PROGRESSION OF SURFACE FLASHOVER IN VACUUM WITH POLYMER INSULATORS

Kimberly M. Faris

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PROGRESSION OF SURFACE FLASHOVER IN VACUUM
WITH POLYMER INSULATORS

by

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B.S., ELECTRICAL ENGINEERING, UNIVERSITY OF NEW MEXICO, 2021

THESIS
Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Electrical Engineering

The University of New Mexico
Albuquerque, New Mexico

August 2023
Acknowledgment

I would first like to take this opportunity to express my deepest gratitude for Dr. Jane Lehr’s invaluable guidance, support, and mentorship throughout my master’s thesis journey. Your commitment, patience, and expertise have been instrumental in shaping the successful completion of my degree. Furthermore, I am grateful to you for creating a collaborative and nurturing environment that fostered creativity, critical thinking, and intellectual curiosity. You have helped me navigate the challenges within this research and helped me discover new perspectives.

I would like to acknowledge the support of the research team at APERIODIC. I’d especially like to extend my gratitude to David Smith, Torin Sammeth, and Nicolas Gonzalez Padilla. Their contributions and insights have enriched my work and without them, this research would not have been possible. The collaborative spirit and camaraderie within this team have made this journey even more rewarding.

To my parents—I am eternally grateful for the values and principles you have instilled in me. Your teachings of dedication and the importance of hard work have been invaluable in shaping my academic and personal growth. Thank you for being my role models.

I’d like to dedicate this master’s thesis to my husband and children, whose unwavering support and understanding have been the foundation of my success throughout this academic endeavor. To Daniel, your sacrifices and understanding of the demands of this journey have been truly remarkable, and I am immensely grateful to have you by my side. To my incredible children, your patience, understanding, and adaptability during the moments when my focus was on my studies are significant.

The following material was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525. Any thoughts, results, or recommendations within this thesis are those of the author(s), and they do not reflect the opinions of Sandia National Laboratories, Honeywell International Inc., or the U.S. Department of Energy’s National Nuclear Security Administration.
Progression of Surface Flashover in Vacuum with Polymer Insulators

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M.S., Electrical Engineering, University of New Mexico, 2023

ABSTRACT

In pulsed power devices, an insulator is needed to isolate the transmission line from vacuum chambers. Vacuum is used as the insulator because it contains no atoms. Since it is being used as an insulator in these pulsed power insulation systems, surface flashover in vacuum is one of the most extensively studied areas since it being the greatest constraint in providing power due to dielectrics that are not able to sustain the voltage the system is operating under. These dielectrics are used in between high voltage electrodes in various pulsed power applications as electrical insulators to limit the electric current while subjected to vacuum. Although, if the dielectric is exposed to a high enough voltage in vacuum, it will become electrically charged. There is a significant push in research and development to optimize surface flashover performance of insulation materials as breakdown can cause damage to the device.
Table of Contents

Acknowledgment ........................................................................................................ iii

ABSTRACT ................................................................................................................... iv

List of Figures .............................................................................................................. viii

List of Tables ............................................................................................................... xi

Chapter 1  Introduction ............................................................................................ 1

1.1 Background .......................................................................................................... 1

1.2 Existing Models and Developments .................................................................. 2

Chapter 2. Theoretical Background ....................................................................... 17

2.1 Electrical Breakdown ......................................................................................... 17

2.2 Electrical Breakdown in Vacuum ...................................................................... 18

2.3 Stages of Surface Flashover of Solids in Vacuum ............................................. 19

2.3.1 Initial Stage .................................................................................................... 19

2.3.2 Development (Growth) Stage ....................................................................... 24

2.3.3 Final Stage .................................................................................................... 25

Chapter 3 Experimental System ............................................................................ 27

3.1 Experimental Setup ............................................................................................ 27

3.1.1 Electrodes ..................................................................................................... 29

3.1.2 Marx Generator ........................................................................................... 30

3.1.3 Vacuum Chamber ....................................................................................... 36
3.1.4 Vacuum Feedthrough ................................................................. 37
3.1.5 Vacuum Pumps ................................................................. 38
3.1.6 D-dot Flange ................................................................. 40
3.1.7 Trigger System ................................................................. 41
3.1.8 Samples ................................................................. 48

3.2 Measurement and Diagnostic Procedures ................................................. 49
3.2.1 D-dot Probe .............................................................................. 49
  3.2.1.1 D-dot Probe Calibration .......................................................... 51
3.2.2 Current Viewing Resistor (CVR) ........................................... 59
3.2.3 Pressure in Marx Bank .......................................................... 61
3.2.4 Pressure in Vacuum Chamber ............................................... 63
3.2.5 Oscilloscope ............................................................................. 65

3.3 Analysis ......................................................................................... 67

Chapter 4 Results ............................................................................... 68
4.1 Experimental Process ........................................................................ 68
4.2 Experimental Results ........................................................................ 72

Chapter 5 Conclusion ........................................................................... 90
5.1 Discussion ..................................................................................... 90
5.2 Future Work .................................................................................. 91

List of Appendices ................................................................................. 95
Appendix A Calibration of D-dot Probe with Screen Room ........................................... 96
Appendix B: Surface Flashover Testing Procedure .............................................. 98
## List of Figures

*Figure 1: Angled Electric Field Due to Insulator's Shape [43]______________________________11*

*Figure 2: Effect of Truncated Cone Angle on Surface Flashover [36]_________________________12*

*Figure 3: Equipotential plots showing the effects of a void and graded relative permittivity. [11]____22*

*Figure 4: SEEA Theory for the Development of Surface Flashover Initiated by Cathode. [9]________26*

*Figure 5: Experimental Setup Schematic________________________________________________28*

*Figure 6: Insulator’s Position for Experiment___________________________________________28*

*Figure 7: Experimental Setup ________________________________________________________29*

*Figure 8: Circuit Schematic of Marx Generator ___________________________________________30*

*Figure 9: One Side of Spark Gaps ______________________________________________________31*

*Figure 10: 25 Stage Marx Generator with Each Stage Using Two Capacitors _________________32*

*Figure 11: Capacitors Connected to Marx Bank Skeleton ____________________________________33*

*Figure 12: Shunt Resistor and Termination Resistor ______________________________________34*

*Figure 13: Marx Generator Enclosed in Nylon Tube and Brass-Coated Steel Tube ____________35*

*Figure 14: Vacuum Chamber Affixed to Marx Generator ____________________________________37*

*Figure 15: SOLIDWORKS model of Vacuum Feedthrough _________________________________38*

*Figure 16: Agilent Technologies IDP-10 Dry Scroll Vacuum Pump [44]______________________39*

*Figure 17: Leybold TURBOVAC 350i Turbo Vacuum Pump [45]____________________________40*

*Figure 18: D-dot Flange to house D-dot Probe ____________________________________________41*

*Figure 19: Trigger Circuit __________________________________________________________________42*

*Figure 20: PVM North Star High Voltage Probe [46]_______________________________________43*

*Figure 21: Sorensen DCS 33-33 VDC Power Supply _________________________________________44*

*Figure 22: DG645 Digital Delay Generator. _____________________________________________44*

*Figure 23: Supplied signal from DG645___________________________________________________45*

*Figure 24: Trigger Output Waveform _____________________________________________________46*

*Figure 25: Calculating Jitter at 100 µs/division._________________________________________47*
Figure 26: Jitter calculation at 10 µs/division

Figure 27: D-dot Probe

Figure 28: Transmission Line Pulser

Figure 29: Pulser Connected to Anode Electrode

Figure 30: Tektronix 6015A High-Voltage Probe

Figure 31: Tektronix MS058 oscilloscope [40]

Figure 32: Circuit of Capacitive Voltage Divider [38]

Figure 33: Calibration Comparison of All Methods

Figure 34: Calibration Factor Generated using Method 2

Figure 35: T&M Research Products, Inc. CVR used [39]

Figure 36: Marx Bank’s Pressure Gauge and Gas Regulator

Figure 37: Agilent Technologies XGS-600 Vacuum Gauge Controller [41]

Figure 38: Ion Gauge [42]

Figure 39: Tektronix DSA 70604C 6 GHz Digital Serial Analyzer for Collection of Waveforms

Figure 40: Surface Flashover Event Occurring (Blue waveform is D-dot, Yellow is CVR)

Figure 41: Side Port Used to Insert Samples

Figure 42: LabVIEW Front Panel to Control Charge Voltage

Figure 43: Epoxy 828/DEA No Mold Release Test Shots

Figure 44: Epoxy 828/DEA 6.1mm Sample Test Shots

Figure 45: Epoxy 828/DEA No Filler SN004 Sample Test Shots

Figure 46: Epoxy 828/DEA No Filler SN005 Sample Test Shots

Figure 47: Epoxy 828/DEA No Filler SN006 Sample Test Shots

Figure 48: Epoxy 828/DEA No Filler SN007 Sample Test Shots

Figure 49: Zinc Infiltrated 1 PMMA Sample Test Shots

Figure 50: PMMA Un-Sanded Sample #32 Test Shots

Figure 51: Boron Carbide doped Epoxy 828/DEA Sample Test Shots

Figure 52: Epoxy No Mold Release Integrated D-dot Signals
Figure 53: Epoxy 828/DEA 6.1mm Integrated D-dot Signals ......................................................... 84

Figure 54: Epoxy 828/DEA No Filler SN004 Integrated D-dot Signals ........................................... 85

Figure 55: Epoxy 828/DEA No Filler SN005 Integrated D-dot Signals ........................................... 86

Figure 56: Epoxy 828/DEA No Filler SN006 Integrated D-dot Signals ........................................... 86

Figure 57: Epoxy 828/DEA No Filler SN007 Integrated D-dot Signals ........................................... 87

Figure 58: Zinc Infiltrated Integrated D-dot Signals ......................................................................... 88

Figure 59: Calibration of D-dot Diagram ......................................................................................... 97
List of Tables

Table 1: Marx Pressure and Marx Output for given Charge Voltage ........................................ 69
Table 2: Polymers Tested and Their Characteristics .................................................................. 73
Table 3: Maximum Breakdown Voltages per Polymer Sample Tested ........................................ 89
Chapter 1 Introduction

1.1 Background

With pulsed power systems, surface flashover can limit the maximum voltage that can be applied to the system. This reduces the system’s performance and can lead to catastrophic failure of the insulation material. Surface flashover can occur in high-power switches, such as spark gaps, which are commonly used in pulsed power applications. It can cause a significant reduction in the switch performance leading to decreased efficiency and increased heating of the device. Surface flashover can also lead to increased electromagnetic interference, which can affect the performance of other components within the system. Surface flashover can occur on the insulating surfaces of transmission lines, capacitors, and other high-voltage components and can lead to insulation breakdown, causing arcing and discharge between the electrodes which can damage the system and cause complete failure. Understanding the mechanisms and factors that affect surface flashover is imperative to design reliable and efficient pulsed power systems. With research, new insulation materials and techniques can be developed that can increase the breakdown strength of the system and prevent surface flashover from occurring.

Researching system parameters of surface flashover of solids in vacuum are crucial to understanding and controlling the occurrence. These parameters include the electrode geometry, applied voltage waveform, and the environment. By controlling these parameters, it is possible to control and optimize the breakdown voltage which is important for many applications such as high-power electrical switches, pulsed power systems, and particle accelerators. This phenomenon is also highly dependent on the
properties of the surface and material of the insulator.[1][3][10][11][20] These properties can include the surface roughness, chemical composition, and the presence of contaminants. Surface and material properties can influence the onset and progression of surface flashover by affecting the behavior of secondary electrons. There have been analyses highlighting the significance of surface conditioning and the effects of surface roughness, contamination, and material properties on flashover but the surface disintegration as a function of thickness has received little attention. [3]

This report contrasts the breakdown voltage of fabricated insulating samples with the geometry of truncated cones using experimental data. This experiment demonstrates how altering the material composition of these insulator samples can affect their voltage breakdown capability.

1.2 Existing Models and Developments

Research on surface flashover has been ongoing since the 1960s. Theoretical models have been developed to understand the mechanisms of electrical breakdown of solids in vacuum by surface flashover and to predict its occurrence under different conditions. These models typically involve numerical simulations of the electric field distribution and electron emission processes and can provide insights into the factors that influence surface flashover. The electron emission process that might result in surface flashover can be conceptualized by considering the Fowler-Nordheim (FN) effect, a quantum mechanical tunneling phenomenon that explains the field emission of electrons from a solid surface in the presence of an intense electric field and is given by the equation

\[
I(E) = \frac{1.54 \times 10^4 A \beta E^2}{\Phi} \exp \left( -\frac{6.84 \times 10^3 \Phi^2}{\beta E} \right)
\]

where \(E\) is the electric field, \(\Phi\) is the work
function of the material, $\beta$ is the field enhancement factor, and $A$ is the effective emitting area. Although the FN theory is typically associated with field emission, it can be useful in the modeling of surface flashover of solids in vacuum by simulating the current flowing across the surface during breakdown and estimating the magnitude of the field emission current, both of which can contribute to the formation and sustainment of the discharge. This model can explain how local electric field distribution and field enhancements play a part in the onset of breakdown. By taking into account the electron emission characteristics defined in the equation and the properties of the insulating material, the FN effect may also be utilized to estimate the beginning of the breakdown and foresee the breakdown voltage. Another model, although not directly applicable to surface flashover of solid insulators in vacuum, is Paschen’s law which relates the breakdown behavior of gases in the presence of various electric field strengths, pressures, and distances. Since ionization and electrical breakdown are aided by more collisions between gas molecules at higher pressures, the breakdown voltage falls with rising pressure and distance. Due to the high gas density in this area, ionization can take place at a relatively low breakdown voltage. As the pressure drops, however, the gas density drops with it, and there are fewer gas molecules to collide and ionize. Therefore, a stronger field is needed to cause a breakdown. This is why the x-axis of the Paschen curve is declined, but then the breakdown voltage rises at very low pressures. It is an important law for comprehending the processes of breakdown in gas-filled gaps or at the electrode-insulator interfaces. At greater pressures, Paschen’s law can be utilized to identify the maximum voltage for uniform field breakdown. Consistent with Paschen’s curve for a uniform field, results have shown that the flashover strength decreases as the
gap distance increases, however, it has been observed that the flashover strength decreased faster than predicted by Paschen’s curve which indicates that other factors such as the presence of surface irregularities and the emission of secondary electrons from the insulator surface are at play. [3]

Significant contributions have been made to the development and study of surface flashover in vacuum by mathematical models that accurately predict the probability of flashover under various conditions. [10] This has been made possible by advancements in computer modeling and simulation techniques, which enable researchers to examine the behavior of the electric field and electrical discharges in a more controlled and precise manner.[22][43] Establishing standard practices has been researched for setting up a system. [1][11][20] Such techniques involve applying an accurate insulator geometry, proper conductor selection for electrodes, a gas or vacuum setup, and resolutions for Laplace’s equation of electric potential and fields. In setting up such systems, mathematical equations are used to model and analyze the electric fields and potentials in the system consisting of insulators, electrodes, and gas or vacuum. Some researchers have simulated the system with a charge distribution, solving Poisson’s equation and predicting the behavior of the electric field and the formation of the plasma layer. [27] Poisson’s equation is also often used in numerical simulations of surface flashover, where it is solved along with other equations describing the behavior of the plasma layer and the solid surface. [26] These simulations aided in the comprehension of the spatial distribution of the electric field close to the solid surface during surface flashover. They demonstrated how the intensity of the electric field varies across the surface and how it interacts with the surrounding medium. The simulations also revealed that deep and
shallow traps in the solid surface layer influence the surface flashover voltage of epoxy composites, with shallow traps mostly affecting surface charge dissipation and deep traps primarily affecting electron emission. Also according to the simulations, the surface flashover voltage rises with increasing levels of deep traps, shallow traps, and carrier mobility but falls with increasing levels of charge and shallow traps on the surface.

By using high-speed photography and other advanced diagnostic techniques, other models have been devised to investigate the dynamics of surface flashover. [24] High-speed cameras can be used to capture rapid events during surface flashover. By recording the breakdown process at high frame rates, researchers can observe the evolution of the plasma discharge, the propagation of the breakdown along the surface, and the associated phenomena such as emission of light, plasma channel dynamics, and material damage. [25] Electric field sensors are also techniques that are being used in experiments to measure the electric field distribution near the surface during flashover. These sensors can provide information about the spatial and temporal variations of the electric field. [5] These advancements in diagnostic techniques aid researchers in gaining a deeper understanding of the physical processes involved in flashover and in identifying the primary factors that contribute to its occurrence. Several experimental methods for investigating surface flashover are evolving and design configurations are advancing to study the behavior of electrons in the breakdown region by measuring the electric field across the surface using high voltages.

Another significant step forward in surface flashover research has been the ability to differentiate surface flashover characteristics under a variety of voltage waveforms and experimental configurations. There was a need to understand whether the flashover
occurred in different ways and at various points for different kinds of applied voltage waveforms. An experimental model showed the effects of the voltage waveform on the surface and the relation to the field’s distribution over the surface of the insulator material. [20] During the initial and development stages, the applied voltage waveform’s properties may have an effect. The amplitude, polarity, pulse width, risetime, and any contributing harmonic or transient components are all aspects. The amplitude of the applied voltage is crucial because greater voltages provide stronger electric fields that might initiate the breakdown, causing surface flashover events to happen more likely. The polarity of the waveform that is applied has an effect on the direction that the electric field will take. It is possible that a positive polarity may be more conducive to flashover depending on the qualities of the insulating material and the design of the electrodes. However, in some cases, a negative polarity may be more favorable to flashover. The duration of the applied voltage pulse is another essential consideration because, if it is longer, it allows more time for the insulating material to recover from the localized breakdown and prevents the propagation of surface flashover. If the pulse is shorter, however, it provides less time for the insulating material to recover from the localized breakdown. When shorter pulses are used, there is a possibility that the material will not have enough time to recover, which will result in a surface flashover event. In addition, the rise time can facilitate the initiation of surface flashover. High electric field gradients can be produced via a rise time that is very fast. Compared to a slow rise time, sharp voltage spikes can also enhance the likelihood of surface flashover. Due to power supply faults or the presence of quick switching events, the applied voltage waveform may additionally include harmonics and transient components. Surface flashover is more
likely to happen because these extra factors amplify electric field distortions and produce localized areas of increased stress.

Identifying the causes of surface flashover of a solid in vacuum is a tough endeavor and knowing how to prevent electrical breakdown requires experimental models. A model was proposed that presented how surface flashover occurs within nanoseconds of a high-voltage application in a vacuum insulator, demonstrating a pre-breakdown avalanche for secondary emissions. [2][13] During the process of surface charging, a buildup of positive surface charges takes place at the cathode’s side of the insulator, also known as the negative electrode. The buildup of positive ions leads to an increase in the cathode’s side emission as well as the gas desorption or ionization rates in the region between the electrodes. This can lead to an enhancement of the electric field at the cathode side. Following this development of a higher electric field can result in a saturation of secondary electrons and then an electron avalanche. Modeling continues to advance with variations that improve the capacity for conducting fairly sophisticated experiments using complex setups. An involved design for a dielectric breakdown in a plane insulator-vacuum interface was used to demonstrate the initiation and suppression of multipactor discharge on an insulator, made of the material fused quartz, by a DC bias. [31] In such setups, as the electric field on the cathode end is enhanced, the probability of field emission from the cathode increases. This bolsters the cathode end electron emission, leading to a further increase in the cathode’s electric field. This feedback loop can lead to rapid growth in the electric field, eventually leading to the insulator’s dielectric breakdown. The critical electric field depends on insulator properties and the surrounding environment. Factors that can influence the high electric field include things
such as the type of insulator material, the temperature and pressure of the surrounding gas, and the presence of contaminants or surface defects. The role of secondary electron emission in propagating and amplifying the conductivity of the excited surface has been emphasized in foundational research. Elaborating on this phenomenon, experiments demonstrated that in the initiation phase, an insulator acquired positive charges at the cathode due to electrode bombardment from a cathode-insulator-vacuum junction.[12][13][16] Secondary electrons reattached to the insulator due to the charged area electric field helping elicit the flashover. A regenerative increase in the surface charge is seen during the flashover. When the flashover subsides, the surface stabilizes if the perpendicularly applied electric field remains fixed. [16]

In addition, research has been conducted to investigate the velocity at which the surface flashover takes place, also known as the propagation velocity. This type of study has led to the identification of the significant elements that determine the velocity of propagation. To have a better understanding of the flashover’s propagation velocity, an experimental study was carried out using cathode-initiated surface flashover. [29] This velocity is the speed at which a breakdown travels along an insulator surface. The speed at which discharges spread towards the anode was measured using a technique that measured in meters per second and utilized a polymethyl-methacrylate rode insulator that was subjected to high voltage pulses. The speed at which discharges spread was around $2 \times 10^7 \text{m/s/pulse}$. This value is the rate at which the discharge travels across the surface and suggests that the electrical discharge has a high velocity, indicating that the electrical phenomenon is propagating rapidly. If a surface flashover is induced by an electron avalanche, which is initiated by secondary electron emission on the insulator’s surface,
then this sort of velocity is typical. According to the findings of this study, the circumstances of a setup or excitation mechanism may also have an effect and influence the optimal propagation velocity that can be obtained. Variations in this velocity are one of the conditions that were tested in the experiment. If the mechanism of the flashover depends on secondary avalanche emissions, it is reasonable to anticipate that there will be rate variations in the propagation of the flashover. [7] [29]

It has also been discovered that the propagation of a cathode-initiated flashover is affected by several elements, such as the insulator geometry, field angle, surface roughness of the electrode, humidity and temperature of the air in the surrounding area, the applied voltage, and the material of the electrode. [1][2][3] The material of the electrode can significantly influence the propagation velocity. Electrodes that have a lesser electrical conductivity, such as steel or glass, tend to have slower propagation speeds. Electrodes that have a high electrical conductivity, such as copper or aluminum, tend to have higher propagation velocities. The roughness of the surface of an electrode can also affect the propagation velocity. Since the electric field will be more consistently spread across a smoother surface, this might result in a quicker propagation velocity. When the voltage that is supplied to the electrodes is increased, the electric field that is present at the surface of the electrodes becomes stronger, which may also cause the propagation velocity to increase.

Modeling has been done in order to gain an understanding of the changes to the insulator’s geometry, how the shape influences the fields in the location of the triple junction region, and how these modifications might improve the insulator’s performance. [1] The electric field is normally aligned with the insulator at an angle of zero orientation,
and it removes electrons from an insulator by drawing them away at positive angles. It has been argued that there are strategies to pick insulators for special applications as well as approaches to selecting the geometry of the insulator. The theory that was developed to explain the phenomenon indicated that the best explanation was that electrons might be released from the triple junction region and travel over the insulator surface, leading to a chain reaction and creating secondary electron emission avalanche. It has been demonstrated that the form of the insulator can have a substantial impact on its capacity to sustain high voltages without experiencing a flashover on its surface. Generally speaking, the breakdown voltages of insulators that have smooth, rounded shapes are higher than the breakdown voltages of objects that have complicated and sharp edges.

The electric field at the surface of the material is at its strongest at the insulator’s corners and edges, as well as other places of extreme curvature or discontinuity. When the electric field’s strength reaches a certain threshold, it is capable of ionizing the gas molecules located close to the surface of the insulator, therefore producing a pathway along the surface in which current can flow causing surface flashover. Using items with smooth, rounded shapes, such as cylinders, is one technique to lessen the possibility of surface flashover because of the smoothness and roundness. A cylinder’s smooth, continuous curvature distributes the electric field to move evenly over its surface, reducing the chances of a high electric field developing at any point. [1] The findings of several experiments have demonstrated that truncated cone shaped insulators are predominately utilized in high-voltage applications due to the numerous benefits associated with their electrical characteristics. [1][36] When compared to insulators with cylindrical form, insulators with this geometric shape are able to have a more progressive
variation in radius. This can result in a more uniform electric field distribution throughout the surface of the insulator, which can help mitigate field enhancements and lower the risk of surface flashover. When compared to insulators with a cylindrical form, those with truncated cone shape have the ability to give greater field stress grading. Field stress grading involves designing the insulator to gradually transition the electric field intensity from high-stress regions to low-stress regions. [43] The way in which the electric field changes depending on the shape of the insulator is seen in Figure 1. Having the insulator in the shape of a truncated cone will reduce the formation of secondary electron emission because the electric field will be angled with the surface, resulting in a higher flashover threshold. [43]

![Figure 1: Angled Electric Field Due to Insulator's Shape [43]](image)
A model was developed to show that the cone angle can also significantly affect an insulator’s breakdown voltage. As the cone angle expands, the electric field at the cone’s apex becomes stronger, increasing the flashover likelihood. Objects with smaller cone angles tend to have lower holdoff voltages than larger ones. It has been proved that positive $+45^\circ$ angle cones are able to sustain the highest voltage, thus having the highest flashover voltage. Figure 2 shows the effect the angle of the truncated cone insulator has on surface flashover. [3][12][36]

*Figure 2: Effect of Truncated Cone Angle on Surface Flashover [36]*
According to several research studies, the composition of an insulator plays a crucial role in determining the breakdown voltage. [11] Different materials have varying electrical properties that influence their breakdown characteristics. Contributing to the effects of the breakdown voltage are the dielectric strength, bandgap energy, electron mobility, and surface contamination. The dielectric strength of an insulating material is measured as the highest electric field that it can withstand for an extended period of time before sustaining an electrical breakdown. Dielectric strengths vary by material, and insulators with greater dielectric strength tend to have higher breakdown voltages. The amount of energy needed to transfer an electron from a material’s valence band to its conduction band is referred to as the material’s bandgap. Materials that have bandgaps that are wider tend to have higher breakdown voltages. This is because it requires a stronger electric field that can supply the necessary energy to free electrons from their bound states and allow them to escape to the conduction band, and take part in electrical conduction, resulting in the disintegration of the material and the formation of a conductive path, initiating the breakdown process. The speed at which electrons may flow through a material when exposed to an applied electric field is known as its electron mobility. Since they can withstand higher electric fields without succumbing to breakdown, insulating materials with high electron mobility often have a higher breakdown voltage. Lastly, over time, impurities can develop on the insulator’s surface which can decrease the breakdown voltage. Because of this, it is essential to think about the material’s electrical characteristics and run experiment models to determine which material can sustain the maximum applied voltage.
Semiconductor impurities in surface flashover have also been studied extensively as they can drastically alter the electrical breakdown of insulating materials. These inclusions refer to tiny particles or impurities that have the ability to conduct electricity and are found within the insulating materials. The inclusions can come in a variety of forms, including semiconductor particles, semiconducting impurities, or foreign materials that have properties of a semiconductor. Semiconductor materials have an electrical conductivity that falls between that of a conductor or that of an insulator. They can display a wide variety of electrical properties, which are determined by parameters such as doping, temperature, and applied voltage. Insulating materials may be contaminated by semiconductor inclusions in a variety of ways, including during the production process, as impurities in the raw materials, as a result of environmental contamination, or by purposely adding it to the insulator material. Their existence can have a considerable impact on the electrical behavior of insulating material, despite the fact that their sizes range from nanometers to micrometers. Numerous experimental studies have been conducted to investigate the effect of semiconducting inclusions on surface flashover. These analyses involve applying high voltage to samples of insulating materials containing various types and concentrations of inclusions and measuring their breakdown characteristics. Metallic inclusions such as copper, aluminum, and silver, have been used in experiments to determine their effects on surface flashover. Due to their high conductivity, metallic inclusions can substantially alter the electric field distribution which can result in localized field enhancements and charge concentration regions. Carbon-based inclusions such as carbon fibers are semiconducting or conductive and can induce localized field enhancements and charge accumulation, thereby also affecting the
flashover behavior of insulating materials. Organic inclusions have also been introduced and tested as they introduce impurities that can alter the breakdown strength of the insulating material.

The electric field can be affected by semiconductor inclusions by field enhancement, charge redistribution, electric field distortion, and composite materials. Inclusions of semiconductors often have distinct electrical properties from the surrounding insulating material, including differing permittivity or conductivity. As a result of these variations, electric field strengths can be concentrated in specific regions. Concentrations of the electric field around the inclusions increase the voltage gradients in those regions when a high voltage is applied. Because this field enhancement encourages electric breakdown at the inclusion-insulation interface, it can increase the likelihood of surface flashover. The distribution of charges inside the insulating material can be altered by the presence of semiconductor inclusions. Inclusions could store or trap charges depending on their electrical properties. High voltages can cause charges to build up on or near the inclusions’ surfaces. This redistribution of charges can disrupt the uniformity of the electric field, leading to charge concentration regions. The existence of semiconductor inclusions can distort the electric field distribution at specific locations. The presence of semiconductor inclusions can result in local variations in the distribution of the electric field. The inclusions’ diverse electrical properties can alter the equipotential contours and electric field lines within the insulating material. These distortions can generate regions of higher or lower electric field intensity, thereby affecting the breakdown characteristics. The influence of semiconductor inclusions on the electric field is dependent on a number of factors such as the size, concentration, distribution, and electrical properties of the
inclusions, as well as the overall geometry and configuration of the insulating material. The interaction between these variables determines the ultimate effect on the electric field and the probability of surface flashover.

While semiconductor inclusions usually do not optimize the performance of insulators in surface flashover, there are certain situations where the deliberate addition of semiconductor inclusions can be used to engineer specific properties in insulating materials. Controlled doping, or modification, is done by carefully selecting the type, concentration, and distribution of semiconductor inclusions. By doing this, it is possible to tailor the electrical behavior of the insulator for certain applications. Controlled doping of insulating materials with semiconductor inclusions can be utilized to enhance charge transport properties, reduce space charge effects, or modify the breakdown characteristics. These engineered inclusions can help in achieving desired electrical properties, such as improved breakdown voltage, reduced electrical losses, or enhanced insulation performance in specific-operating conditions.
Chapter 2. Theoretical Background

In order to acquire a greater comprehension of the processes involved in the surface flashover of solids in vacuum, it is advantageous to review the fundamental principles. An introduction to the basic concept of electrical breakdown and a concise summary of electrical breakdown in vacuum are both provided in this theoretical background section. The final part of this section discusses the theory on the stages of surface flashover of a solid in vacuum. When selecting an insulator for a specific application, having foundational knowledge of these mechanisms will make it reasonable to analyze the necessary alterations that are required to improve the breakdown voltage of the insulating material. This will allow for greater flexibility in the use of the insulator.

2.1 Electrical Breakdown

Electrical breakdown is a phenomenon that occurs when the electric field strength in a medium exceeds a certain threshold value. There are various mechanisms of electrical breakdown in gases, solids, and unique characteristics of electrical breakdown in vacuum. The breakdown process leads to the flow of current, which can cause damage to equipment or even pose a safety hazard. Understanding the mechanisms of electrical breakdown is critical in developing effective mitigation strategies and designing reliable electrical systems. In gases, electrical breakdown can occur through various means, including streamer breakdown and Townsend avalanche breakdown. Townsend Avalanche breakdown occurs when electrons gain enough energy to ionize additional atoms or molecules, resulting in a cascade of ionization events and is given by the equation

\[ i = \frac{i_0 e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)} \]

where \( d \) is the gap spacing, \( \alpha \) is Townsend’s first ionization coefficient, and \( \gamma \) is Townsend’s coefficient of secondary electron emission from ion
bombardment. Streamer breakdown occurs when a localized ionization event propagates through the gas, resulting in a conductive channel. In solids, electrical breakdown can occur through mechanisms such as dielectric breakdown, thermal breakdown, and breakdown due to electron emission. Dielectric breakdown occurs when the electric field strength exceeds the dielectric strength of the material, resulting in the formation of a conductive path through the material. Thermal breakdown occurs when the material undergoes thermal breakdown due to the Joule heating effect of the current flowing through it. Breakdown due to electron emission occurs when electrons are emitted from the surface of the material due to high electric fields.

2.2 Electrical Breakdown in Vacuum

Due to its importance in numerous applications, including vacuum electronics, particle accelerators, and space propulsion, electrical breakdown of a solid in vacuum is a complex phenomenon that has been extensively investigated. The process involves the creation of a plasma within the solid due to the application of an electric field, leading to the formation of a conducting channel that can significantly affect the material’s properties. In this paper, we review the current state of knowledge on electrical breakdown of solids in vacuum, including experimental observations and previously reviewed theoretical models in Section 1.2. Experimental observations have shown that electrical breakdown of solids in vacuum can occur through a primary mechanism called surface flashover. [1][3][5][9][13][14][36] Another means of electrical breakdown of solids in vacuum is bulk breakdown but within this report, the primary focus is on surface flashover as a way of electrical breakdown of a solid in vacuum. Surface flashover of solids in vacuum occur through the accumulation of charge, in this case the formation of
an electron avalanche, on the surface of an insulator due to the initiation of an applied high electric field. The electric field causes the emission of electrons from the surface of the insulator due to field emission, but this would normally only happen at locations of highly concentrated electric fields such as sharp edges or tips. These electrons collide with other atoms or molecules in the gas phase and ionize them, leading to the formation of an electron avalanche. This buildup of charge from the electron avalanche can lead to the formation of a high-density plasma layer that serves as a conducting path for current to flow through that can bridge the gap between the two electrodes. The electrical breakdown, also called breakdown voltage, of a solid insulator depends on various factors such as gap distance, gap pressure, insulator material, and the geometry of the insulator and electrode as discussed in the background section of this report.

### 2.3 Stages of Surface Flashover of Solids in Vacuum

There are three main stages of surface flashover of solids in vacuum: initiation, development, and final. Although there is a widespread consensus on the initiation and final stages, there is a great deal of controversy still about the hypothesis of the development stage (second stage). [11]

#### 2.3.1 Initial Stage

Understanding the initial stage of surface flashover is crucial for designing and optimizing high-voltage insulation systems. Numerous studies have investigated the emission properties of insulating materials and their relationship to surface flashover under different conditions. [1][3][5][9][13][14][36] As previously mentioned, the Fowler-Nordheim theory is the most common theory used to explain electron emission from metals and insulators in high electric fields and explain the onset of surface flashover in...
solid insulators under vacuum conditions. At these high electric fields, according to the Fowler-Nordheim theory, the effect causes electrons to escape from the conduction band of the material through the surface potential barrier. These emitted electrons generate a space charge on the top of the surface. With electrons being emitted, there is an increase in the intensity of the electric field. This can lead to a self-sustained discharge that causes surface flashover. Because the breakdown strength of vacuum is extremely high and only a small number of electrons are required to generate a significant space charge that can contribute to a breakdown, the Fowler-Nordheim theory is particularly relevant to surface flashover in vacuum. Several studies have used this theory to explain surface flashover in vacuum and have shown that it provides valuable insights into the mechanisms behind surface flashover of solid insulators in vacuum and can be used to optimize the design of pulsed power systems that involve the use of insulating materials. [23]

The triple junction region is considered the start of the initiation of surface flashover. This interface is where the vacuum, solid insulator, and the cathode electrode come to a point. In this region, a combination of high electric field strength and local field enhancements can lead to the emission of electrons from the surface. This region is usually where the electric field is the strongest and the probability of electron emission is the greatest. The geometry of the triple junction region strongly influences the flashover behavior; with sharp edges and points that are particularly prone to emission. It is possible for an electron emission to take place whenever the voltage of the electrode is raised. When the electrode potential is elevated a point where it generates an electric field that is strong enough, the potential barrier is breached, and electrons are released from the triple junction region into the surrounding vacuum chamber. It has also been determined
through research that the link between the dielectric constant, $\varepsilon_r$, and the breakdown voltage is directly related to the insulator’s permittivity. [11] When two regions with differing dielectric constants come into contact with one another, the equipotential lines move from the region with the higher dielectric constant to the region with the lower dielectric constant. The ratio of the two dielectric constants is what determines the magnitude of this shift. As can be seen in the equipotential line plots of the triple junction region in Figure 3, this results in the formation of a void that is dependent upon the permittivity of the insulator.
The equipotential lines in the top image are consistent, which demonstrates that the electric field’s distribution and strength are also consistent across the depiction. This is the ideal interface. The most practical case is in the center diagram which has a small void that is introduced, and the equipotential lines in the region where more intense electric fields have been drawn in closer proximity to one another. The bottom picture reveals that there is a small void and an excessive rise in the dielectric constant. This
causes the equipotential lines to move away from the region of the triple junction. Having the equipotential lines farther apart means there would be a weaker electric field and would increase the performance of the insulating system by making the breakdown voltage value higher. [11]

Secondary electron emission plays another crucial role in the initial development of surface flashover. When a high electric field is applied to the insulator surface, it can cause the emission of electrons from the surface due to field emission. These electrons can then accelerate in the strong electric field and collide with the insulator’s surface, causing the ejection of secondary electrons. These secondary electrons can then further be accelerated by the electric field, leading to a cascade effect where more and more secondary electrons are emitted from the surface. This process can create a secondary electron emission avalanche that leads to a significant increase in the local electric field near the surface of the insulator. The presence of these secondary electrons can significantly increase the threshold electric field required for surface flashover to occur. The energy of the collision and the work function of the material both have a role in determining whether or not an electron will be ejected from the material. Depending on the energy of the primary electron’s collision with the insulator’s surface, either the energy is dissipated, or secondary electron emission occurs. If the energy of the primary electron falls below the required work function for exciting or ionizing the surface atoms or molecules, the energy will be dissipated. Nevertheless, if the energy of the primary electron exceeds the work function of the insulator’s material, the excess energy of the primary electron is transferred to the desired atom, thereby elevating one of its electrons to a higher energy level or removing an electron entirely, resulting in the emission of a
secondary electron. The work function of a material is the minimum energy required for
an electron to flee the surface of a material and produce a secondary electron. The work
function is dependent on properties of the material including the composition, crystal
structure, and surface conditions of the material. Since materials with lower work
functions require less energy to liberate an electron, they are inadequate in the use of
preventing surface flashovers. The secondary electron yield (SEY), represented by the
symbol δ, quantifies the effectiveness of the secondary electron’s procedure. The SEY
parameter, δ, can range from zero to greater than one, with equal to zero indicating that
no secondary electrons are emitted for each incident primary electron and δ equal to one
indicating that, on an average basis, one secondary electron is emitted per incident
primary electron. In some situations, δ can be less than one; this typically occurs when
the energy of the primary electron is below the work function or when secondary
electrons are lost via absorption, recombination, or other surface processes. SEY can alter
based on variables such as the material’s properties, the surface’s condition, and the
energy and incidence angle of the primary electron.

2.3.2 Development (Growth) Stage

It is generally agreed that the second stage of surface flashover of a solid in vacuum is
the most contentious of the three stages. This report is based on the saturated secondary
electron emission avalanche (SSEEA) theory presented by Boersch et al. [14] When the
secondary electrons are emitted, the surface of the insulator where the electrons escape
take on a positive charge. This increases the likelihood that the secondary electrons will
strike the surface again, resulting in the emission of more secondary electrons for each
primary electron, leading to an avalanche-like multiplication effect. These secondary
electrons being accelerated by the electric field can cause a secondary electron emission avalanche (SEEA). The secondary electron emission avalanche will continue to increase until it reaches a saturated state at which point it will transform into a saturated secondary electron emission avalanche (SSEEA).

2.3.3 Final Stage

Secondary electron emission avalanche can lead to the formation of a plasma layer that develops close to the surface of the insulator. This plasma causes a significant spike in the surface conductivity, thereby facilitating the progression of surface flashover. With the collision of electrons on the insulator’s surface, free gas molecules are also able to escape. As stated previously, when the high-energy primary electrons interact with the insulator’s surface, they transfer sufficient energy to surface atoms or atoms, causing them to break bonds and escape into the surrounding vacuum as gas molecules. More electrons are attacking the surface of the material as a result of the saturated secondary electron emission avalanche. This knocks off more gas molecules that were adsorbed on the insulator’s surface, which ultimately results in gas molecules becoming more prominent. Following this, the released electrons are able to ionize the molecules of the gas, which results in the production of a plasma. As soon as this plasma is created, it transforms into a conductive state and is able to aid in the passage of current. Electrical breakdown can then take place as a result of the plasma being able to bridge the gap between the two electrodes or traverse over the insulator’s surface. The development of this idea of surface flashover can be viewed below in Figure 4. [9]
Figure 4: SEEA Theory for the Development of Surface Flashover Initiated by Cathode. [9]
Chapter 3 Experimental System

3.1 Experimental Setup

The apparatus that was used to test for surface flashover consisted of a Marx bank generator that can supply a 500kV, 40ns pulse. Above the Marx bank is a vacuum chamber that is capable of getting the vacuum level into the “high vacuum” fifth range ($10^{-5}$ Torr) by using a scroll pump in conjunction with a turbo pump. Separating the vacuum chamber and Marx bank is an insulating vacuum feedthrough. The chamber walls that are considered grounded are separated from the different pressures and the high voltage anode by a vacuum feedthrough made out of Ultem material. To test a sample, an insulator is installed between the anode and cathode electrodes within the vacuum chamber and the linear motion feedthrough is adjusted so the cathode electrode sits on top of the insulator as shown in Figure 6. When the desired pressure is attained, the insulator is stressed with a high voltage pulse supplied by the Marx bank that is controlled by a trigger circuit. To monitor the system’s current response, a current viewing resistor (CVR) purchased from T&M research product is fed through the bottom of the Marx to measure the output. To monitor the voltage of the insulator, a D-dot is contained in a flange that is flush with the vacuum feedthrough walls and is positioned in line with the base of the anode electrode. These two devices were connected to an oscilloscope so that the waveform signals could be observed to determine if a surface flashover occurred or not.
Figure 5: Experimental Setup Schematic

Figure 6: Insulator’s Position for Experiment
3.1.1 Electrodes

Stainless steel electrodes were used to test for surface flashover, with the bottom plate serving as the anode electrode and the upper plate serving as the cathode electrode. The cathode electrode is connected to a linear motion feedthrough so that the cathode plate’s position can be manually adjusted to accommodate varying insulator heights. Polishing of the anode and cathode electrodes was done to ensure that neither had any impurities on their surfaces that may affect the transmission of electrons and alter the results. The
material of the electrodes should have high electrical conductivity, low electron emission, and high melting points. The most common materials used for electrodes include copper, tungsten, stainless steel, and aluminum. In some cases, special coatings, or treatments to the surface of the electrodes may be used to improve their performance or reduce any unwanted effects. It’s been observed that if an insulator is in between the electrodes, the material of the electrodes has no effect on the breakdown voltage. For this purpose, 18.8 stainless steel electrodes were used for the experiment within this paper. [19]

3.1.2 Marx Generator

A Platts-designed Marx bank generator was utilized to stress the insulator samples by applying high intensities of pulsed voltages. [18] A circuit schematic of the Marx is shown in Figure 8. The Marx bank consists of 25 spark-gap switched stages; Figure 9 depicts one side of the Marx with one-half of the brass acorn nuts that are used for spark gaps.

![Figure 8: Circuit Schematic of Marx Generator](image)
As depicted in Figure 10, each stage contains two ceramic high voltage 272K Murata doorknob 2700 pF capacitors which are rated up to 40,000 volts of direct current.
As displayed in Figure 11, the capacitors are affixed to the Marx insulating skeleton using brass acorn nuts.
This insulating skeleton of the Marx consists of two sections that are held together by plastic fastener screws. The capacitors are charged resistively through high-voltage resistors each with a resistance of 1000 ohms. Each of these resistors attaches to the capacitor adjacent to them. The Marx bank is terminated into a 298-ohm sodium carbonate solution resistor that is connected in series with the anode electrode through the use of a connector blanking plug. The shunt resistor is 589 ohms and is connected in parallel with the water resistor.
Once constructed, the Marx bank is encased inside a nylon sleeve. The nylon sleeve is then enclosed within a brass-coated steel tube with a sealed base using threaded screws.
Using this encasement, the Marx generator can be pressurized up to 60 PSI. In order to pressurize the Marx bank in the tube, either ultra-zero air or nitrogen gas was used.
3.1.3 Vacuum Chamber

The Marx bank is connected to the vacuum chamber that has an 8-inch diameter at the connection point by means of the vacuum feedthrough and connector piece. The whole inside of the chamber has five access points. A conflat serves as the connection between the linear motion feedthrough and the top port of the vacuum chamber. This apparatus is in charge of regulating where the cathode plate is positioned inside the vacuum chamber in order to carry out testing on insulators of varying heights. The vacuum chamber has side port apertures that each have a diameter of 6 inches, and they are located on the chamber’s sides. The ion gauge and the turbo pump each take up residence in one of the chamber’s side opening ports. The insulators may be loaded and unloaded into and out of the vacuum chamber using another side port that has a fast access entrance door conflat flange. Additionally, this port features a wide window that can be used to perform imagining diagnostics. The other two side ports are both conflats, one of which is a fixed blank and the other which has a tiny window that is insufficient for imaging diagnostics. In order to keep the vacuum seal intact, a vacuum O-ring seal made of Viton is used on the inner sealing groove between the ultem and the D-dot flange. This seal also enables a vacuum seal that is created to be airtight between the low-pressure and high-pressure parts. To attach the vacuum chamber to the top of the Marx bank, long threaded screws were utilized for this connection.
3.1.4 Vacuum Feedthrough

In order to separate parts of the apparatus that have different pressures while also enabling the voltage pulse to stress the insulator while it is in a vacuum, it is necessary to have a vacuum feedthrough made from a material that has great electrical properties. The material was made from the thermoplastic, Ultem, since it has a high dielectric strength and stability. This separation takes place between the Marx bank and the vacuum chamber. A connector is attached to the Marx bank so the vacuum chamber can be attached to the Marx bank. Through threaded holes on the vacuum feedthrough, the high voltage anode is attached to the Marx bank and isolated from the grounded walls of the vacuum chamber. This also seals the top of the Marx bank brass-coated tube that enables a vacuum seal that is airtight and separates the low-pressure and high-pressure parts.
Figure 15: SOLIDWORKS model of Vacuum Feedthrough

3.1.5 Vacuum Pumps

Since it is difficult for a single pump to bring the pressure down from the atmosphere pressure, two pumps were used in different stages to get the pressure range of high vacuum. Using these pumps with the combination of eliminating any leaks from seals and gaskets, the vacuum chamber was able to get down to the fifth range \(10^{-5}\) Torr. During the first stage of the procedure, an Agilent IDP-10 dry scroll pump was utilized in order to bring the pressure down to a level that was equivalent to a low vacuum range.
When this level of vacuum is accomplished, the process is moved to the second stage, which uses a Leybold TURBOVAC 350i turbo vacuum pump to bring the pressure into the high vacuum range.
3.1.6 D-dot Flange

An aluminum flange was designed in SolidWorks and then machined to contain the D-dot sensor used to measure the voltage of the insulator. The flange allows the D-dot to be flush with the interior of the vacuum chamber and aligns it with the base of the anode electrode. A vacuum O-ring seal made of Viton is used on the inner sealing groove between the ultem and the D-dot flange and another one between the D-dot flange and
the vacuum chamber base to maintain the vacuum seal. In addition to creating an airtight vacuum seal between the low-pressure and high-pressure components, these seals help eradicate any leakage to achieve high vacuum pressure levels.

Figure 18: D-dot Flange to house D-dot Probe

3.1.7 Trigger System

The Marx bank is controlled by a trigger circuit affixed beneath the frame that supports the Marx bank. The Marx bank’s initial spark gap stage is a trigatron. This spark gap switch with a trigger is intended to supply the high voltage discharge to the load. A circuit connects a trigger pin to a digital delay generator. Figure 19 depicts the components of this circuit: a Holley EFI Smart Ignition coil, a voltage regulator, a toroid, a 10-ohm resistor, a .1F capacitor, a digital delay generator, and a DC power supply.
A DC programmable switching supply was utilized in order to provide the trigger circuit with the necessary 14VDC that is required to supply it. The toroid is installed in the circuit so that it may function as a choke, which filters out high-frequency noise while allowing the circuit’s desired DC (direct current) to go through it. A positive voltage regulator with three terminals is utilized here in order to accomplish the task of voltage regulation. Because this voltage regulator is intended to maintain a constant voltage, the output voltage will be 12V (give or take 0.5V) regardless of the input voltage, which can be as high as 35V at its highest point. In the event that it is subjected to an excessive amount of power, this type of voltage regulator is equipped with safety features that will immediately cut power to the circuit. The ignition coil has a current limiting resistor that
has a resistance value of 10 ohms. The addition of the .1F capacitor, which is connected in series with the resistor, was done so that the transient responsiveness may be enhanced.

A high voltage probe was attached to the output of the ignition coil so that the operating properties of the trigger could be measured and documented. The PVM-5 North Star High Voltage Probe, which can be seen in Figure 20, was the one that was utilized. This probe has a maximum pulsed voltage of 60 kV, a bandwidth response of 100-110 MHz with risetime around 3ns, and standard divider ratio of 1000:1.

Figure 20: PVM North Star High Voltage Probe [46]

Figure 21 depicts the Sorensen DCS 33-33 power supply used to furnish the circuit with 14VDC. The high current switched +12V power pin of the coil was brought down to 12VDC using an STMicroelectronics 1 linear L7812CV 1.5A voltage regulator, as shown in the figure of the trigger circuit schematic above.
According to the datasheet for the Holley EFI smart coil, in order to trigger the coil, one would need to supply a signal that is 5V and has a pulse that is 4 to 5 milliseconds long. It became apparent that a pulse width of 4.5 milliseconds was the optimal amount for achieving reproducible outcomes. As a result, the Stanford Research Systems DG645 Digital Delay Generator, which is seen in Figure 22, was utilized to generate a signal with a voltage of 5 volts and a pulse duration of 4.5 milliseconds, as can be seen in Figure 23.
In order to see the pulse, an RG-223 cable was connected directly from the DG645 Digital Delay Generator to the Tektronix DPO7254 2.5GHz digital oscilloscope using the Tektronix DPO7254. A 4.6-meter RG-223 cable was used to make the connection between the Tektronix PVM-5 North Star High Voltage Probe and the Tektronix DPO7254 2.5GHz digital oscilloscope. In order to maintain the accuracy of the probe’s calibration, the length of the cable that was utilized did not deviate from the standard deviation of 0.5% per foot. On the DPO7254 digital oscilloscope, the PVM-5 North Star High Voltage Probe was made to have an impedance of 1 Megaohm so that it could be terminated. The peak voltage is specified to be 44kV in the datasheet for the Holley EFI High Performance Coil-Near-Plug Smart Coil P/N 556-112. The output waveform of the
trigger coil is seen in Figure 24, and this waveform has an output pulse width of about 320 microseconds, a rise time of 22 microseconds, and a peak voltage of 42.84 volts. The peak voltage, when using the usual division ratio of 1000:1, is around 42.84 kV, which corresponds exactly with the datasheet for the coil.

![Figure 24: Trigger Output Waveform](image)

In order to get an accurate reading of the jitter, the Tektronix DPO7254 2.5GHz digital oscilloscope was configured to initiate from the Stanford Research System DG645 Digital Delay Generator’s output signal. It is presumed that the DG645 Digital Delay Generator has high precision and very low latency. In order to measure consecutive shots, the DPO7254 digital oscilloscope’s FastFrame function in the Acquisition portion
supplied a frame duration of 100. Normal mode was configured for the FastFrame source to activate from the DG645 Digital Delay Generator. The mode operation for the DG645 Digital Delay Generator was set to Burst. The Burst commands were configured to tally 100 times per second. Based on Figures 25 and 26, the measured deviation is approximately 1ns for 50% and 3ns for peaks.

![Figure 25: Calculating Jitter at 100 µs/division.](image-url)
3.1.8 Samples

Manufactured samples of various polymers were supplied by Sandia National Labs. The samples were delivered to UNM’s APERIODIC lab wrapped in cloth and sealed individually in plastic zip bags. Powder-free gloves were used to handle the samples, and lint-free Kimwipes were used to protect the surface when handling. The Kimwipes were also used with isopropyl, hexane, or ethanol, depending on the bulk substance being examined, to clean the sample before each sample shot. Samples of rexalite were cleaned with ethanol, boron carbide and epoxy samples were cleaned with
ethanol, whereas hexane was used to clean acrylic. A dopant was present in several samples, with amounts ranging from 5% to 25%. The insulator samples ranged in size from 47 to 50.8 millimeters in diameter at their bases and had a height of 6 to 8 millimeters.

### 3.2 Measurement and Diagnostic Procedures

The experiment has been set up with a variety of instruments in order to take accurate readings of the pressure in the vacuum chamber, the pressure in the area surrounding the Marx bank, and the waveforms on the oscilloscope that are produced by the D-dot sensor and the current viewing resistor (CVR). These readings are necessary for not only the success of the experiment but for validation if a surface flashover occurs. A description of these instruments can be found in this section.

#### 3.2.1 D-dot Probe

Sandia National Laboratories lent a capacitive electric field sensor known as a D-dot so that high-voltage measurements of the insulating sample could be taken. Images of this high frequency sensor is shown in Figure 27.
Figure 27: D-dot Probe

This highly accurate and essential probe was utilized for the purpose of determining the magnitude of the electric field that was present in the region encompassing the anode electrode and the insulator. The sensor implements the capacitance principle, in which the electric field alters the capacitance of the sensing element. Alterations in capacitance are converted into an electric signal, which is then processed and measured on an oscilloscope. Since the D-dot waveform represents the rate of change of voltage with
respect to time, integration was necessary to ascertain the actual amplitude and details of how this was achieved in this experiment are provided in a subsequent section.

3.2.1.1 D-dot Probe Calibration

D-dot probes, like most sensors and measuring systems, need to be calibrated. This is a crucial part as it ensures the measurement provided by the D-dot is accurate and reliable. By comparing the sensor’s output to the calibration source, any systematic errors or deviations can be detected and corrected. To calibrate the D-dot provided by Sandia National Laboratories, a transmission line pulser was used and is shown in Figure 28. [37]
This transmission line pulser was connected to the anode electrode as displayed in Figure 29.
To measure the waveform it provided to the electrode, a Tektronix P6015A High-Voltage Probe (Figure 30) with a probe factor of 1000:1 was also connected to the anode electrode. To observe the output waveform, the P6015A High-Voltage Probe was connected to a Tektronix MS058 oscilloscope and can be seen in Figure 31.

*Figure 29: Pulser Connected to Anode Electrode*
Figure 30: Tektronix 6015A High-Voltage Probe

Figure 31: Tektronix MS058 oscilloscope [40]
For calibration of a D-dot, start by taking a circuit diagram of a capacitive voltage divider (Figure 32)

Looking at the theoretical output of the capacitive divider given by the following equation [38]

\[
\frac{dV_{in}}{dt} = \left(\frac{C_1 + C_2}{C_1}\right)\frac{dV_{out}}{dt} + \frac{V_{out}}{C_1 R_s}
\]

To reconstruct the original signal \(V_{in}\) (measured by the P6015A High-Voltage Probe) from \(V_{out}\) (measured by the D-dot sensor) we must integrate this equation

\[
\int_0^t \frac{dV_{in}}{dt} \, dt = \int_0^t \left(\frac{C_1 + C_2}{C_1}\right)\frac{dV_{out}}{dt} \, dt + \int_0^t \frac{V_{out}}{C_1 R_s} \, dt
\]
This yields two different components of the input signal, a derivative portion, and a linear portion

\[ V_{in} = \left( \frac{C_1 + C_2}{C_1} \right) V_{out} + \int_0^t \frac{V_{out}}{C_1 R_s} dt \]

The first portion is the linear signal associated with the low bandwidth portion of the probe, while the second portion corresponds to the derivative portion of the signal. Due to the fact that the capacitor values are unknown, and the calibration is dependent on a measured signal, these variables are transformed into arbitrary constants in order to solve

\[ V_{in} = A V_{out} + B \int_0^t V_{out} dt \]

Taking into consideration any offset issues on the output signal, including an arbitrary DC offset in the output signal was accounted for

\[ V_{in} = A(V_{out} + C) + B \int_0^t (V_{out} + C) dt \]

Multiplying through and simplifying further

\[ V_{in} = A V_{out} + AC + B \int_0^t V_{out} dt + B \int_0^t C dt \]

\[ V_{in} = A V_{out} + AC + B \int_0^t V_{out} dt + BCt \]

Reconstructing the input signal from the output signal is a summation of four different test functions multiplied by four different constants as seen

\[ V_{in} = A V_{out} + B \int_0^t V_{out} dt + Ct + D \]
This is a system of linear equations with test functions that have been measured and given. This can simply be solved with the use of a least-squares method (LSQR) to find the optimal coefficient values to reconstruct the original signal. The test functions are the original measured signal, the numerical integral of the measured signal, the time array, and a constant 1. In reality, with a high bandwidth D-dot, the most likely values are that \( B \gg A, C, D \).

To calibrate, the D-dot signal waveform was compared to the transmission line pulser by simultaneously measuring the signal waveform of the D-dot sensor and the output waveform of the P6015A High-Voltage Probe. To facilitate calibration, a MATLAB program was developed to evaluate three distinct calibration methods. Before integrating, the first calibration method subtracted the DC offset and then divided the peaks to determine the calibration factor. After removing the DC offset, the least-squares method (LSQR) algorithm was implemented to calculate the calibration factor in the second calibration method. Using the LSQR MATLAB function, the third calibration procedure solved for all four calibration factor values. The program utilized both the raw D-dot signal (taking into account any attenuation) and the signal generated by the P6015A High-Voltage Probe. The DC offset was taken into consideration; the mean of the raw D-dot signal was subtracted from the raw D-dot signal to generate a new signal. The same DC offset was considered when generating a new signal for the high-voltage probe signal. It was matched to 250 nanoseconds to concentrate on the signal’s leading edge. Figure 33 illustrates a comparison of each method. Since calibration 2 is closer to the mean than calibration 1 (which only matches the peaks), it is more accurate. The third calibration is impractical because it requires four variables with two of those variables
varying shot-to-shot making it difficult to calculate an average calibration factor to apply in postprocessing.

Figure 33: Calibration Comparison of All Methods

As depicted in Figure 34, a calibration factor was generated using calibration two. The average calibration factor that was obtained on this date was 9.69E12. This calibration factor is utilized to rectify the measurements obtained from the D-dot sensor’s output. By multiplying the measured output signal value from the D-dot sensor by the calibration factor, the value is adjusted to reflect the actual signal value, which will be presented in Chapter 4. It should be noted that regular calibration was performed when the Marx was
disassembled (for cleaning) and reassembled to assure the D-dot’s continued accuracy and dependability. Appendix A has a breakdown of the procedure that was followed.

![Figure 34: Calibration Factor Generated using Method 2](image)

### 3.2.2 Current Viewing Resistor (CVR)

To measure the Marx circuit’s current flow, a passive electronic component called a current viewing resistor (CVR) was used. The CVR used was a tubular geometry purchased through T&M Research Products, Inc. in Albuquerque, NM. The output connector was the standard BNC after taking into consideration of the frequency response.
and the resistance value is 0.005 ohms. While this will introduce a small amount of resistance into the circuit, the resistance value was chosen carefully to minimize its impact on the circuit’s performance. This simple but essential component consists of a resistive element that is designed to have a low temperature coefficient and high accuracy is housed in a metal enclosure that provides electrical insulation and mechanical protection. The housing has a mounting mechanism that made it easy to install at the base of the Marx. It operates by producing a voltage decrease proportional to the current flowing through it, which is then measured by connecting the CVR to an oscilloscope through an RG-223 coaxial cable. To get accurate data on the output of the Marx bank, the CVR was connected in series with the Marx. The voltage measurement can then be used to calculate the current flowing through the circuit using Ohm’s Law, which states that the current is equal to the voltage divided by resistance \( I = \frac{V}{R} \).
3.2.3 Pressure in Marx Bank

When the Marx bank is in operation, it can produce extremely high voltages, which can cause electrical breakdown and arcing in capacitors, resistors, or a spark gap. This can lead to a loss of efficacy, can damage capacitors and other circuit components within the Marx bank, and make it unachievable to reach high charging voltages to test the insulator samples to their full potential. The atmospheric pressure where the experiment was done, in Albuquerque, NM, is roughly 670 Torr and can fluctuate depending on the day. When keeping the Marx bank at atmospheric pressure, the Marx
will discharge around 10 kV without the use of the trigger pulse which is not efficient for testing surface flashover. In order to experiment on the insulating samples at higher charge voltages, the Marx bank needed to be pressurized. Pressurizing the tube surrounding the Marx bank with either nitrogen or ultra-zero air was done to improve the performance and reliability of the Marx bank by decreasing the likelihood of electrical breakdown. Pressurizing the Marx bank can also enhance the output pulse’s uniformity. This is due to the fact that there will be a more consistent discharge when capacitors are pressurized because the gas within them aids in an evenly uniform distribution of electrical energy.

A gas regulator is affixed to the gas cylinder so that it can manage the pressure and flow of the gas system. This allows the gas regulator to function and monitor the appropriate pressure required to hold off a breakdown of the Marx bank at a certain charge voltage. The purpose of the regulator is to bring the high pressure of the gas supply down to a more manageable level at a lower pressure, and it also makes certain that the amount of gas that is given is constant and under control. The input pressure and output pressure are both shown on the regulator’s gauge, which enables the user to monitor and adjust the pressure as necessary. An OMEGA digital test pressure gauge with an accuracy of ±0.25% is also installed in the line where the gas regulator is located. The readings on this display are presented in terms of the Torr unit of measurement and enables the user to get reliable readings of the pressure.
3.2.4 Pressure in Vacuum Chamber

An Agilent Technologies XGS-600 Vacuum Gauge Controller was utilized in order to keep track of the pressure that is present within the vacuum chamber. This vacuum gauge controller has the ability to operate a maximum of 12 gauges simultaneously, but only 2 are used. The higher pressures, which range from $10^{-2}$ Torr to $10^{-4}$ Torr, are monitored with the use of a thermocouple that is contained inside the controller. After the thermocouple reaches its lowest point, this measurement is replaced with a reading from a Glass Bayard-Alpert Ion Gauge. The ion gauge was affixed to the top of the chamber and used to determine the pressures that are lower than $10^{-4}$ Torr since other instruments are not sensitive enough to provide accurate measurements. The ion gauge measures the number of ions produced in a vacuum chamber and correlates to the pressure in the chamber. It is advantageous to be used for measuring high vacuum in the vacuum chamber due to its high accuracy and sensitivity.
Figure 37: Agilent Technologies XGS-600 Vacuum Gauge Controller [41]

Figure 38: Ion Gauge [42]
3.2.5 Oscilloscope

The waveform signal measurements for the D-dot sensor and the CVR were collected using a Tektronix DSA 70604C 6 GHz Digital Serial Analyzer as presented in Figure 39.

This oscilloscope was protected from any electromagnetic interference caused by the Marx generator by being contained in a screen room. The oscilloscope signals were used
to determine whether or not a surface flashover event occurred. Figure 40 depicts the unprocessed D-dot signal, which indicates that a surface flashover event occurred.

![Figure 40: Surface Flashover Event Occurring (Blue waveform is D-dot, Yellow is CVR)](image)

During the pre-flashover stage, the voltage waveform is typically constant or steadily varying. This occurs as a result of the applied voltage gradually increasing or being scaled up to the breakdown level. During the breakdown stage, the voltage waveform undergoes an abrupt change. As shown, a rapid decrease in voltage indicates the initiation of the flashover. This decrease in voltage is accompanied by a significant increase in the current flowing through the flashover path that can be seen and measured by the CVR. After this stage, the waveform exhibits signs of oscillations, and after the flashover event, the voltage waveform begins to recover and eventually reaches a steady
level. Each measurement was saved for analysis at a later date which will be discussed in Section 3.3 and Section 4.2.

3.3 Analysis

The signals generated by the D-dot probe were used to compute the breakdown voltage by utilizing the peak voltage once the waveforms had been obtained from the oscilloscope after numerous shots had been taken on each sample. This was done so that the breakdown voltage for each material could be determined and compared to one another. In an effort to facilitate convenience, a MATLAB script was developed and implemented to process data. This MATLAB program was developed to read the data from the file, calculate a new signal while taking into account any DC offset, and output the results. After that, the new signal is multiplied by the attenuation that was utilized in the process of measuring the waveform from the D-dot sensor. After the attenuation had been accounted for, the signal was integrated over the period of time that was specified in the data file (provided by the oscilloscope) using the \textit{cumtrapz} MATLAB function. After the integration was complete, the calibration factor was applied so that any deviations or systematic errors could be compensated for, and an accurate voltage waveform could be generated.
Chapter 4 Results

4.1 Experimental Process

The experimental procedure begins with surface preparation of the insulator sample that is going to be tested. This entails cleaning the sample and handling it with powder-free latex gloves to eradicate the possibility of contamination. After cleaning the insulator with the correct cleaning solution and Kimwipes, it is positioned in the center of the anode electrode within the vacuum chamber. Using the linear motion feedthrough, the cathode electrode is steadily placed atop the sample until it cannot be moved any further. The side port that has a fast access entrance door conflat flange is then sealed to produce a vacuum seal by tightening the knob on the door.

![Side Port used for Samples](image)

*Figure 41: Side Port Used to Insert Samples*
The subsequent step is to pressurize the Marx generator. A regulator with roughing pump affixed to its terminals is used to pressurize the interior of the Marx. The pressure within the Marx generator will change according to what the charge voltage needs to be for the sample being tested. Table 1 presents the necessary pressure inside the Marx bank for the specified charge voltage and the approximate output potential applied to the sample.

<table>
<thead>
<tr>
<th>Charge (kV)</th>
<th>Approximate Marx Pressure (Torr)</th>
<th>Approximate Potential Output (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>ATM</td>
<td>126.4</td>
</tr>
<tr>
<td>10</td>
<td>ATM</td>
<td>181.1</td>
</tr>
<tr>
<td>11</td>
<td>736</td>
<td>199.7</td>
</tr>
<tr>
<td>12</td>
<td>841</td>
<td>212.4</td>
</tr>
<tr>
<td>13</td>
<td>940</td>
<td>249.3</td>
</tr>
<tr>
<td>14</td>
<td>1041</td>
<td>268.4</td>
</tr>
<tr>
<td>15</td>
<td>1144</td>
<td>261</td>
</tr>
<tr>
<td>16</td>
<td>1244</td>
<td>286.7</td>
</tr>
<tr>
<td>17</td>
<td>1343</td>
<td>318.3</td>
</tr>
<tr>
<td>18</td>
<td>1443</td>
<td>340.6</td>
</tr>
<tr>
<td>19</td>
<td>1545</td>
<td>345.5</td>
</tr>
<tr>
<td>20</td>
<td>1641</td>
<td>350</td>
</tr>
<tr>
<td>21</td>
<td>1737</td>
<td>360.8</td>
</tr>
<tr>
<td>22</td>
<td>1838</td>
<td>364.5</td>
</tr>
<tr>
<td>23</td>
<td>1948</td>
<td>374.8</td>
</tr>
<tr>
<td>24</td>
<td>2042</td>
<td>406.1</td>
</tr>
<tr>
<td>25</td>
<td>2143</td>
<td>400.8</td>
</tr>
<tr>
<td>26</td>
<td>2245</td>
<td>411.5</td>
</tr>
<tr>
<td>27</td>
<td>2349</td>
<td>436.8</td>
</tr>
<tr>
<td>28</td>
<td>2445</td>
<td>460.6</td>
</tr>
<tr>
<td>29</td>
<td>2549</td>
<td>468.5</td>
</tr>
</tbody>
</table>

*Table 1: Marx Pressure and Marx Output for given Charge Voltage*
Chapter 3 provides additional information about this process. The following phase of the experimental procedure is pulling vacuum. The vent valve and the chamber scroll pump valve must be closed, while the gate valve must be fully rotated to the left and in the open position. The Agilent IDP-10 (backing scroll pump) must be opened by rotating the dial until it is fully open and in its highest position. The Agilent Tech XG5-600 is then started, followed by the backing scroll pump. The controller for the turbo pump is subsequently turned on and permitted to power up. When the pressure on the Agilent Tech XG5-600 falls below $10^{-1}$ Torr the turbo pump can be activated. The ion gauge can then be turned on using the Agilent Tech XG5-600. The ion gauge is maintained in the on position until the vacuum pressure falls below $2.0 \times 10^{-5}$ Torr. Once this threshold is attained, the ion gauge filament is turned off. The Marx’s power supply is then enabled, and the testing apparatus is prepared for use.

To initiate the actual testing procedure, the DAQ box, laptop, and oscilloscope must be powered on, and the LabVIEW program used to control the voltage supplied to the Marx generator must be launched. This portion of the experimental procedure varied minimally between samples. The charge voltage for the Marx generator varied depending on the sample being tested, and the LabVIEW program was set to that desired voltage. After the program measured the required charge voltage, the trigger system that was described in detail in Chapter 3 was triggered by the DG645 Digital Delay Generator. If an insulator sample failed to undergo surface flashover after five shots at the applied charge voltage, the charge voltage was increased by 1kV in the LabVIEW program control panel until a breakdown occurred. Once the oscilloscope had captured the
waveform signal, the charge voltage to the Marx bank was reduced to zero and the waveforms that had been captured were stored for further evaluation and comparison.

![LabVIEW Front Panel to Control Charge Voltage](image)

**Figure 42: LabVIEW Front Panel to Control Charge Voltage**

It is important to note that the vacuum was broken, and the sample’s surface was cleaned with the appropriate cleaning solution in the intervals between each voltage that was applied to the sample. To do this, the gate valve was closed, in order to avoid exposing the turbo pump quickly to the release of pressure, by twisting the knob clockwise until it could not be turned any further and then locked in place with the help of a little silver knob that is connected. To discharge the pressure, the vent valve was turned to the open
position. After this was finished, the sample was removed using powder-free latex
gloves, checked for any signs of surface flashover (carbon tracks or branching), and then
cleaned with Kimwipes and the appropriate solution. After the surface preparation, the
sample was repositioned in the middle of the anode electrode in preparation for the
subsequent shot; the procedure continued the same as described previously in this
section. Appendix B has a breakdown of the procedure that was followed.

4.2 Experimental Results

A comparative study was conducted to assess the surface flashover performance
of various insulator materials. Table 1 shows a list of the different polymers that were
utilized in the experiment. It consists of the polymer, the descriptive name of the sample,
any dopants present in the sample along with its concentration, the height in millimeters,
and the diameter of the base in millimeters.
Table 2: Polymers Tested and Their Characteristics

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Description</th>
<th>Dopant</th>
<th>Dopant Concentration</th>
<th>Height (mm)</th>
<th>Base Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Mold Release</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-6.1mm</td>
<td>NONE</td>
<td>N/A</td>
<td>6.1</td>
<td>47</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Filler SN004</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Filler SN005</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Filler SN006</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Filler SN006</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>Epoxy-No Filler SN007</td>
<td>NONE</td>
<td>N/A</td>
<td>7.2</td>
<td>49.2</td>
</tr>
<tr>
<td>PMMA</td>
<td>Zinc Infiltrated</td>
<td>Zinc</td>
<td>5 Nominal VPI</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>PMMA</td>
<td>PMMA #32</td>
<td>NONE</td>
<td>N/A</td>
<td>8</td>
<td>50.8</td>
</tr>
<tr>
<td>EPON 828/DEA</td>
<td>BORON CARBIDE</td>
<td>N/A</td>
<td>N/A</td>
<td>7.2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

These materials were tested under controlled conditions to analyze their breakdown voltage and the occurrence of surface flashover was evaluated. The experimental data
collected during the surface flashover experiments performed are shown below. Figure 43 through Figure 51 illustrates the results for each insulator, including the number of test shots, the applied charge voltage, and the occurrence of surface flashover. The red indicates that a flashover has occurred, while the green indicates that the insulator was able to resist the applied voltage. This research can aid in assessing the suitability of various insulator materials and contribute to the design, selection, and optimization of a variety of high-voltage applications.

Figure 43: Epoxy 828/DEA No Mold Release Test Shots
Figure 44: Epoxy 828/DEA 6.1mm Sample Test Shots
Figure 45: Epoxy 828/DEA No Filler SN004 Sample Test Shots
Figure 46: Epoxy 828/DEA No Filler SN005 Sample Test Shots
Figure 47: Epoxy 828/DEA No Filler SN006 Sample Test Shots
Figure 48: Epoxy 828/DEA No Filler SN007 Sample Test Shots
Figure 49: Zinc Infiltrated 1 PMMA Sample Test Shots
Figure 50: PMMA Un-Sanded Sample #32 Test Shots
It should be noted that the boron carbide sample was evaluated prior to implementing the D-dot sensor supplied by Sandia National Labs. Therefore, for purposes of comparison in this report, the data for this sample indicates the applied charged voltage to the Marx generator and whether or not a surface flashover event occurred. These results are then compared to the other polymers tested using similar data. Large increases in flashover resistance are shown in the boron carbide-doped epoxy insulator, as seen in Figures 43 through 51 above. With the Marx test stand utilized in this experimental report, a surface flashover event was never achieved. The results indicate

*Figure 51: Boron Carbide doped Epoxy 828/DEA Sample Test Shots.*
that the epoxy insulator treated with boron carbide has the highest applied voltage resistance of any other polymer tested.

The subsequent data shows the integrated voltage waveform measured by the D-dot probe and processed with the Matlab script described in Section 3.3. Each insulator’s maximum breakdown voltage was then calculated using Matlab’s \textit{max} function and broken down in Table 2. Note that Boron Carbide-doped Epoxy and PMMA Un-Sanded Sample #32 will not be included in this evaluation. Testing of PMMA Un-Sanded Sample #32 waveforms was unsuccessful due to oscilloscope data loss and the Boron Carbide-doped epoxy was tested prior to installing the D-dot probe.

![Figure 52: Epoxy No Mold Release Integrated D-dot Signals](image-url)
Figure 53: Epoxy 828/DEA 6.1mm Integrated D-dot Signals
Figure 54: Epoxy 828/DEA No Filler SN004 Integrated D-dot Signals
Figure 55: Epoxy 828/DEA No Filler SN005 Integrated D-dot Signals

Figure 56: Epoxy 828/DEA No Filler SN006 Integrated D-dot Signals
Figure 57: Epoxy 828/DEA No Filler SN007 Integrated D-dot Signals
Figure 58: Zinc Infiltrated Integrated D-dot Signals
Table 2 below compares the experimental data collected to determine which polymer can withstand the highest applied voltage.

Table 3: Maximum Breakdown Voltages per Polymer Sample Tested

<table>
<thead>
<tr>
<th>Polymer Sample</th>
<th>Peak Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy No Mold Release</td>
<td>210.296</td>
</tr>
<tr>
<td>Epoxy 6.1 mm</td>
<td>205.755</td>
</tr>
<tr>
<td>Epoxy SN004</td>
<td>252.489</td>
</tr>
<tr>
<td>Epoxy SN005</td>
<td>248.296</td>
</tr>
<tr>
<td>Epoxy SN006</td>
<td>245.964</td>
</tr>
<tr>
<td>Epoxy SN007</td>
<td>224.342</td>
</tr>
<tr>
<td>Zinc Infiltrated</td>
<td>332.817</td>
</tr>
</tbody>
</table>
Chapter 5 Conclusion

5.1 Discussion

In the context of a vacuum environment, the purpose of this thesis was to study the influence that various polymer materials have on surface flashover events. The goal was to get an understanding of how different polymer insulating materials contribute to surface flashover behavior and to give insights into the appropriateness of these materials for high-voltage applications in conditions involving vacuum. The majority of tests and investigations have been performed, and the results of these endeavors have resulted in noteworthy findings and generalizations. A comparison and contrast of the polymer materials was carried out, and the findings of the experiment were used to identify which one is capable of withstanding the maximum applied voltage. An experimental apparatus was constructed to detect the breakdown voltage of the different insulating samples provided by Sandia National Labs and the polymer samples were put through a series of tests to illustrate how changing the material composition impacts the breakdown voltage capability.

It has been determined that the dielectric properties, surface features, and material composition of an insulator are important elements that influence the breakdown behavior in a vacuum environment. Among the polymers that were put through various tests, it was discovered that the epoxy doped with boron carbide was the only one that did not show any signs of surface flashover. This suggests that the material is capable of withstanding the highest applied voltage that the Marx bank that was utilized in this experiment will permit. This demonstrates that it has the potential to serve as a strong insulating material for applications involving vacuums. Because of its strong breakdown
strength and dielectric characteristics, it may be ideal for use in settings that require dependable insulation. When comparing the polymer samples that were tested with the D-dot probe to measure the highest breakdown voltage, the results show that the Zinc Infiltrated Epoxy was able to withstand the highest applied voltage. On the other hand, the polymer samples Epoxy 828/DEA No Mold Release and Epoxy 828/DEA 6.1mm displayed breakdown voltages that were over 100 kV lower than the Zinc Infiltrated sample which suggests that these polymers are less suitable for use in vacuum applications. When these distinct variances in flashover behavior are understood, it is possible to make an educated material selection for a variety of vacuum applications.

The results of this experiment demonstrate that polymer insulators can be manufactured in a way that allows the electrical breakdown behavior of the insulator to be altered. These insulating materials made of polymer have new energy levels within the bandgap as a result of controlled doping, and these new energy levels change the flow of electrons through the material. These findings provide more evidence that the incorporation of inclusions into the crystal lattice structure can change the electrical behavior of these polymer materials. Specifically, the results show that the performance of epoxy and acrylic can be improved, and the breakdown voltage can be increased because the insulator is able to sustain a higher applied voltage than the samples of undoped polymer materials.

5.2 Future Work

Further testing on samples in this report should be re-tested. For starters, the boron carbide-doped epoxy sample should be completed utilizing the D-dot probe to capture the voltage waveform data. Saving the applied voltage throughout the test is necessary since
the results shown in Section 4 suggest that the boron carbide-doped epoxy sample did not experience a breakdown. Surface flashover and data to determine the breakdown voltage could be obtained by testing this sample on a separate Marx generator that has the capability of a higher applied voltage. Another option would be to fabricate a second sample of boron carbide-doped epoxy with a thickness of about 6mm should also be tested. The breakdown voltage of this thinner sample could be compared to that of other insulating samples since a surface flashover event is more likely to occur during testing. The Zinc Infiltrated sample is another that needs to be retested utilizing the D-dot probe. Problems with the Marx generator prevented more test shots to be taken. If further testing on this sample confirms the breakdown voltage reported in Section 4, this material has the potential to sustain extremely high applied voltages. Material selection for vacuum conditions could benefit from the additional knowledge gained from reexamining these samples.

The gas used to pressurize the Marx generator should also be investigated thoroughly. This variable can determine the desired performance of the Marx and reduce the need for regular maintenance. While SF6 is a commonly used gas in high-voltage applications due to its high dielectric strength, it is not the most cost-effective. Therefore, nitrogen gas or ultra-zero air have been used as alternatives in this experiment. Decreasing the levels of contamination on the electrodes, insulators or terminal can contribute to the performance drop or irregularities occurring. As a result, less data on samples can be collected before the Marx needs to be cleaned, which is an expensive and time-consuming process. The Marx generator utilized in this experiment has enough capability to withstand the higher
charge voltages for about 100 test shots, but there hasn’t been enough data collected to draw any conclusions on which gas increases performance.

Although this thesis has contributed to understanding the behavior of surface flashover of a variety of polymer materials in a vacuum environment, there are still many questions that need to be answered and topics that should be explored to deepen the understanding. More polymer materials should be researched. This experiment investigated the surface flashover characteristics of a specific set of polymer materials, but future research should incorporate a larger range of polymer materials with various properties and compositions to acquire a more comprehensive understanding. Some of the samples provided by Sandia National Labs that would be of interest are epoxy doped with titanium oxide or aluminum oxide or acrylic doped with zinc oxide. New polymers with superior surface flashover resistance could be identified by broadening the material selection. To improve surface flashover resistance of polymer materials, several surface modification approaches, such as coatings and surface treatments, should be investigated. Comparing polymers to other insulating materials should also be studied because it could aid in a better understanding of the relative advantages and limits of different materials and aid in the identification of insulating solutions for specific vacuum applications. There is a significant number of additional doped samples provided by Sandia National Labs that still need to be examined. Future studies should also look into the degradation and aging of materials over time. This can change the material’s electrical characteristics, which in turn can affect surface flashover behavior. This research could also serve to shed light on the long-term stability and reliability of these materials. Multiple physical and chemical mechanisms are at play in the pre-flashover phase of surface flashover.
Understanding the fundamental physics of surface flashover is critical for improving the efficiency and dependability of high-voltage systems. More information on the physics and causes of surface flashovers could be gained through the use of computer modeling and simulation research. The flashover process, electric field distributions, and breakdown characteristics could all be simulated, explored, and predicted using numerical approaches including Monte Carlo simulations. Future studies should focus on these directions to improve the knowledge of insulator behavior and surface flashover in vacuum conditions. The findings of these investigations will aid in the improvement of pulsed power engineering and the creation of more secure insulating systems.
List of Appendices

Appendix A................................................................. 92
Appendix B................................................................. 93
Appendix A Calibration of D-dot Probe with Screen Room

1. Turn on Oscilloscopes
2. Oscilloscopes settings
   a. Channel 1 = probe (MS058 oscilloscope)
      i. Terminated at 1 MΩ
   b. Channel 2 = D-dot (DSA70604C oscilloscope)
      i. Terminated at 50 Ω
   c. Stick around 500 Volts and play around as needed
   d. Source
      i. MS058 – trigger off probe
      ii. DSA70604C – trigger off D-dot
3. Setup Pulser
   a. Using alligator clip, attach 1 end grounded on pulser copper sheet
      and the other end attached to the Marx
   b. Attach ring terminal of black cable with electrical tape or gorilla
      tape to anode, getting as close to the center as possible
   c. Set Pulser potentiometer to 4.
   d. Turn black knob in lower right corner to the right
4. Setup Probe = P6015A
   a. Using camera tripod, attach 3-D printed probe holder
   b. Screw ring terminal of one end of the copper cable onto probe
   c. Using zip-ties, attach the probe to the holder on top of the camera
      tripod
   d. Attach ring terminal connected to the end of the copper cable with
      electrical tape or gorilla tape to anode of the Marx.
      i. Make sure the copper cable is not touching any part of the
         marx or pulser cable
5. Take Shot
   a. Set oscilloscopes to Single shot.
   b. Turn red knob on Pulser to the right until it pops out.
   c. Press green square button to trigger.
   d. View data on oscilloscopes
6. Save data
   a. Insert USB hard drive into scope
   b. File path to save
      i. DSA70604C
         1. File>Save As> Waveform-->Save
         2. On Waveform screen:
            a. Source should be set for Ch 2 for D-dot
            b. Save In : USB location
            c. Name: Test #
            d. Save as MATLAB files (*.dat)
ii. MS058

1. File>Save As>Waveform: ---> Save
2. On Waveform screen:
   a. Save Location: USB Location
   b. File Name: Test #
   c. Save As Type: MATLAB(.mat)
   d. Source: Ch 1

7. Next shot (Go back to 5)
   a. Do this for approximately 10 shots

8. Calculate Calibration in MATLAB
   a. Probe = (Time,Data)
      i. Data = Data*1000;
   b. Remove DC offset
   c. Integrate Ddot(Time,Voltage)
   d. Calibrate
      i. Cal 1
         1. Min(data)/min(integrated Ddot)
      ii. Cal 2
         1. Least square residual
         2. $A = [Ddot, integrated Ddot]$
         3. Cal2 = lsqr(A, probe, 1.0E-25, 200)
   e. Save calibration factor and plot
   f. Take average calibration factor of all shots comparable

\textit{Figure 59: Calibration of D-dot Diagram}
Appendix B: Surface Flashover Testing Procedure

1. Turn on DAQ, laptop, oscilloscopes
3. Open HGI application test controller
   1. *File path:* Desktop – HGI application Folder – HGI tester
4. If using oscilloscope for saving data
   b. Plus USB into oscilloscope
   c. Go to “save as” tab at the top of the screen
   d. Select “WAVEFORM” on tab at the top of the screen
      a. Confirm that “all” is selected under Waveform data range
      b. Nothing is selected under Waveform detail
      c. Data destination is Spreadsheet TXT
      d. Source is Displayed analog, Exit options menu
   e. Select file where data needs to be saved
   f. Nothing under “Save as type” should be selected
   g. After shooting, click save to save to USB
5. If using LabVIEW for saving data
   b. Assign VISA communication appropriately
      a. DGG455 = DG645 (not currently working, not needed for testing)
      b. Scope = GPIB
   c. Adjust integral scale:
      a. Adjust integral scale every time the marx is recalibrated
      b. Make note of integral scale in the comments
   d. Configure experiment name
      a. Make sure that the file name includes “Shot #”, where # is the numbered shot.
      b. Follow the naming convention. If the project lead specifies a naming convention, follow that. Otherwise, here is an example: Example: material type, “Shot” 1-increment with each shot
   e. Configure file path
      a. Open HGI data
      b. Either select material folder or create new
   f. Comments
      a. Sample – describe material
         a. Length
         b. Diameter
         c. Geometry
         d. If cone, include the angle
         e. Vacuum
         f. Marx Pressure
      b. Marx Pressure
         a. Turn on omega sensor on ground near marx
b. Record pressure
c. Oscilloscope Channels
   a. Ch 1 – N/A
   b. Ch 2 – 20dB attenuation
c. Integrated Signal

6. Put on gloves, prepare sample according to test procedure
7. Load Sample
9. Pulling Vacuum
   a. Confirm that the vent valve and chamber scroll pump valve are closed. Confirm the gate valve is in the open position (rotated all the way left)
   b. Confirm the backing scroll pump is open
      Turn dial until completely open
         a. Tallest position corresponds to completely open
c. Turn on Agilent Tech XG5-600 (power switch on back under power cord,
d. Turn on backing scroll pump (Agilent IDP-10
e. Turn on the turbo pump controller, allow it to boot up (power button on back under power cord
f. Once pressure is E-1 on Agilent Tech XG5-600 screen then turn on the turbo pump by pressing the button with a vertical line on the controller.
g. When the turbo is spinning at 1000Hz (Green light will be solid on the pump) turn on the ion gauge.
   a. Turn on using Agilent Tech XGS-600
   b. Hit plus button until “Fill ON” then “OK”
   c. Wait for vacuum to go below 2.0E-5 Torr
d. Turn off filament one by using plus button until “Fill Off” then “OK”
   e. Turn off switch in back

10. Turn on Marx power supply
    c. Red switch on base of Marx
11. Set voltage and begin testing
    1. Set voltage
    2. Monitor voltage. Once at appropriate level, hit the fire button (enter on DSG 645)
    3. Set voltage to 0
    4. Hit refresh on LabVIEW to look at oscilloscope waveforms.
    5. Save waveforms (follow above instructions for either LabView or direct from oscilloscope
12. Loading next Sample
1. Close Gate Valve until it seats in place
2. Open Venting Valve
3. Change Sample
4. Close venting Valve
5. Open Chamber Scroll Pump Valve
6. Turn on Chamber Scroll Pump and wait til 3E-1 or lower vacuum
7. Close Chamber Scroll Pump Valve

8. Open Gate Valve
9. Wait until below 2E-5 Torr vacuum and perform test

13. Turning off
1. Set charge voltage to 0
2. Turn off gas if it is on
3. Turn off the turbo pump and allow it to spin down, keeping the backing scroll pump on.
4. Turn backing scroll pump off
5. Turn off Marx power supply using the red switch
References


