Paschen Breakdown in a CO_2 Atmosphere

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Paschen Breakdown in a CO_2 Atmosphere

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This report observes and analyzes the effect the pressure and gap distance have on the minimum positive breakdown potential between two parallel plate copper electrodes in both air and CO_2. Two gap distances, 0.57 cm and 2.44 cm, were used. Paschen Curves generated in air from these distances had a strong positive correlation with a Spearman correlation coefficient of 0.97. Curves generated in CO_2 had a Spearman correlation coefficient of 0.87. The strong correlation for both gases verifies Paschen's Law. The minimum breakdown potential in air was 361 ± 2 V at a pressure x gap distance of 0.55 ± 0.01 Torr cm. The minimum breakdown potential differs from published data by 2%. The pressure x gap distance differs from published data by 17%. This verifies the Cal Poly Paschen Breakdown Apparatus and procedure. The minimum breakdown potential in CO_2 was 540 ± 20 V at a pressure x gap distance of 0.5 ± 0.1 Torr cm. The minimum breakdown potential differs from published data by 4%. The pressure x gap distance differs from published data by 67%. Differences between the pressure x gap distance results and published data suggest that electric field concentrations present at the edges of the electrodes cause the apparatus to behave as though the electrodes are closer together.

Nomenclature

δ_i	=	error in the i^{th} generic value
PG	=	pressure x gap distance (Torr cm)
P	=	pressure (mTorr)
x	=	gap distance (cm)
y_{wav}	=	weighted average of a generic value
y_i	=	i^{th} generic value
w_i	=	weight of the i^{th} generic value

I. Introduction

THE United States has deployed 7 successful surface missions to Mars, two of which, MSL and Opportunity, are still operating. By the end of the decade NASA plans to add Insight and a refly of MSL to the surface of Mars.[1] It is becoming increasingly important to understand the environment on Mars and its impact on hardware.

One area of concern is electric breakdown between electrical components. Components can become charged from internally generated currents and through interactions with the environment. From the environment, plasma deposits charges on the outer surface of vehicles and dust, blown by the wind, can charge a component through the triboelectric effect. Charging from dust was observed on Mars Pathfinder.[2] However the component is charged, the net effect is a potential difference between two or more components. A breakdown occurs when this difference becomes too great. Breakdown energies on the order of several mJ are enough to cause damage.[3]

In the year 1889, Frederich Paschen discovered that the voltage necessary for breakdown to occur between two electrodes in a gas is dependent upon the pressure and the distance between the electrodes.[4] Through experimentation, curves are created that relate the pressure and electrode gap distance to breakdown voltage. These are called Paschen Curves. These curves are used in designing components. For a given environment, Paschen Curves show the maximum allowable potential difference between any two components. In designing a component or vehicle it is important to consider these curves and ensure the potential difference throughout remain low enough so that no breakdown events occur.

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Separate gases have separate Paschen Curves. Mars has an atmosphere composed mostly of CO_2. The composition is 95.3% CO_2, 2.7 % N, 1.6 % Ar, 0.13% O_2, 0.07% CO. 0.03% water vapor, and the rest trace gases.[4] It is difficult and expensive to create a Mars gas mixture. However, Mars gas and pure CO_2 have comparable Paschen Curves.[4] This allows for high concentration CO_2 gas mixtures greater than, 95% CO_2, to be used to simulate the Martian environment.

The surface pressure at Mars is approximately 1/100th the surface pressure at Earth. Pressures on Mars range from 5 Torr to 12 Torr.[4] During entry, descent, and landing (EDL) a lander or rover will experience pressures ranging from near vacuum to 12 Torr. The reverse is true for launch. During launch the launch vehicle and spacecraft experience 760 Torr to near vacuum. It is inevitable that a pair of conducting materials separated by a small gap will experience the pressure x gap distance where the minimum breakdown voltage occurs. Understanding what the minimum breakdown voltage is and at which pressure it will occur at enables the designer to mitigate the effects or eliminate the possibility of breakdown.

This experiment will verify Paschen's Law using the Cal Poly Paschen Breakdown Apparatus. Paschen Curves will be created at varying gap distances using both air and CO_2. The results will be compared to published data to validate the testing apparatus and procedure.

II. Apparatus and Procedures

A. Electrical Setup

The Cal Poly Paschen Breakdown Apparatus electrical schematic is shown in Fig. 1. Power is supplied using the Glassman High Voltage Power Supply. This supply is able to provide positive voltages up to 1,000 V. This setup uses a parallel plate electrode configuration. The anode and cathode are 2.5 cm x 2.1 cm copper plates. The distance between the plates can be adjusted between 0.5 cm and 11 cm. Voltage measurements are made using a PicoScope 3024A oscilloscope. The scope is protected using a 10,000:1 voltage divider. Multiplying the scope measurement by 10,000 will obtain the true voltage. The oscilloscope measures the voltage at the moment of breakdown accurate to 1 V. The anode and cathode are surrounded by a stainless steel Faraday cage. This prevents arching from the anode to the chamber walls. The convectron gauge controller is grounded to the chamber.

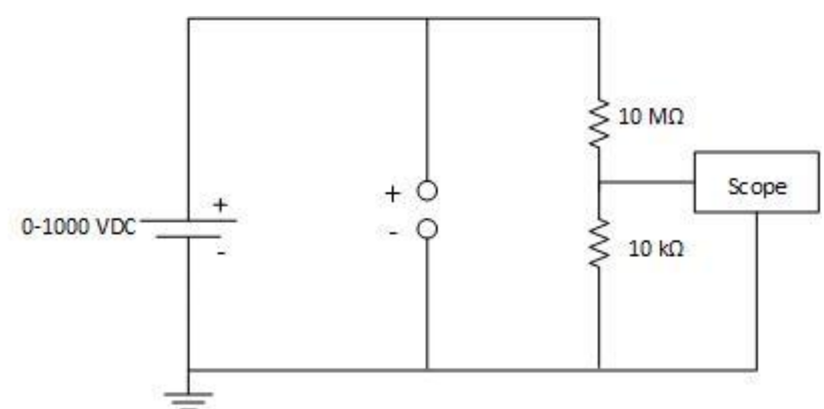

Figure 1. The Cal Poly Paschen Breakdown Apparatus electrical schematic.

The voltage rating on the electrical feedthroughs is unknown. The industry standard is 500 V. It is reasonable to assume the feedthroughs used in this setup have this rating. Arcing from the positive feedthrough to the chamber has been observed at potentials greater than 500 V. The frequency is low for potentials between 500 and 600 V. At higher potentials, however, the frequency increases and care must be taken the ensure the arc that triggers the scope is between the electrodes not the feedthrough and the chamber.

A note about grounding: The power supply return, oscilloscope, and Faraday cage must be grounded to earth ground. Improper grounding can result in ground currents that can harm the oscilloscope. The scope Picoscope 302A connects to ground through the laptop power cord. The laptop must be plugged into an outlet that uses the same ground as the Glassman High Voltage Power Supply. If this is not done, the laptop, voltage divider, scope, and fuse box will all be floating, risking damage to any of these.

B. Experimental Chamber

The Cal Poly Student Chamber I is used to house the Paschen Breakdown apparatus. Figure 1 shows a schematic of this chamber. The chamber is 17 inches in diameter and 24 inches tall. A Welch 1397 Duo Seal Pump is used to pump it down. The base pressure is approximately 0.5 mTorr. One Granville-Phillips 275 convectron gauge and one InstruTech CVG101 convectron gauge are used to measure the pressure at the electrodes and the pump adapter respectively. A Granville-Phillips Series 316 Convectron Gauge Controller displays the pressures. For pressures above 1,000 mTorr the convectron gauge controller is accurate to 10 mTorr. For pressures between 100 mTorr and 1,000 mTorr the controller is accurate to 1 mTorr. At pressures below 100 mTorr the controller is accurate to 0.1 mTorr.

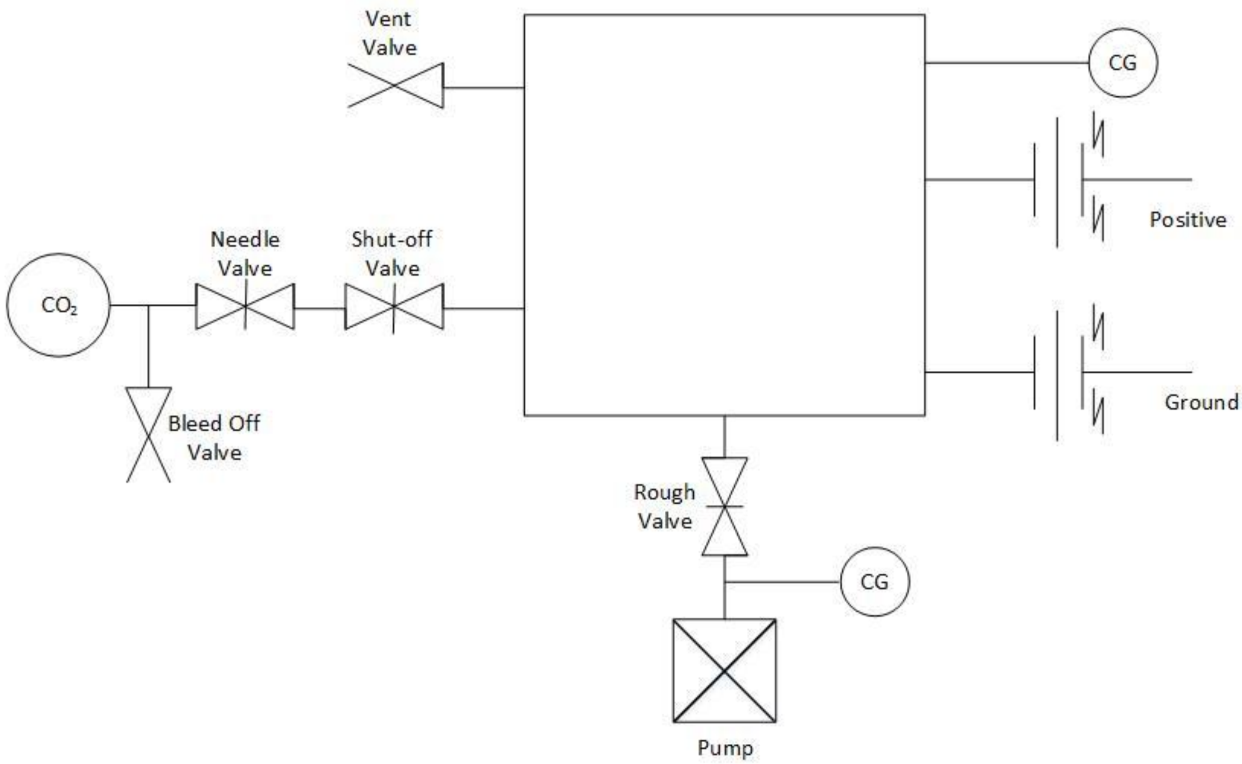

Figure 2. Cal Poly Student Chamber I vacuum schematic. *CG stands for convectron gauge.*

C. Procedure

Two electrode plate gap distances were used: 0.57 ± 0.03 cm and 02.44 ± 0.03 cm. The gap distance was measured using a pair of dial calipers. Though the calipers are accurate to 0.001 in. (0.003 cm), the flexibility of the stand holding the electrodes make the accuracy of the measurement approximately 0.01 in., or 0.03 cm.

The procedure varied slightly whether the test was done in air or in CO_2. These differences were only in obtaining the desired pressure. The electrical portion of the experiment was performed the same regardless of the gas used.

For tests in air, the Cal Poly Student Chamber I was pumped down to its base pressure (~1 mTorr). See Appendix A for the detailed procedure. Starting at a pressure greater than 3,000 mTorr the roughing valve was opened until the desired pressure was reached. The pressure was varied between 3,000 mTorr and 300 mTorr at 100 mTorr intervals for the 0.57 cm gap distance. For the 2.44 cm gap distance the pressure was varied between 750 mTorr and 75 mTorr at 25 mTorr increments. The pressures were kept within 5 mTorr of the target pressure for pressures below 1,000 mTorr. For pressures above 1,000 mTorr the tolerance was 10 mTorr. The reading on the controller was kept at the desired pressure. After each voltage measurement the roughing valve was opened until the next desired pressure was reached. This process was repeated until the final measurement was taken at the lowest pressure in the interval.

For CO_2, the Cal Poly Student Chamber I was pumped down to its base pressure. The chamber was purged of air with CO_2. Appendix B details the purging procedure. Voltage measurements were taken at pressures between 3,000 mTorr and 300 mTorr at 100 mTorr intervals for the 0.57 cm gap distance. For the 2.44 cm gap distance the voltage measurements were taken between 475 mTorr and 75 mTorr at 25 mTorr increments. The pressures were kept within 5 mTorr of the target pressure . Starting at a pressure greater than 5,000 mTorr the roughing valve was opened until the pressure dropped to the first desired pressure, 2,500 mTorr for the 0.57 cm gap distance and 475 mTorr for the 2.44 cm gap distance. For pressures above 1 Torr the chamber was pumped down to a pressure 500 mTorr below the desired pressure. The pressure was increased 500 mTorr to the desired pressure by flowing CO_2 into the chamber. This ensured the concentration of CO_2 was greater than 95%. After each voltage measurement the pressure was lowered to the next desired pressure using the same process of lowering the pressure 500 mTorr below the target and raising the pressure with CO_2. At pressures below 1 Torr the chamber was operated with the valve between the pump and the chamber partially open. Due to the leak rate of the chamber (1.4 mTorr per minute) it was necessary to flow CO_2 into the chamber at a rate greater than 140 mTorr per minute to keep the concentration of CO_2 greater than 99%. The procedure for calibrating the CO_2 flow rate is found in Appendix C.

The oscilloscope was set up so that the x-axis (time) had 200 ms per division. The y-axis (voltage) was set to display ± 100 mV. The scope trigger was set to trigger at 25 mV at the falling edge with a pre-trigger time of 70%. This means that the scope triggered when the potential between the electrodes dropped below 250 V. The waveform was recorded such that 70% of the waveform was before the trigger.

The Glassman High Voltage Power Supply was turned on. The current dial was set to the maximum, 10 mA. Once the desired pressure was reached, the voltage was set to 300 V. The scope was then set to trigger. The order the voltage was raised and the trigger was set was important. If the trigger was set before the voltage was raised to 300 V then the scope would trigger as the voltage was increased from 0 V. The voltage was slowly raised until breakdown occurred. This event was indicated three different ways: the Glassman display showed a current, the oscilloscope triggered and displayed the waveform, and observing the electrodes and seeing an arc or plasma between them. The pressure was recorded. The voltage was recorded using the scope display. A 100 Hz low-pass filter was used to filter out the noise in the waveform. Using the oscilloscope software, the potential difference right before the first arc or corona occurred was measured by zooming in on the waveform. The power supply voltage was lowered to 0 V. The waveform was saved. The pressure was lowered to the next desired pressure. This procedure was repeated until voltage measurements were taken at all pressures in the interval. If the pressure moved outside the tolerance before breakdown occurred, the voltage was set to zero, the scope trigger turned off, and the pressure was adjusted to the tolerance for the desired pressure. The voltage measurement was made using the procedure outlined above. In order to ensure that the first arc did not occur at the feedthrough the operator watched the feedthrough for signs of plasma when the potential was greater than 500 V.

Once all measurements had been taken the current and voltage dials on the power supply were set to zero and the power supply was turned off. If the test used CO_2 the flow was shut off and the CO_2 line depressurized. The Cal Poly Student Chamber I was shut down following the procedure in Appendix A.

A run is a series of pressure and voltage data with one voltage measurement at each desired pressure. A set of data is the combination of the data for all runs for a specific gap distance and gas. Five runs were performed for the 0.57 cm gap distance configuration in air. Three runs were performed for the 2.44 cm gap distance in air. In CO_2, three runs were performed for the 0.57 cm gap distance and for the 2.44 cm gap distance.

III. Analysis

Each set of data contains at least three pressure measurements with corresponding voltage measurements per desired pressure. The voltage measurements were not taken at the exact same pressure. For pressures below 1,000 mTorr the pressures were averaged. The error was found by calculating the standard deviation. For pressures above 1,000 mTorr the convectron gauge controller displayed the pressure to the nearest 10 mTorr. The recorded value was used as the averaged value. The error in this case is 10 mTorr. The voltage value at each pressure the recorded values were averaged. The error in these voltage measurements was found by calculating the standard deviation.

The pressure x gap distance was found using

$$PG = 1000Px \tag{1}$$

where *PG* is the averaged pressure x gap distance in Torr cm, *P* is the averaged pressure in mTorr, and *x* is the gap distance in cm. The error in the averaged pressure and gap distance were propagated to determine the error in the pressure x gap distance.

The averaged voltage was plotted against the averaged pressure x gap distance for a total of four Paschen Curves, two for air and two for CO_2. The minimum breakdown voltage, with the corresponding pressure x gap distance, were determined for each curve.

The minimum breakdown voltage and corresponding pressure x gap distance were compared for each gas. The best values for the measurements were found one of two ways. If the errors in the measurements overlapped then the best value for the potential difference and the best pressure x gap distance were found using a weighted average. The weighted average of a value is calculated by

$$y_{wav} = \frac{\sum w_i y_i}{\sum w_i} \tag{2}$$

where y_{wav} is the weighted average, y_i is the ith value, and w_i is the weight of the ith value. The weight of the ith value is found using

$$w_i = \frac{1}{\delta_i^2} \tag{3}$$

where δ_i is the error in the ith value. [5]

If the errors in the measurements did not overlap then the values were averaged to find the best value. The error in the best value was the standard deviation of the measurements.

IV. Results and Discussion

A. Air

The measurements for the two gap distances are shown in Fig. 3. These curves are not Paschen Cuves; the x-axis has not been converted to pressure x gap distance. As the gap distance decreases the curve shifts to the right and becomes wider. Changing the gap distance does not affect the minimum breakdown voltage.

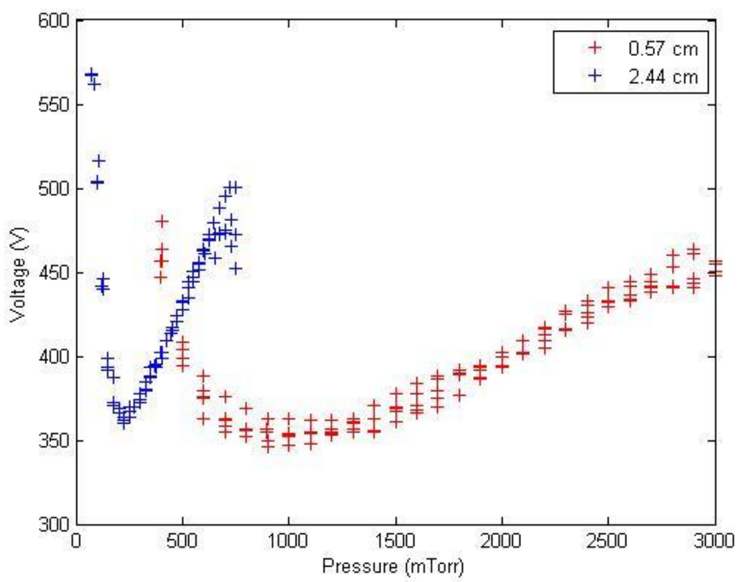

Figure 3. Voltage versus pressure in air. *Unaltered measurements.*

Figure 4 shows the Paschen Curves for each gap distance. The data from Fig. 3 is averaged and the x-axis is converted to pressure x gap distance. The two curves have a strong positive correlation with a Spearman correlation coefficient equal to 0.97. This confirms Paschen's Law. The two points of interest are the minimum breakdown voltage at the bottom of the curves. For the 0.57 cm gap distance the minimum voltage is 354 ± 6 V at a pressure x gap distance of 0.56 ± 0.03 Torr cm. At a gap distance of 2.44 cm the minimum voltage is 362 ± 2 V at a pressure x gap distance of 0.55 ± 0.01 Torr cm. The errors in the minimum voltages and in the pressure x gap distances overlap. The weighted average can be used to determine the best value and error for the both. The best minimum breakdown voltage for air is 361 ± 2 V at a pressure x gap distance of 0.55 ± 0.01 Torr cm.

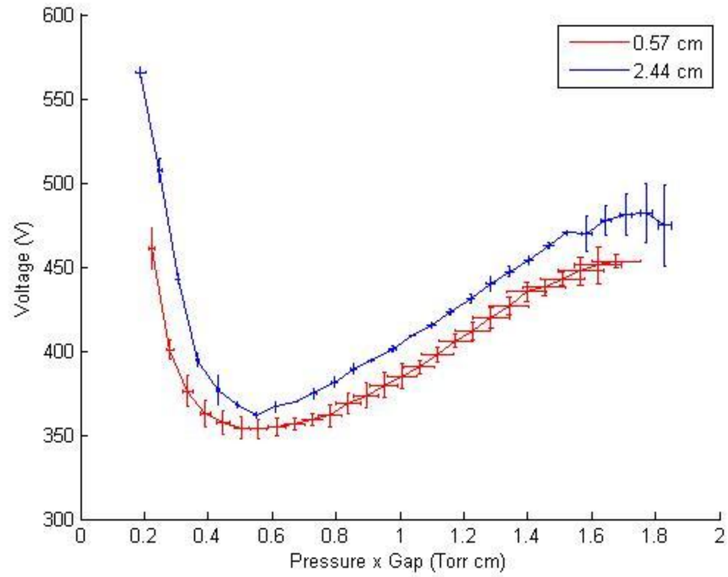

Figure 4. Paschen Curves in air. *The averaged data with error.*

The results closely match published results. Meek and Craggs have a minimum breakdown voltage in air of approximately 350 V at a 0.5 Torr cm pressure x gap distance. The Paschen Curve in their paper averaged data from several electrode types. These include brass, nickel, silver, aluminum, iron, and zinc. Data using a copper electrode was not used in the curve. The gap distances used were not reported. Meek and Craggs corrected their curve to 0^o C.[6] However, temperature does not have an effect on the minimum breakdown voltage.[7] The results of this experiment are 3% off for the breakdown voltage and 10% off for the pressure x gap distance. Husain and Nema report a minimum breakdown voltage in air of 330 V at a 0.5 Torr cm pressure x gap distance. The electrode material, gap distance, and the temperature used in the experiment were not reported.[8] The results from this experiment differ 6% for the minimum voltage and 10% for the pressure x gap distance compared to Husain's and Nema's result. Duniway published a Paschen Curve which was generated using two parallel plate copper electrodes at a 1 in. (2.54 cm) gap distance. The minimum breakdown voltage of this curve occurred at 370 V at a pressure x gap distance of 0.47 Torr cm.[9] The results of this experiment compared to the results of Duniway are: a 2% difference in the minimum voltage and a 17% difference in the pressure x gap distance.

The Duniway setup most closely resembles the setup used in this experiment. The most likely reason for the large difference between the pressure x gap distances determined by Duniway and this experiment is the electrodes. Duniway does not mention the size or the shape of the electrodes. The Cal Poly electrodes have sharp edges at the outside of the plate and at two holes drilled near the corners. These edges create electric field concentrations. This causes the system to behave as though the electrodes are closer together. As noted earlier, electrodes that are closer together shift the graph to the right. This explains the discrepancy between the Duniway results and the results of this paper.

These results clearly show a strong correlation between the data measured using the Cal Poly Paschen Breakdown Apparatus and data found in published data. This validates the Cal Poly test setup and procedure.

B. Carbon Dioxide

Figure 5 shows the unaltered results for the CO_2 tests at both gap distances. The figure shows the same gap distance trend. The curve shifts to the right and widens when the gap distance is decreased. It is apparent from this graph that the minimum breakdown voltage changed between gap distance. This difference will be discussed in detail below.

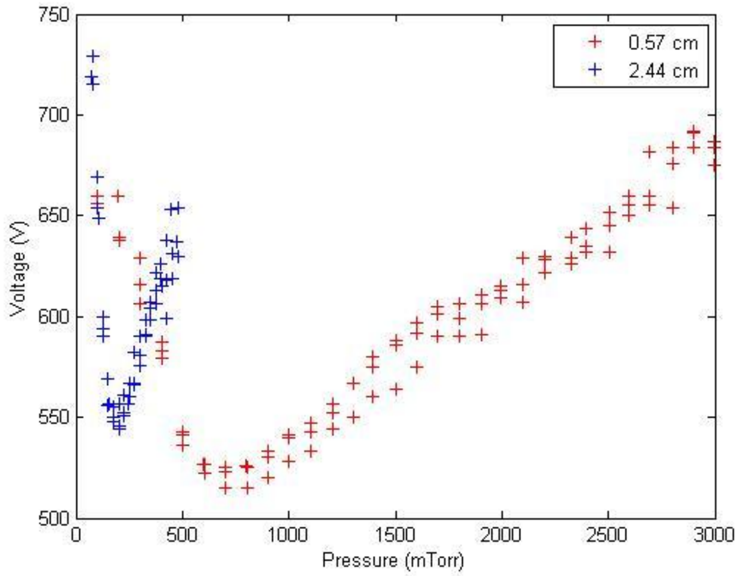

Figure 5. Voltage versus pressure in CO_2. *Unaltered measurements.*

Figure 6 shows the Paschen Curves for each gap distance. The data from Fig. 5 is averaged and the x-axis was converted to pressure x gap distance. The two curves have a strong positive correlation with a Spearman coefficient of 0.87. Like the air results, the CO_2 results confirm Paschen's Law. The 2.44 cm curve, however, is noticeably shifted up and to the right of the 0.57 cm curve. For the 0.57 cm gap distance the minimum voltage is 521 ± 5 V at a pressure x gap distance of 0.39 ± 0.02 Torr cm. At a gap distance of 2.44 cm the minimum voltage is 549 ± 6 V at a pressure x gap distance of 0.55 ± 0.01 Torr cm. The errors in the minimum breakdown potentials do not overlap; nor do the errors in the corresponding pressure x gap distance overlap. Both of these values are averaged to determine the best value. The standard deviation is the error in the values. The minimum breakdown voltage is 540 ± 20 V at a pressure x gap distance of 0.5 ± 0.1 Torr cm.

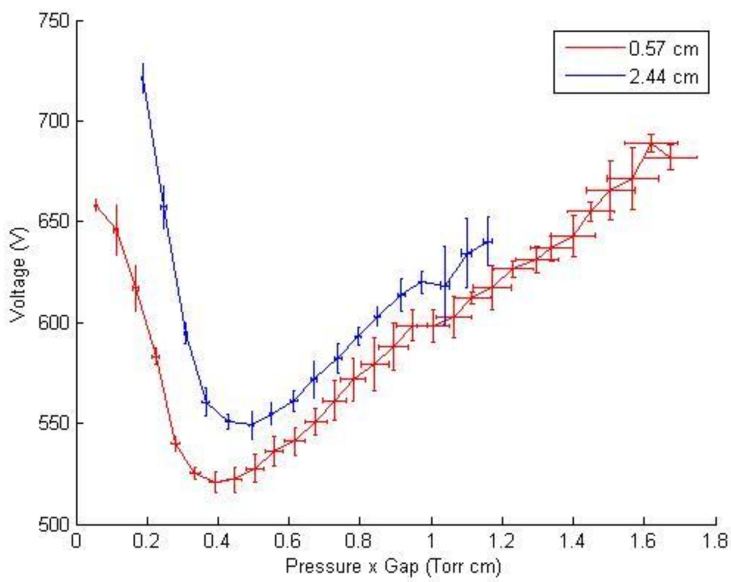

Figure 6. Paschen Curves in CO_2. *Note the difference in the minimum breakdown potentials between the two gap distances.*

The CO_2 data was taken at the same gap distances as the air data. If the gap distance was the reason for discrepancy in the two CO_2 curves then the air curves would exhibit the same trend. The air curves, however, have a very strong correlation. The discrepancy in the curves cannot be attributed to the change in gap distance. The two CO_2 curves follow similar trends until approximately 0.6 Torr cm. This corresponds closely to 1,000 mTorr for the 0.57 cm gap distance. It was at 1,000 mTorr that the procedure for adjusting the pressure changed. It is inadvisable to perform tests in a non-standard way. Following these two methods for adjusting the pressure introduces another variable. It would have been best to collect all of the CO_2 data following the same procedure. This was difficult. There had to be a flow of CO_2 for low pressures. Otherwise, the air leaking into the chamber would decrease the concentration of CO_2 to below 95%. Flowing CO_2 into the chamber at higher pressures, however, made it difficult to maintain a constant pressure. As a result two different procedures were used in the two pressure regimes. Changing the conditions in the chamber from a static environment to one with a flow does appear to have an impact. What is strange is that the curves diverge when the conditions inside the chamber become similar. For the 2.44 cm gap distance CO_2 was flowed to the chamber for all data points. For the 0.57 cm gap distance CO_2 was not flowed to the chamber until the pressure dropped below 1,000 mTorr. It is puzzling why the curves would diverge when the system was under identical conditions.

The variation in collecting the data cannot be overlooked. All breakdown voltage measurements were greater than 500 V. The assumed voltage rating for the feedthroughs casts doubt into whether the first arc occurred between the plates. Though the operator watched for signs of breakdown at the feedthrough, the operator may have missed if breakdown between the feedthrough and the chamber triggered the oscilloscope. If this were the case then the measured potential would be lower than it should be. The 2.44 cm tests were run at night. Lower ambient light made it easier to see if breakdown occurred at the feedthrough. Tests at the 0.57 cm gap distance were performed during the day. It is more likely that the operator missed breakdown at the feedthrough for these tests; day light obscures the light from the plasma. This may explain why the left side of the 0.57 cm curve is so much lower than the 2.44 cm curve. Conducting the experiment again and watching the feedthrough in the dark more closely would test this theory.

The majority of published papers list the minimum breakdown voltage in CO_2 for a negative voltage. This occurs because CO_2 ionizes negatively.[10] The Glassman High Voltage Power Supply used in this experiment is only able to produce positive voltages. The Kennedy Space Center test reports a minimum potential for CO_2 of 460 V at a gap distance of 0.4 Torr cm. This was measured using a negative voltage and cylindrical electrodes at a gap distance of 0.1 cm. The electrode material is not reported.[10] This minimum voltage value is almost 100 V below the value measured in the Cal Poly lab. This is to be expected. The Cal Poly experiment used a positive potential. Manning et al. used stainless steel spherical electrodes at a gap distance of 1.5 mm in their setup. The minimum breakdown voltage for CO_2 with a positive voltage is approximately 520 V at a pressure x gap distance of 0.3 Torr cm.[4] The calculated error for the minimum breakdown voltage in the Cal Poly data includes the Manning et al. value. The Manning et al. voltage result and the Cal Poly voltage result match. The differences between the results of Manning et al. and this experiment are 4% for the minimum breakdown voltage and 67% for the pressure x gap distance. The discrepancy between the pressure x gap distance values can be explained by the sharp edges present on the Cal Poly electrodes. The spherical electrodes used by Manning et al. do not have any electric field concentrations. The electric field concentrations between the edges of the parallel plates cause the system to behave as though the electrodes are closer. This shifts the curve to the right and yields a pressure x gap distance distance that is greater than it should be. The 2.44 cm gap distance result was shifted much further, 0.15 Torr cm, to the right compared to the 0.57 cm gap distance. This suggests that the closer the electrodes get the less of an effect sharp edges have on the results.

V. Conclusion

The threshold for breakdown between parallel plates was 361 ± 2 V for air and 540 ± 20 V for CO_2. These minimum breakdown voltage occurred at 0.55 ± 0.01 Torr cm and 0.5 ± 0.1Torr cm respectively. The strong positive correlation between the Paschen Curves generated at the two gap distances verifies Paschen's Law regarding breakdown in gases. The difference between the pressure x gap distance and published data is attributed to electric field concentrations. Sharp edges on the parallel plate electrodes cause the system to behave as though the electrodes are closer. Appendix E lists suggested future work and ways to improve this experiment.

The results of this experiment are applicable to the design of a spacecraft. Using the results from this experiment, during launch from or re-entry to the Earth, spacecraft or launch vehicles with conducting materials separated by 7 μm or greater have the potential to experience a breakdown event at the minimum breakdown voltage. For assets going to Mars, any pair of conducting materials that are between 0.4 mm and 0.7 mm apart can experience breakdown at the minimum voltage while on the surface. Materials that are closer than 0.4 mm can experience breakdown during EDL at the minimum voltage.

Appendix

A. Cal Poly Student Chamber Operation

Pumping Procedure

1. Close all valves and seal the lid.
2. Turn on the Welch 1397 pump.
3. Open the roughing valve.

Shutdown Procedure

1. Close the roughing valve.
2. Close any valve allowing gases to flow in (ex CO_2 shutoff valve).
3. Slowly open the vent valve.
4. Turn off the Welch 1397 pump.

B. Cal Poly Student Chamber Purge Procedure

1. Pump the chamber down to the base pressure.
2. Open the calibrated CO_2 flow line to the chamber.
3. Fill the chamber to 5 Torr of CO_2. The controller will indicate a pressure of 3.2 Torr.
4. Shut off the CO_2 flow.
5. Repeat steps 1-4 once.
6. The chamber is filled with CO_2 at a concentration greater than 99%.

C. CO_2 Calibration Procedure

The goal of this is to calibrate the CO_2 flow rate. This is done using the convectron gauge controller and a stopwatch. The flow of CO_2 must be at 140 mTorr per minute or greater. This works out to 23.3 mTorr every 10 seconds. For simplicity round up to 25 mTorr per 10 seconds. At this flow rate the concentration of CO_2 will be greater than 99%.

Calibration Procedure

1. Pump the chamber to the base pressure (~1 mTorr).
2. Close the roughing valve.
3. Open the CO_2 shutoff valve.
4. Start the stopwatch when the gauge reads 30 mTorr.
5. Read the convectron gauge controller once 10 seconds have gone by.
6. Adjust the needle valve
   - Open the needle valve slightly if the measured pressure is less than 55 mTorr.
   - Close the needle valve slightly if the measured pressure is greater than 55 mTorr.
7. Repeat steps 1 through 6 until a flow rate of 25 to 30 mTorr per 10 seconds of CO_2 is measured.
   - Too low of a rate decreases the concentration of CO_2 to below 99%.
   - Too high and more CO_2 is being used than necessary.
   - The pump is cannot keep medium vacuum with a flow rate greater than 60 Torr per minute.

The convectron gauge is calibrated to N_2. Measurements of gases other than N_2 may yield values that are different than the true pressure. For pressures below 1 Torr, the true pressure of CO_2 correlates 1:1 with the measured value of the convectron gauge.[11] This is not true for pressures above 1 Torr. Figure 7 shows how the measured pressure value relates to the true pressure value for a variety of gases at pressures from 1 mTorr to 100 Torr.[11] Above 1 Torr, the CO_2 curve does not follow N_2.

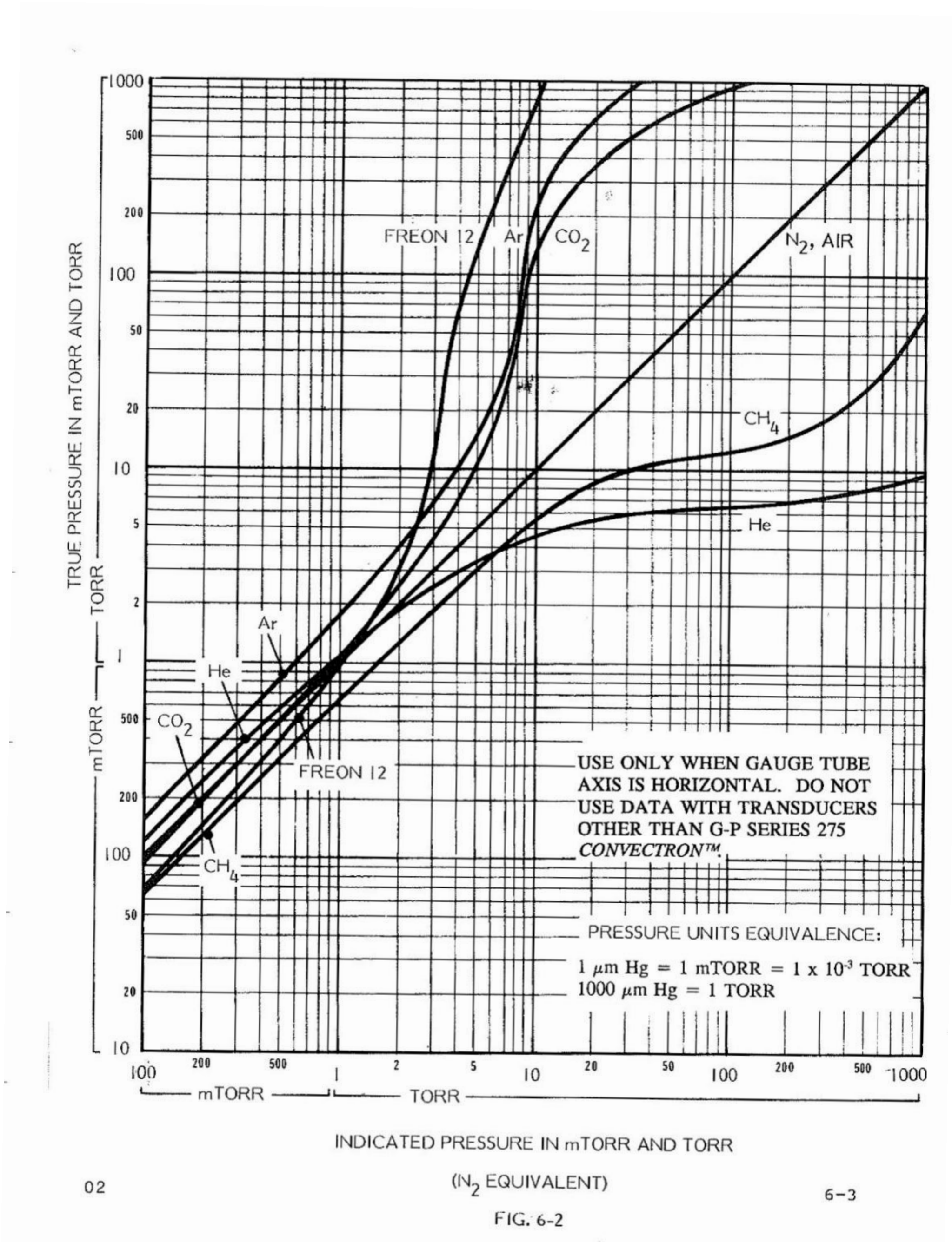

Figure 7. Indicated vs. True Pressure Curves for the Granville-Phillips Series 275 convectron gauge.[11]

D. Lessons Learned

When dealing with high voltage it is important to ensure that the system is properly grounded. Failing to do so can result in the failure of electronic hardware. This did occur a few years ago with the convectron gauge controller. The chamber was floating and the convectron gauge was attached to ground. The after a breakdown the controller no longer worked. The most likely explanation is that an arc bridged the gap between the convectron gauge and the vacuum chamber. Current traveled to the controller via the wire between the controller and he gauge, shorting out the controller. Problems like this can be prevented by grounding the system. For the Cal Poly Paschen Breakdown Apparatus, the only part component that is not grounded is the anode, which is connected to the power supply. The power supply, chamber, cathode, supply rack, voltage divider, oscilloscope, laptop, and faraday cage must all be connected to the earth ground. This not only ensures that the measured potential is the true potential difference between the electrodes, it keeps the operator and electrical equipment safe. The power supply is grounded through the grounding plug that goes into the outlet. The ground on the back of supply should be attached to the rack. This connects anything electrically attached to the rack to ground. The chamber, cathode, and Faraday cage should be connected to the rack. The voltage divider, oscilloscope, and laptop connect to ground through the laptop power cord. This cord must be plugged into the same power strip as the power supply. Failure to do so may create ground loops. These can be dangerous for electrical equipment. Ground loops allow for ground currents to develop, which may harm equipment.

Going into the project the author thought that it would be beneficial to report the data by plotting electric field against pressure rather than the conventional Paschen Curve. The assumption was that there would be a useful trend like the Paschen Curve. Figure 8 shows such a curve for breakdown in air at different gap distances. Plotting the data did not have the expected trend. The author expected the electric field for breakdown to be constant across pressures. The author was wrong. The weakest electric field for breakdown occurs at the furthest gap distance, which went against the author's intuition. The lesson, however, is not that the electric field isn't useful. While Fig. 8 does not have a discernible trend that does not mean there isn't a trend to discover using the electric field. The lesson is to verify assumptions as soon as possible. The author should have plotted a Paschen Curve using existing data and then converted the y-axis to electric field and the x-axis to pressure to observe what happens. Had the author done this at the beginning of the project, which would have been feasible, then he would have had better understanding while testing.

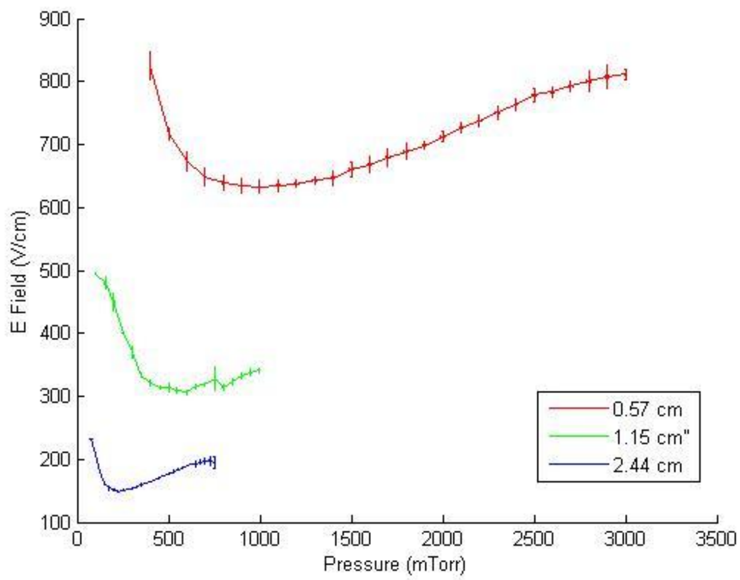

Figure 8. Electric field versus pressure.

Instruments designed to measure properties of gases, such as temperature, pressure, or flow, are typically calibrated to nitrogen. Different gases exhibit different behaviors. It is important to look at the operating manual to understand how the instruments are calibrated and how the indicated measurement relates to the true value when a gas other than nitrogen is used.

E. Future Work and Improvements

The biggest source of error comes from the sharp edges on the electrodes. This shifts pressure x gap distance data to the right. The author highly recommends fabricating new electrodes. Electrodes with round features are best as the electric field remains constant along the surface of the electrode. Manning et al. used spherical electrodes in their experiment. These have the benefit of no corners. Another design, thought up by Dave Esposto, is to round the existing electrodes. This is done by fixing the edges and bulging out the middle. Either way, creating electrodes with smooth surfaces will make for more accurate data.

The author does not know what the electrical feedthroughs are rated to voltage wise. The industry standard is 500 V and the author assumed this to be the rating. Breakdown between the positive feedthrough and chamber at potentials above 500 V support this assumption. It is recommended that the positive feedthrough be replaced with one rated to at least 1 kV. Wire feedthroughs, such as the ones currently being used, need to be taped up to ensure arcs don't occur through the air. This makes this style of feedthrough undesirable. The author recommends finding a coaxial style feedthrough, such as a BNC connector, for the feedthrough. Unfortunately, the only coaxial feedthroughs the author could find were rated to 500 V. When selecting a feedthrough for this application it is important that the it be rated to 1,000 V or greater and that has no exposed wire that enables breakdown to occur between the chamber.

Use of a flow meter would simplify setting the CO_2 flow. Flow meters give quick feedback on the flow into the chamber. This makes it easier to determine if the concentration of CO_2 will remain above 95%.

Several papers reported that the minimum breakdown potential is lower for many gases, including CO_2, if the potential difference is created using a negative potential. For CO_2 this is because the gas ionizes negatively.[10] The Glassman High Voltage Power Supply is a model PS F series power supply, meaning it is only able to produce positive potentials. A good future project would be to conduct this test using negative potentials to see if the results match the published data. Calle does a good job of explaining the mechanism behind breakdown in CO_2 using positive and negative potentials.

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