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Explosive Safety with Regards to Electrostatic Discharge

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EXPLOSIVE SAFETY WITH REGARDS TO ELECTROSTATIC DISCHARGE

by

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THESIS

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Dedication

*To my beautiful and amazing wife, Alicia, and our perfect daughter, Isabella Alessandra
and to our unborn child who we are excited to meet and the one that we never got to meet.
This was done out of love for all of you.*

Acknowledgements

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Abstract

Static charge is something that most individuals recognize as something that happens when they walk across a carpet, touch their refrigerator and get shocked. Most people seldom recognize that a shock due to static charge, or properly called, Electrostatic Discharge (ESD) is a phenomenon that has significantly damaging effects. Most people who stay informed of the current news, have heard stories of static charge causing a pump at a gas station to start on fire. Some individuals may even recognize that when they change the memory on a computer, they need to ensure that they are properly electrically grounded to prevent damage to any of the sensitive electronic components within their computers. However, it is unlikely that very many individuals would ever consider that an ESD event may be significant enough to initiate an explosive material.

Explosives materials are materials that many people might recognize as susceptible to initiation due to mechanical insults. Plastic and foam materials are often used to protect explosives. Unfortunately, often many of these materials are dielectric materials which are susceptible to triboelectric charge transfer, or build-up of static charge, and thus,

become a potential hazardous electrical source that may cause the explosive to inadvertently initiate.

To eliminate the generation of static electricity, it is important to understand the methods in which static electricity is generated on these types of materials. If the method of triboelectric charge transfer is understood, it is possible to minimize the effects to ensure that the device that is designed to prevent mechanical insults to the explosive materials does not become its greatest electrical insult. Once the method of charge transfer is understood, a potential method of charge removal might be possible to ensure that explosive devices are protected from both mechanical and electrical insults.

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CHAPTER 1: INTRODUCTION

1.1 Mechanical Safety of Explosives – Dielectric Materials

For organizations who work with or process explosive materials, great attention is spent

ensuring that the explosives are protected in a manner to ensure that they do not

inadvertently initiate. Organizations that perform explosive experimental tests may be

protecting an experimental assembly that contains not only explosives but may also

contain a detonator on the experiment.   When designing explosive materials, the main

explosive charge is designed to be the least likely explosive to initiate to ensure that it does

not unexpectedly initiate. However, when designing detonators, much more sensitive

explosives are utilized to ensure a reliable initiation of the main explosive [1].

Therefore, when explosive materials and explosive experimental assemblies are packaged

either for storage or transportation, protecting them against mechanical insults is very

important due to their sensitivity to mechanical insults. When explosive devices are

packaged or put in a configuration to protect them against mechanical insults, materials

with very good shock absorbing properties are utilized.

Consider the fact that when individuals purchase items that are to be shipped to their home,

Styrofoam^{TM} is often used. Styrofoam^{TM} is one of the most common materials used to

ensure that packaged materials are mechanically protected. Most individuals are familiar

with the Styrofoam^{TM} "packing peanuts" that are used in packaging to protect their items

from drops or other mechanical insults.

Consider the material properties of typical packaging materials. Most often, materials that are foams and/or plastics are utilized when things are packaged to be protected against mechanical insults. If the material properties of these items are considered, it can be noted that these materials are, when considering electrical properties, insulators. Not only are these items insulators, but most of them are considered to be dielectrics.

Dielectric materials are materials that are a group of electrical insulators that are prone to being polarized when an electric field is applied to them [2]. As dielectric materials are insulators and insulators have a high surface resistivity, when an electric charge is developed on the surface of a dielectric material, the charge is not uniformly distributed across the surface as it is in a conductor. The electric charge can be localized to a specific location upon the dielectric surface. Due to the high surface resistivity, the surface charge is also unlikely to "drain" off of the surface. Therefore, it is difficult to calculate or analyze the specific electric charge that may be generated on a dielectric surface.

Because of their high surface resistance and high permittivity, a dielectric material is also prone to triboelectric effects. Webster's dictionary defines triboelectricity as a charge of electricity generated by friction [3]. When the two materials are placed in contact with one another and then separated, negatively charged electrons are transferred from the surface of one material to the surface of the other material [4]. Which material loses electrons and which gains electrons will depend on the nature of the two materials. The material that loses electrons becomes positively charged, while the material that gains electrons is

negatively charged.

The triboelectric effect is often referred to as triboelectric charging. However, charge is actually transferred from one material to the other. The result is a positively or negatively charged surface but the process will be referred to as triboelectric charge transfer throughout this document as it is a more accurate description.

When a charged material is brought near another material that is of a different charge potential, the effect can often be seen as a spark, or arc, jumping between the two materials. The arc is the evidence that the voltage potential was great enough to breakdown the dielectric strength, or ability to stand-off voltage, of the air [5].

The amount of charge transferred by the triboelectric effect is affected by a number of items including the speed at which the items are rubbed against one another, the temperature, the humidity and the surface area that was contacted [6]. Some of the primary factors that affect the charge transfer are the material properties of the two materials and where they are found in the triboelectric series.

The triboelectric series is a table that lists common materials that may undergo triboelectric charge transfer and ranks them on a list [7]. This list is a relative ranking of how likely a material is to be positively or negatively charged during a triboelectric charge transfer. When two materials are rubbed together, the material that is closer to the top of the triboelectric series will take on a positive charge while the second material will take on a

negative charge. The further apart the two materials are in the triboelectric series, the greater the magnitude of the charge transfer due to the triboelectric effect can be. An example of a triboelectric series table can be found in Figure 1. The charge generated by the triboelectric effect can be extremely high as a carpet shock can often reach voltages of up to 25,000 volts [8].
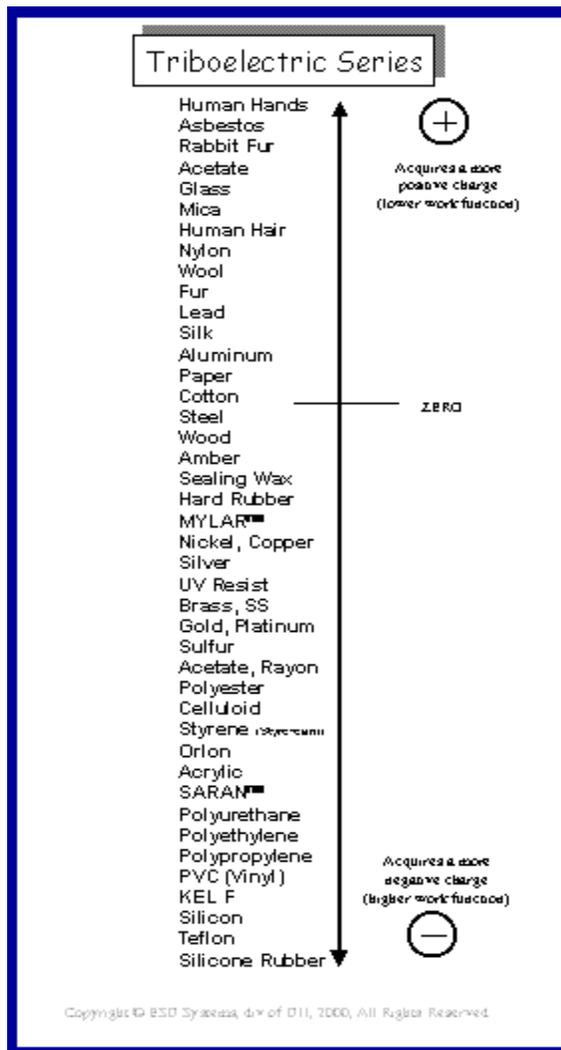
Figure 1 - Triboelectric Series [7]

The transfer of the surface charge energy from a triboelectrically charged surface to another is most commonly known as static shock; appropriately defined as electrostatic discharge (ESD). ESD can be simply defined as the transfer of electrons from two sources that have differing electrical potentials [1]. ESD most often occurs when two items pass by one another or brush up against one another and a transfer of electrons occurs. For example, an individual shuffling his/her feet across the carpet causes the electrons from the carpet to be transferred to the individual's feet and thus, his/her electrical potential changes. When the charged individual comes up to something that is grounded or at a different voltage potential, the energy is transferred in the form of a static shock.

Consider the Styrofoam^{TM} example once again. Although Styrofoam^{TM} makes a good material to protect mechanically sensitive items, it is also susceptible to the triboelectric effect. One example of this phenomenon is to consider the Styrofoam^{TM} packing peanuts example again. Any individual who has received a package with something fragile, is not only familiar with the Styrofoam^{TM} packing peanuts, but also how likely they are to stick to clothing. This is due to the high static field that is generated by the packing peanuts rubbing against one another.

1.2 Explosive Assemblies and Electrostatic Discharge

Is it possible that when protecting explosives against mechanical insult, a potential electrical insult may be introduced to the explosive assembly? An experimental explosive assembly is comprised of a main explosive, which is typically considered to be an insensitive explosive, which is initiated by some type of detonator. The explosive

material used in a detonator is considered to be a "sensitive explosive" and thus, is more

susceptible to unwanted initiations due to a variety of insults. Consider the following

commercially available detonator which is manufactured by Teledyne, RISI, Incorporated.
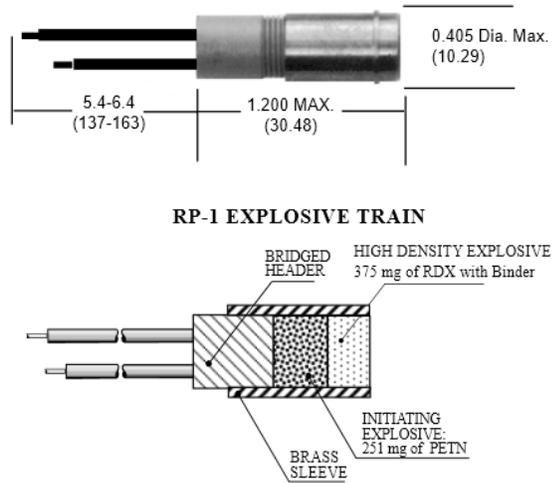
Figure 2 - Teledyne, RISI, Incorporated, RP-1 EBW [9]

This type of detonator is called an Exploding Bridgewire (EBW). The general method in

which an EBW works is a large amount of current is provided to the bridgewire in a short

period of time [10]. The rapid discharge of electrical energy will vaporize the bridgewire to

directly initiate a primary explosive, or PETN in the case of RP-1. A primary explosive is

an explosive that is considered to be a more sensitive explosive and thus, more likely to

inadvertently initiate due to unwanted insults. The initiating explosive then initiates the

high density explosive, or RDX in the case of the RP-1, which in turn initiates the

explosive assembly.

Consider the fact that the initiating explosive in the Teledyne RP-1 EBW detonator is

PETN. When the bridgewire vaporizes, it generates a shock wave which causes the

explosive within the detonator to initiate [10]. A secondary initiation method may exist.

Consider a situation, where an unexpected source of electrical energy, like ESD, could be applied to the detonator and would allow current to flow through the bridgewire. The amount of current may not be enough to vaporize the bridgewire to initiate the explosive. However, as current flows through the bridgewire, its temperature rises. If the temperature was to get high enough, could it cause the explosive material within the detonator to initiate due to the thermal response of the bridgewire?

Every explosive has an autoignition temperature which is defined as the temperature above which the self-heating of an explosive causes a runaway reaction [11]. Above that temperature, the explosive generates its own energy and initiates. For the PETN used in this EBW, the autoignition temperature is documented to be 190° C [12]. Based off the mass of the bridgewire, the bridgewire material and knowing the autoignition temperature, it is possible to calculate the amount of energy it will take to cause the detonator to initiate. To ensure a safety margin, an analysis can be done by assuming 50% the autoignition temperature. Thus, rather than evaluating against the 190 °C threshold, half of that, or 95°C would be the temperature to evaluate against. The reason for evaluating against a 50% autoignition temperature is to ensure a conservative and thus, safe, analysis.

For the RP-1 EBW, the manufacturer has not made the bridgewire information available as it is proprietary. If the bridgewire information had been available for the RP-1 detonator,

that information would have allowed for a calculation of the energy threshold of the

detonator.   However, further research identified a different EBW, which also uses PETN,

with a documented energy threshold of 32.6 milliJoules (mJ) [13]. Thus, the 32.6mJ

information will be used for the analysis which will be performed in Chapter 2.

The analysis will allow for an evaluation to determine if a theoretical dielectric surface

will cause the detonator to initiate, thus causing the secondary explosive to initiate as

well. However, it is also important to understand some of the materials properties of

dielectric materials that may influence the ability of a material to undergo the

triboelectric effect. If these properties are understood, it might be possible to use other

materials or influence the design of materials to limit how much the triboelectric effect

impacts them.

1.3 Influence of Surface Resistivity

The surface resistance of a material may affect the charge generation due to the

triboelectric effect. The surface resistance of a material is the resistance of the flow of

electrical current across the surface of the material. Volume resistance is the resistance

to flow of current through the three-dimensional volume of the material [14]. Static

electricity is considered to be primarily a phenomenon that happens on the surface of a

material. Therefore, only surface resistance will be considered for this thesis. Note that

the units of surface resistance are expressed as ohms/square ($\Omega/\square$) to differentiate from

the volume resistivity of a material [14].

The surface resistance of a material is defined as the ratio of the DC voltage to the current flowing between two electrodes which are in contact with the same side of a material [14]. Note that this is different from the general concept of resistance which measures through a material. Because of the high resistivity, the surface resistance is measured across the surface rather than through the material.

As the intent of studying the surface resistance of a material is to determine its influence on the triboelectric effect, it is important to recognize that the surface resistance is used to evaluate a material's static properties [15]. When considering tools or materials to be used when static charge is to be considered, materials are defined as isolative, antistatic, static dissipative, resistive and conductive relative to their surface resistance as can be seen on Table 1[15].

ESD Categorization	Surface Resistivity (ohms/square)
Antistatic	10^9-10^{12}
Static Dissipative	10^6-10^9
Conductive	10^3-10^6

Table 1 – ESD Categorization Table

The surface resistance of a material affects the ability for a surface to distribute surface charge and also drain the charge. Therefore, it seems reasonable to assume that the surface resistance may influence the ability for a material to transfer charge. As documented in the table above, the electrical resistance of a material is used to evaluate its electrostatic

properties. The question that arises is whether or not the surface resistivity is correlated with the ability to undergo triboelectrification [16].

1.4 Example of a Potentially ESD-initiated Explosive Incident [17]

On October 9, 2008, a group of experimenters were setting up an experiment at Sandia National Laboratories in Albuquerque, NM. The experimental assembly consisted of an experimental package on a rocket sled. The rocket sled utilized rocket motors to propel the experimental assembly along a sled track. The rocket motors utilized an accelerant that would burn and push the rocket sled forward. The accelerant is designed to be relatively insensitive and thus, utilized an initiating device, or initiator, to initiate the rocket motor. The initiator that was utilized was equivalent to an EBW [17].

At some point in the process, a technician began to install a plug type device on a connector that interfaces to the initiator. At that point, the rocket motor initiated and the rocket sled was propelled forward. A number of the involved experimenters suffered burns, broken bones, and damaged hearing. A variety of potential reasons for the inadvertent initiation was investigated including the possibility that the initiator was inadvertently initiated due to ESD.

1.5 Thesis Overview

This thesis will examine the potential issues that must be considered when using dielectric materials to protect explosive materials against mechanical insults. A potential method for a mathematical analysis will be evaluated. In addition, the relationship between the surface resistivity of a material and its ability to transfer charge via the triboelectric effect will be explored. Finally, a method for a reliable and consistent removal of surface charge will be explored. The complete evaluation will allow for a better understanding of analysis, material design for minimizing surface charge transfer and a method to remove any subsequent surface charge to ensure safety between explosives and dielectric materials.

CHAPTER 2: Methods of addressing the problems

2.1 Proposed Analysis Method

If one was to consider an explosive material and mechanically protective barrier made out

of dielectric material, the protective barrier must be considered as a potential source of

electrical energy, ESD, to initiate the explosive. It is also important to consider that the

explosive is also a dielectric and thus, the potential for triboelectric charge transfer is great.

Because of the difficulty in knowing how much surface charge might develop, it is

important to take a conservative approach to analyze how much potential energy might be

stored on the dielectric material.

One method of analysis for this problem is to evaluate the ESD source and its energy level

to determine if the maximum potential ESD energy of the material is high enough to

initiate the explosive assembly.

Because the initiation threshold value of the explosives and detonators is well

characterized, it provides a level to evaluate against to determine if an ESD insult can

initiate the explosive assembly.   For the purpose of this evaluation, the commercial

detonator threshold value is 32.6 mJ. Thus, it is possible to evaluate the maximum amount

of electrical energy that a theoretical dielectric can deliver to the explosive to evaluate if

that energy level is enough to cause the detonator and thus, the explosive assembly to

initiate.

To begin this analysis, it is important to determine what information is known about the

insulator. Consider the fact that the only information that is known and well-defined about the dielectric material is its surface area. With this information alone, the analysis must be performed.

The electric field on a material can increase to some maximum level. Once that level is reached, if a single electron was to be imparted onto the charged material, one electron would have to be "kicked-off." The surface electric field cannot get any higher at that point. Consider the fact that the universally accepted maximum electric field predicted on an insulator is 30kV/cm due to the breakdown strength of air [18].

The surface electric field on a conductor can be assumed to be uniform on the entire surface of the conductor because the relatively low resistivity allows the electrons to flow freely and evenly distribute across the surface area of the conductor. However, the surface electric field on a dielectric material is not uniform. Because of the relatively high resistivity of the material, the electrons have a difficult time flowing across the surface. This phenomenon creates varying pockets of charge across the surface of the dielectric material. If an electric field meter was to be used to measure the electric field on a dielectric material, two measurements that were taken at two locations that are physically located near one another, might measure values that can be orders of magnitude different.

If the maximum surface electric field was known or could be assumed for the dielectric material, it would be possible to use some first-principle electrical engineering equations to work towards calculating the maximum energy that could be delivered to the explosive

assembly by the dielectric material. Once that energy is determined, it is possible to evaluate it against the known initiation thresholds of the detonators and explosives. However, without the ability to assume a realistic electric field on the dielectric material, it seems difficult to perform an analysis.

Considering that the analysis must be conservative, it is possible to make some extremely unusual assumptions that allow for the maximum energy of the dielectric material to be calculated:

Assume that the dielectric material can have a uniform electric field; consider the dielectric material behaves like a conductor.

This radical assumption implies that a 30kv/cm maximum surface electric field is uniformly distributed on the entire surface of the dielectric material. This assumption of a uniform 30kv/cm is enough information to begin to utilize mathematical analysis to calculate the maximum energy that can be stored by the dielectric material.

Because the autoignition temperature and initiation threshold energy for the detonator is known, if some lesser threshold energy level is evaluated against, for example, 50% of the initiation energy, it is possible to try to protect the detonator against an energy level that is high enough to cause it to initiate.

Also note that another level of conservatism exists with the assumption that the dielectric

material behaves like a conductor. When a charged dielectric material is brought near to a second material and a triboelectric charge transfer takes place, the transfer of electrons is limited to the surface area on the charged dielectric material that is exposed to the second material. The discharge is usually in the form of a brush discharge which distributes much less energy than a static discharge which is formed when a conductor discharges energy [19].

When a conductor is brought up to a second material, all the charge on the surface will be transferred. The assumption that the dielectric material behaves like a conductor also means that all the surface charge that is collected on the surface of the dielectric material will be transferred to the detonator for this analysis. Due to the high surface resistivity of dielectric materials, this assumption is not very plausible but is highly conservative. Therefore, this is the assumption that has been made for a worst case scenario.

For the purpose of this analysis, a surface area will be assumed to allow a theoretical analysis to be performed. Assume the total surface area of the explosive protective cover is 1000 cm^2, approximately 12" x 12" surface. In addition, assume that the electric field on the entire dielectric surface is 30kV/cm. Utilizing those two pieces of information and beginning with Gauss's law, it is possible to begin the analysis.

If it is assumed that a dielectric material which is charged is approaching a second conductive surface, the electric field can be calculated by dividing the surface charge density by twice the free space permittivity, or 8.854×10^{-12} F/m. Note the factor of two accounts for electric field radiating from both surfaces of the dielectric. The equation can be rearranged to solve for sigma:

$$E = \frac{\sigma}{2\epsilon_0} \quad \text{Or} \quad \sigma = 2E\epsilon_0$$

Populating the equation with the values available gives:

$$\sigma = 2 * 30\frac{kV}{cm} * 8.854x10^{-14}\frac{F}{cm}$$

The solution is the surface charge density, σ, on the dielectric material is 5.3×10^{-9} coulombs/cm^2.

Utilizing this result for σ and the assumed surface area of 1000cm^2, it is possible to utilize the following equation which calculates charge, q:

$$q = A\sigma$$

The populated equation is:

$$q = 5.3x10^{-9}\frac{C}{cm^2} * 1000cm^2$$

The solution for charge, q, is $5.3x10^{-6}$ Coulombs.

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A method for which to consider this dielectric material surface charge as an energy-source hazard is to assume the charge is stored in a capacitor. Charge has been solved but a value for V is required. Assigning 25 kV, which is an upper-bound value often assumed for analysis purposes for facilities where explosives are handled, would be a conservative assumption as the 25kV voltage maximizes the potential energy. Thus, to solve for the capacitance, the following equation will be solved utilizing the calculated charge, q, and 25,000 volts.

$$C = \frac{q}{V}$$

The populated equation is:

$$C = \frac{5.3 x 10^{-6} Coulombs}{25,000 Volts}$$

The calculated capacitance for the dielectric material is 2.12 x 10^{-10} Farads, or 212 picoFarads (pF).

It is now possible to calculate energy to screen against the 50% threshold initiation energy for explosives. The equation for energy delivered by a capacitor is:

$$Energy = \frac{1}{2}CV^2$$

Explosive facilities within the Department of Energy (DOE) Weapons Complex have their

voltage distributions characterized to ensure a safe working environment within the

facility. These environments may range from an "uncontrolled voltage distribution", a

theoretical 25,000 volts, to a voltage threshold as low as 100 volts in a facility that tries to

control ESD. Utilizing the highest voltage within the voltage distribution and the

capacitance that has been calculated, it is possible to calculate the energy that can be stored

by the dielectric material. Once that energy is calculated, it can be evaluated against the

threshold energy for the detonator.

A maximum voltage of 25,000 volts will be utilized for the purpose of this analysis to

evaluate against a worst case scenario. This allows for the maximum possible energy

stored by the dielectric material to be delivered to the explosive assembly.

$$Energy = \frac{1}{2} * 2.12x10^{-10}F * (25,000V)^2$$

Solving the equation for energy gives a conservative result because a lossless charge

transfer is assumed. The resulting 66.25 MilliJoules (mJ) of energy is the maximum

amount of energy that can be stored by the dielectric material and thus, the maximum

amount of energy that can be delivered from the dielectric material to the detonator.

As noted earlier, the initiation threshold energy for an EBW is 32.6mJ. Thus, based off the

assumptions that were discussed, the size of the dielectric material and the assumed

maximum electric field, the EBW would initiate, thus causing any attached explosive to

initiate. In addition, even if the conservative assumption of 50% was not considered, if the 32.6mJ was doubled, 65.2mJ, the conservative analysis would predict that the detonator would still initiate.

One must recognize that, due to the limited information available on the dielectric material in question and all the conservative assumptions made, the analysis determines that the detonator could detonate. However, because the analysis is conservative, it would have a high probability of ensuring the prevention of an inadvertent initiation of the explosive assembly. Realistically, when considering the results of the theoretical analysis, assuming utilizing a dielectric material less than 1000 cm^2 (12" x 12") is not very realistic as this is a relatively small surface when attempting to protect large explosive charges. Knowing the threshold energy of the detonator, one could calculate the maximum surface area instead. However, the solution would, once again, be extremely conservative and would solve for a surface area that is too small to be realistically implemented to protect against mechanical insults.

Although these conservative analyses are often accepted by organizations like the DOE Weapons Complex and other organizations who are working with explosives to ensure the safety of workers, the conservative values prove costly and difficult to implement. For example, if a room where explosives are processed had conductive floors, metal tools, conductive wrist straps, etc., it is would help minimize voltage potentials but it would still be difficult to guarantee that the potential for ESD is really being limited to a level below the analytical initiation threshold level. In addition, these engineering controls could be

extremely costly. An understanding of the material properties that might affect the charge

transfer due to the triboelectric effect might allow for a design change of the materials to

help reduce the assumed electric field values used in the analysis.

2.2 Understanding Surface Resistivity

A literature review illustrates that there are questions on whether or not the surface

resistance influences the triboelectric effect. There are a variety of material properties that

must be considered when understanding the propensity of a material to undergo the

triboelectric effect. Some of these material properties include the smoothness or roughness

of the surface, how contaminated the surface is, the material's ability to absorb water,

surface resistivity, etc. The intent of this experiment is to focus only on how the surface

resistivity may affect the triboelectric process.

The ability of the surface resistivity to affect the triboelectric process intuitively seems like

it may be an easy answer to determine.   A series of experiments with a variety of materials

was performed for the Kennedy Space Center [20]. The experimenters concluded that the

surface resistivity and the triboelectric charge generation tendencies of materials are not

related to each other [20]. However, there have also been studies that have found the

ability to correlate the relationship to be difficult because of the number of variables that

affect the triboelectric charge transfer process [21].

To study the relationship between surface resistivity and triboelectrification, two important

measurements must be taken. The surface resistivity of the material must be measured. In

addition, because of the linear relationship between surface charge and the electric field, the electric field of the dielectric material must be measured before and after a material undergoes triboelectrification.

2.2.1 Surface Resistivity Experiment

An experiment was performed to determine the surface resistivity of a variety of materials. Standard ESD-ADV53.1 was used to design the experiment. An EMIT 50557 surface resistance test kit was used to measure the surface resistivity of the different materials. The test kit is designed to take measurements for a variety of surface resistance standards as documented in numerous ANSI standards. In addition, the test kit was also calibrated by a National Institute of Standards and Technology (NIST) and American Association for Laboratory Accreditation (A2LA) approved calibration laboratory and was within its calibration date during the time that the experiments were performed.
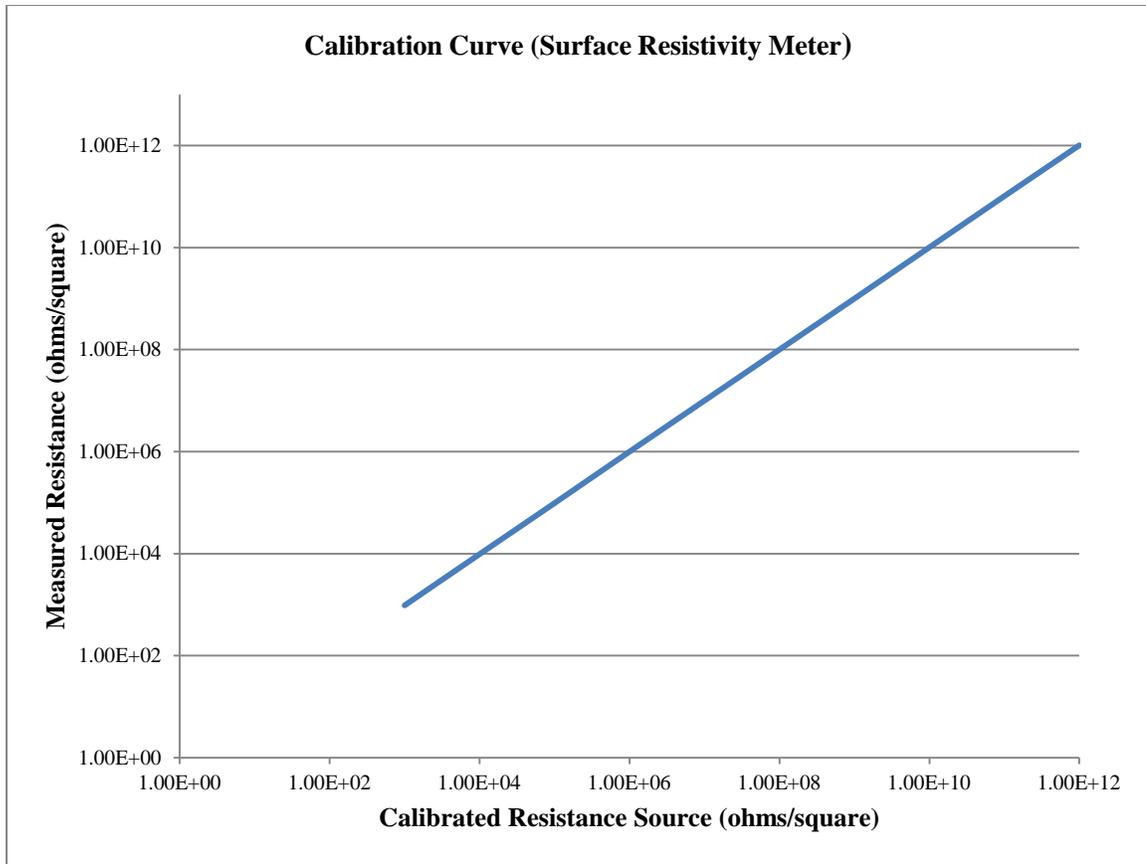
Figure 3 -Calibration Curve – Surface Resistivity Meter

As per ESD-ADV53.1, the experiment utilized two 5 pound electrodes which were placed

10" apart [22]. The surface resistance test kit also provided the proper electrification

period of 15 seconds per ANSI/ESD 4.1. After numerous readings and calculations are

executed, the meter displays the surface resistance mantissa measurement rather than an

instantaneous measurement like many meters [22].

Each material type was tested 3 times minimum and then an average surface resistivity was

calculated. As per ANSI/ESD S4.1, the electrodes were cleaned with a minimum 70%

isopropanol/-water solution in between each measurement. In addition, each of the

materials tested was also cleaned with a minimum 70% isopropanol-water solution to ensure that surface contaminants did not cause errors in the surface resistivity measurements.

The following table documents the materials that were tested and their average measured surface resistivity values. The meter had a measurement range that measured by decades of surface resistivity up to 10^{11}ohms/square. Any resistance higher was measured as $>10^{12}$ ohms/square.. The materials that measured these values also have a documented surface resistivity.

Test Material	Measured Surface Resistivity (ohms/square)	Documented Surface Resistivity (ohms/square)
Aluminum	$<10^3$	
Red HE Adiprene^{TM} Material	10^{10}	
Black HE Adiprene^{TM} Material	10^{10}	
Gray HE polyvinyl chloride (PVC) Material	10^{12}	
Lexan^{TM}	$>10^{12}$	10^{16}
PTFE Teflon®	$>10^{12}$	10^{18}

Table 2 - Test Material Resistance Values

The Red HE Adiprene^{TM}, Black HE Adiprene^{TM} and Gray HE PVC materials were chosen as they are materials that are currently used within the DOE Weapons Complex for the mechanical protection of explosive assemblies. The selection of Lexan^{TM}, Teflon® and Aluminum allowed for additional materials to be tested with varying surface resistivity values.

Once the surface resistivity values of the different materials were measured, a series of experiments were performed to characterize the ability for each of the materials to undergo the triboelectric effect. There are a variety of different variables that will affect the triboelectric effect and thus, an effort was made to control as many variables as possible. Primarily, the temperature, humidity, friction force between the two materials and speed at which they were rubbed together were controlled.

The temperature and humidity were controlled to be 68.2-69.1 °F and 15.6-16.1% RH, respectively. The friction force between the two materials and speed at which they were rubbed together was controlled by the design of the experiment which is discussed later in the document.

2.3 Charge Generation and the Electric Field

A Simco FMX-003 electric field meter was used to measure the surface electric field that was generated on the different materials when manipulating them. The electric field meter was calibrated by a NIST and A2LA approved calibration laboratory and was within its calibration date during the time that the experiments were performed.
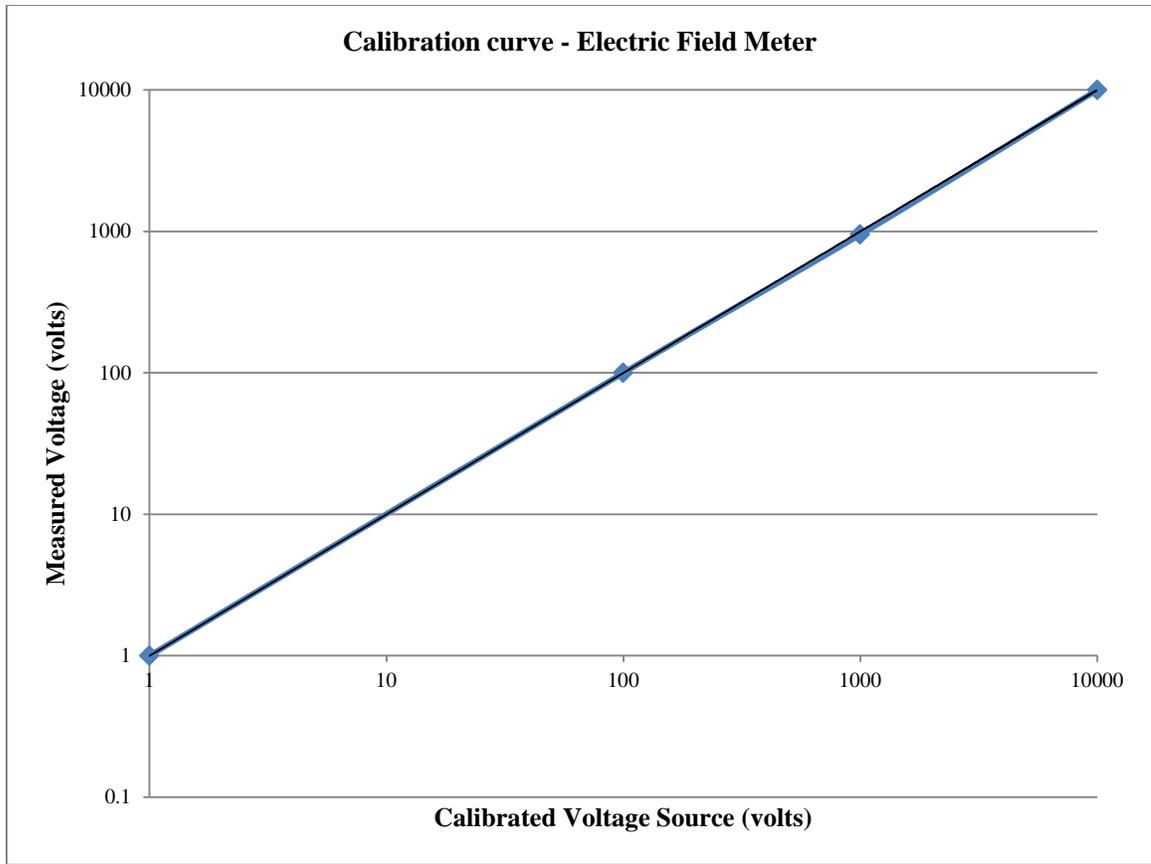
Figure 4 - Calibration Curve - Electric Field Meter

The manufacturer states that the electric field meter must maintain a distance of 1" from the surface which is being measured. A clamp was utilized to maintain the 1" required measurement distance. The clamp was installed on a track which allowed for a linear and controlled movement of the electric field meter. This allowed for a series of measurements to be made along an equally spaced linear section of the dielectric to be tested. The track also allowed for a controlled electric field measurement to be made before and after the dielectric was manipulated to undergo triboelectrification. A series of marks along a straight line parallel to the track were made as reference points to ensure the controlled placement of the electrostatic field measurements. The electric field meter, the clamp and

the track can be seen in Figure 5.

Figure 5 - Electric Field Meter Configuration

A critical requirement to making accurate electric field measurements on charged dielectric materials to ensure data integrity for a valid charge transfer comparison is to maintain a consistent method for charge transfer. Relevant research details a variety of "charging methods" some of which include manual manipulation of dielectric materials with rabbit fur and others which use wheels that have rabbit fur which are spun against the dielectric surface at a controlled rate for a specified length of time. A significant effort was made to ensure that the method of triboelectric charging was consistent from one dielectric material to another.

Some manmade, plastic-based fabric material, which proved to easily generate a large static field (>22kV/in which was the maximum range of the field meter), was used as the controlled dielectric surface. It was extremely important that the surface area, speed of friction and force onto the tested dielectric surfaces were controlled. A piece of aluminum was wrapped in the fabric (referred to as the charge transfer tool from this point on) and had a string attached to it. The second end of the string was installed to a spool which was attached to a variable speed controlled drill to drag the charging tool in a linear manner across the test dielectric material surface. This allowed the friction force, friction speed and contacted surface area to be controlled. The experimental configuration can be seen in Figure 6. The charging tool can be seen attached to the twine that was used to pull it at a consistent rate with the drill.
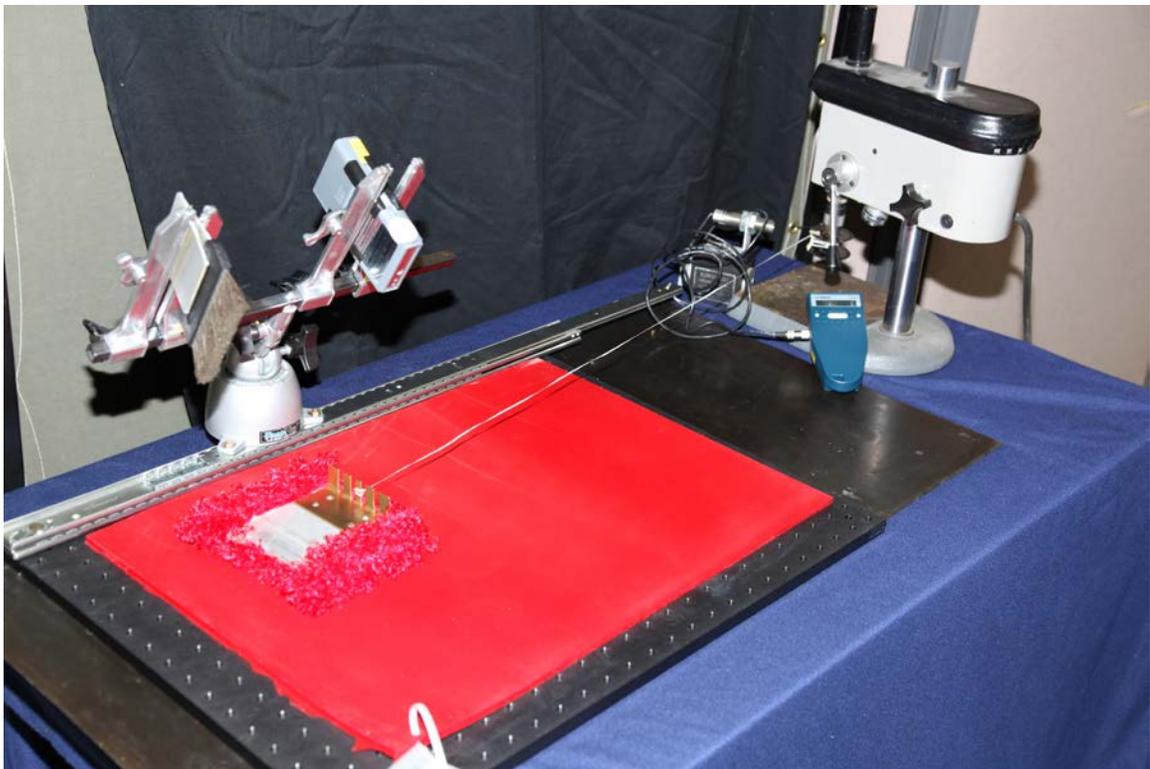
Figure 6 - Experiment 1 Test Configuration

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Prior to each experiment on the test dielectric surface, an attempt was made to remove all possible surface charge from the test dielectric surface. A conductive brush, which will be described at a later section, was used to remove as much surface charge as possible. The EMF meter was used to measure the electric field on the surface of the dielectric material at points that were on a straight line at 2" spacing.

During the first set of experiments, it was determined that additional experiments might be necessary to ensure there was enough data to develop conclusions. All three charge transfer experimental series that were performed will be discussed.

2.3.1 Experiment 1: Triboelectric Charging

The first series of charge transfer experiments utilized the triboelectric charge transfer method that was described above. Each material was tested with the charge transfer tool. As noted, a conductive brush was utilized to remove all possible surface charge. A series of 6 voltages separated by a linear distance of 2" each was measured. The charge transfer tool was then dragged across the surface of the material. The 6 voltages were measured again. This process was performed a total of 4 times for each test material, measuring the voltages at 6 points each time. The conductive brush was only utilized prior to dragging the charge generation tool across the surface the first time. It was not used again for each material after the surface was charged as an incremental increase in the electric field was expected. Thus, a series of increasing electric field measurements was recorded for each test material.

To ensure this document was readable and ensure that the data was not overwhelming and difficult to interpret, the data was displayed using charts and tables in this document to draw conclusions. In addition, as total charge transfer was the focus of the study, all electric field voltage values and percentages displayed are the absolute value of the values measured as the sign of the charge is not of concern for this study. The voltages measured were sometimes positive and sometimes negative but are always displayed as positive in all the comparison charts and tables.

The starting electric field of all the materials must also be considered. Many of the materials maintained a relatively significant electric field even after the charge was removed using the conductive brush.

To ensure a convenient method to interpret the data, all plots and graphs will place the lowest resistance material to the left increasing to the right. This will allow a direct comparison from chart to chart to make the data easy to interpret.

Figure 7 is an example of the increasing electric field measurements that were measured at the 6 locations on the dielectric materials. The test material in the plot below was Lexan® and was chosen as the example because its effects of triboelectrification were significant.
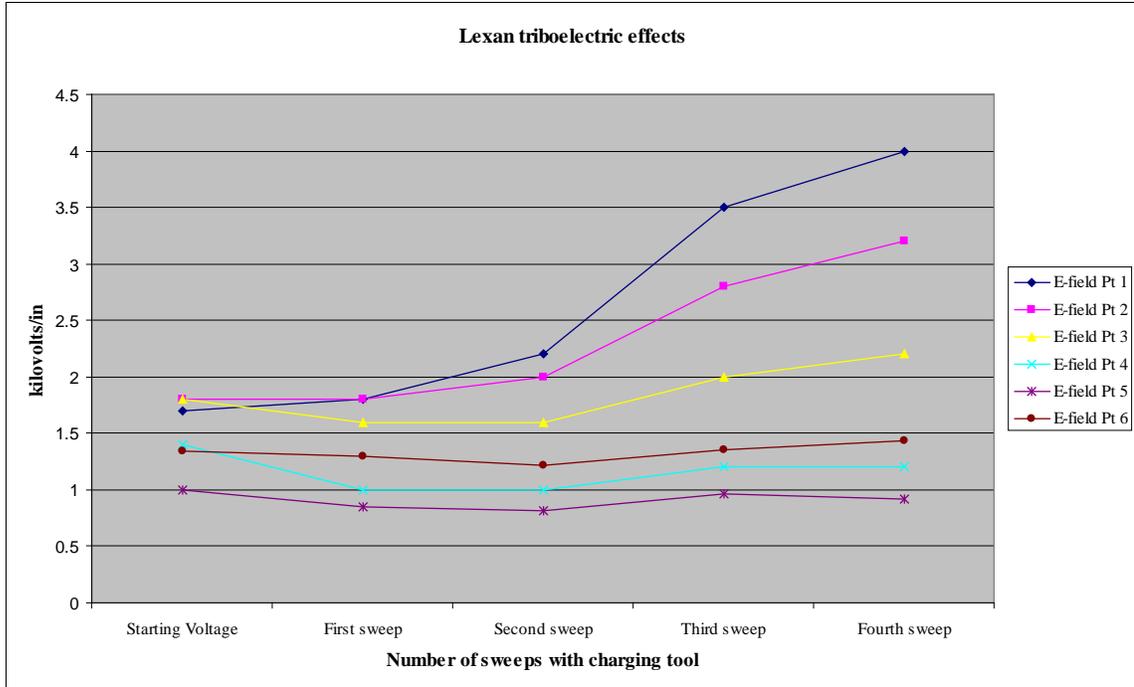
Figure 7 - Experiment 1: Lexan Triboelectric Effects Plot

The following figure displays the maximum charge transfer in kilovolts and percentage relative to the starting electric field that occurred after dragging the charge transfer device across the materials for a total of 4 passes.
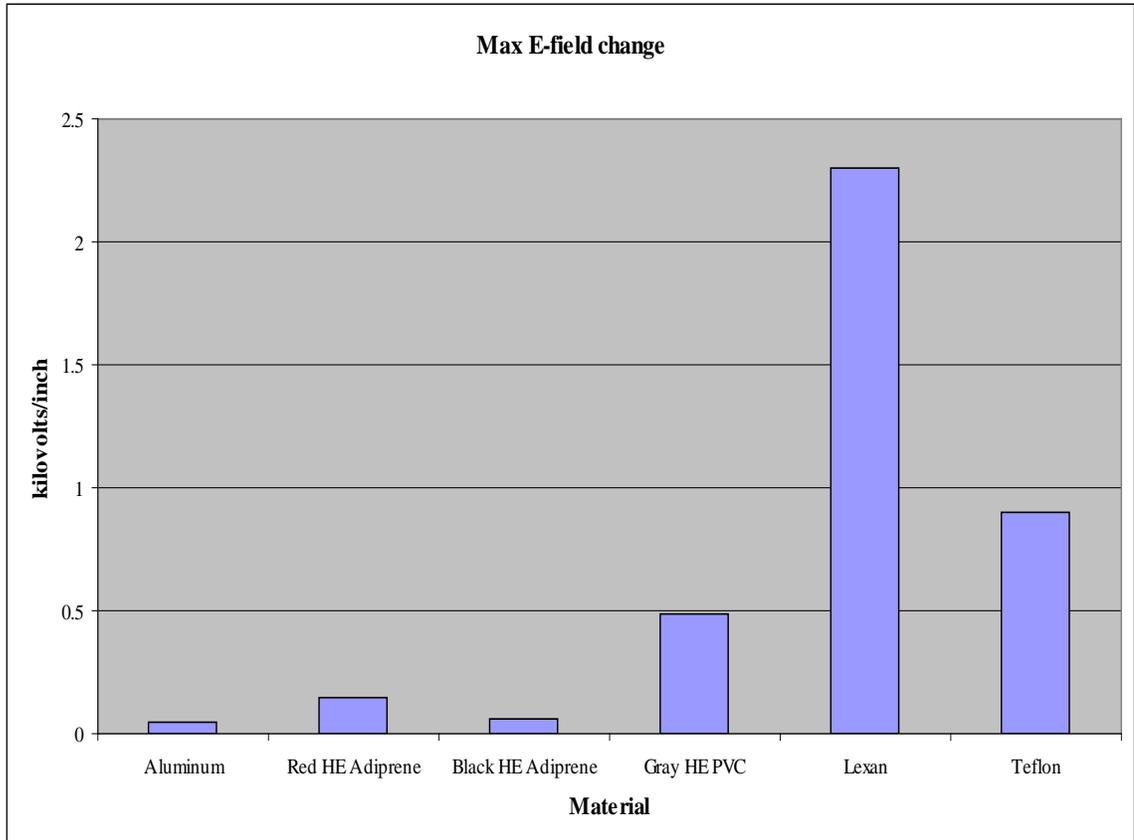
Figure 8 -Experiment 1: Maximum Electric Field Change

A review of Figure 8 appears to correlate the concept that the higher the surface resistivity

of a material, the greater the ability for it to undergo triboelectric charge transfer.

However, it is also important to consider that the Lexan[TM] and Teflon® have measured

surface resistivities of $>10^{12}$ ohms/square whereas the Gray HE PVC material has a surface

resistivity of 10^{12} ohms/square. However, the documented surface resistivities of Lexan[TM]

and Teflon® are 10^{16} ohms/square and 10^{18} ohms/square. Of the 3 materials that have a

surface resistance of at least 10^{12} ohms/square, the Lexan[TM] has the highest maximum

change in the electric field. However, during testing, it also started with one of the highest

electric fields. Thus, the best way to compare the effect of the triboelectric effect is to

compare the different materials with regards to the change of the electric field relative to its

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starting electric field. Figure 9 presents the percentage of charge transferred for the

different materials that were tested.
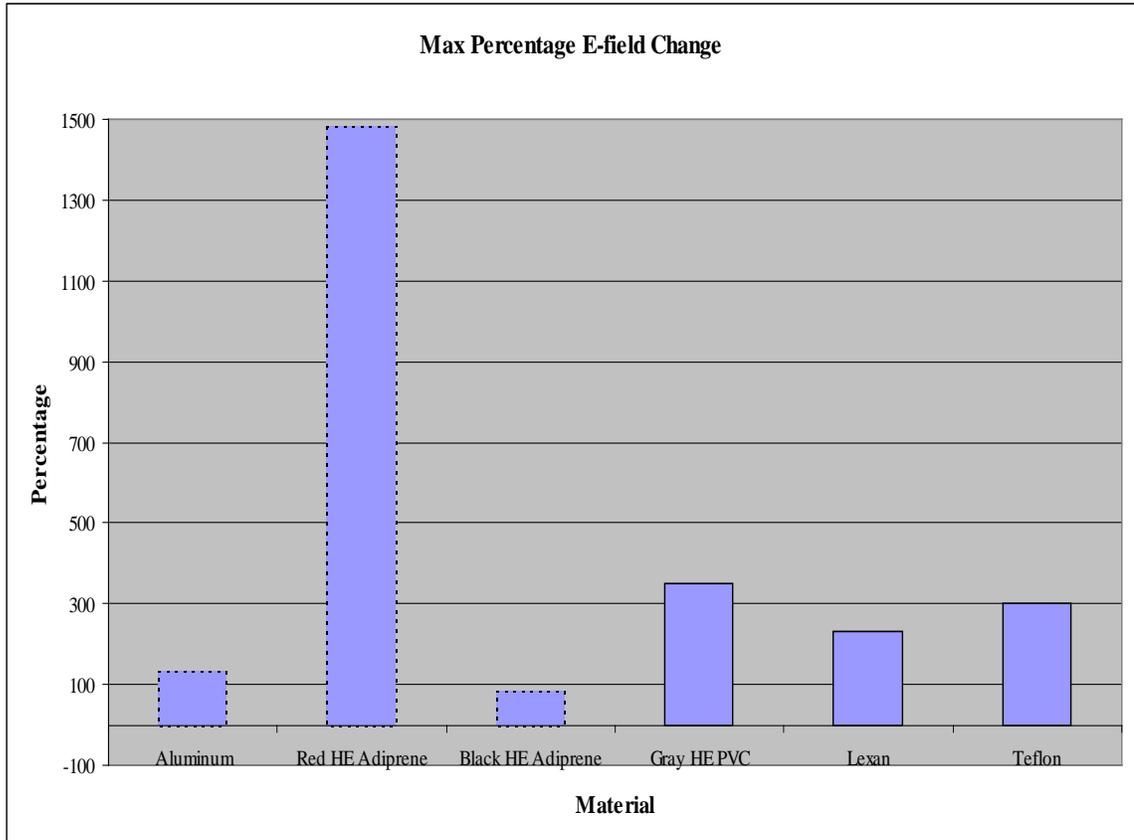
Figure 9 - Experiment 1: Maximum Percentage Electric Field Change

At first glance, it appears like the propensity for charge transfer for all 6 materials is similar

except for the Red HE Adiprene[TM]. However, the Red HE Adiprene[TM], Aluminum and

Black HE Adiprene[TM] only experienced a relative increase of electric field of less than 200

volts. Thus, a small variation of charge reflects in a large percentage change of the electric

field. These materials have been identified as such in the table by the dotted line around the

bars they represent.

The Gray HE PVC, Lexan^{TM} and Teflon® all experienced between approximately 225% and 350% increase relative to the starting electric field. The largest change in electric field of the 3 materials is the Gray HE PVC which underwent a 350% increase in the electric field (or 500 volts). This material has the lowest surface resistivity of the materials that have a surface resistivity of 10^{12} ohms/square or greater. The other materials with the lower surface resistivities demonstrate a lower change in electric field. The Gray HE PVC appears to be an anomaly if one was to assume a correlation that the greater the surface resistance, the greater the intensity of the triboelectric effect.

Due to the relatively low electric field generation utilizing the method of dragging the charge transfer tool across the surface of the test materials, another experiment was performed to attempt to increase the charge transfer that occurred and as a result, a greater delta between starting and ending electric field.

2.3.2 Experiment 2: Drill Experiment

A test was developed to try to integrate some controlled ESD generation methodologies utilizing tools and materials that were available. The intent was to try to generate a greater electric field but maintaining a controlled experiment.

The experiment that was developed allowed for a greater force on the material being tested as well as a faster velocity between the charge generating tool and the test material. A test object was built which entailed covering a spinning wheel with the fabric material which

was used on the first test series. The weight of the electric drill was utilized as the constant force applied on the test material to ensure that the applied force was constant for all the test materials. In addition, the electric drill allowed for a regulated speed by locking the variable speed button at a constant position. The spinning fabric covered wheel was placed against the test material for 5 seconds for all materials that were to be tested. The spinning wheel was placed within a circle that was marked on the dielectric material by a tracing of the spinning wheel. The center of the circle was marked. A measurement of the electric field was made at the mark at the center of the circle before and after the rotating wheel was applied within the circle on the test material.

As was done for the previous experiment, an attempt was made to remove all surface charge from the test material prior to the experiment with the conductive brush. The data that was yielded from this test scenario provided a much larger electric field and the ability for a better understanding of the potential relationship between the surface resistivity and the triboelectric effect.
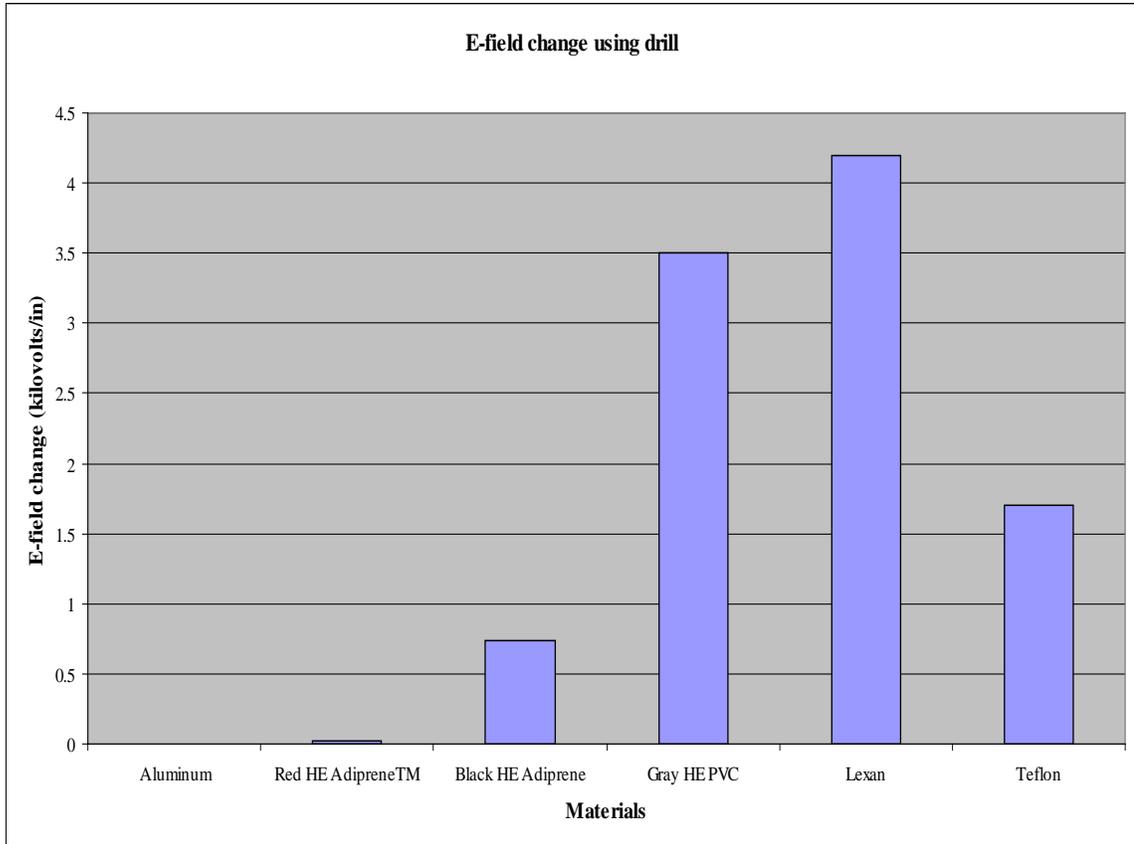
Figure 10 - Experiment 2: Maximum Electric Field Change

As was the case with the prior experiment, the materials with the higher resistivity, as a whole, proved to show the greatest change in Electric field and thus, the greatest charge transfer. However, as was noted for the first experiment, the magnitude of the charge transfer does not appear to be directly correlated to the surface resistivity of the materials.

% E-field increase using drill
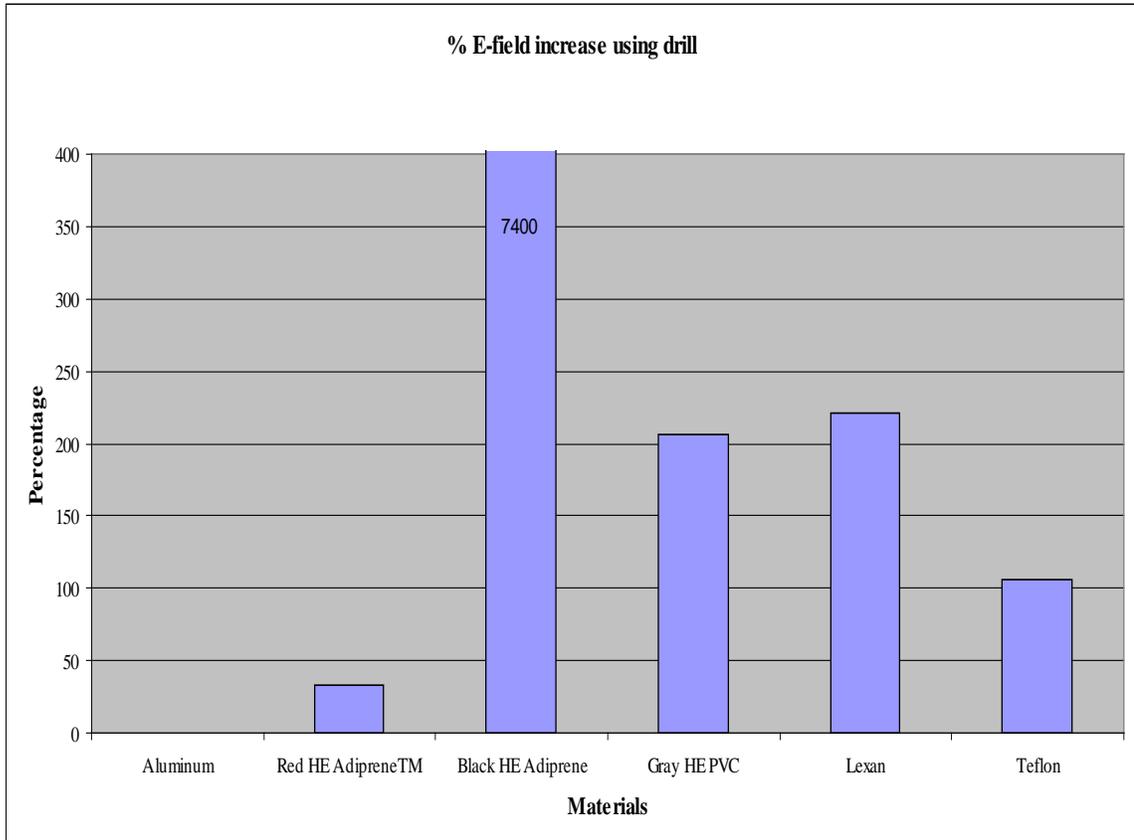
Figure 11 - Experiment 2: Maximum Electric Field Percentage Change

When considering the percentage electric field change before and after the materials were rubbed with the spinning disk, the material that showed the greatest change was the Black HE Adiprene^{TM}. The scale for this chart had to be manipulated due to the 7400% electric field change for the Black HE Adiprene^{TM}. However, once again, although it experienced a large percentage change in the electric field, the electric field measurement was only approximately 750 volts.

2.3.3 Experiment 3: Aggressive Charging

A final experiment was performed to try to ensure that there was a thorough set of data to draw conclusions about the relationship between the surface resistivity and triboelectric effect. To try to generate a large electric field on the test materials, a manual manipulation of the materials was performed. The materials were manually rubbed by hand, aggressively, for 5 seconds with a subjectively uniform force. A foam block was wrapped with the charging fabric material and it was rubbed against the test materials in a back and forth manner. Electric field measurements of the test materials were taken before and after the materials were rubbed. As in the previous experiments, an attempt was made to remove as much surface charge from the materials as possible prior to performing any experiments.
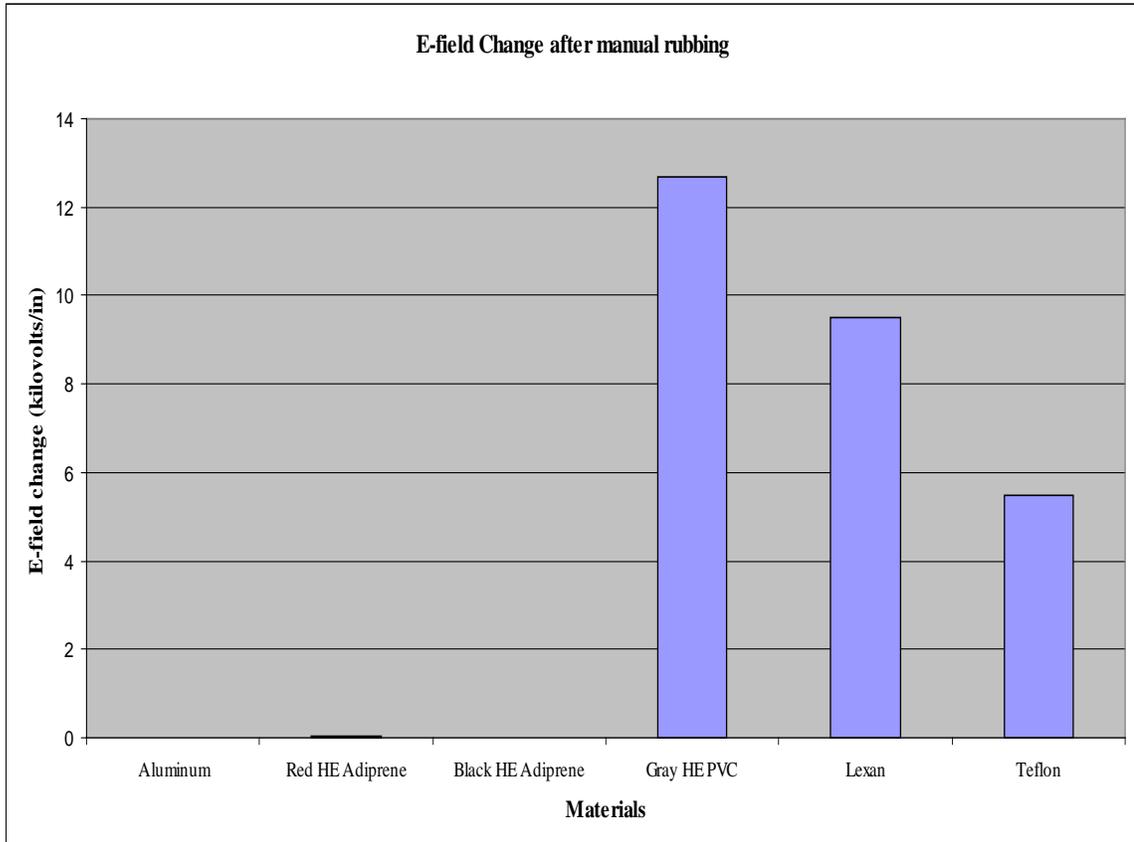
Figure 12 - Experiment 3: Maximum Electric Field Change

The experiment proved to generate a greater surface charge as the greatest electric field that was measured for this series of experiments was -14.2 kilovolts/in. The electric field values across most of the materials were greater than for the previous experiments. Once again, the materials with the higher surface resistivities underwent a greater change in the measured electric field. However, the data demonstrates the fact that the order of the magnitude of the surface resistivity does not directly correlate to the magnitude of the change of the electric field.
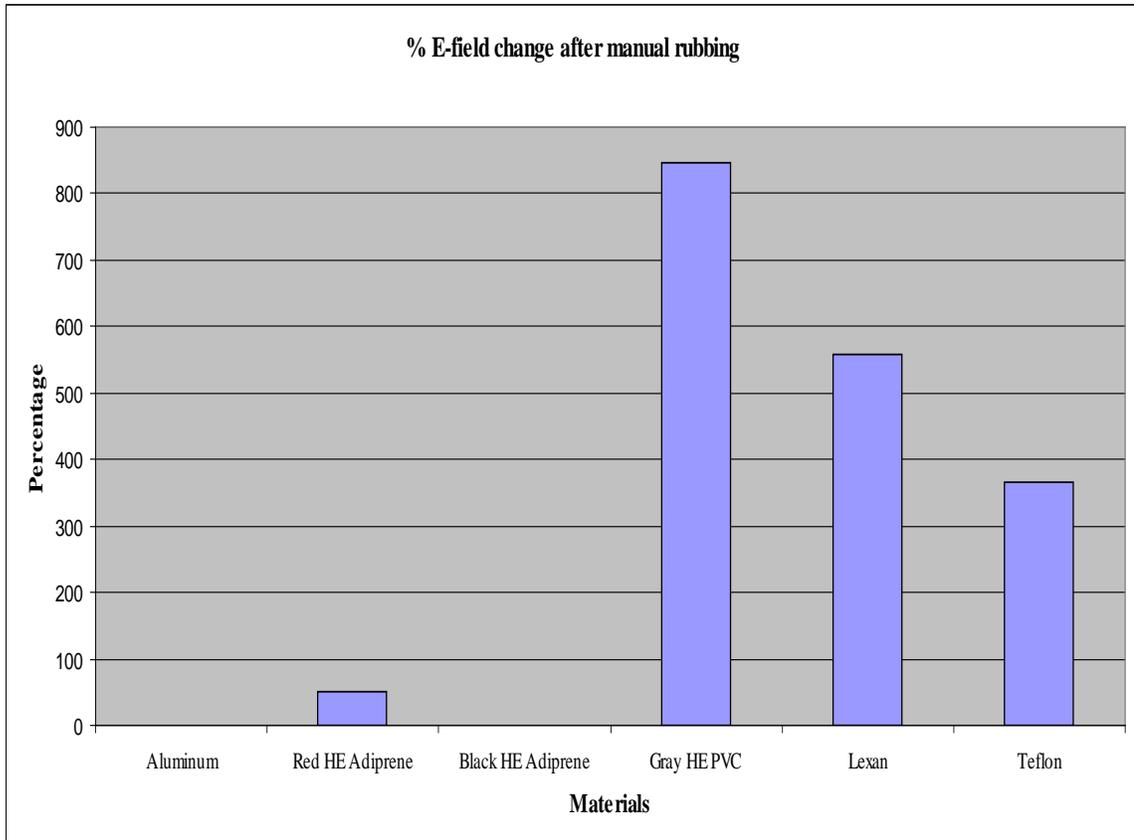
Figure 13 - Experiment 3: Maximum Electric Field Percentage Change

As is visible in Figure 13, the percentage of electric field change does not appear to directly

correlate with the surface resistivity of the test material. The highest resistivity material

did not undergo the greatest magnitude of triboelectric charge transfer. In addition, the

Red HE Adiprene[TM] did prove to undergo a fairly significant charge transfer.

A thorough discussion of the data captured will be discussed later in this document.

CHAPTER 3: SURFACE CHARGE REMOVAL

A consistent and reliable method to do this would prove to be extremely helpful when working with explosive assemblies and dielectric materials. A series of experiments was designed to determine the effectiveness of using a tool to remove surface charge.

3.1 Brush Experiment

The final experiment that was performed to try to determine if it was possible to remove the surface charge that is potentially already existent on the dielectric surface prior to placing an explosive assembly within it. If successful, a process of surface charge removal could be developed to ensure safety when working with dielectric materials and detonators.

For this experiment, the Lexan^{TM} was used as it proved to be a material that was consistent in generating a large electric field regardless of the friction force or rate of rubbing of the two surfaces. The Lexan^{TM} was manually rubbed utilizing the same fabric wrapped foam used in the "uncontrolled" charge generation experiments. The charge generating foam device was rubbed back and forth across the surface of the test materials for 10 seconds. An attempt was made to apply a consistent force and at a consistent rate (5 swipes in each direction for the total of 10 swipes in the 10 seconds). The intent for performing this series of experiments was to determine the most effective and reliable method for surface charge removal. Although the method of charge generation was intended to be consistent, the magnitude of the electric field prior to using the brush to remove surface charge was not as critical as some of the other experiments. This is true as the intent was to measure the greatest percentage reduction in the starting electric field.

Two different commercially available brushes were used to attempt to remove the surface charge. Both brushes were manufactured by Gordon Brush Mfg. Co., Inc. One brush, designed to be a conductive brush, utilized a static dissipative handle (resistance of $10^5\Omega$/cm) with a bristle material, Thunderon, which had a resistivity of $10^{-2}\Omega$/cm. The second brush, designed to be a static dissipative brush, also utilized the same static dissipative handle but utilized Nylon bristles which were also specified as static dissipative and had a resistance of $10^3\Omega$/cm. An additional brush which was not available for testing had Thunderon® bristles and an Aluminum handle.

For each experiment, the brush was mounted in the track system that was also utilized to hold the surface field meter to ensure the brush maintained a constant friction between the brush bristles and the test material. It also allowed the use of the speed control mechanism used in the earlier experiments to ensure that the brush speed was maintained. As the brush handles were static dissipative, each brush was able to drain the collected charge through the brush handle, through the metal track to earth ground.

Because the Aluminum handled brush was not available for testing, it seemed important to simulate the advantage of the conductive handle. Thus, a drain wire was clamped to the conductive Thunderon bristled for one configuration to simulate a low resistance path between the bristles and ground. The following test configurations were used for this test series to allow a variety of serial resistance paths.

Test Reference	Brush Material	Configuration
Conductive with Drain	Conductive Brush (Thunderon® bristles, Static dissipative handle)	Brush handle mounted in metal track; one end of drain wire clamped to conductive fibers, other end tied to ground
Conductive	Conductive Brush (Thunderon® bristles, static dissipative handle)	Brush handle mounted in metal track
Static Dissipative	Static Dissipative Brush (Nylon bristles, Static dissipative handle)	Brush handle mounted in metal track

Table 3 - Surface Charge Removal - Brush Configurations

It is important to recognize the variety of surface charge removal tools and techniques. If these processes prove to be effective, their application may vary. The method of surface charge removal may range from an individual who manually "brushes" the dielectric surface to remove surface charge to passing the dielectric surface through a structure that has conductive brush bristles that are interlapped to ensure a total surface charge removal. Thus, the most effective method will be utilized for the development of a formal surface charge removal method and tool which could be used by the DOE Weapons Complex for its explosives work.

During the series of experiments, a relatively large electric field was generated. The largest measured electric field was more than -17 kilovolts/in. As was done in the surface charge generation experiments, the electric field was measured at 6 points along a straight line on the test material surface. All 6 points were measured after charging the surface and also every time the brush was dragged along the surface. The brush was swiped across the surface a total of 3 times with the electric field being measured after each brush stroke.

The data in the following plot is represented in a manner that displays the percentage of the initial surface charge that was removed, relative to the electric field. The data provides more value being displayed in this manner rather than a numerical value of the change of the electric field as the intent is to reliably quantify a percentage of surface charge removed.
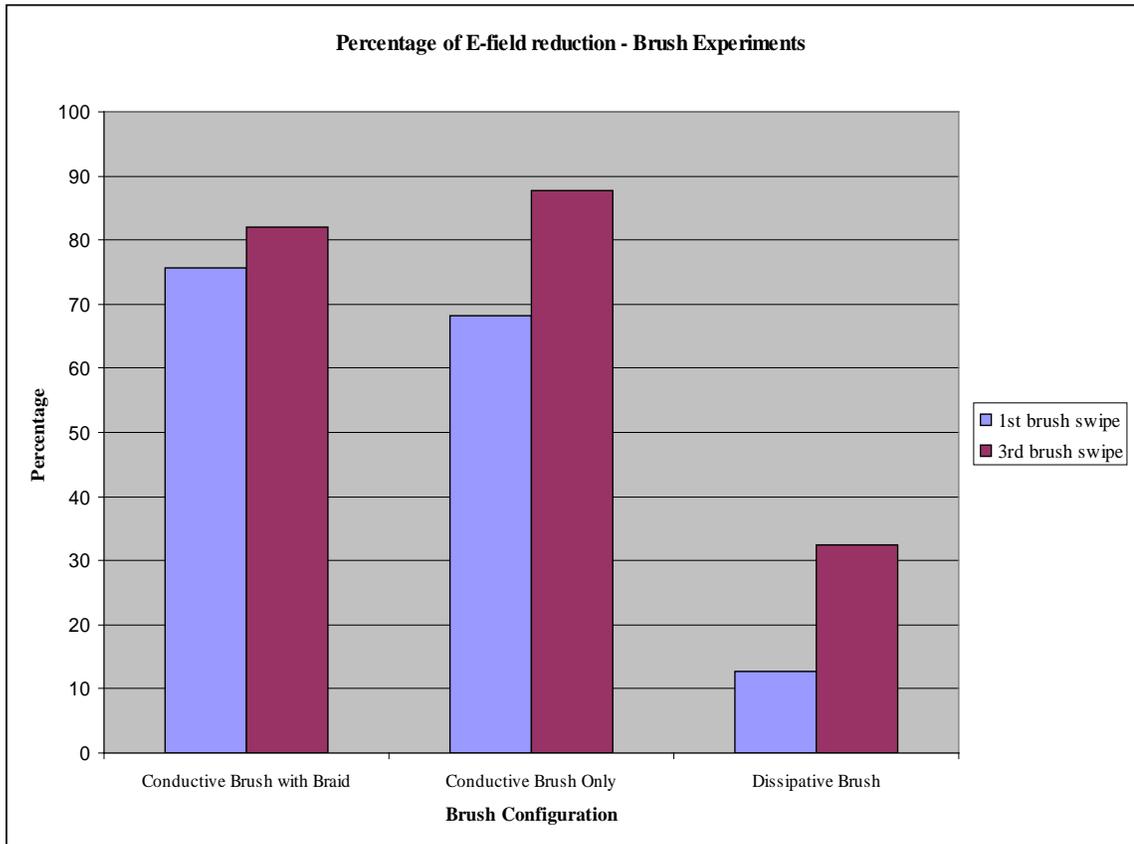
Figure 14 - Surface Charge Removal - Percentage Electric Field Reduction

A significant reduction in surface charge occurred even after a single stroke of the brush with the conductive fibers regardless of whether or not it was terminated from the conductive fibers directly to ground through a conductive braid. An average of

approximately 70% reduction of the electric field was measured with just a single stroke of the brush on the dielectric surface. Considering that the electric field and surface charge density are a 1:1 relationship, the 70% reduction in electric field equates to a 70% reduction in surface charge. The dissipative brush was not nearly as effective as the conductive brush. The higher resistivity of the fibers and handle result in a longer time constant and thus, it would require a much slower stroke speed to remove the charge.

The conductive brush using the braided drain proved to be the most effective. Figure 15 displays the effectiveness of this configuration. As noted before, a significant portion of the surface charge was removed with the first brush stroke. Also note that in some instances, the starting voltage was positive and in others, it was negative. However, this proved to have no effect on the effectiveness of the ability of the conductive brush with the drain to remove surface charge as the electric field measurements quickly converge to zero.
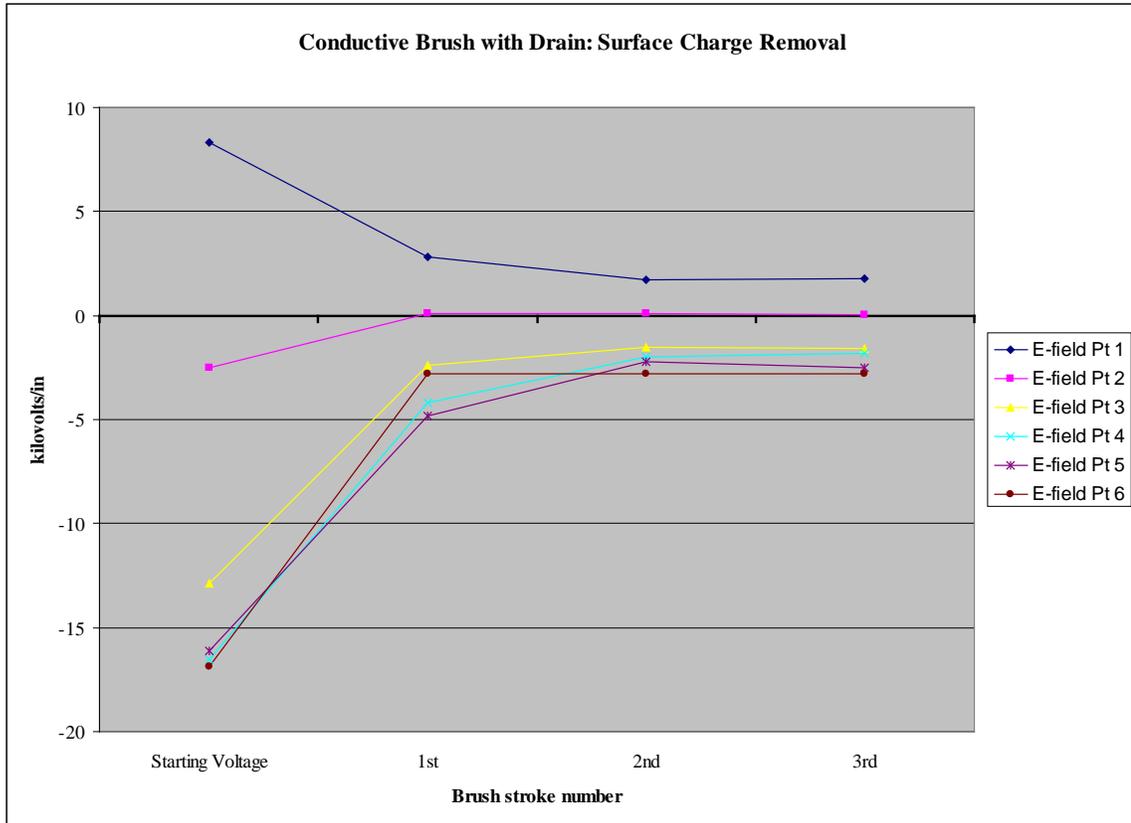
Figure 15 - Surface Charge Removal - Conductive Brush with Drain

From the data, it seems the best method of surface charge removal is to utilize a brush with conductive fibers. The conductive brush either with or without the drain proved to be fairly effective and reliable at removing the surface charge from the dielectric surface.

The drain may prove to be an important thing to consider if this approach or a similar approach was to be implemented. For the testing, there was a period of time between brush strokes that was on the order of a minute or more. In addition, between brush strokes, the brush stayed in the clamp on the track which was tied to earth ground. Because of the relatively long time between brush strokes, the time constant due to the resistance and capacitance of the system was irrelevant. However, in a real-world application, an

individual may be brushing a number of dielectric materials with very little time in
between brush strokes. Thus, the time constant in that situation may become more
important. If the charge gathered by the brush does not have enough time to drain off, the
second stroke to the next surface may actually transfer charge to the next surface rather
than pulling it off.

CHAPTER 4: DISCUSSION OF RESULTS

4.1 Analysis Performed

The method of analysis detailed above may be the only method currently available within the DOE Weapons Complex to evaluate the hazard of ESD and explosives. As was visible from the analysis performed, this analysis is extremely conservative and results in very high energy values. The only way to drive those energy values down using the described method of analysis is to control the voltage applied to the dielectric when it is evaluated as a capacitor. Because the voltage is squared, a change in the voltage will have a dramatic effect on the solution to the equation.

The only method to lower the value of the voltage is to try to control it. If a voltage control process was implemented in an explosive handling facility, it may be possible to assume a lower voltage. Utilizing controls like ESD conductive flooring, ESD conductive shoes, ground straps, non-isolated tool, etc., it may be possible to re-evaluate the voltage distribution within the facility to drive a lower maximum voltage. Once again, this proves to be an extremely expensive solution, but the only viable one if controlling the dielectric or removing the surface charge cannot be implemented.

4.2 Surface Resistivity versus Triboelectric Effect

Throughout the three separate triboelectric charge transfer experiments, one thing that appears to be relatively consistent from the data is the fact that surface resistivity may have some effect on the ability for a material to undergo triboelectric charge transfer. With the data collected, it appears that materials that have a higher surface resistivity are generally

more likely to undergo triboelectric charging and the magnitude of the charge is greater than for materials with lower surface resistivities. Conversely, most of the experiments also had data that contradicted this concept. When the higher resistivity materials were compared to one another, the surface resistivity appeared to have no effect on the magnitude of triboelectric charge transfer that occurred.

However, much research on this subject has also concluded that the higher the surface resistivity of a material, the longer it takes for a surface charge to drain off of a material. If the surface resistance of the material is great enough, the surface charge cannot drain off the surface. Conversely, if the surface resistance of the material is low enough, the surface charge flows freely and thus, may bleed off extremely quickly. Therefore, it is possible that the materials with the lower surface resistivity values actually experienced a greater triboelectric charge transfer than higher resistivity materials, but the charge may have drained off quickly. If it drained off before the electric field was measured, it would be impossible to know how large the electric field might have been. For materials like the Aluminum, this is a very realistic possibility.

More testing would need to be performed before any definitive conclusions regarding surface resistivity and its relationship to the triboelectric effect could be determined. Limitations with the ability to measure the electric field very quickly would need to be resolved. In addition, further research on the properties of these different materials might also provide a clue as to the inconclusiveness with the data.

Unfortunately, the Black HE Adiprene[TM], Red HE Adiprene[TM] and Gray HE PVC

materials all manufactured using a proprietary formula and thus, much of the material

properties are unknown. It is difficult to determine if there are other properties in the

materials that may describe what phenomenon may cause the varying magnitude of

triboelectric charge transfer between the high resistivity materials.

As the goal of this research was to provide input toward the design of new materials that

will be effective in protecting explosive assemblies from mechanical shock, but minimize

the potential of insults due to ESD, it would seem that a variety of things would need to be

considered.

A material with a relatively low resistance seems like it should be cautiously considered.

Another thing that must be considered is that the insulative properties of dielectric foams

might need to be maintained. The insulative properties drive the ability of the material to

prevent outside electrical energy from getting to the explosive assemblies. If the surface

resistivity is lowered to the point that current easily flows through the material, it could

prove to be problematic. For example, if a frayed electrical cord touching the protective

housing passes the electrical energy through the housing to the explosive, an important

safety design feature of high resistance materials was negated.

 An effective material with regards to protecting against both mechanical and electrical

insults may be to design a dielectric material which unaltered, would have a high

resistivity, but may be loaded with carbon or graphite to help lower its surface resistivity to

help ensure its ability to undergo triboelectric charge transfer is minimal. As some of these materials, including the red and black HE Adiprene^{TM} materials and the gray HE PVC material, are poured and molded within the DOE complex, it may be possible to load these materials with conductive materials to help lower their surface resistivity. This is something that will be explored and implemented for future testing that will continue due to the importance of solving this problem.

However, it cannot be ignored that the speed at which the materials were rubbed together and the force at which they were rubbed also had an influence on the ability to undergo triboelectric charge transfer. This would also need to be further tested to determine if these two variables have more influence than the surface resistivity itself.

4.3 Surface Charge Removal Tool

The static dissipative brush proved to be fairly ineffective as it resulted in a reduction of the electric field of a minimum of 5% and a maximum of 40%. However, the ability of the conductive brush to remove surface charge proved to be fairly effective. A single stroke across the surface of the material removed enough surface charge to equate to approximately an average 70% electric field reduction. As noted earlier, this equates to a 70% reduction in total surface charge. The lowest reduction in electric field with a single brush stroke was more than 65% minimum and almost 90% maximum when using the conductive brush with a ground braid. This is a significant reduction and proved to be fairly repeatable across the 3 tests performed with the conductive brush using the ground braid.
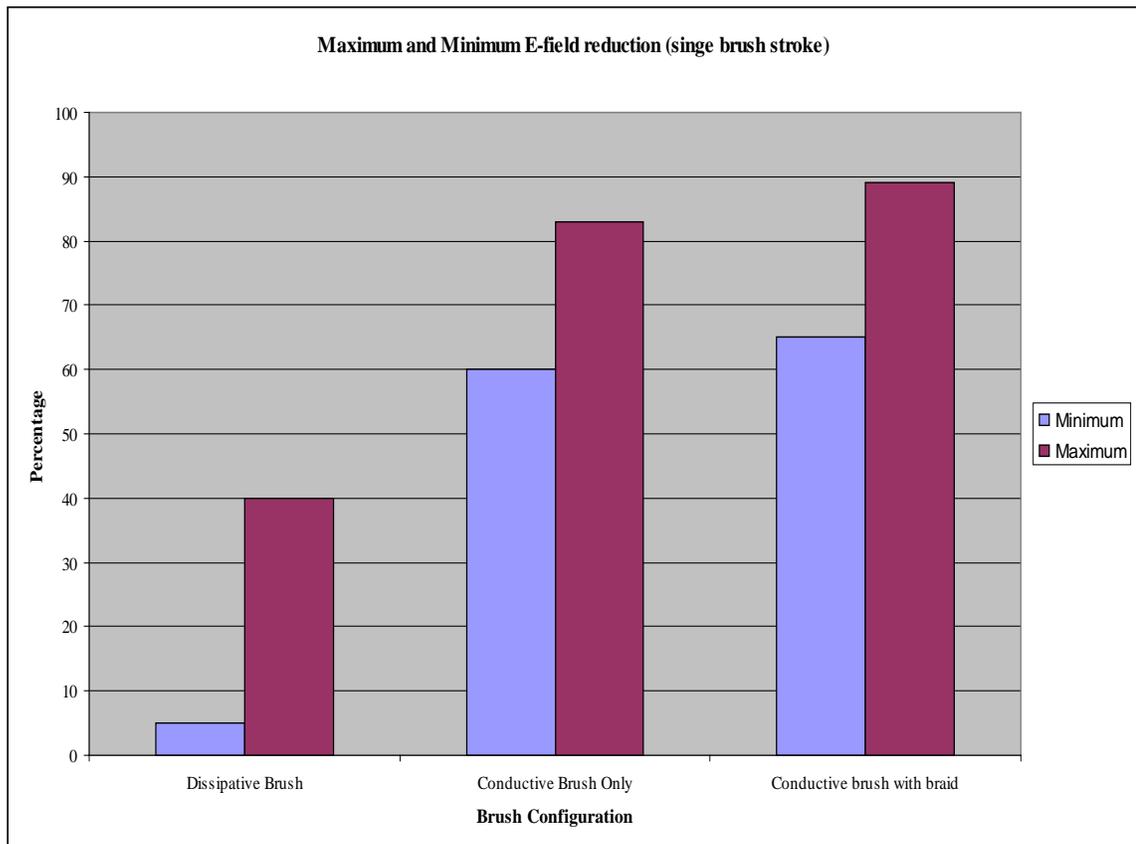
Figure 16 - Maximum/Minimum E-field Reduction versus Brush Configuration

With more testing, it might be possible to statistically show that there is a consistent reduction of electric field when using the brush. For example, if it was found that the use of the brush would consistently remove 50% of the surface charge, the assumption of 30kV/cm made in the analysis could be reduced to 15kV/cm which would reduce the level of conservatism to give a more realistic potential energy level within the dielectric material.

For the most effective brush design, the brush would work most effectively if it utilized conductive fibers. In addition, a conductive handle or a handle with a relatively low

resistance would be most effective. It is also important that the brush handle has a direct current path to a grounding point. In a real world application, it is important to consider that workers who are handling explosive materials and assemblies may or may not be wearing equipment that will ensure that their maximum voltage potential is at a minimum. Thus, a direct current path to ground would provide an engineering control to ensure an effective method of draining the charge to grounding point.

CHAPTER 5: FUTURE WORK

The ability to mechanically isolate explosives without introducing an ESD insult is an important goal for a number of organizations within the DOE weapons complex. The Sandia Rocket Sled accident helped solidify the importance by proving that something that had been predicted theoretically had a reasonable probability of occurring. The Rocket Sled Accident was also more interesting in the fact that there was not a dielectric material present to provide more energy for the ESD; only the human who was available to store and deliver energy. The addition of a dielectric material adds to the total energy that can be imparted to the explosive.

A team of individuals across the DOE Complex has been tasked with solving this problem. More sophisticated mathematical models are being developed to help with the analysis of the maximum "realistic" energy that can be delivered from the dielectric material to the detonator. However, these mathematical models and their implementation in software proves to be extremely difficult, time consuming and expensive. Experiments that help to better understand the material properties of these dielectric materials will prove important to control the ability for the materials to transfer charge. In addition, potential methods of surface charge removal, like the brush removal experiments, will hopefully help drive a method of surface charge removal that can be proven to be reliable and effective.

The research, data and conclusions drawn from this thesis will be utilized as a baseline to begin understanding better methods to ensure explosive safety. A variety of limitations is an extremely important problem to solve.

Many groups within a number of organizations within the DOE Weapons Complex are looking at replacing some of the mechanical isolating materials they use with explosives. This provides an opportunity for electrical engineers to provide input to mechanical engineers to ensure materials are used that protect against both mechanical and electrical insults.

The data that was gathered in these experiments will be a start in understanding material properties and how future materials may be designed to help minimize the triboelectric effect on explosive assemblies. This, coupled with a reliable method of charge removal, will allow for a level of safety improvement for the DOE weapons complex when working with explosive materials.

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