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Analysis of Electrostatic Breakdown Sites

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Physics 4900 Final Report

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Abstract

Materials potentially suitable for spacecraft construction were exposed to electrostatic discharge in the USU Materials Physics Group lab, with hopes of identifying samples that possess greater resistance to breakdown. Breakdown shape and size may be important to determining material suitability for spacecraft construction. The discharge damage sites of tested samples were examined, measured and logged into a matrix file for data analysis. Once logged, data were sorted within the matrix and compared graphically to identify trends. Several interesting discoveries were made. LDPE sample breakdown sites are significantly larger than Kapton varieties. We were unable to link increased energy inputs to larger areal sample damage. Breakdown in all sample types were elliptical in nature rather than near circular. Cryogenic test samples are more eccentric than room temperature tests, in both materials. Potential relationship values were briefly examined as a result of these findings in an attempt to explain processes of breakdown.

Introduction

Electrostatic discharge (ESD) is responsible for more damage to spacecraft than any other environmental cause. It is also a potential hazard for workers and equipment in high voltage scenarios throughout other industries. This phenomenon occurs when excess charge accumulates on material surfaces. Once this potential exceeds the capacity of the insulating material, the material decomposes and conducts electricity through the breakdown site. The USU Materials Physics Group has studied various aspects of ESD already, but has only recently begun investigating the nature of breakdown sites and the possible associations they may have. Various material samples including LDPE (Low Density Polyethylene) and Kapton^{TM} (PI, polyimide) were tested. Tests were performed in a vacuum chamber to simulate a space environment. Chamber temperatures were adjusted to cold temperatures (Cryo Ramp) as well as room temperature (RT Ramp) to simulate a space environment and observe possible effects of temperature on material breakdown. Samples were placed between electrodes with ramping voltage in excess of 10K V to make observations of ESD in a controlled environment.

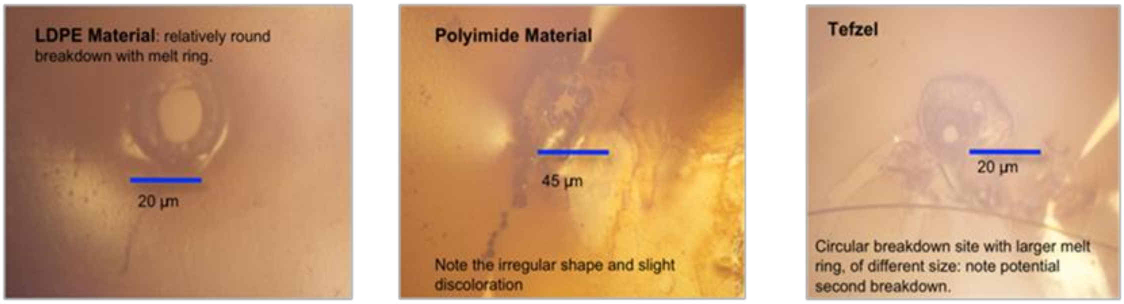

Figure 1.0. Sample images of each material.

Process

Tested samples were analyzed and logged into the matrix based on breakdown size, shape, and noted abnormalities. Processed samples were carefully imaged with a ruler under microscope for scaling purposes, then labeled and saved in our Electrostatic Discharge Quality Summary Table. Once saved, images were analyzed using photo-editing software. Proper scaling was determined for each image and major and minor axis measurements were recorded. Last, the average sample thickness was determined by measuring each material at six locations, this was entered into a separate table and averaged; the average for each sample was then loaded into the Electrostatic Breakdown Quality Summary Table (see Appendix I). Other information regarding the tests, such as the breakdown electric field strength, temperature, test type, and material type were automatically entered in the matrix.

My research focused on looking for correlations in breakdown characteristics of materials and test types. The ESD Quality Summary Table allowed us to search for trends within each group of materials and tests easily. This matrix contains columns for electric field strength at breakdown, material thickness, breakdown voltage, temperature, chamber pressure, time until breakdown, and breakdown site characteristics. Additionally, eccentricity, average breakdown axis length, and relative breakdown area were calculated for each test sample. Eccentricity was calculated by comparing the major and minor axis as a ratio. This allowed us to quantify the uniformity of breakdown shape. Average breakdown diameter was another measurement used to search for trends in the size of breakdown and their material type. The relation of an approximate breakdown area to applied electric field was used to examine this relationship. Relative area was calculated by multiplying the axis (major x minor). A relative areal measurement was used to

Table 1. Data collected for each test sample

Measure	Calculations	Formulas	Description
Major Axis (um) (D)	Damage Area	$\pi\frac{(D+d)^2}{2}$	Melt Ring
Minor Axis (um) (d)			
Thickness (mm) (z)	Damage Volume	$\pi z\frac{(D+d)^2}{2}$	Color/ Char
Potential (V)	E Feild	$\frac{Q}{4\pi\varepsilon_o z^2}$	Regular/Irregular
Image Scale	Eccentricity	$\frac{D}{d}$	Multiple Breakdown

quickly search for a correlation in breakdown size and applied electric field.

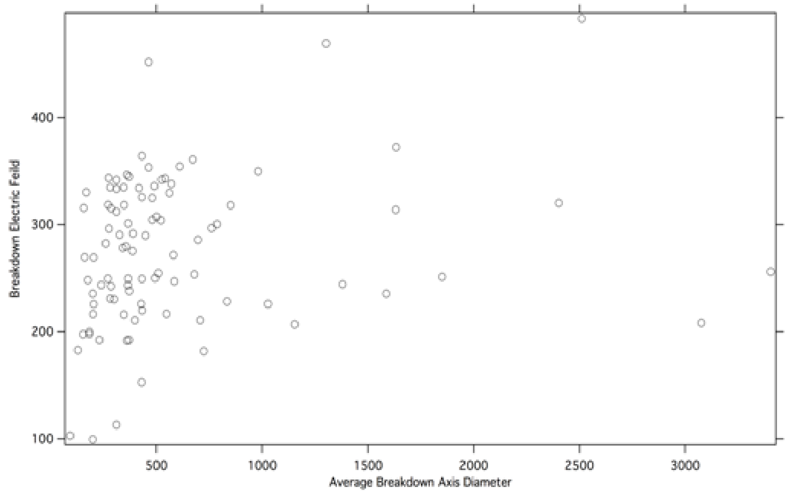

Figure 2.0. Electric field and breakdown area

Results

Of interest at the start of the project was the relationship of destroyed material to the applied electric field. Larger areal damage was expected to positively correlate to an increased electric field since higher energies are capable of larger material displacement. Our plotted data (Figure 2.0) shows a typical range of electric field values for breakdown; however, no correlation was found between this value (E-field) and the average breakdown axes. This data set has a correlation coefficient of only 0.25.


Figure 3.0. Melt ring surrounding damage

Worth noting is the process of determining the extent of areal damage. At the investigation start major and minor axis of displaced material were measured rather than the entire damage zone. A more accurate indicator of damaged material resulting from expended energy may be to measure the associated damage melt area surrounding the displaced material (hole), in addition to the actual hole. *Figure 3.0* shows a classic melt area commonly observed. I believe our graph did not show a correlation as a result of this. Further analysis of this shows that a slight increase in radius has a large effect on the area. Comparing melt area to material displacement in twelve random LDPE RT samples showed that the diameter of the affected material was 220% larger when measuring melt areas rather than displaced material (holes) alone. Relationships between damage type and electric field are unknown and would need to be calculated in order to determine the actual relationship of applied E-field to damage area. It is unknown whether breakdown damage is primarily due to heat damage or destruction at the molecular level from the E-field. Determining the extent of a samples melt zone is more difficult than measuring breakdown holes since melt areas transition slowly from breakdown holes to unaffected material. Making consistent measurements of melt diameter's is subjective since the boundary between unaffected material and melted sample is unclear.

I expected samples to exhibit smaller melt areas as a result of colder chamber temperatures found in our Cryo Ramp tests. Cold chamber temperatures lower a sample material's temperature; this was expected to reduce the rate of melting during a test. The RT Ramp test was chosen as a comparison since it increases voltage across the sample until failure, in the same manner as Cryo Ramp tests except at room temperatures. In LDPE materials tested, Cryo tests were 17% smaller in diameter than Room Temperature Ramp tests. Kapton materials had breakdown that were 5%

smaller at cold temperatures than at Room Temperature. This tells us that LDPE material is more sensitive to cold temperature changes than Kapton material. This comparison does not clarify whether temperature affects a material's propensity to heat damage or molecular destruction more.

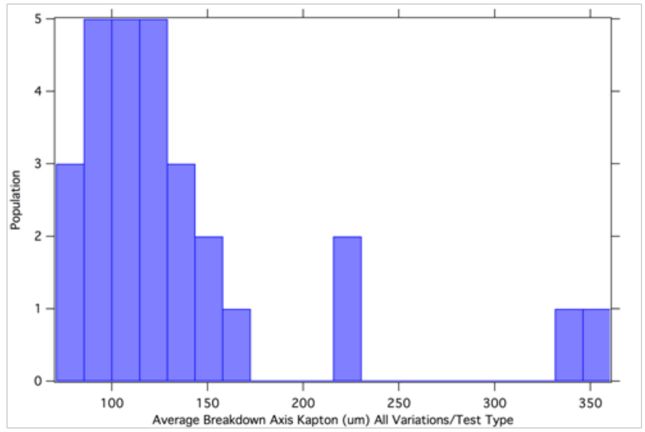

Figure 4.0. Kapton breakdown diameter distribution

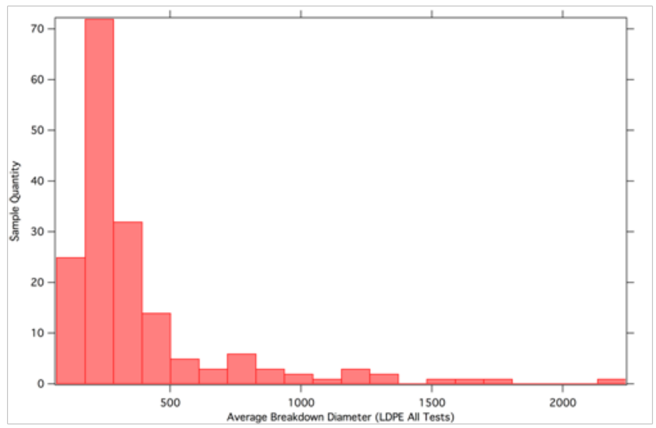

Figure 5.0. LDPE breakdown diameter distribution

Material thickness and breakdown axis diameter were compared graphically. Thickness of the material could correlate to a greater volume of damaged material with higher applied energies. If this were true, we would expect to see a relationship where each sample's areal damage inversely correlated to its thickness. A similar result was also expected when comparing applied voltage to displaced material volume. The volume of damaged material (damage area x thickness) compared to the applied electric field should show the two are connected. This comparison is similar to comparing damage area to electric field, however it would indicate whether material thickness affects the size of damage area. Damage area should be larger in thin material since greater mass is being displaced. Thicker material samples should have smaller damage zones. During initial examinations of this comparison a connection between the two observations was not noted.

My comparisons were made using over 200 analyzed samples, the majority of which (78%) were Low Density Polyethylene samples of varying test types. These conclusions primarily apply to this sample type. Kapton E^{TM} and Kapton HN^{TM} were also included in our analysis, but comprised fewer than 35 test pieces. Populations of each material type were plotted in a histogram (*Figures 4.0 and 5.0*) to compare breakdown diameter of the entire test group. This showed that there is a normal breakdown diameter. A histogram of multiple Kapton types (Figure 4.0) was created to examine whether the predominantly LDPE material *(Figure 5.0)* falsely represented the rest of our data. Initial trends within Kapton materials indicated that the average breakdown site diameter was in fact 240% smaller. Comparing the population of different materials allowed us to locate a potential trend in a materials susceptibility to break down. Our graph shows that this susceptibility is likely due to material type rather than testing differences. Since histograms showed no normal trend when sorted based upon test variations, I believe the trend in smaller breakdown sites of Kapton material is due to better thermal transfer within the LDPE material. LDPE material is a thermoplastic while Kapton is a thermoset plastic. Thermoplastics can be re-formed multiple times while thermosets retain damage in response to heat exposure. As a result; LDPE samples have melt zones referred to as "rings" which often surround breakdown holes. The increased material displacement may be a result of continued deformation from heat generated during breakdown. Kapton material does not exhibit signs of melting, any damaged material would be direct a result of the applied voltage and not necessarily heat.

Table 2.0. Average breakdown diameter by material

Material	Average Breakdown
LDPE	320 μm
Kapton (all types)	132 μm

Eccentricity was examined since the shape of the breakdown site was thought to indicate different information than looking at the actual size of the damage area. As the project was concluded it was noted that there may be errors involved in measuring the actual area of damaged material. Eccentricity measurements would be excluded from this error and could therefore prove more accurate than using a measurement of the areal damage.

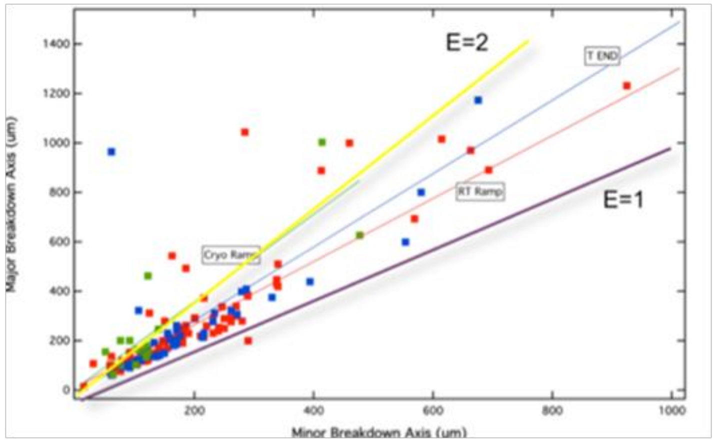

Figure 6.0. Test type eccentricities

Breakdown eccentricity of each material type was examined graphically by plotting major and minor axis against each other (Figure 2.0). This was performed for all material types, as well as the different test types performed on each material. Our work shows that breakdown were elliptical rather than perfectly circular. Eccentricity was measured by creating a ratio between the major and minor axis of each breakdown hole. Our sample group has an average eccentricity of 1.38. The orientation of the ellipse axes was not noted during this investigation. In the future, this would be worth recording since orientation may be important as a system check to determine whether breakdown location is dependant on equipment placement or pre-existing sample deformities.

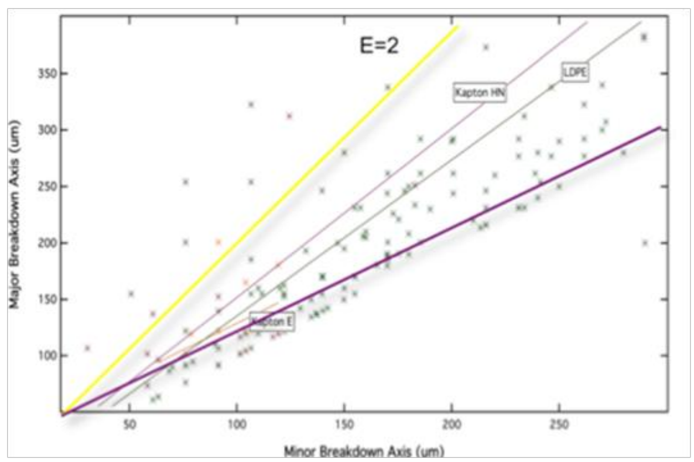

Figure 7.0. Material eccentricities

Different test types were looked at in a similar manner. Types of tests performed on samples included Cryo Ramp (increasing voltage at cold temperatures), RT Ramp (increased voltage at room temperature), and Time Endurance (constant voltage over a prolonged period of time). Cryo Ramping was thought to yield larger areal damage than the other tests. It was thought that material; which was tested at cold temperature would be denser than at room temperature and more brittle. This change in material property was thought to cause damage to propagate further than at room temperature. A higher eccentricity value or a larger average breakdown value of these test types as compared to other tests would lead us to believe breakdown at cold

Table 3.0. Eccentricity and average breakdown axis by test type

Test Type	Average Eccentricity		Average Breakdown Axis	
Cryo Step-up	1.73	LDPE 1.82	221 μm	LDPE 289 μm
		Kapton HN 1.40		Kap. 116 μm
RT Step-up	1.31	LDPE 1.29	296 μm	LDPE 351 μm
		Kapton 1.45		Kap. 122 μm or 268 μm
SVET (Time Endurance)	1.53	LDPE 1.53	270 μm	LDPE 270 μm
		Kapton N/A		Kapton N/A

Table 4.0. Eccentricities and averagebBreakdown axis by materialtType

Material	Average Eccentricity	Average Breakdown Axis
LDPE	1.38	320 μm
Kapton (all types)	1.42	132 μm

temperatures propagate further than at room temperature. Eccentricity was examined in our major and minor axis graph comparison; Cryo Ramp test types had a higher eccentricity value of nearly 2. Room temperature tests had an eccentricity of 1.4. Our graph also demonstrates that breakdown eccentricity increased with breakdown size. Samples deviated from an eccentricity of 1 (circular) as their size increased.

Comparing test type eccentricity as well as the eccentricity of various materials showed a trend in increased breakdown eccentricity for Cryo-Ramp tests. Comparing average eccentricity for each test showed that Cryo ramp tests were 25% and 32% more eccentric than Time Endurance and Room Temperature tests, respectively. Closer examination of the Cryo Test material populations revealed this increased eccentricity was primarily due to LDPE material rather than Kapton material. Average breakdown eccentricity for LDPE undergoing Cryo Test was 30% greater than Kapton material undergoing Cryo Test, and 39% greater than that of Room Temperature tests. Refer to Table 1. Kapton test samples did not exhibit significant increases as a result of Cryo Testing, but were still greater than other test types. This tells us cold LDPE material is more prone to damage propagation as indicated by eccentricity increases. Breakdown orientation may be interesting but is not suspected to affect the likelihood of propagation. Initial breakdown is thought to occur in a random orientation while subsequent damage proceeds along the initial breakdown axis. Cold temperatures cause a magnification in microscopic material defects, which are not detectable prior to our testing [8]. This aids in the cascading breakdown process caused by ESD and leads to the larger eccentric breakdowns observed during cold testing temperatures. It is worth noting that data sheets for our tested materials contain material constants for the samples at high temperature applications in excess of 300^{o} C, indicating these materials have not been extensively tested at cold temperatures.

Error

Systematic error in our measurements was calculated to be 6%. This was determined as a result of our imaging setup, where variations in scaling were determined to be within ±10 pixels with our determined average scaling of 169 pixels:1/100 in. Scaling was determined to be valid if initially measured within this range. If initial scaling deviated by more than 10 pixels from the accepted mean a new scale was created by averaging 5 scaling measurements for that image.

Continued Work

Table 5.0. Average breakdown axis error

(µm)	LDPE RT Ramp	LDPE Cryo	LDPE SVET	Kapton RT Ramp	Kapton Cryo
Mean Diameter	350	290	270	135	116
STDEV	400	200	285	100	40
STDEV of Mean	30	50	30	19	10

Table 6.0. Eccentricity error

Major Axis/Minor Axis	LDPE RT Ramp	LDPE Cryo	LDPE SVET	Kapton Cryo	Kapton RT Ramp
Mean Eccentricity	1.3	1.8	1.5	1.4	1.6
STDEV	0.4	0.9	0.20	0.4	0.9
STDEV of Mean	0.05	0.3	.03	0.2	0.2

Table 7. ESD Breakdown Analysis Table of Contents

1 Overview
2 Instructions
2.10 File Destination
2.11 Imaging
2.12 Thickness Measurement
3 Analysis
3.10 Descriptions and abbreviations
3.12 Measurement of Breakdown Diameter
3.13 Plotting Data
4 Continued Work

Our investigation yielded further questions involving new potential correlations. Changes to the existing process of analysis are necessary to make such comparisons. For example, it is thought that the proximity of the breakdown to the discharging electrode may offer information regarding the actual breakdown process. Recording the location of each material failure would also act as a test of our equipment. The breakdown sites may be associated with electrode positioning, or pre-existing material defects.

In conjunction with my inquiry, I created a laboratory manual (see *Appendix II)* to standardize measurements. It suggests improvements and additional measurements to be made on all future samples including recording the spatial variability of breakdowns and measuring the area directly within photo editing software rather than approximating this using the axis measurements. Table 7 shows a table of contents for the manual.

Presentation of Results

Table 8 Project Time Line

Objective	Completion
Complete processing of currently available test sample set	March 2014
Present summary of compiled work at USU Student Showcase	April 2014
Creation of instructional manual for ESD acquisition and analysis	January 2015
Complete identification of potential correlations to evaluate	January 2015
Identify additional data required to evaluate potential correlations identified	October 2014
Formulate method to map breakdown location on test samples	May 2014
Complete data analysis and search for possible correlations	March 2015
Presentation of completed project, and correlations	October 2014

I successfully presented my research at the following venues:

- Utah State University Student Showcase, Logan UT; April 11 2014 [2].
- American Physical Society Four Corners Regional Meeting, Orem UT; October 17-18 2014 [3].

My project poster presentation received a best poster award at the APS 4 Corners Meeting in Orem, UT in October 2014 [3]. My poster was the only presentation from USU to receive an award. The APS 4 Corners Meeting was beneficial in many respects; it was exposure for our group and it also exposed me to some unique insights and thoughts from distinguished professors in the area on possible correlations.

Personnel Overview

Sam Hansen is a senior undergraduate student majoring in Physics at Utah State University. Sam worked with the Materials Physics Group from Fall 2013 through Fall 2014, under the guidance of graduate student Allen Anderson and faculty mentor J.R. Dennison. During this time Sam became expert at ESD site analysis and classification; after processing hundreds of test samples. In the future, Sam is interested in exploring various other methods through which to mitigate spacecraft and equipment failure due to unwanted charging events and how polymers react to extreme conditions. Sam graduated with a BS in Physics in May 2015.

Allen Andersen is a graduate student pursuing his Ph.D. in the Physics Department at Utah State University. As a member of the Materials Physics Group his research area is the investigation and modeling of electrostatic discharge phenomena in polymeric and ceramic/glassy highly disordered insulating materials. He provided guidance in experimental design, analysis and interpretation of the data, and helped to relate my results to the current understanding in the field.

J. R. Dennison is a professor in the Physics Department at Utah State University, where he leads the Materials Physics Group. He has worked in the area of electron scattering for his entire career and has focused on the electron transport and electron emission of materials related to spacecraft charging for the last two decades. He provided project oversight and worked directly with me on experimental design, analysis methods, and interpretation of the data.

References

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11. Sam Hansen, ESD Breakdown Analysis Laboratory Manual, Utah State University, Logan, UT, 2015

Appendix I. ESD Quality Summary Table Example

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**USU ESD Summary**															
2	**Status and Analysis of Data Runs**															
3																
4	**Run Parameters**															
5	Sample	Sample Thickness [mm]	BD Temp. [K]	Voltage Step [V]	Sample Plate #	Electrode #	Bakeout Date	Chamber Pressure [mbar]	Type of Run	Waiting Voltage [V]	Breakdown Voltage [V]	1/100" Major Axis	1/100" Minor Axis	Image comments	Ramp time [s]	BD Time for Time Dep. [s]
6	LDPE		300	20	_	B3	7/21/10		RT Ramp			0.058	0.058	rnd, melt ring		
7	LDPE				25	B2	10/18/10					0.09	0.73	rnd, melt ring		
8	LDPE				31	B1	3/12/10					0.18	0.18	rnd, melt ring		
9	LDPE				27	A1	7/21/10					0.18	0.18	rnd, melt ring		
10	LDPE		300	20	39	A3	8/3/11		T END			0.24	0.24	rnd, melt ring		
11	LDPE		300	20	4	A3	7/21/10	2.50E-06	T END	4900	4895	0.25	0.25	rnd, melt ring	886.251	258131.392
12	Kapton E			20	4	B3	5/30/08		Cryo Ramp			0.25	0.25	rnd, melt ring		
13	Kapton HN		300	20	5	B3	5/4/12		RT Ramp			0.29	0.23	rnd melt/char?		
14	LDPE		300	20	45	A3	7/21/10		T END			0.3	0.3	rnd, melt ring		
15	LDPE	0.03083	300	20	18	B1	2/23/12	2.20E-05	RT Ramp			0.34	0.27	sm, rnd melt ring		
16	LDPE		300	20	28	A2	3/12/10	4.00E-05	T END	6008	6008	0.36	0.36	rnd, melt ring	1081.25	15856.363
17	LDPE		300	20	28	A3	3/12/10	4.60E-06	T END	6068	6068	0.36	0.36	rnd, melt ring	1110.79	27888.852
18	Kapton HN		300	20	16	A3	5/3/12		RT Ramp			0.36	0.36	rnd melt/char?		
19	Kapton HN		300	20	4	A3	4/22/08		RT Ramp			0.36	0.36	rnd melt/char?		
20	LDPE		300	20	6	B2	3/12/10	3.00E-05	T END EBD	7200	7007	0.36	0.3	rnd, melt ring		
21	LDPE	0.02533	300	20	_	A1	5/10/13		RT Ramp			0.36	0.3	rnd, melt ring		
22	LDPE		300	20	17	A3	12/19/11	1.60E-05	T END	7248	7242	0.373	0.313	rnd, melt ring	830.54	1508.174
23	Kapton HN		300	20	5	B1	5/4/12		RT Ramp			0.38	0.25	rnd melt/char?		

Appendix II

ESD Breakdown Analysis Laboratory Manual

Sam Hansen

USU Materials Physics Group

Version 1.1
1/21/2015

1 Overview

This is an instruction manual on how to record and log information into Big Blue regarding material samples, which have undergone testing for electrostatic breakdown. Instructions and procedures for visually analyzing physical characterizations of actual breakdown sites under microscope are also included, as well as a key for the abbreviated descriptions used in the ESD Quality Summary Table.

2 Instructions

2.1 File Description

Prior to image being taken, the file destination must be selected in the following location on Big Blue: Data + Analysis… Data…Electron Transport… ESD… Material Type… Test Type… Images. Once saved in the correct location, images should be titled using the correct naming convention: material thockness voltage date electrode # and file type: **KapE1mil_K20V 5-30-08 B_2.CR2**.

2.2 Imaging

Tested samples are to be handled carefully to prevent further damage, imaged under the new microscope camera. Images need to be previewed to ensure full breakdown is imaged, and image quality is acceptable for taking measurements and recording attributes; focus, lighting, window size, and background color are of particular importance. Attention needs to be given to the image background surface as well as lighting so that breakdowns are clear in the image for analysis. A measurement scale should be present in each photo for proper scaling while measuring sites graphically. For future reference, a slide cover with increments in micrometers (um) should be used to create an accurate scale.

2.3 Thickness Measurement

Thickness of each sample needs to be measured a total of six times and averaged. Calibrate the equipment, open the correct program, and measure directly above and below each electrode contact point to do this. Data for each measurement is entered into a separate matrix specifically for thickness, and averaged automatically. Care needs to be taken to make sure the correct file destination is used for the automation.

3 Analysis

Images can be analyzed using photo-editing software; the following should be noted within the EST Quality Summary Table:

- Presence of actual breakdown
- Major and Minor Axis Diameter
- Damage area (see suggestions)
- Irregular features notes
- Presence of secondary breakdown and subsequent measurements
- Discolorations

3.1 Axis Measurement

Images Major and minor axis of each breakdown should be measured using the photo software's pixel measurement tool.

For our axis measurements we took 5 measurements of each scale in $1/100^{th}$ inch increments using the software pixel measurement tool. The average of these measurements was used to convert our major/minor axis measurements (in pixels) to $1/100^{th}$ inch measurements, this was later converted into micrometers in our matrix. Scaling of our images was eventually determined to be identical, at which point a single measurement was used to determine the proper scale. If the measurement fell within 10 pixels of our determined data set average scale of 169 pixels to 1/100th inch, then the data set average was used. A standard ratio of 169(check) pixels per 1/100th inch was used for the remainder of our set. This was determined by averaging roughly (#) scale measurements of previous samples. It was determined that our margin of error from this was:

3.2 Analysis

Data entered into the matrix can be sorted based on any recorded trait. So far all graphing has been done in Igor. It is important to note that many values in the ESD Quality summary table are computed, unless the actual value is copied. Corresponding values need to be kept in order during this process. Sorting within a specific population can change the order of appearance for values, if these results are copied into IGOR for graphing without checking the order of corresponding numbers, the resulting graph and data will be wrong.

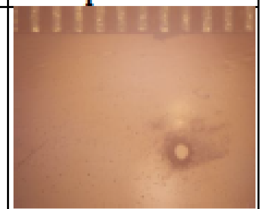
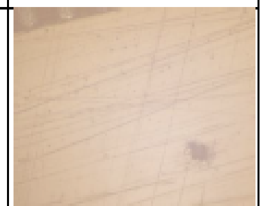
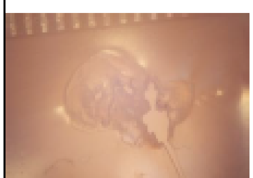
Table I shows shorthand abbreviations which were used.

4 Changes to Future Analysis

Initial samples were measured for major and minor axis of displaced material with the hope of discovering some correlation between the applied E field and destroyed/displaced material. As of 10/31/14 a correlation of this nature was not found, potentially due to a lack of a large enough data set among multiple materials, or not taking into account damaged, rather than displaced material. Future samples should incorporate taking an areal measurement of both the damage zone (melt and char) as well as the actual displaced material (breakdown hole). This could be accomplished using photo-editing software to measure certain coloration differences in measurement.

Future slides should facilitate recording the location of each breakdown, this could be plotted to see if there are any trends in breakdown location. This acts as a system check, and answers whether or not the location of our breakdown is determined by material defects or equipment placement.

Table I. ESD Image Analysis Categories

Category	Comments	Example
1. rnd, melt ring:	round melt ring, no unusual shape or coloration, this is in reference to the shape, not the size. Melt ring refers to the obvious zone around the breakdown hole where material has been melted, but not char is present. This melt zone is the same shape as the actual breakdown hole. This seems to be common in LDPE samples.	
2. part. BD:	partial breakdown, refers to those samples that were obviously effected by melting and or discoloration, however the material did not fail, meaning no breakdown hole was present.	
3. 2nd partial breakdown	a complete breakdown is present and noted appropriately; this ADDITIONAL notation is in reference to a secondary damage zone, though incomplete as in the partial breakdown described above. To be classified as secondary this damage was not connected to the primary ESD site by melting or missing material and appeared independent of the other site.	
4. no vis BD	some samples exhibit no signs of breakdown, a sample under microscope showed no melt ring or breakdown. Major and minor axis are entered as "–". Samples having zero signs of melting, that appear un effected receive this description. Make sure than small breakdown are not mistakenly passed over, since many pin hole sized breakdowns are easy to miss.	
5. Irregular	irregular breakdown do not exhibit uniform roundness as in the case of "rnd, melt ring" and do not have a standard description. For this reason, the term "irregular" should be followed with a short justification, or description of the irregularity. Breakdowns exhibiting a jagged breakdown perimeter are considered irregular. Due to the shape being irregular, a major and minor axis measurement does little to indicate the actual size of the area in question. These measurements (major and minor axis) should still be taken however. Shown at right is an irregular breakdown, the shape is not elliptical, there is no correlation of the melt zone to displaced material, and multiple holes are present.	
6. rnd melt/char:	refers to the rnd melt rings that exhibited a dark or black discoloration in the melt ring surrounding a rnd melt ring breakdown. The discoloration may indicate a different process of destruction than other non-colored sites.	
7. rnd, melt ring, mult part bd:	same as in #1, with the note of additional partial breakdowns as in #2