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# ELECTROSTATIC PHENOMENA IN TEXTILE AND CLOTHING SYSTEMS

ARMY NATICK LABS.

OCTOBER 1973

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Scientific observation of the general phenomenon of static electricity has shown that the phenomenon is electronic in nature. It is particularly generated in textile materials due to impurities adsorbed both during fiber production and in subsequent processing. Data on materials in isolation are limited in meaning in relation to ultimate performance in a clothing system. To achieve full understanding of the phenomenon in the case of a clothing system, the system as a whole must be considered. The referenced system consists of the man, his total clothing, including his footwear, the environment (temperature, R.H.. physical elements, etc.) and the nature of the platform or surface on which the individual is standing. The surface on which the individual is standing and the nature of the footwear dictate the level of charge generated by the individual, the rate of decay of the charge from the system and whether there is a reinduction on the individual from residual charges on the clothing. It is also shown that while the charge on the individual can be discharged, the mobility of the charges on the clothing materials may be so low as to leave a high charge on the materials which, under appropriate conditions, can create a reinduction of charges on the individual. Treatments to the surface, including the use of stainless steel fibers, provide appropriate electrical paths for the movement of charges but the presence of these materials does not in itself lead to a complete dissipation of charges on a clothed individual unless the individual is capable of being brought to ground level either through his footwear and the surface on which he stands or by deliberate means. During the time the individual is at ground potential, any charges on the clothing system cannot create a hazard so long as the mobility of the charges on the outermost clothing surface is low.

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| Textiles | | | | | | |
| Clothing | | | | | | |
| Moisture | | | | | | |
| Resistivity | | | | | | |
| Charge | | | | | | |
| Excited State | | | | | | |
| Induction | | | | | | |
| Charge Mobility | | | | | | |
| Ion Pairs | | | | | | |



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TECHNICAL REPORT
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# ELECTROSTATIC PHENOMENA IN TEXTILE AND CLOTHING SYSTEMS

by

Frank J. Rizzo

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October 1973

Clothing and Personal Life Support Equipment Laboratory
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## FOREWORD

Static electricity is generally prevalent and affects both industrial operations and the individual. It possesses both beneficial and detrimental attributes. In the case of the latter as related to clothing, there are two general aspects to the problem which are of concern. The most overriding of these is the question of hazard to the individual in those many areas where sensitive materials are involved. Of lesser importance, but nevertheless of great discomfort to the person, is the tendency of clothing to adhere to the body as a result of electrostatic charges or the attraction of extraneous matter to the clothing with consequent unsightly effects.

This report is presented from the point of view of the military where potentially many sensitive and hazardous situations can be encountered. Notable among these would be cases involving ammunition, fueling of vehicles and aircraft and the care and treatment of patients in military hospitals.

The report as presented constitutes a general review of the current state-of-the-art for a general understanding of the phenomenon as a whole. In the development of this paper, considerable reference has been made to an abundant literature and to considerable experimentation within the present Natick Laboratories and predecessor organizations. In this regard, a prior document, Textile Series Report No. 110 entitled "M[illegible]uring and Predicting the Generation of Static Electricity in Milit[illegible] Clothing", summarized the knowledge existing up to approximately 1959. In the development of the present paper, the author has had the help of many individuals. Most recently, this help has come from the personnel of the Dyeing and Finishing Branch, namely, Messrs. A. M. Campbell, Norman S. Buchan and Alfred Merola. Much of the data developed in-house have been obtained by the named individuals at the specific request of the author. This work has been carried out variously in connection with studies of materials under Project 1T062105-A329, Organic Materials Research and also under Production Engineering, Project 728012.12. The paper itself was in part presented before the Gordon Research Conference held at New London, N. H., the week of 8 July 1973.

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ABSTRACT

Scientific observation of the general phenomenon of static electricity has shown that the phenomenon is electronic in nature. It is particularly generated in textile materials due to impurities adsorbed both during fiber production and in subsequent processing. Data on materials in isolation are limited in meaning in relation to ultimate performance in a clothing system. To achieve full understanding of the phenomenon in the case of a clothing system, the system as a whole must be considered. The referenced system consists of the man, his total clothing, including his footwear, the environment (temperature, R.H., physical elements, etc.) and the nature of the platform or surface on which the individual is standing. The surface on which the individual is standing and the nature of the footwear dictate the level of charge generated by the individual, the rate of decay of the charge from the system and whether there is a reinduction on the individual from residual charges on the clothing. It is also shown that while the charge on the individual can be discharged, the mobility of the charges on the clothing materials may be so low as to leave a high charge on the materials which, under appropriate conditions, can create a reinduction of charges on the individual. Treatments to the surface, including the use of stainless steel fibers, provide appropriate electrical paths for the movement of charges but the presence of these materials does not in itself lead to a complete dissipation of charges on a clothed individual unless the individual is capable of being brought to ground level either through his footwear and the surface on which he stands or by deliberate means. During the time the individual is at ground potential, any charges on the clothing system cannot create a hazard so long as the mobility of the charges on the outermost clothing surface is low.

ELECTROSTATIC PHENOMENA IN TEXTILE
AND
CLOTHING SYSTEMS

## 1. Static Electricity - a General Phenomenon

All of us, at one time or another, have observed or experienced a static electrical charge in the form of a spark as we have approached or touched a grounding element, or as a crackling sound most often associated with a corona discharge from clothing items seen in darkness. It is also observed by the clinging of garments to our bodies or by the annoying attraction and adhering of foreign particulate matter to our clothing, such as ashes, hair or other light materials, and the matter's reattraction as we attempt to brush it away. These several aspects of a basic phenomenon occur generally under specific ambient conditions, notably in dry and/or cold weather, with certain types of materials more than with others, and after certain forms of activity, such as walking down a long carpeted hallway, sliding across the seat of our car, or removing a garment. We know the phenomenon best in the form of lightning, which gives us a good appreciation for the energy levels that can be attained.

Static electricity is also a source of problems to the textile industry in many operations and is a general nuisance that is difficult and expensive to control. To this end, the industry maintains high humidities in the several working areas, or uses 'static eliminators' and sophisticated grounding methods to reduce these problems. Thus, the impact of static electrification varies over a wide spectrum of effects from individual discomfort, to loss of productivity, to poor quality of product, and even to serious hazard. Under control, it has been put to work in cleaning particulate matter from gaseous streams, in spray painting, in fiber spinning, in floc printing, and in the production of many useful and decorative products, to name just a few from a whole list of utilitarian systems. Our main concern, however, is not with industrial problems but rather with the phenomenon as it relates to the human subject and his clothing system.

While the discomfort and nuisance aspects of static effects generated on the individual in relation to his clothing are disquieting, the question of danger poses a greater problem. The fundamental question of the relationship of static electrical charges on clothing to this matter of hazard is an extremely difficult one to answer for many reasons. Probably one of the more significant reasons is the inability,

in a post-situation analysis, to identify the elements that may have created the situation. This is significantly so after an unfortunate accident in which static is suspected, because the needed evidence is likely to have disappeared with the accident itself. Reports of such accidents detail elements of conjecture and circumstance concerning conditions that may have prevailed at the time and the possible sequence of events that may have led to the obvious end result. Accordingly, there is a dearth of real facts from which to derive a solid base for protective measures. In consequence, effective elimination methods are generally constructed entirely upon a theoretical base and scientific observations of the phenomenon under the controlled conditions of the research laboratory. On rare occasions, suspicions have been rewarded by demonstrations in which the effect is achieved experimentally.

## 2. General Characteristics of Electrostatic Phenomenon

In approaching the subject, let us first of all review certain broadly held generalities about the phenomenon of static electrification and its dissipation.

a. Static electrical charges are generated when layers of materials, isolated from the ground, come into contact[1] and are then separated, the two layers thus developing opposing charges. Reason enforces judgment that the separated layers develop equal charge densities. This implies a redistribution of negative and positive charges as the two layers are separated, leading to negative charges in dominant concentration on one surface and positive charges on the other. This situation is illustrated in Figure 1.

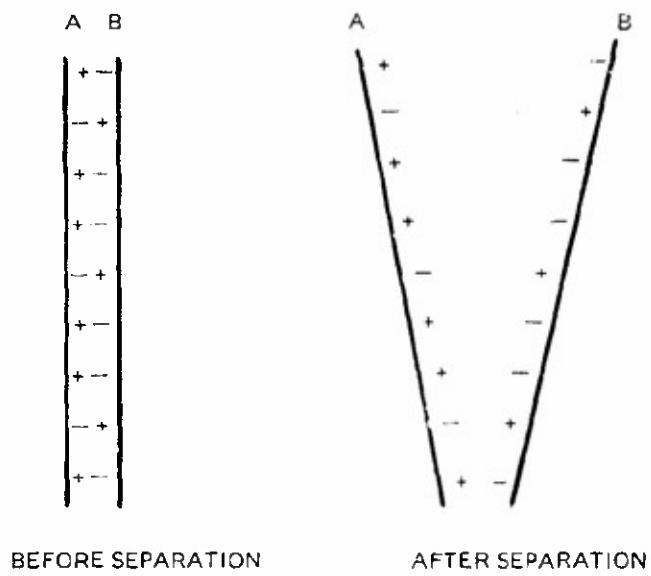



Fig. 1. Distribution of Charges on Separation of Layers

b. The electrical state of each separated layer may then be characterized on the basis of: the sign of the charge, the potential difference relative to ground and to the other layer, the resistance which defines the degree of restraint to movement of the charges to ground, and the charge density or population per unit of area on the fabric surface.

c. Static generation is fundamentally a surface phenomenon, but volume densities can be achieved in certain materials and under given conditions, particularly by induction in strong electrical fields. In fact, some authors believe that volume conduction is the only mode of charge transport.(4) Under such conditions, a space charge is generated between the volume and the surface.

d. Fibrous materials vary in their susceptibility, extent and rate of charge generation and decay, and in the sign of charge. These characteristics depend upon the specific chemical composition and structure of the two layers in contact and the degree of surface conformation of one layer to the other prior to separation. There is thus a definite relationship between the molecular structure of the two materials in contact and their static propensity. Also, there is implied a relationship between loading of one layer upon the other, the degree of intimacy of the contact of the surfaces thus achieved, the mode and rate of separation, and the charge densities accumulated. Because of these factors, some reversal of charge has been known to occur.(5)

e. When polymeric materials of different chemical composition are examined in systems in which a layer of one material is used as a common contact with all systems, it is found that such materials assume an order of ranking with certain having predominantly positive charges and others negative charges of varying densities and strength. Such an arrangement obtained from surface-to-surface contact followed by separation leads to an 'electrostatic series.' Generally, the series results from the rubbing of the materials against each other, and for this reason the series so obtained is designated as a 'triboelectric series' of which those in Table I are typical. There is reasonable coincidence in order of ranking between electrostatic and triboelectric series for the same materials under comparable conditions.

In such series, the relative positions and the spacing of any two materials from each other in the ranking order define, qualitatively at least, the electronegativity or electropositivity of one material relative to the other and some measure of the potential difference that

TABLE I

TYPICAL TRIBOELECTRIC RANKING OF MATERIALS

| Hersh and Montgomery[6] | Lehmicke[7] |
|---|---|
| + | + |
| Wool | Glass |
| Nylon | Human Hair |
| Viscose | Nylon |
| Cotton | Wool |
| Silk | Silk |
| Acetate | Viscose |
| Lucite | Cotton |
| Polyvinylchloride | Ramie |
| Dacron | Steel |
| Orlon | Rubber (Natural) |
| Dynel | Acetate |
| Velon | Rubber (Synthetic) |
| Polyethylene | Saran |
| Teflon | Orlon |
| | Polyethylene |

exists between them. In Table II the potential differences between selected fabric combinations are shown:

TABLE II

VARIATION IN VOLTAGE ON SECOND LAYER OF TWO-FABRIC COMBINATIONS AFTER SEPARATION

| FABRIC REMOVED | VOLTAGE ON SECOND LAYER | | |
|---|---|---|---|
| | 85 Wool/ 15 Nylon | Nylon | Nylon (Antistatic) |
| 50/50 Blend Viscose/Polyester | 600 | 2700 | 2200 |
| Cotton | 1400 | 3800 | 3400 |
| Nylon | 4600 | ---- | 1800 |
| Nylon-Antistatically Treated | 7500 | 2600 | ---- |
| 85% Wool/15% Nylon | ---- | 7500 | 7800 |

f. Any two unlike surfaces, including one metal surface, ungrounded or grounded, will develop a charge upon separation. Thus, Henry[8] reports a series in which metals are ranked in relation to a number of polymeric materials as seen in Table III.

TABLE III

METALS IN TRIBOELECTRIC RELATION TO POLYMERIC MATERIALS[8]

Platinum
Formvar
Filter Paper
Cellulose Acetate
Cellulose Triacetate
Polyethylene
Aluminium
Polystyrene
Copper
Rubber (Natural)

g. Since the charge developed in the separation of two surfaces is dependent upon many factors beyond the chemical nature of the materials involved, among these being the character of the two surfaces and the extent and nature of the manipulation of the two materials in contact prior to separation, it is not surprising to find that published versions of triboelectric series can differ substantially from one another. For this reason, a given series is not meaningful unless the conditions of its achievement are known, and the degree of reproducibility experienced under the cited conditions is defined.

h. The tenacity with which the charges are held on materials varies from one material to another, and even for the same material, depending on inherent surface energy as well as external elements within the immediate environment.

i. The development of electrical charges on textile materials is highly influenced by the regain properties of the fiber and is thus related to ambient environmental conditions. High regain fibers, such as cotton and wool, are less static prone at normal temperatures and relative humidities (R.H.) than are most man-made fibers. However, all organic polymeric fibrous materials, man-made and natural alike, become increasingly static prone as the moisture content of the fiber is reduced and as the temperature-R.H. conditions in the ambient are lowered. Table IV provides data on this point for two natural and one man-made fiber. The same considerations apply to antistatically treated fibers, data for which are shown in Table V. This response to change in moisture

TABLE IV

LOG R PER UNIT AREA FOR FIBERS AT DIFFERENT TEMPERATURE - R.H. CONDITIONS

| | 2% R.H./ -1°C | 2% R.H./ 0°C | 2% R.H./ 50°C | 50% R.H./ 24°C | 70% R.H./ 0°C |
|---|---|---|---|---|---|
| Cotton | 15.5 | 15.5 | 14.5 | 10.3 | 10.0 |
| Wool | 15.5 | 15.7 | 16.0 | 12.3 | 12.5 |
| Nylon | 15.5 | 15.7 | 14.9 | 14.3 | 13.0 |

TABLE V

LOG R PER UNIT AREA FOR ANTISTATICALLY-TREATED NYLON FIBERS AT DIFFERENT TEMP.-R.H. CONDITIONS

| | 1% R.H./ -0°C | 1% R.H./ 26.5°C | 17% R.H./ 26.5°C | 27% R.H./ 26.5°C | 45% R.H./ 26.5°C |
|---|---|---|---|---|---|
| Thermo Setting Resin | 12.5 | 11.2 | 10.2 | 10.0 | 9.4 |
| Organic Ester | 12.7 | 11.1 | 10.4 | 10.3 | 9.7 |
| Acrylate Resin | 15.0 | 13.5 | 9.6 | 9.8 | 7.6 |
| Reference (Untreated Cotton) | 15.0 | 14.2 | ---- | 11.4 | 10.0 |

content varies with the material, an observation that signifies differences in charge-holding capacity as related to molecular constitution and/or organization. Some materials have been observed even in the grounded state to hold their charge ever so tenaciously and for long periods of time. It is assumed in this instance that the restraining forces are so strong that charge mobility is well-nigh nonexistent.

3. Understanding the Phenomenon of Static Electrification

We have stated that the charge carriers are of two different signs, but we have not identified them. To understand the phenomenon of static electrification adequately, we need to know what these charges are. But, to understand the phenomenon significantly, we must have more definitive information regarding the charges and the laws that govern their behavior.

Henry[9] has defined certain of these needs as:

Which charge carriers move?

Why do they move?

What terminates the action?

For our purposes we need to know more, namely:

What is the nature of the charge carriers?

What is their origin?

How do they move?

What forces aid or abet their movement?

What interactions are involved in multilayer assemblies, such as we have in our clothing systems, and how does the human presence in the system influence the course of events?

It must be obvious that at the practical level interactions among systems are the important concern and also that data achieved with materials in isolation can be expected to alter to some degree in the human-materials-clothing system. Thus, extreme caution is required in drawing conclusions from the behavior of materials evaluated as single entities.

Several theories have been advanced by various investigators on the source and nature of electrostatic phenomenon. One of the earliest, and still supported by some investigators, is that the phenomenon is capacitative in nature whereby the material serves as a storage medium for electrical charges induced or generated within the material by external stimuli. In this sense, the charge densities developed within the fibrous material would be related to the specific inductive capacity or dielectric constant of the material which in turn would relate to the mass specific resistance, Rs, of the material and to the degree of electrical breakdown at the material-air interface, due notably to the moisture content of the latter. A relationship between dielectric constant and mass specific resistance, Rs, has been reported by Hearle[10] and is reproduced in Table VI. He reports a sigmoidal relationship between Log $R_s$ and R.H. over a wide range of resistances. While the data in Table VI tend to rank materials in a sequence that is similar in arrangement to a triboelectric series, other studies have indicated that they should be taken in a qualitative sense only.

In any given situation, the charge manifested on a human subject is directly related to the charge developed on the outermost residual material surface of the clothing system as the result of an external layer of the clothing assembly being removed. The surface-to-surface

TABLE VI

DIELECTRIC CONSTANTS AND LOGARITHMS OF MASS SPECIFIC RESISTANCES ($R_s$)

| | Dielectric Constant At 65% R.H. + 1 Kc/s | $Log_{10} R_s$ At 65% R.H. |
|---|---|---|
| Cotton | 18.0 | 6.8 |
| Viscose | 15.0 | 7.0 |
| Wool | 5.5 | 8.4 |
| Fiberglass | 4.4 | --- |
| Polyamide | 4.0 | 9-12 |
| Acetate | 4.0 | 11.7 |
| Polyvinylchloride | 3.0 | --- |
| Vinylidenechloride | 2.9 | --- |
| Polyacrylonitrile | 2.8 | 14.0 |
| Polyester | 2.3 | 14.0 |

interactions between garment layers and between garments and the human are illustrated in Figure 2. However, the charge accumulated on the human subject in ungrounded state is related to intrinsic body capacitance, which in turn depends in large measure upon body size, mass, sub-skin layer composition and thickness, and skin surface properties, notably moisture, salt content, and hairiness. This last element affects surface to surface contact and conformity. Consequently, some variation in charge levels will exist among individuals, as seen in Table VII for two persons using the same uniform under the same conditions. A human body of normal average size may have a capacitance relative to ground of 200 picofarads and a surface resistance of 20,000 ohms/square. In an ungrounded situation, a potential as high as 10,000 electrostatic volts is thus attainable.

The capacitative concept previously mentioned falters by failing to define the origin of the charges, but on first examination it does provide what would seem to be a reasonable mechanism for the observed higher potentials and generally lower charge mobilities with decreasing size of the dielectric constant. Hence, the source of the charges must be in the material itself, either inherently by virtue of its structure or by impurity components. It is recognized, however, that charges may be induced by creating their own dielectric image in the substrate surface. In the final analysis, electrostatic phenomenon achieves appropriate definition and resolution in solid state theory.

Solid state theory defines a series of energy states for atoms and energy bands (band theory) for molecules and provides a basis for

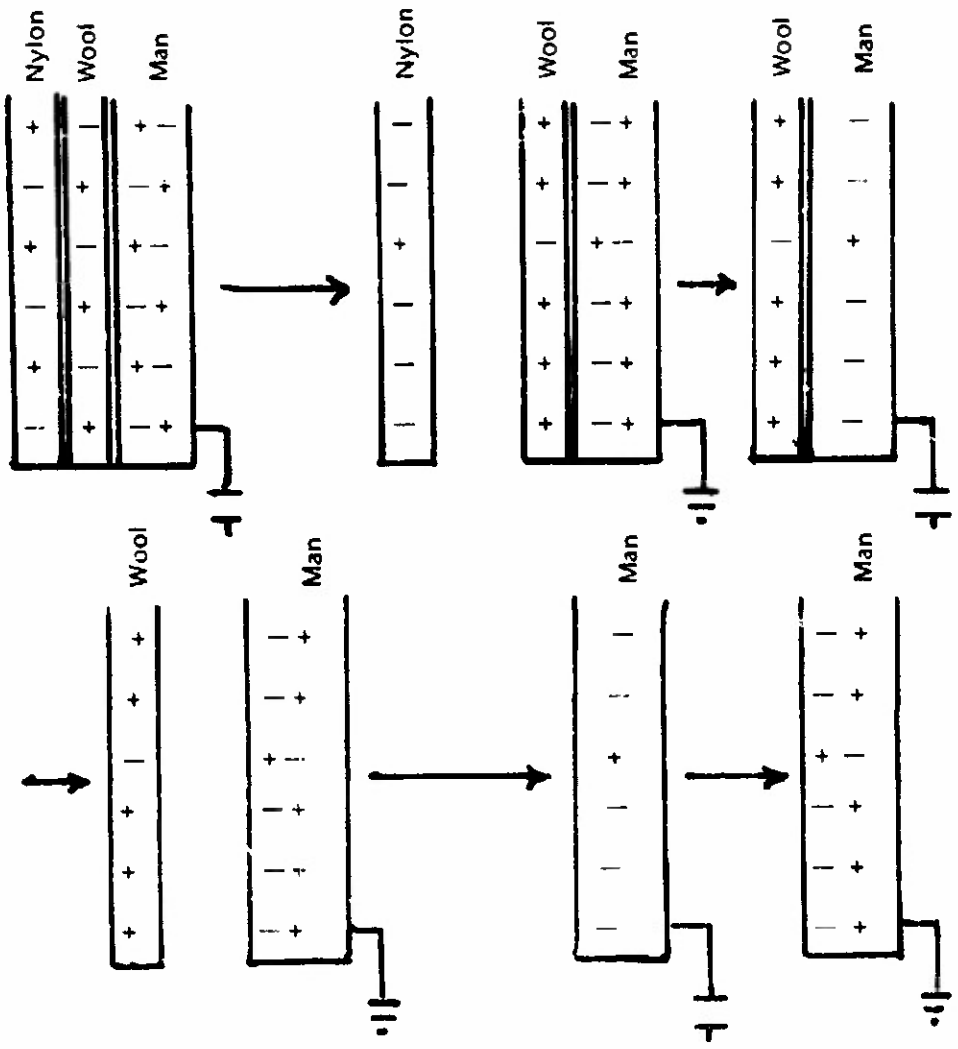



Fig. 2 Charge Distribution in Clothing-Materials-Man System

TABLE VII

STATIC POTENTIAL INDUCED ON HUMAN SUBJECTS
WEARING POLYESTER/COTTON BENGALINE UNIFORMS
AT 22.2°C (72°F) and 33% R.H.

| WEAR STATUS | INDUCED POTENTIAL (VOLTS) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Test Subject A | | | | Test Subject B | | | |
| | NEW | | LAUNDERED | | NEW | | LAUNDERED | |
| | AV | PEAK | AV | PEAK | AV | PEAK | AV | PEAK |
| After donning uniform and exercise | 390 | 1800 | 5200 | 7200 | 200 | 1300 | 200 | 1950 |
| Uniform removed (layer separation) | 600 | 4000 | 1750 | 4600 | 1100 | 1300 | 1500 | 1700 |

electrons to be rasied by excitation from the valence band to an upper conduction band, thus leaving a 'hole' or deficiency in the valence band as illustrated in Figure 3. 'Hole' conduction takes place by a series of sequential movements of an electron from one position to another, thereby leaving a 'hole' where it was and so on. The achievement of a conduction band of electrons depends upon the width of the energy gap between valence and conduction bands. This energy gap is

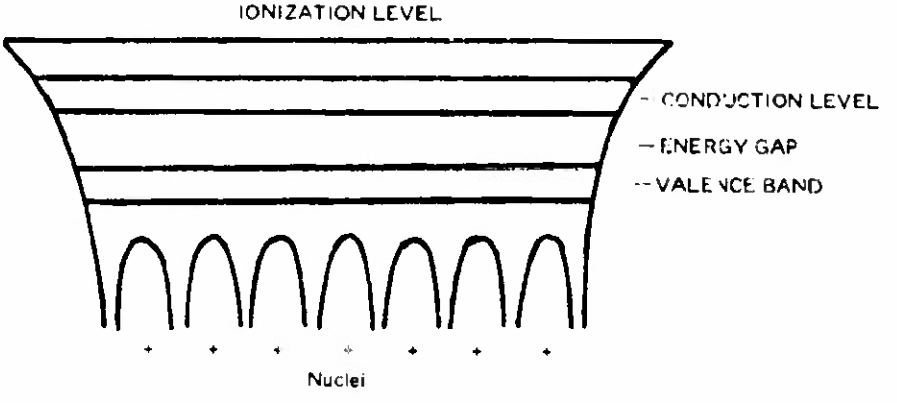



Fig. 3 Energy Bands in Solids*

*Gutman and Lyons, Organic Semiconductors, NY and London, Wiley, 1966

a forbidden region, in which charge carriers cannot exist. As seen in Figure 4, if the energy gap is so wide that electrons cannot bridge

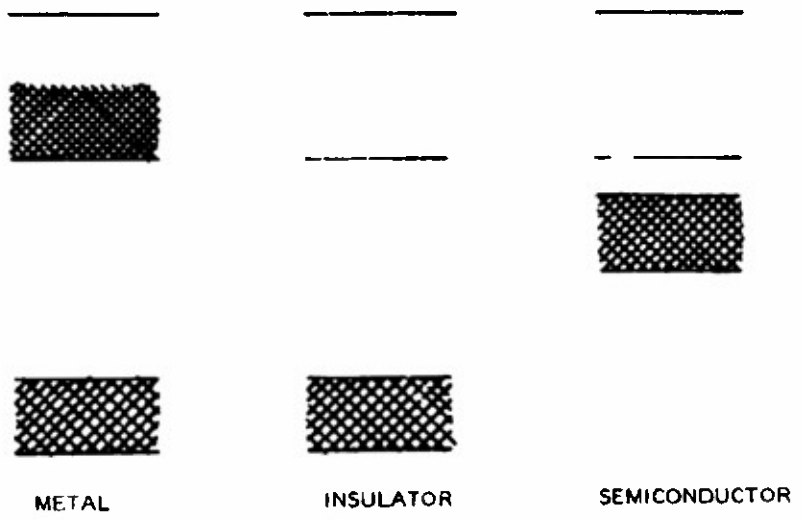



Fig. 4 Valence and Conduction Bands in Crystals*

it by thermal agitation (i.e., if the band is wider then kT where k is the Boltzmann constant and T is the temperature in degrees Kelvin) the material is an insulator and a current flow in an applied field is not possible. A material in which the energy gap is equal to kT will display semiconducting properties.

Solids are generally categorized in one of four classes: metals, ionic crystals, valence crystals, or molecular crystals. The fibrous materials with which we are concerned in this study fall in the category of molecular crystals. These materials, if obtainable in their pure state, would vary in their electronic properties in relation to chemical structure as do pure molecular crystals generally. The saturated linear polymers which today represent the major fibers are insulators because they possess $\sigma$-bonds having localized valence electrons and an energy gap that is too large to be spanned thermally. Organic solids possessing semiconducting response have been found mainly in the group of polyaromatic compounds with extensive conjugation. These compounds are planar molecules of rather large size[11], having $\pi$-electrons as valence electrons which can distribute themselves throughout the molecular plane in more or less a diffuse cloud. It is suggested that the molecular orbitals of $\pi$-electrons overlap those of neighboring molecules thus achieving the diffuse cloud configuration. Linear polymers having conjugated double bonds would be expected to behave

*Gutman and Lyons, Organic Semiconductors, NY and London, Wiley, 1966

similarly due to $\pi$-bond structure. The diffuse cloud around aromatic structures achieves a configuration that is somewhat metalloidal in character. In metals, the conducting band is partially filled or the valence band overlaps the conduction band thus achieving an electronic population of the conducting band of sufficient magnitude to carry a current under an electric field.

It follows from the above that commercial types of fibrous materials, such as those used in normal clothing systems, which do give a current flow under an impressed field, are extrinsic semiconductors. This means that their electronic conduction is the result of impurities, discontinuities within the crystalline region, interstitial atoms, imperfections, or dislocations in the crystal order. All of these can contribute 'free' electrons and 'holes' capable of moving with an application of energy. The outer molecular surface of a material theoretically constitutes a major discontinuity in the crystal order. Davidson and Levine(12) state in quantum mechanical terms: "Free solid surfaces present electronic states, surface states that are not part of the eigenvalue spectra of the Hamiltonian of a perfect lattice of infinite extent."

Conductivity due to impurities falls into one of two categories: defect or p-type and excess or n-type. The former is 'hole' (positive) conduction; the latter electron conduction. These impurities and other aberrations in the aggregated molecular structure provide either electron-donating or electron-accepting levels which lie within the energy gap region or forbidden band of the host material.

Donor levels lie close to the conduction band of the host and acceptor levels close to the valence band as seen in Figure 5. Either may give

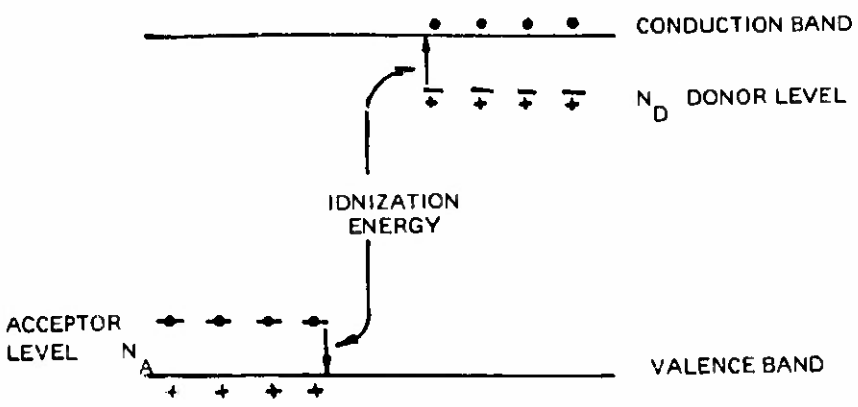



Fig. 5 Donor-Acceptor Levels in Extrinsic Conductivity

rise to localized electron levels within the forbidden band.

The ability of an impurity, dislocation, etc., to perform the donor or acceptor function is determined by the position of the Fermi level. This is defined by the Fermi/Dirac distribution as:

$$\rho/\rho_o = \frac{1}{1 + \exp. \ (E-E_F)/kT}$$

The Fermi/Dirac function is a quantum mechanical derivative of the classical Boltzmann-Maxwell law:

$$\rho/\rho_o = K \exp.(-E_o/kT)$$

where $\rho/\rho_o$ is the relative concentration of electrons with energies above a given level $-E_o$, K is a constant, k is the Boltzmann constant and T is the absolute temperature. $E_F$ is thus the limiting energy or the free energy change of the system per electron and may be considered as equal to the thermodynamical potential or chemical potential of the quantum mechanical system per electron. Its shape depends on temperature only and is independent of any physical processes that may be operative.

The form of the Fermi/Dirac distribution function is shown in Figure 6.

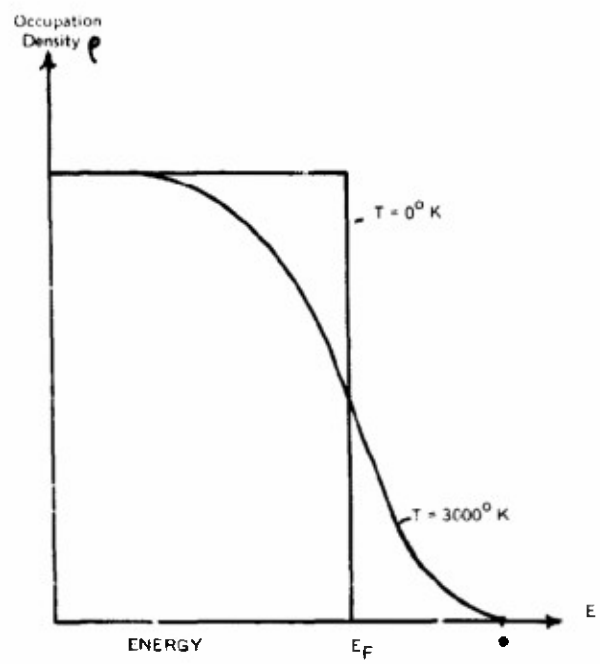



Fig. 6 Fermi/Dirac Function*

*Gutman and Lyons, Organic Semiconductors, NY and London, Wiley, 1966

From the form of the Fermi/Dirac distribution, the probability of a level above the Fermi level being unoccupied is equalled by the probability that a level below it will be occupied.

Thus, when $E - E_F \gg KT$ $\quad \rho = o$

when $E_F - E \gg KT$ $\quad \rho = 1$

In semiconductors at normal temperatures, the Fermi level is one-half between the top of the valence band and the bottom of the conduction band. In n-type semiconductors at sufficiently low temperature, the Fermi level is in the forbidden region close to the conduction band; in p-type conductors it is in the forbidden region close to the valence band. At sufficiently high temperatures, both n- and p-type semiconductors show intrinsic conductivity because the electrons can be excited into the conduction band across the forbidden region. As the temperature increases, a point is reached where the Fermi level is at the middle of the forbidden region between the impurity level and the conduction band as seen in Figure 7. In semiconductors the Fermi level can in fact be almost anywhere in the forbidden region depending upon the type of conductivity and the temperature. The Fermi level moves down as saturation or ionization of the impurity atoms has been attained. To know its position one must know the disposition of all of the impurities in the system.

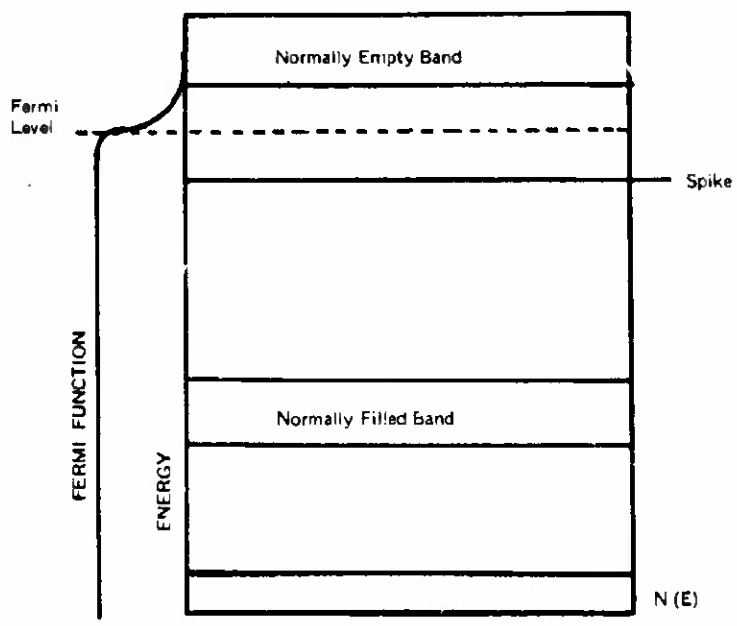



Fig. 7 Fermi Level (n-type impurity)

If the impurity level is sufficiently removed so that the donor or acceptor function cannot be performed, it can nonetheless receive and trap opposing charges. In such cases, thermal energies are generally smaller than the width of the energy gap between the impurity level and the host material so that effective trapping within the forbidden band of the host can occur.

The impurity content of an insulating material, such as a textile fibrous polymeric material, need not be very great to achieve a high degree of trapping of charges entering from external sources by attraction. As stated earlier, the termination of the periodic lattice structure at the surface of the material gives rise to surface levels which lie within the forbidden gap. While distortion of the surface layers of atoms does occur by mutual saturation of free bonds with neighboring atoms, some free bonds remain and thus provide the levels for attracting charges from other media. The formation of double layers can be a consequence of such actions. One possibility for contamination can be the adsorption of oxygen. Low lying levels in the oxygen atoms are capable of receiving electrons from the host molecules that would normally be excited into the conduction band of those molecules, leaving 'holes' in the valence band. A surface layer of negative oxygen ions would thus be formed with which the 'holes' in the valence band would form an ion-pair or double layer. Another source of contamination, particularly in textile materials, is in the many chemical solutions used in the preparation, dyeing, and finishing of such materials. These also provide electronic levels which may lie in the forbidden gap of the host material and can thus act as donors or acceptors, as the case may be. In effect, therefore, the presence of impurity levels in the surface of the insulator capable of attracting or providing electrons permits ions from the surrounding media to be accepted to form ion pairs or even double layers. Ions so attracted, depending upon the strength of the attraction forces generated, could be transferred to another surface to some degree or other in a contact situation.

If we view the process of electrification of surfaces as deriving from impurities attracted to them by surface energy and from asperities in such surfaces, the variations in charge densities observed at different times by the same investigator and by different individuals become readily understood. In a simple separation of layers with a degree of manipulation of the materials such that a significant input of energy into the system is precluded, differences in charge densities and in electrical potential obtained at different times can arise simply from nonreproducibility in the degree of transfer of one ion of an ion-pair or one component of an electrical double layer.

Rubbing achieves greater intimacy of contact of the surfaces and increases the probability of more effective transfer of charges. The occasionally observed reversal of the sign of the charges between layers following rubbing of one layer against the other or following

sliding of surfaces across each other, can be accepted as evidence of particulate contamination resulting from non-uniform transfer of material from one layer to the other, as a consequence of wear. Such transferred detritus would provide donor/acceptor levels.

When two surfaces in contact are separated, a potential gradient is produced in relation to charge mobilities across the material surfaces toward the advancing point of separation. The rate of diffusion of the charges toward this point of separation not only expresses the mobility of the charges but also the relaxation time for their redistribution, and determines the ultimate electrostatic strength of each layer. Mobility and relaxation time, in turn, reflect the tenacity with which charges are held and thus the depth and frequency of traps (points of strong activity requiring higher energy inputs to achieve release). These two factors and charge density together relate significantly to the practical problem of whether a spark, a corona discharge, or slow leakage to ground occurs and thus whether a hazardous situation could develop.

Charge drift mobility is related to the frequency of distribution of traps and to the height, shape, and transparency of the potential energy barriers that are to be overcome. It is obviously also related to the mass of the charge, an electron being capable of greater mobility than a proton or an ion. Depending upon these factors and its kinetic energy, a given charge may be repulsed or reflected at a barrier; it may penetrate or tunnel through[13-17]; or it may surmount the barrier by hopping over.[18] The further movement of the charge then depends upon its energy state beyond the barrier and upon the degree of polarization of the medium.

Conventional textile fibrous materials in the pure state derived from linear saturated polymers are considered to be electrophobic.[19] Commercial fibrous materials electrify by virtue of their impurity content, structural aberrations, and/or surface asperities. As has been mentioned in prior paragraphs, oxygen adsorbed on the surface is one such impurity; another is moisture. The specific role of moisture seems to be anomalous. Sereda and Feldman[20] have shown that a maximum in charge generation is achieved at that specific relative humidity in the ambient, with which the material is in equilibrium, associated with the formation of a monomolecular layer on the surface of the fiber. This fact implies that the electrification that occurs is not a property of the basic substrate but rather of a new surface constituting a continuous layer of water molecules. To support this postulate, evidence has been brought forth that shows that all textile fibers at that

relative humidity at which the monomolecular layer is formed actually do have the same charge density.[20] This is reasonable since ionic transport does not occur in a monomolecular layer. At higher levels of moisture than that which forms the monomolecular layer, conductivity is achieved presumably through the ionic content of the excess water molecules and by the hydration of impurity ions. However, Sereda and Feldman[20] found that some fibers generate more static at higher than at lower R.H. levels. This is ascribed to the greater facility for the formation of ion pairs thus reducing the number of uncompensated carriers and thereby the conductivity. In this same regard, Keggin et al[21], report that it is the R.H. that makes the difference in the residual charge on a material surface. They confirm that at low moisture regain levels, all materials acquire the same charge.

## 4. Methods of Control of Static Charge

The foregoing theoretical review suggests that the triboelectric effects in polymeric materials, such as textiles, derive from contained or adsorbed impurities and/or surface discontinuities which are capable of trapping charges and thereby achieving a high charge density. The obvious solutions to the problem must then come from:

(1) Achieving a higher degree of purity in the substrate.

(2) Using additives that will lower the energy barriers and increase electrical conductivity of the material.

(3) Using additives that will provide a new surface on the material with electronic configurations having smaller energy gaps.

(4) Modifying the polymer structure to achieve a molecular orbital configuration with a high $\pi$-electron cloud or ionic strength.

In practice, the solutions are found in:

(1) Blending of fibers from opposing positions in the triboelectric series.

(2) Applying antistatic finishes.

(3) Admixing of organic and metallic fibers.

(4) Grafting ionizing functional groups on existing fibers.

### a. Fiber Blends

The achievement of a neutral electrical state by admixing fibers holding opposing positions in the triboelectric series is theoretically

possible but, in fact, is impractical for a number of reasons. These include: the precision required in the ratio of the two fibers in relation to their respective positions in the series; the intimacy of blending achieved; the nature of the fabric surface; moisture content levels; relative charge densities; and the correctness of the choice of the specific triboelectric series. This last element is important since the placement of members in the series depends upon the conditions under which the series was developed.

At best, fiber blends produced on the basis of the positions held by the component fibers in the triboelectric series relative to each other permit a reduction in residual unneutralized charge density. However, the fibers themselves and their proportions in the fiber blend are chosen more for their functional properties in relation to a specific use or for aesthetics, without specific regard or concern for electrostatic propensity. As a result, orders of magnitude of residual static charge tend to reflect the level of imbalance in opposing charge densities, the relative mobilities of the charges and thus the depth of the traps in each fiber type, field effects, and the blend ratio at the fabric surface. For these reasons, one finds that the degree of reduction in static propensity in fiber blends tends to be less than is expected on theoretical grounds

b. Antistatic Finishes

Since surface properties of materials dominate in static electrical phenomenon, any additives to the surface will tend to alter the electrical behavior in the direction of the additive, provided there is a sufficient amount to give a uniform multimolecular layer on the material surface. Thus, hydrophobic treatments, such as water repellents, increase static propensity of textile surfaces, even of those that are not normally too static prone. The application of such materials achieves electrophobicity as well as hydrophobicity. Conversely, antistatic treatments consist of the application of surface-active compounds or polymeric substances containing ionizable groups and achieve a reduction in static propensity in all fibers, even in those that normally develop high charge densities. These treatments have been considered heretofore to provide an electrical path for the charges generated on the fibrous substrate. This may indeed be one mechanism. Another theory is that the treatments achieve a new electrophylic, more hygroscopic surface by virtue of ionizing groups. Thus, the antistatic compound would appear to promote the formation of a multimolecular water layer in which the ionization of its functional groups is facilitated. Evidence for both of these concepts comes from the gradual return of inherent fiber electrostatic properties as the finish is removed, for instance, after multiple launderings.

Industry categorizes two general classes of antistatic compounds. These are differentiated simply on the basis of their durability in fabric or garment cleaning processes. The 'non-durable' types are those that wash out of the material in one or two launderings and thus must be reapplied after laundering to restore effective static control. The chemical composition of these types varies widely; most 'non-durables' are hydroxy, amino, ester or sulfonate compounds. Inorganic salts are also used. All such compounds have one or both of two basic properties; they are hydrophylic and may be hygroscopic. They appear to work on the basis of moisture adsorption from the atmosphere and thus function better as the humidity in the ambient rises, thereby implying increasing facility of ionization of the functional groups. Also, they become ineffective gradually as the humidity (and temperature) in the ambient is reduced achieving a cut-off in effectiveness at some particular point, namely, that at which ionization is inhibited.

The durable types of antistatic compounds are reacted on or with the substrate through polymerization processes. They are applied to a fabric during the final stages of manufacture and remain effective over very substantial numbers of cleanings of the garment made from the treated fabric. Some are effective over the life of the garment. These compounds are polyhydroxy- or polyamino-prepolymers or monomers which are polymerized on the fabric surface. Some are compositions consisting of compounds with strong ionic functional groups and an additive resin which "fixes" the electrophylic substance on the fiber. The extent of chemical interaction between such materials and the fiber substrate is not known. It is reasonable to assume that a strong element in their effectiveness is the formation of a new surface with different electrical and electronic properties than those the substrate possess. Moisture plays a role as it does in the case of the non-durables and apparently promotes ionic mobility. This concept is supported by the fact that the effectiveness of the treatment is reduced as the temperature and the humidity decrease, with a cut-off being achieved at some temperature, usually in the range between 0°C and -30°C, where moisture content of the ambient is low.

c. Admixtures of Conducting Metallic Fibers

Small percentages of metallic fibers in a blend with organic fibers have the property of dissipating electrostatic charges.[22] This capability is achieved even when these fibers fail to provide a continuous electrical path, either as the result of insufficiency in amount or of being highly dispersed in the blend. It is theorized that they act as dipoles interacting with the electrostatic fields of the trapped charges thus tending to promote charge delocalization through a smearing of the fields. Their effectiveness is indisputable as seen in Table VIII, which gives resistivity and clinging data for Nomex fabric

containing 1% stainless steel fiber and in Table IX, which gives charge build-up and dissipative rate for the same blended fabric.

TABLE VIII

EFFECTIVENESS OF STAINLESS STEEL FIBER ON STATIC GENERATING ON NOMEX FABRIC CONTAINING 1% STAINLESS STEEL IN BLEND

| Fabric Direction/ Condition | Surface Resistivity Ohms Per Square 70°F, 35% R.H. | Cling Test 72°F, 28% R.H. AATCC 115-1969 | |
|---|---|---|---|
| | | Nylon Rub | Poly Rub |
| Warp Wise, as rec'd | $3 \times 10^{12}$ | No Cling | No Cling |
| Filling Wise, as rec'd | $3.7 \times 10^{12}$ | No Cling | No Cling |
| Warp Wise after 5-#5610 washes | $5 \times 10^{13}$ | No Cling | No Cling |
| Filling Wise after 5-#5610 washes | $6 \times 10^{13}$ | No Cling | No Cling |

Maximum Peak Voltage Attained with Stainless Steel - 1,000 volts
Nomex without Stainless Steel - 5,000 volts

TABLE IX

CHARGE BUILD-UP AND DECAY IN NOMEX FABRIC CONTAINING 1% STAINLESS STEEL IN BLEND

| Condition | Initial Charge | Charge Ungrounded Situation | | | Charge Grounded Situation Immed. Reading |
|---|---|---|---|---|---|
| | | Half Life | Full Life | Charge After 1 Min. | |
| Warp Wise, as rec'd | 80MA | - | 3 Min | 80MA | 0 |
| Filling Wise, as rec'd | 75 | - | 3 Min | 85 | 0 |
| Warp Wise after 5-#5610 washes | 80 | - | 3 Min | 80 | 0 |
| Filling Wise after 5-#5610 washes | 75 | - | 3 Min | 80 | 0 |

### d. Polymer Modification by Grafting to Achieve Static Dissipation

The most recent avenue of attack on the electrification problem is the modification of the fibrous polymer structure by free radical mechanisms[23,24,25] using high energy radiation or chemical techniques to achieve grafting of functional elements leading to ionic configurations, greater moisture sensitivity, or molecular structures with much narrower band gaps. Many new modifications of well-known fibrous polymers have been achieved, the most notable being in the polyamide (nylon) and polyester classes. Many of these work effectively as long as hard water is avoided. This implies that the functional groups are either $-COO^-$ or $-SO_3^-$ and are incapable of ionizing when heavy metal salts form. In-house data developed on commercially available polymer fibers of this type are given in Table X.

TABLE X

ELECTROSTATIC PROPERTIES OF GRAFTED POLYMER FIBER FABRICS

| Fabric Garment | Resistivity (ohm/sq) 25% R.H. Initial | Resistivity (ohm/sq) 21.1°C (70°F) After 5 TM5610 | Clinging Propensity (secs) 32% R.H. Polyester Initial | Clinging Propensity (secs) 21.1°C (70°F) Rubbing Fabric A3U After 5 TM5610 | Charge Decay 21.1°C Charge (amps) Init. | Charge Decay 21.1°C Charge (amps) After 60 sec | Charge Decay 32% R.H. Rise (secs) Half Life | Charge Decay 32% R.H. Rise (secs) Full Life |
|---|---|---|---|---|---|---|---|---|
| Garment, Fiber Polymer, Code B-4-T | $4.4 \times 10^{11}$ | $0.7 \times 10^{14}$ | 0 | 300 | 50 | — | 25 | 75 |
| Garment, Fiber Polymer, Code B-5-T | $6.0 \times 10^{11}$ | $1.7 \times 10^{13}$ | 0 | 300 | — | — | — | - |
| Garment, Fiber Polymer, Code B-6-T | — | — | 0 | 300 | - | — | — | [illegible] |
| Garment, Fiber Polymer, Code C-6-P | $7.5 \times 10^{11}$ | $6.9 \times 10^{12}$ | 0 | 300 | 80 | 90 | — | — |
| Garment, Fiber Polymer, Code C-5-P | $8.5 \times 10^{13}$ | $9.9 \times 10^{13}$ | 0 | 300 | 50 | 50 | 90 | 180 |

| CODE | DESCRIPTION |
|---|---|
| A3U | Filament Polyester Taffeta 2 oz/yd² - Untreated |
| B-4-T | Polyester Tricot — Non Durable Commercial Finish |
| B-5-T | Polyester Tricot — Non Durable Commercial Finish |
| B-6-T | Polyester Tricot — Polyglycol ester Finish |
| C-6-P | Polyester Tricot - Polymer Modified (-COOH) |
| C-5-P | Polyester Tricot — Polymer Modified (-COOH) |

## 5. Testing for Static Propensity

### a. General Considerations

In the preceding paragraphs, as theoretical and practical aspects of electrostatic phenomenon have been examined, certain parameters have stood out. These relate to conduction, charge motion as related to molecular, structural and electronic restraints, surface forces, contact influences, and the contribution of adsorbed gaseous elements, notably moisture and oxygen, and impurities. The testing procedure used in evaluating electrostatic propensity as a scientific phenomenon generally concern themselves with all of these factors and with structural contributions at the atomic, molecular and macromolecular levels and with the kinetics of charge transport.

At the practical level, there are two categories of tests used. The first group, consisting of bench-type tests, assesses the performance of materials essentially in isolation with subsequent correlation to potential end-use behavior; the second involves participation of human subjects and attempts to relate to problems of comfort and safety. In the first category, the behavior is characteristic of the molecular and surface contributions as modified by environmental and other element ; the second assesses, first, the effect of material properties on the human subject and, secondly, the response of the materials-man-environment system as the result of interactions between the elements of the system.

b. Laboratory Methods for Assessing Static Propensity of Materials

(1) General

Crugnola and Robinson[26] summarized the several laboratory techniques used to measure electrostatic levels up to 1959. Of the many procedures outlined at that time, the significant methods still extant are:

Resistivity - which in essence measures the integration of the number of traps and the height of barriers which influence charge drift mobility

Total Charge Density - which expresses a measure of the population of impurity or imperfection centers

Charge Decay Rate - a kinetic description of the degree of impedance to electronic motion

To determine the combined total charge density and decay (dissipation) rate, two methods of inducing charges are used. In the first, the experimental material is rubbed against a second material of different composition or nature. In the second method, the charge is achieved through induction in an electric field. In this latter instance, the total charge that can be held by the material up to the point of electrical breakdown into the medium is assessed and the ensuing rate of dissipation is recorded. This procedure needs to be scrutinized for possible unrealistic volume effects.

(2) Resistivity

Resistivity is a measure of the restraint to a current

passing either across the surface or through the volume of a material under an impressed potential difference. As an index of static propensity, it assumes the direct applicability of Ohm's Law (an assumption which may not be valid necessarily in all instances). However, it does provide an order of ranking with which use experience can be correlated. Its value derives from the assumption that the probability of charge build-up, and, therefore, the degree of hazard from an electrostatic potential, is directly related to conductivity. Experience has shown a reasonable degree of validity for these assumptions; however, the question of hazard is complex and will be further reviewed in later paragraphs.

As a general rule, the resistivity of cellulosic materials, namely cotton, is taken as representative of an electrostatically comfortable and safe material. For this generalization to be useful, the conditions under which the comparison is made need to be defined, since cotton, at low levels of ambient relative humidity and/or temperature, achieves very high values of resistivity in the range considered hazardous. On the basis of the conditions normally used for testing, namely, in equilibrium with an atmosphere of 30% relative humidity and 21°C (70°F), the following are the generally accepted degrees of 'safety' associated with resistivity values (Ohms per square):

| | |
|---|---|
| $< 10^9$ | safer than cotton |
| $10^9 - 10^{11}$ | practical safe levels - as safe as cotton or better |
| $10^{11} - 10^{12}$ | marginal for safety |
| $> - 10^{12}$ | progressively unsafe |

(3) Total Charge Density and Decay Rate

These two parameters are measured concurrently and in one of two ways depending upon end purposes. In the first, the material is mounted on a rotating wheel[27] or other isolatable-from-ground device and is rubbed gently and reproducibly against a second surface. The total charge induced on a sensitive electrometer is read immediately upon stopping the rubbing and the rate of decay of the induced charge is then assessed. In the second, the experimental material is rubbed manually in a prescribed manner against a second surface, then applied to a metal surface held at an angle of 70° to the horizontal and the time to unclinging is measured.[28] Since this time is a function of many factors among which weight and the smoothness of the material surface are significant, these characteristics need to be reported in addition to the definition of the temperature and relative humidity conditions existing at the time of test. Another method is to charge

the material and transfer it to a Faraday Cylinder[16,29] from which the charge and the rate of decay can be determined. Henry et al[30] have reported the effect of sample size on the amount of the charge which is generated on a material surface. These authors state that edge effects exist which influence the decay rate and the amount of the charge that is generated. Obviously, the larger the specimen the more likely is the charge and the decay rate representative of the material.

c. Materials-Clothing-Man-Environment Interactions

It is generally known that the human body is a good conductor of electricity primarily as a consequence of its water content and the presence of large quantities of ionic compounds. Prior examination of materials in layered systems has shown how charges distribute themselves between any two layers in intimate contact prior to separation and we can see, as we did in Figure 2, that this act leads to a further balancing of charges by induction throughout the several layers and upon the human subject. One would predict on the strength of these facts and on theoretical grounds that the rate of discharge through the human should be comparable to that through a metallic conductor. Further examination will show that there are a number of restraints to charge motion. Some restraints relate to the potential, the charge density, and the drift mobility of the charges on the outer material surface following separation of layers; others are concerned with the characteristics of the individual as mentioned earlier; and still others are connected with the degree of insulation from ground which influences the leakage rate of the charge. This last factor is illustrated in Tables XI and XII for several clothing combinations under two R.H. conditions at the same temperature. Further, the charge parameters as measured on the fabric surface may not, and usually do not, achieve a

TABLE XI

EFFECT OF PLATFORM MATERIAL AND FOOTWEAR CHARACTERISTICS ON CHARGE GENERATED ON CLOTHED INDIVIDUAL

21°C – 20% R.H

Rubbing Fabric – Polyester Plain Weave

| | | METHACRYLATE PLATFORM | | GROUNDED COPPER PLATFORM | |
|---|---|---|---|---|---|
| | | Initial Voltage | Voltage After 1 Min. | Initial Voltage | Voltage After 1 Min. |
| 1 | UNTREATED NOMEX LAYER OVER | | | | |
| | A. ANTISTATIC NOMEX LAYER | 1250 | 1250 | 2375 | 625 |
| | B. "A" – WASHED | 1000 | 800 | 0 | – |
| | C. COTTON FATIGUES | 1150 | 125 | 0 | – |
| | D. WOOL FIELD UNIFORM | 1250 | 1250 | 0 | |
| 2 | NOMEX W. 1% STAINLESS STEEL FIBER OVER | | | | |
| | A. ANTISTATIC NOMEX LAYER | 1875 | 1250 | 0 | – |
| | B. "A" – WASHED | 1250 | 1000 | 0 | – |
| | C. COTTON FATIGUES | 1875 | 1125 | 1875 | 2000 |
| | D. WOOL FIELD UNIFORM | 2700 | 750 | 100 | 150 |
| 3 | DIRECT RUBBING ON | | | | |
| | A. ANTISTATIC NOMEX LAYER | 2570 | 1750 | 2500 | 1000 |
| | B. "A" – WASHED | 2250 | 1525 | 900 | 450 |
| | C. COTTON FATIGUES | 2875 | 2690 | 2500 | 1250 |
| | D. WOOL FIELD UNIFORM | 2800 | 750 | 1250 | 350 |

TABLE XIII

EFFECT OF PLATFORM MATERIALS AND FOOTWEAR CHARACTERISTICS ON CHARGE GENERATED ON CLOTHED INDIVIDUAL

21°C – 50% R.H.

| | METHACRYLATE PLATFORM | | GROUNDED COPPER PLATFORM | |
|---|---|---|---|---|
| | Initial Voltage | Voltage after 1 min. | Initial Voltage | Voltage after 1 min. |
| 1. UNTREATED NOMEX LAYER OVER: | | | | |
| A. Antistatic Nomex Layer | 1000 | 1000 | 2500 | 0 |
| B. "A" – Washed | 1625 | 625 | 0 | – |
| C. Cotton Fatigues | 1400 | 1180 | 1300 | 340 |
| 2. NOMEX WITH 1% STAINLESS STEEL FIBER OVER | | | | |
| A. Antistatic Nomex Layer | 875 | 325 | 50 | 0 |
| B. "A" – Washed | 2125 | 1050 | 0 | – |
| C. Cotton Fatigues | 625 | 75 | 175 | 50 |
| 3. DIRECT RUBBING ON | | | | |
| A. Antistatic Nomex Layer | 1650 | 1250 | 650 | 25 |
| B. "A" – Washed | 300 | 275 | 0 | – |
| C. Cotton Fatigues | 475 | 125 | 120 | 25 |
| D. Wool Field Uniform | 5.0 | 525 | 0 | – |

quantitative translation to the human in the system because of drape and contact aspects of the clothing system which determine surface-to-surface conformities and layer separation energies.

Petrick[31] of the Naval Weapons Laboratory has made an attempt to compute the charge generated on separation of layers of a clothing system by using a double drum arrangement, a Faraday cage, and a capacitor in series with the cage. While he introduces clothing dimensions in the computation of the charge generated, he does not take into account many factors that are part of the clothing-man-environment relationship such as spacing of clothing layers, nature of the platform on which the individual is standing, nature of the footgear the individual is wearing, etc. The equations he uses are:

$$\alpha = C^1(\Delta V/\Delta T)$$

$$V = 0.2\ A\alpha/C$$

$$A = 2\ \ ab + l(w+c)/2$$

where $C^1$ is the capacitance of the Faraday cage and the capacitor

$\Delta V/\Delta T$ is the rate of voltage rise

A is the area of contact of the clothing

C is the human capacitance

a is the sleeve length

c the average sleeve diameter

c is the chest size

w is the waist size

$\sigma$ is the charge generated

Despite the indications from laboratory data on materials, it becomes evident that the ultimate test must be with the material-clothing-man-environment system under conditions typical of those in end-use.

In performing tests of clothing systems, two variations of procedures are used. One involves a simulated layer separation performed within a conditioned laboratory; the other is executed in controlled climatic chambers. In the first of these, an individual with a layer of one fabric draped across the back and shoulders stands on a polymethylmethacrylate platform that isolates him from ground. A second individual on a conducting base then rubs the back and shoulders area of the first person with a material located at a significant separation distance 'in the triboelectric series' from that being rubbed. When the rubbing is completed, the isolated individual on the insulating platform either takes hold of the leads to a sensitive electronic instrument to record the total charge induced on his body or a non-contact probe is used. Average and peak values from several replications are recorded. The individual may then step over to a grounded metal platform and the charge under these conditions is assessed. To avoid energy transfer, the PMMA platform is often overlayed with a groundable metal plate connected to ground through a high capacitance switch.

A more realistic variation of this technique is performed in climatic chambers in which temperature-humidity conditions are carefully controlled and where the test subject can perform routine activities. Temperatures as low as -30°C and as high as +60°C can be attained with selected relative humidity levels. In this situation, the clothed individual is first discharged with a low energy radioactive source and by physical grounding; he then proceeds on a rubber apron treadmill walking at 1 meter/sec while performing certain prescribed body movements which induce motion of the clothing layers relative to each other and to the body. Care is taken to avoid surface contact of the outer garment with chamber walls, etc. The exercise time is established on the basis of pre-test calibrations to achieve the maximum or peak charge level when the outer garment is removed. In practice, before the outer garment is removed, the charge on the

surface of the outer garment is determined using a non-contact detector. The individual then removes the outer garment and discards it while still on the treadmill. The charge on the new outer layer surface is obtained; he then discharges his body by deliberate grounding and the charge on the outer layer is rechecked. This procedure may be repeated with each clothing layer down to the bare skin. Variations of this include a grounded metal apron on the treadmill and the use of footgear either highly insulating or lightly conductive, depending upon the conditions to be evaluated. In Table XIII are data on several clothing assemblies tested in the above manner on both platforms. These are laboratory technique data using technical personnel as subjects; footgear was not controlled. These data and those in Tables XI and XII reveal a number of significant facts:

TABLE XIII

ELECTROSTATIC SUSCEPTIBILITY OF UNIFORM ASSEMBLIES

70°F 20% R.H.

| Uniform Assembly | Insulated Platform | | | | Conducting Platform | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial (Volts) | | Decay (1 Min) (Volts) | | Initial (Volts) | | Decay (1 Min) (Volts) | |
| | A | B | A | B | A | B | A | B |
| UNTREATED NOMEX 100% | | | | | | | | |
| Over Cotton Layer | 750 | 1375 | 75 | 1200 | 0 | 1875 | 0 | 2000 |
| Over Antistatic Treated Nomex Underwear | 1250 | 1875 | 1250 | 1250 | 0 | 2375 | 0 | 625 |
| Over Wool/Ctn Underwear | 1250 | 2700 | 750 | 1250 | 0 | 100 | 0 | 10[illegible] |
| COTTON FATIGUES | | | | | | | | |
| Over T-Shirt and Shorts (Cotton) | 3125 | 4375 | 2500 | 2875 | 0 | 2500 | 0 | 1250 |
| Over Antistatic Treated Nomex Underwear | 2500 | 2625 | 1625 | 1875 | 0 | 5000 | 0 | 0 |
| WOOL SHIRT & TROUSERS | | | | | | | | |
| Over Wool/Ctn Underwear | 3125 | 2500 | 2625 | 1875 | 25 | 1250 | 100 | 275 |
| NOMEX STAINLESS STEEL BLEND (2% In Filling) | | | | | | | | |
| Over Cotton Layer | 1375 | 1875 | 1000 | 1125 | 0 | 750 | 0 | 250 |
| Over Antistatic Treated Nomex Underwear | 150 | 1500 | 100 | 675 | 0 | 850 | 0 | 250 |

(1) The importance of electrical conductivity of the platform and also of the footgear (Subject A had conducting footwear).

(2) The significant contribution of moisture regain value to static charge density on the specific fibers (at 21°C - 30% R.H.).

(3) The differences between individuals of comparable body dimensions and mass. In this regard, Ramer and Richards[32] quote an Aero-jet General report showing differences between men and women in their ability to develop an electrostatic charge. This is attributed to the degree of looseness of the clothing. Women's clothing tends to be more free flowing. Men's clothing tends to be tight; therefore, women generate more static than do the men.

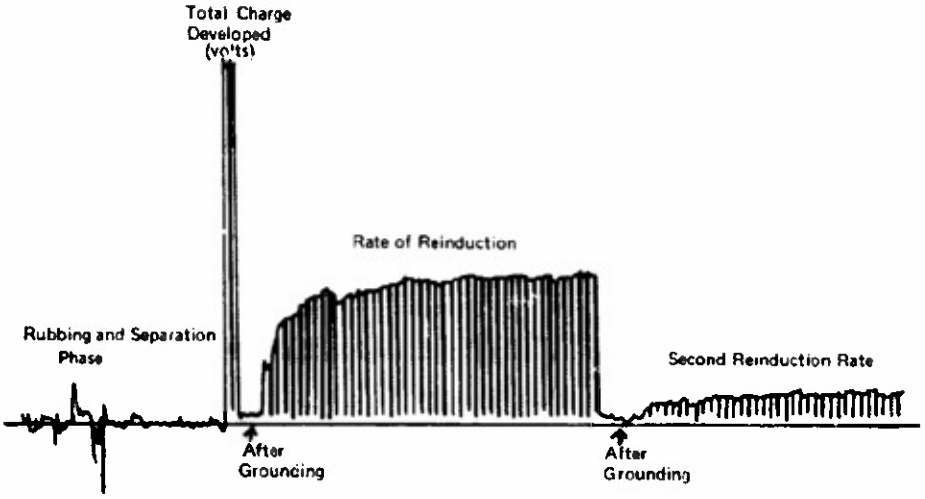
(4) The contributions of the electrical characteristics of the several layers in the clothing systems to the charge density found on the individual.

A significant fact emerges from these studies, namely, that while the individual may reach ground potential, the several clothing surfaces themselves still retain a charge. This retention, of course, is related to charge potential, density, and barrier heights affecting mobility, and also to layer-to-layer and clothing-to-body contact. In consequence, we can have a situation of a reinduction of charge on the body once the connection to ground is broken and an insulating condition is re-established. This can give rise to the occasionally reported incidence of a second spark. In Figures 8 and 9, we illustrate this reinduction process under two experimental conditions, one where the individual stays on the insulated platform full time during the experiment but grounds himself momentarily by contact with a ground wire (Figure 8); the other where the individual, standing on a grounded platform, brings his body to zero potential as in the insulated platform situation but then allows the conductivity of the footgear to determine the level of reinduced charge (Figure 9).

Measurements of the type mentioned include the electrical and areal contributions of the footgear. In one series of experiments, the clothed individual, wearing non-conductive footgear, stepped from the insulating platform to an adjacent grounded metal platform. There was a significant reduction in total system charge, due unquestionably to a change in system capacitance or to 'contact potential' differences, which were regained upon stepping back to the insulated platform. We saw these conditions illustrated in Figures 8 and 9. Similar changes were noted on the insulated platform by just raising one foot off the platform. For this reason, a more recent technique has mounted the metal on the methacrylate platform and the grounding connection to the metal is controlled by a high capacitance switch. The individual's movements are restricted once the initial exercise phase is terminated.

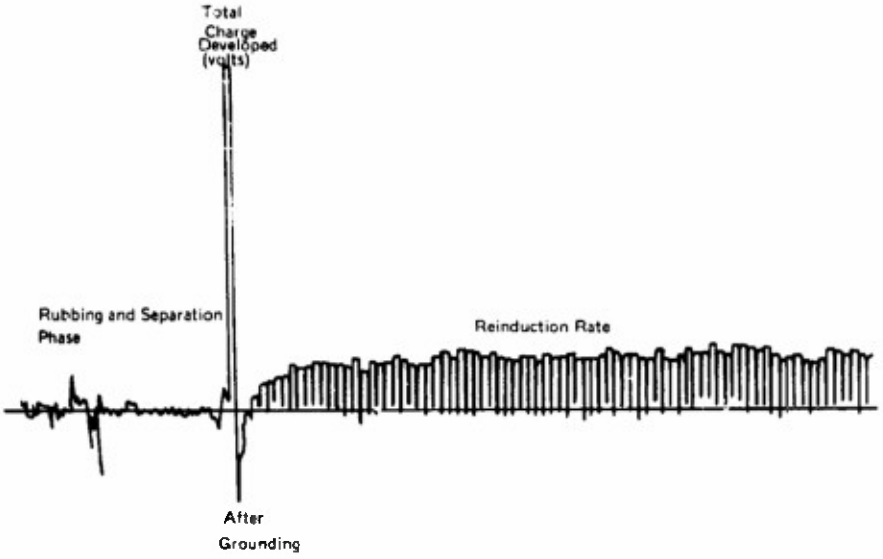
## 6. Implications of Fabric Electrostatic Properties on the Materials-Clothing-Man System Performance

Our interest in electrostatic phenomena in textile materials lies in a desire to understand the forces and the mechanisms involved, but when such materials are combined in clothing worn by the individual we acquire an overriding concern for the unpleasant facets of the release of the energies represented in the system. We become deeply involved in the question of hazard, which of course implies the presence of sensitive materials or a critical situation. We turn then, on the one hand, to the significant parameters of the materials and




REINDUCTION OF CHARGE FOLLOWING GROUNDING
WOOL UNIFORM RUBBED WITH NOMEX FABRIC
METHACRYLATE PLATFORM

FIGURE 8




REINDUCTION OF CHARGE FOLLOWING GROUNDING
WOOL UNIFORM RUBBED WITH NOMEX FABRIC
GROUNDED METAL PLATFORM

FIGURE 9

the system and, on the other hand, to the properties of the secondary elements or sub-systems in an expanded new system which must now contain not only the original materials-clothing-man components but the sensitive materials and the parameters of the hazard environment. If we examine the ignition energies and potentials for a typical group of sensitive materials in Table XIV, we must conclude that data previously

TABLE XIV

ENERGIES AND CORRESPONDING POTENTIALS FOR IGNITION OF SENSITIVE MATERIALS(33)

| Material | Ignition Energy (Millijoules) | Corresponding Potential Necessary for Ignition (Volts) |
|---|---|---|
| Methane | 0.5 | 2150 |
| Gasoline | 0.8 | 2650 |
| Ethylether | 0.2 | 1350 |
| Cyclopropane | 0.2 | 1350 |
| Benzene | 0.5 | 2150 |
| Acetone | 0.6 | 2350 |
| Cu-Acetylide | 0.002 | 150 |
| Pb-Azide | 0.04 | 650 |

presented reveal many materials-clothing-man systems which at least provide or exceed the ignition potential of these materials.(33,34,35) Such has apparently occurred in at least one recorded incident. Veghte and Millard(36) of the Air Force Arctic Aero-Medical Laboratory report a case of a man removing a flight jacket before picking up a gasoline can. The can exploded on contact.

Generally, in the reports of such situations there are two missing features: one has to do with whether the right composition and state of the sensitive materials existed; the other has to do with the requirement for energy and mobility levels needed by the kinetics of the discharge from the individual to satisfy the reaction constants of the sensitive materials, namely, their activation or ignition energy and time constants.

The question of relative charge mobilities in the materials-man-clothing system deserves discussion, as it is quite often the cause of misunderstanding. It is reasonable to expect the existence of a relationship between total charge density and charge mobility on the material with the rate of charge release from the man on grounding,

but the degree of hazard is not as readily perceived. A high rate of charge mobility (relatively few or shallow trapping centers) on the material surface insures a rapid redistribution of charges as the layers are separated (charges are able to tunnel through at the point of separation). The residual charge density on the material is thus reduced and with it the charge induced on the individual. Where resistivity is high (high barriers) and mobility is low (high barriers and deep traps), charge density is high and there is a significant increase in the charge induced on the individual. The achievement of a high charge mobility on the fabric layers of a clothing system is thus one essential to reducing the induced charge and in minimizing both discomfort and hazard effects.

At any given total charge density, the rate of release of charges from the individual upon grounding is determined by individual characteristics but is secondarily influenced by the rate of charge transport across the outer layer surface and through the several layers in the clothing system. Under a given set of conditions, then, the hazard develops only when the full charge density is instantaneously released in its full capacity, providing that the energy so released is at least equal to the energy requirements of the hazard producing reaction.

There are many other factors in the hazard situation. Thus, Heidelberg[37] has shown that the probability of ignition of gaseous mixtures depends upon both the composition of the mixture and on the diameter of the element from which the charge is released. He proved that grounded point sources such as needles will not ignite hydrogen-air mixtures. With an increase in diameter of the discharging element, both the concentration range in which ignition becomes possible and ignition probability increase simultaneously. The area over which the charge density is distributed is obviously related to total capacity of the system. Zichy[38] has also shown that charge density on polymer films is high if a large capacity is provided by a backing conductor. In the materials-man-clothing system, the human body with a relatively high capacity could be considered as the backing conductor.

Uniformity of distribution of charges on the material surface is another factor. Bertein[39] has shown the existence of both positive and negative charge islands on surfaces of high resistivity. She has also shown that the relative concentrations of these charges can be displayed by the use of sulfur and red lead powders. The yellow sulfur goes to the positive charges and the red lead to the negative charges. By this means, positive and negative regions have been found to co-exist. Discharge occurs according to an exponential law (typical n-type semiconductor response). She showed further that rubbing produces

charges which are evenly distributed but the rubbed areas are spotted with charges of the opposing polarity. She further postulates the existence of mixed and superficial doublets and reports that these doublets have force lines. Air ionization will not eliminate the doublets very readily. In this regard, Heidlberg[40] states that doublets are due to the non-uniformity of the charge. They are particularly present in textile materials. Similar results have been observed by this author and coworkers. It has been shown that rubbing a small discrete area will induce a confined area charge on underlayers and on the body only in that area so long as the systems remains unaltered.

## 7. Conclusion

The data revealed in the preceding review indicate quite conclusively that the phenomenon of static electrification of textile materials is electronic in nature, that the charges derive from defects, ionic impurities, etc., associated with molecular structure and order, and that rate of movement of the charges is dependent on barrier heights and trapping centers which are also related to molecular structure and order. Methods of charge dissipation must depend upon the removal of barriers to charge mobility.

The study shows that there are several chemical and physicochemical approaches to increase charge mobility on textile materials surfaces, and further that, in a clothing system involving a human, the achievement of high conductivity in all layers is important to effective dissipation of the charges. The electrical properties of the footgear as well as of the platform are important. It has also been shown that, in order to determine whether a hazard potential exists, the 'system' must be analyzed to include the material, clothing, man, sensitive materials properties, and the physical, spatial, and environmental conditions. Humans vary in their susceptibility to charge accumulation under insulating conditions. Finally, the possibilities of reinduction from high charge density situations and moderate grounding conditions have been shown to exist.

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