

CHARACTERIZATION OF PASCHEN CURVE ANOMOLIES AT HIGH P*D VALUES

W.J. Carey, A.J. Wiebe, R.D. Nord
ARC Technology, 13076 NW 120th St.
Whitewater, Kansas, USA

L.L. Altgilbers (Senior Member)
US Army Space and Missile Defense Command / Army Forces Strategic Command
Huntsville, Alabama, USA

Abstract

Paschen's law is often used to estimate the breakdown voltage of high pressure gas switches commonly used in high voltage pulsed power systems based on the product of pressure and distance (pd) in a given gas. Paschen's law predicts breakdown voltages for high pd values that scale approximately linearly with pd. However, it is clear from published literature and ARC Technology's experimental data that the breakdown voltage deviates significantly from the theoretical Paschen curve at relatively high pd product values. It is also clear that these results are not consistent for different gap spacings and pressures with the same pd product. Therefore, initial tests have been performed to characterize this region of the paschen curve for N₂, H₂, and SF₆ for pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm.

I. INTRODUCTION

A. Background to Paschen's law

Friedrich Paschen studied the breakdown voltage of parallel plates in a gas. In 1889 he stated what became known as Paschen's law which describes the relationship between breakdown voltage, and the product of pressure and distance for a parallel plate geometry for a given gas composition [1]. Paschen's law can be written as Eq. (1), where a and b are constants dependent on gas composition. A plot of this equation produces a characteristic shape known as the Paschen curve, which is shown in Fig. 1 for air in a log-log plot.

$$V = \frac{a(pd)}{\ln(pd)+b} \quad (1)$$

Significant research has been conducted over many years to determine the physical mechanisms that dominate the gas breakdown process. A good reference on the subject is [2], which describes in detail the Townsend discharge theory and the streamer theory.

B. Applications of Paschen's law.

Observations of the Paschen curve show three distinct regions of operation for a system operating in a gaseous

environment. High voltage hold-off is achieved by operating in either the low or the high pd region, which are often referenced as operating on the left-hand or right-hand side of the Paschen curve. The third region is the area around the Paschen minimum.

High voltage pulsed power systems often employ gas switches due to their high power and voltage handling capabilities. Vacuum switches such as the thyratrons operate on the left-hand side of the Paschen curve. Pressurized spark gaps operate on the right-hand side of the Paschen curve. Both of them stay away from the middle region to maximize voltage hold-off.

Microelectromechanical systems (MEMS), on the other hand, are typically concerned with the middle region of the Paschen curve for design safety. The Paschen minimum is applied to designing systems that will never experience voltage breakdown with any gap spacing for a given pressure, provided that it is operated below a maximum threshold voltage.

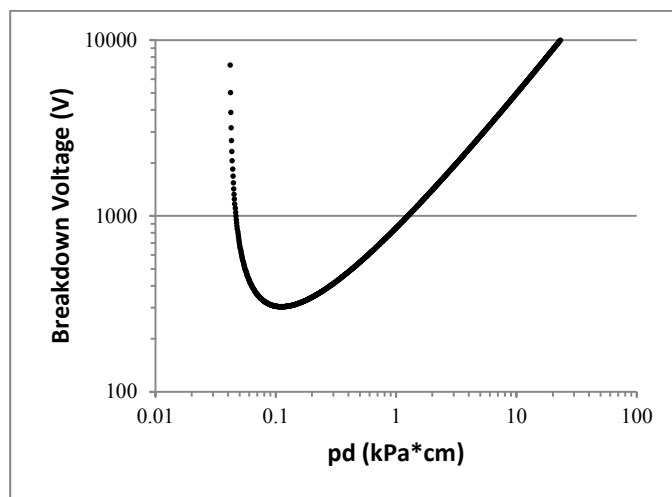


Figure 1. Paschen curve for air.

C. Limitations of Paschen's law

The limitations of Paschen's law for the micron gaps commonly employed in MEMS is well-documented, and has lead to the development of the "modified Paschen curve"[3]. These limitations normally affect devices with gaps in the low

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE JUN 2011	2. REPORT TYPE N/A	3. DATES COVERED -			
4. TITLE AND SUBTITLE Characterization Of Paschen Curve Anomalies At High P*D Values		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ARC Technology, 13076 NW 120th St. Whitewater, Kansas, USA		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.					
14. ABSTRACT Paschens law is often used to estimate the breakdown voltage of high pressure gas switches commonly used in high voltage pulsed power systems based on the product of pressure and distance (pd) in a given gas. Paschens law predicts breakdown voltages for high pd values that scale approximately linearly with pd. However, it is clear from published literature and ARC Technologys experimental data that the breakdown voltage deviates significantly from the theoretical Paschen curve at relatively high pd product values. It is also clear that these results are not consistent for different gap spacings and pressures with the same pd product. Therefore, initial tests have been performed to characterize this region of the paschen curve for N2, H2, and SF6 for pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

micron range operating at atmospheric pressure and are attributed to field emission.

Similar departures from Paschen’s law are observed with spark gaps in the millimeter and centimeter range when operating at higher pd values. Preliminary tests to characterize these limitations at higher pressures have been performed and presented in this paper.

II. EXPERIMENTAL SETUP

The experimental setup, shown in Figure 2, was designed to automate the tests as much as possible to obtain consistent results. A 125kV Glassman power supply was set to ramp from zero to maximum voltage in 120 seconds by driving its external control with a reference voltage from a function generator. The high voltage output of Glassman power supply was connected to a pair of 2.54cm spherical stainless steel electrodes in a G10 pressure chamber capable of 2000psi. The voltage monitor output of the high voltage power supply was measured by a Tektronix TDS6154C oscilloscope, which can capture data prior to triggering by recording a continuous window and then freezing when triggered. An antenna located near the electrodes detected the breakdown event and triggered the oscilloscope which then recorded the voltage just prior to breakdown.

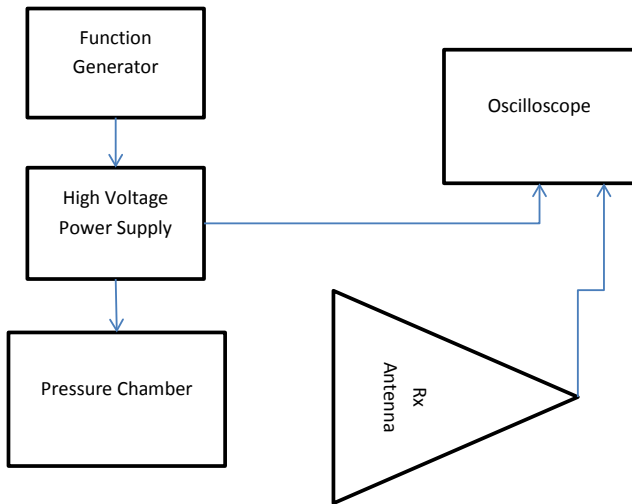


Figure 2. Block diagram of test setup for determining breakdown voltage.

III. RESULTS AND DISCUSSION

A. Test parameters

The Paschen curve breakdown characteristics were measured for N₂, H₂, and N₂ with 10% SF₆ at pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm. The test was replicated ten times at each parameter setting to determine the average breakdown voltage and standard deviation.

B. Experimental Paschen Curve Testing

Test results for a typical data set are shown in Fig. 3, which is measured with N₂ at 1.27mm. The initial steep slope is consistent with the Paschen curve (green line). However, a departure occurs at approximately 1400kPa where the slope decreases. This change is accompanied by an increased standard deviation in the data for tests within the same set, which is represented in Fig. 4. This general pattern occurred for all gases and spacings, with the point of departure from the theoretical Paschen curve changing based on the specific gas and spacing.

The ten sample data set is adequate for the linear region where the standard deviation is low. However, it is noted that the regions of high standard deviation require many more data points for statistical accuracy, which explains the widely varying data in Fig. 4 above 200 kPa*cm. However, the focus of the paper is to investigate the point of departure from Paschen theory. Since the high standard deviation data clearly shows the general trends it is included in the plots.

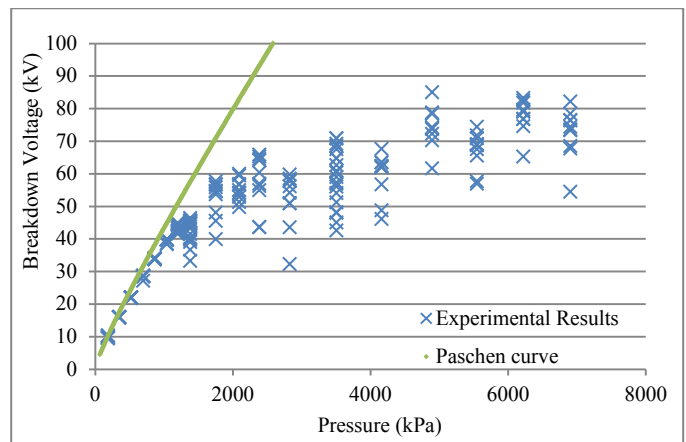


Figure 3. Test results with N₂ and electrode spacing fixed at 1.27mm.

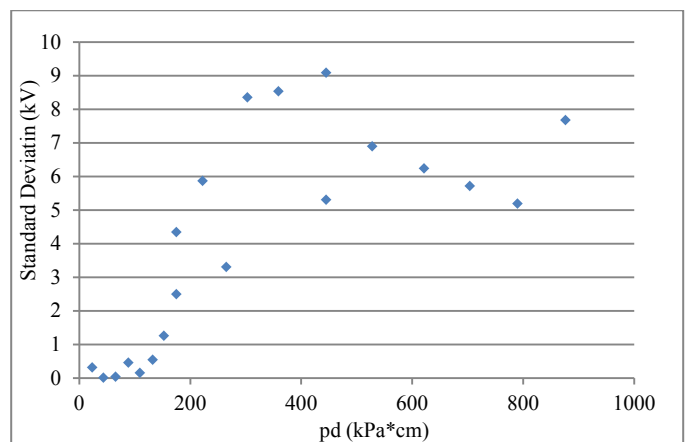


Figure 4. Standard deviation of the 1.27mm N₂ gap

The average breakdown voltages versus pd were measured for each gas over the designated parameter space and are summarized in Fig. 5, Fig. 6, and Fig. 7. The figures are

plotted linearly, rather than with log scales, to more easily interpret the data visually. It is important to note that for high pd values the theoretical Paschen curve is linear. The data tracks this line for lower pd values, which is especially evident below 100kPa*cm. Each set of data ultimately changes slope, which indicates a departure from the theoretical Paschen curve. Unfortunately, the power supply limit of 125kV prevented the characterization of the SF₆-N₂ mixture at the higher pd values of the other gases.

Larger gap spacings enable the spark gap to maintain conformance with the theoretical model to higher pd values, which is consistent with published literature from many references. The point divergence of the measured data from theoretical for N₂ and H₂ at the 2.54 mm gap spacing is consistent with an interpolation of the results published by [4], but no comparable results were presented for the 0.508mm and 1.27mm gap spacings. In fact, the Paschen predictions have been verified to be accurate for a spark gap filled with SF₆ with a 1.8cm spacing operating at 1,600kPa*cm [5]. Therefore, the departure from theoretical cannot be predicted simply based on a threshold pd product.

Analysis of the higher pd data suggests that in some cases the breakdown voltage begins to plateau for a given gap spacing while the pressure continues to increase. This would be an expected result of field emission at high electric fields, which is a known factor that can influence voltage breakdown characteristics. However, this characteristic is not consistent for all data sets. In fact, Figs. 6 and 7 show 3 data sets that indicate not only a plateau, but also a decrease in breakdown voltage with increased pd. This is not an expected result of field emission and indicates that another factor is influencing the performance. Clearly, much more data would be required to characterize this portion of the Paschen curve.

C. Electric field calculations

The maximum electric field strength **E_m** is calculated by Eqn. (2), where **V_{bd}** is the average breakdown voltage, **d** is the respective gap distance, and **f** is the field enhancement factor for the given spark gap geometry. The calculation of **f** for two spherical spark gaps with a radius **r** that are separated by a distance **d** is shown in Eqn. (3). The field enhancement factor is nearly unity for the dimensions in this series of tests.

$$E_m = \frac{f(V_{bd})}{d} \quad (2)$$

$$f = \frac{0.9(r + \frac{d}{2})}{r} \quad (3)$$

The electric field breakdown for the three gasses is plotted in Fig. 8, Fig. 9, and Fig. 10 with respect to pressure. It is important to note that the electric field at breakdown is very similar for all three gap spacings until the 25 to 35kV/mm region is achieved. Beyond this point, the smaller gap spacing actually provides a greater field strength. Further study is required to understand the reason for this effect.

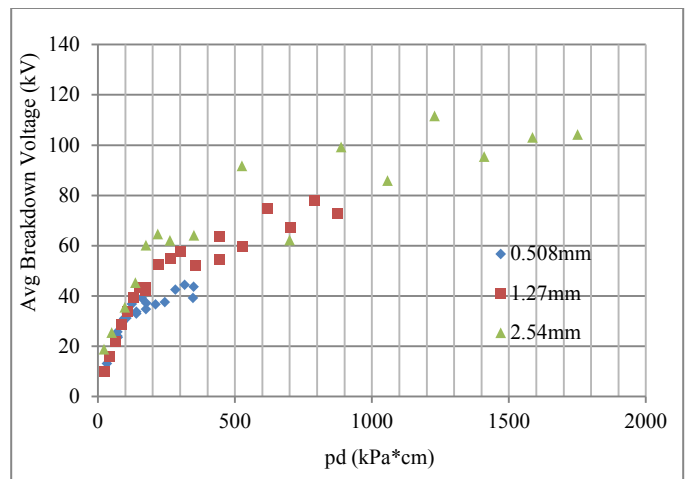


Figure 5. Breakdown voltage compared to pd for N₂.

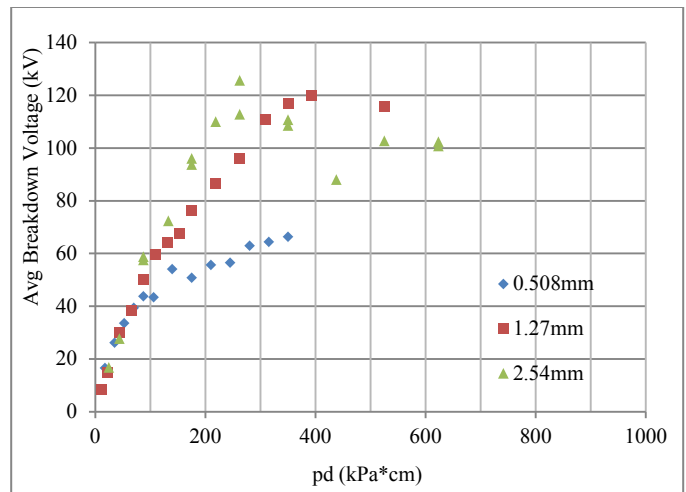


Figure 6. Breakdown voltage compared to pd for 10% SF₆.

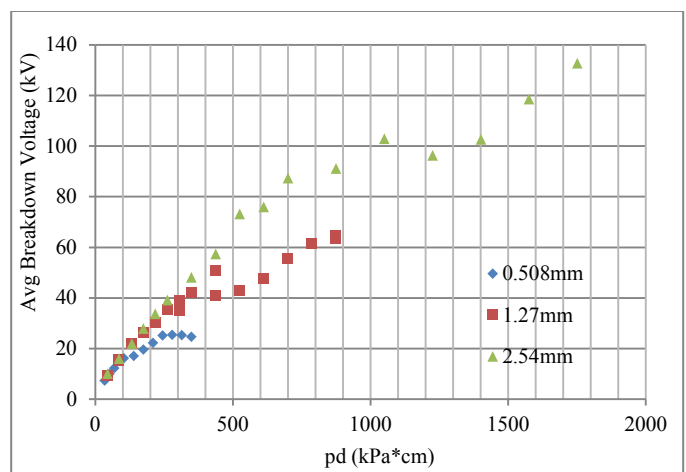


Figure 7. Breakdown voltage compared to pd for H₂.

IV. CONCLUSIONS

Experimental testing has quantified the breakdown voltage versus pd for N_2 , H_2 , and N_2 with 10% SF_6 at pressures between 96.5 and 6900kPa and gap spacings of 0.508, 1.27 and 2.54 mm. The following observations are made with respect to that data.

1. For a given spark gap geometry and spacing, increasing the pressure above a maximum level results in voltage breakdown behavior that deviates from Paschen's Law.
2. This non-Paschen region is characterized by both a reduced voltage breakdown from the predicted level and a high standard deviation between measurements at the same parameters.
3. The beginning of the non-Paschen region cannot be predicted simply by a threshold pd level.
4. Larger gap spacings maintain their conformity to Paschen's Law at higher pd values.
5. The beginning of the non-Paschen region cannot be predicted simply by a threshold electric field.
6. Smaller gap spacings permit higher electric field strengths.

This work directly applies to the design of high voltage spark gap switches. First, it may be possible to find published literature for designing a spark gap with the same gas and similar operating voltages. If not, the correct operating point will need to be determined empirically. Second, if the spark gap is smooth and clean but fires at a range of voltages, it may need to have a wider gap spacing with less pressure to stabilize for a given operating voltage.

Future work is necessary to more accurately quantify the data regions that diverge from the theoretical Paschen values due to their high standard deviations.

V. REFERENCES

- [1] Friedrich Paschen, "Ueber die zum Funkenübergang in Luft, Wasserstoff und Kohlensäure bei verschiedenen Drucken erforderliche Potentialdifferenz", *Annalen der Physik*, pp.69-75, 1889.
- [2] Yu D. Korolev and G. A. Mesyats, *Physics of Pulsed Breakdown in Gases*, Yekaterinburg, Ural, Russian Academy of Sciences, ISBN 5-7691-0779-0.
- [3] Allyson L. Harzell, Mark G. da Silva, Herbert R. Shea, *MEMS Reliability*. New York, Springer, 2011.
- [4] Yu D. Korolev and G. A. Mesyats, *Physics of Pulsed Breakdown in Gases*, Yekaterinburg, Ural, Russian Academy of Sciences, ISBN 5-7691-0779-0, p. 7.
- [5] S. H. Nam, et. Al., "Empirical Analysis of High Pressure SF_6 Gas Preakdown Strength in a Spark Gap Switch," *IEEE Trans. Dielectrics and Electrical Insulation*, Vol 16, No. 4, pp. 1106-1110, Aug. 2009.

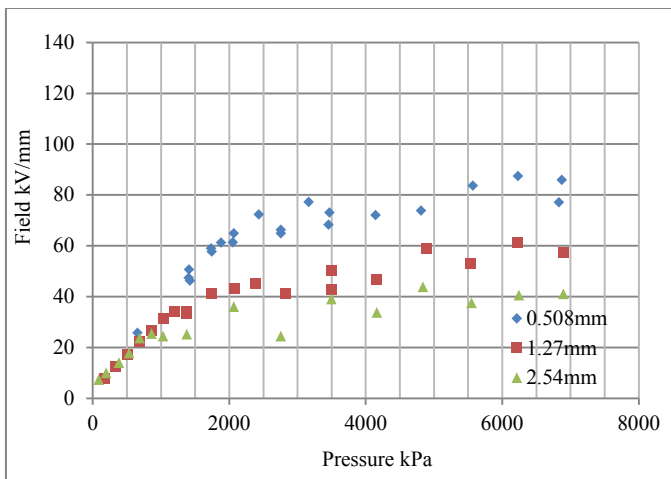


Figure 8. Electric field compared to pressure for N_2 .

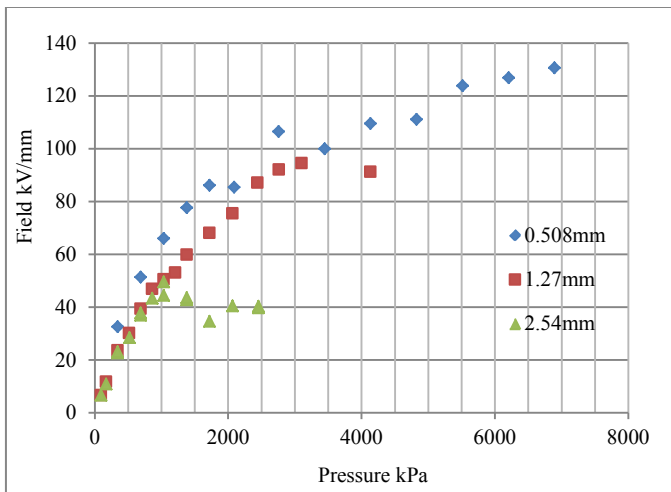


Figure 9. Electric field compared to pressure for 10% SF_6 .

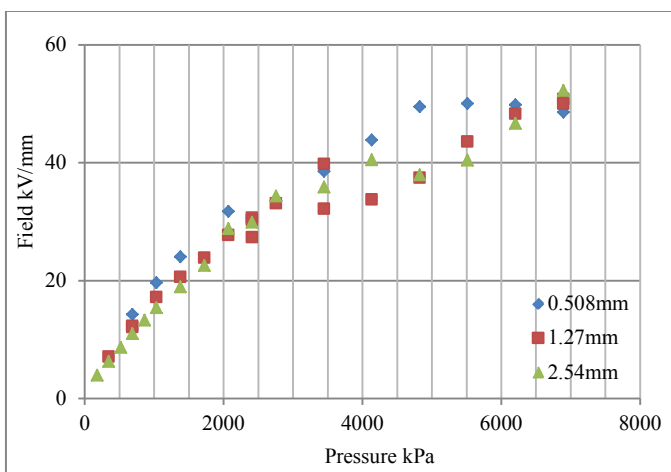


Figure 10. Electric field compared to pressure for H_2 .