inner layer had an effect on the charge generated, and when the two materials were similar, lower charges were generated. This research also demonstrated that those systems containing cotton performed no better than those consisting of synthetic fibers. The effect of humidity on charge generation generally resulted in greater discharge energies from the body at 0% than at 20% RH.

Summary

Charge generation occurs readily on clothing during wear and use. The amount of charge generated depends on the conductivity of the material, and the amount and speed of contact. How quickly the charge generated dissipates, in part, depends on the resistivity of the material. Clothing which is prone to static build-up will develop problems such as static cling and soiling, while in more hazardous situations when charge is induced onto the body, a resulting spark with enough energy could ignite incendive air-gas mixtures. Each of the electrostatic properties described contribute to the electrostatic behavior of a textile. Because some of these issues are interrelated, the knowledge of some properties may allow for the prediction of others. However, relationships do not exist among all properties, stressing the importance to study all factors related to electrical properties in order to predict how a material will behave. In measuring these electrostatic properties, it is important to consider the purpose of such information, as often the test methods used have limited application to real-life situations.

CHAPTER 3
PRELIMINARY EXPERIMENTS

This is an experimental study to develop and evaluate a small-scale test method which accurately measures peak discharge potential from a capacitor in contact with a material which contacts and is separated from a different material. The aim is to simulate the removal of an outer layer garment, the transfer of charge to the human body, and the subsequent discharge from the body. Preliminary experiments were conducted following a modified version of the proposed ASTM F23.20.05 method as described by Gonzalez, Rizvi, Crown & Smy (1997). The objective of this preliminary work was to determine the appropriate speed and pressure to simulate separation of two clothing layers. This chapter reports the necessary modifications to the previously developed method, and the results of this experimental work.

Independent variables in the experiments included rubbing speed, weight, and fabric, the latter comprising different fiber contents and fabric structures. The dependent variables were peak discharge potential measured in volts (V) using the small-scale test method developed, and the calculated discharge energies in joules (J).

Procedures

Fabric Sampling

Fabrics chosen for this research were those used in fabrication of the garments worn in the human-body experiments (HBE's) conducted by Rizvi et al. (in press) and, with the exception of aramid/PBI, are commonly used in manufacturing thermal-protective garments. Two components of a garment system are to be considered: the parka and coverall. Table 1 lists the characteristics of the fabrics composing each system. Fabric count was performed according to CAN/CGSB-4.2 Method 6-M89/ISO 7211/2-1984(E): Determination of number of threads per unit length (CGSB, 1989). Mass was measured according to CAN/CGSB-4.2 Method 5.1-M90: Unit Mass of Fabrics (CGSB, 1990).

Table 1
Fabric Components and Characteristics of the Thermal-Protective Garments Used

GARMENT (and components)	FIBER CONTENT	WEAVE	COUNT (warp x weft) (yarns/cm)	MASS (g/m^2)
PARKA				
1 outer layer	FR cotton	satin	35 x 19	303
vapor barrier	nylon[a]	plain	40 x 27	79
interlining	FR modacrylic	nonwoven	-	} 346
lining	FR cotton	plain	32 x 35	}
2 outer layer	aramid/carbon	plain	29 x 18	211
vapor barrier	nylon[a]	plain	40 x 27	}
interlining	aramid	nonwoven	-	} 455
lining	aramid	rip stop	32 x 39	}
COVERALL				
1	aramid/carbon (new)[b]	plain	29 x 18	211
2	aramid/carbon (HBE)[c]	plain	23 x 21	205
3	aramid/PBI[d]	plain	26 x 22	145
4	FR cotton	satin	35 x 19	303
5	aramid/FR viscose	twill	33 x 20	258

[a] Fabric has been treated with a water-repellent finish
[b] Fabric was newly purchased for this study, has been treated with a wicking finish
[c] Fabric was taken from the garment worn in the human-body experiment
[d] Fabric which is not commercially available, has a topical anti-static treatment

Conditioning

The four coverall fabrics were washed following CAN/CGSB-4.2 No.58 M90, Colourfastness and Dimensional Change in Domestic Laundering of Textiles, washing procedure III and drying procedure E (CGSB, 1990). Five specimens of each coverall fabric were cut, measuring 205 mm x 205 mm, with no two specimens containing the same warp or weft yarns. One circular specimen of 127 mm diameter was cut from each of the parka components to be used as rubbing materials. All specimens were conditioned at 0%, and 22 $\pm$ 2 ^{0}C.

Measurement of Dependent Variables

The equipment used to reproduce triboelectric charge generation was the Triboelectric Test Device and rubbing wheel used in a modified version of ASTM F23.20.05 as described by Gonzalez et al. (1997) (Figure 1). The conducting plate is connected to a 200pF capacitor, meant to represent the capacitance of an average human-body. A Simco Static Eliminator Model 300 was used prior to testing each specimen in order to eliminate any initial charge. The real area of contact between the rubbing material and specimen was 127cm^2, equivalent to the surface area of the rubbing wheel. The peak discharge potential was measured and recorded by a Tektronix Digitizing Oscilloscope Model TDS 340A.

Calculation of total discharge energy. The total transferred charge (Q) was calculated from the voltage waveform for each specimen:

$$Q = I\ dt = (1/R)\ V\ dt \qquad (1)$$

The total discharge energy was then calculated:

$$E = (1/2)\ QV \qquad (2)$$

Development of Test Device

The various changes in the design of the equipment and to the procedure of the modified version of ATSM F23.20.05 are as follows.

1. The materials used on the rubbing wheel surface were those multiple-layer fabrics composing the two parkas, FR cotton and aramid/carbon. The composite specimens were attached to the rubbing wheel with the lining fabric layer to the outside surface (Figure 2).

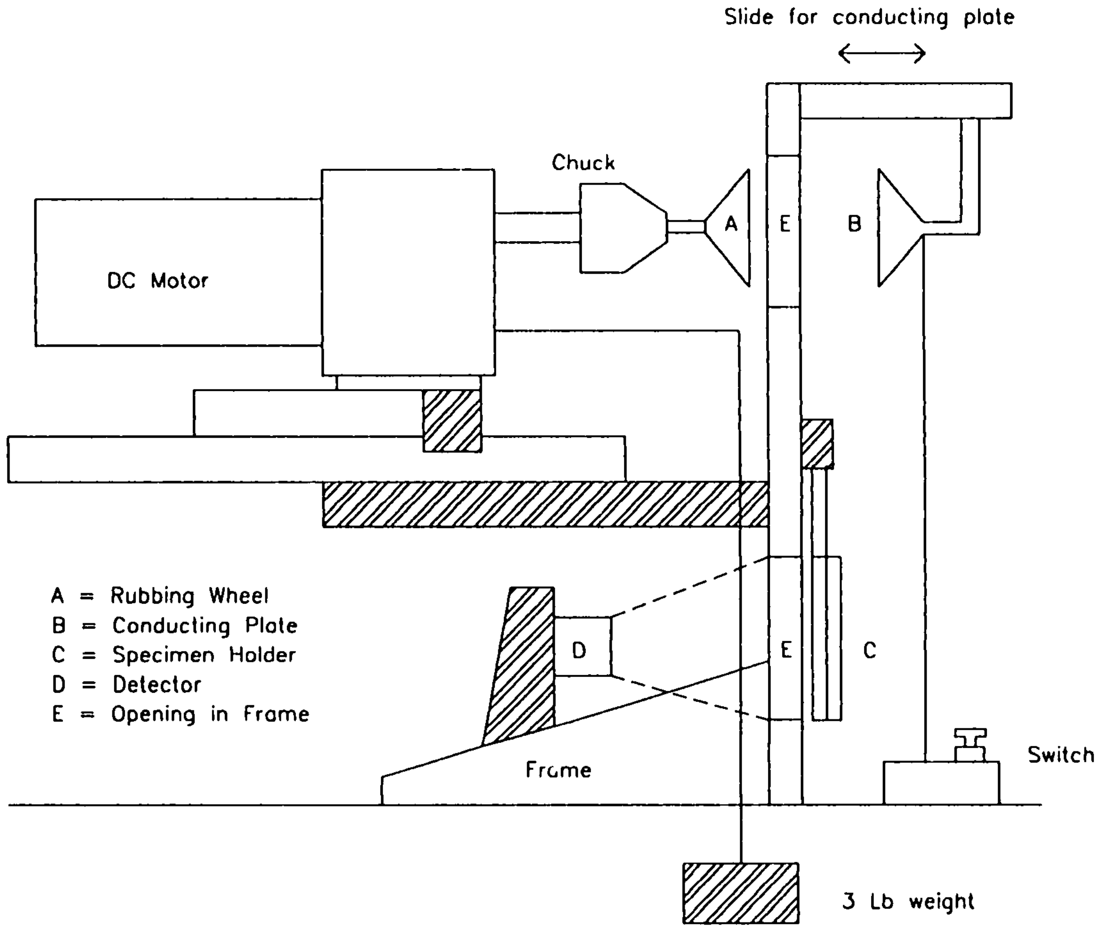

Figure 1. Triboelectric test device used.

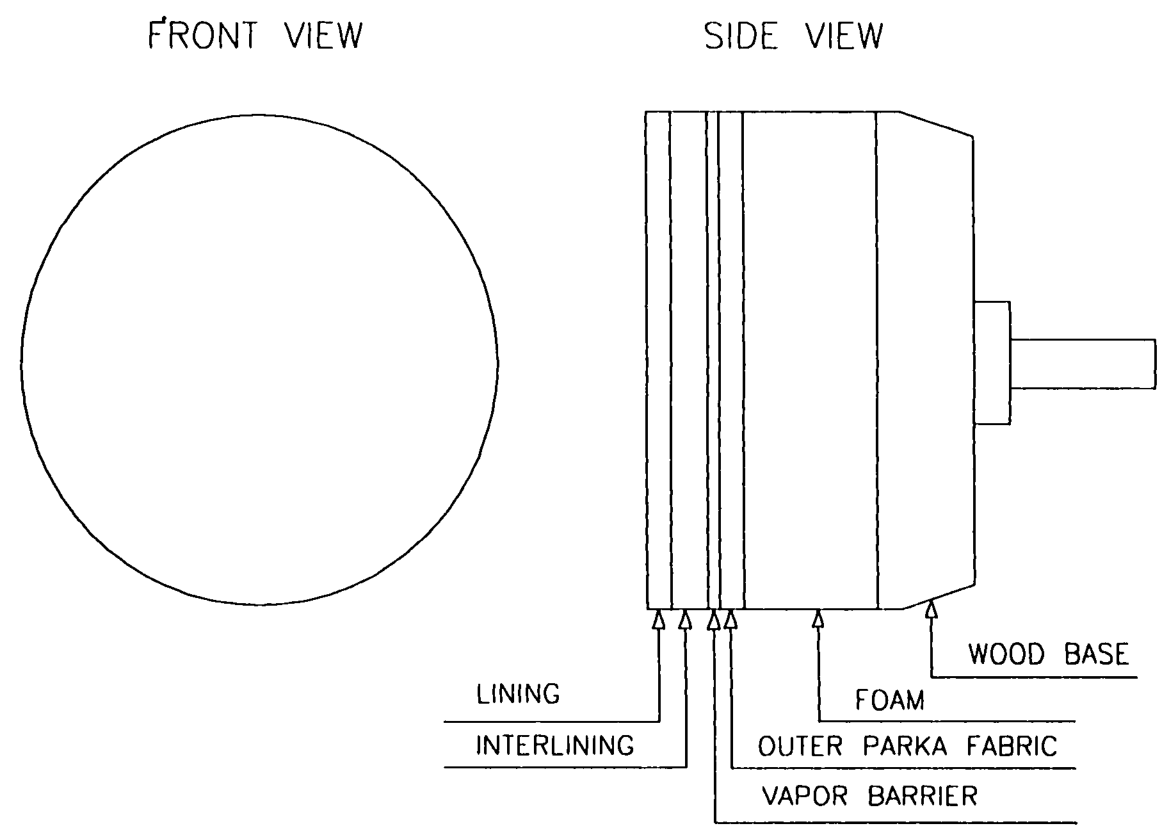

Figure 2. Rubbing materials attached to the rubbing wheel in the order present in the parkas worn in the human-body experiment.

Specimens against which these surfaces were rubbed are those representing the coveralls (Table 1).

2. The standard method does not specify how to attach the rubbing material to the actual rubbing wheel. Two techniques were considered and experiments conducted to determine the better method: (i) wrapping the material over the foam and taping it to the underside of the wheel, and (ii) sewing the materials to the foam of the wheel using the same thread as used in the construction of each parka. From the results of this preliminary experiment (Table 2) the sewing technique was selected. Wrapping tended to compress the foam and reduce the rubbing surface area, which may account for the lower results with the wrapped wheel.

3. The modified version of ASTM F23.20.05 (Gonzalez et al., 1997) uses a conducting plate placed against the coverall fabric allowing charge to be transferred from the fabric to the plate, and stored in a capacitor until it is discharged at the end of the test. The conducting plate is removed before discharging the capacitor. In comparing the components with that of the HBE, removing the conducting plate at the end of the charging process and before discharging the capacitor would be similar to having the subject remove the coverall before touching the electrode. Since in the HBE of interest to this research, the subjects remove only the parka, it was decided that the conducting plate should remain in place until after the capacitor is discharged.

4. The test method specifies use of a fresh specimen for each test, but does not mention the condition of the rubbing wheel. For the preliminary experiments, in order to reduce the amount of fabric used as some were in short supply, specimens and rubbing wheel surfaces were repeatedly used in determining the appropriate levels of speed and pressure. A small experiment was conducted to determine the effect of history of both the rubbing wheel and test specimens. Fresh specimens and rubbing wheel were conditioned at 0% RH. Five specimens of each of three fabrics were used. Testing began on day one with all five FR cotton specimens, followed by aramid/FR viscose and then aramid/carbon, using the components of the FR cotton parka as the rubbing surface. This was continued for six days, after which results of the first and sixth days were compared (Table 3). On the seventh day, used specimens were tested with a fresh wheel to determine whether the

Table 2
Mean Peak Potential and Discharge Energies Following ASTM F23.20.05[a] When Rubbing Material[b] is Wrapped Or Sewn to the Rubbing Wheel

FABRIC	MEAN[c] PEAK POTENTIAL (V)		MEAN[c] DISCHARGE ENERGY (μJ)	
	Wrapped	Sewn	Wrapped	Sewn
aramid/PBI	243[d]	474	3.18[d]	10.76
FR cotton	102	299	0.58	4.08
aramid/carbon (new)	126	254	0.80	2.94
aramid/FR viscose	82[e]	171[f]	0.49[e]	1.40[f]

[a] Testing was carried out at 0% RH, using a rubbing speed of 100 RPM and weight of 1360g
[b] Rubbing wheel surface comprised those materials composing the FR cotton parka
[c] Means are of 10 measurements unless indicated otherwise
[d] Means are of 7 measurements only
[e] Means are of 4 measurements only
[f] Means are of 9 measurements only

Table 3

Mean Peak Potential and Discharge Energies Following ASTM F23.20.05[a] to Determine the Effect of Rubbing History on These Properties

FABRIC		MEAN[b] PEAK POTENTIAL (V)				MEAN[b] DISCHARGE ENERGY (μJ)		
	Specimens:	Fresh	Used[c]	Used[d]	Specimens:	Fresh	Used[c]	Used[d]
	Wheel:	Fresh	Used[c]	Fresh	Wheel:	Fresh	Used[c]	Fresh
FR cotton		+77[e]	+24[e]	+38[f]		1.04[e]	0.19[e]	0.22[f]
aramid/FR viscose		-191	-213	-202		4.84	6.40	5.62
aramid/carbon (new)		- 86	-108	-92		1.37	1.91	1.54

[a] Rubbing wheel surface comprised those materials composing the FR cotton parka, testing was carried out at 0% RH, using a rubbing speed of 25 RPM and weight of 200g

[b] Reported means are of 5 measurements unless indicated otherwise

[c] Specimens and rubbing wheel materials used five times previously

[d] Specimens used six times previously

[e] Means are of 4 measurements only

[f] Means are of 2 measurements only

change in peak potentials and discharge energies were due to the history of the rubbing wheel or of the test specimens. Results indicate that after six sets of testing the peak potential becomes more negative. When the rubbing wheel is changed, the values become more positive, but do not return back to the initial level, suggesting a history effect of both rubbing wheel and specimens in combination. In order to prevent misleading results in the preliminary experiments, it was decided, based on these findings, that specimens and rubbing wheels would be used a maximum of six times, after which fresh materials would be cut and conditioned as previously described.

Preliminary Experimentation Technique

The specimens were cut and conditioned as described earlier. The procedure followed that of a modified version of ASTM F23.20.05 (Gonzalez et al., 1997) and incorporated additional modifications previously discussed. The standard rubbing speed and weight indicated in ASTM F23.20.05 are 200 revolutions per minute (RPM) and 1360g (3lbs). Experiments were conducted with different levels of these variables to simulate the human-body activity of removing a parka. Tables 4 and 5 show the combinations of speed and weight tested, and the results of this work. Five specimens were each tested only once for each variable set resulting in a maximum of five data points. The reported averages in Tables 4 and 5 may be of fewer than five values as accurate readings were not always obtained for all specimens. The order of testing each set was always FR cotton, aramid/FR viscose, aramid/carbon and aramid/PBI, when used. All five specimens of each fabric were tested before moving on to the next. Absolute values only are reported to allow for ranking of the materials and comparison with results from the human body experiment (Appendix A).

Results

The purpose of these preliminary experiments was to:

1) Determine which levels of rubbing speed and pressure, when incorporated into the modified version of ASTM F23.20.05 method would best simulate the separation of garment layers as in the removal of a parka; and

2) Determine the other levels of these variables to include in the final experiments to determine an effect of rubbing speed and pressure.

Table 4

Analysis of Variance: Peak Potentials and Discharge Energies From Preliminary Experiments Following a Further Modified Version of ASTM F23.20.05 at 0% RH Using the Components of the FR Cotton Parka as the Rubbing Materials

WEIGHT (g)	SPEED (RPM)									
	25		50		75		100		200	
FABRIC SYSTEM (Outer - Inner Layers)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)
200g										
FR cotton - aramid/carbon (new)	93.00^{a}	1.45^{a}	110.80^{a}	2.10^{a}	109.20^{a}	2.02^{a}	84.67^{a}	1.35^{a}	141.20^{a}	3.32^{a}
FR cotton - FR cotton	77.00^{a}	1.00^{a}	85.00^{a}	1.22^{a}	133.00^{a}	2.58^{a}	**124.67^{a}**	**2.28^{a}**	211.00^{ab}	6.66^{ab}
FR cotton - aramid/PBI	N/A		N/A		N/A		**266.33^{b}**	**9.37^{b}**	241.00^{b}	8.23^{ab}
FR cotton - aramid/FR viscose	190.80^{b}	4.72^{b}	261.20^{b}	8.98^{b}	266.00^{b}	9.60^{b}	**262.00^{b}**	**9.21^{b}**	281.20^{b}	10.75^{b}
FR cotton - aramid/carbon (HBE)	N/A		N/A		N/A		**418.00^{c}**	**26.49^{c}**	386.00^{c}	23.71^{c}
500g										
FR cotton - aramid/carbon (new)	121.20^{a}	2.46^{a}					179.60^{a}	6.07^{a}	179.60^{a}	5.58^{a}
FR cotton - FR cotton	138.00^{a}	2.88^{a}					191.33^{a}	4.96^{a}	408.67^{b}	23.80^{b}
FR cotton - aramid/PBI	N/A		N/A		N/A		315.00^{b}	13.44^{b}	N/A	
FR cotton - aramid/FR viscose	310.80^{b}	12.58^{b}					533.00^{c}	38.40^{c}	574.00^{c}	44.07^{c}
FR cotton - aramid/carbon (HBE)	N/A						512.00^{c}	40.02^{c}	N/A	
1360g										
FR cotton - aramid/carbon (new)	226.80^{b}	8.71^{b}					220.00^{a}	8.06^{a}	N/A	
FR cotton - FR cotton	128.67^{a}	2.55^{a}					320.00^{b}	13.69^{a}	18.00	0.11
FR cotton - aramid/PBI	N/A		N/A		N/A		N/A		502.00	36.20
FR cotton - aramid/FR viscose	543.60^{c}	40.55^{c}					714.80^{c}	71.51^{b}	772.80	82.23
FR cotton - aramid/carbon (HBE)	N/A						N/A		528.00	45.38

$^{a, b, etc}$ In each column for each variable set, means (n ranging from 1 to 5) with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test ($p<.05$).

Table 5

Analysis of Variance: Peak Potentials and Discharge Energies From Preliminary Experiments Following a Further Modified Version of ASTM F23.20.05 at 0% RH Using the Components of the Aramid/carbon Parka as the Rubbing Materials

WEIGHT (g)	SPEED (RPM)									
	25		50		75		100		200	
FABRIC SYSTEM (Outer - Inner Layers)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)	MEAN POTENTIAL (V)	MEAN ENERGY (uJ)
200g										
aramid/carbon - aramid/carbon (HBE)	90.00	1.23					**176.00^{a}**	**4.67^{a}**	230.00^{a}	8.39^{a}
aramid/carbon - aramid/PBI	130.00^{a}	2.71^{a}					**379.33^{b}**	**19.78^{b}**	242.00^{a}	9.06^{a}
aramid/carbon - aramid/FR viscose	262.80^{b}	9.87^{a}	N/A		N/A		**367.60^{b}**	**17.87^{b}**	208.40^{a}	6.35^{a}
aramid/carbon - FR cotton	531.00^{c}	38.53^{b}					**482.00^{c}**	**30.73^{c}**	426.00^{b}	25.60^{b}
500g										
aramid/carbon - aramid/carbon (new)							265.00^{a}	12.34^{a}		
aramid/carbon - aramid/carbon (HBE)							314.00^{ab}	15.17^{a}		
aramid/carbon - aramid/PBI	N/A		N/A		N/A		346.00^{ab}	17.04^{a}	N/A	
aramid/carbon - aramid/FR viscose							353.00^{ab}	16.79^{a}		
aramid/carbon - FR cotton							480.00^{c}	30.89^{b}		
1360g										
aramid/carbon - aramid/carbon (HBE)									310.00	14.66
aramid/carbon - aramid/PBI	N/A		N/A		N/A		N/A		350.00^{a}	18.18^{a}
aramid/carbon - aramid/FR viscose									388.40^{a}	20.65^{a}
aramid/carbon - FR cotton									376.00^{a}	20.14^{a}

$^{a, b, etc}$ In each column for each variable set, means (n ranging from 1 to 5) with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test ($p<.05$)

In analysing the results part way through the preliminary experiments, the aramid/carbon fabric being tested using the FR cotton parka components as the rubbing wheel, was consistently giving the lowest results when in the case of the HBE it was the highest. The fabric used in these preliminary experiments was a newer fabric than that used in the construction of the coveralls. Testing of the actual fabric from the garments used in the HBE was necessary in order to determine if the fabrics had different electrostatic properties. A shirt made of the same material as the coveralls allowed for such testing. Results for this material are labelled in Tables 4 and 5 as "aramid/carbon (HBE)", while the newer fabric is labelled "aramid/carbon (new)". These results indicate that there is a significant difference in electrostatic properties of these two fabrics, making it necessary to use the actual fabric from the coveralls worn in the human-body experiments. A similar problem occurred with pre-preliminary experiments using the purchased aramid/carbon parka materials, in that the results were not corresponding with those from the HBE. When the rubbing material was taken from the actual parka, fabrics were ranked in a similar order. This effect is due to changes in materials on the market over several years. The materials reported in Table 1 are those from the actual parka.

The criterion used to determine the levels of rubbing speed and weight, thought to simulate garment layer separation, was the differentiation among fabric systems from the HBE data collected when human subjects performed such an activity (those data highlighted in Appendix A1). The choice was originally made based on the results of the systems with the FR cotton outer layer as more data were collected for these systems, allowing for more comparisons among speed and weight combinations. As the levels were narrowed down, comparisons were made between data collected using the small-scale test method and data from the HBE of systems comprising systems with the aramid/carbon outer-layer fabric. Only one set of results from the small-scale data matched the same trend as in the HBE. Considering this, and the above criteria, the combination of 100 RPM and 200g, as the rubbing speed and weight respectively, was chosen to simulate garment layer separation (data highlighted in Tables 4 and 5). One other rubbing speed (25 RPM) and two other weights (780g, 1360g) were chosen for the final experiments to demonstrate the effect of these variables on peak potential and discharge energy.

CHAPTER 4
FINAL EXPERIMENTS AND RESULTS

Research Design

The final experiments presented in this chapter were guided by the findings from the preliminary experiments. The modified version of ASTM F23.20.05 (Gonzalez et al., 1997) was followed using the additional modifications outlined in Chapter 3. The objectives of these final experiments were to: (i) determine the effect of humidity on electrostatic properties of various fabric systems, (ii) determine the effect of rubbing speed and weight, and (iii) determine the relationship between the data collected using the small-scale experiment and those of the HBE. Humidity experiments were conducted at 0% and 20% RH, while the speed and weight experiments were conducted at 0% RH, with only the FR cotton parka components as the rubbing material, and using the newer aramid/carbon inner-layer fabric due to limitations in fabric supply.

Procedures

Fabric Selection and Preparation

Fabrics used in the preliminary experiments, as reported in Table 1, were also used for the final experiments. The five coverall fabrics were washed following CAN/CGSB-4.2 No.58 M90, washing procedure III and drying procedure E (CGSB, 1990). The aramid/carbon (HBE) material taken from the coverall had been washed prior to the human-body experiments, and was not washed a second time. For each of the six levels of speed and weight, and for each applicable humidity level, five specimens of each coverall fabric were cut, measuring 20.5 cm x 20.5 cm, with no two of the five specimens within a set containing the same warp or weft yarns. For each of the six levels of speed and weight, and at each applicable humidity level, two circular specimens of 12.7 cm diameter were cut from each of the parka components. This allowed for two rubbing surfaces for each combination of speed and weight to prevent the effect of repeated rubbings on peak discharge potential and subsequently discharge energy. Since the vapor barrier, lining and interlining fabrics of the aramid/carbon parka, and the interlining and lining fabrics of the

FR cotton parka were quilted together, specimens were cut so that the stitching placement was the same in each specimen. All specimens were conditioned at 0% and 20% RH, and 22°C.

Measurement of Dependent Variables

The equipment used to measure peak discharge potential and calculations for discharge energy are the same as described in Chapter 3. Order of specimen testing during the final experiments was randomized for each variable set.

Statistical Analysis of Data

The following analyses were carried out using commercially available SPSS, Release 7.5.1 software, with the level of significance for acceptance or rejection of hypotheses set at $p<.05$:

1. Descriptive statistics were used to characterize each fabric system with respect to peak discharge potential and calculated discharge energy;
2. Three-way analysis of variance (ANOVA) was performed to test the null hypothesis that there are no main effects of outer-layer fabric, inner-layer fabric and relative humidity, or interaction effects among these variables;
3. Three-way ANOVA was conducted to test the null hypothesis that there are no main effects of inner-layer fabric, rubbing speed and weight, or interaction effects among these variables;
4. One-way ANOVA with Duncan's multiple range tests were performed at each humidity level for each parka system, and combination of rubbing speed and weight, to determine which inner-layer systems differ significantly from the others; and
5. Pearson's correlation coefficient was used to test the null hypothesis that there is no significant correlation between the data from the small-scale tests and those from the human-body experiment.

Results

Non-equality of variance among groups existed in the form of increased variation as absolute values increased. To ensure valid analyses of variance, therefore, log transformation of data was required for values of peak potential and discharge energy. Transformed data were used in all analyses which follow.

Effect of Humidity on Electrostatic Properties

Ho_1. When fabric systems are tested following the newly developed method at 0% and 20% RH, there are no significant main effects of outer-layer fabric, inner-layer fabric, or relative humidity on electrostatic properties, and there are no interaction effects.

Null hypothesis 1 was rejected. Three-way ANOVA (Appendixes B1 and B2) found significant main effects of inner- and outer-layer fabric and humidity, as well as two-way and three-way interaction effects on peak discharge potential and discharge energy. These results indicate that humidity does have an effect on these two properties, but this effect differs with both inner and outer layers of the fabric system tested.

One-way ANOVA and Duncan's multiple range test (Table 6) suggest that there is greater differentiation for both peak discharge potential and discharge energy among systems with the FR cotton outer layer than among systems with the aramid/carbon outer layer at both 0% and 20% RH. The latter systems had more homogeneous subsets for each of the two properties. For both outer layers, however, less differentiation occured at 20% RH than at 0% RH. If polarity of peak discharge potentials were taken into account, the differentiation among fabric systems would increase somewhat. This is an important factor theoretically, however, for predicting the incendivity hazard of static electricity, absolute values are of greater importance.

The range in absolute values of peak discharge potential and discharge energy of those systems with FR cotton outer layer is very close to the range for systems with aramid/carbon outer layers, with the latter being higher overall (Table 6). At 0% RH,

Table 6

Analysis of Variance: Effect of Garment System and Relative Humidity on Peak Discharge Potentials and Discharge Energies[1]

FABRIC SYSTEM	RELATIVE HUMIDITY							
	0%				20%			
	POTENTIAL (V)		ENERGY (uJ)		POTENTIAL (V)		ENERGY (uJ)	
CONTENTS (Outer - Inner Layers)	MEAN	STD. DEV.	MEAN	STD DEV.	MEAN	STD. DEV.	MEAN	STD. DEV.
	(n = 10)		(n = 10)		(n = 10)		(n = 10)	
FR cotton - aramid/carbon (new)	51.98^{a}	8.70	0.44^{a}	0.15	129.48^{a}	16.82	2.67^{a}	0.72
FR cotton - FR cotton	186.00^{c}	52.19	5.32^{c}	2.74	129.04^{a}	19.50	2.20^{a}	0.61
FR cotton - aramid/PBI	136.14^{b}	28.31	2.54^{b}	1.05	190.10^{b}	21.03	4.76^{b}	1.10
FR cotton - aramid/FR viscose	258.60^{d}	48.92	9.51^{d}	3.60	273.80^{c}	42.53	9.79^{c}	3.12
FR cotton - aramid/carbon (HBE)	374.80^{e}	44.57	23.43^{e}	5.71	395.60^{d}	36.32	25.99^{d}	4.92
aramid/carbon - aramid/carbon (new)	291.20^{b}	47.26	15.14^{b}	5.03	170.00^{ab}	48.47	5.54^{bc}	2.81
aramid/carbon - FR cotton	542.00^{d}	78.32	41.29^{c}	11.87	512.40^{c}	87.11	37.45^{d}	13.30
aramid/carbon - aramid/PBI	261.50^{b}	49.37	10.55^{a}	3.62	132.20^{a}	17.80	2.79^{a}	0.78
aramid/carbon - aramid/FR viscose	370.80^{c}	61.01	19.73^{b}	6.62	151.20^{ab}	36.57	3.61^{ab}	1.63
aramid/carbon - aramid/carbon (HBE)	215.60^{a}	57.94	8.19^{a}	3.85	188.00^{b}	55.05	6.16^{c}	3.67

[1] These experiments were conducted using a rubbing speed of 100 RPM and a weight of 200g

[a,b, etc] In each column for each outer layer, means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when log of actual values subjected to Duncan's multiple range test ($p<.05$)

results for systems with the aramid/carbon outer layer are higher than those with the FR cotton outer layer with the corresponding inner layers, with the exception of the aramid/carbon - aramid/carbon (HBE) system. At 20% RH the aramid/carbon outer-layer systems are lower with two exceptions, aramid/carbon - aramid/carbon (new) and aramid/carbon - FR cotton.

Comparison of results at 0% and 20% RH shows that those fabric systems with the aramid/carbon outer layer, had consistently lower peak discharge potentials and discharge energies at 20% RH than at 0% RH. For systems with the FR cotton outer layer, however, these properties are higher at 20% RH than at 0% RH, with the exception of the FR cotton - FR cotton system. This one anomaly in absolute values can be partly explained when polarity is taken into consideration (Table 7). The peak discharge potential of the FR cotton outer-layer systems are all more negative (less positive) at 20% RH than at 0% RH. The FR cotton - FR cotton system is the only positive system and although the absolute value is lower at 20% RH, it followed the same trend in that it became more negative. The aramid/carbon systems are also more negative at 20% RH than at 0% RH, with the exception of the aramid/carbon - aramid/carbon (HBE) system which is less negative, but is also the only negative system. Without considering polarity of the systems with the aramid/carbon outer layer, all peak potentials are lower at 20% than at 0% RH. Only aramid/carbon (HBE) and FR cotton inner-layer fabrics maintained the same polarity regardless of the outer layer from which they were separated. Systems with the aramid/carbon outer layer are all more positive than systems with the FR cotton outer layer at both 0% and 20% RH.

The discharge energy of systems with the FR cotton outer layer is greater at 20% RH, again with the exception of the FR cotton - FR cotton system. This exception can be explained as energy is calculated using absolute values of potential, which in this case is lower at 20% RH. Discharge energies of all systems with the aramid/carbon outer layer are lower at 20% RH than at 0% RH.

Systems comprising dissimilar layers, FR cotton - aramid/carbon (HBE) and aramid/carbon - FR cotton, generate higher potentials and discharge energies than systems in which the two layers are the same, or similar.

Table 7
Effect of Garment System and Relative Humidity on Polarity of Peak Discharge Potentials

FABRIC SYSTEM	RELATIVE HUMIDITY	
	0%	20%
CONTENTS (Outer - Inner Layers)	MEAN POTENTIAL (V) (n = 10)	MEAN POTENTIAL (V) (n = 10)
FR cotton - aramid/carbon (new)	-51.98	-129.48
FR cotton - FR cotton	+186.00	+129.04
FR cotton - aramid/PBI	-136.14	-190.10
FR cotton - aramid/FR viscose	-258.60	-273.80
FR cotton - aramid/carbon (HBE)	-374.80	-395.60
aramid/carbon - aramid/carbon (new)	+291.20	+170.00
aramid/carbon - FR cotton	+542.00	+512.40
aramid/carbon - aramid/PBI	+261.50	+132.20
aramid/carbon - aramid/FR viscose	+370.80	+151.20
aramid/carbon - aramid/carbon (HBE)	-215.60	-188.00

Effect of Rubbing Speed and Pressure on Electrostatic Properties

Ho_2. When rubbing speed and weight used for the new method are varied, there are no main effects of inner-layer fabric, rubbing speed and pressure on electrostatic properties, and there are no interaction effects.

Null hypothesis 2 was rejected. Three-way ANOVA (Appendixes B3 and B4) found significant main effects for inner-layer systems, rubbing speed and rubbing weight, as well as two-way and three-way interaction effects on peak discharge potential and discharge energy. Differentiation among electrostatic properties of fabric systems exists, but is affected differently when rubbing speed is altered and differently yet when rubbing weight is changed.

While not entirely consistent, the trend is for both peak discharge potential and discharge energy to increase as both rubbing speed and weight increase (Table 8), regardless of the polarity (Table 9). The FR cotton - aramid/carbon (new) system had a lower peak discharge potential and discharge energy at 200g and 100 RPM than at 25 RPM. The FR cotton - aramid/PBI system had a slightly lower peak discharge potential at 1360g and 100 RPM than at 780g, while the discharge energy remained the same. Finally, this same system had a lower peak discharge potential and discharge energy at 1360g and 100 RPM than at 25 RPM. These differences can be seen in Table 8, however, statistical analyses were not conducted to determine whether these differences are significiant.

Significant interaction effects suggest that both electrostatic properties change at different rates among the various systems. Likewise, differences among fabrics vary depending on the level of rubbing speed and weight. One-way ANOVA and Duncan's multiple range test (Table 8) suggest that lower speeds, 25 RPM, with low and high weights (200g and 1360g) do not differentiate among fabric systems in terms of both peak discharge potential and discharge energy as well as does a medium weight (780g) at this speed. At higher speeds, 100 RPM, differentiation is very good at mid- to low weights (200g and 780g) with no systems sharing homogeneous subsets for either electrostatic property, however, at the highest weight of 1360g, differentiation was not as good.

Table 8

Analysis of Variance: Effect of Inner-Layer Fabric in a System, Rubbing Speed and Rubbing Weight on Peak Discharge Potentials and Discharge Energies[1]

SPEED (RPM)	WEIGHT (g)											
	200g				780g				1360g			
FABRIC SYSTEM CONTENTS (Outer - Inner Layers)	POTENTIAL (V)		ENERGY (uJ)		POTENTIAL (V)		ENERGY (uJ)		POTENTIAL (V)		ENERGY (uJ)	
	MEAN	STD. DEV.	MEAN	STD DEV.	MEAN	STD. DEV.	MEAN	STD DEV	MEAN	STD. DEV.	MEAN	STD DEV
	(n = 10)		(n = 10)		(n = 10)		(n = 10)		(n = 10)		(n = 10)	
25 RPM												
FR cotton - aramid/carbon (new)	70.80^{a}	18.24	0.87^{a}	0.40	111.68^{b}	20.58	2.05^{b}	0.70	161.40^{a}	27.39	4.42^{b}	1.57
FR cotton - FR cotton	71.72^{a}	22.02	0.67^{a}	0.40	92.04^{a}	15.59	1.06^{a}	0.38	141.56^{a}	29.70	2.58^{a}	0.96
FR cotton - aramid/PBI	115.52^{b}	26.48	1.78^{b}	0.73	218.90^{c}	33.76	6.28^{c}	1.78	324.90^{b}	36.73	14.26^{c}	3.57
FR cotton - aramid/FR viscose	154.00^{c}	16.55	3.20^{c}	0.68	293.60^{d}	40.20	11.72^{d}	3.31	480.80^{c}	48.99	32.47^{d}	6.96
100 RPM												
FR cotton - aramid/carbon (new)	51.98^{a}	8.70	0.44^{a}	0.15	194.80^{a}	35.88	6.50^{a}	2.35	225.40^{a}	21.47	8.43^{a}	1.80
FR cotton - FR cotton	186.00^{c}	52.19	5.32^{c}	2.74	259.60^{b}	45.21	8.98^{b}	3.16	335.40^{b}	39.46	14.91^{b}	3.47
FR cotton - aramid/PBI	136.14^{b}	28.31	2.54^{b}	1.05	317.30^{c}	48.41	13.60^{c}	4.00	307.90^{b}	53.08	13.60^{b}	4.43
FR cotton - aramid/FR viscose	258.60^{d}	48.92	9.51^{d}	3.60	580.00^{d}	50.75	47.12^{d}	8.20	685.60^{c}	42.35	64.64^{c}	8.23

[1] Experiments were conducted at 0% RH for systems with the FR cotton outer-layer. Duncan's multiple range test may not be valid for variable set 25 RPM and 1360g as variance of peak potentials and discharge energies remains unequal after log transformation

[a,b, etc] In each column for each variable set, means with the same letter indicate homogeneous subsets (highest and lowest means are not significantly different) when log of actual values subjected to Duncan's multiple range test ($p<.05$)

Table 9

Effect of Inner-Layer Fabric in a System, Rubbing Speed and Rubbing Weight on Polarity of Peak Discharge Potentials[1]

SPEED (RPM)	WEIGHT (g) 200g	780g	1360g
FABRIC SYSTEM CONTENTS (Outer - Inner Layers)	POTENTIAL (V) MEAN (n = 10)	POTENTIAL (V) MEAN (n = 10)	POTENTIAL (V) MEAN (n = 10)
25 RPM			
FR cotton - aramid/carbon (new)	-70.80	-111.68	-161.40
FR cotton - FR cotton	+71.72	+92.04	+141.56
FR cotton - aramid/PBI	-115.52	-218.90	-324.90
FR cotton - aramid/FR viscose	-154.00	-293.60	-480.80
100 RPM			
FR cotton - aramid/carbon (new)	-51.98	-194.80	-225.40
FR cotton - FR cotton	+186.00	+259.60	+335.40
FR cotton - aramid/PBI	-136.14	-317.30	-307.90
FR cotton - aramid/FR viscose	-258.60	-580.00	-685.60

[1] Experiments conducted at 0% RH for systems with the FR cotton outer-layer

Differentiation among fabric systems for discharge energy at higher speeds (100 RPM) is similar to that at lower speeds (25 RPM).

Correlation Between Human-Body and Small-Scale Data

Ho_3. There are no significant correlations between electrostatic properties as measured from the new small-scale test method and those obtained from the human body experiment.

Null hypothesis 3 was rejected. Pearson's correlation analyses were performed separately for systems with the same outer-layer fabric at each humidity level (Table 10). All correlations were significant at $p<.05$, and most were significant at $p<.01$ (Appendixes C1-C4).

Correlations between the HBE and small-scale data were all greater at 20% RH than at 0% RH. With one exception, the correlations between systems with the aramid/carbon outer layer were greater than those with the FR cotton outer layer. Correlation of peak discharge potential for FR cotton outer-layer systems at 0% RH was fairly low as the ordering of the inner-layer garments differed. The discharge energies at this condition had moderate correlation (.439), as less differentiation among inner-layer fabrics occurred in the small-scale test method than in the HBE. At 0% RH, higher correlation exists among peak discharge potentials of systems with the aramid/carbon outer layer than of systems with the FR cotton outer layer, as more similar trends occur with these systems in both the HBE and small-scale data. The correlation is much lower between discharge energies as the system with the aramid/FR viscose inner layer is among the lowest systems in the HBE, but is one of the highest in the small-scale test method. The systems with the highest correlations of both peak discharge potentials and discharge energies were those with the aramid/carbon outer layer at 20% RH. The ordering and differentiation of these systems were similar for both the small-scale method and HBE.

Table 10

Pearson's Correlations (r) Between Human-Body and Small-Scale Data on Peak Potential and Discharge Energy

RELATIVE HUMIDITY	PEAK POTENTIAL			DISCHARGE ENERGY		
	OUTER LAYER FABRIC					
	FR cotton	Aramid/carbon	All Systems	FR cotton	Aramid/carbon	All Systems
0%	.385*	.516**	-.297**	.439**	.337*	-.323**
20%	.669**	.790**	.424**	.663*	.819**	.416**

* Correlation is significant at the $p<.05$ level

** Correlation is significant at the $p<.01$ level

Analyses of all systems together at each humidity level showed even lower correlations than when categorized into two separate systems (Table 10) (Appendixes C5 and C6). At 0% RH correlations were very low and negative, while at 20% RH they were slightly higher and positive. Appendixes D1 through D4 show scatterplots of human-body versus small-scale data.

CHAPTER 5
DISCUSSION

Test Method Development

The first objective was to develop a small-scale test method which would simulate the phenomenon of electrostatic charge generation from the separation of garment layers on the human body. The method developed was based on a previously modified standard method. This technique involves triboelectrification as the form of charge generation between two layers of fabric representing outer and inner garments in a two-garment system. It includes a conducting plate and capacitor which carries the charge transferred to the outer surface of the inner-layer fabric and stores it until the charging process is complete. Once complete the capacitor is discharged to represent grounding of the human body. The peak discharge potential is measured, and from this the total discharge energy is calculated. Preliminary experiments with rubbing speed and weight lead to a combination of these variables to simulate garment layer separation. Relatively low correlations between the data from this study and the human-body experiment suggest this may not be the best procedure to represent such activity. Further experimentation with levels of rubbing speed and weight is recommended.

Differences in Electrostatic Properties at Various Humidity Levels

The second objective was to determine the differences in peak discharge potentials and discharge energies among the thermal-protective fabrics at 0% and 20% RH. The objective was accomplished through experiments using two different outer-layer fabrics, each combined with five inner-layer fabrics, repeated at both humidity levels.

Three-way ANOVA tested null hypothesis 1 and found significant differences among the inner-layer fabric specimens, but those differences were affected by the outer-layer fabric in the system and by humidity. One can expect that at different humidity levels, different peak potentials and discharge energies will be obtained. This effect, however, is different for the different outer- and inner-layer fabrics of the systems tested.

The electrostatic properties of systems with the aramid/carbon outer layer were higher at 0% RH than at 20% RH, while those with the FR cotton outer layer were lower at 0% RH. The latter phenomenon has been documented by other researchers (Medley, 1950; Sereda & Feldman, 1964; Onogi, Sugiura & Nakaoka, 1996; and Onogi, Sugiura & Matsuda, 1997). Sereda and Feldman (1964) explained the higher potentials at humidities higher than 0% RH to be due to the monomolecular, or directly bound layer of water formed within a fiber. The water molecules in this layer are tightly bound to the fiber molecules and as such, do not participate in charge dissipation as is traditionally thought to occur at increasing humidity levels. They suggest that the molecules in the monomolecular layer actually contribute to the number of sites available to trap electrons within the structure of the fiber. The importance of the internal properties of the fibers were stressed by Hersh and Montgomery (1956) who stated that triboelectrification charge transfer is affected primarily by properties within the structure versus those of the surface. Sereda and Feldman found that maximum potentials were obtained at the point where the monomolecular layer was complete, and reported this to be between 17% and 18% RH for cotton. This would explain why, in this study, the systems containing an FR cotton layer all were more negative at 20% RH regardless of the polarity. Beyond the point at which the monomolecular layer is formed, the absorbed water is more loosely bound and aids in conduction of electrostatic charges. One reason why there was a reverse effect with the aramid/carbon outer-layer systems may be that the humidity level at which this fabric achieves a complete monomolecular layer of water is lower, as the nominal standard moisture regain (4.5%) is lower than that of FR cotton (8%). This water will carry away any charges generated and would explain the reason why the peak potentials of these systems are closer to zero at 20% RH, and higher at 0% RH. Although this discussion has focused on the moisture content to explain differences between fiber types, it must be remembered that aramid/carbon is an anti-static fabric. This property, inherent to the fibers, may also contribute to the low charge generation at 20% RH.

One-way ANOVA, performed separately for systems with the same outer-layer fabric, found that peak potentials and discharge energies for different inner-layer fabrics differed significantly in most cases at 0% RH, with less differentiation at 20% RH. Greater differentiation exists among the systems with the FR cotton outer layer than among the systems with the aramid/carbon outer layer, at both humidity levels and for both electrostatic properties. The inner-layer fabrics vary at different rates from each other, and from the same fabric in the different outer-layer systems.

Systems with the aramid/carbon outer layer generated higher potentials overall, at both humidity levels, than the corresponding inner-layer systems with the FR cotton outer layer. Considering the aramid/carbon layer is an anti-static fabric, one would expect the opposite, as was found in the HBE. Carbon fibers are incorporated into this fabric to reduce charge generation and build-up without depending on the moisture in either the surrounding environment or the material itself. The carbon fibers work by attracting charge from the fabric which induce an opposite charge on the carbon. When the induced charge reaches a certain level, the surrounding air becomes ionized. The ions are then attracted to the fabric and neutralize the charges. The technique of the test method developed from this research maintains intimate contact between the rubbing wheel, specimen and conducting plate throughout the charge generation process, with only separation of the rubbing wheel at the end. Perhaps this contact reduces the number of surrounding air molecules available for ionization and neutralization of the charges on the fabric, resulting in greater charge generation, build-up and potential. The garments worn in the HBE were not tight fitting which would allow for small layers of air between garments and between garments and the body. In addition, the energies obtained in this study are very low and would only constitute a hazard in very few air-gas environments. Perhaps the low level of charge generation is not sufficient to initiate the air ionization process, in which case this fabric does not have an advantage over other, non-antistatic fabrics. This is not a major concern, however, as the low energies generated are not enough to pose a hazard.

The polarity of a system depends on both the inner and the outer layer of the system. The two inner-layer fabrics which maintained the same polarity regardless of the outer-layer fabric from which they were separated were aramid/carbon (HBE) and FR cotton. An explanation may be found if a triboelectric series were developed using the same method of triboelectrification. From these results it could be predicted that such a series would place the FR cotton inner-layer fabric at the top, or positive end, and the aramid/carbon (HBE) inner-layer fabric at the bottom, negative end. Gonsalves (1953) suggests that the farther apart two materials are in such a series, the greater amount of charge generation will occur, as the structures are so much different. The results of this study support this as both the FR cotton-aramid/carbon(HBE) and aramid/carbon-FR cotton systems had the highest potentials within each set of systems.

Changes in Electrostatic Properties with Rubbing Speed and Pressure

The third objective was to determine the effect of rubbing speed and weight on electrostatic properties. This objective was achieved by testing the five systems containing the FR cotton outer layer using the small-scale test method with six combinations of two different speeds and three weights.

Three-way ANOVA tested null hypothesis 2. From this analysis it was determined that the five different systems differed significantly but that these differences were affected by both rubbing speed and weight. With two exceptions, peak discharge potential and discharge energy increased as each variable increased. This effect was explained by Gonzalves (1953) who stated that increasing pressure used in triboelectrification causes greater surface contact between two materials which results in greater charge generation. A possible explanation to the one exception, the FR cotton - aramid/PBI system, may be offered by Hersh and Montgomery (1955). They found that charge generation increased as velocity increased, to a point, after which it remained constant. This system had a peak potential at 1360g and 100 RPM similar to 1360g and 25 RPM or 780g and 100RPM, suggesting that a maximum had been reached. Increasing velocity increases charge generation and build-up by decreasing the time available for charge to flow away from the area of contact, and increasing the temperature at the point of contact (Hersh & Montgomery, 1956, p.912).

One-way ANOVA found, in general, that fabric systems are less significantly different from each other at high weights (1360g) regardless of the rubbing speed used. At low speeds (25 RPM) FR cotton, when separated from itself, tends to generate an equal or lower potential than when separated from anti-static fabric layers. At higher speeds (100

RPM) FR cotton, when separated from itself is more likely to produce a greater potential than the anti-static layers. Traditionally, one might expect that when a material is separated from itself the potential generated would be low compared with the seperation of two different materials, therefore, the influence of anti-static materials is more apparent at higher speeds. This may support the explanation suggested earlier that the energies created at the lower speed are not high enough to initiate the air ionization process. At the higher speed greater potentials are generated, and thus energies may be approaching the levels necessary to ionize the surrounding air molecules.

Human-Body and Small-Scale Experiment Correlations

The final objective was to determine relationships between the human-body experiment and small-scale data in terms of both peak discharge potentials and discharge energies. As expected, potentials and energies generated from the small-scale experiment are at least an order of magnitude smaller than those from the HBE. This is due to the fact that the area of contact for triboelectrification is considerably less in the small-scale than in the HBE, whereas the capacitance is similar. This difference in scale may possibly affect the relationship between the two sets of data.

Pearson's correlation coefficients were calculated with the small-scale data obtained using the levels of rubbing speed and weight thought to simulate the HB activity (100 RPM, 200g). When correlations were performed separately for each set of systems with different outer layers, positive correlations were obtained. This occured as the ordering of the four systems with the same outer layer was similar in both the small-scale and HBE. The analyses showed, however, that correlations were better under certain conditions. Highest correlations were found at 20% RH, with the systems containing the aramid/carbon outer layer correlating better than the systems with the FR cotton outer layer at this condition. The data at 0% RH had much lower correlations for both peak discharge potential and discharge energies. This analysis suggests that better levels of rubbing speed and weight might be found to simulate the separation of garment layers from the body. However, at 0% RH, the small-scale experiments differentiate among the fabric systems better than the HBE did. Low differentiation among systems in the HBE may be caused, in part, by the high variance among the data (Appendix A), and could also explain the low correlations.

The low correlation at 0% RH may indicate a problem in trying to simulate an activity performed by a person, that being the effect of the human body. Although environmental conditions during the human-body experiments were controlled at 0% and 20% RH, the relative humidity level within the garment system while on the human body was not controlled and may not have been the same as that external to it. The negative correlation at 0% RH when data from all systems were pooled reflects the differences between the two sets of systems with different outer-layer fabrics. Potentials and energies from the small-scale test method for systems with the aramid/carbon outer layer are greater than for systems with the FR cotton outer layer. In the human-body experiment the opposite was true, these data for systems with the aramid/carbon outer layer were lower than systems with the FR cotton outer layer. Again, this reversed order may be caused by the low potentials which prevent the aramid/carbon fabric from performing in the manner intended during the small-scale test method. Another possible reason could be that during the HBE's the humidity level within the garment systems were different than the external environment. This explanation, however, would require that at '0% RH' the relative humidity of the system was closer to 20% RH, while at '20% RH' the humidity level within the garments would have to be even higher to account for the lower results at this level.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

Summary

Most test methods commonly used to determine electrostatic properties of various fabrics are not practical, in that they fail to represent the conditions such fabrics will encounter when worn as a garment on the human body. Three areas of concern include the form of electrification utilized, the property being measured, and the ability to determine the characteristics of fabric systems. Often the form of electrification is an applied voltage to the fabric, which is not the form encountered during wear and use of garments. Triboelectrification is most common in real life, as it involves contact and friction between two or more materials. The majority of test methods concentrate on the electrostatic properties of the fabric itself, away from the human body. Although these are useful measures, the ability of the body to store large amounts of charge often induced by charged garments laying next to it may be a greater hazard. Finally, most test methods cannot adequately measure electrostatic properties of fabric layers composing a system. From the results of this study, this is an important limitation as both layers in a two-layer system affect these properties.

In order to simulate the separation of clothing layers from the human body, a method was developed based on a modified version of a standard test method. The technique uses triboelectrification between two layers of interest, simulating an outer and an inner garment. Measurements of peak discharge potential and discharge energy were taken in such a manner to represent discharge from the human body when charge is transferred to it from the garments worn. The ability of this method to replicate the trend found in a HBE, and thus the activity, was determined.

The fabrics used in these experiments were those commonly found in thermal-protective garments, and included materials from two outer-garments (i.e. parkas) and five inner-garments (coveralls). Each outer-garment fabric was combined with each inner-garment fabric to represent a two-layer system. Experiments were conducted at both 0% and 20%

RH to determine the effect of humidity on electrostatic properties of the various thermal-protective systems. Experiments were conducted using five systems, all including the same outer-layer fabric, to determine the effect of rubbing speed and weight on the electrostatic properties of these systems.

Conclusions

The conclusions reached from this study are as follows.

1) A small-scale test method has been developed, allowing for the testing of fabrics as a system, which simulates the HBE better under certain conditions than others. Correlations may be improved through further refinement of this method, as discussed below.

2) Humidity affects charge generation of fabric systems, however, the effect is not universal for all fabric types as this relationship could be either direct or indirect. The direction of this relationship may be linked to the amount of moisture absorbed by a fiber type and the amount of moisture consisting of directly bound water molecules.

3) Greater differentiation among fabric systems occurs at 0% RH than at 20% RH. In other words, at higher humidity levels, different fabric systems tend to have more similar electrostatic properties than at lower humidity levels.

4) An increase in either rubbing speed or pressure (weight) used to generate triboelectric charge will lead to an increase in both peak potentials and discharge energies. The differences in these properties among various levels of speed and pressure are different for each fabric, and are not consistent for each fabric as the variables are systematically increased or decreased. This suggests that selecting certain levels of these variables may give preference to some fabrics, while other levels may do the opposite.

5) When two layers being separated are of the same fiber content, similar electrostatic properties are observed as when the inner layer is an anti-static fiber.

Recommendations

Based on the results and conclusions of this study, three sets of recommendations can be made.

Recommendations Regarding Standard Test Method Development

- Several variables have been identified which need to be controlled to ensure the standard method from which this work stems is reliable. Such issues include method of attaching materials to the rubbing wheel, positioning of the conducting plate, and the effect of history on the rubbing material.
- Test methods intending to simulate human-body activities must account for and be able to handle all layers which may be found within a garment system.
- Methods dealing with electrostatic properties of textiles should allow for, and encourage, testing at various environmental conditions to which the fabrics might be exposed during their intended use.

Recommendations to Industry

- In order to understand how certain garments will behave when worn by workers in the field, industry must consider the environmental conditions under which they will be worn. The key environmental condition which must be identified is humidity as this has a great effect on charge generation and is not always generalizable across a range of garment systems comprising different outer-and inner-layer fabrics.
- It is important to consider all garments worn together as a system in determining the electrostatic properties and relative safety levels of garments, as fiber content of adjacent layers affect these properties.
- The type of activities performed by those wearing the garment systems will also influence the above properties. These need to be identified in order to understand the effect of a garment system during an activity, such as removing a garment layer.

Recommendations for Future Research

- An extension of this work between and 0% and 20% RH, and just higher than 20% RH, needs to be done with regard to the effect of humidity on electrostatic properties. This would help address the relationships between electrostatic properties and humidity and may explain the reversal effect between the two different outer-layer systems, to support or disprove the hypotheses presented regarding the effect of a monomolecular layer of water.

- In addition to work at various other humidity levels, experiments might be conducted at other temperatures, as low humidity levels in outdoor work environments often occur when temperatures are also very low.
- Additional work with various levels of rubbing speeds and weights might help show a pattern of change among different fabrics, and may also result in a better combination of these variables to simulate garment layer separation. Measurement of the temperature at the interface of two surfaces during the triboelectrification process may help explain any patterns.
- Investigations regarding the difference in scale between the small-scale and HBE, in terms of rubbing area and capacitance, should be carried out to determine whether such discrepancies affect measured potentials, or relationships between the two sets of data.
- A triboelectric series developed using the test method presented here, with the same levels of rubbing speed and weight, may explain the polarities of the potentials generated by the various systems.
- Further studies regarding the process of charge neutralization of the aramid/carbon fabric may account for some discrepancies among findings in this study, and for the low correlation between data presented here and that from the HBE. Issues which should be addressed include the level of energy required to initiate air ionization, and whether substances in the atmosphere such as flammable gases or vapours affect this.
- Not considered in either this study or the HBE was the charge generated on the discarded outer layer. This is of importance as the garment itself could be a potential hazard. The method used would require additional modifications to allow for such a measurement.
- Additional HBE's conducted using some of the newer fabrics on the market today to determine the performance of such products. Human-body experiments in which subjects perform other common activities may result in different trends.
- Determining relative humidity within a garment system when worn on the human body may identify differences between the controlled external environment and the

uncontrolled internal garment environment, and the effect of this on electrostatic properties.

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APPENDIX A

Appendix A. Peak Potential and Discharge Energies From Human Body Experiment[1] (from "Electrostatic Characteristics of Thermal-Protective Garment Systems at Various Low Humidities," by S. A. H. Rizvi et al., in press)

Garment System	Relative Humidity							
	0%				20%			
Contents (Outer - Inner Layers)	Potential (kV)		Energy (mJ)		Potential (kV)		Energy (mJ)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
FR cotton - FR cotton	**3.5955**[a]	0.5880	1.2797[a]	0.4016	0.4344[a]	0.2294	0.0229[a]	0.0190
FR cotton - aramid/FR viscose	**4.4120**[b]	0.8781	2.0724[b]	0.7874	1.8463[b]	0.4533	0.3466[b]	0.1747
FR cotton - aramid/PBI	**4.4925**[b]	0.8292	2.1892[b]	0.7907	2.3102[c]	0.6382	0.5383[c]	0.3038
FR cotton - aramid/carbon	**5.5100**[c]	0.5473	3.3553[c]	0.8130	3.0069[d]	0.6080	0.8766[d]	0.3253
aramid/carbon - aramid/PBI	**0.4280**[a]	0.2285	0.0343[a]	0.0312	0.0787[a]	0.0404	0.0020[a]	0.0023
aramid/carbon - aramid/FR viscose	**0.3945**[a]	0.1810	0.0267[a]	0.0209	0.1418[ab]	0.0953	0.0040[a]	0.0046
aramid/carbon - aramid/carbon	**0.4213**[ab]	0.1422	0.0259[a]	0.0174	0.1459[ab]	0.1371	0.0046[a]	0.0086
aramid/carbon - FR cotton	**0.6188**[b]	0.3035	0.0481[a]	0.0437	0.1834[b]	0.1369	0.0096[b]	0.0123

[1] Duncan's multiple range test may not be valid for systems with the FR cotton outer-layer at 20% RH as variance of peak potentials and discharge energies remains unequal after log transformations

[a, b, etc.] In each column for each outer layer, means with the same letter indicate homogeneoues subsets (highest and lowest means are not significantly different) when log of actual values subjected to Duncan's multiple range test ($p<.05$)

APPENDIX B

Case Processing Summary[a]

Cases					
Included		Excluded		Total	
N	Percent	N	Percent	N	Percent
200	100.0%	0	.0%	200	100.0%

a. LOGSSPOT by relative humidity (%), fabric specimen, rubbing wheel

ANOVA[a,b]

			Unique Method				
			Sum of Squares	df	Mean Square	F	Sig.
LOGSSPOT	Main Effects	(Combined)	22.989	6	3.831	96.752	.000
		relative humidity (%)	.845	1	.845	21.332	.000
		fabric specimen	17.275	4	4.319	109.058	.000
		rubbing wheel	4.869	1	4.869	122.950	.000
	2-Way Interactions	(Combined)	32.755	9	3.639	91.904	.000
		relative humidity (%) * fabric specimen	1.941	4	.485	12.251	.000
		relative humidity (%) * rubbing wheel	5.768	1	5.768	145.648	.000
		fabric specimen * rubbing wheel	25.047	4	6.262	158.122	.000
	3-Way Interactions	relative humidity (%) * fabric specimen * rubbing wheel	5.014	4	1.254	31.654	.000
	Model		60.757	19	3.198	80.751	.000
	Residual		7.128	180	4.0E-02		
	Total		67.885	199	.341		

a. LOGSSPOT by relative humidity (%), fabric specimen, rubbing wheel

b. All effects entered simultaneously

Appendix B1. Three-way ANOVA of outer-layer, inner-layer and relative humidity for log of peak discharge potentials

Case Processing Summary[a]

Cases					
Included		Excluded		Total	
N	Percent	N	Percent	N	Percent
200	100.0%	0	.0%	200	100.0%

a. LOGSSENG by relative humidity (%), fabric specimen, rubbing wheel

ANOVA[a,b]

			Unique Method				
			Sum of Squares	df	Mean Square	F	Sig.
LOGSSENG	Main Effects	(Combined)	90.078	6	15.013	94.385	.000
		relative humidity (%)	3.601	1	3.601	22.640	.000
		fabric specimen	62.346	4	15.586	97.991	.000
		rubbing wheel	24.131	1	24.131	151.71	.000
	2-Way Interactions	(Combined)	129.490	9	14.388	90.455	.000
		relative humidity (%) * fabric specimen	7.965	4	1.991	12.518	.000
		relative humidity (%) * rubbing wheel	20.720	1	20.720	130.27	.000
		fabric specimen * rubbing wheel	100.805	4	25.201	158.44	.000
	3-Way Interactions	relative humidity (%) * fabric specimen * rubbing wheel	20.006	4	5.001	31.444	.000
	Model		239.574	19	12.609	79.273	.000
	Residual		28.631	180	.159		
	Total		268.204	199	1.348		

a. LOGSSENG by relative humidity (%), fabric specimen, rubbing wheel

b. All effects entered simultaneously

Appendix B2. Three-way ANOVA of outer-layer, inner-layer and relative humidity for log of discharge energies

Case Processing Summary[a]

Cases					
Included		Excluded		Total	
N	Percent	N	Percent	N	Percent
240	100.0%	0	.0%	240	100.0%

a. LOGSSPOT by fabric specimen, rubbing speed (RPM), rubbing weight (g)

ANOVA[a,b]

			Unique Method				
			Sum of Squares	df	Mean Square	F	Sig.
LOGSSPOT	Main Effects	(Combined)	92.952	6	15.492	455.991	.000
		fabric specimen	41.677	3	13.892	408.902	.000
		rubbing speed (RPM)	12.662	1	12.662	372.678	.000
		rubbing weight (g)	38.614	2	19.307	568.280	.000
	2-Way Interactions	(Combined)	9.625	11	.875	25.755	.000
		fabric specimen * rubbing speed (RPM)	6.076	3	2.025	59.618	.000
		fabric specimen * rubbing weight (g)	2.296	6	.383	11.261	.000
		rubbing speed (RPM) * rubbing weight (g)	1.253	2	.627	18.441	.000
	3-Way Interactions	fabric specimen * rubbing speed (RPM) * rubbing weight (g)	1.474	6	.246	7.230	.000
	Model		104.051	23	4.524	133.158	.000
	Residual		7.338	216	3.4E-02		
	Total		111.389	239	.466		

a. LOGSSPOT by fabric specimen, rubbing speed (RPM), rubbing weight (g)

b. All effects entered simultaneously

Appendix B3. Three-way ANOVA of inner-layer, rubbing speed and rubbing weight for log of peak discharge potentials

Case Processing Summary[a]

Cases					
Included		Excluded		Total	
N	Percent	N	Percent	N	Percent
240	100.0%	0	.0%	240	100.0%

a. LOGSSENG by fabric specimen, rubbing speed (RPM), rubbing weight (g)

ANOVA[a,b]

			Unique Method				
			Sum of Squares	df	Mean Square	F	Sig.
LOGSSENG	Main Effects	(Combined)	360.993	6	60.165	444.61	.000
		fabric specimen	150.207	3	50.069	370.00	.000
		rubbing speed (RPM)	55.222	1	55.222	408.08	.000
		rubbing weight (g)	155.563	2	77.782	574.80	.000
	2-Way Interactions	(Combined)	41.932	11	3.812	28.170	.000
		fabric specimen * rubbing speed (RPM)	26.748	3	8.916	65.887	.000
		fabric specimen * rubbing weight (g)	10.202	6	1.700	12.566	.000
		rubbing speed (RPM) * rubbing weight (g)	4.982	2	2.491	18.406	.000
	3-Way Interactions	fabric specimen * rubbing speed (RPM) * rubbing weight (g)	6.506	6	1.084	8.013	.000
	Model		409.430	23	17.801	131.55	.000
	Residual		29.229	216	.135		
	Total		438.659	239	1.835		

a. LOGSSENG by fabric specimen, rubbing speed (RPM), rubbing weight (g)

b. All effects entered simultaneously

Appendix B4. Three-way ANOVA of inner-layer, rubbing speed and rubbing weight for log of discharge energies

APPENDIX C

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	.385*
	LOGHBPOT	.385*	1.000
Sig. (2-tailed)	LOGSSPOT	.	.014
	LOGHBPOT	.014	.
N	LOGSSPOT	40	40
	LOGHBPOT	40	79

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	.439**
	LOGHBENG	.439**	1.000
Sig. (2-tailed)	LOGSSENG	.	.005
	LOGHBENG	.005	.
N	LOGSSENG	40	40
	LOGHBENG	40	79

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C1. Correlations between small-scale and HBE data for systems with the FR cotton outer-layer at 0% RH

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	.516**
	LOGHBPOT	.516**	1.000
Sig. (2-tailed)	LOGSSPOT	.	.001
	LOGHBPOT	.001	.
N	LOGSSPOT	40	40
	LOGHBPOT	40	80

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	.337*
	LOGHBENG	.337*	1.000
Sig. (2-tailed)	LOGSSENG	.	.034
	LOGHBENG	.034	.
N	LOGSSENG	40	40
	LOGHBENG	40	80

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix C2. Correlations between small-scale and HBE data for systems with the aramid/carbon outer-layer at 0% RH

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	.669**
	LOGHBPOT	.669**	1.000
Sig. (2-tailed)	LOGSSPOT	.	.000
	LOGHBPOT	.000	.
N	LOGSSPOT	40	40
	LOGHBPOT	40	125

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	.663**
	LOGHBENG	.663**	1.000
Sig. (2-tailed)	LOGSSENG	.	.000
	LOGHBENG	.000	.
N	LOGSSENG	40	40
	LOGHBENG	40	125

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C3. Correlations between small-scale and HBE data for systems with the FR cotton outer-layer at 20% RH

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	.790**
	LOGHBPOT	.790**	1.000
Sig. (2-tailed)	LOGSSPOT	.	.000
	LOGHBPOT	.000	.
N	LOGSSPOT	40	40
	LOGHBPOT	40	80

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	.819**
	LOGHBENG	.819**	1.000
Sig. (2-tailed)	LOGSSENG	.	.000
	LOGHBENG	.000	.
N	LOGSSENG	40	40
	LOGHBENG	40	80

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C4. Correlations between small-scale and HBE data for systems with the aramid/carbon outer-layer at 20% RH

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	-.297**
	LOGHBPOT	-.297**	1.000
Sig. (2-tailed)	LOGSSPOT	.	.007
	LOGHBPOT	.007	.
N	LOGSSPOT	80	80
	LOGHBPOT	80	159

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	-.323**
	LOGHBENG	-.323**	1.000
Sig. (2-tailed)	LOGSSENG	.	.003
	LOGHBENG	.003	.
N	LOGSSENG	80	80
	LOGHBENG	80	159

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C5. Correlations between small-scale and HBE data for all systems at 0% RH

Correlations

		LOGSSPOT	LOGHBPOT
Pearson Correlation	LOGSSPOT	1.000	.424**
	LOGHBPOT	.424**	1.000
Sig. (2-tailed)	LOGSSPOT	.	.000
	LOGHBPOT	.000	.
N	LOGSSPOT	80	80
	LOGHBPOT	80	205

**. Correlation is significant at the 0.01 level (2-tailed).

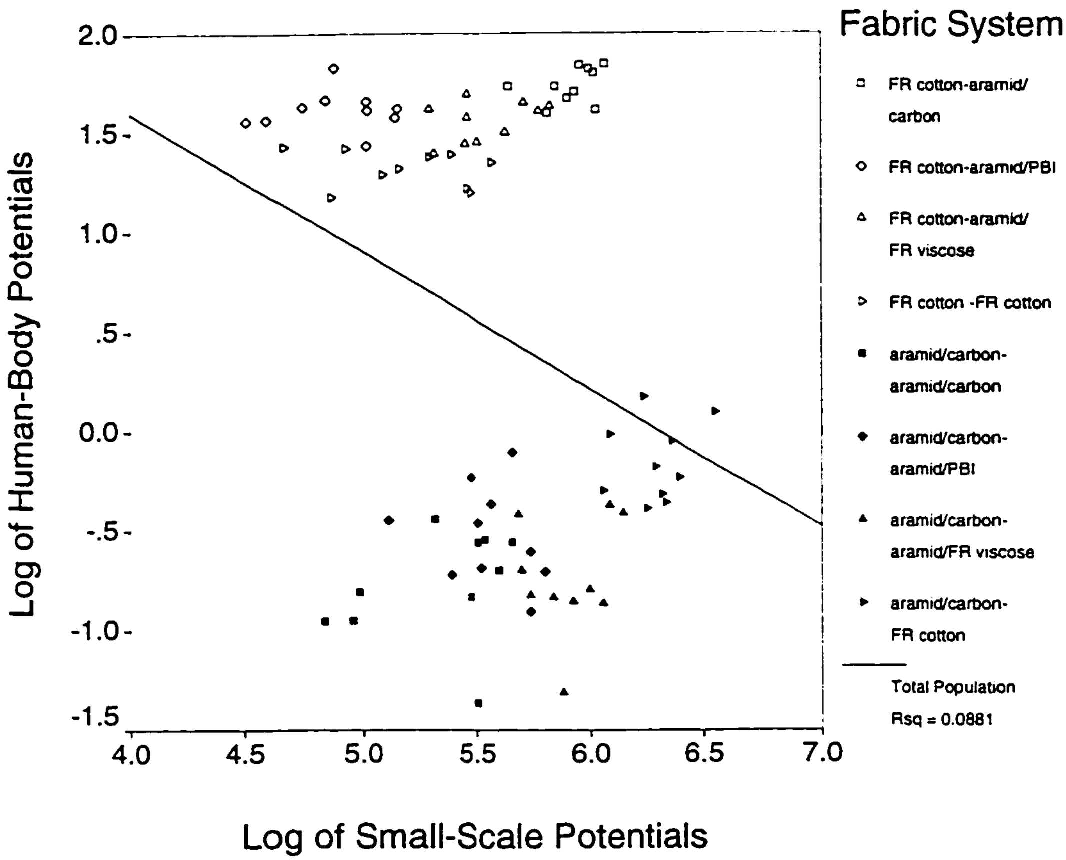
Correlations

		LOGSSENG	LOGHBENG
Pearson Correlation	LOGSSENG	1.000	.416**
	LOGHBENG	.416**	1.000
Sig. (2-tailed)	LOGSSENG	.	.000
	LOGHBENG	.000	.
N	LOGSSENG	80	80
	LOGHBENG	80	205

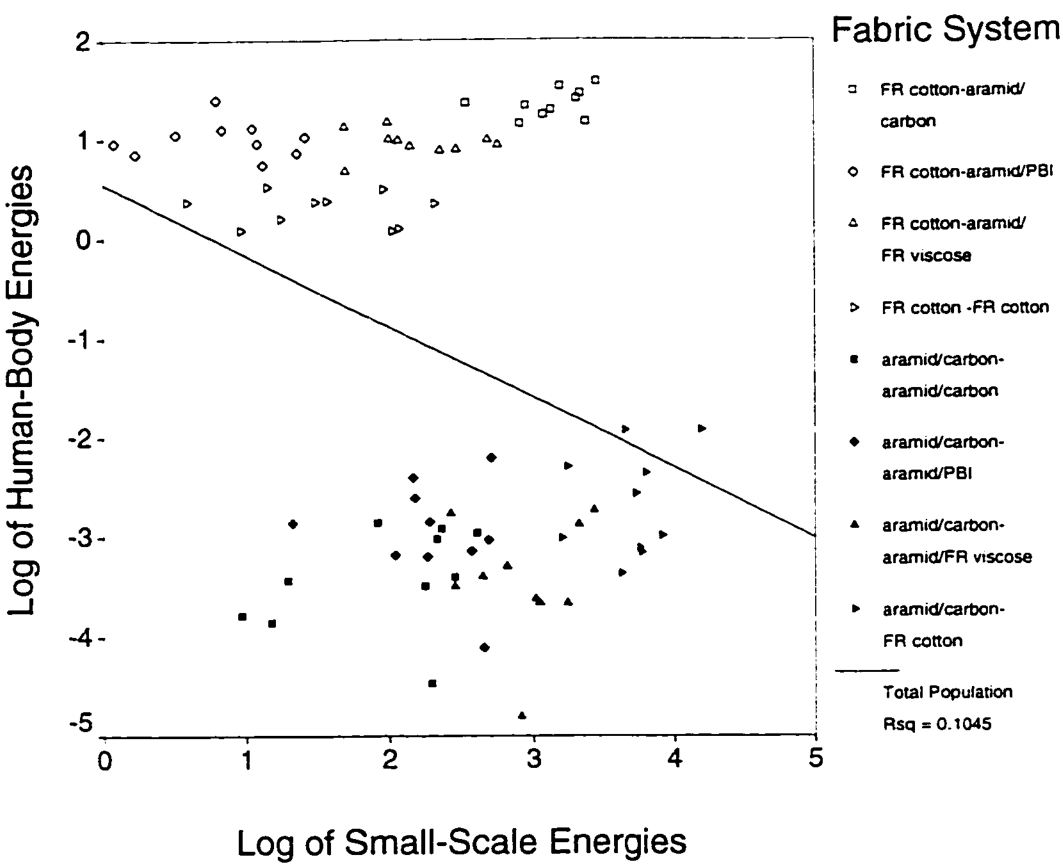
**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C6. Correlations between small-scale and HBE data for all systems at 20% RH

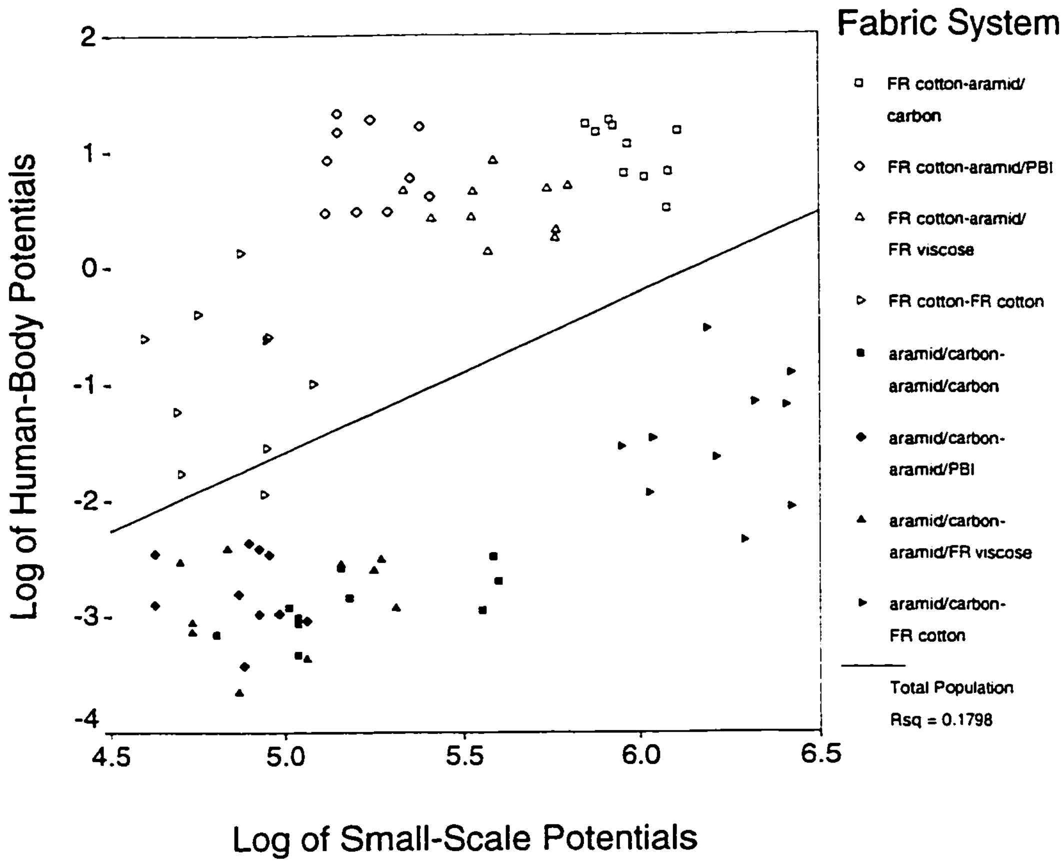
APPENDIX D



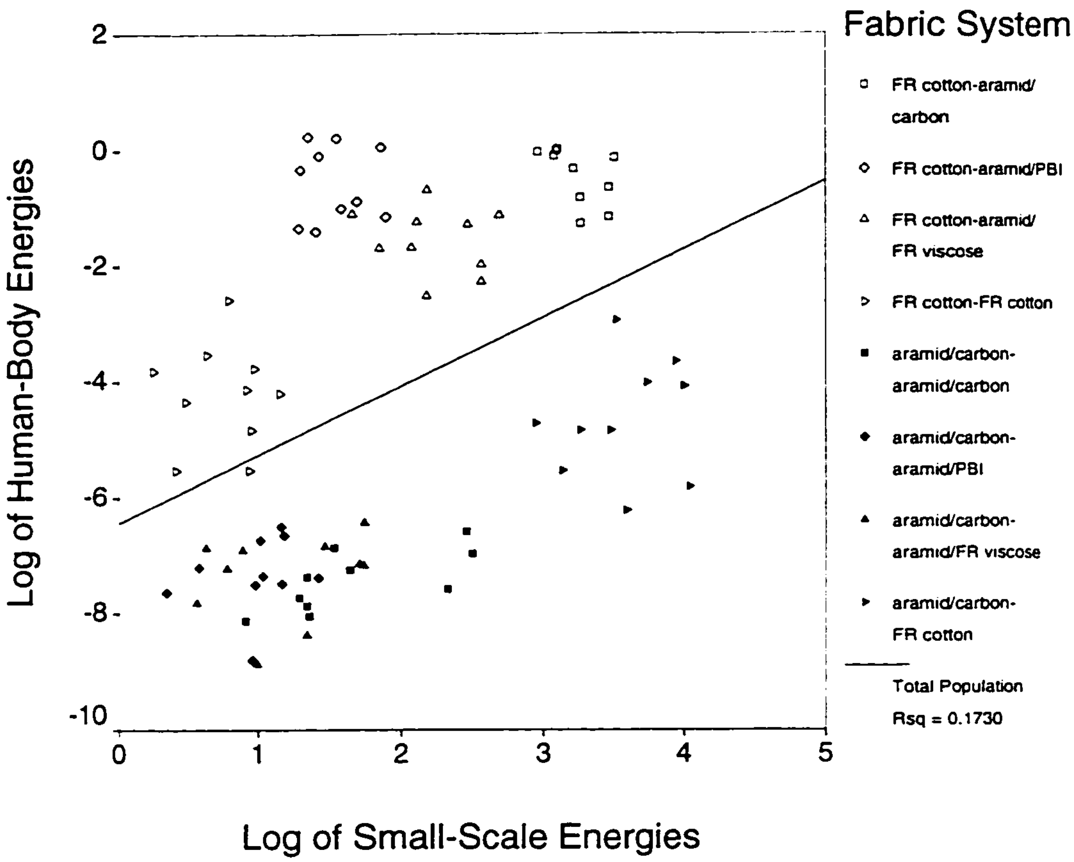
Appendix D1. Scatterplot of human-body versus small-scale potentials at 0% RH



Appendix D2. Scatterplot of human-body versus small-scale energies at 0% RH



Appendix D3. Scatterplot of human-body versus small-scale potentials at 20% RH



Appendix D4. Scatterplot of human-body versus small-scale energies at 20% RH

IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

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