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U.R.C.O. Grant Proposal

October 14, 2016

Temperature Dependence of Electrostatic Breakdown in Highly Disordered Polymers

Tyler Kippen, Principle Investigator

JR Dennison, Faculty Mentor

Allen Anderson, Graduate Student Mentor

*Materials Physics Group
Physics Department
Utah State University*



Narrative

The primary objective of the proposed work is to test the temperature dependence of electrostatic field strength for spacecraft materials by applying an increasing electrostatic field until electrostatic breakdown occurs. The goal will be to better simulate real world charging situations at varying temperatures and to test the temperature dependence predicted by our dual-defect breakdown model.

Enhanced understanding of prolonged exposure to high static electric fields (DC aging) of insulating materials based on expanded experimental studies is of critical importance to understand the physics of highly disordered insulating materials (HDIM). It also has direct applications in spacecraft charging [2-3], high voltage DC power transmission cables and switching [3], thin film dielectrics, and semiconductor devices and sensors. Electrostatic discharge (ESD) is a permanent, catastrophic failure of a dielectric material. ESD and the associated material breakdown is the primary cause for spacecraft damage due to space environmental interactions [1]. This phenomenon occurs when the space plasma fluxes charge a craft to high voltages where insulating materials then break down [2]. This breakdown allows current to flow freely through the material, which can damage or destroy on board electrical components and other vital systems [3]. Recent literature on DC power cable aging calls for better models and more data on the details of electrical ageing in HDIM under DC high electric fields, especially with regards to finding a DC equivalent for AC partial discharge diagnostic tests [5-8].

Theoretical Models

Building on single process ESD models developed elsewhere [5], models developed at USU consider two breakdown processes [12]. The first process is a lower energy reversible process with a significant rate of defect repair and a low enough activation energy, ΔG_{def} , that the defects can be spontaneously repaired due to thermal activation. The second process is a higher energy, largely irreversible process with a negligible defect repair rate. This is due to direct stress on molecular segments which causes unreparable damage such as creation of broken bonds with unpaired sites which can act as electron traps [12]. Equation (1) is the mathematical description of this model. In it, high and low energy defects are treated as terms in the sum A and B respectively. It should be

$$P_{def}^{Tot}(F, T) = \sum_{i=A,B} P_{def}^i = \sum_{i=A,B} \left(\frac{2k_B T}{h\nu_{A,B}} \right) \exp \left[\frac{-\Delta G_{def}^i}{k_B T} \right] \sinh \left[\frac{\epsilon_r \epsilon_0 F^2}{2N_{def}^i k_B T} \right]. \quad (1)$$

noted that temperature, T, appears in each term in the equation. Importantly, on the right hand side of the Equation (1), the exponential term involves the ratio of the defect energy, ΔG_{def} , to the thermal energy, where k_B , is Boltzmann's constant. The hyperbolic sine function involves the ratio of the energy gained in the electric field, F, from charge moving from one defect to the next defect (of density, N_{def} ,) to the thermal energy. Also important to define is Planck's constant, h , the tunneling frequency, $\nu_{A,B}$, and the vacuum and relative permittivity, ϵ_0 and ϵ_r [9]. One possible effect that temperature could have on this model is that higher temperatures could cause low energy defects to be annealed more rapidly, which would decrease the overall breakdown field strength. However, temperature is complex and can be significantly different for different materials, depending on the material parameters ΔG_{def} , N_{def} , and ϵ_r .

Previous Experiments

Preliminary tests done by the USU Materials Physics Group (MPG) over the last decade using our electrostatic discharge custom vacuum chamber [12] have found that the electrostatic field strength (F_{ESD}) at breakdown depends on the temperature applied during ESD testing of the materials [11, 12]. The materials that have been tested to date are low-density polyethylene (LDPE) and polyetheretherketone (PEEK); I was involved in some of these tests over the last six months.

To analyze these results a particular type of statistical analysis is used, known as the Weibull distribution. This distribution has been shown to agree with the dual-defect model fit over a wide range of fields, but is as yet largely untested for different temperatures[13]. Figure 1 shows the Weibull fit of the probability of breakdown versus the breakdown field strength for LDPE at three temperatures [11]. Figure 1 shows that as the temperature changes, the shape and position of the distribution also changes. Figure 1, and similar fits done for PEEK data implies that the breakdown field strength does depend on temperature, though more data are needed to understand better how temperature affects the breakdown field [11].

Proposed Experiments

We propose to continue similar temperature dependent tests this spring for these and additional materials over a wider range of temperatures. The hope is that through testing more materials at various temperatures, we can begin to understand how the breakdown field strength varies with the temperature and material used. While the data and our model suggest that temperature has an effect on the breakdown field strength, more data and better statistics are needed to verify result to determine material's parameters and to further test our dual-defect model. We will extend testing to temperatures from 150 K up to 350 K.

These tests will use the same custom vacuum chamber ($<10^{-3}$ Pa base pressure) [13], as shown in Figure 2. Samples of the materials to be tested will be placed between a metal sample mounting plate and six highly polished copper high voltage electrodes. This will allow testing of six samples during a single vacuum cycle to save time, as it takes about an hour to switch samples out between vacuum cycles. A spring clamping mechanism will be used

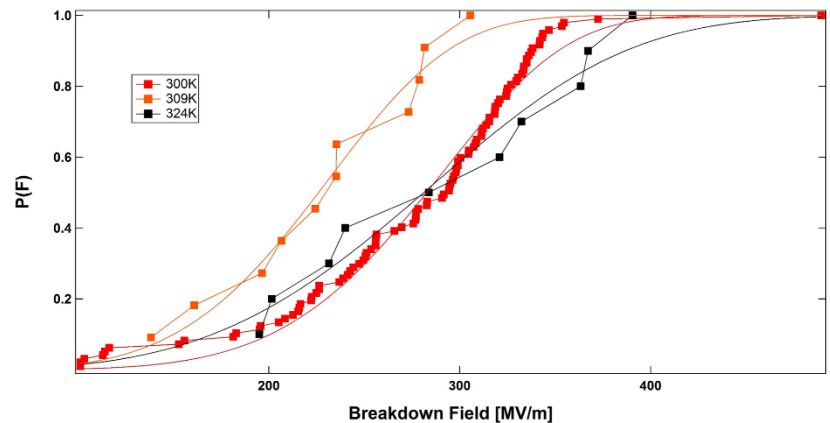


Fig 1: The probability of breakdown versus the breakdown field strength at three temperatures. Note the difference in the curve at each temperature.

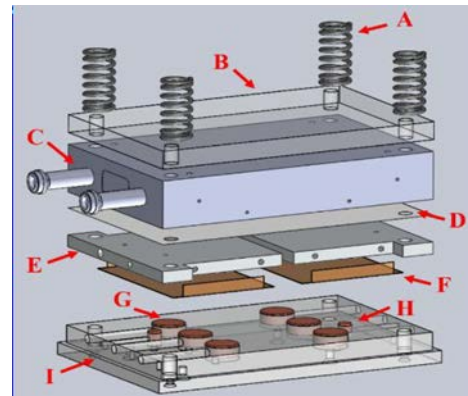


Fig. 2: ESD chamber assembly.
A. Adjustable pressure springs.
B. Insulating plate.
C. cryogen reservoir.
D. thermally conductive, electrically isolating layer.
E. sample and mounting plate.
F. sample
G. High Voltage Cu electrode.
H. Cu thermocouple electrode.
I. Insulating base. [13]

to apply uniform sample contact pressure of about 0.4 MPa, in compliance with standard methods [14]. In order to perform the low temperature tests, either liquid nitrogen or a chilled coolant will be pumped through the cryogen reservoir to cool the sample. For high temperature tests a heating coil is wrapped around the outside of the chamber and the entire chamber is heated. The temperature is monitored with type k thermocouples that are in contact with the sample. For both sets of tests, voltage will be incrementally increased at a constant rate until breakdown occurs, which will be evident by the current increasing significantly and continuing to rise linearly above breakdown. Data will be analyzed using the previously explained Weibull statistics and then compared to similar data obtained from past room temperature tests.

Timeline

Depending on the temperature being tested, a typical vacuum cycle with six samples can take one to three days to complete. The proposed timeline in Table 1 describes data acquisition between January and April. There will be twelve samples tested per temperature and five different temperatures will be tested per material. This will result in a total time for data acquisition of about twenty days, or four weeks, per material. Considering one week total to prepare samples and two weeks at the end to finish analysis and prepare the presentation, the total amount of work time should equal thirteen weeks. This timeline will have the project finished the week before it is to be presented at NCUR. In this short time frame, Kapton HN will be the main focus when testing at each temperature until all the tests for that material are completed. After that BOPP, or even additional LDPE and PEEK, will be tested as much as time allows.

Table 1: Project Timeline

URCO Project Time Line	
Objective	Completion
<ul style="list-style-type: none"> • Sample preparation: cut sample sheets, bake out, and place in glove box • Verify all equipment is working properly • Test new cooling setup • Begin collecting high temperature data 	January, 2016
<ul style="list-style-type: none"> • Finish collecting high temperature data • Any equipment maintenance or repairs • Analyze high temperature data • Begin collecting low temperature data 	February, 2016
<ul style="list-style-type: none"> • Finish collecting low temperature data • Analyze low temperature data • Do final analysis and prepare presentation 	March, 2016
<ul style="list-style-type: none"> • Present conclusions at NCUR • Present at Student Research Symposium • Submit final URCO report 	April, 2016

Educational Plan

The overall purpose of this project is to determine whether or not our proposed dual-defect theory adequately models our experimental results or if a more refined model is needed to describe the data. The scientific conclusions of this study will have important practical applications, as discussed in the narrative.

My primary goal for this project is to be able to more fully participate in all aspects of the research process. This summer I was trained on the equipment and given responsibility of the laboratory operations—including sample preparation, data acquisition, and analysis—while Allen Andersen was on a summer internship. I would like to be able to further my understanding of the physical processes and theoretical models behind the experiment and to have the opportunity to develop my own conclusions and test them against the data.

Another important aspect is the opportunity to present the research that I have done. This is why I wish to present at the Student Research Symposium and at NCUR. These opportunities will help me gain experience with writing and presenting research, and I will also have a chance to interact with peers who have done similar research projects and learn from them.

Additionally, I will be able to apply knowledge I gain from advanced courses that I will be taking, such as Electromagnetism and Thermodynamics. Lastly this project will help me to improve my ability to collaborate and work with others, as I will continue to discuss the experiments with Andersen and Dennison. I will expand my role of supervising junior undergraduate researchers who will aid with data acquisition.

Personnel Overview

Tyler Kippen is a junior undergraduate student pursuing a degree in Physics with a Professional Emphasis, with a minors in both Computer Science and Mathematics. He has been a member of the Material Physics Group since the spring of 2016 and has helped to design and build equipment to irradiate samples at the Idaho Accelerator Center. He also ran the Electrostatic Discharge chamber (ESD) during that time.

Allen Anderson is currently a graduate student at Utah State University in Logan, UT pursuing a PhD in physics. He received a BS degree in physics from BYU-Idaho in 2012. He has worked with the Materials Physics Group for four years on electron transport measurements, electrostatic discharge tests, and electron emission measurements related to spacecraft charging.

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 will provide project oversight and will work directly with Tyler and Allen on analysis methods and interpretation of the data.

Budget

Table 2 describes the budget summary for the proposed work. Kapton and biaxially-oriented polypropylene (BOPP) are the two materials that will be tested. Funds will also be needed to prepare a poster to present at NCUR and to assist in traveling to the conference, as it is in Memphis, Tennessee.

Table 2. Budget Summary

URCO BUDGET SUMMARY		
EXPENSES:	VENDOR	AMOUNT:
Supplies		
Poster printing and supplies	USU Engineering Lab	\$50
BOPP 300 mm x 300 mmx 0.025 mm 5 pcs	GoodFellow	\$200
Kapton HN 300 mm x 300 mm x 0.025 mm 5 pcs	GoodFellow	\$450
Travel		
NCUR		\$300
Stipend		
Tyler Kippen		\$1000
TOTAL BUDGET:		\$ 2000
VP for Research URCO Funds		\$1250
Materials Physics Group Matching Funds (A07563)		\$750
TOTAL FUNDING SOURCES		\$2000

References

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- [2] H. B. Garrett, and A. C. Whittlesey, “Spacecraft charging, an update,” *Plasma Science, IEEE Transactions on*, vol. 28, no. 6, pp. 2017-2028, 2000.
- [3] K. L. Bedingfield, R. D. Leach, and M. B. Alexander, *Spacecraft system failures and anomalies attributed to the natural space environment: National Aeronautics and Space Administration, Marshall Space Flight Center*, 1996.
- [4] G. Teyssedre, and C. Laurent, “Advances in high-field insulating polymeric materials over the past 50 years,” *Electrical Insulation Magazine, IEEE*, vol. 29, no. 5, pp. 26-36, 2013.
- [5] J. P. Crine, “On the interpretation of some electrical aging and relaxation phenomena in solid dielectrics,” *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 12, no. 6, pp. 1089-1107, 2005.
- [6] T. T. N. Vu, G. Teyssedre, B. Vissouvanadin et al., "Electric field profile measurement and modeling in multi-dielectrics for HVDC application." pp. 413-416.
- [7] P. Trnka, M. Sirucek, M. Svoboda et al., “Condition-based maintenance of high-voltage machines-a practical application to electrical insulation,” *Electrical Insulation Magazine, IEEE*, vol. 30, no. 1, pp. 32-38, 2014.
- [8] T. Czaszejko, “High-voltage testing fundamentals: a cable testing perspective,” *Electrical Insulation Magazine, IEEE*, vol. 30, no. 1, pp. 7-13, 2014.
- [9] Allen Andersen, and JR Dennison, “A Dual-defect Model for Predicting Lifetimes for Polymeric Discharges from Accelerated Testing,” *American Physical Society Four Corner Section Meeting*, Utah Valley University, Orem, UT, October 17-18, 2014.
- [10] Allen Andersen and JR Dennison, “Pre-breakdown Arcing as a Proxy for DC Dielectric Breakdown Testing of Polymeric Insulators,” *Proceedings of the 2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2015)*, 2015.
- [11] Tyler Kippen, Allen Andersen, and JR Dennison, “Temperature Dependence of Electrostatic Breakdown in LDPE and PEEK,” *American Physical Society Four Corner Section Meeting*, New Mexico State University, Las Cruces, NM, October 21-22, 2016.
- [12] Allen Andersen, JR Dennison, Alec M. Sim and Charles Sim, “Electrostatic Discharge and Endurance Time Measurements of Spacecraft Materials: A Defect-Driven Dynamic Model,” *IEEE Tran. Plasma Science*, **43**(9), 2015, 2941-2953.
- [13] Allen Andersen and JR Dennison, “Mixed Weibull Distribution Model of DC Dielectric Breakdowns with Dual Defect Modes,” *Proceedings of the 2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena—(CEIDP 2015)*, 2015.
- [14] ASTM D-5213-12, “Standard Specification for Polymeric Resin Film for Electrical Insulation and Dielectric Applications,” (American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA, 2012).

Curriculum Vita

EDUCATION

H.S. Diploma

Morgan High School, Morgan UT

May 2012

GPA 3.9

B.S., Physics, Professional Emphasis

Math Minor, Computer Science Minor

Utah State University, Logan, UT

May 2018

GPA 3.9

TECHNICAL WORK EXPERIENCE

Research Assistant

USU Materials Physics Group

05/16 - current

Logan, UT

- Operated high vacuum testing facilities
- Performed preparation and analysis of sensitive spacecraft materials
- Performed data analysis using Igor
- Designed and built system to irradiate materials at the Idaho Accelerator Center

COMPUTER SKILLS

C++ LabVIEW Igor Pro Microsoft Office

AWARDS

USU

- Dean's List 2012 - current
- USU Presidential Scholarship 2012 - current
- Sigma Pi Sigma: Physics honor society member 2016
- Honor's Program 2012 - current

High School

- National Honor Society Member 2010-12
- Valedictorian 2012
- State Academic Decathlon individual champion 2012

ACHIEVEMENTS & ACTIVITIES

Society of Physics Students: Physics outreach activities

2012 - current

PRESENTATIONS

Alexandra Hughlett, **Tyler Kippen**, and JR Dennison, "Relaxation of Radiation Effects on the Optical Transmission of Polymers," *American Physical Society Four Corner Section Meeting*, New Mexico State University, Las Cruces, NM, October 21-22, 2016.

Tyler Kippen, Allen Andersen, and JR Dennison, "Temperature Dependency of Electrostatic Breakdown in LDPE and PEEK," *American Physical Society Four Corner Section Meeting*, New Mexico State University, Las Cruces, NM, October 21-22, 2016.