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Development of a Laboratory Protocol to Predict the Electrostatic Propensity of Clothing Systems

by

Jose Alberto Gonzalez ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

Master of Science

in

Clothing and Textiles

Department of Human Ecology

Edmonton, Alberta

Spring 1995

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Betty Crown
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DR. P.R. SMY

Nancy Kerr
DR. N KERR

DATE: November 28/14

TO MY WIFE CRISTY,
AND OUR CHILDREN LUIS, LAURA AND ANDRES.
TO MY PARENTS FRANCISCO AND ALBERTINA,
MY SISTERS YENI AND ALMA, MY BROTHERS
GUILLERMO AND FRANCISCO

ABSTRACT

An accurate and general method to measure the electrostatic propensity of textile systems has been an elusive goal for many years. Numerous small-scale techniques have been tried, but unsuccessfully for some conditions. One of the most serious difficulties is a poor relationship between measurements taken by such methods and the values of electrostatic discharges from garment systems in real-life situations.

This thesis describes a study to develop a laboratory protocol to measure the electrostatic properties of clothing systems. Three small-scale test methods, both existing and new, were evaluated and compared in order to choose the method or set of methods that could best assess the electrostatic propensity of protective garment systems to be worn by workers in hazardous environments under dry conditions.

Several one- and two-layer fabric systems that included non-FR 100% cotton, as well as protective fabrics of 100% aramid/carbon, aramid/PBI, aramid/FR viscose, and FR cotton were tested. Experiments were conducted at 20% relative humidity and room temperature.

Results showed a trend where antistatic fabrics could be charged to lower discharge potentials and showed lower decay times than regular fabrics of either synthetic or cellulose fibres. These discharge potentials and decay times were compared with data from human-body experiments. Significant coefficients of determination (R^2) of up to .97 were found when results from different test methods were combined and regressed on human-body data.

It seems, therefore, that measuring peak discharge potentials and charge decay times from charged fabric systems using a battery of test methods can be sufficient to assess with high accuracy the static behavior of garment systems in real-life conditions.

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Chapter 1
Introduction

Static electricity has long been cited by investigators as a possible cause of accidental or premature ignition of flammable or explosive liquids, vapors, gases, and solids. Many cases have been documented (Scott, 1981) in which the energy generated on a charged object reaches the level at which the resistance of the air-gap between the object and a conductor at a lower potential breaks down, producing a spark.

Some of the well known undesirable effects include clinging of charged clothing together or to the body as well as dust attraction to charged materials, thereby causing soiling of clothing in places like department stores. Often people experience shocks when, after walking over a carpet, they touch a metal light switch; or when after sliding off a car seat, they touch the car body. The resulting shock is caused by the discharge of several thousand volts in the form of a spark to the conductor (Roth,1990).

In the electronic and other high-tech industries, there can be damage to or malfunctioning of equipment when a static-sensitive component comes into contact with a person or a material with a static build-up. The electrostatic field on a charged person or material can destroy a component by an induction mechanism (Matisoff,1986; Roth,1990). The most serious effect of an electrostatic discharge is its ability to ignite flammable gases, vapors, or powders at work sites, resulting in fires and explosions and the possible loss of human life (Wilson, 1977). These hazards associated with static propensity are a safety and financial concern to the industrial world. Therefore, they have generated the need for improved methods to predict the electrostatic tendency of textile systems.

At the present time, there is no generally accepted method to measure electrostatic properties of textile systems that can reliably and accurately predict the static propensity of protective garment systems which comprise combinations of different garments, worn by workers in hazardous environments, especially in low humidity conditions. Numerous measurement techniques have been tried, but problems remain with all of these methods. One of the most serious difficulties is a poor relationship between measurements taken by such methods and the real-life values of electrostatic discharges from a charged clothed human body. Also, these methods normally measure the electrostatic characteristics of a surface of an insulator which does not represent the real phenomenon of a charged capacitor being discharged by a grounded object, as the human-body static discharge is.

Background

The term "electrostatic" or "static electricity" refers to the phenomenon associated with the build up of electrical charges generated, for example, by contact and/or rubbing of two objects. Static electricity is generated by unbalancing the molecular configuration of relatively non-conductive materials.

The word "electricity" comes from "electron" (amber in Greek) and it was Thales of Miletus (640-548 BC) who first observed this specific property. It was termed "electrical" in 1600 by William Gilbert who is said to have begun the scientific study of electricity and magnetism.

Our current ideas on the nature of electricity stem from the knowledge of atomic structure and the existence of tiny indivisible particles of both kinds of electricity. The existence of these positive and negative electrical particles is inherent in the structure of matter, and they possess a mass and a quantity of electrical charge.

Electrostatics on Textiles

Many years ago the problems arising from static charges were relatively small with natural fibres in high humidity environments, but these problems became recognized as serious when synthetic fibres of a hydrophobic nature were introduced. Even natural fibres like wool and cotton, when completely dry, are very poor conductors, but their conductivity increases in high humidity atmospheres, because they absorb substantial amounts of moisture (of the order of 10%, calculated on the weight of the fibre). On the other hand, many manufactured fibres absorb little or no moisture and remain poor conductors in atmospheres of more than 60% relative humidity (Datyner, 1983).

Antistatic Solutions

Some finishes have been developed that attempt to decrease static build-up by one or more of three basic methods: (1) by increasing the material's conductivity, whereby the charged electrons move to the air or are grounded, (2) by increasing absorption of water by the finish, providing a conductive surface on the fabric that carries away the static charge, and (3) by neutralizing negative and positive charges. These finishes, however, tend to have limited effectiveness, largely because they are gradually lost during the final stages of fabric processing or care of finished products, and/or they do not work properly under cold and dry conditions.

More successful reduction in static build-up of synthetics is achieved through the modification of the polymer prior to extrusion. Such modification, which is permanent, incorporates in the fibre structure compounds such as cationic polyelectrolytes containing polyethylene oxide segments, that increase the moisture absorbency which, in turn, increases conductivity.

Another approach is to use special high-performance antistatic fibres. Metal, metallized, and bi-component fibres containing metal or carbon are among those used. A small quantity of these fibres is blended with conventional synthetic fibres. Being more conductive, these fibre blends serve to dissipate static charges mainly to the air, or to ensure that no accumulation can occur.

Statement of the Problem

At present, there is not a single small-scale laboratory method that can accurately predict the electrostatic propensity of protective garment systems to be worn by workers in hazardous environments. Existing methods measure only the static characteristics of surface insulators, such as discharge potential and decay rate. The values of these variables differ greatly from an electrostatic discharge from a clothed human body because the mechanisms of charging and discharging in each case are different. Charge build-up depends on the conductivity of the material (Hayek and Chromey, 1951), and the resistivity and decay rate of the textile surface (Ramer and Richards, 1968; Chubb, 1988), while discharging depends on the capacitance and resistance of the charged object as well as the geometry of the grounding device (Greason, 1992; Berkey, Pratt and Williams, 1988).

Justification and Purpose

There is general concern about the electrostatic phenomenon on textile surfaces. Many accidents involving static discharges from charged textiles have been reported. It is very simple to generate such a condition: if a jacket is removed quickly, or if a lab coat is rubbed briskly against a chair, if the materials involved are dissimilar, and if the relative humidity is sufficiently low, then a charge large enough to induce a sparking potential can occur. Actually, the discharge will likely be from the wearer due to the fact that the static charge is induced onto the individual wearing the charged garment. Friction, dissimilar surfaces, and low relative humidity are conditions tending to favor the production of high static charge. A resulting spark can ignite flammable substances or most certainly destroy static sensitive electronic devices. This electrostatic propensity is a serious hazard in hospital operating rooms, and in the oil, military, chemical, electronic, and other high-tech industries.

The major determinants of sparking potential are humidity, the fabrics/substances involved, and the degree of friction involved (Wilson, 1977). In cold regions like Alberta, the absolute humidity level declines extremely with very cold temperatures, so the electrostatic threat can be more significant than in warmer regions. People who work outdoors in extremely cold conditions may be required to wear thermal protective clothing when working in unsafe circumstances. It has been shown that clothing made of thermal protective fabrics such as aramids or flame retardant cotton may generate enough energy to ignite a fuel vapor-air mixture (Osei-Ntiri, 1992).

By walking over a non-conducting floor covering, the body potential can be raised to over 10 kilovolts (kV) (Roth, 1990), but the charge involved is only approximately 1 microcoulomb (mC) (Greason, 1992). On discharge, less than 10 milijoules (mJ) is released, which is only a thousandth of the amount regarded as harmful (Wandel, Gutschik & Carl, 1972). Although a spark produced as a result of a body voltage of 1.25 V (0.2 mJ) is considered insufficient to ignite a gasoline-air mixture (Lewis and von Elbe, 1951), recent research has found values for threshold energy as low as 26 mJ for incendive sparks (Rizvi and Smy,1992).

Some people believe that 100% cotton garments are less prone to static electricity than fabrics such as aramids. This belief is based on its high moisture regain at high relative humidity, and on the mid-position of cotton in the triboelectric series, which ranks different materials according to charge polarity generated when they, in pairs, are rubbed against each other and separated (frictional separation). The amount of static generation depends not only on the atmospheric conditions but also on the substance being rubbed against, as well as the degree of rubbing (Klein and Kaswell, 1990). At 20% relative humidity, aramid fabrics have a slightly lower apparent surface resistivity than regular cotton or FR cotton fabrics. At 50% relative humidity, the cotton products have somewhat lower values. The decrease of resistivity with an increase in humidity is greater for cotton than for fabrics made of most synthetic fibres (Red Kap Industries report, 1990).

Today, in most jurisdictions including Alberta, there is no definite policy regarding electrostatics in clothing nor is there any prevalent, accepted industry-wide standard. Such standards are needed for proper evaluation and description of protective garments, but little progress in the field has been made to date. The determination of appropriate policy regarding protective clothing is essentially left to each firm. As a result, there is a lack of control of electrostatic phenomenon, and its subsequent elimination.

The present study was planned to overcome the lack of relationship between small-scale tests and real-life static discharges by developing a laboratory protocol that can accurately and reliably assess the electrostatic propensity of protective clothing systems that workers wear in hazardous environments under cold and dry conditions. Existing and new methods were compared and evaluated in order to choose the method or set of methods that can best assess the electrostatic behavior.

Specific Objectives

The objectives of the study were to:

1. develop new methods for the measurement of the electrostatic characteristics of fabric systems;
2. a) measure peak discharge potential of static discharges from fabric systems following new and known methods at low humidity, and b) determine differences in potential among the various fabric systems;
3. a) measure the charge decay time for the surface charge on fabric systems at low humidity, and b) determine differences in decay time among the various fabric systems;
4. compare and evaluate different small-scale laboratory methods for the prediction of the electrostatic propensity of protective fabric systems at low humidity;
5. determine the relationship between charge decay time and peak discharge potential of different protective fabric systems as measured by small-scale tests; and
6. determine the relationship between data from small-scale tests (multilayer specimens) and that from human-body experiments.

Statement of Null Hypotheses

To meet objectives 2, 3, 5, and 6, the following null hypotheses were tested:

Ho_1. There will be no significant difference in peak discharge potential measured by small-scale laboratory tests among different fabric systems.

Ho$_2$. There will be no significant difference in charge decay time among different fabric systems.

Ho$_3$. There will be no significant correlation between peak discharge potential, and the charge decay time obtained by small-scale laboratory tests.

Ho$_4$. There will be no significant correlation between peak discharge potential and charge decay time measured by small-scale laboratory tests (multilayer specimens) and those obtained in human-body experiments.

Delimitations and Limitations of the Study

The delimitations established for the research were:

1. The composition of fabric systems was restricted to protective fabrics made of aramid/carbon, FR cotton, aramid/PBI, and aramid/FR viscose fibres. The control fabric was 100% cotton.
3. Experiments were conducted only at 20 ± 2% relative humidity and 22 ± 2°C.
4. The charge decay cut-off levels were at 10%, and 50% of the charge initially applied.

A limitation that affected the present study was the availability of only limited data from human-body experiments obtained during another phase of the larger project. Only one human activity, a clothed human body sliding off a car seat, was considered for the analysis and comparison.

Definitions of Terms

For the purpose of the present research, the following definitions applied:

Static Electricity: "Static electricity connotes the phenomena of attraction and repulsion observed between electrically-charged bodies differentiated from the effect of 'dynamic electricity' which is utilized in the generation of power or energy when it passes through a system".

(Crugnola and Robinson, 1959, p.2)

Electrostatic Propensity: The capacity of a non-conducting material to acquire and hold an electrical charge by induction (via corona discharge) or by triboelectric means (rubbing with another material).

(ASTM D4238-90, p.399)

Electrostatic Discharge (ESD): ESD is a transfer of static charges between bodies at different potentials caused by direct contact or induced by an electrostatic field.

Triboelectrification: the generation of a static charge between two materials by rubbing them together.

Static Charge (q): If an object exerts an electrical force on another object, it is said to be charged. The force exerted is dependent on the amount of the charge; that is, a static charge is considered an amount or quantity of electricity. If a body is electrically neutral, the resultant charge is zero. The unit of static charge, Coulomb (C), corresponds to a charge of 6.25×10^{18} electrons.

Potential (V): The potential difference dV between two points in a dielectric field is defined as:

$$dV = V_f - V_i = - W_{if}/q_o$$

where qo is a test charge on which work (W_{if}) is done by the field, V_f is the final potential, and V_i is the initial potential.

The SI unit of potential is the Volt (V) where 1 V = 1 Joule/Coulomb.

(Halliday-Resnick, 1988, p.608)

Capacitance (C): is the ratio of the charge on one electrode to the potential difference between the electrodes. The SI unit of capacitance is the Farad (F). Generally, the capacitance of a capacitor is evaluated by (1) assuming charge q to have been placed on the plates, (2) finding the electric field E due to this charge, (3) evaluating the potential difference V, and (4) calculating C from equation:

$$C \text{ (Farads)} = q \text{ (Coulombs)}/V \text{ (Volts)}$$

(Halliday-Resnick, 1988, p.632)

Potential Energy (U): The potential energy of a charged capacitor, given by

$$U = q^2/2C = CV^2/2$$

is the work required to charge it. This energy is conveniently thought of as stored in the electric field E associated with the capacitor. By extension, the stored energy can be associated with an electric field generally, no matter what is its origin. The SI unit of potential energy is the Joule (J).

(Halliday-Resnick, 1988, p.632)

Electrostatic decay half-life: The time in seconds for the maximum voltage induced on a textile to be reduced to one-half of the maximum voltage (50% cut off level) by the various decay mechanisms: conduction and ionization of the air.

(ASTM D4238-90, p.399)

In the research, a charge dissipation to one tenth (10% cut off level) of the maximum voltage induced on a textile was considered, too.

Electric Current (I): An electric current I in a conductor is defined by:

$$I = dq/dt$$

Here, dq is the amount of (positive) charge that passes in time dt through a hypothetical surface that cuts across the conductor. The direction of electric current is the direction in which positive charge carriers would move. The SI unit of electric current is the Ampere (A) which is equal to 1 Coulomb/second.

(Halliday-Resnick, 1988, p.655)

Resistance (R): The resistance R between any two equipotential surfaces of a conductor is defined from:

$$R = V/I$$

The SI unit of resistance is the ohm where 1 ohm = 1 volt/ampere

(Serway, 1990, p.746)

Chapter 2

Review of Literature

Principles Related to Static Electricity

Principles of Electrostatics

Although magnetism was known in China as early as around 2000 B.C., and electric and magnetic phenomena were observed by Greeks as early as 700 B.C., it was not until the late part of the 18th century and the early part of the 19th century that scientists established the bases for electrostatic knowledge (Serway, 1990). In 1733 Charles F. Du Fay observed two kinds of electricity, which were subsequently named positive and negative by Lichtenberg in 1778. In 1785, Charles Coulomb established the fundamental law of electric force (F_E) between two stationary, charged particles. The entire subject of electrostatics is based upon this one force law (Cheston, 1964). During the nineteenth century, a number of machines were made in which electrostatic charges were multiplied by induction and accumulated. The machines could be described as mechanized versions of Volta's electric charge-storage device and a Leyden jar (Bowers, 1982).

In 1909, Robert Millikan discovered that electric charge always occurs as some integral multiple of some fundamental unit of charge, **e**. The charge is said to be quantized, that is, electric charge exists as discrete "packets". This elementary charge can be positive or negative and its value is 1.60219 x 10^{-19} Coulombs (Serway, 1990).

Electrostatic charges are invariably produced at the interface between two dissimilar materials when they are brought into firm contact with each other. These charges may comprise electrons, ions, and charged particles of the bulk materials -or any combination of these (Wilson, 1987). Henry (1953) reported that when these two surfaces are separated, either with or without obvious rubbing, charged particles are found to have crossed the boundary, with the usual result that the two surfaces have gained equal and opposite charges. Materials differ in their propensity to lose some of their electrons when in contact with another material (Crow, 1991). Wilson (1987) called this phenomenon "work function" which is defined as the energy required to cause the removal of an electron from a material. When two bodies make contact, that which has the lower work function loses electrons to that with the higher work function.

For materials which are poor conductors of electricity as are most textiles and polymers, the causes of contact charging are very complex. Experiments with certain well cleaned polymers under carefully controlled conditions, however have shown that, as with good conductors, the charging is largely electronic in nature. However, in practice, the surfaces of textiles are usually contaminated with additives, finishes, dirt and moisture in all of which resides an abundance of ions (Henry, 1971).

Charge Generation

Considerable research has been done on the charge generation characteristics of textiles used in clothing. The static charge which is involved in a spark phenomenon is often generated on the clothing or footwear of the individual and induced onto the skin. Hence, the charging characteristics of clothing and shoes play a critical role in determining the possibility to produce a spark which could ignite flammable gases (Berkey et al, 1988).

Static electricity is generated when almost any pair of surfaces is separated. The amount of charge transferred from one surface to another depends on the relative affinities of the materials for a charge of given polarity (Sello & Stevens, 1984). Shaw and Jex (1951) stated that the static electrification between two insulators of the same material is caused by asymmetric friction or temperature difference. But Shirai (1984) determined that the electric charge of two sheets of polyester depended on their thickness rather than their asymmetric friction or temperature difference.

A separation of charges may occur between two surfaces when they are rubbed "asymmetrically". When one surface is rough and the other smooth, the two surfaces become charged as if they were made of different materials (Henry, 1953).

Although rubbing is not necessary for charge generation, it usually increases the amount of charge produced. "Triboelectrification" is the term that applies when an electrical charge is generated on a body by frictional forces and is probably the major mechanism for the generation of electrostatic charge in textile materials (Wilson and Cavanaugh, 1972).

Charges may also be generated between a non-conductor and a conductor by induction. Consider a negatively charged rubber rod (non-conductor) brought near a neutral (uncharged) conducting sphere insulated from ground. The region of the sphere nearest the negatively charged rod will obtain an excess of positive charge, while the region of the sphere farthest from the rod will obtain an equal excess of negative charge. If the sphere is grounded, some of the electrons will be conducted to earth. When the grounding connection is removed, the sphere will contain an excess of induced positive charge (Haase, 1977).

A third type of charging can occur between two conductors, one of which is initially charged. In this case a charge transfer takes place at the time of contact, and results in new body potentials after separation (Greason, 1992).

Charge Dissipation

A charged human body is a primary cause of electrostatic discharges (ESD). The charging process for the human body involves both triboelectrification and induction processes (Roth, 1990). Consider the case where a person, wearing insulating shoes, walks across another insulating surface, such as a carpet. The bottom of the shoe sole and the surface of the carpet become charged due to triboelectrification. Since the human body can be modeled as a neutral conductor, insulated from ground by the footwear worn, the charges trapped on the footwear cause a polarization of charge on the human body. A charge equal and opposite in polarity to the trapped charge, moves to the human feet, leaving a charge distributed over the body. If the person now touches a grounded conductor, a charge flow will take place to balance the polarized charge. The effective electrical equivalent circuit of the charge source, the discharge path and the charge sink, determines the dynamic characteristics of the ESD (Boxleitner, 1989).

Some interesting observations can be made from this simple model. If a human body, wearing charged soles, is discharged as described, its potential would again rise if the shoes were removed. A similar problem would occur if a human body, wearing a charged garment, were discharged and then the garment were subsequently removed. These examples demonstrate that zero potential on a conductor does not necessarily imply a neutral condition (Greason, 1992).

In all the cases described above, the static charging current is very low so that the total charge a human body can accumulate is normally only of the order of a few microcoulombs. The voltage relative to the earth potential depends on the capacitance, since the following relation holds:

$$Q = VC$$

where the human body capacitance is also very small and therefore requires little charge to cause a rise in potential of several thousand volts, depending on the environmental conditions (Roth, 1990).

Hazards from Electrostatics

Evaluation of Hazards Created by ESD

Static electricity manifests its destructive nature mainly through electrostatic discharges. The electrostatic build-up on people or materials, particularly non-conductive materials (textiles), can be significant in the dry cold conditions of Canada's Arctic. The average individual walking across a non-conductive floor or sliding off a car seat can generate discharge potentials from 3 to 7 kV (Matisoff, 1986; Sclater, 1990), or depending on the environment (e.g. low relative humidity), the voltage can rise to 15 kV or more (Sclater, 1990). The ability of many fabrics to hold on to a static charge is a function of the relative humidity of the environment (Sereda and Feldman, 1955; Ramer and Richards, 1968).

The main danger of ESD, or sparks, is their incendiary properties. They usually pose no electrical danger to human beings because the voltages and charges generated are too small. Depending on the individual, the human body has a threshold for shock of over 3 kV (Sclater,1990). However, a discharge spark of less than 50 V can cause damage to ESD-sensitive electronic devices (McAteer, 1987; Sclater, 1990). The energy dissipated in the spark as heat also provides the source for ignition of flammable gases (Tolson, 1980).

Spark discharge occurs when the electric field strength exceeds the air breakdown value of 30 kV/cm at atmospheric pressure (Gibson and Lloyd, 1965). This means that the maximum free charge density which can exist on a plane surface is about 34 mC/m^2 (Ji, Takahashi, Komai and Kobayashi, 1989).

Tolson (1980) reported that the incendivity of a discharge can be estimated once the circumstances of charge accumulation are known. Charge accumulation on a ungrounded conductor (human body or discrete conductive fabric) and charge accumulation on an insulator (synthetic fabrics and plastics) are two very different situations. The former represents by far the greatest risk because it can discharge all the electrostatic energy instantaneously in the form of a spark given by:

$$U = CV^2/2 = QV/2 \text{ [joules]}$$

In the case of electrically insulating materials (fabric), however, their high surface and volume resistivity impede the flow of charge to the point of discharge and only a fraction of the total charge on the surface is released in the discharge. The above equation can not therefore be used to calculate the energy of the discharge because the charged insulator is not intrinsically an equipotential surface (Löbel, 1987). The character of a discharge from an insulator may be described in terms of the total charge transferred in the discharge and its distribution with space and time. Thus, the incendivity of a discharge depends not only upon the total amount of energy or charge released, but also upon the time distribution of the energy (Glor, 1988). A corona discharge extended in time is less incendive than a short-lived spark of the same total energy (Gibson and Lloyd, 1965).

For the various types of fabrics (non-conducting and conductive) the main electrostatic discharges of concern are the spark energies from brush discharges (Lövstrand, 1981). Brush discharges, unlike the Lichtenberg or propagating brush discharges (which could have incendive energy as high as 75 mJ), are not expected to have energy that exceed about 2 mJ (Owens, 1984; Glor, 1988; Rizvi, Smy, Crown and Osei-Ntiri, 1992).

Minimum Ignition Energy (MIE)

Assessment of the ignition risk from an electrostatic charged body essentially requires comparison of the igniting power of any discharge from the body with the minimum ignition energy of the flammable atmosphere (Gibson & Lloyd, 1965; Glor, 1988; Owens, 1984). According to Bustin and Dukek (1983), saturated hydrocarbon gases and vapors require about 0.25 mJ of stored energy for spark ignition of optimum gas-air mixtures. Wilson (1977/1978) also showed that the minimum ignition energy of coal gas and air is 0.03 mJ, of natural gas and air is 0.3 mJ and fuel vapor and air is 0.20 mJ. Rizvi and Smy (1992) found that the threshold energy, the product of the threshold energy density and the surface area of the discharge, was a far less reliable measurement than the threshold energy density. The minimum energy density thresholds for incendive and non-incendive sparks were found to be 10 J/m^2 and 0.25 J/m^2 , respectively.

Measurements Static Electricity in Textiles

Human Body Experiments

Almost all previous work on human spark scenarios has involved the clothed person, often wearing a pair of insulating shoes, performing common movements such as walking across a carpet, sliding off a seat or removing a garment. Research at institutions such as the Arctic Aeromedical Laboratory (USA), the Quartermaster Research Establishment and Engineering Command (USA) and the Shirley Institute (UK) all investigated the generation and subsequent discharge of static electricity in military or arctic clothing systems and other work wear, using clothed persons as the subjects and conducting the experiment in the laboratory.

The Arctic Aeromedical Laboratory research (Veghte & Millard, 1963) focused specifically on the accumulation of static electricity on Arctic clothing. In the experiment, three different Arctic clothing outfits made mainly from nylon were worn by fifteen different subjects. They walked outside and did some physical exercise. The electrostatic charges on the clothing systems and the capacitance of the subjects were measured. The subjects re-entered the laboratory and removed their outer garments and the electrostatic discharges from the body measured. The experiments were conducted at outdoor temperatures ranging from 5°C to -43°C and relative humidity at between 50% and 74%. The research pointed out the dangers of personnel working outside, coming indoors and removing exterior clothing in a warm dry environment, a situation which tends to produce very high electrostatic charges.

Wilson's study (1977/1978) was intended to investigate the charge generation characteristics of clothing in normal use by workers. The objective of this project was to assist in developing a specification which could be used to identify safe fabrics for use when handling flammable materials. The garments were the type worn by military personnel and were made of fabrics such as polyester and linen/polyester coveralls, aramid and cotton flying suits and polyurethane coated nylon foul weather suits. The chair cover materials were lambswool, PVC-coated cotton, leather, and cotton canvas. The subject wearing a garment and a pair of rubber-soled shoes, sat down on a covered chair and slid off it into a standing position. In all cases, the body voltages were discharged to ground via the fingers to produce sparks (corona discharge), which were measured. This work was done at relative humidity in the range of 15 to 80%, at 21°C. The result showed that cotton as well as synthetic fabrics are static prone at low humidity.

Osei-Ntiri (1992) described the characteristics of ESD from the human body wearing thermal protective garment systems and doing two human activities: sliding off a car seat, and walking and removing a garment. The experiments were conducted at very low humidity and room temperature. It was found that garment systems made of antistatic fibres (Aramid/carbon and aramid/stainless steel) generated static charges of less energy than those made of non-antistatic fibres (aramid and FR cotton).

Small-Scale Tests

There are basically two approaches to assessing the electrostatic propensity of textiles: measure either the surface resistivity, or the charge decay rate. Several standard methods, widely used in the industry, have been derived from these two parameters. Examples included AATCC Test Method 84-1987: Electrical resistivity of yarns; AATCC Test Method 76-1987: Electrical resistivity of fabrics; ASTM D 4238-90: Standard Test Method for electrostatic propensity of textiles; Federal Test Method Standard 191A method 5931: Determination of electrostatic decay of fabrics; Federal Test Method Standard No. 101B method 4046: Electrostatic properties of materials; EOS/ESD Standard No. 2: Standard for protection of electrostatic discharge susceptible items: personnel garments (draft August 1987); AATCC Test Method 115-1986: Electrostatic clinging of fabrics: fabric-to-metal test;

AATCC Test Method 134-1986: Electrostatic propensity of carpets; ASTM F2350.05: Standard test method for evaluating triboelectric (static) charge generation on protective clothing (draft January 1994).

Much has been written about methods to evaluate the electrostatic properties of textiles but there seems to be little consensus. Hearle in 1957 and Wilson in 1963 reported that the build up of static charge depends upon the electrical resistance. Crugnola and Robinson (1959), McLean (1955), and Teixeira & Edelstein (1954) listed the limitations of this assumption, as follows: 1) inaccurate for a textile fabric, 2) ignores effect of second surface, 3) ignores the effect of a blend, and 4) resistivity can at best furnish only a clue to one mechanism of charge dissipation, namely conduction.

Current standard test methods have not been entirely satisfactory, as discussed in detail by Crow (1991). The ASTM "Standard Test Method for Electrostatic Propensity of Textiles" D4238-90 measures the charge induced onto a rotating specimen by a D.C. current and its subsequent rate of decay. The test method states that inter-laboratory precision has not been established. In AATCC Test Method 76-1987 "Electrical Resistivity of Fabrics", the surface electrical resistivity is determined by means of an electrical resistance meter. This method recommends measurements be done at various humidities because the "accumulation of static electricity generally is greater the lower the relative humidity is".

Field intensity

An electrostatic field exists in the region surrounding an electrically charged object. This charged object, when brought in close proximity to an uncharged object, can induce a charge on the formerly neutral object. This is known as an induced charge. Quantitatively, this induced charge is the voltage gradient between two points at different potentials (Matisoff, 1986). In most situations, it is the electric field from the charge which causes electrostatic effects.

One technique for evaluating the possible sparking hazard is therefore to measure the electric field intensity (kV/cm) at the surface of the charged fabric (Owens, 1984). It has been demonstrated that field intensities less than 5 kV/cm cannot ignite any fuel that has a minimum ignition energy (MIE) greater than 0.15 mJ (Rizvi and Smy, 1992). The equivalent energy of possible sparks from a fabric can also be measured directly by attempting to ignite a gas or vapor that has a known ignition energy (Lövstrand, 1981; Owens, 1984; Glor, 1988).

Electrical resistivity

Measurement of electrical resistivity is a standardized and frequently used technique for the evaluation of electrostatic propensity of fabrics (Coelho, 1985; Löbel, 1987; Morisseau and Lewiner, 1987). The most widely accepted laboratory method used is that of surface resistivity and, occasionally, volume resistivity. The advantages of this kind of measurement over the determination of surface potentials are many. Measurement of electrical resistivity is described as simple and reproducible. Further advantages are the availability of commercial equipment and standardized prescriptions for measurement and testing (Löbel, 1987; Ramer and Richards, 1968). Despite the advantages, the electrical resistance characterizes merely that component of an antistatic property which is responsible for the dissipation of separated charge, in most cases in an incomplete manner. There is a discrepancy in using the resistance measurement: by using a commercial measuring device for high resistance, the result is available not earlier than one second or more after switching on the voltage due to the inertia of the measuring equipment. In practical situations, however, the available discharge time is only milliseconds. That means if the resistance depends upon the time period, it is evident that some inaccuracy is to be expected (Löbel, 1987).

Charge decay rate

Because of the limitations of electrical resistivity measurement as an index of electrostatic propensity of fabrics, measurement of charge decay rate on fabrics is most often the alternative (Ramer and Richards, 1968; Taylor and Elias, 1987; Chubb and Malinverni, 1993). To measure the speed at which a material will dissipate a charge requires a charge decay meter. In using these devices, decay time indicates the ability of the surface to transfer the electrons from a charged body through the work surface to ground. The decay rate varies inversely to the resistivity. Thus the greater the resistance, the slower the static charge decay rate (Matisoff, 1986). The amount of electrostatic charge developed on a textile fabric will depend on both the rate of electrostatic charge generation and the simultaneous rate of charge decay. If the latter is great enough, no charge will usually be detectable. For example, a fabric with resistivity of 1.0×10^9 ohms per square, such as natural cotton at 65% relative humidity, has a time constant for leakage of about 0.01 second, so that any charge produced leaks away so rapidly without electrostatic charge effects (Wilson, 1963). On the other hand, a fabric with a resistivity of 1.0×10^{15} ohms/square has a time constant for leakage of about 2 to 5×10^3 seconds or 40 minutes

(Wilson, 1963). Any charge produced will, therefore, remain on the fabric for a considerable length of time.

For a fabric to meet the antistatic or static decay requirement of various military and/or National Fire Protection Association (USA) specifications, the potential on the fabric must decay from 5 kV to 500 V (to 10%) within 3 seconds or less (Matisoff, 1986; Owens, 1984).

The Federal Test Standard 101C, method 4046 and the Federal Test Standard 191A, method 5931 are used for measuring the decay rate of an applied high voltage. A number of comments have been made about the interpretation of observations by these methods (Baumgartner & Havermann, 1984; Chubb, 1990). The methods are restricted to "homogeneous" and sheet materials and are not applicable to installed surfaces and "non-homogeneous" materials like textiles (Chubb and Malinverni, 1993).

Other measurement techniques

Matsui, Naito, Okamoto, and Kashiwamura, (1989) reported that static charge (potential) and its decay curve from a manually rubbed fabric could be measured and recorded automatically by a newly developed KB system.

Makwana, Munshi and Jadhav (1991) reported an apparatus which was designed and fabricated to study DC electrical conduction through textile materials. The current through a sample was measured varying applied voltages from 0 to 150 V, and the electrical conductivity was calculated

Summary

The numerous experiments carried out by textile scientists in various institutions, especially the military, confirm that electrostatic discharges will occur when an ungrounded clothed body doing any common activity is placed in specific atmospheric conditions. The experiments also show the impact electrostatic discharges have on our daily lives, from the nuisance of small electric shocks to the catastrophe of fire or explosion of flammable gases or vapors.

Even though science has enabled researchers to understand the concept of electrostatics, the subject of static discharges is still complex and misunderstood. Therefore, knowledge of the possible occurrence and incendivity of discharges which may be generated during particular industrial operations and common human activities is important for the proper assessment of electrostatic propensity.

Chapter 3

Methods

Research Design

This research was conducted as an experimental study comprising three test methods on both single layer and multilayer specimens. The independent and dependent variables for each experiment are outlined in Tables 1 and 2. For each test the fabric system, and the fabric direction were varied. When the charge decay rate was measured, the cut-off voltage was also varied. In Test No.3 the polarity of the applied charge was also considered as an independent variable.

In Test 1, the University of Alberta ESD Test System (UA ESD TS) the dependent variables were the discharge potential measured in volts [V], and the discharge energy measured in joules [J]. In Test No.2, the modified Federal Test Method Standard 191A, method 5931 (MFTMS), and Test No.3 the Federal Test Method Standard 191A, method 5931 (FTMS), the measured variables were the peak discharge potential [V], and the decay time [s].

Procedures

Fabric Sampling

All thermal protective fabrics were purchased from the same supplier. Three linear meters of each fabric were bought. The size of each specimen was 127 mm by 76 mm, as specified by the Federal Test Method Standard 191A, method 5931. Fifteen specimens of warp direction and fifteen specimens of filling direction were obtained from each sample, according to standard sampling procedures (Appendix A1). This provided five specimens for each test.

Conditioning

Each fabric sample was washed in an automatic washer and dried in a drier before cutting the specimens, following CAN/CGSB-4.2 No.58 M90, procedure III. Then, all specimens were conditioned according to CAN/CGSB-4.2 No.2 M88 inside an environmental chamber (4.12 m x 3.23 m x 3.81 m) where the relative humidity was carefully controlled and monitored at 20% relative humidity.

Table 1. Experimental design

TEST	INDEPENDENT VARIABLES				DEPENDENT VARIABLES
	FABRIC DIRECTION	CUT-OFF LEVEL	POLARITY	FABRIC SYSTEM	
1. UA ESD TEST SYSTEM	Warp Weft	N/A	N/A	Unilayer (Table 2)	Discharge potential and energy
1. UA ESD TEST SYSTEM	Warp Weft	N/A	N/A	Multilayer (Table 2)	Discharge potential and energy
2. MODIFIED FEDERAL TEST 191A, METHOD 5931	Warp Weft	10% 50%	N/A	Unilayer (Table 2)	Peak potential and decay time
2. MODIFIED FEDERAL TEST 191A, METHOD 5931	Warp Weft	10% 50%	N/A	Multilayer (Table 2)	Peak potential and decay time
3. FEDERAL TEST 191A METHOD 5931	Warp Weft	10% 50%	Positive Negative	Unilayer (Table 2)	Peak potential and decay time
3. FEDERAL TEST 191A METHOD 5931	Warp Weft	10% 50%	Positive Negative	Multilayer (Table 2)	Peak potential and decay time

Table 2. Fabrics used in the experiment

SYSTEM CODE	OUTER LAYER	INNER LAYER	WEAVE	COUNT (W x F) (yarns/cm)	MASS (g/sq.m)
MULTILAYER FABRIC SYSTEMS					
01	FR cotton	100% cotton			
02	Aramid/carbon	100% cotton			
03	Aramid/PBI	100% cotton			
04	Aramid/FR viscose	100% cotton			
05	FR cotton	FR cotton			
06	Aramid/carbon	Aramid/carbon			
07	Aramid/PBI	Aramid/carbon			
08	Aramid/FR viscose	Aramid/carbon			
UNILAYER FABRIC SYSTEMS					
09	100% cotton		3/1 Twill	37 x 22	210
10	FR cotton		Sateen	35 x 19	320
11	Aramid/carbon		Plain	23 x 21	205
12	Aramid/PBI		Plain	26 x 22	145
13	Aramid/FR viscose		Twill	32 x 21	265

The tests were performed inside an Electro-tech Systems model 506 humidity control chamber (91.44 cm x 60.96 cm x 45.72 cm) equipped with a desiccant-pump drying system. The dessicator contained a self-indicating drying agent (anhydrous CaSO4) and was mounted externally on the chamber.

Measurement of Dependent Variables

The discharge potential was measured and recorded by a Tektronix model 2430A digital oscilloscope, and the discharge potential waveform obtained was printed-out by a Hewlett-Packard model 7475A plotter. The decay time was measured and recorded by an Electro-tech Systems model 406C static decay meter. A Simco model A300 static eliminator was used for the elimination of any initial charge in the specimen.

Test No.1 (UA ESD Test System)

The UA ESD test system is a device developed and employed to simulate generation of charge by triboelectrification and measure electrostatic discharges from layered fabric systems (Figure 1). It has the following components: a specimen holder, a rubbing element, a lap counter, a conducting plate, collecting wires, a resistance-capacitor unit, a quick discharge switch, an oscilloscope, and a plotter.

An outer layer of fabric is rubbed by the rubbing element, generating a charge that is transferred onto the inner layer. This inner fabric transfers that generated charge onto a conducting plate. Then, the charge is conducted to, and stored in a capacitor, from where it is discharged through a resistor to an oscilloscope. See Appendix A2 for details of the test procedure.

Test No.2 (Modified Federal Test Method Standard 191A)

The device used in Test No.2 was a modification of the apparatus utilized in the Federal Test Method Standard 191A, method 5931 (Figure 2). An Electro-tech Systems model 406C static decay meter with a Pasco roller were the main components of this device. The test system was able to charge a textile surface by friction with the use of the roller, and measure peak potential and decay time. See Appendix A3 for details of the test procedure.

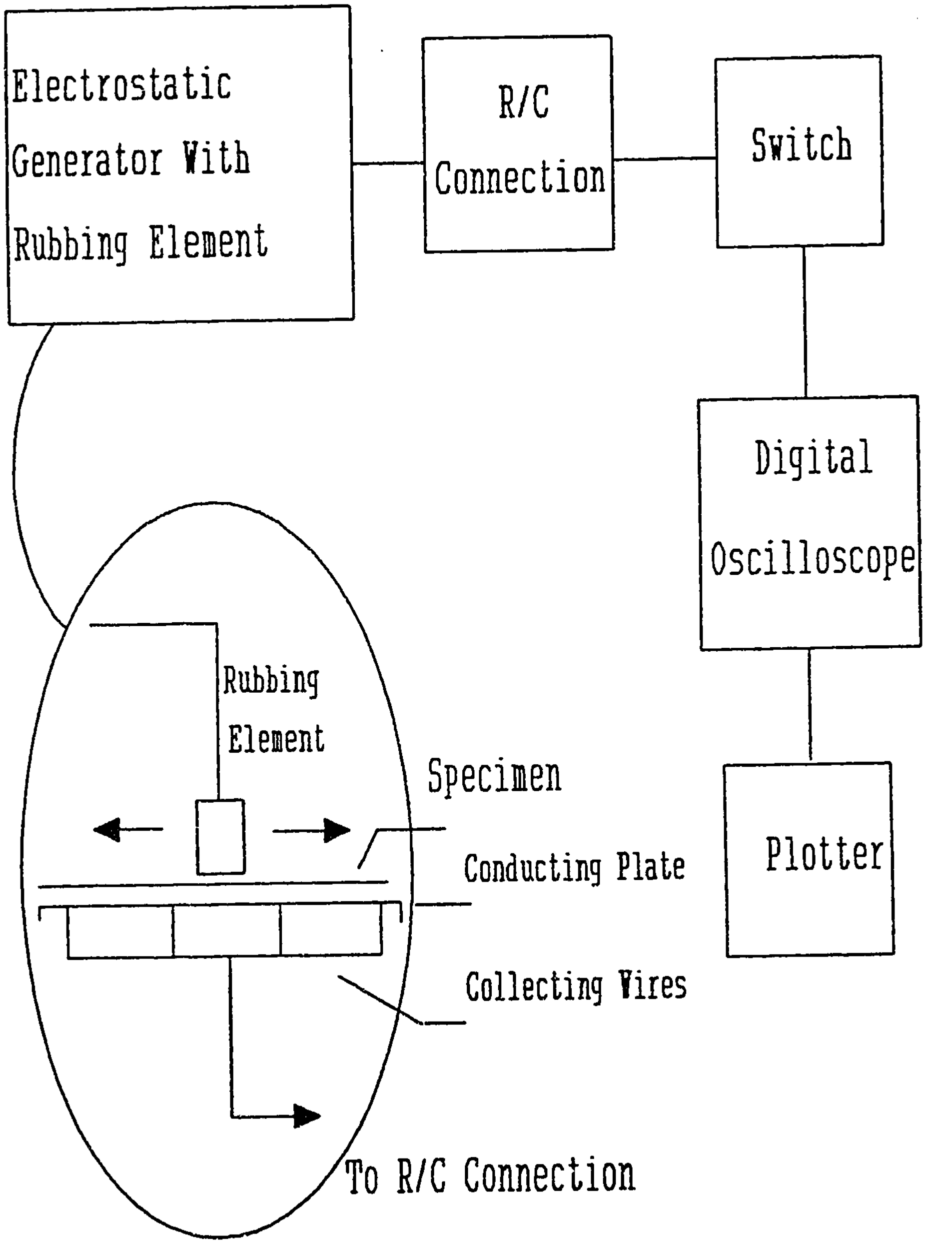

Figure 1. The UA ESD Test System

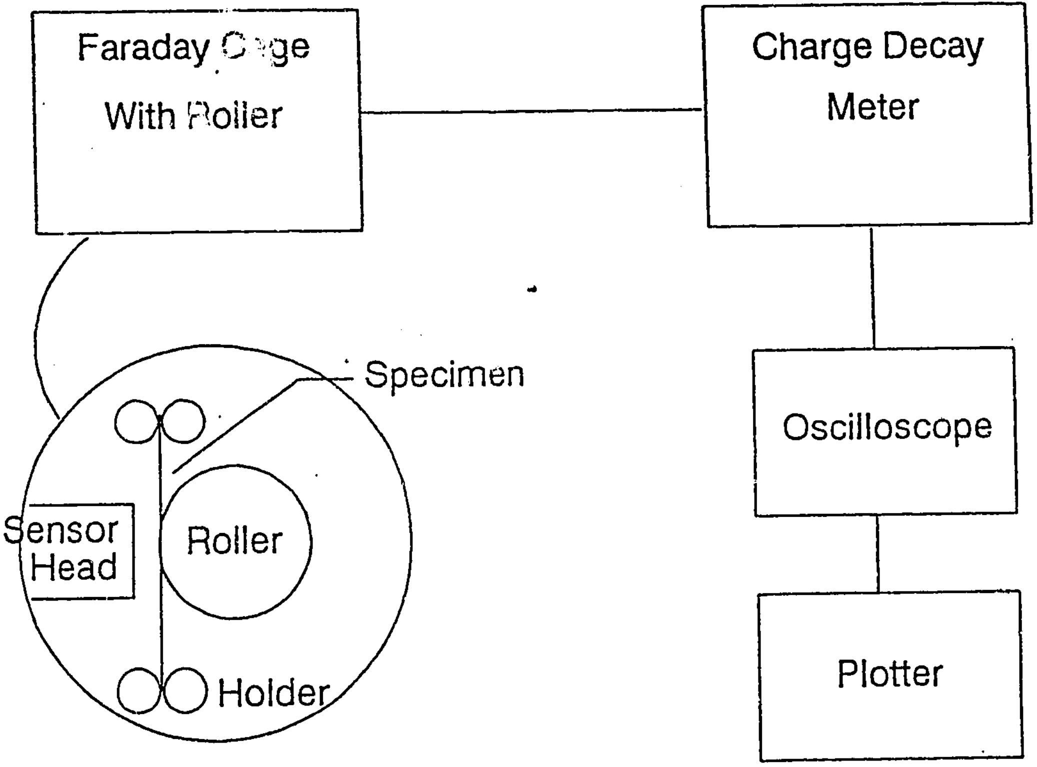

Figure 2. The Friction Charge Decay Test

Test No.3 (Federal Test Method Standard 191A)

In this test, the Federal Test Method Standard 191A, method 5931 was used. The same static decay meter described in Test No.2 was used. In this case, the specimen was charged by induced positive and negative potentials of 5 kV, as specified by method 5931.

Data Collection

The results obtained were recorded on a specific form for each part of the test (Appendix A4) where the date, the atmospheric conditions, the type of experiment, the fabric system, and the respective results were printed.

The voltage waveform print-out from the plotter was used to calculate transferred charge, discharge energy, peak current, duration of the event, and other parameters of interest, in the case of the UA ESD Test System. The total charge flow (transferred) Q was calculated by integrating the discharge potential V waveform and dividing this by the grounding resistance:

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

The total energy was then determined by taking the product of the total charge, from eq.(1), and the potential:

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

Statistical Analysis: Hypotheses Testing

The statistical analyses that were performed were as follow:

1) Descriptive statistics and box plots. These analyses were used to characterize each fabric group with respect to the dependent variables.
2) Multivariate ANOVA, to test hypotheses 1 and 2.
3) One-way ANOVA and Duncan's multiple range tests, to determine which fabric groups differ significantly from each other.
4) Pearson's correlation coefficient to test hypotheses 3 and 4.
5) Multiple linear regression to build a testing model to predict the electrostatic propensity of protective clothing.

The multivariate ANOVA and the One-way ANOVA were used to test the null hypotheses that there were no significant differences among the different fabric combinations in discharge potential, or charge decay time. The correlation coefficient was used to test the null hypothesis that there was no significant correlation between potential and charge decay time; in addition, it was used to test the null hypothesis that there was no significant correlation between the small-scale test results and those from the human-body experiments. The significance level was set at p £ 0.05. These statistical analyses were carried out using commercially available software, SPSS version 6.1.

Summary

This research was conducted as six different experiments. Three test methods were used with both unilayer and multilayer specimens: (i) the study of tribo-electrostatic discharges using the ESD Test System; (ii) the study of charge decay rate from frictional charging using a modified static decay meter; and (iii) the analysis of charge decay rate from induction charging using a static decay meter.

The independent variables considered for the first test method were fabric system and fabric direction. For the second and third tests, the cut-off decay level was added. For the third test method, charge polarity was also added as an independent variable.

The dependent variables were the peak discharge potentials (volts) and energies (joules) for the UA ESD test system, and the peak discharge potentials (volts) and the decay time (seconds) for the other two tests.

Chapter 4

Results

The results obtained from this study are presented in two parts: for unilayer specimens and for multilayer specimens. For each part, results are analyzed for both dependent variables, peak discharge potential and charge decay time, as well as by null hypotheses.

Unilayer Specimens

Peak Discharge Potential

Ho$_1$: "There will be no significant differences in peak discharge potential among different fabrics".

Three-way analysis of variance (ANOVA) (Appendix B1) indicated significant main effects of fabric system, test method, and fabric direction as well as both two-way and three-way interaction effects on **peak discharge potential**, indicating that there were significant differences in this parameter among fabrics, but these effects varied somewhat by test method and by fabric direction. Thus, the null hypothesis was rejected.

Individual multivariate ANOVA's (Appendices B2, B3, and B4).were then performed on data from each test method. Two-way ANOVA on data from Test No.1 (UA ESD TS) found significant main effects of fabric and fabric direction as well as two-way interaction effects. Three-way ANOVA on Test No.2 (MFTMS) showed significant main effect of fabric only, but two- and three-way interaction effects of fabric, fabric direction, and cut off level. Four-way ANOVA on Test No.3 (FTMS) found significant main effects of fabric, fabric direction, cut off level, and charge polarity, as well as all two-way and most three-way interaction effects; there was no significant three-way interaction among fabric, cut off level, and charge polarity. There were no four-way interaction effects.

Mean peak potentials for each test method for each unilayer fabric are plotted in Figure 3. Although the three-way ANOVA found interaction effects, these data are plotted for the mean of warp and weft directions for Tests No.1 and No.2, and for the mean of warp, weft, positive and negative applied charge in the case of Test No.3. Although the magnitude

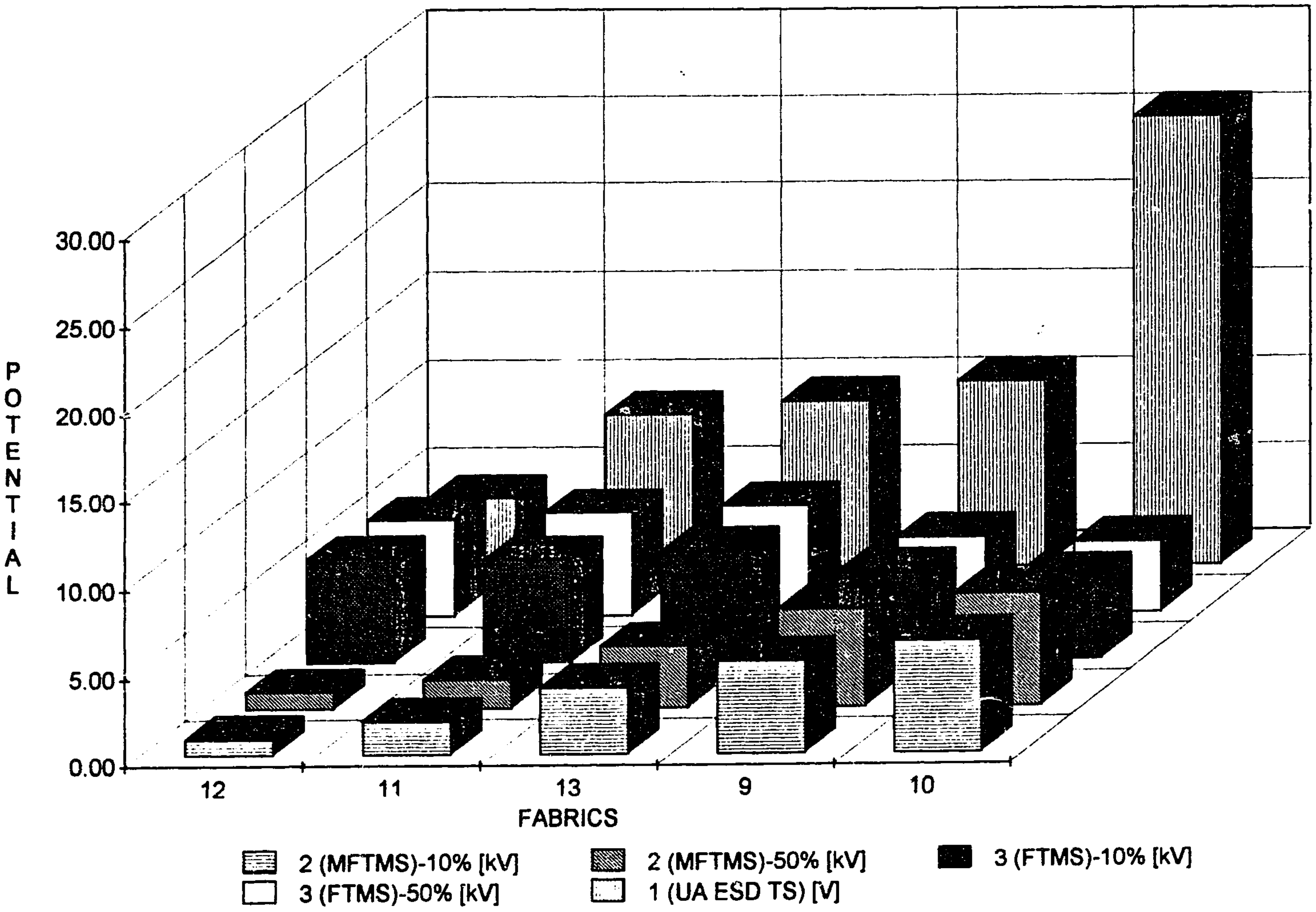

Figure 3. Peak discharge potentials for unilayer fabrics by test method

differed, with very few exceptions the same trend in direction was observed for warp and weft, and for positive and negative applied charge.

Results of the one-way ANOVA and Duncan's multiple range test, which are summarized in Table 3, generally suggest that for peak potential, most fabrics differed significantly ($p<.05$) from each other, but there were some homogeneous subsets in all but Test No.2.

Charge Decay Time

> Ho_2: "There will be no significant differences in charge decay time among different fabrics".

Three-way analysis of variance (Appendix B1) found significant main effects of fabric system and test method on **decay time**, as well as two-way interaction effects of test method by fabric system and three-way interaction effects, indicating that there were significant differences in this parameter among fabrics, but the effects differed according to test method. Therefore, the null hypothesis was rejected at 0.05 significance level. There was no main effect of fabric direction. There were no significant two-way interactions between fabric direction and either test method or fabric.

Separate multivariate ANOVA's were performed on data from each charge decay test. Three-way ANOVA on data from Test No.2 (MFTMS) showed significant main effects of fabric system, fabric direction, and cut off level as well as two- and three-way interaction effects (Appendix B3). Four-way ANOVA on data from Test No.3 (FTMS) found significant main effects of fabric system, fabric direction, cut off level, and charge polarity (Appendix B4). Two-way interactions between fabric system and fabric direction, fabric system and cut off level, and fabric direction and cut off level were significant. Similarly, three-way interactions among fabric system, fabric direction and cut off level, and among fabric direction, cut off level and charge polarity were significant . There were no four-way interaction effects.

Mean charge decay times for each test method for each unilayer fabric are plotted in Figure 4. Although the multivariate ANOVA's found interaction effects these data are plotted for the mean of warp and weft directions in Test No.2, and for the mean of warp and weft, and positive and negative applied charge in the case of the Test No.3, because the

Table 3. Analysis of variance: Peak potentials and decay times by test method and fabric for unilayer specimens.

FABRIC SYSTEM		TEST METHODS									
CODE	CONTENTS	1 (UA ESD TS)		2 (MFTMS191A)				3 (FTMS191A)			
				10% CUT OFF		50% CUT OFF		10% CUT OFF		50% CUT OFF	
		Peak Potentials (V or kV)									
		MEAN (V)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.
12	Aramid/PBI	4.07a	0.90	0.93a	0.46	0.98a	0.51	5.85c	0.30	5.45c	0.29
11	Aramid/carbon	8.84b	3.84	1.89b	0.58	1.67b	0.81	5.79c	0.16	5.85d	0.19
13	Aramid/FR viscose	9.57b	3.86	3.81c	0.85	3.52c	0.47	6.26d	0.19	6.21e	0.11
09	100% cotton	10.67b	3.52	5.27d	0.55	5.54d	0.95	4.99b	0.36	4.34b	0.24
10	FR cotton	25.71c	7.46	6.40e	0.04	6.41e	0.12	4.64a	0.27	4.02a	0.20
		Decay Times (s)									
				MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.
11	Aramid/carbon	N/A		>300e	0.00	>300e	0.00	0.01a	0.00	0.01a	0.00
13	Aramid/FR viscose			39.61a	4.80	3.54a	0.73	7.12b	1.35	2.27c	0.62
12	Aramid/PBI			99.40b	11.44	9.94b	3.05	23.21c	5.36	2.29c	1.20
09	100% cotton			202.62c	36.83	20.20c	7.85	43.44d	8.92	0.41b	0.27
10	FR cotton			469.05d	132.59	29.92d	12.72	47.05e	5.88	0.12a	0.19

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

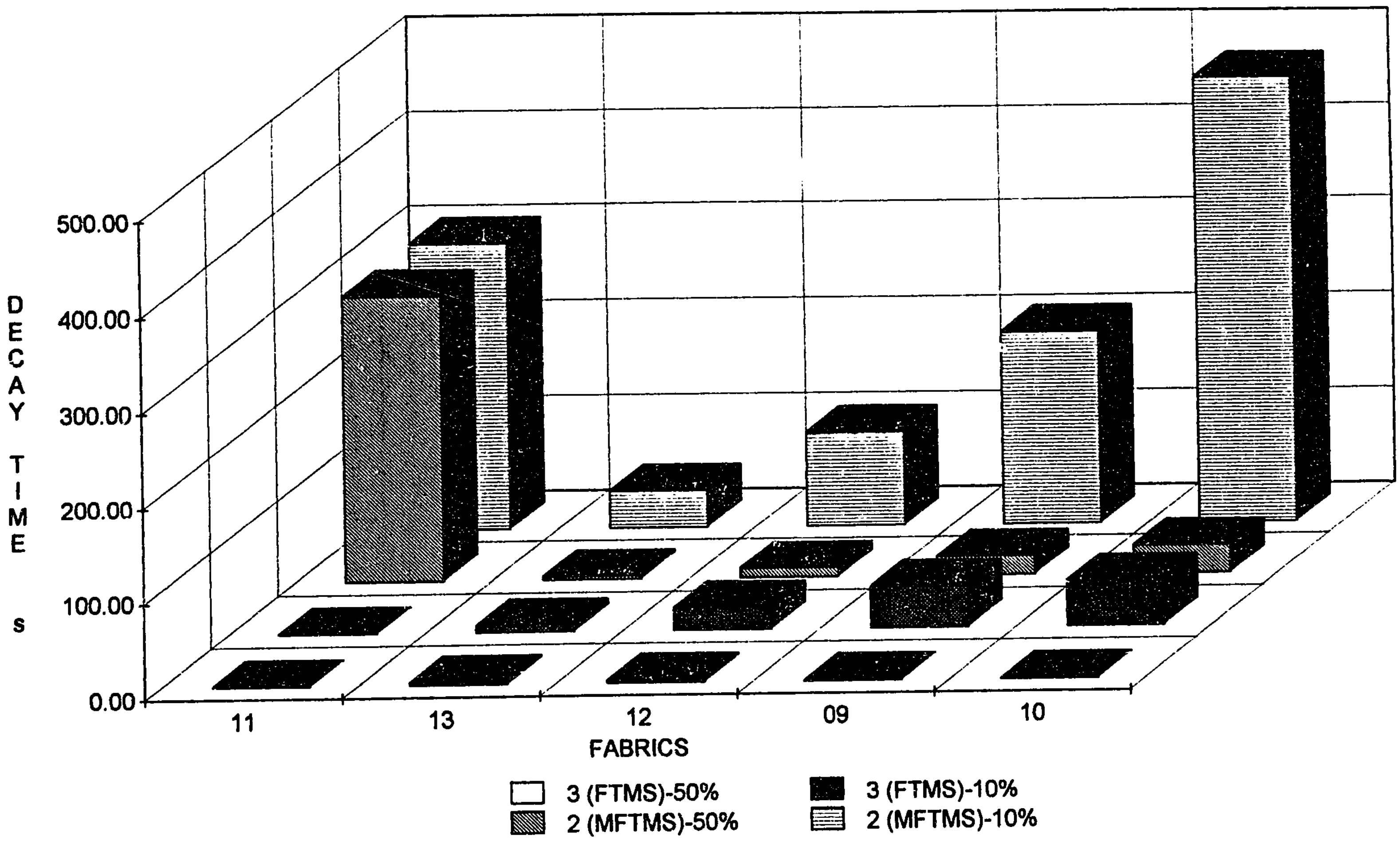

Figure 4. Charge decay times for unilayer fabrics by test method

same trend in direction was observed for each test with very few exceptions, although the magnitude differed.

Results of the one-way analysis of variance and Duncan's multiple range test, which are summarized in Table 3, revealed significant differences among fabrics in all tests, but in Test No.3 at 50% cut off there were some homogeneous subsets. It should be noted that the aramid/carbon fabric showed the slowest charge decay when charged by friction, although it had the fastest charge decay when tested by test No.3, where it was charged by induction.

Correlation between Potential and Decay Time

> Ho_3: "There will be no significant correlation between peak discharge potentials and charge decay rates obtained by small-scale laboratory tests".

Pearson's correlation analyses (Tables 4, 5, and 6) were used to test the null hypotheses of no correlation among various tests for peak potential and charge decay time. Three different correlation analyses were performed. One analysis (Table 4) correlated peak potentials obtained by the three tests; a second analysis (Table 5) correlated decay times from two of the tests; and a third analysis (Table 6) correlated peak potentials with decay times among different test methods. Values for both fabric directions and both charge polarities were considered together when applicable.

All correlations in Tables 4 and 5 and all but two in Table 6 were significant at $p < .05$. From the tables above, it can be seen that peak potentials were more highly correlated among the test methods (Table 4) than were decay times (Table 5). The highest correlation of peak potential was between Test No.2 at 10% and Test No.2 at 50% cut off, confirming the ANOVA results which showed no effects of cut-off levels. Also, high correlations were obtained between Tests No.1 and No.2 at each of 10% and 50% cut off level, as both methods similarly charge the specimen by friction. For decay time (Table 5), the highest correlations between tests No.2 and No.3 were negative, although there was a low but significant positive correlation between the two tests at 10% cut off level.

Table 4. Correlation (R) of peak potentials among test methods : Unilayer specimens

TEST METHODS	1 (UA ESD)^a	2(MFTMS)^b-10%	2(MFTMS)-50%	3(FTMS)^c-10%
2(MFTMS)-10%	.7958			
2(MFTMS)-50%	.7860	.9773		
3(FTMS)-10%	-.7046	-.7271	-.7634	
3(FTMS)-50%	-.6558	-.6558	-.7169	-.7665

[a] University of Alberta ESD Test System
[b] Modified Federal Test Method Standard 191A, method 5931
[c] Federal Test Method Standard 191A, method 5931

Table 5. Correlation (R) of decay times among test methods

TEST METHODS	2(MFTMS)^b-10%	2(MFTMS)-50%	3(FTMS)^c-10%
2(MFTMS)-50%	.3275		
3(FTMS)-10%	.4572	-.5755	
3(FTMS)-50%	-.8053	-.5195	-.2792

Table 6. Correlation (R) between peak potentials and decay times from different test methods.

POTENTIAL TEST METHODS	DECAY TIME TEST METHODS 2(MFTMS)^b-10%	2(MFTMS)-50%	3(FTMS)^c-10%	3(FTMS)^c-50%
1 (UA ESD	.7988	-.1312	.5661	-.5135
2(MFTMS)-10%	.5196	-.3773	.7047	-.4553
2(MFTMS)-50%	.5170	-.4031	.7566	-.4436
3(FTMS)-10%	-.7762	.1596	-.8856	.6247
3(FTMS)-50%	-.6701	.3230	-.9567	.5164

When peak potentials and decay times were correlated with each other (Table 6), peak potentials from tests that charge the specimen by friction (No.1 and 2) showed positive correlation with decay times at 10% cut off level, and negative correlation with decay times at 50% cut off. Peak potentials from Test No.3 (charging by induction) revealed negative correlation with decay times at 10% cut off, and positive correlation at 50% cut off level.

Multilayer Specimens

Peak Discharge Potential

Ho_1: "There will be no significant differences in peak discharge potential among different fabric systems".

Three-way ANOVA (Appendix B5) found significant main effects of fabric system, test method, and fabric direction as well as both two-way and three-way interaction effects on **peak discharge potential**, indicating that there were significant differences in this parameter among fabric systems, but these effects differed to some extent by test method and by fabric direction. Thus, the null hypothesis was rejected.

Separate multivariate ANOVA's were also performed on data from each test method. Two-way ANOVA on Test No.1 (UA ESD TS) found significant main effects of fabric system and fabric direction as well as a two-way interaction effects (Appendix B6). Three-way ANOVA of data from Test No.2 (MFTMS) showed significant main effects of fabric system and cut off level only, but two- and three-way interaction effects of fabric system, fabric direction and cut off level (Appendix B7). Four-way ANOVA of data from Test No.3 found significant main effects of fabric system, fabric direction, cut off level, and charge polarity, as well some two-, three- and four-way interaction effects (Appendix B8) All two-way interactions were significant except those between fabric direction and both cut off level, and charge polarity. Also, most of the three-way interactions were significant except for that among fabric system, fabric direction and charge polarity.

Mean peak potentials for each test method and fabric system are plotted in Figure 5. Although the multivariate ANOVA's found interaction effects these data are plotted for the mean of warp and weft directions for Tests No.1 and 2, and for the mean of warp and weft, and positive and negative applied charge in the case of Test No.3. A similar trend in direction was observed for warp and weft, and for positive and negative applied charge with very few exceptions, although the magnitude differed.

Results of the one-way ANOVA and Duncan's multiple range test (Table 7) for peak potential suggest that the fabric systems generally can be grouped according to the outer layer; therefore they have been grouped in that way in Table 7 and in Figure 5.

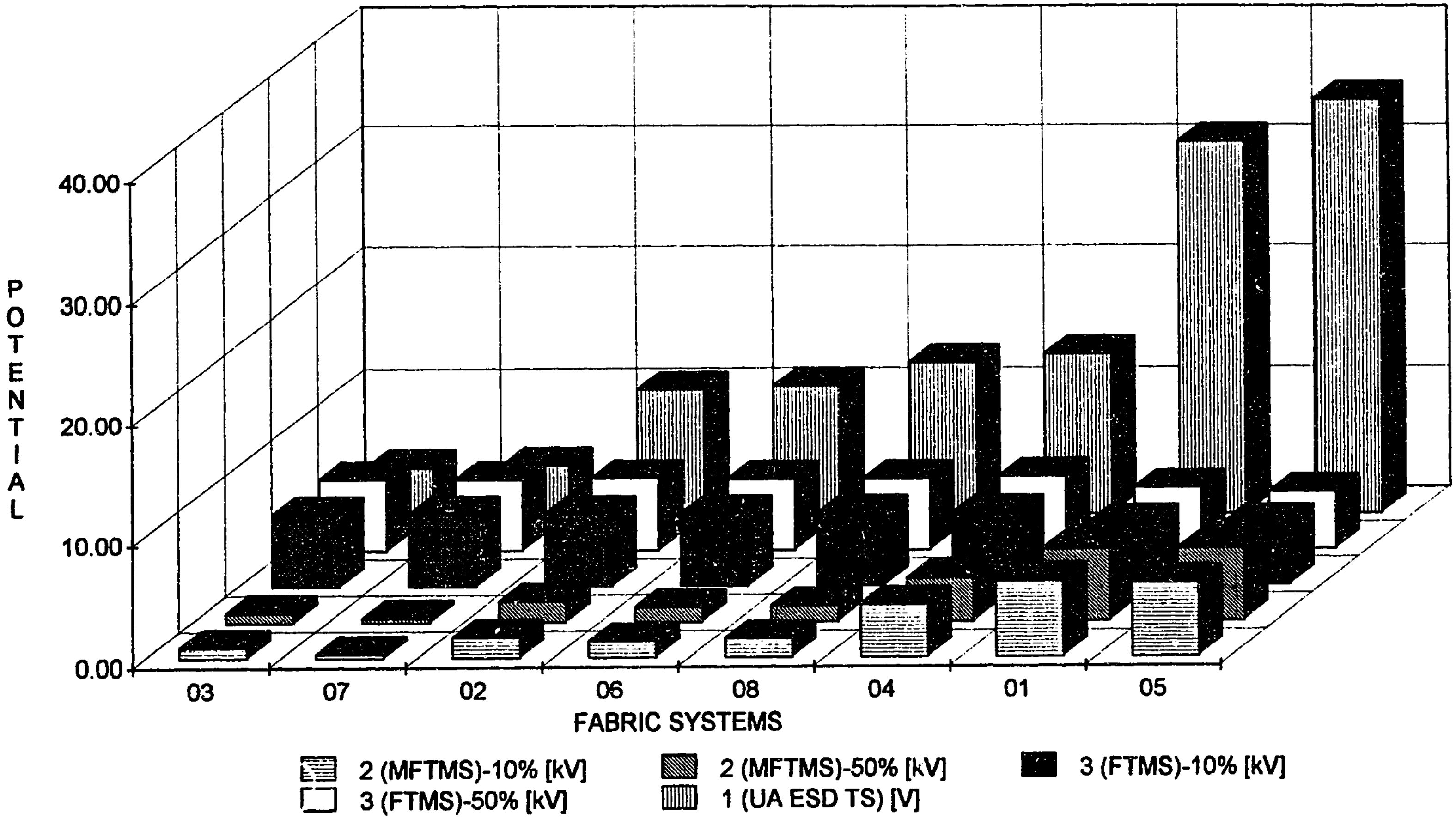

Figure 5. Peak discharge potentials for multilayer fabric systems by test method

Table 7. Analysis of Variance: Mean potentials and decay times with their standard deviations by fabric system for multilayer specimens.

FABRIC SYSTEM		TEST METHODS									
CODE	CONTENTS (OUTER - INNER)	1 (UA ESD TS)		2 (MFTMS191A)				3 (FTMS191A)			
				10% CUT OFF		50% CUT OFF		10% CUT OFF		50% CUT OFF	
		Peak Potentials (V or kV)									
		MEAN (V)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.	MEAN (kV)	STD.DEV.
03	Aramid/PBI-100% cotton	4.03a	1.07	0.91b	0.44	0.82b	0.31	6.00b	0.00	5.97c	0.25
07	Aramid/PBI-Aramid/carbon	4.20a	1.43	0.34a	0.17	0.36a	0.12	6.00b	0.00	5.94c	0.08
02	Aramid/carbon-100% cotton	10.47b	4.75	1.72d	0.72	1.70d	0.60	6.00b	0.00	6.05c	0.13
06	Aramid/carbon-Aramid/carbon	10.72b	6.16	1.36c	0.39	1.20c	0.36	6.00b	0.00	5.95c	0.11
08	Aramid/FR viscose-Aramid/carbon	12.64b	5.58	1.57c,d	0.39	1.29c	0.35	6.00b	0.00	5.94c	0.09
04	Aramid/FR viscose-100% cotton	13.34b	6.03	4.34e	0.86	3.54e	0.70	6.00b	0.00	6.12c	0.20
01	FR cotton-100% cotton	30.83c	6.35	6.25f	0.29	5.92f	0.63	5.12a	0.94	5.13b	0.63
05	FR cotton-FR cotton	34.37d	7.95	6.05f	0.42	5.93f	0.67	5.11a	1.00	4.74a	0.82
		Decay Times (s)									
				MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.	MEAN (s)	STD.DEV.
06	Aramid/carbon-Aramid/carbon	N/A		>300e	0.00	206.95c	97.55	0.008a	0.00	0.006a	0.00
07	Aramid/PBI-Aramid/carbon			121.54c	20.92	54.27b	20.57	0.009a	0.00	0.005a	0.01
08	Aramid/FR viscose-Aramid/carbon			>300e	0.00	74.17b	29.24	0.199a	0.59	0.007a	0.00
02	Aramid/carbon-100% cotton			>300e	0.00	57.81b	12.82	1.489a	1.18	0.007a	0.00
04	Aramid/FR viscose-100% cotton			45.86a	5.68	4.20a	0.66	15.191b	6.93	1.939a	0.69
03	Aramid/PBI-100% cotton			86.58b	28.15	11.73a	4.97	17.526b	3.14	0.333a	0.60
05	FR cotton-FR cotton			233.79d	76.63	13.03a	4.15	42.969c	16.92	10.266b	17.11
01	FR cotton-100% cotton			241.18d	62.93	12.13a	5.22	44.559c	16.71	1.454a	0.88

a,b,etc. In each column, means with the same letter indiacte homogeneous subsets (highest and lowest means are not significantly different) when subjected to Duncan's multiple range test ($p<.05$).

When means were analyzed, Tests No.1 and 2 showed similar trends in grouping systems together. Also, it was observed that non-FR 100% cotton as inner layer yielded lower discharge potentials than aramid/carbon except in combination with aramid/FR viscose as an outer layer.

Charge Decay Time

Ho_3: "There will be no significant differences in charge decay time among different fabric systems".

Four-way analysis of variance found significant main effects of fabric system, test method, fabric direction, and cut off level, on **charge decay time** (Appendix B5). All two-way, three-way and four-way interaction effects were significant except there was no significant three-way interaction effect among fabric direction, test method, and cut off level.

Separate multivariate ANOVA's were then performed on data from each test method. Three-way ANOVA on data from Test No.2 revealed significant main effects of fabric system, fabric direction, and cut off level, and all two-way and three-way interaction effects were significant (Appendix B7). Four-way ANOVA on Test No.3 found significant main effects of fabric system, fabric direction, cut off level, and charge polarity (Appendix B8). Most two-way, three- and four-way interaction effects were significant except there were no two-way interaction effects between fabric direction and charge polarity, or between cut off level and charge polarity.

Mean decay times for each test method and fabric system are plotted in Figure 6. Although the multivariate ANOVA's found interaction effects these data are plotted for the mean of warp and weft directions for Test No.2, and for the mean of warp and weft, and positive and negative applied charge for Test No.3, because a similar trend was found for each test with very few exceptions.

From the one-way ANOVA and Duncan's multiple range test (Table 7), it can be seen that fabric systems could be clustered by the inner layer, those systems with aramid/carbon having lower decay times than those systems with cotton inner layers.

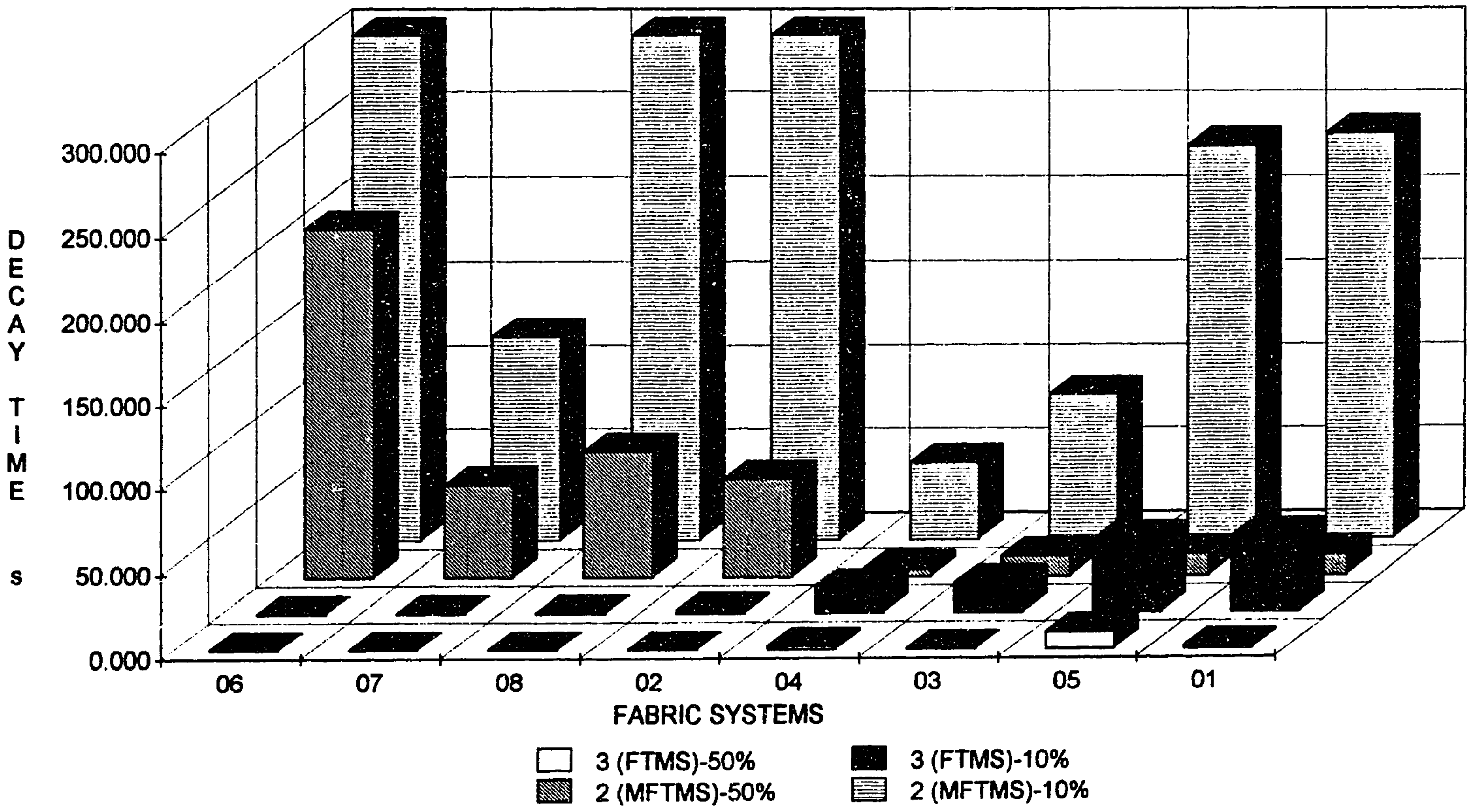

Figure 6. Charge decay times for multilayer fabric systems by test method

Correlation Between Potential and Decay Time

Ho_3: "There will be no significant correlation between peak discharge potentials and charge decay times obtained by small-scale laboratory tests".

Pearson's correlation analyses were performed to test this null hypotheses. Three different correlation analyses were performed. One analysis (Table 8) correlated peak potentials from the five different tests, a second analysis (Table 9) correlated decay times, and a third one (Table 10) correlated peak potentials with decay times for all test methods. Values for both fabric directions and both charge polarities were considered together. All correlations in Tables 8 and 9, and all but two in Table 10 were significant. Thus, null hypothesis 3 was rejected.

As in the case of the unilayer experiments, peak potentials were more highly correlated among the tests than were decay times. The highest correlation of peak potentials (Table 8) was between Test No.2 at 10% and Test No.2 at 50% cut off levels. Also, high correlations were obtained between Test No.1 and Test No.2 at both 10% and 50% cut off, as both methods similarly charge the specimen by friction.

Table 8. Correlation (R) of peak potentials among test methods: multilayer specimens.

TEST METHODS	1 (UA ESD)[a]	2(MFTMS)[b]-10%	2(MFTMS)-50%	3(FTMS)[c]-10%
2(MFTMS)-10%	.8943			
2(MFTMS)-50%	.9369	.9618		
3(FTMS)-10%	-.8665	-.7812	-.8708	
3(FTMS)-50%	-.8847	-.7200	-.8305	.8730

[a] University of Alberta ESD Test System
[b] Modified Federal Test method Standard 191A, method 5931
[c] Federal Test Method Standard 191A, method 5931

Table 9. Correlation (R) of decay times among test methods

TEST METHODS	2(MFTMS)^{b}-10%	2(MFTMS)-50%	3(FTMS)^{c}-10%
2(MFTMS)-50%	.5478		
3(FTMS)-10%	-.0925	-.5710	
3(FTMS)-50%	.0104	-.3529	.6748

Table 10. Correlation (R) between peak potentials and decay times from different test methods.

POTENTIAL TEST METHODS	DECAY TIME TEST METHODS			
	2(MFTMS)^{b}-10%	2(MFTMS)-50%	3(FTMS)^{c}-10%	3(FTMS)^{c}-50%
1 (UA ESD)	.2993	-.2979	.8407	.7472
2(MFTMS)-10%	.0317	-.4409	.8428	.6740
2(MFTMS)-50%	.0697	-.4758	.9252	.7045
3(FTMS)-10%	-.1923	.3577	-.8846	-.6377
3(FTMS)-50%	-.2311	.3015	-.8318	-.8035

For decay time (Table 9), the correlation between Tests No.2 and 3 was negative, but was positive between the two cut-off levels for the same test. When potentials and decay times were correlated with each other (Table 10), peak potentials from tests that charge the specimen by friction (Tests No.1 and 2) showed negative correlation with decay times of Test No.2 at 50% cut off; but positive correlations with other decay time measurements. Peak potentials from Test No.3 (charging by induction) revealed positive correlation with decay times of Test No.2 at 50% cut off; but negative correlations with other decay time measurements. Correlations among decay times were up to 43% less than those obtained for peak potentials

Correlation Between Small-Scale and Human-Body Data

> Ho$_4$: "There will be no significant correlation between the peak discharge potentials and charge decay times measured by the small-scale laboratory tests and those potentials obtained in human-body experiments".

To test this null hypothesis Pearson's correlation analysis (Table 11) correlated both peak potentials and decay times from all the tests with human-body discharge potentials. All correlations were significant; therefore null hypothesis 4 was rejected.

Table 11. Correlations between human-body discharge potentials and both peak potentials and decay times measured by small-scale tests.

TEST	POTENTIAL	DECAY TIME
1 (UA ESD)	.9692	N/A
2(MFTMS)-10%	.8953	.2216
2(MFTMS)-50%	.9462	-.4183
3(FTMS)-10%	-.8802	.8716
3(FTMS)-50%	-.8847	.7544

From Table 11, it seems that peak potentials correlated better than decay times with human-body discharge potentials. The highest correlations are for tests that charge a specimen by friction as happens during the human-body experiment. The highest correlation between a decay time test and the human-body data (R = .87) was for Test No.3 which charges the specimen by induction at 10% cut off.

Building a Testing Model

In order to determine the best laboratory test protocol, various models for predicting the static propensity of clothing systems were developed through multiple linear regression analyses of potential and decay time data obtained from small-scale tests on potential data from human-body experiments. Table 12 shows the coefficients of correlation (R) and determination (R^2) as well as the R^2 adjusted for population. The highest coefficient of determination (R^2 = .97) was obtained when both peak potentials and decay times from all three tests were regressed with human-body data (regression #1). An equally high R^2 was obtained when only Test No.1 and Test No.2 at 50% cut-off were included (regressions #2 and #3). Also, peak potentials of Tests No.1 and 2 and decay times from Test No.3 regressed with human-body potentials gave R^2 of .95 (regression #4).

In terms of single tests, the UA ESD Test System, the modified Federal Test Method Standard 191A at 10% and 50% cut off, and the Federal Test Method Standard 191A at 10% and 50% cut off had coefficients of determination of .94, .80, .90, .76, and .57, respectively.(regressions #9, 14, 12, 17, and 18).

Table 12. Coefficients of determination R Sq. among different laboratory test methods and human-body data

REGRESSION No.	TEST METHOD	VARIABLE	MULTIPLE R	R SQUARE	ADJUSTED* R SQUARE
1	1 (UA ESD TS)	potential	0.98	0.97	0.96
	2 (MFTMS)-10%	potential decay time			
	2 (MFTMS)-50%	potential decay time			
	3 (FTMS)-10%	potential decay time			
	3 (FTMS)-50%	potential decay time			
2	1 (UA ESD TS)	potential	0.98	0.96	0.96
	2 (MFTMS)-50%	potential decay time			
3	1 (UA ESD TS)	potential	0.98	0.96	0.96
	2 (MFTMS)-50%	decay time			
4	1 (UA ESD TS)	potential	0.98	0.95	0.95
	2 (MFTMS)-10%	potential			
	2 (MFTMS)-50%	potential			
	3 (FTMS)-10%	decay time			
	3 (FTMS)-50%	decay time			
5	1 (UA ESD TS)	potential	0.98	0.95	0.95
	3 (FTMS)-10%	potential decay time			
6	1 (UA ESD TS)	potential	0.97	0.95	0.95
	3 (FTMS)-10%	decay time			
7	1 (UA ESD TS)	potential	0.97	0.95	0.94
	2 (MFTMS)-10%	potential decay time			
8	1 (UA ESD TS)	potential	0.97	0.94	0.94
	2 (MFTMS)-10%	decay time			
9	1 (UA ESD TS)	potential	0.97	0.94	0.94
10	2 (MFTMS)-50%	potential decay time	0.96	0.91	0.91
	3 (FTMS)-10%	potential decay time			

* R Square adjusted to population

Table 12. Coefficients of determination R Sq. among different laboratory test methods and human-body data (cont.)

REGRESSION No.	TEST METHOD	VARIABLE	MULTIPLE R	R SQUARE	ADJUSTED* R SQUARE
11	2 (MFTMS)-50% 3 (FTMS)-10%	potential decay time	0.95	0.90	0.89
12	2 (MFTMS)-50%	potential	0.95	0.90	0.89
13	2 (MFTMS)-10% 3 (FTMS)-10%	potential decay time	0.92	0.85	0.84
14	2 (MFTMS)-10%	potential	0.91	0.80	0.80
15	3 (FTMS)-50%	potential	0.88	0.78	0.78
16	3 (FTMS)-10%	potential	0.88	0.77	0.77
17	3 (FTMS)-10%	decay time	0.87	0.76	0.76
18	3 (FTMS)-50%	decay time	0.75	0.57	0.56
19	2 (MFTMS)-50%	decay time	0.42	0.17	0.16
20	2 (MFTMS)-10%	decay time	0.22	0.05	0.04

* R Square adjusted to population

Chapter 5

Discussion

This research was part of a larger project to study the problem of electrostatic propensity in protective clothing systems. The main purpose was to determine appropriate small-scale laboratory tests to predict the static propensity of protective garment systems.

Known and new test methods were used to meet the main objective of the present research. Tests were conducted using single layer specimens to measure their electrostatic characteristics for further development of mathematical models. Multilayer specimen tests simulated the configuration of clothing systems worn in human body experiments which comprised an earlier project. Thus, data collected in small-scale tests could be compared to those obtained in human-body experiments to find any relationship between small-scale and human-body experiments.

Objective 1

The first objective was to develop new methods for the measurement of the electrostatic characteristics of fabric systems. One device was entirely developed by the researcher, and another one was modified from a standard method. The former was intended to resemble the phenomenon of electrostatic discharges experienced on a clothed human body, measuring potential and energy from those discharges. The latter was to measure peak potential and charge decay rate from a specimen charged by friction.

The University of Alberta ESD Test System (Test No.1) was built and employed to simulate generation of charge by triboelectrification and can measure electrostatic discharges from layered fabric systems. The new device contains the same elements involved in a clothed-human-body electrostatic discharge. An outer fabric is charged by friction which generates a charge that is transferred onto the inner fabric. This inner fabric transfers that generated charge onto a conducting plate. Then, the charge is conducted to, and stored in a capacitor, from which it is discharged through a resistor to the oscilloscope. The 2-layer fabric system represents a garment system comprising both outer and inner garments such as a coverall and shirt. The capacitor and resistor represent the average capacitance and resistance of a human body. The action of the switch represents the instant when a charged human body touches a grounded object resulting in a discharge.

The Federal Test Method Standard 191A, method 5931 and a static decay meter from Electronic-Tech Systems were modified in order to develop Test No.2. A Pasco roller covered with vinyl was added for frictional charging. Since triboelectrification is responsible for most practical static problems (Wilson, 1987), the main goal in building this device was to measure potential and decay time from charges generated by frictional work, charging the outer layer and measuring those charges from the inner layer, as it is the path of charge flow in real life conditions. Test No.3 used the method and device mentioned above without any modification.

Both new methods and devices were successfully tested, as these two tests showed good reliability and accuracy in testing as well as high correlation with human-body discharge potentials.

Objective 2

The second objective was to measure peak discharge potential of static discharges from fabric systems following the new and existing methods and to determine differences in potential among the various fabric systems. This objective was accomplished through the three tests utilized, with both unilayer and multilayer specimens.

Three-way analysis of variance (ANOVA) tested null hypothesis 1, and found significant differences among fabric systems, both unilayer and multilayer specimens, but those differences were affected by test method and fabric direction. Thus, it can be expected that different test methods yield different peak discharge potentials, and testing both directions (warp and weft) is important to obtaining reliable results.

One-way ANOVA found that peak potentials for different single layer fabrics differed significantly and did not form homogeneous subsets in most cases, suggesting that each fabric could be characterized in terms of peak discharge potential with specific values. The multilayer analysis showed that some fabric systems were not significantly different from each other, with various homogeneous subsets, suggesting that variation of the outer layer in a fabric combination seems to have the greatest effect in the magnitude of the discharge potential, and variation of the inner layer in the system has a lesser effect.

Similar trends in direction of peak potentials among fabric systems were observed in Test No.1 and Test No.2, at both 10% and 50% cut off, testing both unilayer and multilayer specimens, and those were in agreement with the one observed in the human-body experiment. Thus, it seems that protective fabrics have consistent patterns in terms of discharge potentials when specimens are charged by friction.

Objective 3

The third objective was to measure the charge decay time for the surface charge on fabric systems, and to determine differences in those decay times. This objective was successfully achieved.

Three-way ANOVA in the case of unilayer specimens and four-way ANOVA in the case of multilayer specimens tested null hypothesis 2. The first analysis found that fabrics differed significantly but those differences were affected by test method and cut off level. The second analysis showed that fabric systems were different, and those effects were influenced by test method, fabric direction and cut off level. Thus, it can be foreseen that for different test methods and cut off levels charge decay time will differ, and that testing both directions (warp and weft) is important to obtaining reliable results in the case of multilayer specimens.

One-way ANOVA found that charge decay times for various single-layer fabrics were significantly different and in all cases except Test No.3 at 50% cut off, did not form homogeneous subsets, confirming that each fabric could be characterized with specific values in terms of both decay time and peak potential . Although this analysis showed that some multilayer fabric systems were not significantly different, and various homogeneous subsets could be formed, results suggested that variation of both the outer and the inner layer in a fabric system seems to affect greatly the magnitude of the charge decay time.

The differences in decay times for Tests No.2 and 3 could be explained in terms of the type of charging method: triboelectrification of a specimens applies a friction force that removes more valence electrons, and therefore, the specimen takes more time to neutralize any unbalanced electronic configuration. On the other hand, induction charging applies a high potential charge that is supposed to flow across the specimen from an electrode due to its intrinsic conductive characteristics. But this procedure does not ensure reliable charging of any relatively insulating feature, which is where the charge is likely to be retained-(Chubb, 1988).

A phenomenon was observed in Table 6 where correlations between decay times at 10% and 50% cut off levels and both potentials from tribocharging and potentials from induction charging had opposite trends. This could be explained in terms of changes in decay rates for antistatic and non-antistatic fabrics during the discharge. It seems that non-antistatic fabrics (for example, FR cotton) have faster initial charge dissipation than antistatic fabrics (for example, aramid/PBI), but they take more time to decay to 10% of the applied charge. In the case of potentials from tribocharging, it is expected that antistatic fabrics yield lower potentials and decay times than regular fabrics, as is supported by the positive correlation between potentials and decay times at 10% cut off.

Objective 4

Objective 4 was to compare and evaluate the three test methods used during the research. That comparison and evaluation was achieved in terms of the consistency and accuracy of the results obtained in this study as well as the trends in direction and clustering showed by fabrics and fabric systems in each test method.

Table 13 shows mean coefficients of variation calculated for data from the three test methods. Measurements of peak potential yielded similar coefficients of variations for both unilayer and multilayer specimens, while decay times for unilayer specimens showed lower coefficients of variation than multilayer specimens, except Test No.2 at 10% cut off. This suggests that measuring peak potential for multilayer specimens gives as reliable results as do unilayer specimens. This is not true for decay time measurements which seem to be more accurate for single layered fabrics than for multilayer fabric systems.

Table 13. Mean coefficients of variation (CV%) in peak potential and decay time for different test methods.

TEST METHOD	PEAK POTENTIAL		DECAY TIME	
	UNILAYER	MULTILAYER	UNILAYER	MULTILAYER
1 (UA ESD TS).	33.6	37.1	N/A	
2 (MFTMS)-10%	22.5	24.4	14.0	15.1
2 (MFTMS)-50%	26.9	29.4	20.5	34.9
3 (FTMS)-10%	3.8	4.5	15.0	64.5
3 (FTMS)-50%	4.9	5.7	60.8	80.4

Results and statistical analyses (one-way ANOVA, correlation, and linear regression) on Test No.1 (UA ESD Test System) showed that measurements taken by this system are reliable and accurate to some extent. The peak potential results showed high correlation with potentials measured by the other two tests, and had the highest coefficient of determination (R^2), as a single test method, when regressed with human-body discharge potentials. It is important to note that discharge energy could be measured and evaluated only with the UA ESD Test System, since this parameter was easily calculated from the discharge waveform obtained by the oscilloscope. Those results were found to have a high relationship with human-body discharge energy and are shown in Appendix C1.

Results and statistical analyses on Test No.2 (modified Federal Standard Test 191A method 5931) showed that peak potential measurements taken by this test were accurate and reliable for both unilayer and multilayer specimens, since they had low variation, and were in agreement with those observed in the human-body experiment. But decay time measurements had poor correlation with measurements taken by other small-scale tests and with human-body data.

Results and statistical analyses for Test No.3 (Federal Standard Test 191A method 5931) showed poor outcome for peak potential since the method failed to differentiate various fabric systems in terms of this parameter and these results were not in agreement with human-body potentials. Decay time measurements taken at 10% cut off showed somewhat similar trend to those observed for potentials from the other two tests, and yielded a good correlation with data from human-body experiments. The main purpose of this test method is to measure decay time of the induced charges, and usually 10% cut off is recommended.

Objective 5

The fifth objective was to study the relationship between charge decay rate and peak discharge potentials for different fabric systems as measured by small-scale tests. Null hypothesis 3 was tested using Pearson's correlation coefficient, and this hypothesis was rejected since most of the correlations were significant.

Correlation of peak potentials among test methods confirmed that potentials from triboelectrification show similar trends. Also, it was confirmed that measurements from tribocharging and induction show opposite trends, suggesting that each charging process uses a different mechanism to generate, build up, and/or transfer a charge. Likewise, poor correlation of decay times among test methods suggested that different charge decay times can be expected when charging the specimen by friction or by induction.

When peak potentials and decay times were correlated, potentials from tests which charge by friction (No.1 and No.2 at both 10% and 50% cut off) have high and positive relationship with decay times from Test No.3 where specimens are charged by induction. This can be explained, since the charging process and subsequent discharge potential of the first two methods depend on the conductivity of the specimen, as does the decay time for Test No.3.

Objective 6

Objective 6 was to study the relationship between data from small-scale tests (multilayer specimens) and that from human-body experiments. Pearson's correlation coefficients were used to determine any such relationship. No attempt was made to correlate the experimental data from unilayer small-scale and human-body experiment since the configuration of the specimens and garment systems differed from each other. Multiple linear regression was used to propose a laboratory protocol that can accurately and reliably predict the electrostatic propensity of garment systems.

One of the main concerns was to determine if peak discharge potential or charge decay time, or both, from different test methods could best predict the electrostatic propensity of garment systems, and specifically of protective garments. Correlation analysis showed that potentials from Tests No.1 and 2 and decay times from Test No.3 had the highest correlations with human-body discharge potentials, supporting what was stated previously about the relationship among potential from tribocharging, decay time from induction, and the intrinsic conductive characteristics of a textile surface.

A test protocol was suggested from different testing models built with the help of multiple linear regressions. According to preliminary analysis, a linear relationship was determined for small-scale and human-body data (Figure 7, and Appendices C2 and C3). A test battery was chosen not only because of its high coefficient of determination (R^2) but also because it had the best relationship between the small-scale tests and the human-body experiment.

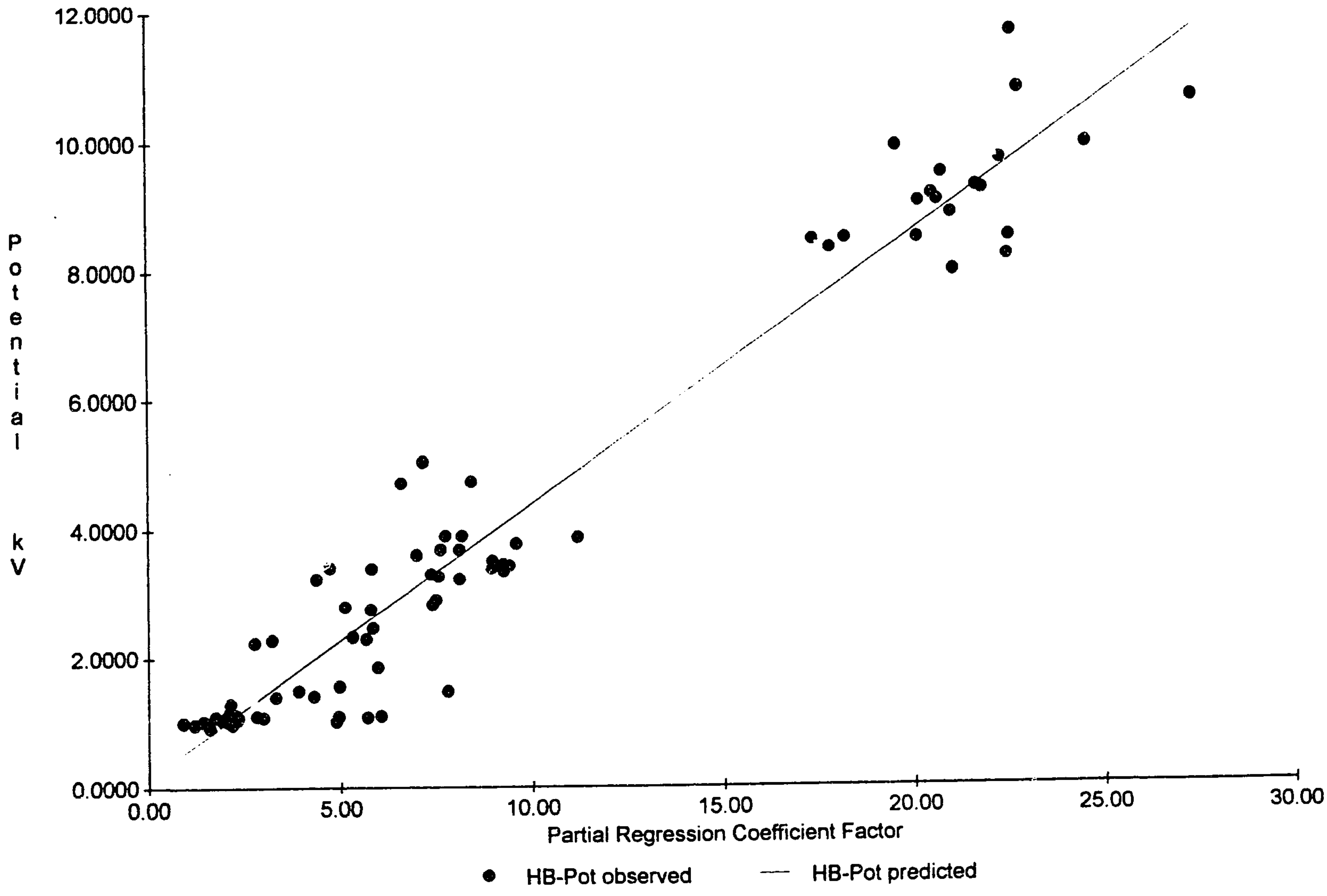

Figure 7. Linear relationship between Test Battery 1 and human-body experiment

Although combinations of the three methods (potentials and decay times) had the highest coefficients of determination (R^2) when regressed with human-body potentials they were considered impractical test protocols since they involve the use of three different methods and devices. A combination of peak discharge potential as measured by the UA ESD Test System (Test No.1) , and potential and charge decay time as measured by the modified Federal Standard Test 191A Method No.5931 (test No.2 at 50% cut off) was chosen and named Test Battery 1. This protocol was selected because its R^2 of .96 was the highest among the different models built, both independent variables were significant, the constant (y-intercept) and the two independent variables had high eigenvalues to the same level, and the tolerance of the three independent variables was very small (Appendix B9).

Norusis (1992) stated that if a high proportion of the variance of two or more coefficients is associated with the same eigenvalue, there is evidence for a near-dependency among the variables. Also, this author mentioned that if the tolerance of a variable, which is a commonly used measure of collinearity, is small, it is almost a linear combination of the other independent variable(s).

Different plots were obtained to confirm the assumption of linear relationship: standardized residuals vs. standardized predicted values, histogram of standardized residuals, normal probability (P-P plot), and actual vs. predicted values (see Appendixes C4, C5, and C6).

A second test battery chosen because of its high values of R^2 (.95), was the combination of peak potential measured by the UA ESD Test System , and decay time measured by the Federal Standard Test 191A Method 5931 (named Test Battery 2). As in the test battery 1, all the assumptions were validated with the help of the collinearity analysis (tolerance and eigenvalues indexes) and plots (Appendix B10). This protocol could be very practical in real-life conditions because it combines one new method that has proven to be reliable and very valid, and a second method that is well established in the field, easy to operate, and its results are very consistent (See Appendices C7 and C8). Results from the Federal Standard Test 191A lacked linear relationship when individually regressed with those from the human-body; however, when it was combined with Test No.1, it had one of the highest R^2.

As an individual test method, the UA ESD Test System showed the best relationship compared to the human-body data with coefficients of correlation and determination of .97 and .94, respectively. These high values mean that more than 94% of the human-body discharge potentials can be explained by the results from this test. As mentioned before, only with this method could the discharge energy be calculated. It has been stated that discharge energy is an important parameter to determine criteria for both incendive and non-incendive sparks due to electrostatic discharges (Owens, 1984; Glor, 1988; and Rizvi et al, 1992). This criterion could be used towards a general standard, based on minimum ignition energies (M.I.E.), for predicting safe wearing of protective clothing under hazardous environments.

The theoretical considerations on which this method is based can be stated as follows:

1) The 2-layer system represents a garment system comprising both outer and inner garments such as a coverall and a shirt, the capacitor and resistor represent the average capacitance and resistance of a human body, and the action of the switch represents the instant when a charged human body touches a grounded object resulting in a discharge.

2) This process could be divided in two parts: the tribo-charging process when the rubbing element charges the outer layer and, consequently, through induction, the inner layer and the capacitor; and the discharge process when the charged capacitor is discharged through the resistor to the ground, as happens in real-life conditions.

3) It seems that during triboelectrification most of the generated charge is transferred to the R/C unit rather than dissipating to the air because the charge will flow to the more conductive route, that is in this case, to the capacitor through the conducting plate and connecting wires. The charge cannot easily leak to the air because electrons travel through it with difficulty as the air has a high electrical resistance. Thus, the charge will leak slowly through the air to ground after charging has stopped (Crow, 1991).

4) It has been established (Serway, 1990) that the charge on the capacitor decays exponentially at a rate characterized by the time constant t of the circuit (t=RC). Thus, it may be hypothesized that the rate of such discharge from a capacitor such as the human body is not related to the intrinsic decay rate of the textile surface, but to the capacitance and resistance of the system.

Chapter 6

Conclusions and Recommendations

Summary

Peak discharge potentials and charge decay times were measured by three different test methods for both unilayer and multilayer specimens. In general, the pattern of results for these methods was predictable on the basis of other studies and the theory of static electricity. The magnitude of charge generation is influenced by such factors as contact pressure, the type of charging, contact area, and fabric combination. However, the magnitude of electrostatic discharges for each fabric system and the relationships among the three methods and the human-body experiment were unknown. Thus, three different laboratory protocol involving different combinations of the three test methods and one single method were proposed. These three test batteries showed high abilities to predict the outcome of human-body experiments.

Conclusions

Some conclusions reached on the basis of this study or confirmed by this investigation can be stated as follow:

1) Anti-static fabrics generate triboelectric discharge potentials and energies which are smaller in magnitude than non-antistatic fabrics.

2) While variation of the outer layer in a fabric system seems to have the greatest effect on the variables measured, variation of the inner layer in the system may have a lesser but significant effect.

3) Based on the results of correlation and linear regression, it is possible to establish a small-scale laboratory protocol to predict accurately and reliably the electrostatic propensity of garment systems worn by workers in hazardous environments.

4) According to correlation and regression analyses, peak discharge potentials have stronger relationships with data from the human-body experiment than do charge decay times.

5) It seems that peak discharge potentials from methods based on triboelectric charging mechanisms correlate better with human-body discharge potentials than do those based on high potential induced charging

6) Measurement of charge decay rate from induced charges correlate better with both small-scale and human-body potentials than do those from tribocharging because the former uses the ability of charge to flow across a specimen from an electrode due to its intrinsic conducting characteristics, and the latter depends on the electronic configuration, the removal of valence electrons by a friction force, and the specimen's ability to re-balance its electronic arrangement.

7) As a single test method, the UA ESD Test System showed a very strong relationship with data (potentials and energies) from the human-body experiment. Therefore, the high correlation between this method and human-body data in the present study suggests that measuring discharge potentials and energies from charged [illegible] systems using the new device and procedure is sufficient to predict with high accuracy the electrostatic propensity of protective clothing systems in real-life conditions.

Recommendations

Recommendations for Industry

Electrostatic discharges from a charged object cannot be completely eliminated but their effects can be minimized and controlled. The recommendations that follow are made on the basis of this study only and must be considered in light of other factors, not included in the present research, in the development of any safety code or industry specification.

Since in most jurisdictions including Alberta, there is no definite policy regarding electrostatics in clothing nor is there any prevalent, accepted industry-wide standard, it is strongly recommended that one of the small-scale laboratory protocols developed in this study be accepted as a standard protocol to predict electrostatic propensity of protective garment systems worn by persons working in hazardous environments under low humidity and temperature.

Moreover, a safety code for wearing protective clothing in explosive environments could be developed from discharge energies obtained from the UA ESD Test System. This safety code would be based on minimum ignition energies for different flammable gas and vapor mixtures.

Recommendations for Further Research

The following are suggestions for further work in this field:

1) The research should be replicated at different humidities to determine if there are significant differences between measurements taken at 20% and those taken at different relative humidity. Special attention should be placed on measurements taken at 0 humidity since it seems that the worst case scenario happens at this level.

2) The incendive characteristics of the spark discharges from both small-scale and human-body experiments should be investigated and their discharge energies compared to the minimum ignition energies of various flammable gases.

3) Further research should be pursued to develop a mathematical model that could predict the electrostatic propensity of a protective clothing system from measurements on single layers comprising the system. This model should involve four main variables: humidity, temperature, fabric system, and type of physical activity.

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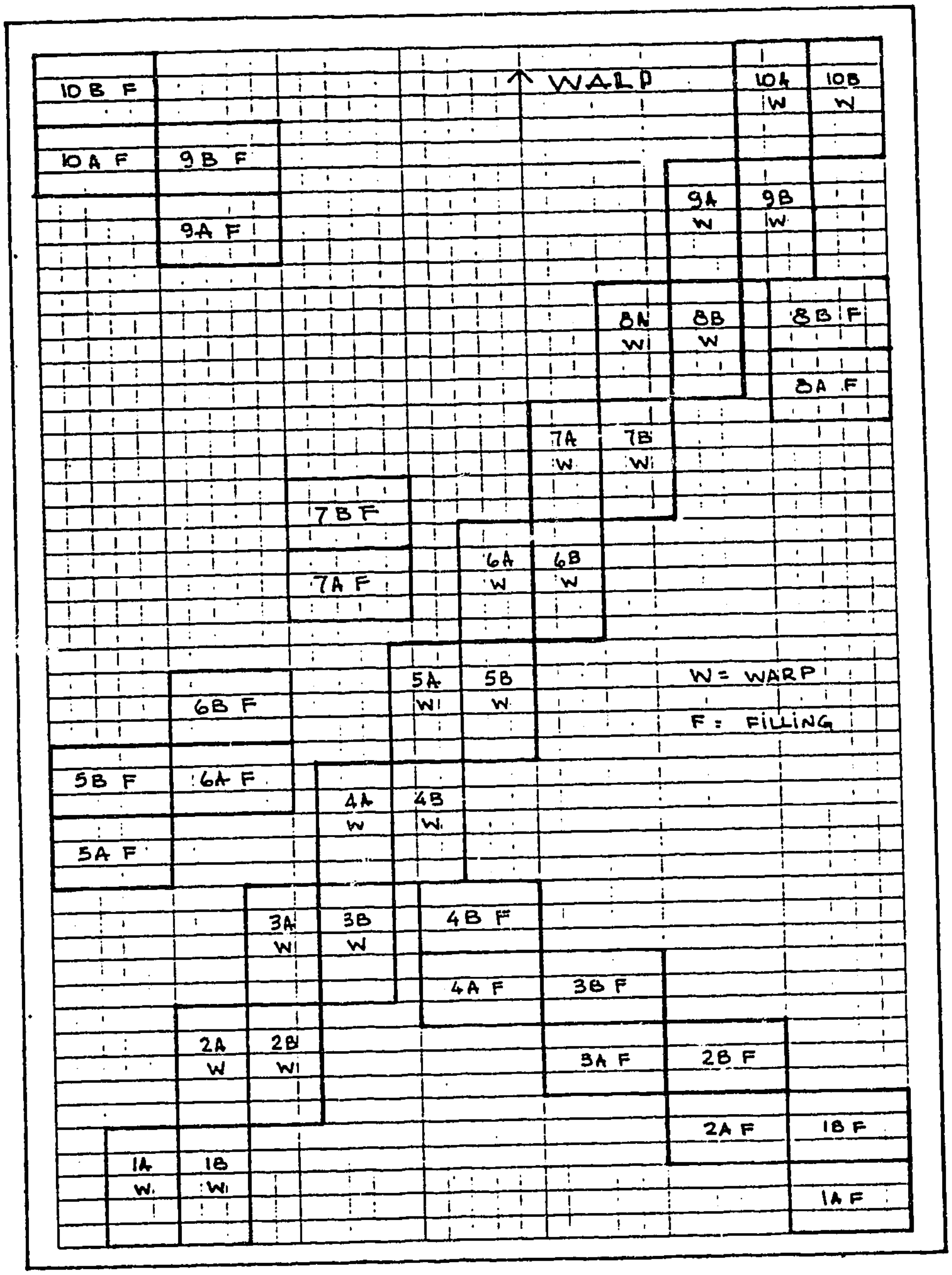
APPENDIX A



Appendix A1. Sampling diagram

Appendix A2. Test No.1 testing procedure

The procedure in Test No.1 (UA ESD Test System) was as follow:

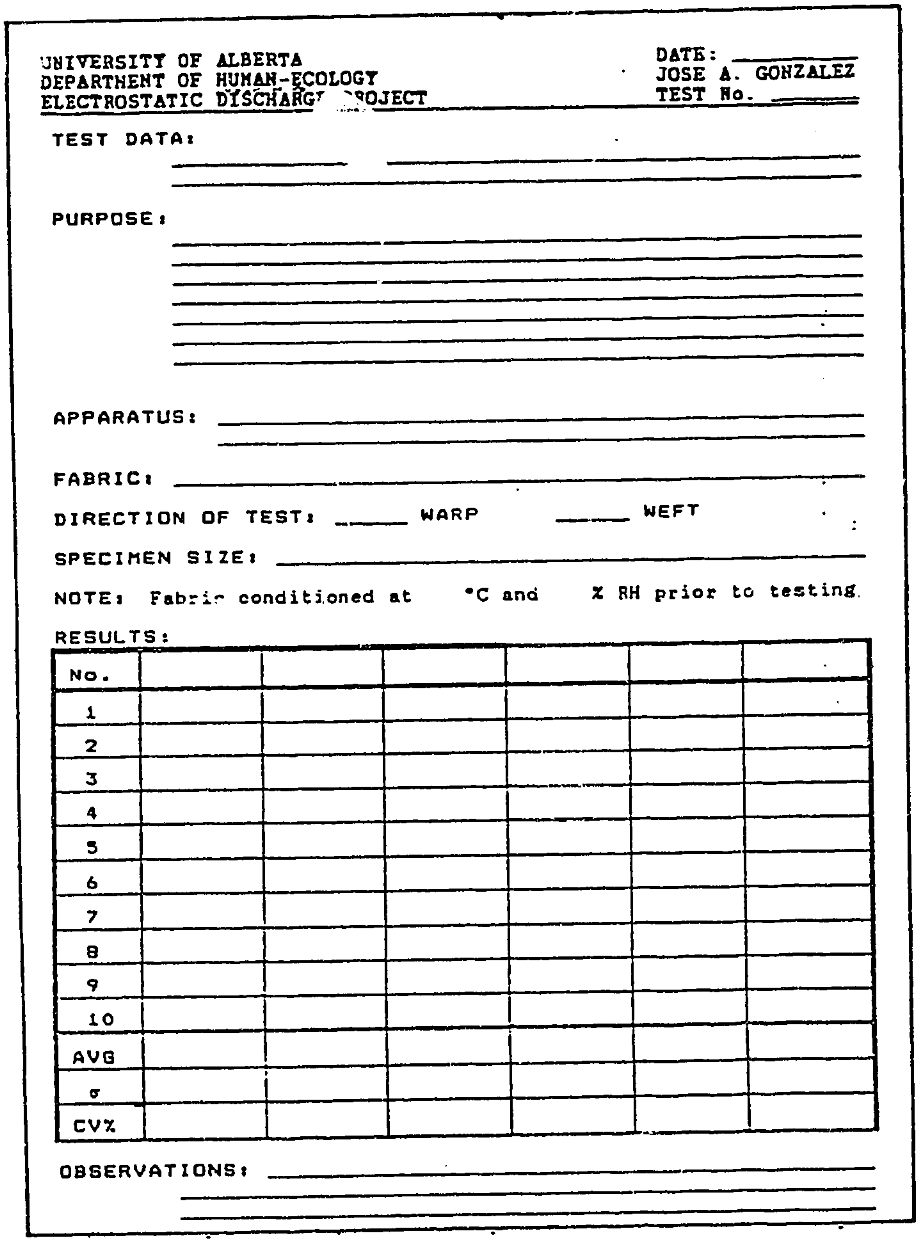
1) Place the specimen (unilayer or multilayer) on the conducting plate, and secure it with the grips. Handle the specimen with insulated tongs, wearing gloves.
2) Ground the specimen to cancel any initial charge on the surface of the outer fabric as well as the surface of the rubbing element.
3) Ground the system by pushing the discharge button.
4) Rub outer fabric surface with the rubbing element ten complete laps.
5) Press discharge button and monitor the discharge voltage waveform on the oscilloscope screen.
6) Print out the voltage waveform with the plotter.
7) Using tongs, carefully remove the specimen, and put it back in the conditioning box.
8) Repeat steps 1 to 7 for the rest of four specimens.
9) Repeat the experiment (steps 1 to 8) for each specimen after the first test with at least 24 hours of re-conditioning.

Appendix A3. Testing procedure for Test No.2

The procedure for Test No.2 (modified Federal Test Method Standard 191A, method 5931) was as follow:

1) Mount the specimen on the holders, securing it with the magnetized bars. Do not touch the surface of the specimen with the hands. Use tongs and wear gloves.
2) Eliminate any initial charge on the surface of the specimen using the static eliminator.
3) Move the roller up to the mark on the frame of the apparatus and make sure that it touches the specimen.
4) Press the starting button in the roller and keep rubbing the specimen until the roller stop automatically.
5) As the roller stops, move it away from the specimen and press the test button in the static decay meter. Record the maximum accepted voltage that the specimen obtained.
6) When the test is finished (i.e. when the decay voltage has reached the selected level of cut-off), record the decay time measured by the meter.
7) Remove the specimen from the holders and put it back in the conditioning box.
8) Repeat steps 1 to 7 for the rest of four specimens.
9) Repeat the experiment (steps 1 to 8) for each specimen with at least 24 hours of re-conditioning.

This procedure produced ten readings per fabric system and per fabric direction.



UNIVERSITY OF ALBERTA
DEPARTMENT OF HUMAN-ECOLOGY
ELECTROSTATIC DISCHARGE PROJECT

DATE:
JOSE A. GONZALEZ
TEST No.

TEST DATA:

PURPOSE:

APPARATUS:

FABRIC:

DIRECTION OF TEST: ______ WARP ______ WEFT

SPECIMEN SIZE:

NOTE: Fabric conditioned at °C and % RH prior to testing.

RESULTS:

No.						
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
AVG						
σ						
CV%						

OBSERVATIONS:

Appendix A4. Data collection form

APPENDIX B

```
               * * * A N A L Y S I S   O F   V A R I A N C E * * *

                    POTENT   POTENTIAL (V or kV)
               by   SYSTEM   FABRIC SYSTEM
                    EXPERIM  EXPERIMENT TYPE
                    FABDIR   FABRIC DIRECTION

                                        Sum of                 Mean              Sig
Source of Variation                    Squares      DF        Square        F    of F

Main Effects                          5849.603       7       835.658   693.263   .000
   SYSTEM                             1149.334       4       287.333   238.372   .000
   EXPERIM                            4582.403       2      2291.201  1900.785   .000
   FABDIR                              117.867       1       117.867    97.783   .000

2-Way Interactions                    5982.049      14       427.289   354.480   .000
   SYSTEM    EXPERIM                  5282.159       8       660.270   547.761   .000
   SYSTEM    FABDIR                     49.657       4        12.414    10.299   .000
   EXPERIM   FABDIR                    650.233       2       325.116   269.717   .000

3-Way Interactions                     357.933       8        44.742    37.118   .000
   SYSTEM    EXPERIM   FABDIR          357.933       8        44.742    37.118   .000

Explained                            12189.584      29       420.330   348.707   .000
Residual                               807.616     670         1.205
Total                                12997.201     699        18.594

700 cases were processed.
0 cases (.0 pct) were missing.

                    DECTIME  DECAY TIME (s)
               by   SYSTEM   FABRIC SYSTEM
                    EXPERIM  EXPERIMENT TYPE
                    FABDIR   FABRIC DIRECTION

                                        Sum of                 Mean              Sig
Source of Variation                    Squares      DF        Square        F    of F

Main Effects                       3233798.453       6    538966.409   117.358   .000
   SYSTEM                           807074.539       4    201768.635    43.934   .000
   EXPERIM                         2424072.619       1   2424072.619   527.832   .000
   FABDIR                             2651.295       1      2651.295      .577   .448

2-Way Interactions                 1662017.535       9    184668.615    40.211   .000
   SYSTEM    EXPERIM               1604575.658       4    401143.914    87.347   .000
   SYSTEM    FABDIR                  44148.780       4     11037.195     2.403   .049
   EXPERIM   FABDIR                  13293.097       1     13293.097     2.895   .089

3-Way Interactions                   93612.045       4     23403.011     5.096   .000
   SYSTEM    EXPERIM   FABDIR        93612.045       4     23403.011     5.096   .000

Explained                          4989428.033      19    262601.475    57.180   .000
Residual                           2663654.832     580      4592.508
Total                              7653082.865     599     12776.432

600 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B1. ANOVA of unilayer specimens peak potential and decay time

```
              * * *  A N A L Y S I S   O F   V A R I A N C E  * * *

                   POTENT    POTENTIAL (V or kV)
              by   SYSTEM    FABRIC SYSTEM
                   FABDIR    FABRIC DIRECTION

                   EXPERIMENTAL sums of squares
                   Covariates entered FIRST

                                    Sum of               Mean                Sig
Source of Variation                 Squares      DF     Square         F     of F

Main Effects                       6132.868       5   1226.574   154.699     .000
   SYSTEM                          5365.799       4   1341.450   169.188     .000
   FABDIR                           767.068       1    767.068    96.745     .000

  Way Interactions                  390.316       4     97.579    12.307     .000
   SYSTEM    FABDIR                 390.316       4     97.579    12.307     .000

Explained                          6523.183       9    724.798    91.414     .000

Residual                            713.589      90      7.929

Total                              7236.772      99     73.099

100 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B2. ANOVA of Test No.1 peak potential (unilayer specimens)

```
            * * * A N A L Y S I S   O F   V A R I A N C E * * *

                 POTENT    POTENTIAL (V or kV)
            by   SYSTEM    FABRIC SYSTEM
                 FABDIR    FABRIC DIRECTION
                 CUTOFF    CUT OFF LEVEL

                                      Sum of              Mean              Sig
Source of Variation                  Squares      DF     Square        F    of F

Main Effects                         857.654       6    142.942    793.200  .000
   SYSTEM                            857.328       4    214.332   1189.348  .000
   FABDIR                               .263       1       .263      1.458  .229
   CUTOFF                               .063       1       .063       .350  .555

2-Way Interactions                    26.665       9      2.963     16.441  .000
   SYSTEM    FABDIR                   15.698       4      3.925     21.778  .000
   SYSTEM    CUTOFF                    2.050       4       .512      2.844  .026
   FABDIR    CUTOFF                    8.917       1      8.917     49.481  .000

3-Way Interactions                    11.580       4      2.895     16.064  .000
   SYSTEM    FABDIR    CUTOFF         11.580       4      2.895     16.064  .000

Explained                            895.898      19     47.153    261.654  .000
Residual                              32.438     180       .180
Total                                928.336     199      4.665

200 cases were processed.
0 cases (.0 pct) were missing.

                 DECTIME   DECAY TIME (s)
            by   SYSTEM    FABRIC SYSTEM
                 FABDIR    FABRIC DIRECTION
                 CUTOFF    CUT OFF LEVEL

                                      Sum of              Mean              Sig
Source of Variation                  Squares      DF     Square        F    of F

Main Effects                     3508971.150       6   584828.525   5489.486  .000
   SYSTEM                        2377362.167       4   594340.542   5578.770  .000
   FABDIR                          15342.965       1    15342.965    144.017  .000
   CUTOFF                        1116266.018       1  1116266.018  10477.817  .000

2-Way Interactions               1406035.174       9   156226.130   1466.415  .000
   SYSTEM    FABDIR               136681.581       4    34170.395    320.740  .000
   SYSTEM    CUTOFF              1237933.863       4   309483.466   2904.963  .000
   FABDIR    CUTOFF                31419.730       1    31419.730    294.921  .000

3-Way Interactions                164510.949       4    41127.737    386.045  .000
   SYSTEM    FABDIR    CUTOFF     164510.949       4    41127.737    386.045  .000

Explained                        5079517.274      19   267343.014   2509.412  .000
Residual                           19176.503     180      106.536
Total                            5098693.776     199    25621.577

200 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B3. ANOVA of Test No.2 peak potential and decay time (unilayer specimens)

```
* * *  A N A L Y S I S   O F   V A R I A N C E  * * *

          POTENT   POTENTIAL (V or kV)
   by     SYSTEM   FABRIC SYSTEM
          FABDIR   FABRIC DIRECTION
          CUTOFF   CUT OFF LEVEL
          POLAR    POLARITY OF CHARGE

          EXPERIMENTAL sums of squares
          Covariates entered FIRST

                                      Sum of               Mean                Sig
Source of Variation                  Squares      DF      Square         F     of F

Main Effects                         221.586       7      31.655  1192.661     .000
  SYSTEM                             208.365       4      52.091  1962.628     .000
  FABDIR                                .768       1        .768    28.945     .000
  CUTOFF                              11.059       1      11.059   416.664     .000
  POLAR                                1.394       1       1.394    52.505     .000

2-Way Interactions                    15.870      15       1.058    39.863     .000
  SYSTEM   FABDIR                      1.576       4        .394    14.842     .000
  SYSTEM   CUTOFF                      8.448       4       2.112    79.572     .000
  SYSTEM   POLAR                       2.928       4        .732    27.576     .000
  FABDIR   CUTOFF                      1.953       1       1.953    73.583     .000
  FABDIR   POLAR                        .119       1        .119     4.471     .035
  CUTOFF   POLAR                        .847       1        .847    31.924     .000

3-Way Interactions                     2.460      13        .189     7.130     .000
  SYSTEM   FABDIR   CUTOFF             1.460       4        .365    13.753     .000
  SYSTEM   FABDIR   POLAR               .558       4        .139     5.251     .000
  SYSTEM   CUTOFF   POLAR               .083       4        .021      .783     .537
  FABDIR   CUTOFF   POLAR               .359       1        .359    13.541     .000

4-Way Interactions                      .218       4        .055     2.057     .086
  SYSTEM   FABDIR   CUTOFF              .218       4        .055     2.057     .086
       POLAR

Explained                            240.135      39       6.157   231.987     .000

Residual                               9.555     360        .027

Total                                249.690     399        .626

400 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B4. ANOVA of Test No.3 potential & decay time (unilayer specimens).

Cont'd...

```
          * * *  A N A L Y S I S   O F   V A R I A N C E  * * *

                  DECTIME   DECAY TIME (s)
          by      SYSTEM    FABRIC SYSTEM
                  FABDIR    FABRIC DIRECTION
                  CUTOFF    CUT OFF LEVEL
                  POLAR     POLARITY OF CHARGE

                  EXPERIMENTAL sums of squares
                  Covariates entered FIRST

                                       Sum of               Mean                Sig
Source of Variation                   Squares      DF      Square          F    of F

Main Effects                         88503.386      7   12643.341   2045.556   .000
   SYSTEM                            34288.030      4    8572.008   1386.858   .000
   FABDIR                              601.427      1     601.427     97.304   .000
   CUTOFF                            53584.379      1   53584.379   8669.375   .000
   POLAR                                29.550      1      29.550      4.781   .029

2-Way Interactions                   38446.044     15    2563.070    414.677   .000
   SYSTEM    FABDIR                   1079.244      4     269.811     43.653   .000
   SYSTEM    CUTOFF                  36726.185      4    9181.546   1485.475   .000
   SYSTEM    POLAR                      24.403      4       6.101       .987   .415
   FABDIR    CUTOFF                    594.287      1     594.287     96.149   .000
   FABDIR    POLAR                      16.459      1      16.459      2.663   .104
   CUTOFF    POLAR                       5.466      1       5.466       .884   .348

3-Way Interactions                    1088.264     13      83.713     13.544   .000
   SYSTEM    FABDIR    CUTOFF          974.265      4     243.566     39.406   .000
   SYSTEM    FABDIR    POLAR            53.930      4      13.482      2.181   .071
   SYSTEM    CUTOFF    POLAR            21.193      4       5.298       .857   .490
   FABDIR    CUTOFF    POLAR            38.875      1      38.875      6.290   .013

4-Way Interactions                      53.658      4      13.415      2.170   .072
   SYSTEM    FABDIR    CUTOFF           53.658      4      13.415      2.170   .072
       POLAR

Explained                           128091.352     39    3284.394    531.380   .000

Residual                              2225.117    360       6.181

Total                               130316.470    399     326.608

400 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B4 (continued). ANOVA of Test No.3 peak potential & decay time (unilayer specimens)

```
              * * *  A N A L Y S I S   O F   V A R I A N C E  * * *

                      POTENT    POTENTIAL (V or kV)
              by      SYSTEM    FABRIC SYSTEM
                      EXPERIM   EXPERIMENT TYPE
                      FABDIR    FABRIC DIRECTION

                      EXPERIMENTAL sums of squares
                      Covariates entered FIRST

                                           Sum of               Mean             Sig
Source of Variation                       Squares     DF       Square       F    of F

Main Effects                            20655.944     10     2065.594  1313.379  .000
   SYSTEM                                4015.589      7      573.656   364.751  .000
   EXPERIM                              16634.137      2     8317.068  5288.292  .000
   FABDIR                                   6.219      1        6.219     3.954  .047

2-Way Interactions                      16512.276     23      717.925   456.483  .000
   SYSTEM    EXPERIM                    15786.487     14     1127.606   716.973  .000
   SYSTEM    FABDIR                       499.541      7       71.363    45.375  .000
   EXPERIM   FABDIR                       226.248      2      113.124    71.928  .000

3-Way Interactions                       2247.585     14      160.542   102.078  .000
   SYSTEM    EXPERIM   FABDIR            2247.585     14      160.542   102.078  .000

Explained                               39415.805     47      838.634   533.234  .000

Residual                                 1685.969   1072        1.573

Total                                   41101.774   1119       36.731

1120 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B5. ANOVA of multilayer specimens peak potential & decay time. Cont'd...

```
               * * * A N A L Y S I S   O F   V A R I A N C E * * *

                    DECTIME   DECAY TIME (s)
               by   SYSTEM    FABRIC SYSTEM
                    EXPERIM   EXPERIMENT TYPE
                    FABDIR    FABRIC DIRECTION
                    CUTOFF    CUT OFF LEVEL

                    EXPERIMENTAL sums of squares
                    Covariates entered FIRST

                                         Sum of              Mean                Sig
Source of Variation                     Squares     DF      Square         F    of F

Main Effects                        4421230.423     10   442123.042  5526.119   .000
   SYSTEM                            486503.892      7    69500.556   868.691   .000
   EXPERIM                          3095275.923      1  3095275.923 38688.014   .000
   FABDIR                             10418.066      1    10418.066   130.216   .000
   CUTOFF                            829032.543      1   829032.543 10362.121   .000

2-Way Interactions                  2504766.401     24   104365.267  1304.467   .000
   SYSTEM    EXPERIM                1189358.617      7   169908.374  2123.694   .000
   SYSTEM    FABDIR                   39318.099      7     5616.871    70.206   .000
   SYSTEM    CUTOFF                  245395.761      7    35056.537   438.173   .000
   EXPERIM   FABDIR                   40637.873      1    40637.873   507.935   .000
   EXPERIM   CUTOFF                  984209.704      1   984209.704 12301.688   .000
   FABDIR    CUTOFF                    5846.347      1     5846.347    73.074   .000

3-Way Interactions                   444988.333     22    20226.742   252.815   .000
   SYSTEM    EXPERIM   FABDIR         83691.943      7    11955.992   149.439   .000
   SYSTEM    EXPERIM   CUTOFF        323228.275      7    46175.468   577.150   .000
   SYSTEM    FABDIR    CUTOFF         38034.501      7     5433.500    67.914   .000
   EXPERIM   FABDIR    CUTOFF            33.613      1       33.613      .420   .517

4-Way Interactions                   166509.474      7    23787.068   297.316   .000
   SYSTEM    EXPERIM   FABDIR        166509.474      7    23787.068   297.316   .000
       CUTOFF

Explained                           7537494.631     63   119642.772  1495.421   .000
Residual                              71685.439    896       80.006
Total                               7609180.069    959     7934.494

960 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B5 (continued). ANOVA of multilayer specimens peak potential & decay time

```
                 * * * A N A L Y S I S   O F   V A R I A N C E * * *

                    POTENT    POTENTIAL (V or kV)
                 by SYSTEM    FABRIC SYSTEM
                    FABDIR    FABRIC DIRECTION

                    EXPERIMENTAL sums of squares
                    Covariates entered FIRST

                                        Sum of                  Mean                Sig
Source of Variation                    Squares       DF        Square          F    of F

Main Effects                          18409.143       8      2301.143    212.371    .000
   SYSTEM                             18194.473       7      2599.210    239.879    .000
   FABDIR                               214.670       1       214.670     19.812    .000

2-Way Interactions                     2682.563       7       383.223     35.367    .000
   SYSTEM    FABDIR                    2682.563       7       383.223     35.367    .000

Explained                             21091.706      15      1406.114    129.769    .000

Residual                               1560.310     144        10.835

Total                                 22652.016     159       142.466

160 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B6. ANOVA of Test No.1 peak potential (multilayer specimens)

```
          * * * A N A L Y S I S   O F   V A R I A N C E * * *

                POTENT    POTENTIAL (V or kV)
          by    SYSTEM    FABRIC SYSTEM
                FABDIR    FABRIC DIRECTION
                CUTOFF    CUT OFF LEVEL

                EXPERIMENTAL sums of squares
                Covariates entered FIRST

                                          Sum of                Mean                Sig
Source of Variation                       Squares      DF       Square         F    of F

Main Effects                             1495.560       9      166.173  1407.356    .000
   SYSTEM                                1491.571       7      213.082  1804.631    .000
   FABDIR                                    .067       1         .067      .571    .450
   CUTOFF                                   3.922       1        3.922    33.213    .000

2-Way Interactions                         38.285      15        2.552    21.616    .000
   SYSTEM    FABDIR                        20.979       7        2.997    25.382    .000
   SYSTEM    CUTOFF                         4.803       7         .686     5.811    .000
   FABDIR    CUTOFF                        12.504       1       12.504   105.897    .000

3-Way Interactions                          8.515       7        1.216    10.302    .000
   SYSTEM    FABDIR    CUTOFF               8.515       7        1.216    10.302    .000

Explained                                1542.360      31       49.754   421.373    .000
Residual                                   34.006     288         .118
Total                                    1576.366     319        4.942

320 cases were processed.
0 cases (.0 pct) were missing.

                DECTIME   DECAY TIME (s)
          by    SYSTEM    FABRIC SYSTEM
                FABDIR    FABRIC DIRECTION
                CUTOFF    CUT OFF LEVEL

                                          Sum of                Mean                Sig
Source of Variation                       Squares      DF       Square         F    of F

Main Effects                          3444845.097       9   382760.566  2080.484    .000
   SYSTEM                             1610762.655       7   230108.951  1250.750    .000
   FABDIR                               49963.757       1    49963.757   271.577    .000
   CUTOFF                             1784118.685       1  1784118.685  9697.525    .000

2-Way Interactions                     651541.203      15    43436.080   236.096    .000
   SYSTEM    FABDIR                    120259.611       7    17179.944    93.381    .000
   SYSTEM    CUTOFF                    529728.345       7    75675.478   411.332    .000
   FABDIR    CUTOFF                      1553.247       1     1553.247     8.443    .004

3-Way Interactions                     195551.132       7    27935.876   151.845    .000
   SYSTEM    FABDIR    CUTOFF          195551.132       7    27935.876   151.845    .000

Explained                             4291937.432      31   138449.595   752.539    .000
Residual                                52985.292     288      183.977
Total                                 4344922.723     319    13620.447

320 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B7. ANOVA of Test No.2 potential and decay time (multilayer specimens)

```
            * * *  A N A L Y S I S   O F   V A R I A N C E  * * *

                  POTENT    POTENTIAL (V or kV)
            by    SYSTEM    FABRIC SYSTEM
                  FABDIR    FABRIC DIRECTION
                  CUTOFF    CUT OFF LEVEL
                  POLAR     POLARITY OF CHARGE

                  EXPERIMENTAL sums of squares
                  Covariates entered FIRST

                                           Sum of                Mean              Sig
Source of Variation                       Squares       DF      Square         F    of F

Main Effects                              135.949       10      13.595   187.602    .000
   SYSTEM                                 116.032        7      16.576   228.738    .000
   FABDIR                                  17.729        1      17.729   244.648    .000
   CUTOFF                                    .380        1        .380     5.247    .022
   POLAR                                    1.808        1       1.808    24.954    .000

2-Way Interactions                         52.413       24       2.184    30.136    .000
   SYSTEM    FABDIR                        43.585        7       6.226    85.921    .000
   SYSTEM    CUTOFF                         2.866        7        .409     5.649    .000
   SYSTEM    POLAR                          5.548        7        .793    10.936    .000
   FABDIR    CUTOFF                          .044        1        .044      .601    .438
   FABDIR    POLAR                           .002        1        .002      .022    .881
   CUTOFF    POLAR                           .370        1        .370     5.100    .024

3-Way Interactions                          4.847       22        .220     3.040    .000
   SYSTEM    FABDIR    CUTOFF               1.904        7        .272     3.754    .001
   SYSTEM    FABDIR    POLAR                 .802        7        .115     1.581    .138
   SYSTEM    CUTOFF    POLAR                1.601        7        .229     3.156    .003
   FABDIR    CUTOFF    POLAR                 .539        1        .539     7.443    .007

4-Way Interactions                          4.305        7        .615     8.488    .000
   SYSTEM    FABDIR    CUTOFF               4.305        7        .615     8.488    .000
       POLAR

Explained                                 197.515       63       3.135    43.263    .000
Residual                                   41.741      576        .072
Total                                     239.256      639        .374

640 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B8. ANOVA of Test No.3 peak potential & decay time (multilayer specimens).

Cont'd...

```
          * * * A N A L Y S I S   O F   V A R I A N C E * * *

                DECTIME  DECAY TIME (s)
          by    SYSTEM   FABRIC SYSTEM
                FABDIR   FABRIC DIRECTION
                CUTOFF   CUT OFF LEVEL
                POLAR    POLARITY OF CHARGE

                EXPERIMENTAL sums of squares
                Covariates entered FIRST

                                    Sum of                Mean              Sig
Source of Variation                 Squares      DF      Square        F    of F

Main Effects                       96428.306     10    9642.831   712.278   .000
   SYSTEM                          65099.854      7    9299.979   686.953   .000
   FABDIR                           1092.182      1    1092.182    80.675   .000
   CUTOFF                          29123.561      1   29123.561  2151.244   .000
   POLAR                            1112.709      1    1112.709    82.191   .000

2-Way Interactions                 49913.182     24    2079.716   153.620   .000
   SYSTEM   FABDIR                  2750.432      7     392.919    29.023   .000
   SYSTEM   CUTOFF                 38895.692      7    5556.527   410.439   .000
   SYSTEM   POLAR                   3925.449      7     560.778    41.423   .000
   FABDIR   CUTOFF                  4326.712      1    4326.712   319.597   .000
   FABDIR   POLAR                       .099      1        .099      .007   .932
   CUTOFF   POLAR                     14.799      1      14.799     1.093   .296

3-Way Interactions                 11311.459     22     514.157    37.979   .000
   SYSTEM   FABDIR   CUTOFF         8992.843      7    1284.692    94.895   .000
   SYSTEM   FABDIR   POLAR           678.459      7      96.923     7.159   .000
   SYSTEM   CUTOFF   POLAR           849.035      7     121.291     8.959   .000
   FABDIR   CUTOFF   POLAR           791.121      1     791.121    58.437   .000

4-Way Interactions                  3530.581      7     504.369    37.256   .000
   SYSTEM   FABDIR   CUTOFF         3530.581      7     504.369    37.256   .000
       POLAR

Explained                         161183.528     63    2558.469   188.984   .000
Residual                            7797.895    576      13.538
Total                             168981.423    639     264.447

640 cases were processed.
0 cases (.0 pct) were missing.
```

Appendix B8 (continued). ANOVA of Test No.3 peak potential & decay time (multilayer specimens)

```
           * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   HBEPOT   HUMAN-BODY EXPERIMENT 1

Block Number  1.  Method:  Enter      SSE1BP

Step    MultR      Rsq    F(Eqn)  SigF        Variable  BetaIn
   1    .9692    .9394  1210.096  .000   In:  SSE1BP      .9692

Block Number  2.  Method:  Enter      SSE2B2D  SSE2B2P


Variable(s) Entered on Step Number
   2..    SSE2B2D   sse2b2dectime (w+f) 50% cutoff
   3..    SSE2B2P   sse2b2pot (w+f) 50% cutoff

Multiple R           .97936
R Square             .95914
Adjusted R Square    .95753
Standard Error       .67593

Equation Number 1    Dependent Variable..   HBEPOT   HUMAN-BODY EXPERIMENT 1

------------------------- Variables in the Equation -------------------------

Variable               B         SE B        Beta  Tolerance       VIF         T

SSE1BP           .245171      .022746     .815640    .093880    10.652    10.779
SSE2B2D         -.005921      .001554    -.114588    .594563     1.682    -3.811
SSE2B2P          .186064      .119842     .127511    .079700    12.547     1.553
(Constant)       .136369      .171854                                       .794

------ in -------

Variable     Sig T

SSE1BP       .0000
SSE2B2D      .0003
SSE2B2P      .1247
(Constant)   .4299

Collinearity Diagnostics

Number  Eigenval      Cond  Variance Proportions
                     Index  Constant    SSE1BP   SSE2B2D   SSE2B2P
    1    2.99979     1.000    .01898    .00320    .01463    .00296
    2     .84416     1.885    .00596    .00332    .28419    .00700
    3     .13988     4.631    .04039    .02851    .32573    .01045
    4     .01617    13.619    .93467    .96496    .37545    .97959
```

Appendix B9. Multiple linear regression for Test Battery 1

```
        * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Equation Number 1    Dependent Variable..   HBEPOT   HUMAN-BODY EXPERIMENT 1

Block Number  1.  Method:  Enter      SSE1BP

Step    MultR      Rsq    F(Eqn)  SigF        Variable  BetaIn
   1    .9692    .9394  1210.096  .000   In:  SSE1BP     .9692

Block Number  2.  Method:  Enter      SSE3B1D

Variable(s) Entered on Step Number
   2..     SSE3B1D    sse3b1dectime (w+f+p+n) 10% cutoff

Multiple R           .97491
R Square             .95045
Adjusted R Square    .94916
Standard Error       .73956

------------------------- Variables in the Equation -------------------------

Variable                B          SE B         Beta  Tolerance        VIF          T

SSE1BP            .242402       .014081     .806426    .293249      3.410     17.214
SSE3B1D           .035356       .008552     .193680    .293249      3.410      4.134
(Constant)       -.176137       .149540                                        -1.178

------ in -------

Variable     Sig T

SSE1BP       .0000
SSE3B1D      .0001
(Constant)   .2425

Equation Number 1    Dependent Variable..   HBEPOT   HUMAN-BODY EXPERIMENT 1

Collinearity Diagnostics

Number  Eigenval     Cond   Variance  Proportions
                    Index   Constant    SSE1BP   SSE3B1D
    1    2.57883    1.000     .03569    .01437    .02159
    2     .35864    2.682     .51802    .00435    .17817
    3     .06254    6.422     .44629    .98127    .80024
```

Appendix B10. Multiple linear regression for Test Battery 2

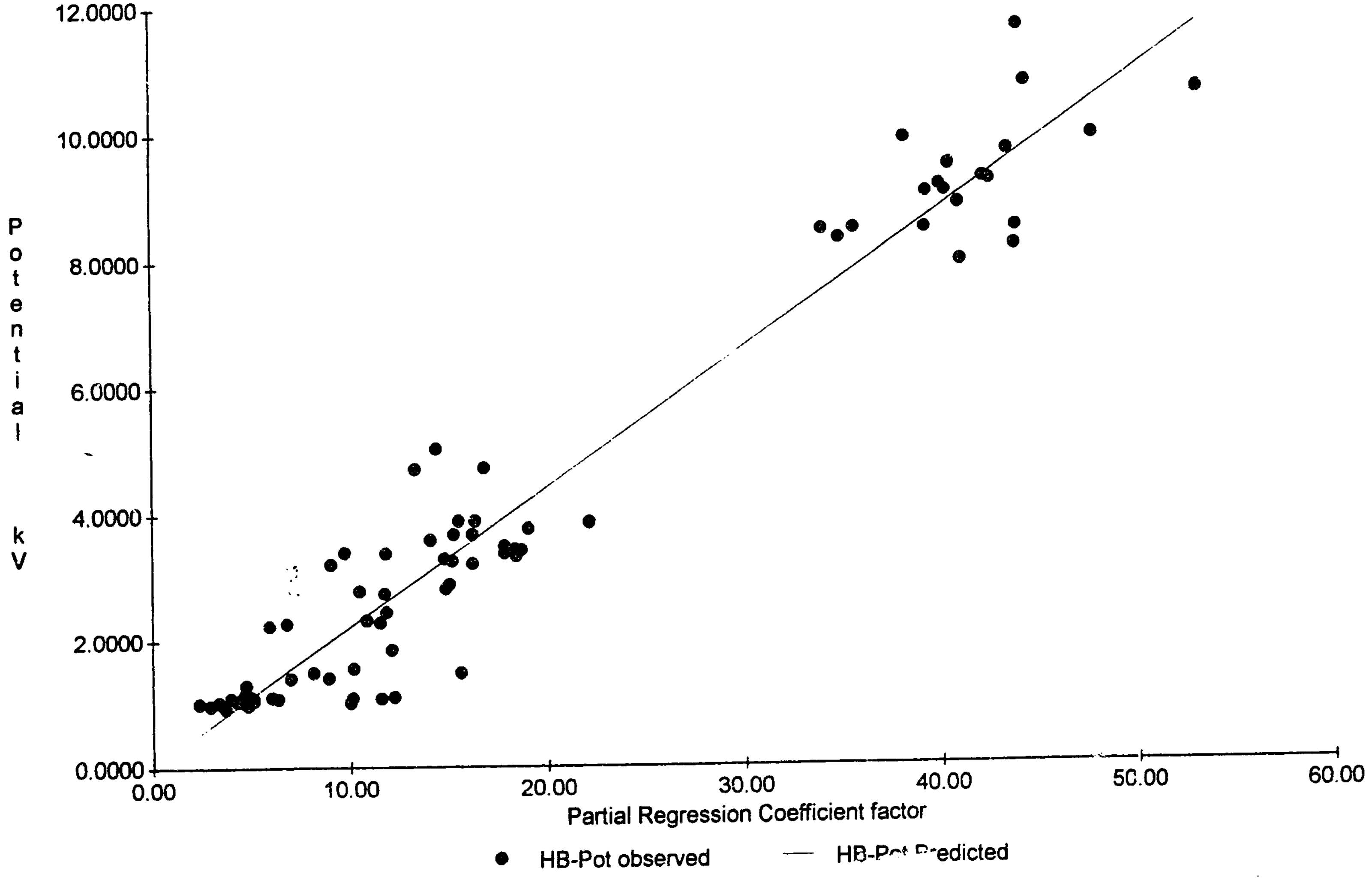
APPENDIX C

FABRIC SYSTEM		Small-scale	Human-Body Energy	
OUTER	INNER	Energy (uJ)	Observed (mJ)	Predicted (mJ)
Aramid/PBI	100% cotton	0.0026	0.07	0.04
Aramid/PBI	Aramid/carbon	0.0029	0.07	0.05
Aramid/carbon	Aramid/carbon	0.0060	0.12	0.10
Aramid/carbon	100% cotton	0.0094	0.24	0.16
Aramid/FR viscose	100% cotton	0.0112	0.78	0.19
Aramid/FR viscose	Aramid/carbon	0.0123	0.77	0.20
FR cotton	100% cotton	0.2093	4.19	3.47
FR cotton	FR cotton	0.2958	4.35	4.91

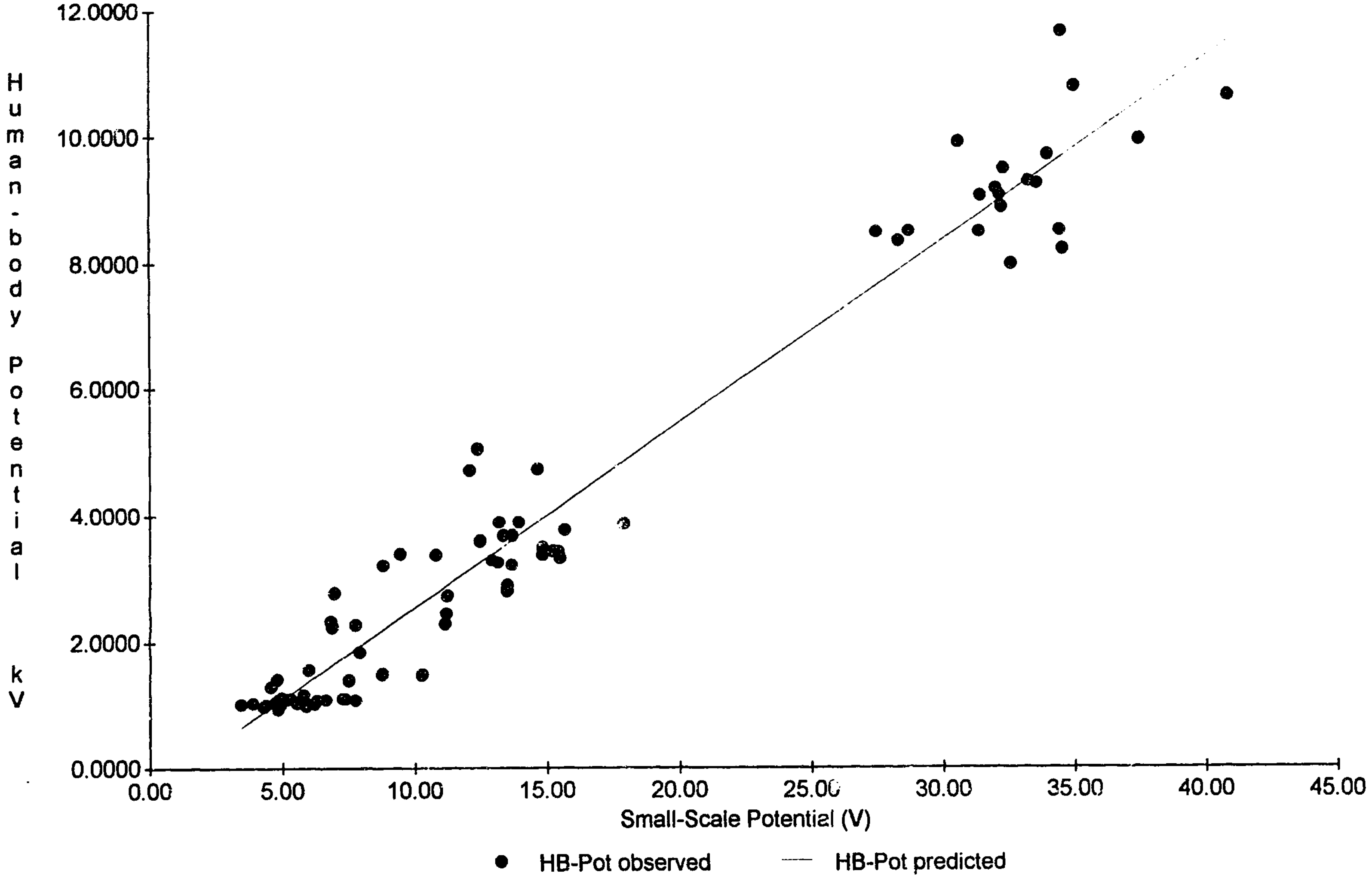
ENERGY
Regression Output:

Std Err of Y Est	0.4632
R Squared	0.9368
No. of Observations	80.0000
Degrees of Freedom	78.0000
X Coefficient	16.5984
Std Err of Coef.	1.2762

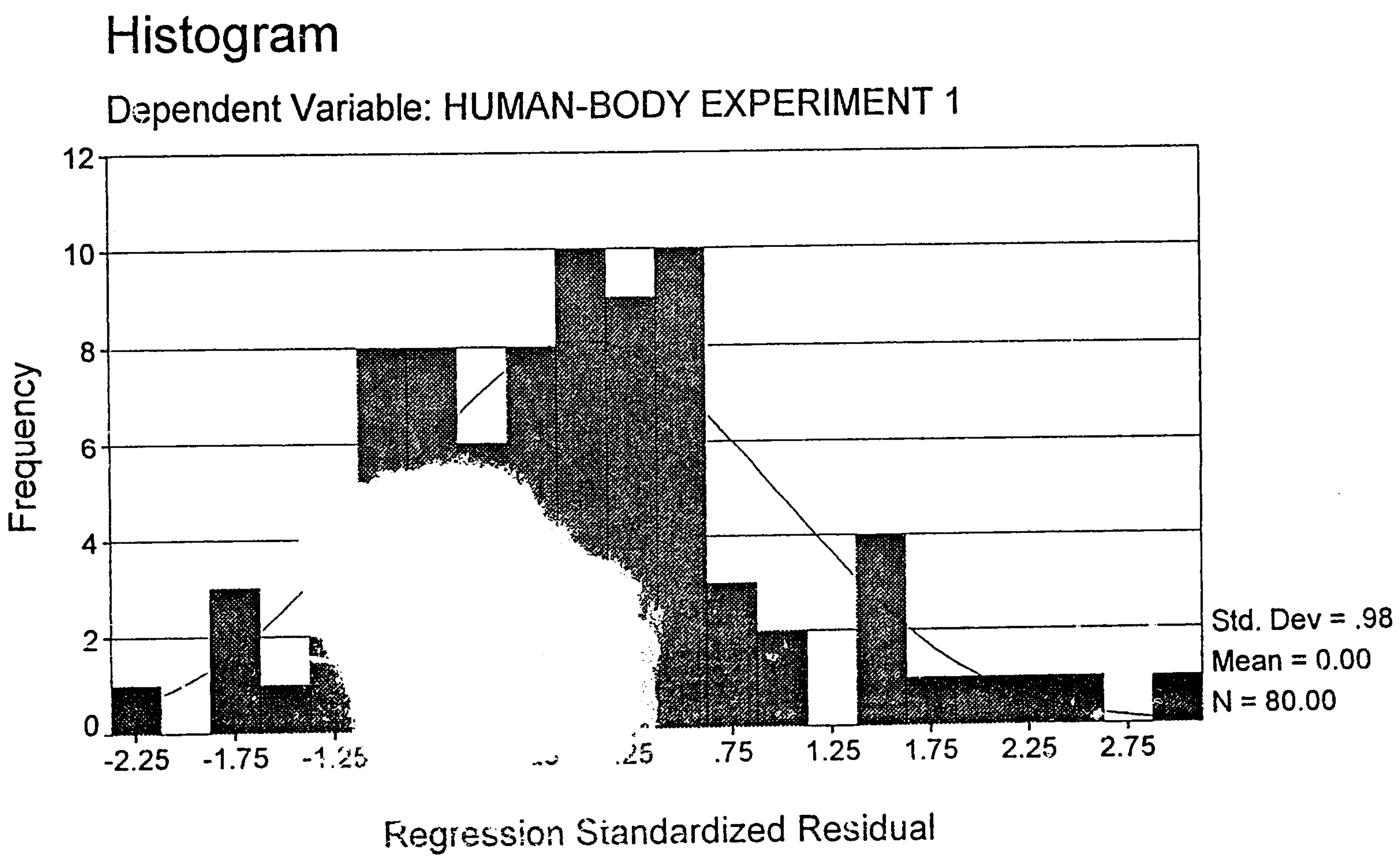
Appendix C1. Regression analysis of discharge energies from the UA ESD Test System and human-body experiment



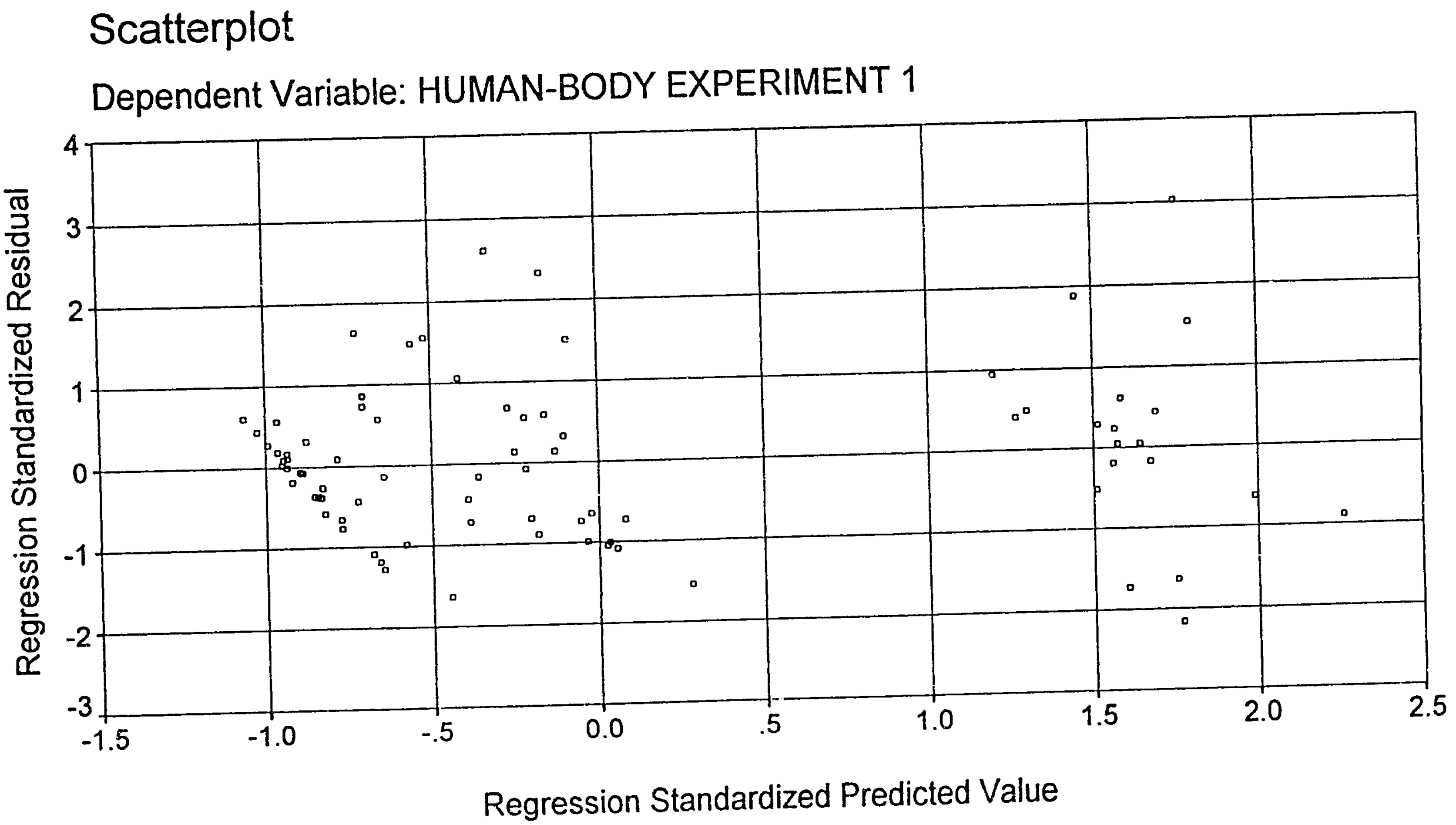
Appendix C2. Linear relationship between Test Battery 2 and human-body experiment



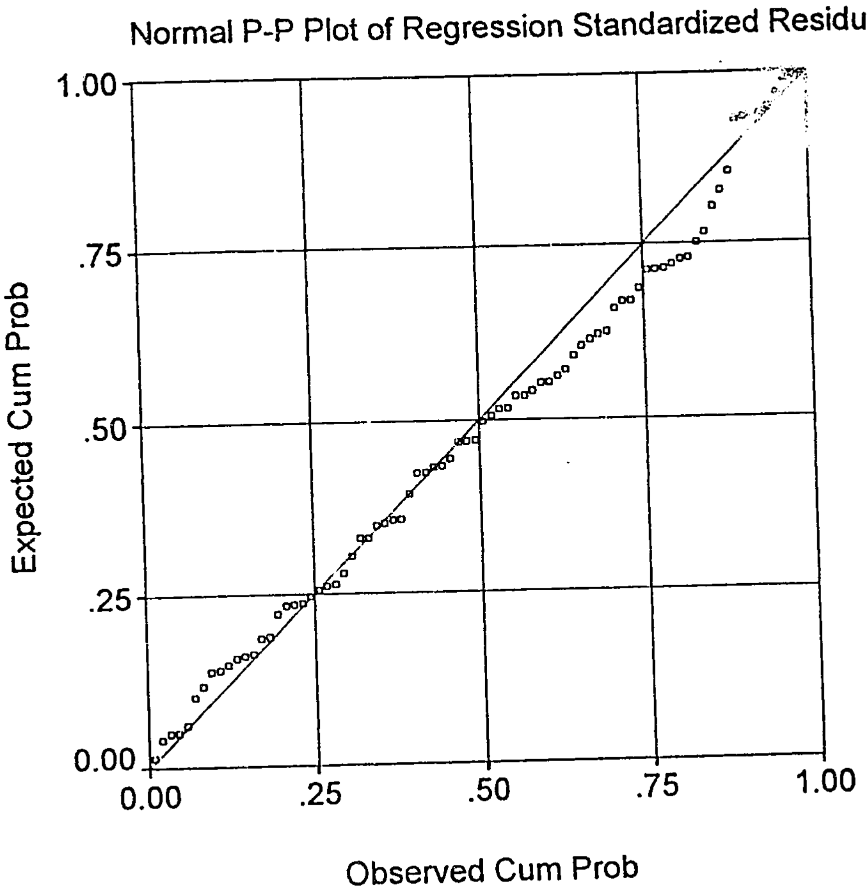
Appendix C3. Linear relationship between UA ESD Test System (multilayer specimens) and human-body experiment



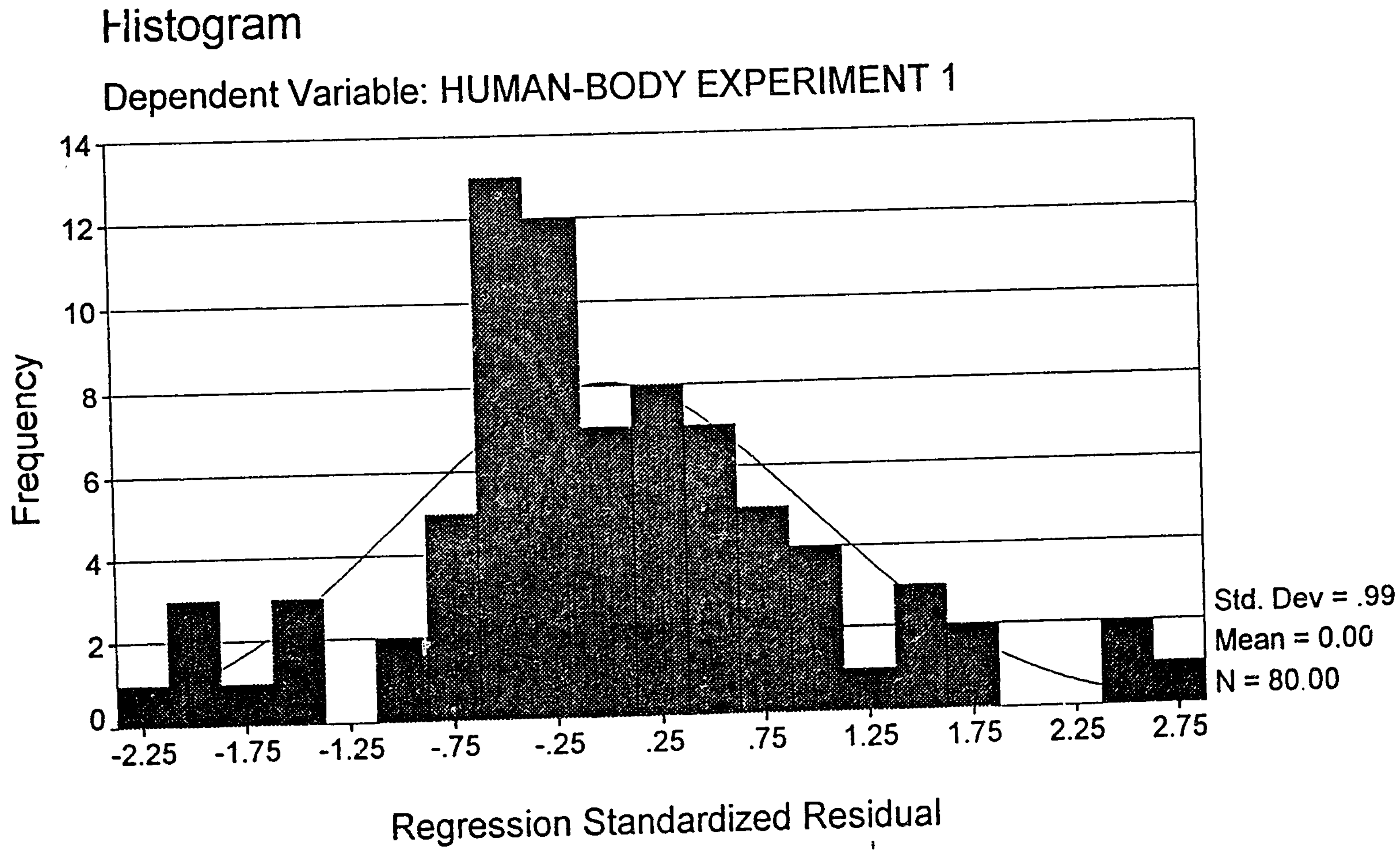
Appendix C4. Histogram of standardized residuals for Test Battery 1



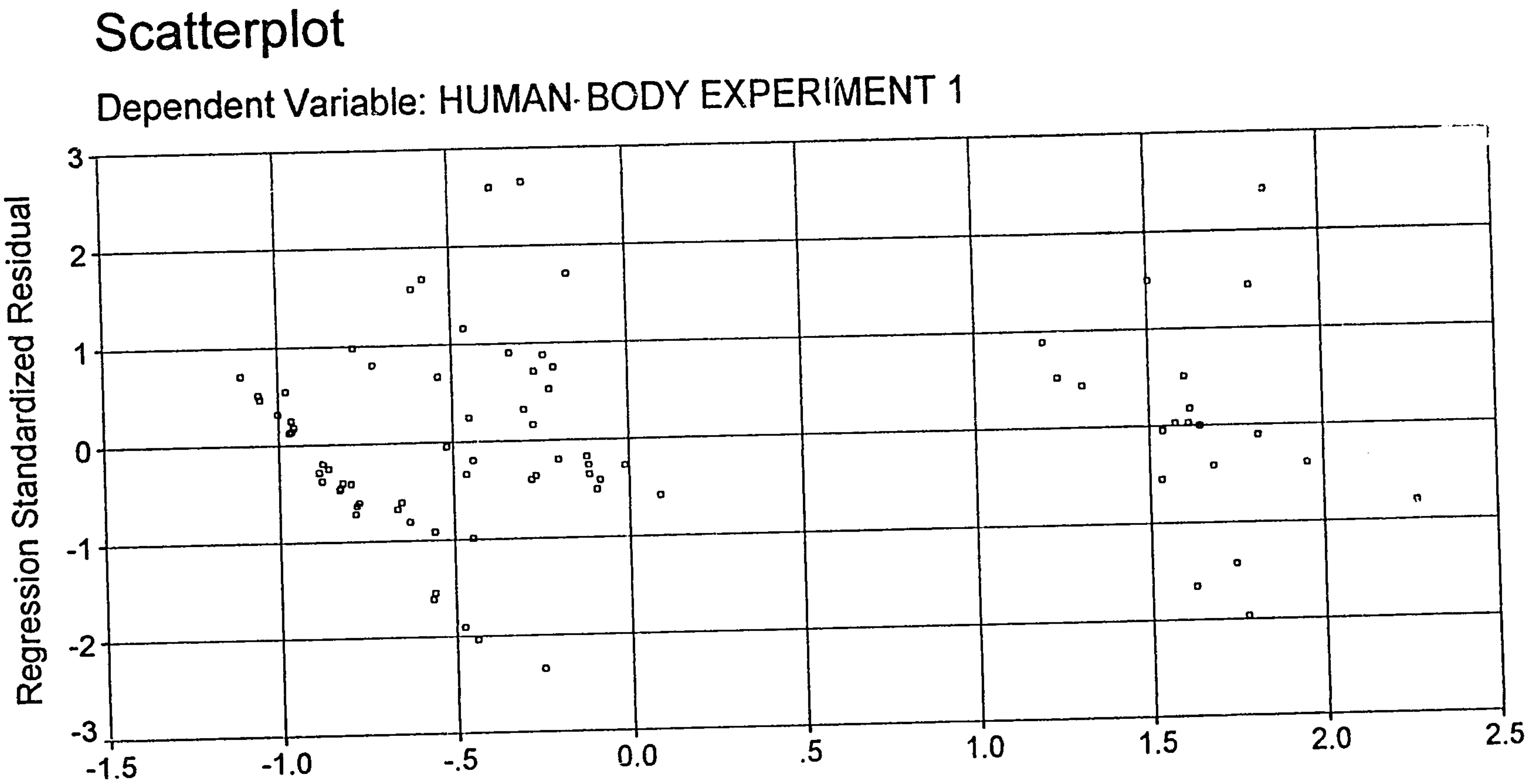
Appendix C5. Scatterplot of standardized residuals for Test Battery 1



Appendix C6. Plot of normal probability of standardized residuals for Test Battery 1



Appendix C7. Histogram of standardized residuals for Test Battery 2



Appendix C8. Scatterplot of standardized residuals for Test Battery 2