Marshall Plan Scholarship Program
In Collaboration with
The University of Applied Sciences Upper Austria,
The Center for Advanced Power Systems,
and The Florida State University

Investigation of Breakdown Behavior at Medium Voltage Stand Off and Voltage Steps

SUBMITTED AS A PROJECT REPORT

In Fulfilment of the Terms of the Marshall Plan Scholarship

by

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September 2019

Preface/Acknowledgements

Thanks to the Marshall Plan Scholarship, which made this journey possible and to all the people in Austria who made my time in the country both happy and productive. Thanks to the members of the Electrical Engineering department at the University of Applied Sciences Upper Austria for their tireless insight and support throughout this project. Particular thanks to Dr. Peter Zeller, Christoph Diendorfer MSc, and Christian Gruberbauer BSc for their contributions to the success of this project both professionally and personally. Thanks to the unwavering support of my mentors at the Center for Advanced Power Systems, including the encouragement and administrative support of Dr. Mischa Steurer and Dr. Peter Cheetham. Special thanks finally as well to my mother and father, who were of great emotional support during my trip and more importantly raised me with the tools necessary to be ready for it.

Sincerely,

James McAuley

Abstract

In the development of Naval DC standards of creepage and clearance, an understanding of all the major variables associated with surface flashover must be understood. While the standards for AC based power systems are well documented, differences between the two waveforms have other impacts on the system. DC surface charge agglomeration, inverted field effects caused by temperature gradients along the surface of electrical insulators, and even polarity inversion stresses may cause surface breakdowns at voltage levels lower than typical AC recommendations. Within this investigation was included the development of test circuits to agglomerate charge carriers, induce stress due to polarity inversion, and investigate the influence of thermal gradients on system stability. A preliminary investigation into the effects of the voltage ramp rates, space charge accumulation, polarity inversion, and thermal gradient development was completed. Even the marginal impacts on breakdown voltage are relevant when developing creepage and clearance standards, and this investigation begins to shine a light on the more relevant factors in surface flashover behavior.

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1 Introduction

There is an increasingly wide interest in the development of medium and high voltage DC power systems, particularly for use in naval applications. Historically, the US Navy has used only AC power systems for distribution of electricity in shipboard power systems. Due to advances in DC technologies, DC power systems have become increasingly viable from both an economic and engineering perspective. Properties of DC power systems like the lack of eddy currents and skin effect lead to it being a strong candidate for future power systems. [1-3] The newfound interest in developing scalable DC power systems has been driven in large part by the US Navy's goal to develop a fully electric naval ship. There are multiple potential advantages to electric ships, such as reducing the life-cycle costs of the ship, increasing the ship's stealth, payload, survivability, and the amount of power available for non-propulsion uses. Of interest to the Navy in this endeavor is obtaining the maximum space efficiency possible in tandem with a desire for operational reliability over the system's lifetime. Due to the unique design characteristics of the Naval all electric ship, current standards surrounding creepage distances have been deemed unsatisfactory, and need to be further developed. The improper application or development of design standards could lead to decreased reliability in the ship or economically inefficient designs, both of which are detrimental to the development of the project at large. There are many aspects of DC breakdown to be investigated, but this project focuses particularly on the characterization of surface breakdowns in medium voltage DC environments. The development of large-scale DC power systems for naval applications clearly requires a high level of reliability for shipboard use and has sparked an interest in the development of fault prevention systems. The development of these fault prevention systems and algorithms has been complicated by a lack of engineering standards for shipboard DC applications. Currently the only military specification standards (MIL-SPEC) that exist for cables and accessories are designed for shipboard power systems at voltages higher than 1,000 V, AC [MIL-STD-1399-680]. There is a lack of adequate standards for DC power, which is the most likely current to be used in future all electric ships. It is critical to the development of fully electric ships to develop MIL-SPECs that have relevance for the likely prevalent use of DC power. These are to be enshrined in a new section of [MIL-STD-1399]. [4] This development will, out of necessity, occur in stages. To begin with, the absence of applicable DC standards makes evaluation of potential shipboard DC topologies difficult. While the current AC Standards can be used as a rough starting estimate in lieu of the nonexistent DC Standards, it is important to note that electrical properties of insulation materials differ when subjected to an AC voltage as opposed to a DC voltage. Therefore, to appropriately develop a DC power system infrastructure, a more coherent and sequential understanding of DC design parameters must be established. This involves understanding the fundamentals of minimum clearance and creepage distances at several voltage levels within the medium voltage range. The minimum creepage distance is based on several variables including gap distance, dielectric material, electric field profile, operating environment, electric field strength, and the profiles of possible fault voltages observed while in service.

A Medium Voltage Direct Current (MVDC) shipboard power system has two power buses which are both operated at the same voltage (V_{DC}). If a fault occurs on one bus, the second bus will increase in voltage to $2V_{DC}$ until the electronic control system detects and interrupts the fault. This redundancy is in place to buttress against one of the worst fault conditions expected for the insulators to be exposed to while in service. Therefore, the insulators must be designed and verified to withstand at least twice the intended operational voltage without surface flashover occurring. The necessary creepage distance of the insulator varies based on the voltage level selected for V_{DC}, the dielectric capabilities of the insulator, and the dielectric strength of the gaseous dielectric. Creepage distance refers to the distance required to be maintained between two conductors in order to prevent breakdown from having a real chance of occurring. The purpose of this investigation is to test certain design factors, environmental factors, and operational factors pertinent to understanding the design parameters associated with the development of DC shipboard creepage and clearance standards for one particular form of electrical breakdown. This is referred to as surface breakdown, which involves two conductors breaking down across a solid insulator separating them. The scope of this investigation is on rapid surface flashover breakdowns, so breakdown by tracking or any long-term effects on insulators will not be considered within the breadth of this research. Various experiments were designed and executed in order to begin to quantify the impact of various variables on the stability of these basic conductor insulator conductor systems in a medium voltage DC setting. These experiments covered a range of potential scenarios, both generalized and shipboard, due to their focus being into the underlying physical mechanics of surface flashover. In order to develop a grasp on the most important physical factors in the analysis of these DC scenarios, an investigation into the basic physics of how breakdown should occur in such a case was necessary. The breakdown expected across stand-off insulators is not through a purely gaseous dielectric, like air, but across the surface of the insulator itself. This distinction brings with it complications in the analysis of breakdown. Factors like space charge accumulation and insulator geometry become very relevant. There is limited knowledge of the mechanics of surface breakdown in DC environments, as well as the effects of factors like humidity on its behavior. This lack of understanding of the implications of these factors complicates the analysis of results and demands appropriate controls be placed in order to not conflate variance in environment with variance in breakdown physics. The main four factors in surface flashover considered in this investigation were 1) space charge accumulation, 2) voltage polarity inversion, 3) voltage ramp rate variation, and 4) thermal gradient development. [4] These factors were chosen to serve as a basis to take a small look into the various physical phenomena which impact surface breakdown, particularly their impact on the withstand voltages of surface breakdown prone systems. It is important to initially get an idea for how significant each factor is under which conditions before moving on to pursue individual factors only to determine they aren't relevant. Due to the lack of understanding about the nature of DC surface flashover, these four individual factors were determined to be most important to developing our understanding of the wide array of factors at hand.

2 THEORY

Creepage distance for a given voltage depends primarily on the dielectric insulating the two conductors. Other factors which play significant roles in determining creepage distance include humidity, atmospheric pressure, and temperature, as these all impact the dielectric strength of the air. For the case investigated in this report, where the conductors are separated by a solid dielectric, the creepage distance refers to the shortest path possible along the surface of the material between the two conductors at potential. Any breakdown over the insulator is referred to as a surface breakdown, due to the path traversed by the spark being typically along the surface of the insulator. The focus on the path along the surface of the conductor derives from the surface of the conductor being a boundary condition with the surrounding dielectric, which is assumed to be air. Air almost always has a lower dielectric strength than that of an installed solid insulator and thus the boundary condition along the surface of the insulator leads to the shortest path of least resistance for the spark to be along the surface of the insulator. The voltage at which a system of two conductors at a DC voltage potential V_{DC} separated by a solid insulator breaks down is referred to as the "breakdown voltage" of the system. Voltage ramp is defined in this paper as the time derivative of the time dependent voltage graph V(t). The voltage ramp would hence be dV/dt, and is referred to as such throughout the work.

It is well known that the pre-breakdown processes in liquid dielectrics have a stochastic nature. (A. L. Kupershtokh, 2002) This statistical variance appears to be heavily reflected in our collected measurements with surface flashover in air. The analysis of breakdown data is complicated by these statistical processes. Since there are many unknown or hidden factors surrounding breakdowns, defining an exact "breakdown voltage", the inception voltage at which surface flashover is observed, is difficult. The breakdown strength of a given conductor insulator conductor setup is best described as a probability density function μ(E) where the probability of observing a breakdown in a system for any given electric field E(V) is represented as a time density measure, (N breakdowns on average across a time period T). This leads to breakdowns following Poisson statistical distribution curves. This does imply that any current description of the 'breakdown voltage' of a given system must be inherently statistically based, since the phenomenon itself is currently only statistically describable. The stochastic nature of breakdowns for the experiments conducted in this report was addressed by having a static definition for "Withstand Voltage" for each experimental setup.

Since our conclusions formed from the study of breakdowns must be statistically based, one individual breakdown is insufficient to build an understanding of the underlying impacts of changing a single factor. The rationale used in this paper's analysis of breakdown strength was to measure the voltage at which breakdown occurred, and to observe the trend of how the average of all breakdowns changed alongside the variation of the factor being tested. This follows the assumption that if the breakdown inception voltage is on average lower, more breakdowns in the lower voltage ranges would be observed, and therefore the average breakdown voltage would be lower and vice-versa. This method of analysis lacks precision and only grants the ability to track general trends in breakdown voltage, as well as to an extent measuring the impact on the overall system of changing a single given factor.

As was discussed in the introduction, the surface breakdown strength of the insulator is heavily based on three factors: the geometry of the insulator, the strength of the electric field, and the dielectric strength of the air around it. Since the geometry of the insulator is stable, and the strength of the electric field is often the tested variable, the only factor which could pose the risk of heavy contribution to error would be the dielectric strength of the surrounding air. The dielectric strength of air is mainly determined by three factors: the pressure, the temperature, and the humidity. In order to mitigate variance from these environmental factors, environmental data was recorded after every breakdown, and run through a voltage correction algorithm. [1] The correction algorithm is as follows.

Given standard temperature: $T_0 = 293°K$

Measured room temperature: T ℃

Standard atmospheric pressure: $p_0 = 1013\ mbar$

Measured atmospheric pressure: *p*

Standard humidity: $h_0 = 8.5\ g/m^3$

And measured humidity: $h\ (g/m^3)$

The corrected Voltage V_C is given by $V_C = V_{measured} * \delta * k$

Where $\delta = \frac{p}{p_0} * \frac{T_0}{273°K + T}$ and $k = 1 + 0.002 * (\frac{h}{\delta} - h_0)$

The humidity, atmospheric pressure, and temperature were recorded after each measurement for use in the voltage correction calculation. These environmental variables were recorded from an environmental monitor which was also inside the faraday cage but was not directly next to the insulator itself. This allowed for the temperature readings to be with respect to the ambient, as opposed to being impacted by the gradient, as well as being much more convenient for testing. This does run the risk of some minor inaccuracy of the environmental readings, but these inaccuracies would result in voltage differences orders of magnitude smaller than our level of measurement accuracy and therefore irrelevant with respect to the measurements themselves. The correction factor was used to adjust the measured voltages to one consistent relative scale so that withstand voltages which were measured in slightly varying environments could be compared directly. Fortunately, all of the tests were done within the relatively stable temperature environment of the faraday cage and thus this correction factor appears to be a linear shift down in measured voltages by between 4.6% - 4.9% of the initially measured voltage. Figure 2 shows how the environmental correction results only in a slight downshift of the whole curve. The most important factor in data collection for our analysis is that the environmental factors be controlled for, since the geometry will stay constant. Only the “Corrected Voltage” will be considered in the analysis for these investigations. All data presented in this paper will be using this environmental correction factor as to ensure the comparability of each dataset by isolating the factor of breakdown voltage as much as possible. It is important to note that Küchler notes in his text that the role of humidity in short distance medium voltage breakdowns is not entirely understood, but this algorithm was used nonetheless. [4] The algorithm was used only as a tool for taking away the factor of environment and so to the extent that the standardization of the voltages occurs, the accuracy of the shift in voltage isn't entirely relevant, as our analysis depends on the shift in the average breakdown value, as opposed to the magnitude of the values themselves. In future investigations, it may be of interest to actively control humidity in temperature in a more controlled setting, as to be sure the environmental variance isn't playing a large role in the withstand voltage of the system.

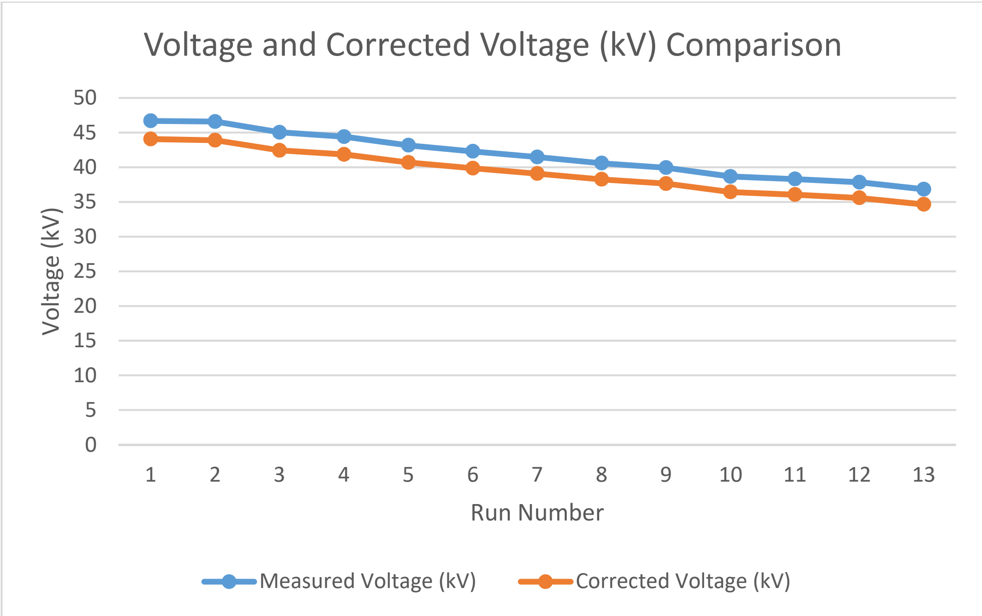

Figure 1: Shows the tight concurrence between the measured and environmentally corrected voltages as well as the effects of testing insulator in rapid succession

The factor of material was considered for investigation and variance in the early days of the experiment and it was decided to be an overly broad factor where the only variance of the material in the experiments was between using the standard cylindrical insulator and an industrial insulator. Material properties such as relative permittivity do have the potential to be factors in surface breakdown but are not amongst the most interesting of the potential factors to be investigated. The research done in this project is a preliminary step towards developing the background understanding for engineering standards for naval applications. With that in mind, there were various factors to be considered. Factors of 1) voltage profiles, 2) space charge effects, and 3) thermal gradients all appeared to be the most interesting phenomena for study in the experiments.

A potentially important factor that was investigated during the experiments is that of the accumulation of surface and space charges. This is an effect where the shape of the electric field itself can pull various charged particles towards the surface of the insulator. These charged electrons and ions trapped by the electric field are referred to as "space charges" and "surface charges". It is important to investigate the effects of these agglomerated charge carriers in DC applications because in AC applications, the variation in the electric fields allows for these charges to recombine [3]. Only in the relatively stable DC waveform are the particles given the chance to accumulate to any real extent. It is expected that these charged particles will be attracted primarily due to lack of uniformity in the electric field along the surface of insulators. Even in simulations of very basic insulator geometries, there are clearly portions of the electric field with the potential of acting as surface charge accumulation points. It is expected that the main factor in determining where this charge attraction occurs is the shape of the electric field along the height of the insulator. More particularly, the strength and polarity of the radial component of the electric field in cylindrical coordinates. Given a positive radial component of the electric field, it is clear to see that any negatively charged electrons or ions would be pulled towards the surface of the insulator. Figure 4 shows the full range of height along the insulator which experiences a positive radial component of the electric field.

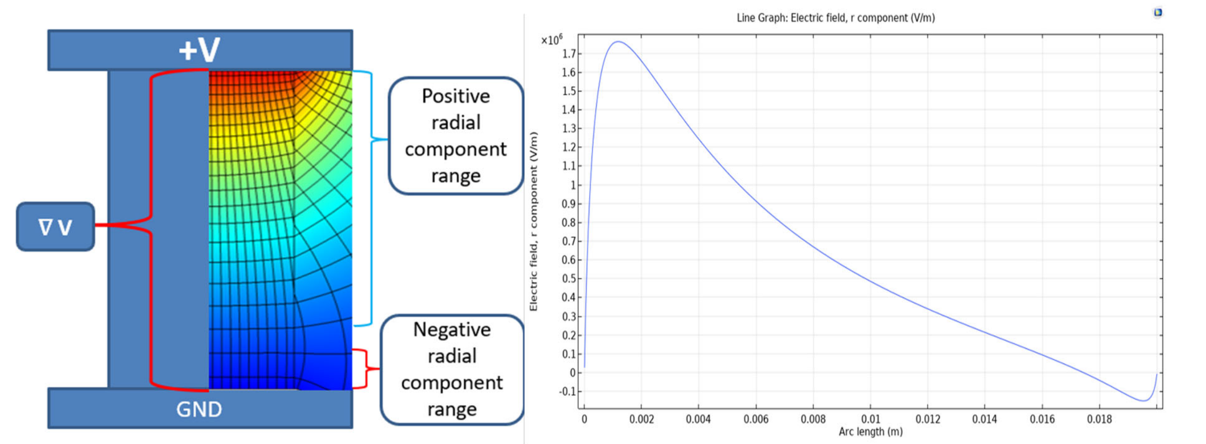

Figure 2 (Right): Strength of radial component of electric field (N/m) vs. location along length of insulator (m).

Figure 3 (Left): Half section of spacer between plates with overlay of COMSOL model of the resultant electric field.

These are the areas to which negatively charged ions and electrons will be attracted. Were the particles stagnant, they would accumulate with a charge density whose Coulombic potential would be equivalent to the strength of the electric field at each point along the height of the insulator. It is expected that the state of the particles remains transient, however. With both Coulombic and recursive magnetic fields being created by the motion of charges, the nature of the motion of the charges being attracted is not entirely understood, clearly free electrons would be the easiest to attract due to their small masses but electronegative molecules or ions may be attracted as well. Some measurements of the density of space charges are possible through the use of electrostatic voltmeters, electrostatic field meters, or even through use of the Pockels effect but this wasn't a possibility for this investigation. [9] It is of interest to determine to what extent the accumulation of space charges affects the withstand voltage characteristics of a system.

3 EXPERIMENTAL CONSIDERATIONS AND SETUP

For the experiments several factors which potentially impact the withstand voltage of an insulator were selected to be considered, as determining the required creepage distance for a set voltage level also necessitates the investigation of scenarios which may increase the probability of surface flashover occurring. These variables include the 1) magnitude of the voltage ramp rate from 0.5kV/s to 12kV/s, 2) the shape of the insulator, 3) the thermal gradient across the insulator, and 4) the profile of the voltage curve experienced by the insulator.

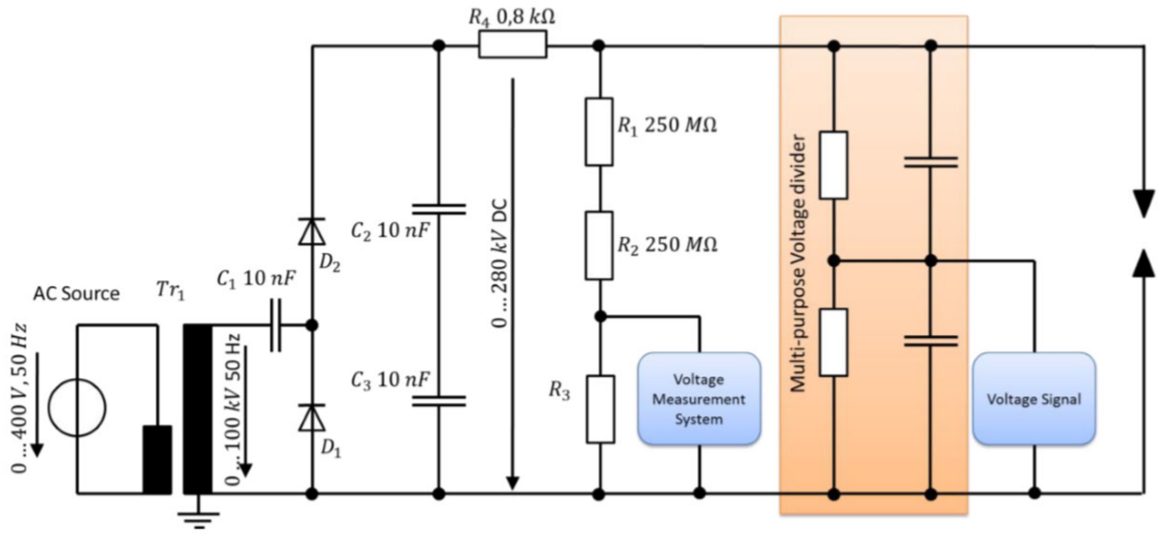

Figure 4: Main DC circuit setup for breakdown testing

Figure 1 above is the circuit used for the Effect of Varying Ramp Rate investigation, the Effect of Space Charge Accumulation investigation, and the Effect of Thermal Gradient Formation investigation. It is relatively simple with the main purpose to have one conductor sitting at V_{DC} above the ground conductor. Our ground conductor was supported by a small motor which could raise and lower the height of the ground in order to decrease or increase the gap distance between the conductors.

The majority of experiments that took place used a cylinder made out of a plastic polycarbonate as an insulator. This cylinder had a radius of 1.75cm and a height of 5.5cm. The decision to use a straight right polycarbonate cylinder was based solely on the desire to avoid overly complex geometries as well as to grant ease in computer modelling. The simplicity of the insulator design also allows for easy replication with various other materials were the need to arise. The cylinder did not seem to sustain any pollution or evident damage during breakdowns, as the amount of power in each breakdown was relatively low and the breakdowns do not necessarily occur directly across the surface of the insulator. After each measurement the sample would be brushed with a grounding wire in order to ensure no excess charges remained. Other than the polycarbonate cylinder during the experiments into the effects of thermal gradient formation an actual commercial insulator was used which was rated for voltages up to 600V, sourced from STORM Power Components model number R2137-A4. This material differentiation was done mainly in order to create the most similar situation possible to that of an electric ship environment for the thermal gradient results. The maximum temperature in the gradient itself was also based on the estimates of the highest temperatures likely to be seen in shipboard applications.

After have made multiple initial measurements, it became evident that tests done in rapid succession of one another resulted in increasingly lower breakdown values (this can be seen in Figure 1, section 2.1), likely due to the inability of the system to completely disseminate its space charges and ionized particles after each subsequent breakdown. Due to this issue, which arose early in the experiments, the experimental procedure was altered such that there always be at least one minute given between measurements to allow for the adequate dispersal of surrounding space charges. However, this was only the case for measurements involving immediate ramps, if the sample was to be left to accumulate space charges or reach thermal equilibrium, it would be immediately taken to the accumulation voltage and left to reach thermal equilibrium or accumulate charge. The experiments took place in a large Faraday cage with an internal air conditioner. In order to keep the room temperature relatively stable, the air conditioner was used in an attempt to maintain a temperature between 25 and 27 degrees Celsius. Any effects due to this variation in temperature should be rendered *de minimis* by the Küchler correction factor (See section 2.1) [4]. The volume of the Faraday cage was quite large (approximately $100m^3$) given the size of the setup itself, which acted as a benefit for the stability of thermal gradient experiments.

The general procedure for experiments consisted of increasing the voltage at some rate across the insulator being used until breakdown is observed, then observing the measured withstand voltage at which the system underwent breakdown. These withstand voltages, as well as the environmental factors of each experiment are then recorded and used to normalize the withstand voltages using the Küchler correction factor [4]. After these tests, the insulator is touched with a grounding pole or wire in order to clear away any residual space charges before the next measurement is initiated.

While the phenomena being observed is surface breakdown along an insulator, the spark itself is likely initiated by a process very similar to the pure gas dielectric scenario. It was theorized that the initiation of fast surface flashovers in air was due to a secondary-electron-emission or Townsend avalanche occurring within the very strong electric field. Even in tests done on surface flashover in a vacuum, Townsend ionization avalanches can still be initiated by emissions of space charges from the triple point of the system. The triple point of the system is the set of points at which the 3 media: conductors, insulator, and air all come into contact. Townsend avalanches are a phenomenon in which an initial electron or ion travelling with a high kinetic energy is accelerated in the high electric field gradient and reaches an energy high to ionize other particles in the air. These ionized particles then are subsequently accelerated and ionize other particles, leading to an "avalanche" effect of exponential growth of particles ionizing each other and results in a breakdown. This high energy particle can accrue its energy through a variety of means. One of these is through field emission, which is the particle being accelerated through a particularly high electric field strength. It also is affected by thermionic emission, which is directly correlated with the temperature of the surrounding environment but is typically only a factor at high temperatures. It can evidently be affected by ion impacts, receiving kinetic energy after colliding with other charged particles accelerated by the electric field. Lastly there can be effects of photoelectric emission, which are energy inputs from sources like high energy photons or even potentially cosmic radiation. It is clear that the main source of energy is due to the high electric field strength, but there are other factors at play in determining long term safe breakdown values, the unpredictability of many of these factors lead to breakdowns being so heavily statistically driven.

4 THE IMPACT OF VOLTAGE RAMP ON BREAKDOWN

The first investigation undergone was one to test how breakdown voltage was affected by a higher or lower rate of change in voltage (dV/dt). Our interest in this matter was brought about initially by a logistical issue in the development of the experimental setup where it wasn't possible to construct a circuit capable of achieving a true step function in voltage. It was unclear as to whether increasing the voltage quasi-instantaneously with a device like a spark gap would provide fundamentally different results from different values of ramp rate. The power supply available was able to achieve ramp rates up to a maximum of 12kV/s and had to increase at a minimum of 0.5kV/s. The theory behind the mechanism of Townsend breakdowns implied that the only relevant factor in inducing breakdown was that of the energies of the charged particles. Since these charged particles get the vast majority of their energy through interaction with the very strong electric field between the electrodes, the magnitude of the field itself appeared to be the most significant factor in withstand voltage. Introducing a time derivative to the magnitude of the field appeared to only introduce a complementary time derivative to our breakdown probability density μ(E(t)).

To test the effects of varying ramp rate, breakdown testing was done on the cylindrical insulator at these highest and lowest values of ramp rate possible. The sample was taken to a stable voltage of 20kV and allowed to sit for 5 minutes until it reached a "steady state". After these 5 minutes, the sample underwent a rising voltage at either 0.5kV/s or 12kV/s. The voltage rose until breakdown was observed. Upon breakdown being observed the voltage and environmental factors were recorded and the setup taken back to 20kV for the next measurement. The voltages and environmental factors were put through the Küchler formula and recorded. After each measurement the sample was brushed with a grounding

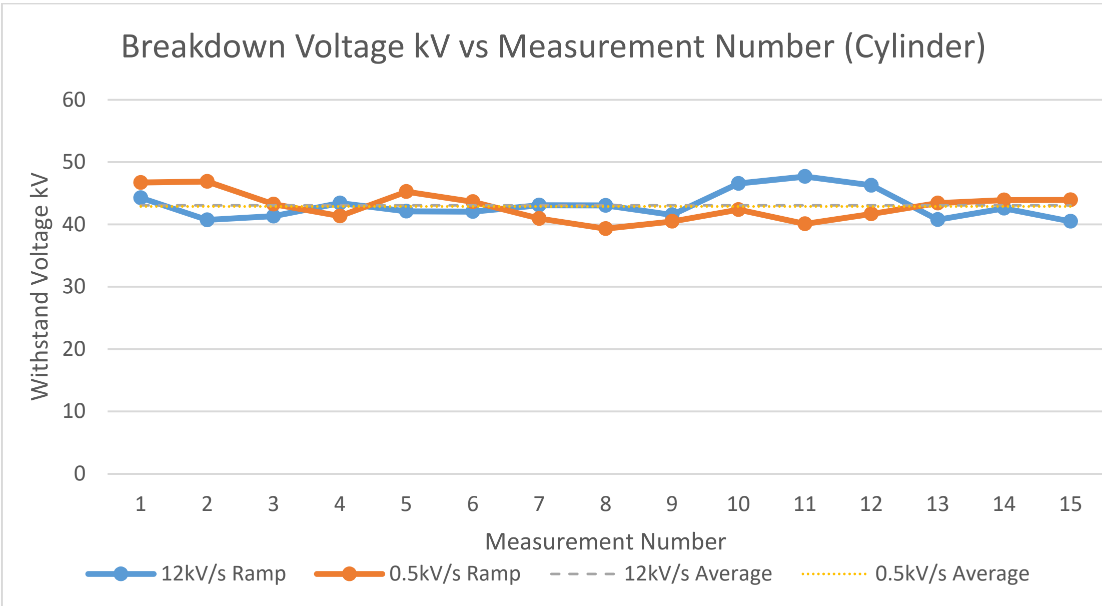

Figure 5: Strong concurrence between the 12kV/s and 0.5kV/s ramp speeds

wire in order to remove any excess surface charges. These experiments showed very little relation between the breakdown voltage and the ramp rate, with the higher ramp rate of 12kV/s having an average breakdown voltage less than one percent higher than the 0.5kV/s rate.

In another experiment, the data for which is shown in Figure 4, the same experimental procedure was done with the separate Storm insulator to see if the similarities between ramp rates may have been reliant upon the simple geometry or material. The voltage was increased by 0.5kV/s and at 12kV/s just like in the first experiment. This was repeated 10 times with the same environmental data and after each measurement the sample was also brushed with a grounding wire to disperse excess space charges. While the averages showed a more significant disparity in magnitude, the high ramp rate of 12.0 kV/s held the higher withstand voltage of 32.8kV versus 30.33kV. This does seem to be skewed by the first half of the measurements, and in later tests there seems to be a trend reverting to the mean around 33kV. The discrepancy in the average is less than 10% of either withstand voltage, which does not suggest that this single factor alone has a significant impact.

The results of these tests suggested a minimal, if not nonexistent difference between having a slow ramp rate and a significantly higher one. Regardless of the existence or nonexistence of this minimal distinction between the two ramp rates, this result was taken as license to carry on taking measurements without a true step function of voltage, under the assumption that this ramp rate wouldn't be of sufficient importance as to change fundamentally the results of breakdown characteristics.

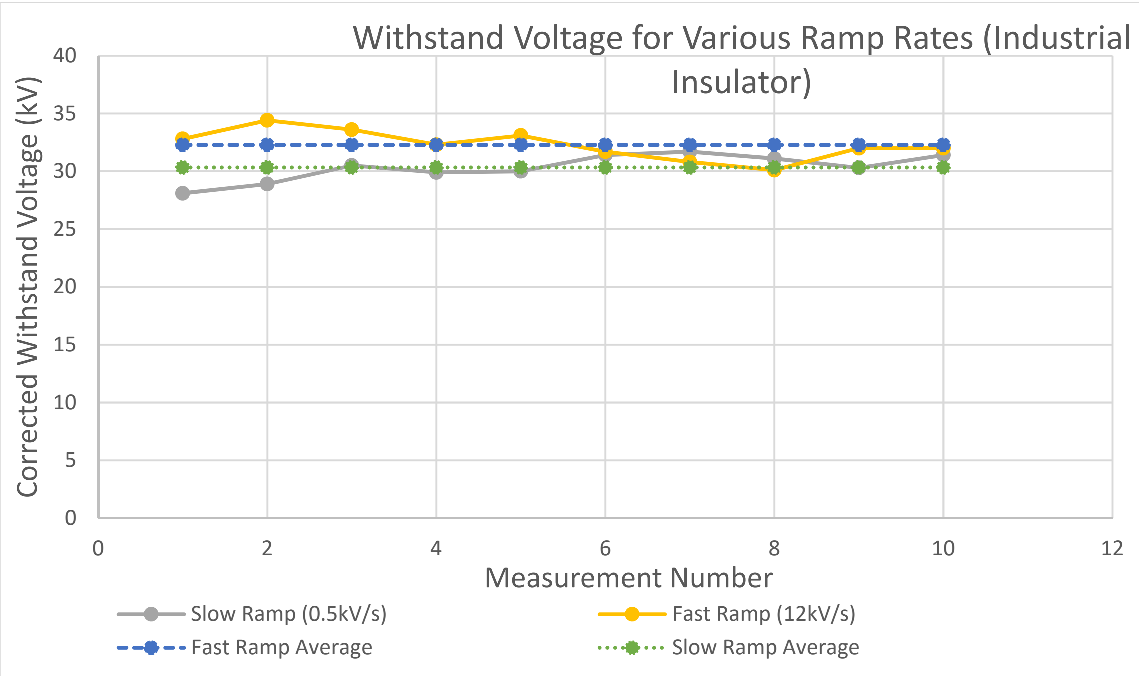

Figure 6: Data using the same test procedure but on the industrial insulator

5 The Impact of Space Charge Accumulation on Breakdown

To observe the effects of the accumulation, breakdown tests were completed upon the cylindrical insulator which was held for 4 minutes at a given voltage in order to allow for the accumulation of space charges. This experiment was repeated on the same spacer but the rise in voltage occurred immediately, as opposed to after the four-minute wait. The difference in average breakdown value between the instantaneous and delayed experiments allowed for observation of the effect the four minutes had on the withstand voltage of the spacer and gave some indication as to how the four minutes of space charge accumulation affected the system overall. The lack of a true step function in voltage was a large concern for investigating space charge effects, but this was of less concern after seeing that space charge dissemination into the ambient occurs in the time frame of minutes according to research done by researchers at the Georgia Institute of Technology. Figures 5 and 6 both represent the same COMSOL

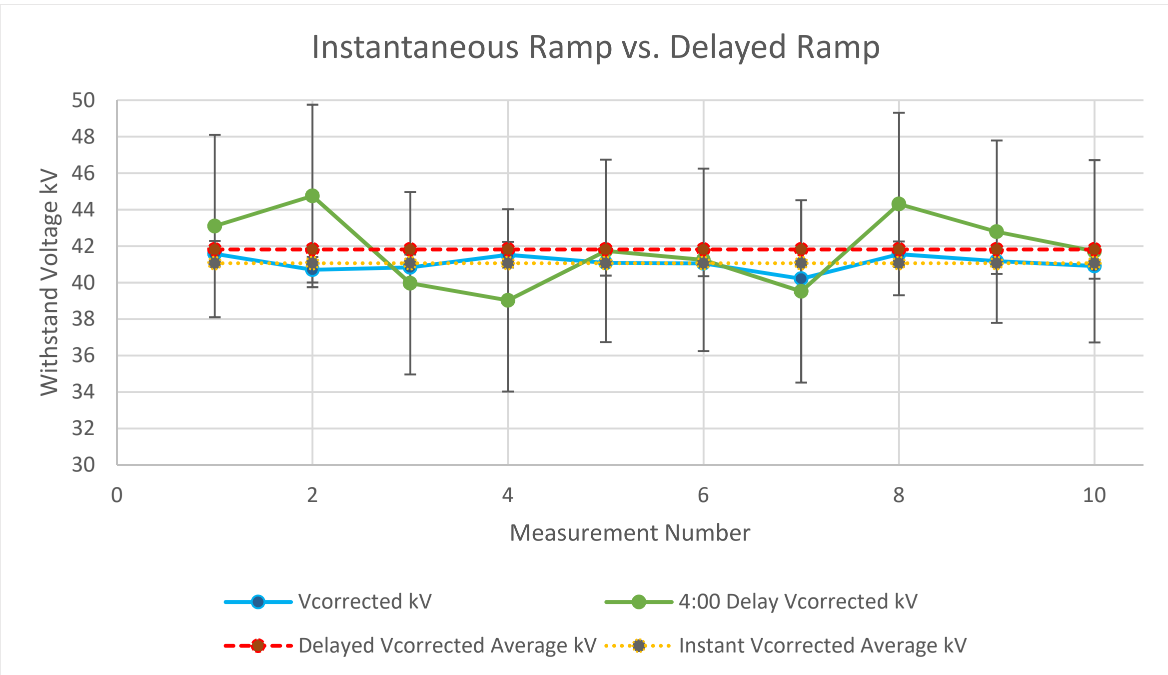

Figure 5: Comparison in withstand voltages between an insulator left to accumulate space charges and one which underwent voltage ramping immediately.

simulation of the electric field along the insulator in different ways. Figure 6 shows the shape and strength of the field itself, while Figure 5 shows solely the radial component of the electric field. The lack of uniformity of the radial component of the electric field would then indicate a buildup of space charges in and around the area of high field strength and could alter the withstand voltage of the system overall. This accumulation of space charges could also have an effect on the electric field and could result in field instability. Testing the effects of space charge accumulation was done by initially finding the system's "withstand voltage". This was done by finding the lowest voltage at which no breakdown would be observed for 10 consecutive minutes. This was done to give an approximate idea as to the withstand voltage for the system overall as well as giving a baseline off which to base the voltage hold. The insulator was then taken to 70% of the voltage found and left to wait 4 minutes in order to accumulate space charges. This setup would then have its voltage increased at 12kV/s until the system broke down. The same physical setup would then be immediately subjected to the 12kV/s ramp rate, until breakdown occurred. This method of testing allowed us to directly compare the effects of leaving the sample for some minutes to accumulate space charges to the sample being immediately subjected to voltage. The time frame necessary for the accumulation of space charges is not entirely clear, and four minutes may prove to be an insufficient amount of time. Four minutes was chosen in this case solely due to its correspondence with another test's procedure. Figure 5 shows the results from this test.

The average of the withstand voltages for the delayed tests was 41.81kV. The average of the withstand voltages for the instantaneous tests was 41.06kV. This is a 1.8% difference where the test allowing for space charge accumulation had the higher average. Of note was the fact that the space charge covered insulator had a wider spread of withstand voltages than the insulator without space charge buildup. This instability could be simply a question of variance, but it may be signal of instability caused by the charge accumulation. Since the goal of these investigations is to get an idea of the effects of certain factors on the stability of the system, these results show a distinct destabilizing effect from the accumulation of space charges, left to accumulate for just 4 minutes. This is clearly indicative of there being a necessity to investigate further the effects of space charge accumulation, as the instability suggested by these data would have a significant impact on any creepage and clearance standards associated with the insulators.

6 EFFECT OF POLARITY INVERSION ON BREAKDOWN

Discussion of the results seen in section 2.4 with other researchers brought about yet another question. There was a concern as to whether the accumulation of space charges could seed instability across an insulator experiencing a total polarity inversion. There have been computer models of shipboard DC power systems which indicate that in some fault scenarios a large polarity inversion of the voltage is possible. This seemed initially to be a relatively difficult voltage effect to achieve as there was only one DC power supply available. This problem was resolved by the development of a circuit which utilized a pneumatic switch, which achieved negative voltages of approximately 86% of the initial positive voltage. The pneumatic switch was controlled by an air compressor outside the Faraday cage connected through a small hole in the wall of the cage. The process for the polarity inversion testing was similar to that of the space charge accumulation testing. Initially, the withstand voltage of the insulator system was determined by finding the lowest potential at which the system would not undergo breakdown for 10 consecutive minutes. This was done by starting at a voltage where the system breaks down immediately and then lowering the voltage by 0.1 kV at a time until the 10 minute threshold was met. Once the withstand voltage was determined the insulator was taken to 70% of its breakdown potential and held for 4 minutes in order to allow for the accumulation of space charges. After the four minute hold, the voltage was taken up to 1kV less than the breakdown voltage, and the pneumatic switch was triggered. The insulator would then be exposed to the inversion of the voltage polarity, down to approximately negative 86% of the positive initial voltage. This test was repeated over 60 times with the variations of having various thermal gradients, different materials, and a different geometry and a breakdown occurrence was never observed after the pneumatic switch engagement (switch shown in figure 4, above). There were some breakdowns observed but they all occurred in between the time that the 4 minutes passed and when the pneumatic switch was engaged simply due to the system being just 1kV under its withstand voltage. While this is strongly indicative of the polarity inversion not being a substantial or burdensome problem for the insulator system, the time which was

Figure 7: The pneumatic switched used to insight polarity inversion

allowed for space charge accumulation was only four minutes – orders of magnitude smaller than the operating times expected for such devices.

7 EFFECT OF THERMAL GRADIENT ON BREAKDOWN

The effects of temperature on surface charge and flashover characteristics have been shown to have relatively high impacts on the withstand voltage of the DC system. [8] While the temperature itself is evidently an important factor, the potential of having a temperature gradient in a system is entirely possible, particularly in shipboard applications. There are various shipboard applications where the thermal characteristics of a system will not be entirely environmentally based. This might be seen particularly in closed systems which don't receive ample opportunity for convectional air currents to cycle away heat losses, and the potential for hotspots is increased. These closed systems with high heat loss

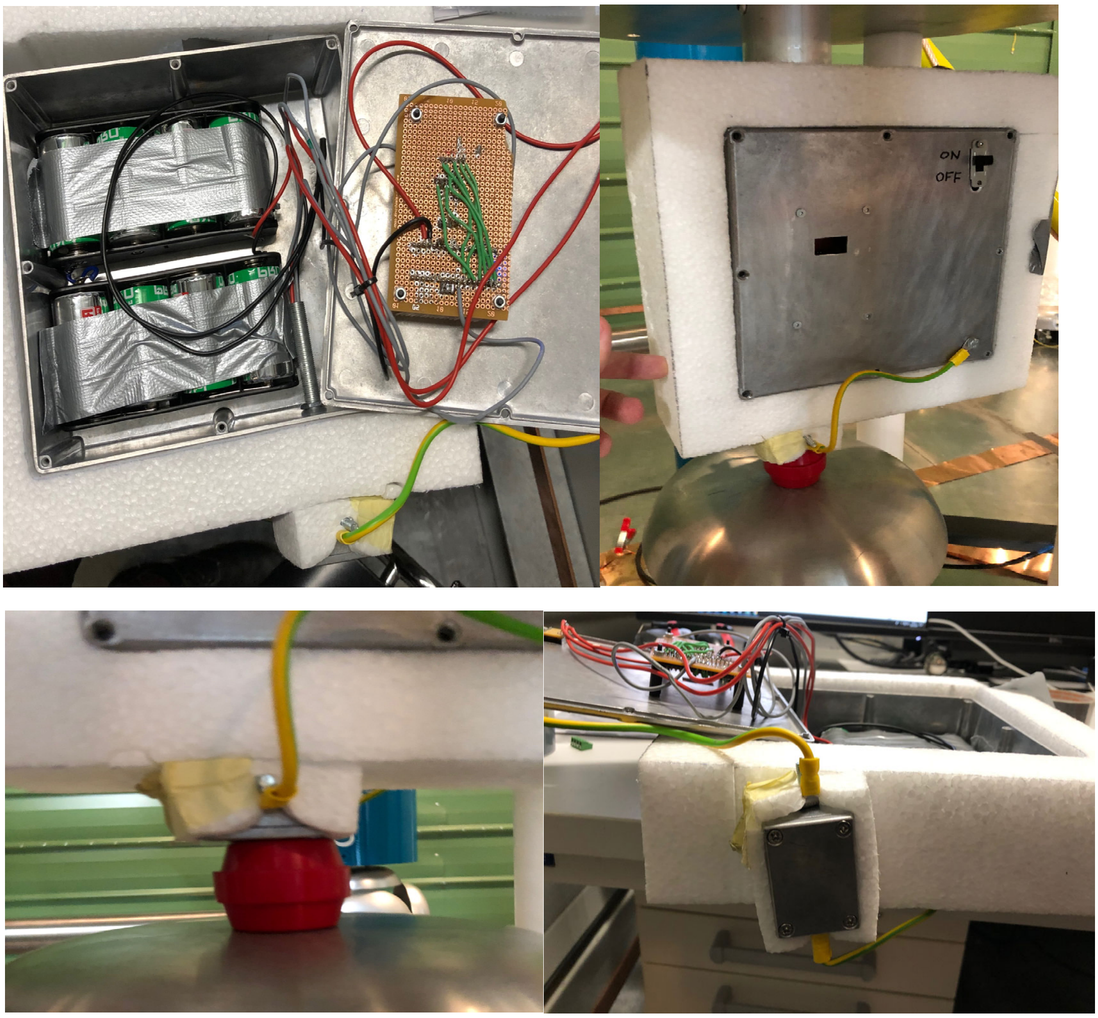

Figure 8.1 (Top Left), 9.2 (Top Right), 9.3 (Bottom Left), 9.4 (Bottom Right): 9.1 – Opened housing for batteries and Arduino Circuit, 9.2 – Wide shot of full setup, 9.3 – Closeup of heating element on insulator, 9.4 – Closed housing of heating elements with background of open battery housing.

also tend to be areas of high power density within the ship, like MMCs (Module Multilevel Converters) or PEBBs (Power Electronic Building Blocks). These are both areas within a ship which can build up thermal losses due to ohmic heating, and heat flow models of PEBB modules show the potential of developing hotspots up to 80°C. Much of the heat accumulates at the top of the enclosure within the PEBB block. This

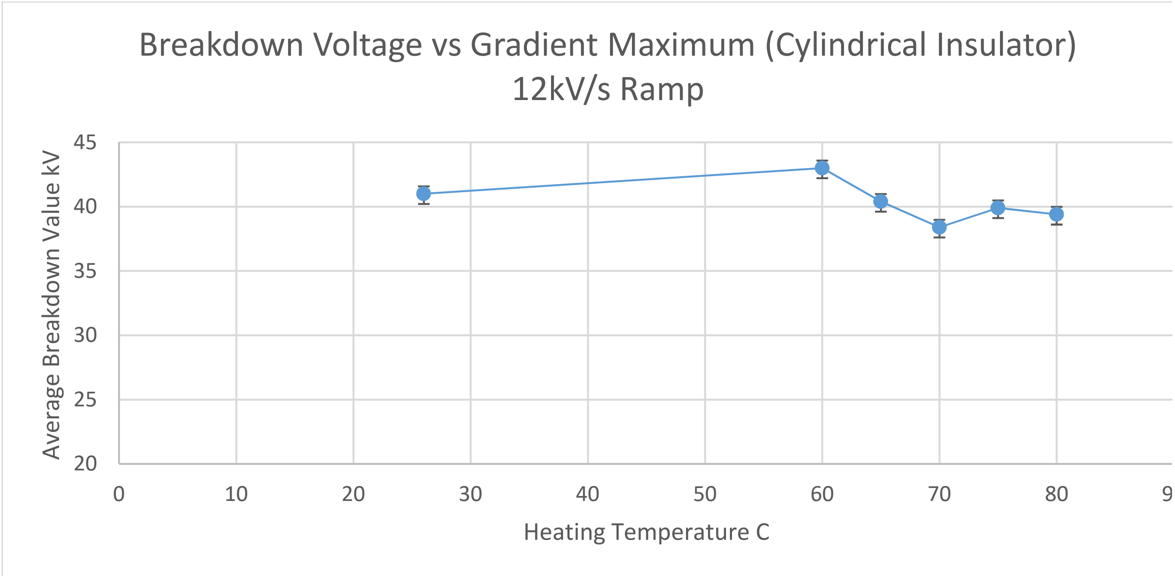

Figure 9: Data from thermal gradient breakdown measurements, only breakdowns at 12kV/s included

accumulation means that the top side of the PEBB accrues lots of heat, potentially creating a hotspot on an insulator. These hotspots are not necessarily indicative of a uniform temperature field, in fact they imply more the appearance of a temperature gradient. While the exact profile of this gradient is not entirely clear, it would certainly be dynamic due to convectional currents within the PEBB system. The maximum temperature expected from this gradient would be approximately 80°C. This portion of the investigation focused on the effects of a thermal gradient on breakdown. There were some engineering difficulties which arose in the development of a setup which was capable of forming a consistent gradient as well as being able to run for hours on end. The design (shown in Figures 9.1 – 9.4) needed to be easily alterable, in order to change the required heat setting. It needed to be relatively lightweight, in order to allow it to be compatible with the experimental setup. It also needed to have a way of communicating the temperature being tested, in order to ensure a proper gradient was reached. These design constraints were met by using 8 rechargeable D batteries sealed within a metal box alongside an Arduino Nano computer. This computer was connected to a thermal probe which was placed near the MOSFET transistor and resistor which served as heating elements. The Arduino was programmed to simply engage the heating elements while reading a temperature below the desired temperature and disengage when reading too high of a temperature. The setup itself was wedged between the conductors and had some physical instability – it fell multiple times throughout the weeks of testing. The metal housing protected all the electrical components and the worst consequence of these falls was simply having to open the box and push the batteries back into place. The instability of the setup meant that it couldn't sit properly on top of the insulator and had to be wedged slightly to the left in order to stay stable – see Figure 9.3. In testing the effects of having a thermal gradient, testing was done on both the polycarbonate cylinder as well as a commercial insulator. The tests were done by rising the plate temperature to the given heating level and then increasing the voltage across each insulator at a rate of 12kV/s until breakdown was observed. Once breakdown was observed the environmental data as well as the voltage level was recorded. The hypothesis for the effect of introducing the thermal gradient was initially that this would result in strictly decreased average breakdown values, as the increased average kinetic energy of particles in the higher temperature air would lead to a higher likelihood of initiating the avalanche necessary in the Townsend mechanism. The graphs observed were not at all following such a simple theory (See Figures 10 - 12). Initially in both datasets, one for the cylinder and one for the commercial insulator, the breakdown voltage increases with a small gradient of 60°C. The behavior thereafter becomes somewhat divergent and unpredictable, with neither of the two showing any strong linearity. These results are clearly very interesting and while they aren't conclusive in dictating the presence of a pertinent effect, they do

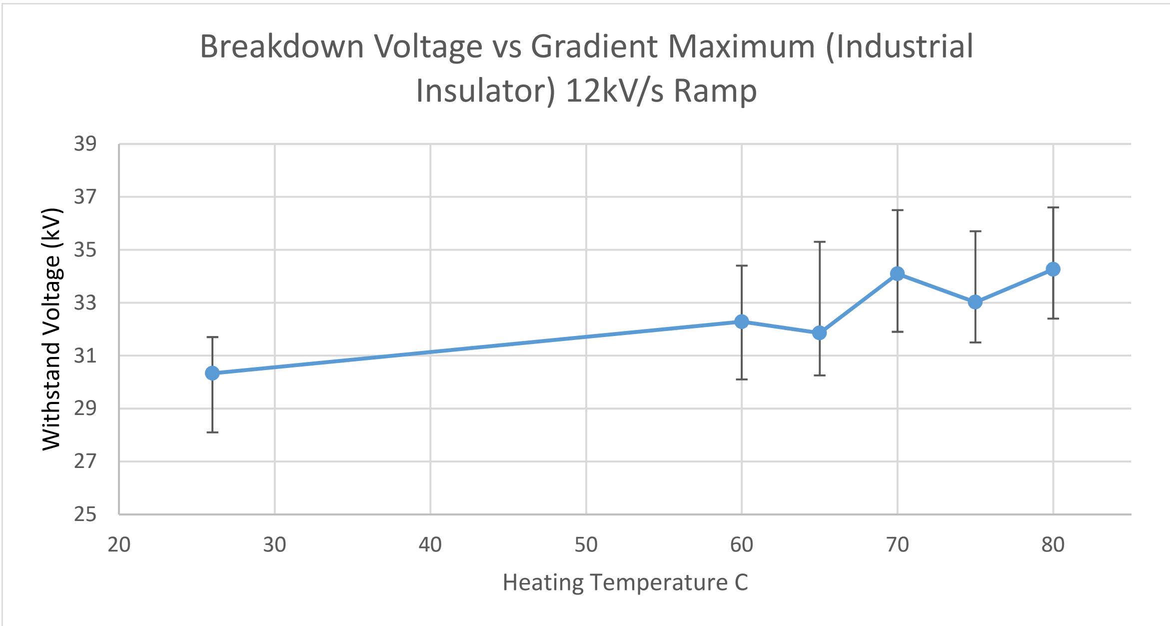

Figure 10: Data from thermal gradient breakdown measurements on the industrial insulator instead of the cylindrical insulator

show that even with quite low power heating, relatively significant effects can arise in the breakdown mechanism. The impact of both a temperature gradient as well as a uniform temperature field should be considered in any development of creepage and clearance standards. The gradient which was used in these experiments was likely very steep, since the power induced was limited to the losses from the metal heating plate into the ambient, the temperature gradient likely dissipated quite quickly into the large volume of air in the room temperature faraday cage. In order to have a more realistic experiment and in such more realistic results, the insulator should be subjected to a less steep gradient. The ambient temperature inside of a PEBB, which must have an ambient temperature considerably higher than room temperature due to the high heat losses from the power electronics it holds. Given this, the actual gradient experienced by insulators within the PEBB would be less steep, and would also have a higher overall temperature, and therefore higher overall average kinetic energy of free electrons and ions.

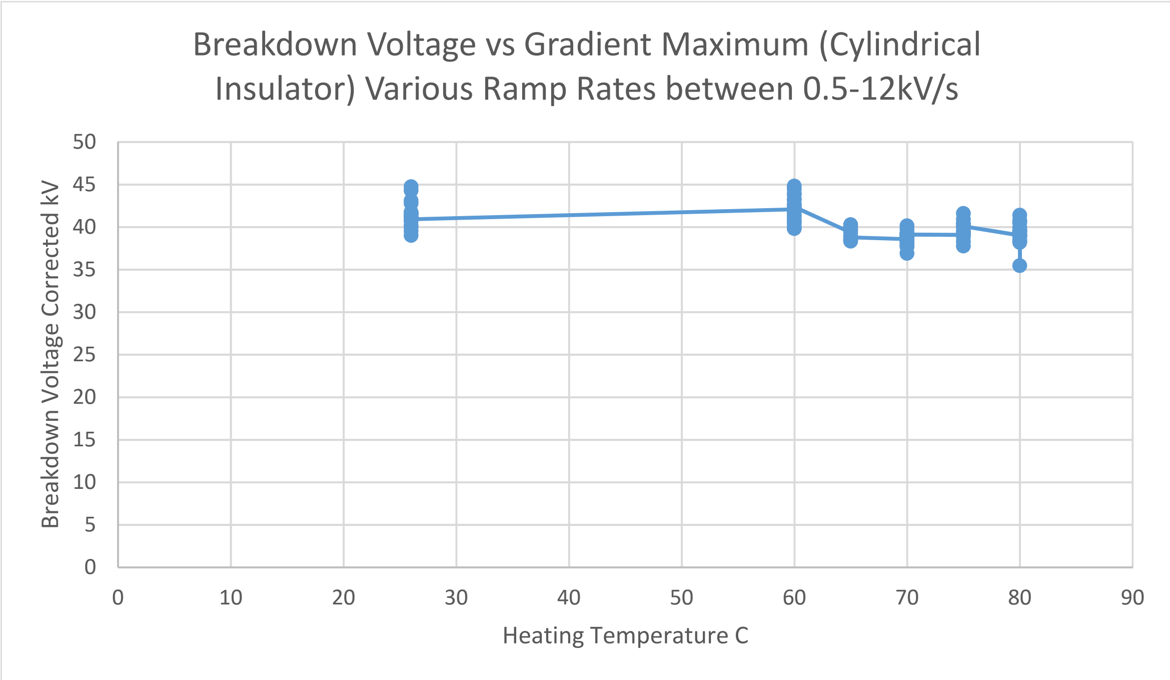

Figure 11: Withstand voltages of the cylindrical insulator at each given heating level, tests occured across a range of dV/dt between 0.5kV/s and 12kV/s

Multiple rounds of testing were done at various voltage derivatives, Figure 10's data set represents only tests done with a 12kV/s ramp, while Figure 11 is a combination of all different voltage ramp rates – all of which fall between 0.5kV/s and 12kV/s - combined. The similarity between the trends in the graph is striking and supports the notion of a system's thermal characteristics being important factors to consider. The effects of the thermal gradient seemed to be dependent on the material used. A comparison of Figure 10 and Figure 11 - which discuss the effects on the cylinder and industrial insulator respectively – shows a clear difference in the effect of the introduction of the thermal gradient. The industrial insulator appeared to marginally improve its dielectric properties, while the polycarbonate cylinder had somewhat diminished dielectric strength as the gradient steepened past 60℃.

8 CONCLUSION

For the most part, the data was indicative of there being a lack of striking impact from any of the test factors. For our testing into the impact of ramp rate on breakdown potential, we saw no significant differences between 0.5kV/s and 12kV/s breakdown tests, this difference in ramp rate while not insignificant, is many orders of magnitude smaller than a true spark. Our expectation of there not being significant difference was correct albeit not entirely relevant. Any real impact held by the magnitude of the ramp rate would likely be much more pronounced in testing done with a true step function. While it is fair to conclude there would be no significant difference between our two ramp rates of 0.5kV/s and 12kV/s, it is unreasonable to fully extend these results to apply to spark “ramp rates” many orders of magnitude higher. The investigation into the effects of the accumulation of space charges was equally indeterminate. While the data observed showed no significant variation based on the accumulation of space charge, there aren’t enough data points to make a solid conclusion. In addition, the amount of time which the insulators were left to accumulate space charge was quite short at only 4:00 minutes, this time frame is not reflective of the stresses of a true shipboard scenario. The variance shown in the breakdowns which had been left to accumulate space charges may be an indicator of a larger macro effect being developed. Particularly across the lifetime of an insulator, the accumulation of space charges could prove to be much more significant factor than what was observed under our conditions.

Among the more conclusive tests was the polarity inversion testing, which saw no breakdowns whatsoever even for a ninety percent voltage inversion. Given that under typical breakdown conditions withstand voltage can have breakdown possibility within 50% of breakdown voltage is indicative of the factors tested in this investigation not being of sufficient significance as to be considerable from the perspective of developing creepage and clearance standards. It should be considered that the time held to accumulate charge carriers was only 4 minutes, which is significantly less than the lifetime of a warship. The time frame during which charge carriers are left to agglomerate is a potential problem with the assumption of polarity inversion being an insignificant factor.

The effects of implementing a thermal gradient onto the system were deeply interesting particularly in their incongruence with respect to material used. The profiles of the voltage curves were expected to decrease as the temperature went up, due to there being a higher average kinetic energy of charge carriers which was expected to increase the likelihood of a Townsend avalanche commencing. This didn’t appear to be the case, or at least it was not the whole story. The variations in the conductivity of the material due to the thermal gradient likely lead to field distortions along the insulator. Clearly these other factors determine what the impact of a thermal gradient will be on a system. The difference in the profile of the cylindrical insulator and the industrial insulator show that either due to material or geometry some factor has changed the overall impact of the gradient. It is important to recall that the overall temperature field experienced by the insulator was not necessarily comparable to that which would be experienced in a shipboard scenario. There were no effects which showed the potential of shifting the breakdown voltage by over 25% of the withstand voltage. All the effects seen in this investigation would easily be shifting the mean breakdown value within the window of breakdown potential. In the Navy’s push to maximize space efficiency and develop new standards however, these effects could be very relevant. Continued research is both warranted and necessary.

9 FURTHER RESEARCH (OUTLOOK)

There are various topics from this report into which research should be pursued and there are various other factors to consider in establishing DC voltage standards. In particular, accretion of pollution on insulator surfaces is an interesting topic given the difficulty of developing a systemic method of achieving uniform and easily producible pollution which is relevant to a shipboard scenario. Some investigation into this has occurred and it is possible to predict the breakdown characteristics of an insulator depending on the level of salt pollution it sees. [10] The insulators used in this experiment were nearly exclusively polymers. A series of experiments providing variation of the material used in insulation would be interesting and could provide insight into the extent to which material selection effects breakdown initiation characteristics. This variable proved to be of great interest in the discrepancies shown in section 7. One big point of concern with the data collected in this investigation was that the time necessary for data collection was much too high. Being able to automate in some capacity the breakdown measurements would be greatly beneficial to experimentation purely by enabling the possibility of deeper sample sizes to be examined. With processes as stochastic as breakdown, having a large sample size is the only way to increase resolution on the impact changing variables has.

For the thermal gradient testing, the curve observed from our tests was deeply interesting and its nonlinearity likely indicates the fluctuating significance of the influence of various physical phenomena. The differences in withstand voltage were quite small, however it seems that maintaining solely a temperature gradient is insufficient to fully test the conditions expected to be observed within the confines of Power Electronic Building Block units. The power being emitted from the hot plate on our thermal gradient device was clearly much lower than the total power emitted from ohmic losses within PEBB units. The testing also did not take place in a tightly closed environment. The convectional flows in a smaller volume would be different within PEBB units and would cause higher overall temperatures within the volume. The combination of these factors suggests the importance of studying the hybrid effect of a temperature gradient as well as an elevated temperature uniform throughout the PEBB. A gradient of 80℃ into a uniform temperature field of 50℃ would be an interesting scenario and could show stronger influence on the withstand voltage of the system. For the question of inverted polarity, more time should be dedicated to the accumulation of space charges. Even though no breakdowns were observed in our tests on polarity inversion, the time these systems had been left to accumulate charge is not sufficient to consider the question irrelevant.

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