UNIVERSITY OF ALBERTA

MEASUREMENT OF ELECTROSTATIC CHARGE ON PROTECTIVE CLOTHING IN LOW HUMIDITY ENVIRONMENT

BY

KWABENA OSEI-NTIRI

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS ENTITLED **MEASUREMENT OF ELECTROSTATIC CHARGE ON PROTECTIVE CLOTHING IN LOW HUMIDITY ENVIRONMENT** SUBMITTED BY KWABENA OSEI-NTIRI IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN CLOTHING AND TEXTILES.

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ABSTRACT

This research describes and gives results of tests performed with three clothed human subjects to measure the static propensity of a series of protective garment systems. Garments tested were made of Nomex III®, No-Mo-Stat®, FR cotton and untreated cotton. Electrostatic discharge potential was measured and transferred charge and discharge energy were calculated after human activities: rubbing coveralls across a truck seat, (Experiment 1) and walking and removing parkas worn by test subjects (Experiment 2). Experiments were conducted in an environmental chamber at room temperature and 0% r.h. Garment systems with inherently antistatic fibres (Nomex IIIA® and No-Mo-Stat®) in outer layers produced the least energy in both experiments. Non-antistatic outer layers (Nomex III® and FR cotton) in the clothing system produced high energies. In systems with non-antistatic outer layers (for Experiment 1) the systems with similar generic fibre content in both coveralls and shirts produced the highest energies. Systems with anti-static fibres in the shirt but in which the outer layer is made from different fibres produced negative electrostatic discharges in experiment 2. All other systems produced positive charges.

Frictional charging produced larger energy values than charging through contact-separation. Under dry environmental conditions both anti-static and non-antistatic fibres are

capable of producing sufficient energy to cause ignition of most flammable gases.

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CHAPTER 1 INTRODUCTION

Background

The phenomenon of static electricity was first reported as far back as 600 BC by the Greeks (Cross,1987). However, only by the sixteenth century were efforts made to investigate the general characteristics of electrostatic phenomena. Such phenomena were demonstrated in various experiments by such pioneers as William Gilbert in 1603 and Du Fay in 1733 (Glor, 1988). It was only comparatively recently, particularly during the industrial revolution, that great concern was expressed and the importance of electrostatic effects recognized. A great increase in the production and corresponding widespread use of synthetic fibres (clothing, carpets, upholstery) during the latter half of the 20th century have made the generation and accumulation of static electricity inevitable, mainly because of the hydrophobic nature of the products, especially at lower relative humidities (Ramer and Richards,1968).

A majority of these materials readily become charged with static electricity upon making contact with, and subsequent separation from, other materials. They are able to retain the charge for long periods of time, especially in dry conditions when their ability to dissipate the charge is very poor (Wilson,1987).

The effects that can arise from the build-up of electrostatic charges can be described as being on a continuum from nuisance to catastrophe. Some of the well known undesirable effects include clinging of charged clothing together or to the body. Dust is attracted 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 out of the seat of a car, 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. A discharge can occur without direct contact. The electrostatic field on a charged person or material can destroy or zap a component by an induction mechanism (Matisoff,1986; Roth,1990). Another most serious effect of electrostatic spark discharge is the ability to ignite flammable gases, vapors, or powders at industrial sites, resulting in fires and explosions and the possible loss of human life. For example, in the petrochemical or oil industries there are often highly flammable and explosive gases and chemicals which can be ignited by static sparks developing from the rubbing of clothing worn by personnel (Wilson,1987).

"Static electricity is a fact of life and is around us at all times. It cannot be eliminated, but it can be controlled"

(Matisoff,1986, p.6). Electrostatic discharge (ESD) is defined in the U.S.A. military handbook DOD-HKBK-263 (cited in Matisoff,1986, p.9) as a transfer of electrostatic charges between bodies at different potentials caused by direct contact or induced by an electrostatic field. This transfer of electrostatic charge causes the various hazards and problems described earlier. Many countries as a precautionary measure control undesirable static electricity by means of codes of practice and industry guidelines. In the United States the most commonly used general industry guideline is the American Petroleum Institute Recommended Practice 2003,- "protection against ignitions arising out of static, lightning, and stray current" (Bustin and Dukek,1983).

Many antistatic treatments are available for use with clothing and other textiles to reduce the effect of electrostatic discharges. One modern approach to solving the electrostatic problem has been to provide a permanent antistat such as inclusion of small quantities of either carbonized fibre or metal filament.

Statement of Problem

This research was part of a larger study which addresses the problem of predicting the static propensity of protective clothing assemblies for use in hazardous environments where explosive gases are present, especially at very low temperatures and low relative humidities. The overall purpose is to determine appropriate methods for the measurement of charge generated on different types of protective clothing assemblies due to human activity in a dry climate, and the subsequent dissipation of such charges. Based on incendive criteria for the discharge or spark which can arise when such charged clothing is brought into proximity with the ground, it should then be possible to make recommendations regarding the specification of safety levels and or the provision of suitable clothing for various hazardous environments, as in the petrochemical and oil industry.

Objectives

The specific objectives of this research can be stated for each of two main experimental procedures that were conducted: Experiment 1 (rubbing of the garments against a simulated truck seat) and Experiment 2 (removal of the outer garments in a garment system).

Experiment 1. The objectives were:

a. to simulate the rubbing of a clothed body over a vinyl covered truck seat;

b. to measure (and characterize) the resulting discharge from the human body when it comes in contact with ground; and

c. to compare the magnitude of such discharges for various protective clothing systems at normal room temperature (approximately 22°C) and zero percent relative humidity.

Experiment 2. The objectives were:

a. to determine (i) the quantity of charge generated and (ii) the energy of the discharge from the human body when the outer garments in a clothing system are removed; and

b. to compare the magnitude of discharge for various protective clothing systems at 0% relative humidity and normal room temperature (approximately 22°C).

Justification

The concerns expressed by textile scientists and others regarding electrostatic phenomena on clothing have resulted in all kinds of antistatic products, both temporary organic additives and permanent solutions. Examples of permanent antistatic protective clothing fabrics are Nomex IIIA® (93% Nomex aramid, 5% Kevlar® aramid and 2% nylon sheath/carbon core fibre) and No-Mo-Stat® (99% aramid and 1% stainless steel fibre).

It should be noted that the determination of appropriate policy regarding static propensity of protective clothing in such industrial work places as the petrochemical industry has never been unanimously agreed upon. Therefore at present, there is no specific clothing policy regarding static electricity nor are there any generally accepted industry-wide standards. Standards are needed for proper evaluation and characterization of all static control materials (fabrics), and little progress has been made to date. Clothing policy and standards are essentially left to each firm to design any method they find fit in evaluating static control products and measures. The consequences of such "laissez-faire" safety policy, are the undesirable effects of electrostatic phenomena in the industry (McAteer,1987).

Many workers in these hazardous environments where highly flammable and explosive gases and vapors are found wear thermal protective clothing like Nomex® (aramid fibre) or flame retardant cotton, but some of these workers have questioned the safety of these, especially Nomex® when it comes to electrostatic dissipation as compared to that of 100% untreated cotton garments.

Cotton, a hydrophillic fibre is known to have a surface resistivity at standard textile testing conditions of about 10^{10} ohms per square which in the view of textile scientists is considered safe as far as static charge accumulation is concerned. These conditions are not present in Alberta, however. At low temperature and low relative humidity, both cotton and aramids are considered static prone (Wilson,1977/78).

E.I. Dupont de Nemours and Co. has strongly defended the antistatic characteristics of No-Mo-Stat® fabrics as "satisfactory throughout the life of the garment". But there is no independent confirmation of its antistatic behaviour under very dry conditions. Although an experiment was conducted by the U.S. Air Force (Opt and Ross,1974) to study the electrostatic properties of some protective clothing materials such as Nomex®, pbi®, Nomex/stainless steel, it was done at normal room temperatures (21°C) and at 20% relative humidity. What such work and most others have been measuring was the effect of relative humidity on static electricity or, in other words, what was being demonstrated was really the effect of moisture content. Research such as the Quartermaster Cold Chamber Studies (Crugnola and Robinson,1959) which was conducted at a very low temperature (-40°F) did not use protective garments but used ordinary synthetic and natural fabrics. Thus there has been no low temperature and low humidity research carried out with today's protective fabrics such as No-Mo-Stat®, Nomex IIIA®,pbi®,Kermel® or Proban® (flame retardant cotton). Even though some of these are protective fabrics which are also designed to reduce the problem of static electricity, and which would be expected to do so at low humidities, it is not yet clear how well these may work under conditions of very low relative humidity. This research is intended to address this gap in our current knowledge as textile scientists.

Definition of Terms

In discussing static electricity, it is very important that there be a clear definition of terminology and basic mathematical relationships. The following definitions are used for this research.

Static Electricity

Static electricity deals with the relationships between stationary charges. It also connotes the phenomena of attraction (when two opposite electrically charged bodies come into contact) and repulsion (when similarly charged bodies come together) due to electric flow (dynamic electricity). The level of static electricity is governed by two mechanisms: charge generation and charge dissipation (Glor,1988).

Electrostatic Propensity

is the capacity of a non conducting material to acquire an electrical charge by induction or triboelectric means (rubbing with another material) and to hold such charge.

Static Charge or Charge Generation (Q)

A static charge (positive or negative) is considered to be the amount or quantity of electricity generated in a body or material. Charge generation is created by the separation of materials which were previously in contact. During contact, the dissimilar materials are considered electrically neutral (state of equilibrium). The unit of static charge is the coulomb (c), which corresponds to a charge of 6.25×10^{18} electrons.

Electrostatic Discharge (ESD)

ESD is a transfer of electrostatic charges between bodies at different potentials caused by direct contact or induced by an electrostatic field.

Charge Decay or Electrostatic Decay Half-Life

Charge decay may be indicated by the electrostatic decay half-life which is the time required for the maximum charge (or voltage) induced on the fabric (material) to be reduced to one-half of the maximum charge (or voltage) by various decay mechanisms, for example conduction and ionization of the air.

Potential (V)

Potential is an energy stored in stationary electric charges. In other words, potential is a measure of the electrical forces which are present in a given situation. The potential at a point is the work done carrying a unit charge to that position from a position of zero potential. The unit of electric potential (the volt) is the same as work/unit charge or energy/unit charge (Cross,1987).

Capacitance or Capacity (C)

The capacitance of an article is a measure of its ability to store charge. When an isolated conductor is given a charge (Q) it attracts or repels other charges and may be said to have a potential (V). The ratio of the charge on the conductor and the potential to which it rises is called capacitance (C) and it is represented by this equation:

$$C = Q / V$$

$$\text{(farads)} = \text{(coulombs)}/\text{(volts)}$$

The value of the capacitance depends on the size and geometry of the conductor and its position with respect to earth. The unit of capacitance is the farad.

Current

Current is the rate of transfer of charge. The practical unit of current is the ampere, a transfer of one coulomb per second.

Conductor and Non-Conductor

A conductor is a medium through or on which electricity can pass easily. A non-conductor or insulator, is a medium which prevents or reduces the flow of electricity. There is no sharp distinction between conductors and insulators; instead materials can be rated from good conductors or poor insulators to good insulators.

Resistance/Surface Resistivity

The electrical resistance of a specimen is the voltage across the specimen divided by the current through it as per Ohm's law:

$$R \text{ (ohms)} = V \text{ (volts)}/I \text{ (amps)}$$

In surface resistivity of a fabric (resistance across the surface of a fabric), the geometric shape is very important and therefore surface resistivity (R) is defined as the resistance in ohms per square. Because of the wide range of resistivity values, results are often expressed in terms of the logarithm of resistance.

CHAPTER 2 LITERATURE REVIEW

The Basic Theory of Static Electricity

Triboelectric Effects

The phenomenon of static electricity can be divided into two separate ones, charge generation and charge dissipation (electrostatic discharge). According to Roth (1990), the primary sources of charge generation are usually the triboelectric and induction effects. Electrostatic charges are invariably produced at the interface between two dissimilar materials when they are brought into firm contact with each other and separated. In that position, electrons pass from one material to the other without the addition of energy.

The direction of transfer of the electrons depends upon the relative position of the energy levels of the surface electrons. The orbits around the nucleus of atoms of a material are considered to be energy levels which are either occupied or unoccupied by an electron. The outer electrons of the atoms have a greater influence on each other than the inner ones and therefore the energy levels represent the outer orbits. The energy required to cause the removal of an electron from the surface of cne material to the other is called the "work function" (Wilson,1987,p.17). When the two materials make contact, the one with the lower work function loses electrons to that with the higher work function. The surface of the material from which there is a net loss of electrons then acquires a positive charge and the other one receiving electrons becomes negatively charged.

Energy level models are used to explain the difference in electrical conductivity between metals (conductors), insulators and semiconductors. A material (eg. metal) is considered to be a good conductor if the outer energy level has just one electron. If the energy level is full, this means no electrons can be detached easily by an electric field. The material is therefore an insulator. The number of mobile electrons and "holes" within an insulator is very low and electronic conduction in insulators is also very low (Cross,1987).

Many textiles and polymers come into this category and the causes of contact charging are more complex. In practice the surfaces of textiles are usually contaminated with additives, finishes, dirt and moisture in all of which resides an abundance of ions. Thus in these materials, ionic conductivity exceeds electronic conductivity. Ions are positively or negatively charged particles which are produced when the individual atoms and mclecules of a material lose or gain one or more electrons. That is, ions as well as electrons which are at the surfaces of twc fabrics may take part in the charging process when the materials are brought into contact. Even if all the energy levels are occupied, there may be a charged layer at the surface of an insulator. Thus ionic conductivity in polymers is mostly due to the various (charge layer) additives applied to the fabric before and after processing. In No-Mo-Stat® (protective clothing) the blending of stainless steel fibre with aramid fibres creates discrete conductors on the fabric and thus reduces static electrification to safe levels by an air ionization phenomenon rather than by electrical conductivity (Owens,1984).

The explanation and examples cited so far describe electrification due to simple contact and separation. In practice, however, charges are often produced by rubbing surfaces together which increases contact. The characterization of the charging behaviour of materials, textile fabrics, is determined by observing the polarity (sign) of the charges on pairs of different fabrics after rubbing and then separating. A triboelectric series can be established such that any fibre when rubbed against another lower down the series become positively charged and vice-versa.

Induction Effect

Charge generation through induction occurs on a conductive material that comes within range of an electric field. (Here no electrical contact is necessary between the object to be charged and the source of the electric field). In a majority of cases (e.g.in a real life situation with a clothed person), the person carries the electrostatic charge. The human body is a good conductor of static electricity and therefore one of the primary sources responsible for electrostatic discharges and can be used to illustrate both triboelectricity and induction (Roth,1990). In a typical clothed person, the uter layer of the clothing of such a person, insulated from ground by the footwear and the floor covering, may be charged after contact with an external surface from which it has then separated. The electric field from the charge is directed towards the body by induction and the neutral body then becomes polarised and the charge builds up with each contact with other external surfaces. The electrostatic charging current is very low under these conditions so that the total electrostatic charge that can accumulate on a person is normally of the order of a few microcoulombs. The electrical capacitance of the human body is also very small and therefore requires little charge to cause a rise in potential of several thousand volts, depending of course on the environment, since the following relation holds (Wilson,1987):

$$Q = VC \text{ or } V = Q/C,$$

where Q (charge) is measured in coulombs, V (potential) in volts and C (capacitance) in farads. Should the person in this charged condition touch a grounded conductor, a spark discharge is produced which in a hazardous environment can cause an explosion or fire.

Electrostatic Hazards Defined

Static electricity manifests its destructive nature mainly through electrostatic discharges (ESD). The electrostatic build-up on people or materials, particularly non-conductive materials (fabrics), can be significant in the dry cold conditions of Canada's Arctic (Hidson,1976) or even Alberta. The average individual walking across a non-conductive floor or sliding across the seat of an automobile can generate from 3000 to 7000 volts (Matisoff,1986 and Sclater,1990), or depending on the environment (e.g.low relative humidity), the voltage can rise to 15,000 volts or more (Sclater,1990). The ability of many fabrics to hold on to an electrostatic charge is a function of the relative humidity of the environment (Gibson and Lloyd,1965; Ramer and Richards,1968; Sereda and Feldman,1955,).

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 encountered are too small. Depending on the individual, the human body has a threshold for shock of over 3000 volts (Sclater,1990). However, a discharge spark of less than 50 volts can cause damage to ESD-sensitive components (McAteer,1987 and Sclater,1990). The energy dissipated in the spark as heat also provides the source for ignition of flammable gases and solvent-air atmospheres and causes other damage (Gibson and Lloyd,1965; Hidson,1976).

Spark discharge occurs when the electric field strength exceeds the breakdown value for the surrounding atmosphere (Gibson and Lloyd,1965; Wilson,1987). For a person, the discharge is initiated by the electric field in the gap between, say, a touching finger and the grounded conductor, which causes the air to become ionized because of the movement between electrons from the body and ions in the air. The electrons and ions are accelerated in the field, and by colliding with one another gain energy which is finally dissipated. As a result of this dissipation of energy, other active molecule fragments are created and the temperature increases which, when it reaches a certain critical value, can ignite a mixture of air and a flammable gas or vapor present (Wilson,1987). In the case of insulating and discrete conducting fabrics, surface discharge is initiated when a grounded probe is moved towards the charged object. The possible ignition of flammable gases and vapors in the atmosphere of certain industrial environments, for example, oil refineries, is a cause for concern to persons responsible for the safety of workers.

The possibility of an incendive discharge can be estimated once the circumstances of charge accumulation are known. Charge accumulation on an 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 a conductor can discharge all the static electrical energy instantaneously in the form of a spark of energy E (joule) given by:

$$E = \frac{1}{2} CV^2 = \frac{1}{2} QV$$

where, Q (coulomb) is charge, C (farads) is capacitance, V (voltage) is electrical potential (Gibson and Lloyd,1965; Owens,1984; Glor,1988).

In the case of electrically insulating materials (fabric), however, their high surface and volume resistance 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 cannot 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. This means, the incendivity of a discharge depends not only upon the amount of energy or charge released, but also upon the time distribution of the energy (Gibson and Lloyd,1965; Glor,1988). A corona discharge extended in time is less incendive than a short-lived spark discharge 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 (Löbel,1987). The brush discharges, unlike the lichtenberg or propagating brush discharges (which could have incendive energies as high as 75 mJ), are not expected to have energies that exceed about 2 mJ (Owens,1984; Glor,1988). A clothed person upon removal of outer clothing, however, could be charged up to 15 kv due to brush discharges. The resulting sparks may zap an eletronic system or device or it may ignite gas/air-mixtures (Löbel,1987)

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 and Lloyd,1965; Gibson and Harper,1987; Glor,1988; Owens,1984). According to Bustin and Dukek (1983), saturated hydrocarbon gases and vapors require about 0.25 milijoules of stored energy for spark ignition of optimum gas-air mixtures. Wilson (1977/78) also showed that the minimum ignition energy of coal gas and air is 0.03 mJ, of natural gas and air is 0.30 mJ and fuel vapor and air is 0.20 mJ.

The figures in Table 1 are representative of the minimum ignition energy (MIE) and corresponding potentials in an individual (C = 200×10^{-12} farads) necessary for ignition (Crugnola and Robinson,1959; Opt and Ross,1974). Thus, a clothing system which produces a potential on the person exceeding 2650 volts is capable of igniting gasoline-air mixtures as well as all the other compositions listed. A potential of 650 volts is capable of igniting certain primer materials, such as lead azide, which are important in military uses. In general terms, and for safety purposes, one estimate takes the minimum ignition energy for most flammable vapor/air mixtures within the range 0.15 to 2 milijoules (Wilson,1987).

Table 1. Ignition Energy And Corresponding Potential[a]

GASES	IGNITION ENERGY (mJ)	CORRESPONDING POTENTIAL FOR IGNITION (volts)
Methane	0.5	2150
Gasoline	0.8	2650
Ether (diethyl)	0.2	1350
Cyclopropane	0.2	1350
Benzene	0.5	2150
Acetone	0.6	2350
Copper acetylide	0.002	150
Lead azide	0.04	650

[a]adapted from Opt and Ross (1974); Crugnola & Robinson (1959)

Small Scale Laboratory Tests

Field Intensity

An electrostatic field is the region surrounding an electrically charged object. This charged object, when brought in close proximity with an uncharged object, can induce a charge on the formerly neutral object. This is known as an induced charge. Quantitatively, it 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 (electrostatic effect) 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 et al,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

Measurement of electrical resistivity is a standardized and frequently used technique for the evaluation of electrostatic propensity of fabrics (Coelo,1985; Löbel,1985; Morisseau and Lewiner,1987). The most widely accepted laboratory method used is that of electrical surface resistivity and, occasionally, volume resistivity. The advantage of this kind of measurement over the determination of surface potentials are many fold. 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,1985; 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 measuring technique: 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 a fraction of a second or only milliseconds. That means if the resistance depends upon the time period it is evident that an inaccuracy is to be expected (Löbel,1985).

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). 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 (built up) on a textile fabric will depend both on 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).

For a fabric to meet the anti-static or static decay requirement of various military and /or National Fire Protection Association (USA) specifications, the potential on the fabric must decay from 5,000 to 500 volts (90%) within 3 seconds or less (Matisoff,1986; Owens,1984). On the other hand, a fabric with a resistivity of 1.0×10^{15} ohms per square has a time constant for leakage of about $2\text{-}5 \times 10^3$ seconds or 40 minutes (Wilson,1963). Any charge produced will, therefore remain on the fabric for a considerable length of time.

Methods For Characterizing Spark Discharges

For ignition characteristics, electrostatic discharge between a planar distribution of a charge on an insulator surface and grounded electrode in an open (air/propane) atmosphere was investigated by Rizvi and Smy (1992). Most of the discharges were found to be fragmented into a series of small sparks (non-incendive and incendive). The non-incendive sparks threshold was found to be controlled by the applied surface potential. On the other hand, the incendive threshold showed a variation of surface potential with charge density. Similar experimental procedures were employed to investigate the spark discharges from different protective fabrics such as Nomex III®, No-Mo-Stat® and Nomex IIIA® (Rizvi, Smy, Crown & Osei-Ntiri,1991). Charges were generated on the fabric surface inductively by applying an external potential. Discharges from the conductive fabrics showed varying degrees of discreteness and the electrical discharges were quite energetic. The possible explanation for the high discharge energies were that charges are drawn by conducting fibres from across the surface, resulting in the higher discharge energies. This experiment was conducted by charging the fabrics to maximum theoretical limit and thus may not be true representation of the real situation. Thus, the importance of conducting experiments with the clothed human body.

Human Experiments

The primary sources of charge generation of concern in electrostatic discharge, in practical situations, are usually the combination of triboelectrification effect (to charge the clothing) and induction (to charge the body). The electrostatic charge which is involved in a human spark scenario is thus often generated on the clothing or foot wear of the individual and induced onto the skin.

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. Such human activities generate and induce enough charge onto the body for subsequent discharge of sufficient energy to ignite flammable gases and vapors. None of these experiments were carried out in the field and thus the electrostatic discharges measured were not a reflection of real life situations where the clothed person has to operate under natural environmental conditions. Research at institutions such as the Arctic Aeromedical Laboratory (U.S.A.), the Quartermaster Research Establishment and Engineering Command (U.S.A.) and the Shirley Institute (U.K.) 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 and Millard, 1963) was specifically on the accumulation of static electricity on Arctic clothing. In the experiment, three different Arctic clothing outfits mainly made from nylon were worn by fifteen different subjects. The experimental procedure was to dress the subject in a given clothing assembly in the laboratory. He then walked outside where an insulated clip leading to a condenser was attached to the various parts of clothing in turn while he exercised. The electrostatic charges on the clothing systems and the capacitances of the subjects were measured using a Sweeney Model 1170 electrostatic voltmeter. The subjects re-entered the laboratory and removed their outer garments one after the other and the electrostatic discharges from the body measured. The experiments were conducted at ambient temperature 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 (1977/78) study 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. A variety of garments and chair coverings were tested. The garments were the type worn by military personnel and were made of fabrics such as Teklan (polyester) and linen/polyester coveralls, Nomex® and cotton flying suits and polyurethane coated nylon foul weather suits. The chair cover materials were types used in aircraft and armoured fighting vehicles. They included 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 by means of a Rothschild Static Voltmeter Type R-1020. This work was done at relative humidities in the range 15% to 80%, at 21°C. The result showed that cotton as well as synthetic fabrics are static prone at low humudities. The relative positions of the fabrics in the triboelectric series also help to determine their various magnitude of electrostatic discharges when rubbed against the chair cover.

Crugnola and Robinson (1959) investigated the extent of electrostatic hazard due to military clothing under both warm and very cold conditions. Thus there were two main experiments. The experiment at 75°F was to demonstrate the effect of removing garments and the effect of humidity on the magnitude of energy produced. The second experiment conducted in a cold chamber measured body voltages at temperatures ranging from 20°F to -40°F. The clothed person was insulated by either a rubberized or a plywood platform. The clothing system worn by the subjects comprised a cotton field jacket, a nylon body armour vest, and a wool/nylon shirt. A Keithley Model 200 Electrometer and Rawson Electrostatic Voltmeter Type 518 were used to measure the electrostatic potentials with respect to ground over a range of -10,000 to 10,000 volts. This study demonstrated that when an outer layer of clothing was removed, the energy produced was significantly higher at -40°F than at 20°F, likely due to the difference in moisture content of the air and thus the clothing.

The research reviewed above has concerned the measurement of charges accumulating on the body or the material on a clothed human subject. Voltages measured on separate items of clothing give an insight into the relative contributions of different materials. Magnitude of body voltages generated tend to vary widely from one research laboratory to another, depending on the condition and technique of testing, but the general trends are usually very similar.

The present research followed similar procedures. However, this experiment differed from previous ones in that the clothing systems included modern thermal protective clothing materials, and the experiments were conducted at 0% relative humidity.

Generally, some of the reasons researchers give in support of laboratory experiments in electrostatic assessment have been the large number of variables present in real situations: values of ignition energies, the capacitance of the human body, relative humidities and the overall test conditions vary according to location and may be constantly changing (Hidson,1976, and Haase,1977). Also, it is often difficult to define electrostatic hazard in general terms. This means it is not possible to set up the worst electrostatic conditions likely to be met in the use of a particular clothing system. Therefore, the attempt is always made to approximate these worst conditions likely to be met in the field in the laboratory (Wilson and Cavanagh,1972).

Triboelectricity (rubbing/contact and separation) as in removal of outer clothing is the main electrostatic charging mechanism in the real situation (Wilson,1977/78; Roth,1990). Experiments involving the discharge of electricity from a clothed person, essentially depend on the electrical capacity of the body relative to its surroundings (Wilson and Cavanagh,1972; Wilson,1987). Also, the measurement of body voltage from a clothed person demonstrates that in most practical situations, it is the electric field from the charged body which causes the undesirable electrostatic effects (Matisoff,1986). The human experiments show an important property of electric fields, that is, their ability to cause conductors placed in them to become charged by electrostatic induction. The human body is a good conductor of static electricity and it may be used to illustrate the effects of induction (Wilson,1987).

Summary

The numerous experiments carried out by textile scientists in various institutions, especially the military, confirm in the first place, the occurrence of static electricity on the human being and on the clothing and shoes that we put on, given the right atmospheric conditions. The experiments also show the impact electrostatic discharges (ESD) have on our daily lives, from shocks to the human being, and in severe cases fire or explosion in oil and gas industries. All these characteristics were manifested when measurements of electrostatic discharges were taken on the fabrics and on a clothed person. The measurement of electrostatic charges has enabled experts to determine the minimum ignition energy of the various types of discharges (e.g. brush discharges) needed to ignite explosive atmospheres. It has been established from these studies that electrostatic charges on insulating surfaces or on the human body can produce sparks of sufficient energy to ignite flammable gases and vapors.

Even though science has enabled textile scientists to understand the concept of electrostatics, the subject of electrical discharges is still complex and misunderstood. This means, in considering a particular situation, it is often difficult to decide unequivocally whether say, a corona discharge, brush discharge or spark-like discharge (Glor,1988) will occur, and whether or not this discharge would be incendive. Therefore, knowledge of possible occurrence and incendivity of discharges which may be generated during particular industrial operations is important for electrostatic assessment.

CHAPTER 3 PROCEDURES

The research was divided into two phases. The first phase consisted mainly of exploratory laboratory experiments in which a few variables and small samples were involved. Structured observation was employed in the investigation to establish the reliability and validity of the observational data. The second phase involved two different experiments (human activities). Experiment 1 was the rubbing of the clothed human body over external surfaces: sliding on a simulated truck seat. Experiment 2 involved the removal of outer garments of the clothing systems.

Exploratory Phase I

The Determination of a Triboelectric Series

The first phase of the research is described as an exploratory one. The initial preliminary work was done to establish an appropriate triboelectric series, determining the relative polarities for several protective clothing fabrics. The different fabrics, in pairs, were rolled around each other and separated (frictional separation). The static charges on the fabric systems were measured, by an induction process, in a cylindrical Faraday-cage and the respective polarities recorded using an electrometer. It was possible to place both the protective clothing and vehicle seat cover fabrics in a triboelectric series (Table 2). The other fabrics (nylon, cotton, polyester and polyester/cotton blend) served as a guide since their location in a more general series is already known.

Table 2. Triboelectric Series.

FABRIC	CHARGE
Nomex III®	+ ve
Proban® FR cotton	|
Nomex IIIA	|
Vulcan	|
cotton	|
nylon	|
polyester/cotton blend	|
polyester	|
pbi®	|
vinyl (textured surface)	|
vinyl (smooth surface)	- ve

The series indicates that fabric of Nomex III® (aramid fibre) and Proban® (flame retardant cotton) will be positively charged and others such as pbi® and vinyl will acquire a negative charge when rubbed with other materials in the series. The development of this series helped to determine the best combination of layers for clothing systems to be selected and evaluated. Thus this process helped to qualitatively characterize the charging behaviour of the various fabrics, especially those used in protective clothing and both vinyl and nylon auto upholstery fabrics.

Development of Procedures for Phase II

Another exploratory phase of the research was the development of reliable procedures to produce, measure and characterize the charge generated and subsequently discharged on the different types of clothing assemblies due to human activities. The objectives of this preliminary work were:

i. to determine which activities could be replicated with sufficient reliability to be included in the final experiments which were to form the second phase of the research; and

ii. to experiment with the use of sensitive instruments like the high speed oscilloscope to measure and read the discharge characteristics from the clothed human body.

The preliminary experiments were conducted in a 122cm x 122cm x 213 cm high wooden structure which was enclosed (covered) with a transparent plastic. Two tubes connected to a dry air outlet supplied air into the chamber through two small holes at the top. There was an opening for the test subject to enter and to leave the chamber. The relative humidity in the chamber, at the beginning of the experiment was at zero percent, but it increased to approximately 5% while the subject was performing the experiment due to perspiration and breathing.

Three different protective clothing assemblies were worn by a subject alternatively during each experiment. The clothing systems used in the experiments included Nomex III®, No-Mo-Stat® and FR cotton coveralls, cotton shirt and jeans, cotton underwear and rubber-soled canvas shoes.

Two exploratory procedures were tried. The major difference between them was how the charge generated during the human activities was measured. The first procedure was to measure the charge on the garment directly, while the second was to measure the body voltage. The experimenter wore a cotton long sleeve shirt over a cotton T-shirt, and jeans. He then put on one of the experimental protective coveralls and rubber-soled shoes, walked into the chamber, and sat on the chair covered with nylon fabric. The subject slid over the chair five consecutive times and stood up. The charges generated on the outer garment were discharged through a grounded carbon fibre brush (electrode), via a capacitor to the oscilloscope for recording. The procedure was repeated for each protective garment five consecutive times at 0 - 5% relative humidity and 26°C. With this method of measurement, there was practically no signal recorded on the oscilloscope with any of the three protective coveralls, even though the subject always felt a shock at the moment the electrode (carbon fibre brush) touched the charged portion of the garment. A possible explanation for these observations is the fact that the electric field from the charge on the garment is largely directed towards the human body (a conductor) by an induction process. The outward field is too small to discharge substantially to a nearby grounded conductor, the carbon fibre brush in this context (Wilson,1987; Rizvi and Smy,1992).

From the above observation, it was concluded that for a meaningful and reliable measurement of electrostatic discharges from a clothed person, attention should be focused on the measurement of the body voltage. The second experimental procedure was the same as the first except for the technique of discharging the accumulated electrostatic charge. The charged person touched his fingers to a brass metal plate, (15 cm x 15 cm) which was grounded through a 100 kilo ohms resistor with a 100x or 1000x probe of an oscilloscope attached to it. The oscilloscope measured the corresponding discharge potential signal (which ranged from 2.2 - 2.9 kV) from the person wearing the NomexIII®, No-Mo-Stat®, and the FR cotton coveralls. For the final experiments the electrode was replaced by a spherical shaped metal electrode grounded through a 10^5 kilo ohms resistor. The latter device was used because this study was considered a worst case scenario and thus spark discharges were anticipated with their high amount of charges.

Phase II: Experiments on the Clothed Human Body

Phase II of the research included two experiments simulating two different human activities:

a. **Experiment 1:** In this experiment human subjects wearing the specified protective garment system slid over a vinyl covered truck seat and touched a grounded object.

b. **Experiment 2:** This experiment simulated conditions when a human body is charged due to simple movements such as walking for a distance and then removing outer garments.

Dry Chamber Laboratory

The experiments were conducted in a very dry environmental condition (close to zero percent relative humidity), and at normal room temperature (approximately 22°C). To achieve these conditions, a simple chamber was built based on the enclosed wooden structure for the exploratory experiments described previously. However, the second dry chamber had enough space (411.8 cm x 323.3 cm x 381.2 cm) to allow the subject to perform the various activities with little disturbance to the dry condition and to allow the experiments to be conducted with the sensitive measuring devices in place. Two tubes connected to a dry air compressor outlet supplied air into the chamber which was sealed with a heavy transparent plastic. There was a door the size of a normal size door for the test subjects to enter and to leave the chamber. This exit was provided both to maintain the zero percent relative humidity condition, as a longer stay in the chamber would have increased the moisture content, and to relieve the subject from the very dry environment. There were small holes at the door which were necessitated to balance the air pressure within and without.

Test Subjects

Three human subjects ("K","J" and "R" from hereon) with different physical characteristics such as height and weight, and wearing different sizes of garments were used in both experiments (See Table 3). The test subjects all wore identical insulating rubber-soled canvas shoes (Converse "All Star" brand) and identical cotton underwear during the experiments. They also wore latex gloves on both hands but had an opening for the finger to touch the spherical grounded electrode to discharge the accumulated charges.

Table 3. Physical Characteristics of Three Male Subjects.

SUBJECT	HEIGHT	WEIGHT	SIZE WORN			
			SHIRT	PANTS	COVERALL*	PARKA*
K	178 cm	84 kg	L	34	44	L
J	163 cm	77 kg	M	36	42	M
R	168 cm	68 kg	M	32	42	M

*All subjects wore size 44 No-Mo-Stat® coverall and No-Mo-Stat® parka.

Garment systems (independent variable)

Details regarding the garment systems worn by the subjects for Experiments 1 and 2 are given in Table 4 and 5 respectively. The parka components are detailed further in Appendices A1 and A2. During the experiment, Nomex IIIA® parka was worn inside out because the parka lining was Nomex III® rather than Nomex IIIA® (i.e. it did not contain the conductive carbon fibre). The parka lining was thought to be the crucial layer in determining charge generation for Experiment 2 (contact /separation charging).

Except for those made of No-Mo-Stat® the protective coveralls and parkas were purchased from Protective Apparel Inc. Cnada (P.A.I.). They were made from the same pattern. The No-Mo-Stat® garments were supplied by Alberta Occupational Health and Safety but were very similar to the other garments. All garments except the parkas were laudered, prior to testing according to CAN/CGSB 4.2 M58 procedures (see Appendix A3). The parkas were tested in their manufactured state. All garments were conditioned in the environmental chamber for at least 24 hours prior to conducting the experiments.

Table 4. Garment Systems For Experiment 1.

SYSTEM CODE #	COMPONENTS		
	COVERALL	SHIRT	PANTS
1	Nomex III®	cotton	cotton
2A	No-Mo-stat®	cotton	cotton
2B	Nomex IIIA®	cotton	cotton
3	FR cotton	cotton	cotton
4	Nomex III®	FR cotton	FR cotton
5A	No-Mo-Stat®	FR cotton	FR cotton
5B	Nomex IIIA®	FR cotton	FR cotton
6	FR cotton	FR cotton	FR cotton
7	Nomex III®	Nomex III®	FR cotton
8A	No-Mo-Stat®	Nomex III®	FR cotton
8B	Nomex IIIA®	Nomex III®	FR cotton
9	FR cotton	Nomex III®	FR cotton
10	Nomex III®	Nomex IIIA®	cotton
11	Nomex IIIA®	Nomex IIIA®	cotton
12	FR cotton	Nomex IIIA®	cotton

Table 5. Garment System For Experiment 2.

SYSTEM CODE #	COMPONENTS		
	PARKA	SHIRT	PANTS
A	Nomex IIIA®	cotton	cotton
B	Nomex IIIA®	FR cotton	FR cotton
C	Nomex IIIA®	Nomex III®	FR cotton
D	Nomex III®	cotton	cotton
E	Nomex III®	FR cotton	FR cotton
F	Nomex III®	Nomex IIIA®	cotton
G	FR cotton	FR cotton	FR cotton
H	FR cotton	Nomex IIIA®	cotton

Procedure For Experiment 1

For experiment 1 the subject picked up the specified undergarments and pants from the environmental chamber, put them on outside the dry chamber, re-entered the chamber and immediately grounded himself. After grounding, the subject subsequently put on the appropriate shirt and coverall (maintained in the dry environment) and again grounded himself. The subject approached the vinyl covered truck seat which was 147 centimetres wide, and sat halfway. He immediately began to slide from that position to the very end of the seat, stood up, walked two steps and with two feet firmly on the ground, touched the finger tip to a spherical electrode. The distance between the end of the truck seat and the grounded electrode was 251 cm. and it took approximately two seconds for the charged subject to discharge. The procedure was repeated at least ten times for each garment for each subject, with five minute intervals between repeated measures.

Measurement of Dependent Variables

The dependent variables for experiment 1 included discharge potential, total charge transferred and discharge energy. The charged person discharged by touching the electrode (as described earlier). A fast digital Tektronix model 2430A oscilloscope was connected to the electrode (iron metal) which has a 2 cm. diameter spherical tip and was grounded through a 10^5 kilo ohms resistor. The resultant discharge potential was measured across the grounded resistor through the oscilloscope within the shortest possible time (microseconds). A 7475A (Hewlett Packard) plotter was used to plot the graphic configuration of the spark discharges for analysis. The current was determined by dividing the discharge potential by the resistance. Total charge transferred was calculated by integrating the current wave form (see Appendix A4). Discharge energy was then calculated by the formula $E = \frac{1}{2} QV$. The body capacitance was estimated from the charge transferred in a discharge.

Procedure For Experiment 2

For experiment 2 the clothed subject walked around in a circle (an equivalent of 28 meters), stopped and removed the parka before discharging the induced body charge by touching the grounded electrode as in Experiment 1. The variables (potential, charge and discharge energy) were measured and calculated as for Experiment 1.

CHAPTER 4 RESULTS OF EXPERIMENTS

Results for Experiment 1.

Average and maximum discharge energies for each garment system are shown for each subject in figures 1 and 2. These values were plotted in increasing order of magnitude and the trend for each is similar. The positions of some of the garment systems and the absolute values are not the same for all subjects. Mean energy data are summarized in Table 6. Data on discharge potential and charge transferred are in Appendices B1 and B3. The trends for these latter variables are the same as those for energy.

When the clothed person slid across the vinyl covered truck seat, garment system 8B, (Nomex IIIA® coverall, Nomex III® shirt and FR cotton pant) was found to produce the lowest discharge energy, both average and maximum for all three subjects. Garment system 6, (FR cotton coverall, shirt and pants) produced the highest average discharge energies for two subjects and the second highest for the third subject. Table 6 summarizes the average energy data by garment system, grouped according to the material in the coverall (outer layer). It can be seen that the systems with the inherently anti-static fibres (Nomex IIIA® and No-Mo-Stat®) in the outer layer produced the least energy. In the systems without antistatic coveralls, those with shirts containing conductive fibres or regular cotton produced the lowest energy within such groups.

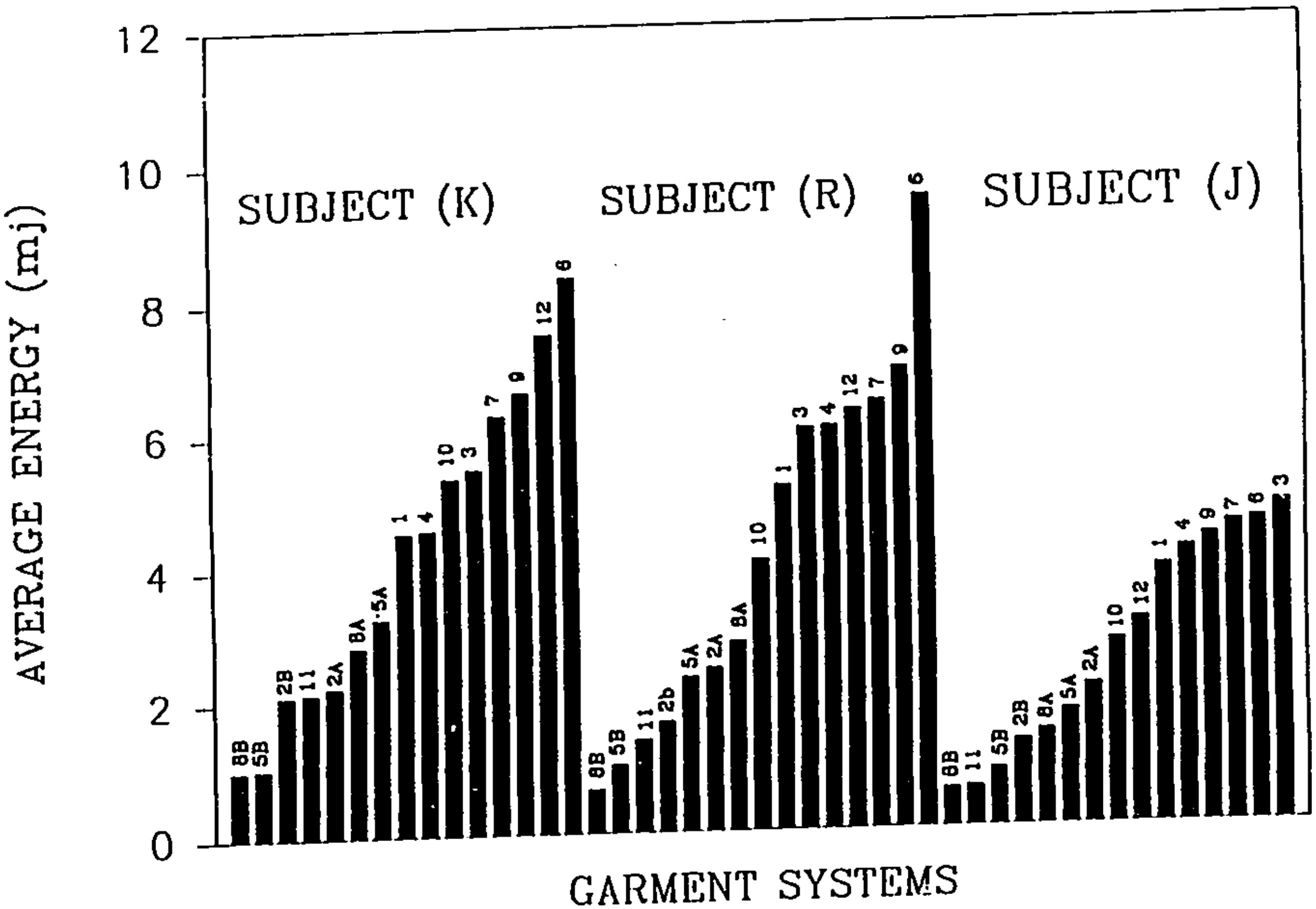

Figure 1. Average energy for three subjects

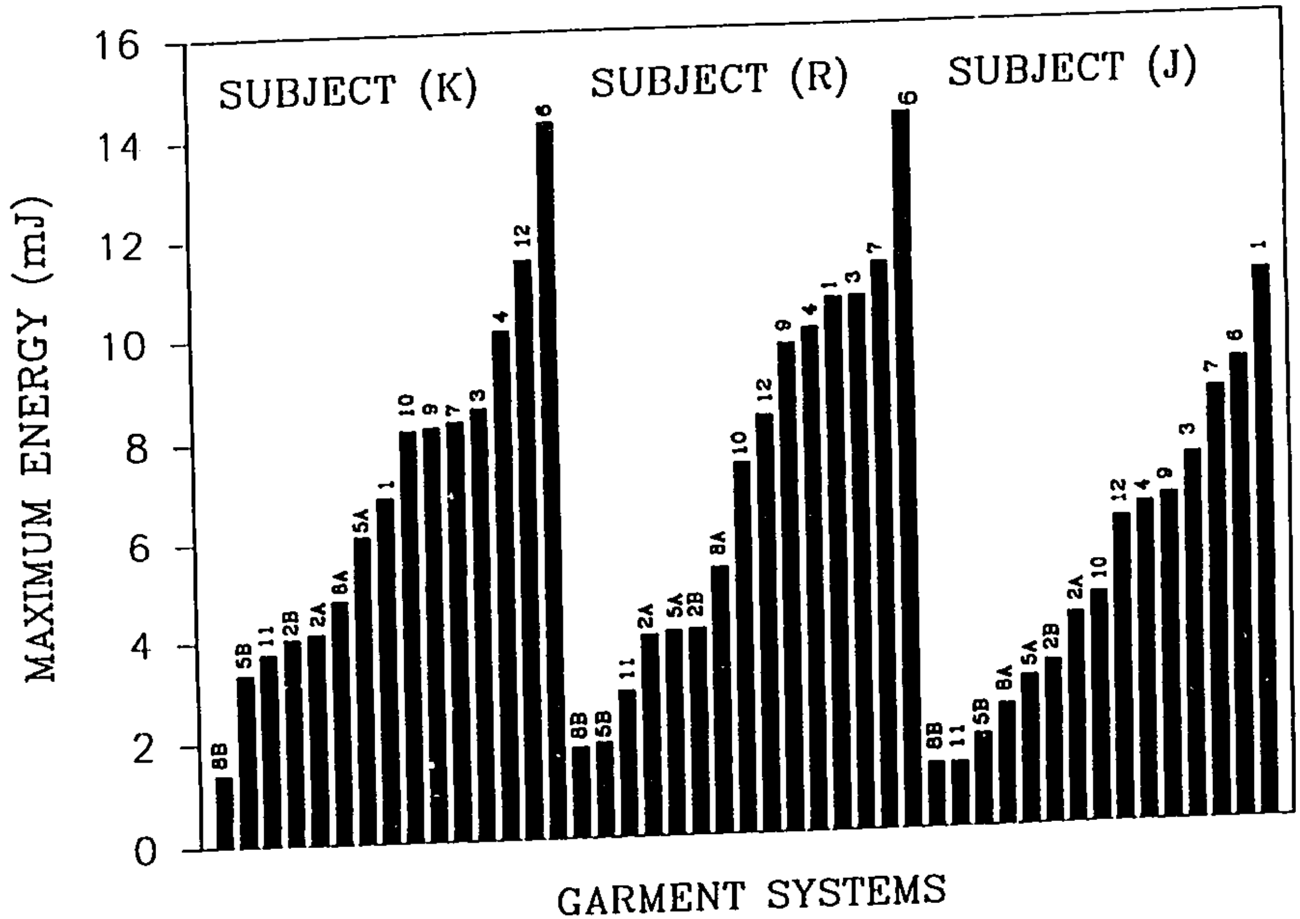

Figure 2. Maximum energy for three subjects

Table 6. Average Body Discharge Energies For Three Subjects

(Experiment 1)

SYSTEM	COMPONENTS COVERALL	SHIRT	PANTS	MEAN ENERGY FOR 3 SUBJECTS (mJ)
8B	Nomex IIIA®	NomexIII®	FR cotton	0.73
5B		FR cotton	FR cotton	0.95
11		NomexIIIA®	cotton	1.36
2B		cotton	cotton	1.66
			Mean	1.18
			Standard Deviation	0.41
2A	No-Mo-Stat®	cotton	cotton	2.24
8A		Nomex III®	FR cotton	2.35
5A		FR cotton	FR cotton	2.41
			Mean	2.33
			Standard Deviation	0.09
10	Nomex III®	NomexIIIA®	cotton	4.04
1		cotton	cotton	4.50
4		FR cotton	FR cotton	4.89
7		Nomex III®	FR cotton	5.70
			Mean	4.78
			Standard Deviation	0.70
3	FR cotton	cotton	cotton	5.41
12		NomexIIIA®	cotton	5.60
9		Nomex III®	FR cotton	5.92
6		FR cotton	FR cotton	7.42
			Mean	6.09
			Standard Deviation	0.91

There is some overlap between the systems with the Nomex III® coveralls and those with the FR cotton coveralls. In each of the latter two groupings, the system with similar generic fibre content in both coveralls and shirts (systems 7 and 6) produced the highest energies.

The polarity of the discharge energies from the body was positive for all of the garment systems worn. These discharge energies could also be described as spark discharges. Spark discharges normally occur in practice and involve conductive objects such as personnel insulated from ground. The total energy stored in such systems is released in a single spark and is therefore considered incendive (Glor,1987).

For any garment system, average discharge energy varied among subjects by as much as 50%. The sums of the average discharge energies produced from fifteen garment systems were almost the same for subjects K and J as was their weight/height ratio. Subject R, however, had relatively lower value in both parameters (See Table 7). The weight/height ratio of subject R was about 14% lower and the sum of average discharge energies was about 30% less than those for the other two subjects.

Table 7. Electrostatic Discharge Energies and Weight/Height Ratio.

SUBJECT	SUM OF AVERAGE ENERGIES FOR 15 EXPERIMENTS (mJ)	WEIGHT/HEIGHT RATIO
K	63.04	47.19
J	63.09	47.24
R	40.14	40.47

Results for Experiment 2

Discharge energies from the subjects produced by the removal of outer garments (parkas) from the clothing system are shown in figure 3 for two subjects and are summarized in Table 8. Similar data for charge and potential are found in Appendices B4 and B5.

The values are plotted in increasing order and the trend for each subject is similar. Garment system C (Nomex IIIA® parka, Nomex III shirt and FR cotton pants) produced the lowest discharge energy and garment system D (Nomex III parka, cotton shirt and cotton pants) produced the highest energy among the eight garment systems studied in experiment 2.

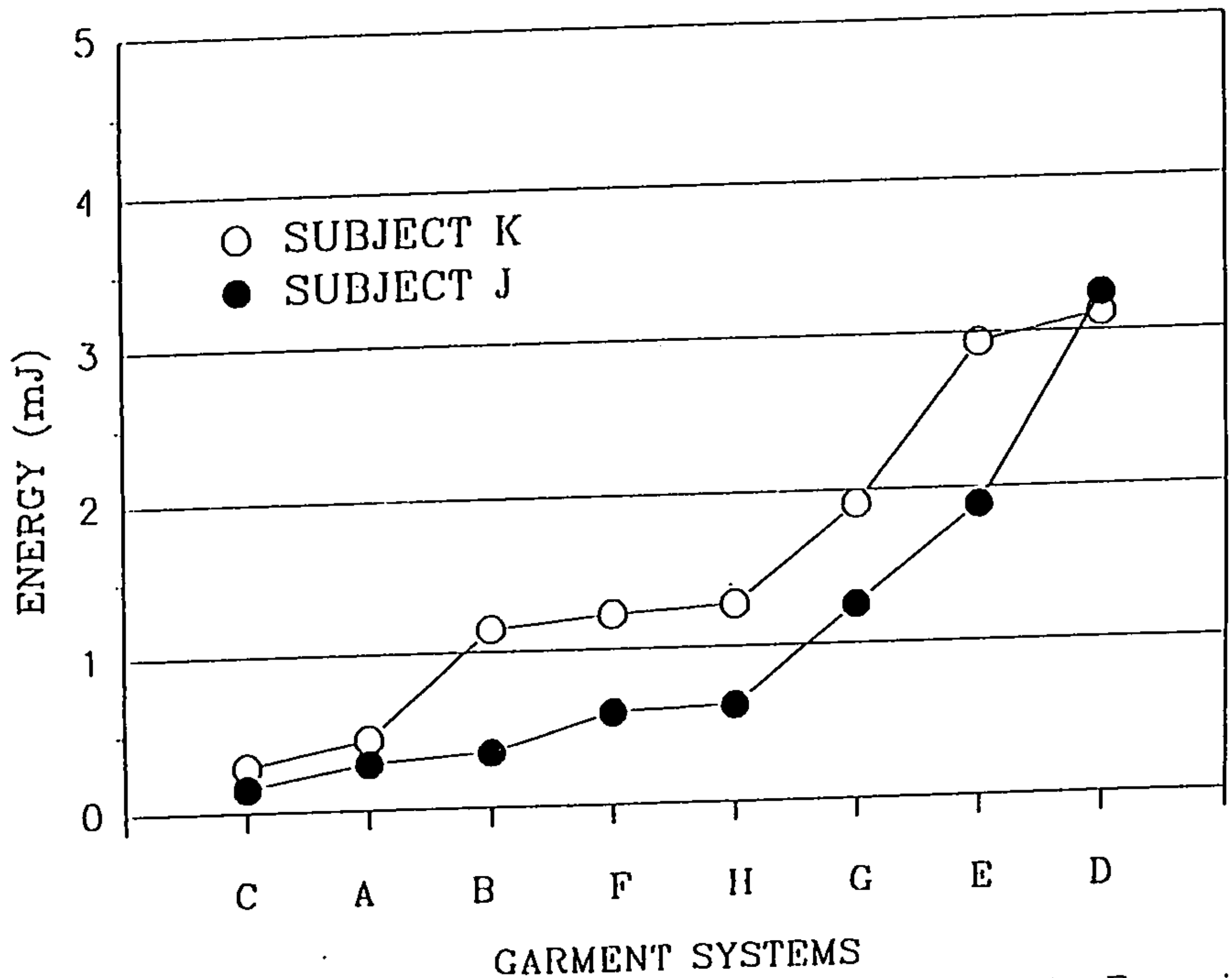

Figure 3. Average Discharge Energy for Subjects K & J in Experiment 2.

The magnitude of discharge energy in the charge separation experiment was found to vary with the time involved in the removal of the outer garments. The slower removal time of a parka (before discharging) produced lower body voltages as shown in figure 4.

Comparison of Experiments 1 and 2

Dependent variables (discharge potential, charge transferred and discharge energy) measured for the frictional charging (experiment 1) were found to be higher in magnitude than for separation charging in experiment 2. The mean and maximum body discharge energies for three subjects in experiment 1 were higher than those in experiment 2 by about 60%. In both experiments, however, systems with inherently anti-static garments (Nomex IIIA® and No-Mo-Stat®) produced the lowest average and maximum discharge energies as well as potential and transferred charge.

Table 8. Mean and Maximum Body Discharge Energies

(Experiment 2)

SYSTEM	COMPONENTS		ENERGY (mJ)	
	PARKA	SHIRT	MEAN[a]	MAXIMUM
C	NomexIIIA®	Nomex®	0.19	0.46
A		cotton	0.37	1.07
B		FR cotton	0.75	1.72
H	FR cotton	NomexIIIA®	0.95	2.03
G		FR cotton	1.59	4.10
F	Nomex III®	NomexIIIA®	0.91	2.14
E		FR cotton	2.42	6.00
D		cotton	3.19	5.80

[a]Mean based on 10 or more measurement per subject.

The garment systems with inherently anti-static fibres in parka layer (C, A, and B) produced the lowest energies, followed by the systems with the anti-static fibres in the shirts (F and H). The systems which produced the highest energies (E and D) had no anti-static fibres in the system and had parkas and shirts made from different fibres.

Garment systems F (Nomex III® parka and Nomex IIIA® shirt) and H, both with anti-static fibres in the shirt layer, produced negative electrostatic discharges from the body while all other systems produced positive charges.

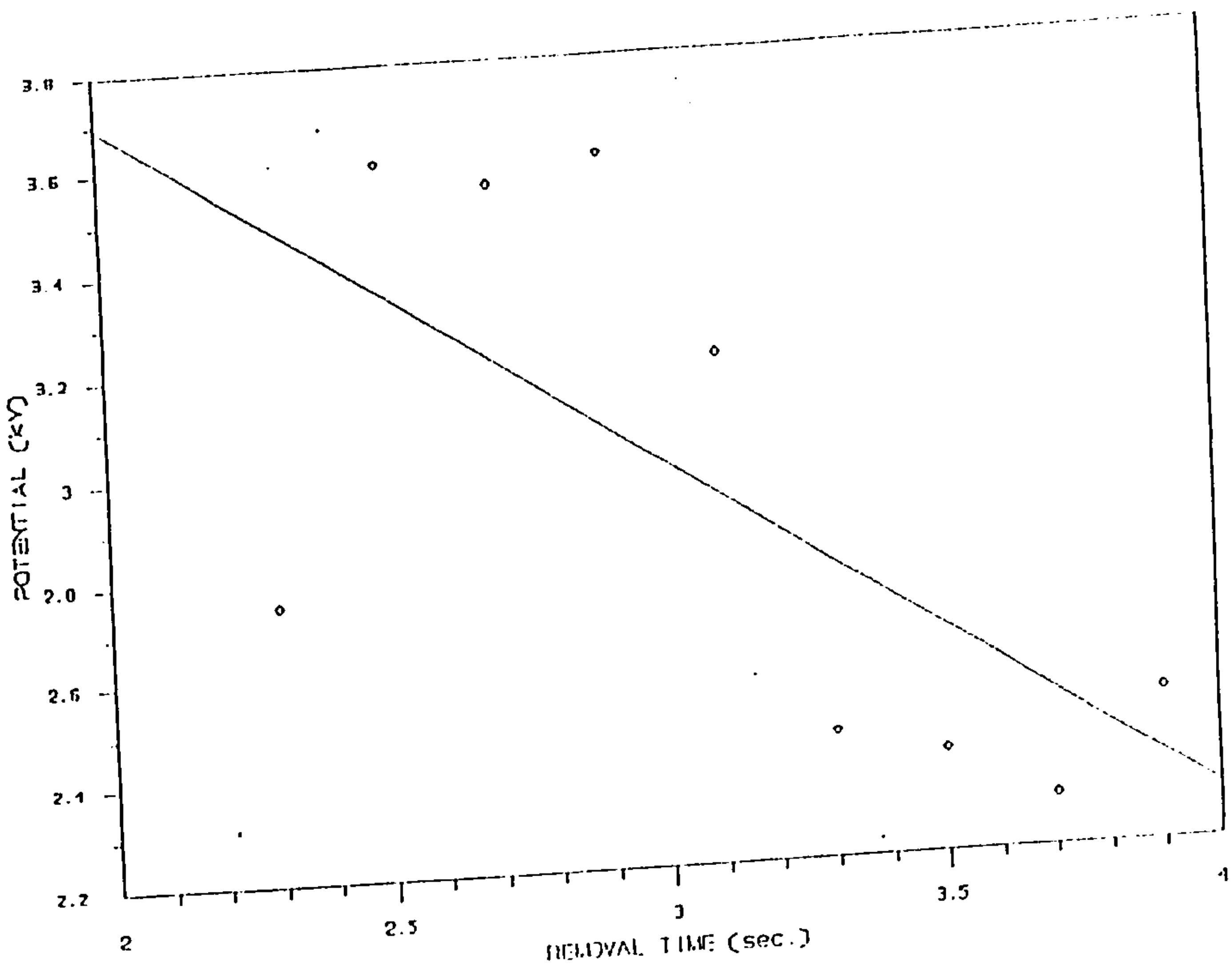

Figure 4. Effect of Rate of Removal of an Outer Garment on Body Charge.

CHAPTER 5 DISCUSSION

Experiment 1

This research was part of a larger study to address the problem of static propensity in protective clothing. The main objectives were to produce, measure and characterize the charge generated and subsequently discharged from garment systems due to human activities. Appropriate reliable procedures to meet these objectives were determined through many preliminary experiments. Experiment 1 simulated the frictional rubbing of a clothed human subject over a vinyl truck seat followed by touching a grounded object.

The ignition characteristics of electrostatic discharges from different but single layer thermal protective fabrics, were rather controversial. (No-Mo-Stat® and Nomex IIIA® have been marketed as anti-static conductive materials and should allow only minimal accumulation of electrostatic charges on their surfaces). When charged inductively to the maximum theoretical limit by applying an external potential they were found to produce higher discharge energies than the non-antistatic fabric Nomex III® at 22°C and 25% r.h. (Rizvi et al,1991). In the human subject experiments at severe environmental conditions described here, however, different results were achieved. Garment systems with anti-static fibres produced the lowest discharge energy compared to non-antistatic garment systems. These differences in findings are due in part to the fact that the fabrics in the human body experiment were part of a larger system which included several garment layers as well as the human body. Thus such factors as human body capacitance and resistance come into play. Another reason for difference in results is the different mechanisms of charging in the two studies.

As observed in figures 1 and 2, the garment systems with Nomex IIIA® coveralls would be preferable followed by those with No-Mo-Stat® coveralls. The systems without anti-static fibres in the coveralls are most likely to cause ignition in hazardous environments because of the high energy discharges. At very low relative humidity conditions (0% r.h.) non-antistatic fabrics (Nomex III® and FR cotton) can be charged by triboelectrification up to 12 kV (see Appendix B3). Garment systems with cotton as the outer layer, and even those with cotton in two outer layers performed no better than systems containing Nomex III®. This electrostatic behaviour of cotton at very low humidities agrees with findings of Wilson (1977/78). In low relative humidity environments cotton fabrics become static prone because their electrical resistivity is increased significantly when they absorb no moisture.

All of the protective garments can produce discharge energies higher than the threshold minimum ignition energy of 0.25 mJ (Lövstrand,1981 and Scott,1981). Even though systems with inherently anti-static fibres appear to perform the best in low humidity environments, they may still produce sufficient electrostatic charge to ignite some flammable gases when the clothed person discharges to a grounded object.

The electrostatic behaviour of non-antistatic garment systems with similar generic fibre content in the shirts and coveralls could be explained in part by understanding the charge generation mechanism and the resultant electron activities. Experiment 1 predominantly involved friction charging through rubbing coveralls against a truck seat. However, the subject's weight on the systems brought the inner layer into firm contact with the outer layer which later may have separated. When the subject stood up to discharge the induced charge on the body, he discharged a net charge from friction and separation not only of the coverall and truck seat but possibly of the coverall and shirt as well. The nature of the garment system (multiple layers) and the similarity of the outer and inner layers resulted in rather complex electron activities producing a net discharge energy that was both positive and high in magnitude.

The thickness of the fabrics in the clothing systems (especially, the non-anti-static systems) may also be a significant factor for the difference in magnitude of energy produced. It has been demonstrated elsewhere that electric charge increases with thickness of each layer when two layers of the same non-antistatic non-textile material are compressed and separated (Sharai,1981). In Experiment 1, FR cotton fabric of 0.64 mm thickness (CAN/CGSB-4.2 No.37-M87) produced discharge energy higher than did Nomex III® of 0.48 mm thickness. It is, however, difficult to use similar criteria (eg. thickness) to categorize Nomex IIIA® because of the presence of the discrete conductive fibre. The effect of fabric thickness requires further investigations.

The positive discharges from the human body suggest that the garment systems were charged negatively during the triboelectrification process (Cross, 1987; Scott,1981). The ignition probability for such positive discharges is normally high because of assumed formation of luminous channels at the grounded electrode (Lövstrand,1981).

The selection of three subjects with different physical characteristics for the experiments was mainly to assess the influence human body capacitance has on the magnitude of electrostatic discharges. In this study, the weight/height ratio of the subjects was used as a representation of capacitance (normally defined by formula $C = Q/V$) because the charge generated could not be measured directly.

Experiment 2

The electrostatic characteristic and corresponding incendive criteria of the energies in experiment 2, could be explained in part based on the findings of Lövstrand (1981) and Scott (1981) concerning the nature and behaviour of electrostatic discharges. For garment systems F and H (Nomex

IIIA® shirt), which gave negative body discharges, the charge generated on the remaining garments after the removal of the parka was a positive charge. This positive surface charge transferred and became a negative charge on the clothed human body. The incendive or ignition probability of the negative discharge energies to various flammable gases/air mixture is normally considered to be less than those for positive discharge energies. This means negative sparks do not form luminous channels but only very weak cones at the electrode surface (Lövstrand,1981).

Experiment I and 2

Many factors could have contributed to the electrostatic characteristics observed in the two experiments. The different methods of charging the systems (namely, the triboelectric charging through friction or only contact-separation charging mechanism) in themselves contributed to a great extent to the difference in the magnitude of energy produced in the two experiments. It has been demonstrated by Wilson (1977/78) that rubbing two surfaces together increases the area of contact between them, thereby producing more charge than if they make contact and separate only. Thus friction charging results in greater discharge energies compared to mere contact-separation charging.

The position of the various fabrics on the triboelectric series could also be a significant factor accounting for the difference in magnitude of energy discharge for experiments 1 and 2. By convention, the triboelectric series indicates the polarity (negative or positive) of charged material when such a material is rubbed against one below it in the series or when any two materials are pressed together then separated. It is presumed (Morton and Hearle,1986; Sclater,1990) that the magnitude of charge generated may be correlated with the relative distance between the various materials on the triboelectric scale. Thus fabrics well separated from one another on the scale may give in general, a greater magnitude of charge than those relatively close. In experiment 1 the FR cotton coveralls near the top of the triboelectric series (Table 2) rubbed against the vinyl seat at the bottom of the scale resulting in the highest production of discharge energy. Similarly, electrostatic discharge characteristics were observed for all the other outer garment systems for Experiment 1. They are all relatively farther apart on the triboelectric series from the vinyl surface they rubbed against. For Experiment 2, the separation of the parkas from the clothing systems produced less charge in part because the fabrics involved are relatively closer together in the series.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Two experiments simulated normal activities of workers wearing protective clothing: sliding across a truck seat, and removal of an outer garment (parka) from the clothing system. Both experiments were carried out at dry environmental conditions (0% r.h. and room temperature). Discharge potentials of electrostatic discharges from the body were measured and transferred charge and discharge energies were calculated. In general, the pattern of results for these experiments was predictable on the basis of other studies and the theory of static electricity. This means the magnitude of charge generation is influenced by such factors as contact pressure, the speed of separation or rubbing, contact area and ambient conditions. The magnitude of electrostatic discharges for each garment system and the interactions between certain materials were unknown, however.

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

1. Under dry environmental conditions (0% r.h. and 22°C) almost all of the protective garment systems can produce electrostatic discharge from the clothed human subjects in excess of 2650 volts in activities involving both frictional charging and contact-separation charging of outer garments. With average capacitance for the three subject of 207 pico farads, a potential exceeding 2650 volts on an individual is

capable of providing sufficient energy to cause ignition of gasoline - air mixtures and also all the other compositions listed in Table 1. Thus getting out of a vehicle, walking and removing a garment, or other activities that involve contact and separation of materials are capable of producing discharge energies equal to or even exceeding those demonstrated in the experiments conducted for this research. Even systems with inherently anti-static fibres which appear to perform the best in low humidity environments still develop sufficient charge to ignite flammable gases when discharged.

2. The average energy varied by approximately one order of magnitude among various systems. Garment systems with anti-static fibres produced the lowest energies. When there is no humidity in the air, systems with cotton garments as the outer layer, and even those with the two outer layers of cotton, perform no better than systems containing NomexIII®.

3. While variation of the outer layer in a garment system seems to have the greatest effect on the variables measured, variation of the other layers in the system also has an effect. This is more so for Experiment 2.

4. Of the two experiments, frictional charging produced larger energy values with most materials than did charging through counterpart contact-separation alone and therefore the former is the most relevant to hazard evaluation.

Recommendations

Recommendations for Industry

For industry, electrostatic discharges cannot be eliminated entirely but their effects can be 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 study in the development of any safety code or industry specification. The study tried to simulate a worse case scenario (i.e. extremely dry conditions).

It is recommended that protective garment systems for use in flammable atmospheres should be made from materials which include conductive fibres. In selecting garments for a system, the relative position in the triboelectric series of the materials of the various layers might be taken into account. The electrostatic discharge values obtained from this study have shown that discharge energies even from the inherently anti-static garment systems are capable of igniting most hydrocarbon-air mixtures and obviously the more sensitive primary explosives. It would therefore be quite unsafe to rely on anti-static clothing materials alone without more reliable methods of grounding personnel, for example by means of conductive footwear when possible.

The appropriate behaviour of personnel could also help to control electrostatic effects. The clothed person should never remove any garment from the clothing system while in the vicinity of an ignitable mixture or while handling explosive materials.

Recommendation For Further Research

The following are suggestions for further work in this area:

1. Parts of experiments 1 and 2 should be replicated at -40°C to determine if measurements taken at room temperature and 0% r.h. represent the low temperature conditions.
2. Parts of experiments 1 and 2 (i.e. the best and the worst garment systems) should be replicated at higher humidities (e.g. 5%, 10% and 20%). Special attention should be placed on garment systems with similar generic fibre content in both coveralls and shirts (7 and 6 systems).
3. The incendive characteristics of the spark discharges from the clothed person (i.e. positive vs negative charges) should be investigated further and their energy densities compared to the minimum ignition energies of various flammable gases.
4. Results of this research (human subject experiments) as well as those proposed above, should be compared to results of small scale laboratory tests such as electrical resistivity and different static decay tests. Such comparisons will help to determine which, if any, of the small scale tests can most accurately predict the

static propensity of garment systems in real life situations.

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APPENDICES A

Appendix - A1 : Generic Description of Protective Outer Garments for Experiment 2.

Fibre (Trade) name	Generic composition
Nomex III®	aramid fibre- 95/5% Nomex/kevlar
Nomex IIIA®	93% Nomex aramid, 5% Kevlar aramid and 2% nylon sheath/carbon core fibre.
No-Mo-Stat®	99% Nomex III aramid and 1% stainless steel fibre.
FR cotton or Proban®	cotton with flame resistant finish

Appendix - A2 : Parka Label

Parka shell	Vapour barrier	Lining
Nomex IIIA®	Dermaflex® polyurethane coated nylon.	100% Nomex III®
Nomex III®	Dermaflex® coated nylon.	100% Nomex III®
FR cotton	FR modacrylic	FR cotton

Appendix - A3 : Laundry Conditions and Procedure (CAN/CGSB4.2 M58).

Garment	Washing Procedure[a]	Drying Procedure
Underwear: cotton	Warm wash/warm rinse (50°C); Normal cycle; 10 minute wash.	Regular dryer cycle for 25-30 minutes.
Pants/coveralls[b]: FR cotton, untreated cotton	Warm wash/warm rinse (50°C). Normal cycle -10 minutes wash.	Regular dryer cycle for 25 - 30 minutes.
FR cotton & cotton shirt	permanent press cycle 10 minutes wash. warm wash/cold rinse.	Permanent press dryer cycle.
Coverall & shirt NomexIIIA,No-Mo-Stat,Nomex III®	permanent press cycle 10 minutes warm wash (50°C) & cold rinse.	Hang to dry

[a]Detergent used: 150 gm/load powdered "Ultra Tide".

[b]Shirt, pants were washed separately from coveralls.

Appendix - A4 : Calibration For Charge and Discharge Energy

1 square division of graph paper = $18 \times 177\ mm^2 = 3.14\ cm^2$

$= 1v \times 200 \times 10^{-6}$ sec.

$= 2 \times 10^{-4}$ v/sec.

1cm $= 2 \times 10^{-4}/3.14 = 6.37 \times 10^{-5}$

1 small division of graph paper $= 0.256\ cm^2$

$= 1.63 \times 10^{-5}$ v/sec.

1 small division $= 1.631 \times 10^{-2}$ v/s (x1000)

1 small division $= 1.6 \times 10^{-2}/10^{5}$ c.

$= 0.4 \times 10^{-7}$ c.

Energy (E) $= \frac{1}{2} CV^2$ or $\frac{1}{2} QV$

APPENDICES B

SYSTEM	COMPONENTS			MEAN POTENTIAL (kV)		
	COVERALL	SHIRT	PANTS	R	K	J
8B	NOMEX IIIA	NOMEX III	FR COTTON	2.41	2.84	2.57
5B		FR COTTON	FR COTTON	2.70	2.73	3.27
11		NOMEX IIIA	COTTON	2.24	4.22	3.63
2B		COTTON	COTTON	3.45	4.31	4.03
			MEAN	2.70	3.53	3.38
			STANDARD DEVIATION	0.46	0.74	0.54
2A	No-Mo-Stat	COTTON	COTTON	4.56	4.29	4.78
8A		NOMEX III	FR COTTON	3.73	4.79	5.35
5A		FR COTTON	FR COTTON	4.10	5.23	4.84
			MEAN	4.13	4.77	4.99
			STANDARD DEVIATION	0.34	0.38	0.26
1	NOMEX III	COTTON	COTTON	5.85	5.66	5.63
10		NOMEX IIIA	COTTON	5.22	6.89	6.63
4		FR COTTON	FR COTTON	6.34	6.30	7.70
7		NOMEX III	FR COTTON	6.93	7.45	8.05
			MEAN	6.09	6.58	7.25
			STANDARD DEVIATION	0.63	0.67	0.63
3	FR COTTON	COTTON	COTTON	6.80	6.22	8.16
12		NOMEX IIIA	COTTON	5.28	8.10	8.01
9		NOMEX III	FR COTTON	6.64	7.79	8.09
6		FR COTTON	FR COTTON	6.73	8.78	9.83
			MEAN	6.36	7.72	8.52
			STANDARD DEVIATION	0.63	0.94	0.76

Appendix-B1. Average Body Potentials for different garment System in Experiment 1

SYSTEM	COMPONENTS			AVERAGE CHARGE (μC)		
	COVERALL	SHIRT	PANTS	R	J	K
8B	NOMEX IIIA	NOMEX III	FR COTTON	0.44	0.46	0.64
5B		FR COTTON	FR COTTON	0.59	0.60	0.68
11		NOMEX IIIA	COTTON	0.48	0.71	0.99
2B		COTTON	COTTON	0.67	0.75	0.94
			MEAN	0.55	0.63	0.81
			STANDARD DEVIATION	0.09	0.11	0.15
2A	No-Mo-Stat	COTTON	COTTON	0.86	0.98	0.99
8A		NOMEX III	FR COTTON	0.74	1.02	1.07
5A		FR COTTON	FR COTTON	0.81	0.93	1.20
			MEAN	0.80	0.98	1.09
			STANDARD DEVIATION	0.05	0.04	0.09
10	NOMEX III	NOMEX IIIA	COTTON	1.02	1.20	1.52
1		COTTON	COTTON	1.18	1.45	1.50
4		FR COTTON	FR COTTON	1.26	1.53	1.39
7		NOMEX III	FR COTTON	1.25	1.53	1.66
			MEAN	1.18	1.43	1.52
			STANDARD DEVIATION	0.10	0.14	0.10
12	FR COTTON	NOMEX IIIA	COTTON	1.12	1.55	1.81
3		COTTON	COTTON	1.35	1.45	1.71
9		NOMEX III	FR COTTON	1.25	1.67	1.68
6		FR COTTON	FR COTTON	1.28	1.87	1.82
			MEAN	1.25	1.64	1.76
			STANDARD DEVIATION	0.08	0.16	0.06

Appendix-B2. Average Charge Transferred for different garment systems in Experiment 1

SYSTEM	COMPONENTS			MEAN CHARGE FOR 3 SUBJECTS (μC)
	COVERALL	SHIRT	PANTS	
8B	NOMEX IIIA	NOMEX III	FR COTTON	0.51
5B		FR COTTON	FR COTTON	0.62
11		NOMEX IIIA	COTTON	0.73
2B		COTTON	COTTON	0.79
			MEAN	0.66
			STANDARD DEVIATION	0.11
2A	Nc-Mo-Stat	COTTON	COTTON	0.94
8A		NOMEX III	FR COTTON	0.94
5A		FR COTTON	FR COTTON	0.98
			MEAN	0.95
			STANDARD DEVIATION	0.02
10	NOMEX III	NOMEX IIIA	COTTON	1.25
1		COTTON	COTTON	1.38
4		FR COTTON	FR COTTON	1.39
7		NOMEX III	FR COTTON	1.48
			MEAN	1.38
			STANDARD DEVIATION	0.08
12	FR COTTON	NOMEX IIIA	COTTON	1.49
3		COTTON	COTTON	1.50
9		NOMEX III	FR COTTON	1.53
6		FR COTTON	FR COTTON	1.66
			MEAN	1.55
			STANDARD DEVIATION	0.07

Appendix-B2.1. Mean of the average charges for three subjects for different garment systems in a discharge.

SYSTEM	COMPONENTS			MEAN POTENTIAL FOR 3 SUBJECTS (kV)
	COVERALL	SHIRT	PANTS	
8B	NOMEX IIIA	NOMEX III	FR COTTON	2.61
5B		FR COTTON	FR COTTON	2.90
11		NOMEX IIIA	COTTON	3.36
2B		COTTON	COTTON	3.93
			MEAN	3.20
			STANDARD DEVIATION	0.50
2A	No-Mo-Stat	COTTON	COTTON	4.54
8A		NOMEX III	FR COTTON	4.62
5A		FR COTTON	FR COTTON	4.72
			MEAN	4.63
			STANDARD DEVIATION	0.07
1	NOMEX III	COTTON	COTTON	6.05
10		NOMEX IIIA	COTTON	6.25
4		FR COTTON	FR COTTON	6.78
7		NOMEX III	FR COTTON	7.48
			MEAN	6.64
			STANDARD DEVIATION	0.55
3	FR COTTON	COTTON	COTTON	7.06
12		NOMEX IIIA	COTTON	7.13
9		NOMEX III	FR COTTON	7.51
6		FR COTTON	FR COTTON	8.45
			MEAN	7.54
			STANDARD DEVIATION	0.55

Appendix-B2.2. Mean of average potentials for three subjects for different garment combinations in a discharge.

SYSTEM	COMPONENTS			MAXIMUM VALUES OF		
	COVERALL	SHIRT	PANTS	POTENT (kV)	CHARGE (μC)	ENERGY (mJ)
8B	NOMEX IIIA	NOMEX III	FR COTTON	4.21	0.84	1.76
5B		FR COTTON	FR COTTON	5.19	1.28	3.33
11		NOMEX IIIA	COTTON	5.72	1.30	3.73
2B		COTTON	COTTON	6.82	1.30	4.03
			MEAN	5.49	1.18	3.21
			STANDARD DEVIATION	0.94	0.20	0.87
2A	No-Mo-Stat	COTTON	COTTON	6.53	1.39	4.12
8A		NOMEX III	FR COTTON	7.58	1.47	5.25
5A		FR COTTON	FR COTTON	7.46	1.63	6.08
			MEAN	7.19	1.50	5.15
			STANDARD DEVIATION	0.47	0.10	0.80
10	NOMEX III	NOMEX IIIA	COTTON	9.26	1.94	8.17
4		FR COTTON	FR COTTON	9.98	1.99	10.06
1		COTTON	COTTON	10.86	2.49	10.85
7		NOMEX III	FR COTTON	11.00	2.08	11.21
			MEAN	10.28	2.13	10.07
			STANDARD DEVIATION	0.70	0.22	1.17
9	FR COTTON	NOMEX III	FR COTTON	9.86	1.96	9.65
3		COTTON	COTTON	10.80	2.36	10.56
12		NOMEX IIIA	COTTON	10.04	2.28	11.46
6		FR COTTON	FR COTTON	12.60	2.36	14.89
			MEAN	10.83	2.24	11.64
			STANDARD DEVIATION	1.08	0.16	1.98

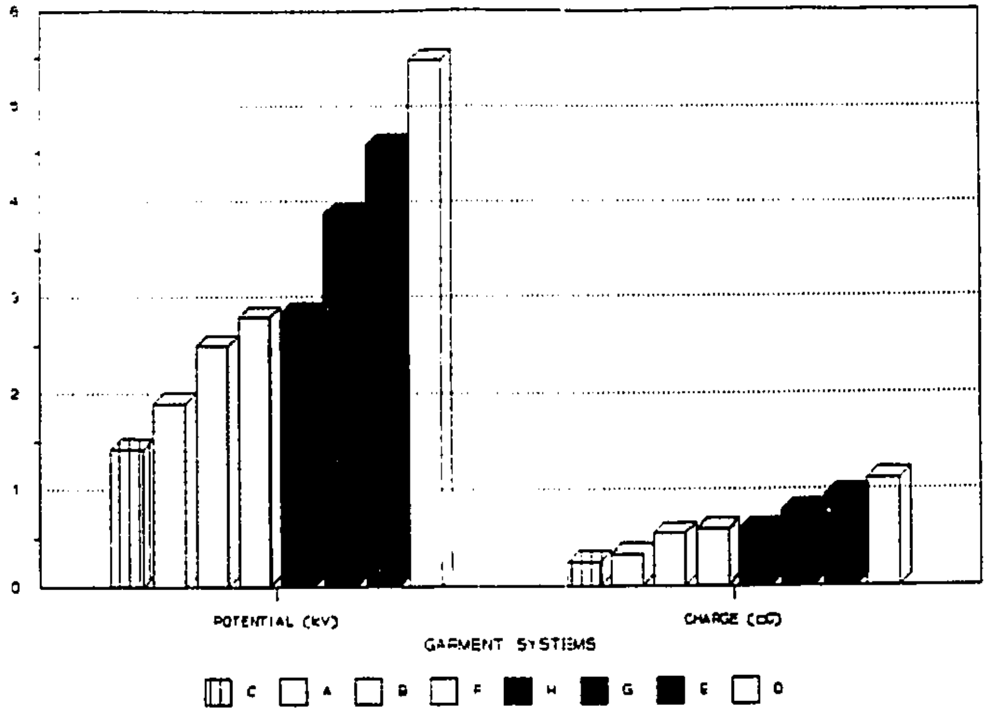
Appendix-B3. Maximum Values of the Potential, Charge Transferred and Discharge Energy for Three Subjects In Experiment 1

SYSTEM	COMPONENTS		MEAN POTENTIAL (kV)			MAX
	PARKA	SHIRT	K	J	AVG.	
8B	NOMEX IIIA	NOMEX III	1.56	1.28	1.42	2.29
2B		COTTON	1.99	1.82	1.90	3.18
5B		FR COTTON	2.99	1.99	2.49	3.75
12	FR COTTON	NOMEX IIIA	3.23	2.42	2.83	4.44
6		FR COTTON	4.13	3.60	3.86	6.28
10	NOMEX III	NOMEX IIIA	3.14	2.44	2.79	4.46
4		FR COTTON	5.00	4.15	4.58	7.51
1		COTTON	5.18	5.77	5.47	7.63

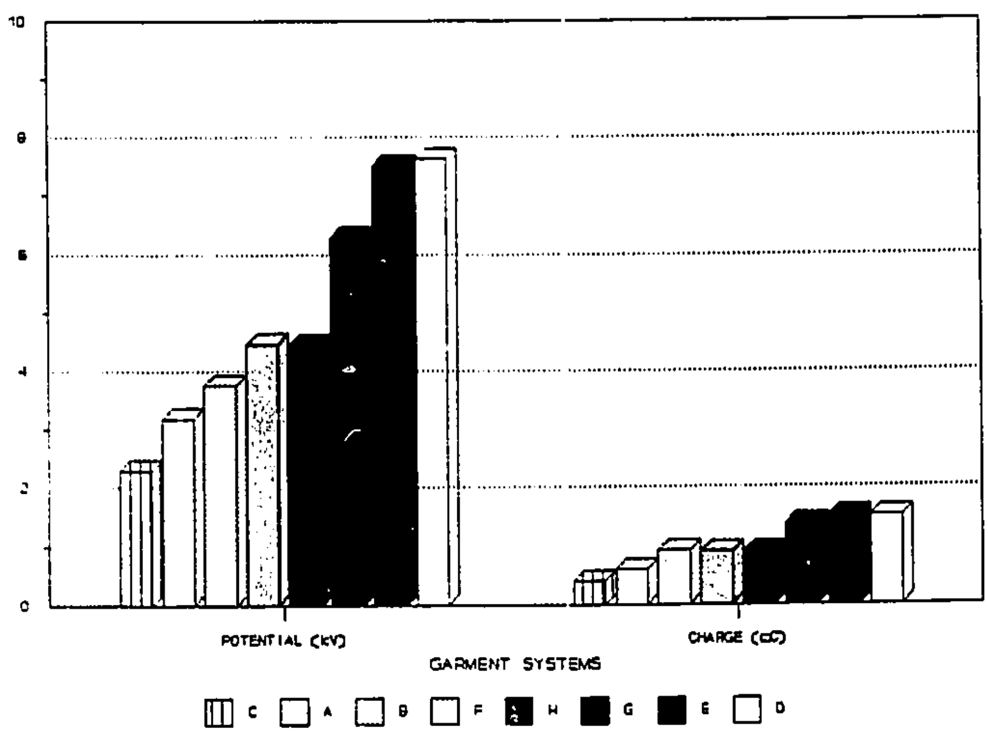
Mean and maximum body potentials for each subject in experiment 2.

SYSTEM	COMPONENTS		MEAN CHARGE (μC)			MAX
	PARKA	SHIRT	K	J	AVG.	
8B	NOMEX IIIA	NOMEX III	0.28	0.22	0.25	0.40
2B		COTTON	0.36	0.30	0.33	0.60
5B		FR COTTON	0.75	0.33	0.54	0.92
12	FR COTTON	NOMEX IIIA	0.69	0.49	0.59	0.90
6		FR COTTON	0.89	0.67	0.78	1.30
10	NOMEX III	NOMEX IIIA	0.71	0.47	0.59	0.90
4		FR COTTON	1.06	0.81	0.94	1.50
1		COTTON	1.12	1.09	1.11	1.50

Appendix-B4. Mean and maximum body charges for each subject in experiment 2.



Mean potential and charge for two subjects in experiment 2.



Maximum potential and energy for all the subjects in experiment 2.

SYSTEM	COMPONENTS			AVERAGE ENERGY (mJ)		
	COVERALL	SHIRT	PANTS	R	J	K
8B	NOMEX IIIA	NOMEX III	FR COTTON	0.56	0.64	1.00
5B		FR COTTON	FR COTTON	0.83	1.00	1.02
11		NOMEX IIIA	COTTON	0.58	1.36	2.13
2B		COTTON	COTTON	1.26	1.62	2.09
			MEAN	0.81	1.16	1.56
			STANDARD DEVIATION	0.28	0.37	0.55
2A	No-Mo-Stat	COTTON	COTTON	2.07	2.43	2.22
8A		NOMEX III	FR COTTON	1.40	2.82	2.83
5A		FR COTTON	FR COTTON	1.69	2.29	3.25
			MEAN	1.72	2.51	2.77
			STANDARD DEVIATION	0.27	0.22	0.42
10	NOMEX III	NOMEX IIIA	COTTON	2.75	4.04	5.33
1		COTTON	COTTON	3.84	5.13	4.53
4		FR COTTON	FR COTTON	4.10	6.02	4.56
7		NOMEX III	FR COTTON	4.46	6.38	6.26
			MEAN	3.79	5.39	5.17
			STANDARD DEVIATION	0.64	0.90	0.71
3	FR COTTON	COTTON	COTTON	4.76	6.00	5.47
12		NOMEX IIIA	COTTON	3.06	6.26	7.47
9		NOMEX III	FR COTTON	4.29	6.88	6.60
6		FR COTTON	FR COTTON	4.50	9.43	8.33
			MEAN	4.15	7.14	6.97
			STANDARD DEVIATION	0.65	1.36	1.06

Appendix-B6. Average energy for each subject for different garment systems in a body discharge.

SYSTEM	COMPONENTS		MEAN ENERGY (mJ)			MAX
	PARKA	SHIRT	K	J	AVG.	
8B	NOMEX IIIA	NOMEX III	0.23	0.15	0.19	0.46
2B		COTTON	0.45	0.29	0.37	1.07
5B		FR COTTON	1.15	0.35	0.75	1.72
12	FR COTTON	NOMEX IIIA	1.28	0.62	0.95	2.03
6		FR COTTON	1.91	1.26	1.59	4.10
10	NOMEX III	NOMEX IIIA	1.23	0.59	0.91	2.14
4		FR COTTON	2.94	1.89	2.42	6.00
1		COTTON	3.12	3.25	3.19	5.80

Appendix-B7. Mean and maximum body discharge energy for each subject in experiment 2.