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Dielectric Discharges in Conductive Tapes

Nelson W. Green and Matthew Stumbo

***Abstract*— Four conductive adhesive tapes typically used for electromagnetic and electrostatic shielding on spacecraft were mounted in a vacuum chamber and exposed to a beam of energetic electrons from 50 keV to 60 keV with fluxes from 1 to 4 nA/cm2. While exposed to the electron beam, samples were monitored for electromagnetic discharges. In all cases discharges were observed and recorded by an oscilloscope measuring the voltage drop across a 50 ohm resistor. Upon completion of the electron exposure, the surface potential of each sample was measured by a non-contact voltmeter within 60 seconds after turning off the electron beam. All samples retained a surface potential indicating that some aspect of the material was capable of storing electrons. Care needs to be taken when using these materials as shielding material to ensure that these discharges, however small, do not disrupt spacecraft operations either by direct products of discharges, or by resulting electromagnetic noise.**

Keywords—charging; shielding tapes; dielectric discharge;

I. Introduction

Designing and building spacecraft is a complex task involving many separate issues. Beyond the intricacies involved with the electrical and mechanical functions there exists a need to build in an ability to operate successfully in the space environment. From a designer's point of view, these environments include vibrations associated with launch, temperatures associated with orbital operations or the extreme cold of deep space, electromagnetic noise that is either from external or internal sources, and the charged particles, solar spectrum, radiation, and micro-meteoroids of the natural space environment.

With established design principles developed from the experience of building many spacecraft, many problems involving these environments have been solved. With each new design, however, unexpected issues can still be discovered when a spacecraft or component is undergoing environmental testing. In some unfortunate cases, the problems require re-work or a re-design of the item being tested. In other cases, particularly during Electromagnetic Compatibility (EMC) or in the spacecraft charging aspects of the natural space environment testing, adding additional shielding to problem areas can provide sufficient attenuation of the problem to continue moving forward with construction. For both EMC and spacecraft charging aspects, the use of conductive tapes to patch or seal problems areas is a common practice. In many cases, this tape is composed of a thin metal such as copper or aluminum with an adhesive applied to one side. In other cases where the added mass or stiffness of the metallic tape is problematic, conductor impregnated cloth or polymer-based tapes are used as a substitute.

From shielding point of view, particularly with regard to EMC issues, these non-metallic shielding tapes can be quite effective. They are, however, composed of multiple materials that can and do possess different characteristics. When evaluating their suitability for use from a spacecraft charging perspective, more consideration and testing is needed.

Much work has been performed to attempt to understand the effects of charged particles on non-conductive materials used on spacecraft [1-4]. The majority of these studies have focused their efforts on homogeneous materials, or at least materials with semi-homogeneous properties. A more limited amount of work has been performed on composite materials that exhibit vastly different properties when exposed to an electron beam [5-7]. In the case of conductive shielding tapes, the general perception is that the conductive properties of the fillers impregnated into the materials will dominate the overall performance of the product. From a macroscopic point of view, this perception is generally valid, particularly in the generation of a Faraday cage in EMC uses, or creating an electrically conductive path in general. In the presence of an electron beam, or in the charged particle environment of space, this assumption may not be entirely true.

II. Test Description

To provide some insight into the behavior of several of these non-metallic shielding tapes, four samples were obtained and exposed to energetic electrons while being held in space-like vacuum. Samples included Black Kapton 100XC, Black Kapton 160XC, Laird Nickel-Copper cloth, and Laird Copper-Tin cloth tapes. A sample of Kapton HN tape was also included in the testing as a reference.

Black Kapton tapes have been used on spacecraft to provide non-metallic shielding of cables and harnesses where some conductivity is needed, but the bulk of metallic overwrapping is impractical. Where the two materials differ is their rated resistivity with the 100XC being more resistive than the 160XC. Laird tape is commonly used to help attenuate electromagnetic noise leaking out or in to electronics boxes or cables on spacecraft instruments. By wrapping the metal infused cloth tape around cable bundles, connectors, or seams on instrument chassis, much of the radiated electromagnetic energy can be blocked. With sufficient coverage, the noise due to unintentional radio emissions can be contained an attenuated to levels below the interference thresholds on spacecraft instruments.

Samples of all four shielding tapes were mounted to 18 cm^2 copper plates and mounted on a rotating carousel and inserted into a vacuum chamber. Vacuum levels were held at or near 1×10^{-6} torr. All testing was performed at room temperature of approximately 23°C. The test setup was designed to keep all

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samples in vacuum, but only allows one sample to be exposed to the electron beam at any time. This test system has been previously used to measure dielectric discharges and charge storage in homogeneous dielectric samples [8-10]. Two control samples, one with a dual layer of Kapton HN and the second an aluminum plate, were added to the sample set inside of the chamber. The aluminum plate was also used as both a Faraday plate and a ground reference.

As seen in Figure 1, the electron gun for this system is a simple filament mounted inside of the vacuum chamber on the negative terminal of a high voltage power supply. When a current is passed through the filament, electrons are thermionically generated. Since the filament is mounted on the negative end of the power supply, the electrons are driven away from the electrode and travel through the vacuum chamber toward the grounded sample and the vacuum chamber walls. The energy of the electrons is equivalent to the voltage potential difference between their origin and where the electron comes to rest. In the case of the grounded sample and chamber walls, the energy of the electron is equivalent to the negative potential of the high voltage power supply. After each sample was exposed to the electron beam, its surface potential was measured using a capacitive sensor system and a non-contact electrostatic voltmeter. Any charges embedded in the material after the stimulus of the electron beam would produce a negative surface potential.

The energy of the electrons directed at the samples was chosen to correspond with the approximate thickness of the sample. It was desired to have the electrons penetrate approximately one half the way through the material. Due to scattering within the material, this would distribute the electron charge just inside the surface of the material. In the case of the Laird tapes, the thickness could vary due to the texture of the cloth, but an approximate cross section was used as a general guide.

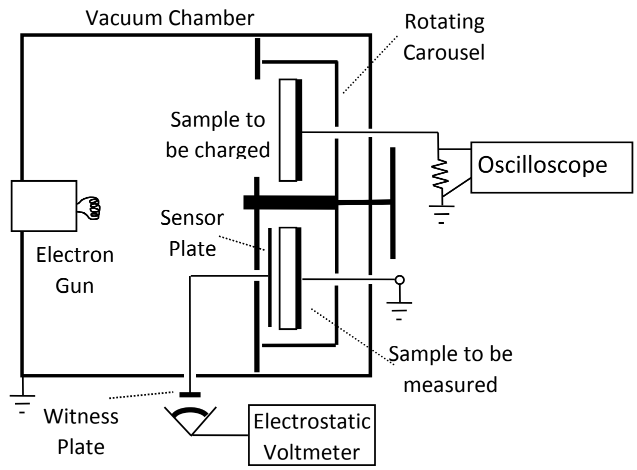

Figure 1. Electron gun and sample measurement system

During exposure to an electron beam, conductive materials absorb the incoming charges and conduct them to ground to complete the electrical circuit generated by the power supply generating the electric field. In the case of non-conductors, the incoming electrons will imbed themselves in the target material rather than being directed to ground. In these cases, the stuck charges form an electric field within the non-conductive material in proportion to the localized quantity of charge. Within nearby conductors, image charges will form to neutralize the fields within the bulk of the conductor. Since the sample tapes were attached to copper disks, the majority of this image charge was formed within these mounting plates. In essence, the samples under the electron beam became simple capacitors with the charges gathered on the surface of the samples and the copper plates serving as the electrodes and the non-conductive portions of the tapes serving as the dielectric between them.

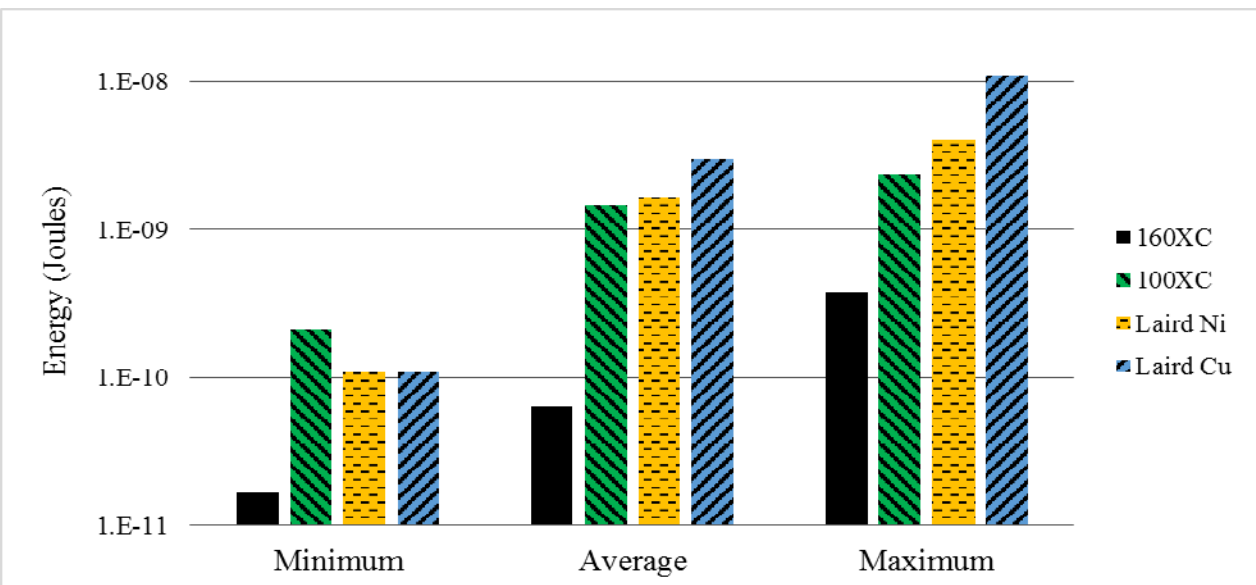

Figure 2. Discharge energy for four conductive tapes

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When localized electric fields inside of the samples became large enough to exceed the material breakdown strength, a dielectric discharge occurred. During a discharge, a plume of plasma was emitted from the surface of the sample. Due to the collection of electrons on the surface of the material, the positive ions from the plasma were re-attracted to the sample surface. The electrons in the ion cloud, however, were repelled toward the grounded chamber walls and sample apparatus causing a temporary current path between the sample surface and ground. In the process, the electric fields on the sample were reduced causing a reciprocal movement of image charge from the copper electrodes connected to the bottom of the sample.

To observe these discharges, a 50 ohm resistor was placed in series between the copper sample mounting plate and ground. During a dielectric discharge, the rapid movement of image charge caused a voltage spike across the series resistor that could be observed with an oscilloscope. By observing the movement of image charge, the time dependent magnitude of the discharge could be recorded and analyzed. The energy of each pulse was determined by calculating the instantaneous power for each pulse and integrating the area under the curve with respect to time.

III. Test Results

All testing was performed inside of a vacuum chamber held at 2×10^{-6} torr or better. Each sample was individually exposed to electrons with energies of 50 to 60 keV at current densities from 1 to 4 nA/cm^2 depending on the sample thickness. Higher current densities were used on the more conductive samples to induce discharges in a more rapid time period.

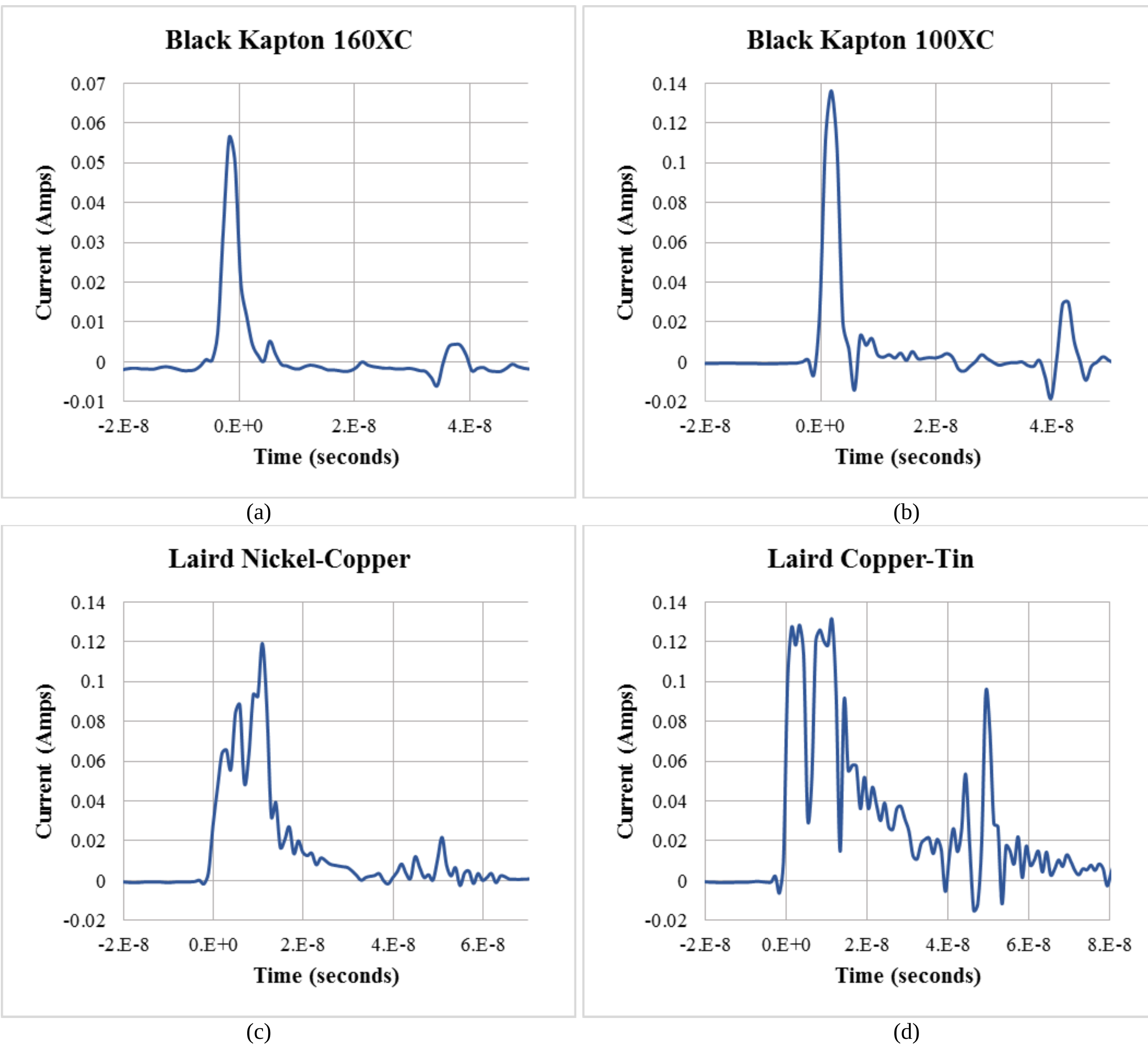

Figure 3. Largest discharges for all four conductive tapes

Table 1. Summary of Results

Sample Material	Electron Energy (keV)	Current Density (nA/cm^2)	Exposure Time (minutes)	Number of Discharges	Maximum Discharge Energy (Joules)	Surface Potential (volts)
Black Kapton 160XC (first exposure)	60	4	150	1	3.8×10^{-10}	-125
Black Kapton 160XC (second exposure)	60	4	130	14	8.4×10^{-11}	-369
Black Kapton 100XC	50	1	150	3	2.3×10^{-9}	-237
Laird Nickel-Copper	50	1	180	7	4.1×10^{-9}	-159
Laird Copper-Tin	50	1	130	47	1.1×10^{-8}	-260
Kapton HN	50	1	75	29	4.5×10^{-4}	-3750

Samples were exposed for 150 to 300 minutes. Over that interval all of the conductive tapes produced electric discharges with magnitude from 1.6×10^{-11} to 1.1×10^{-8} Joules as see in Figure 2.

Of the four tapes tested, the size of the resulting discharges followed the approximate resistivity of the base material with Black Kapton 160XC producing the smallest discharges followed in order by Black Kapton 100XC, Laird Nickel-Copper, and Laird Copper-Tin.

The manufacture listed surface resistance for Black Kapton 160XC is given as 300 to 430 ohms/square [11]. While surface resistance and bulk resistivity are not the same, the relatively low surface resistance for this material gives an indication of the bulk properties. The high concentration of conductive carbon in the material drives the measured resistance when conventional measurement methods are employed with this material. When placed in an electron beam, much of the charge implanted in the material is indeed conducted to ground, but enough charge made its way in between the conductors to produce a measureable surface potential and to create high enough electric fields to induce dielectric discharges. Black Kapton 160XC was tested two separate times during this round of testing. During the 150 minute run, only one discharge was recorded with an energy of 3.8×10^{-10} Joules, seen in Figure 3a. During the second exposure conducted several days later, a total of fourteen additional discharges were observed over a span of 130 minutes. After each exposure, the surface potential was measured using a capacitive divider system. After the initial exposure, the Black Kapton 160XC had a surface potential of -125 volts measured approximately one minute after the electron beam was turned off. After the second exposure, the surface potential was -369 volts. These surface potentials, in addition to the measured discharges, indicates that while on a macroscopic scale, the material is quite conductive, there are non-conductive regions that can store charge and build up large electric fields.

Similar to Black Kapton 160XC is Black Kapton 100XC. In the case of this material, the quantity conductive additives is reduced and the associated surface resistance is listed as 10^5 to 10^9 ohms/square [11]. As a result, the overall properties of this version of Black Kapton are more resistive. During testing, this material was given a single 150 minute exposure. During that time, only three discharges were observed, but at 2.3×10^{-9} Joules, the maximum discharge was larger than any found with the 160XC v10ersion of Black Kapton. This discharge can be seen in Figure 3b. After the beam was turned off, the surface potential for this material was measured as -237 volts measured 30 seconds after the beam was removed. It is interesting to note that while the listed resistance of the 100XC is a great deal higher than that of the 160XC, the measured surface potential after the same time period is very similar. It would seem that base Kapton material is the driving factor for stored charge and, by extraction, the dielectric discharges that occurred while under electron bombardment.

The Laird tapes were more responsive to the electron beam than the two types of Black Kapton. According to the manufacture's data sheets, the surface resistance of the Nickel-Copper tape is less than 0.07 ohms/square. When this tape was exposed to a 50 keV beam at 1 nA/cm^2 for 180 minutes, seven discharges were recorded with the largest, shown in Figure 3c, producing an energy of 4.1×10^{-9} Joules. The surface potential of this sample, measured one minute after the beam was removed, was -159 volts. In contrast to the Nickel-Copper tape, the Copper-Tin Laird tape produced 47 discharges over 130 minutes of exposure to the same beam parameters with a maximum discharge of 1.1×10^{-8} Joules seen in Figure 3d. When the beam was removed from the Copper-Tin tape sample, the surface potential was measured to be -260 volts. In both types of tapes, the conductive material is imbedded into a woven cloth matrix. The resistivity of this cloth is not known, but these results indicate that it is sufficiently high to allow for charges to collect and produce dielectric discharges.

In all cases, the size of the discharges was quite small, with the largest being in the 10's of nanoJoules. For samples with a larger area, the size of the discharges would be expected to increase, but still remain quite small provided that the conductive elements of the tapes were well connected to ground. Table 1 summarizes the results for all materials tested. For comparison, the results from exposing the Kapton HN control sample are also included in the results. Kapton HN is known to store charge well and produce large dielectric discharges. Under the same stimulus, this material produced discharges with up to four magnitudes more energy and had a surface potential more than ten time higher than any of the conductive shielding tapes tested.

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IV. Conclusion

All four of the conductive tapes selected for this experiment are used on spacecraft to provide spot shielding to reduce spacecraft charging or electromagnetic compatibility issues. In general, they are considered as pure conductors when in use. Under an electron beam, however, the composite nature of these materials is shown.

All of the materials tested were shown to produce dielectric discharges and were capable of storing charge when exposed to a 50 to 60 keV electron beam. The discharges and resulting surface potentials were orders of magnitude smaller than those produced by the nonconductive version of Kapton HN, but not negligible. Care needs to be taken when using these materials as shielding material to ensure that these discharges, however small, do not disrupt spacecraft operations either by direct products of discharges, or by any resulting electromagnetic noise.

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Agenda

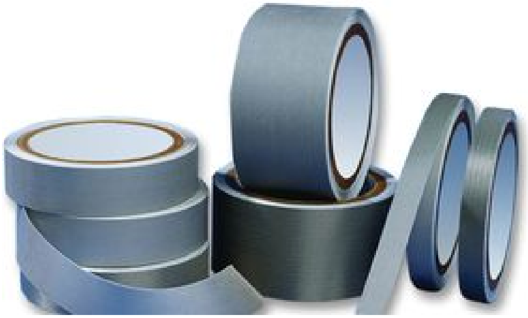
- Introduction
- Conductive Tapes
- Test Methods
- Test Results
- Conclusion

Introduction

- One of the important aspects of building a spacecraft is designing for the space environments
  - Launch Vibration
  - Thermal Cycling
  - Electromagnetic Compatibility (EMC)
  - Natural Space
    - Radiation
    - Micrometeroid
    - Energetic particles
      - Includes spacecraft charging issues
- To ensure that a spacecraft will work in these environments, testing is required
  - Non-compliances are often found
- For EMC or spacecraft charging issues, sometimes these areas just need a ‘patch’ to take care of the issue
  - Quick and dirty fix, but often quite effective
  - Particularly useful to add shielding to cables and to cover and seal gaps in boxes

Conductive Tapes

- Most common conductive tapes are metallic
  - Copper
  - Aluminum
  - Very conductive, but sometimes too stiff or heavy
- Other types of conductive tapes
  - Black Kapton
    - Carbon filled polyimide
    - Conductivity is dependent on the amount of carbon embedded in the polyimide binder
  - Metal impregnated cloth
    - Common type: Laird Nickel-Copper



Conductive Tapes

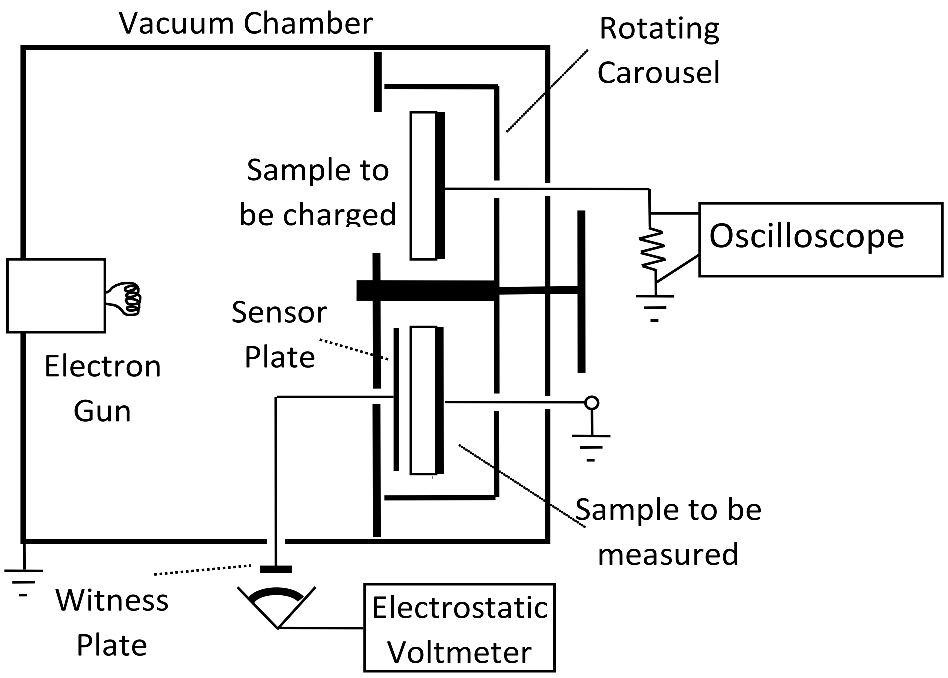
- Advantages of using non-metallic tape
  - Less conductive, but more flexible
  - Lighter weight
  - More effective in many situations
- Conductive Tapes are often treated as a pure conductors
  - Generally true for metallic tapes
  - Other tapes are composite materials
    - Conductive elements suspended in a non-conductive medium
    - Overall performance is as a conductor
    - Localized performance may be different

Test Methods

- **Conductive tapes exposed to electron beam**
  - 50 to 60 keV at 1 to 4 nA/cm^2
  - Energy and current density tailored for material thickness and overall conductivity
  - Exposed under a vacuum of ~2×10^{-6} torr
- **All samples mounted in a rotating carousel on 18 cm^2 copper disks**
  - Multiple samples in the chamber at once
  - Mechanical mounting for samples
  - Provided good ground plane
- **Simple capacitor formed during electron exposure**
  - Electrons embedded on surface
  - Positive image charge in copper disks

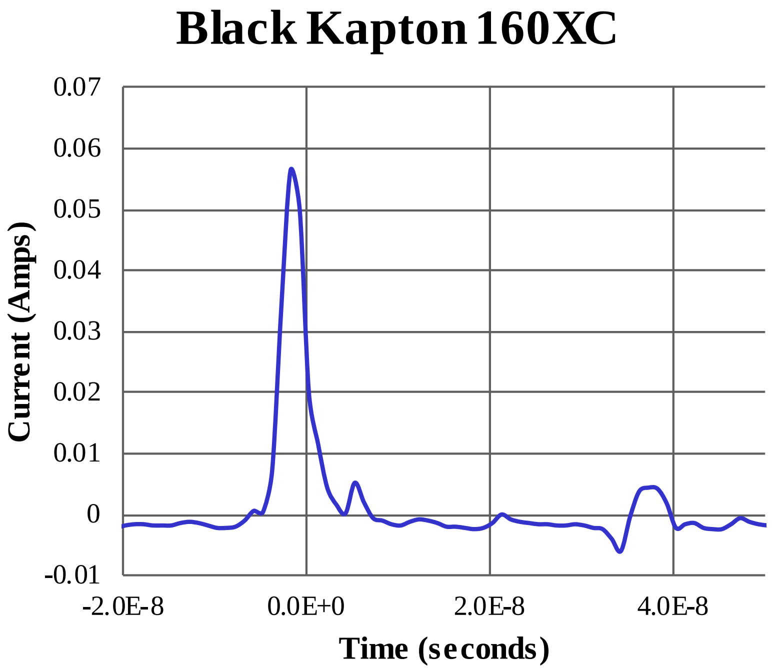
Test Methods

- Discharges monitored through flow of image charge
  - Copper plates grounded through a 50 Ω resistor
  - Large reciprocal image charge movement during dielectric discharges
- Oscilloscope captured voltage spike on resistor
  - Used Ohm's Law to convert measured voltage to current
- Calculated pulse energy
  - Calculated power by $P=I^2R$
  - Integrated area under the pulse power curve (rectangular approximation)
- Surface Potential measurement
  - Obtained ~ 1 minute after beam turned off
  - Capacitive divider system using a non-contact electrostatic voltmeter



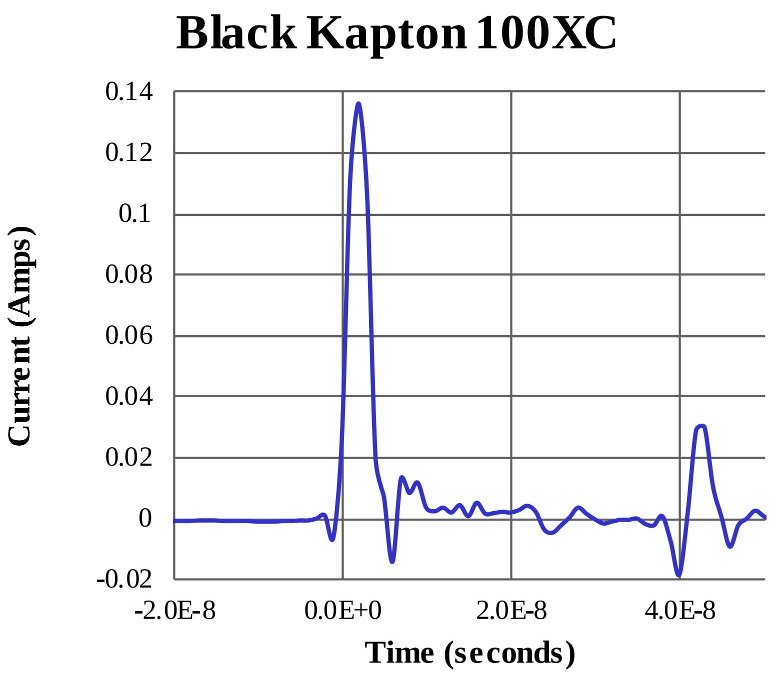
Test Results – Black Kapton 160XC

- Black Kapton 160XC
  - Surface resistance
    - 300 to 430 ohms/square
  - No bulk resistivity given
  - Most conductive of the Black Kapton samples tested
- Exposure
  - 60 keV electrons
  - 4 nA/cm^2
- Results
  - First run: 1 discharge during 150 minute exposure
    - Surface Potential: -125 volts
  - Second run: 14 discharges over 130 minute exposure
    - Surface Potential: -369 volts
  - Maximum energy: 3.8×10^{-10} Joules



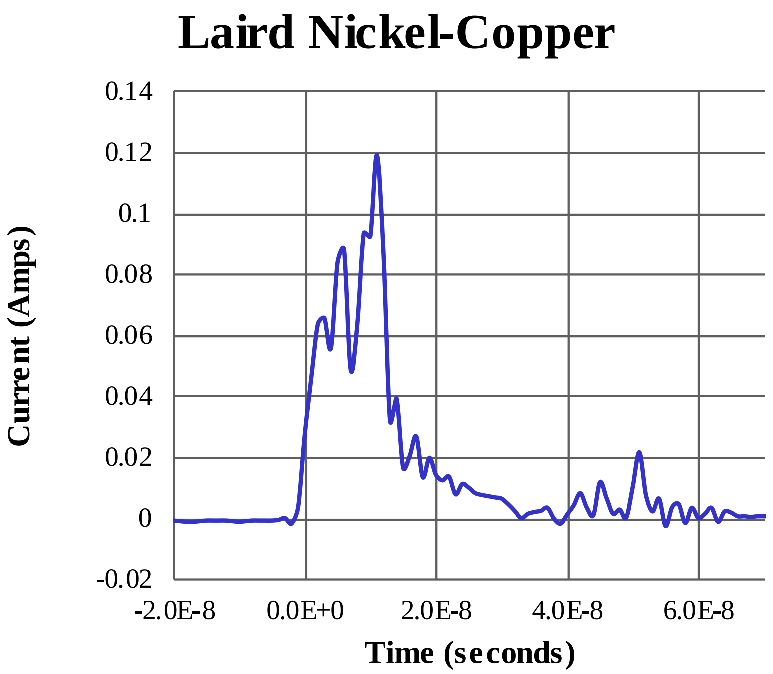
Test Results – Black Kapton 100XC

- **Black Kapton 100XC**
  - Surface resistance
    - 10^5 to 10^9 ohms/square
  - No bulk resistivity given
  - Moderately conductive Black Kapton
- **Exposure**
  - 50 keV electrons
  - 1 nA/cm²
- **Results**
  - 3 discharges during 150 minute exposure
  - Surface Potential: -237 volts
  - Maximum energy: 2.3×10^{-9} Joules



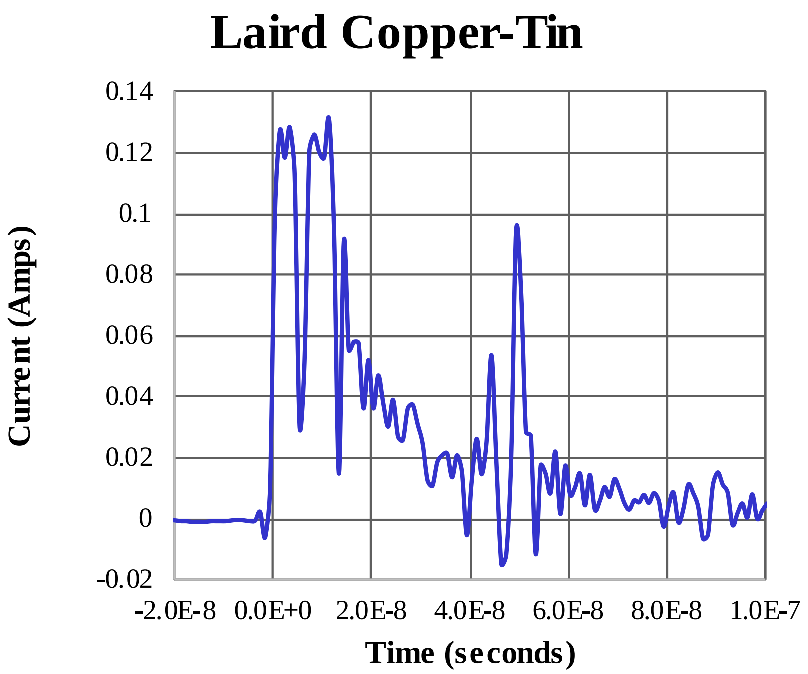
Test Results – Laird Tape Nickel-Copper

- Laird Nickel-Copper Tape
  - Surface resistance
    - 0.07 ohms/square
  - No bulk resistivity given
  - Grey colored cloth tape
- Exposure
  - 50 keV electrons
  - 1 nA/cm^2
- Results
  - 7 discharge during 180 minute exposure
  - Surface Potential: -159 volts
  - Maximum energy: 4.1×10^{-9} Joules



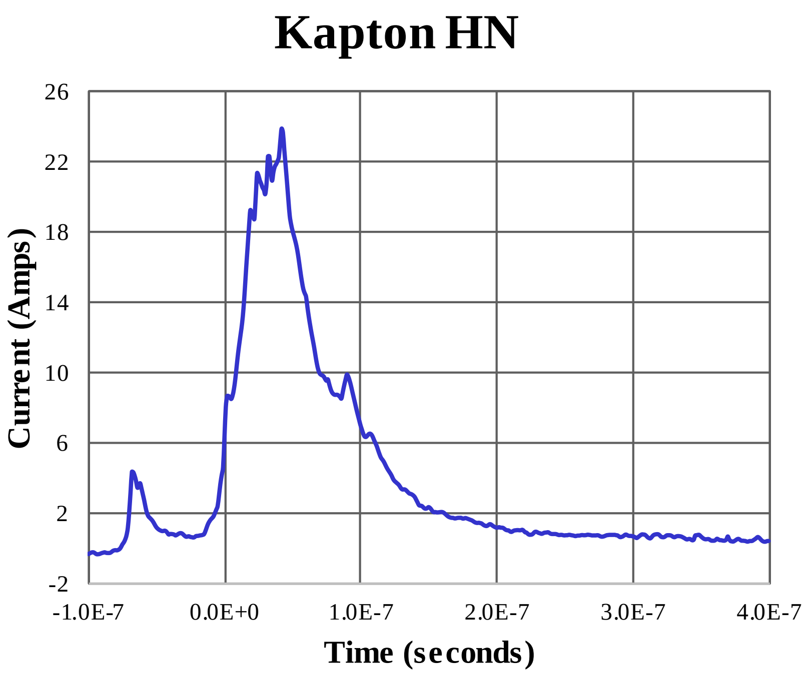
Test Results – Laird Tape Copper-Tin

- **Laird Copper-Tin Tape**
  - Surface resistance
    - unknown
    - Likely similar to Nickel-Copper
  - No bulk resistivity given
- **Exposure**
  - 50 keV electrons
  - 1 nA/cm^2
- **Results**
  - 47 discharges during 130 minute exposure
  - Surface Potential: -260 volts
  - Maximum energy: 1.1×10^{-8} Joules



Test Results – Kapton HN

- **Kapton HN**
  - Surface resistance
    - 10^{16} ohms/square
  - Bulk resistivity
    - 10^{16} manufacture value
    - 10^{19} by charge storage method
  - Standard polyimide tape
  - Very commonly used
  - Reference material for this test
    - Not a conductive tape
- **Exposure**
  - 50 keV electrons
  - 1 nA/cm^2
- **Results**
  - 29 discharges over 75 minute exposure
  - Surface Potential: -3750 volts
  - Maximum energy: 4.5×10^{-4} Joules



Test Results

Sample Material	Electron Energy (keV)	Current Density (nA/cm^2)	Exposure Time (minutes)	Number of Discharges	Maximum Discharge Energy (Joules)	Surface Potential (volts)
Black Kapton 160XC (first exposure)	60	4	120	1	3.8×10^{-10}	-125
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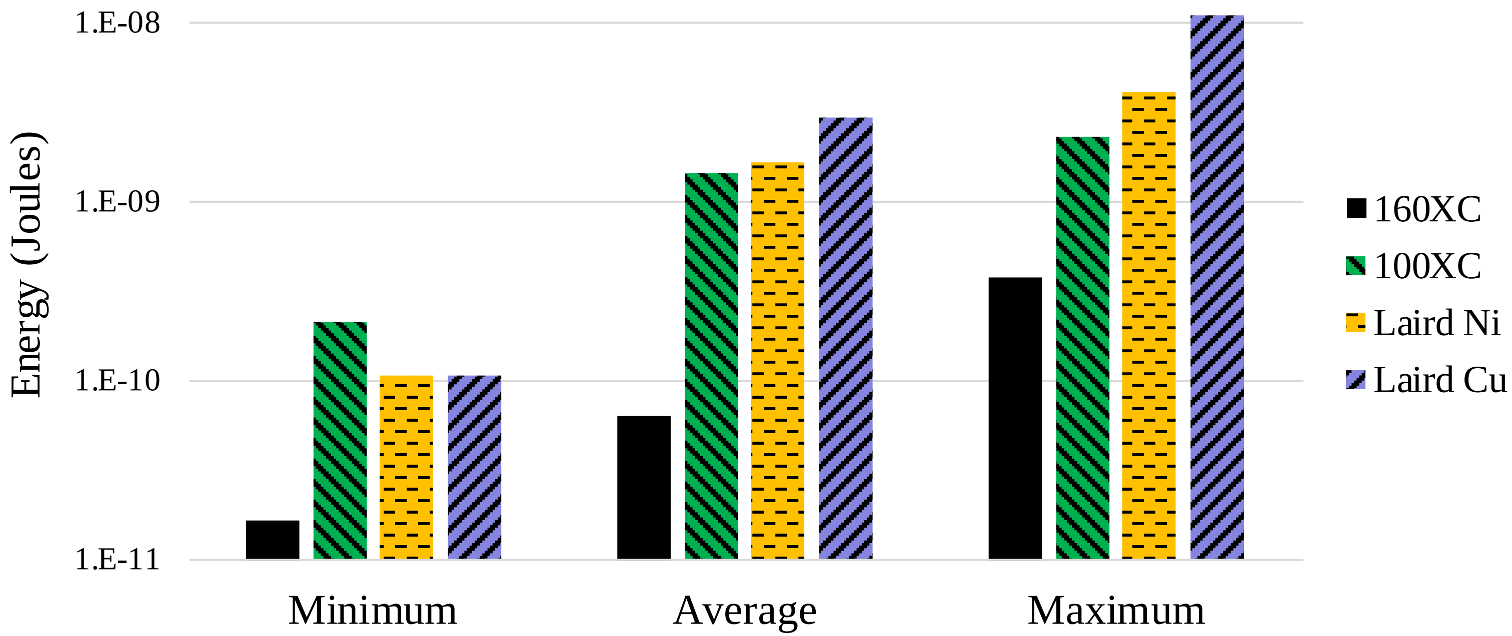
Black Kapton 100XC	50	1	150	3	2.3×10^{-9}	-237
Laird Nickel-Copper	50	1	180	7	4.1×10^{-9}	-159
Laird Copper-Tin	50	1	130	47	1.1×10^{-8}	-260
Kapton HN	50	1	75	29	4.5×10^{-4}	-3750

- Results collected into one table
  - Easier to see relationships
- None of the Conductive tapes produce large discharges
  - Four or more orders of magnitude less than regular Kapton
- No large surface potentials
  - All conductive tapes do retain some charge
  - Indicates composite nature

Test Results – Discharge Energy



- Statistics for all discharges recorded on 18 cm^2 samples
  - Black Kapton 160XC discharges the least energy
  - Laird Copper-Tin discharged the most energy
- Average discharge energy: 10^{-9} Joules
- Maximum discharge energy: 10^{-9} Joules

Conclusions

- All four conductive tapes produced discharges
  - Relatively small
  - Multiple orders of magnitude less than Kapton HN
  - More than a pure conductor
- All tapes stored charge
  - Surface potential in the hundreds of volts after ~1 minute
  - Non-zero electric fields
- Both results show composite nature of the tapes
  - Conductive elements bleed most of the charge
  - Non-conductive areas stored charge until fields exceeded material breakdown strength
- Results may scale with increased area
- Care is needed when using these tapes around sensitive instruments/components

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