Minimum Conductor Spacing for Electronic Packaging

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1. Introduction

Paschen's law was originally discovered by experimental evidence in 1889. It deals with the phenomenon of the conduction of electricity through gases. This phenomenon is of concern because of increased density in today's microelectronics packaging technologies. Metal conductors placed at a distance of a few mils or even microns are common and susceptible to spark-breakdown at high voltages. For high-power, high-voltage applications, spark-breakdown is one of the major potential failure mechanisms.

Paschen's original experiment involved two parallel-plate iron electrodes that were placed at a distance d in air with a pressure p. The voltage between the two electrodes was V. By analyzing the results, Paschen obtained the following conclusions:

a. There exists a minimum voltage defined as "minimum spark-breakdown voltage". Different gases have different values of this minimum voltage.

b. Electricity conduction through gases can only occur when the voltage between the two electrodes is equal to or higher than the minimum voltage.

c. The spark-breakdown voltage can be determined if the gas pressure and the electrodes distances are known. Furthermore, the spark-breakdown voltage is the function of the product of pressure and the distance only.

Two plots obtained by Paschen are shown in Figure 1 and Figure 2. Figure 1 plots the spark-breakdown voltage as well as the spark-breakdown intensity of the electrical field vs. the gap spacing between the electrodes. The pressure is kept at the atmospheric level (760 mmHg). The spark-breakdown voltage vs. the gas pressure is shown in Figure 2 with the gap spacing as parameters. Note that Figure 1 and Figure 2 are for iron conductors in air. Several conclusions can be obtained from these plots:

a. For iron electrodes in air, the minimum spark-breakdown voltage is about 300 V, regardless of the gas pressure or the gap spacing.

b. The spark-breakdown voltage causing gas conduction increases with the increase of the gas pressure and the gap spacing. This is true when the pressure is not too low and the spacing is not too close.

c. When the gas pressure is very low (0.1 - 0.6 Torr in Figure 2) and when the gap spacing is very close (0.0006 - 0.008 mm in Figure 1), the spark-breakdown voltage decreases with the increase of the pressure and spacing.

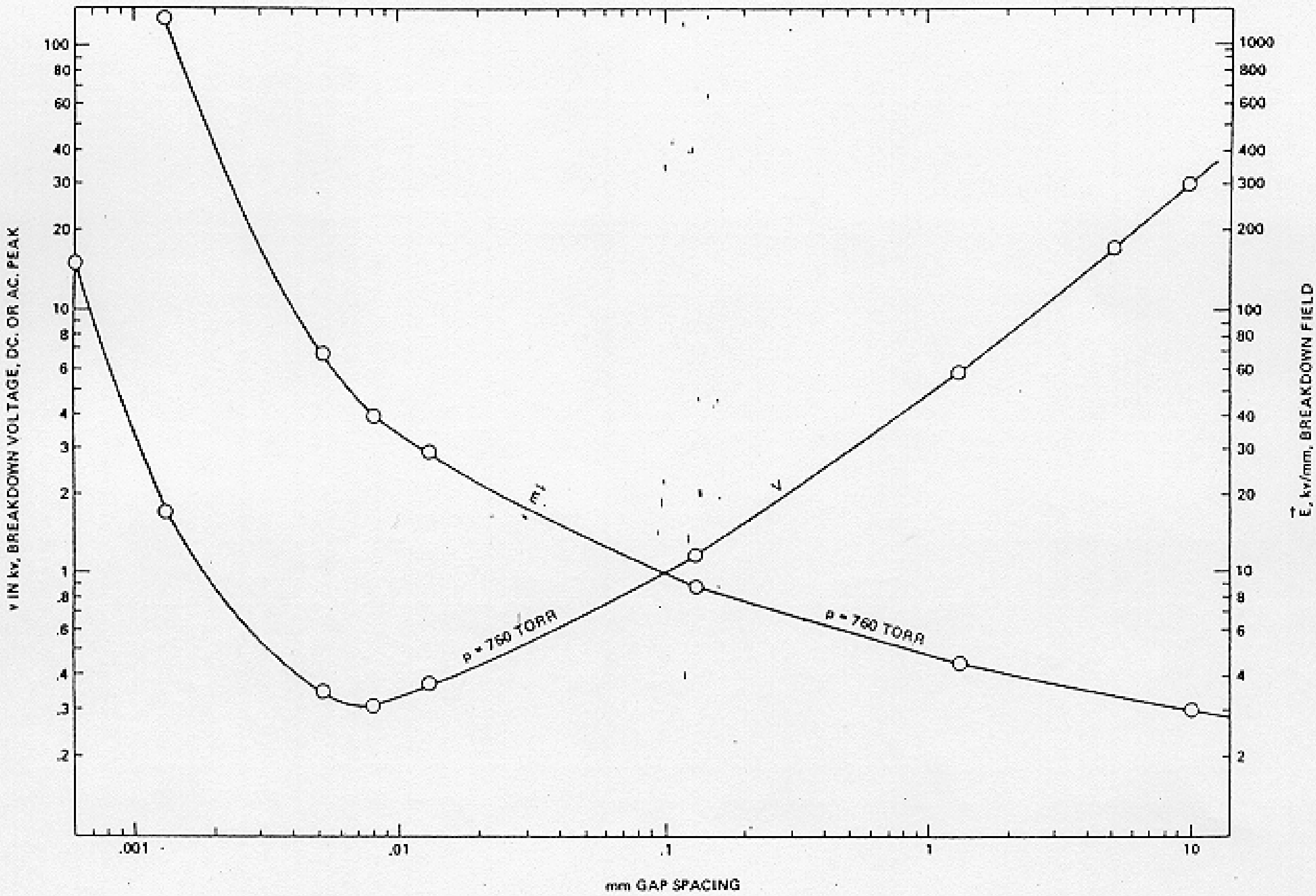


Figure 1. Paschen's Curve, V. Field Strength Curve, E. (Iron Electrodes)

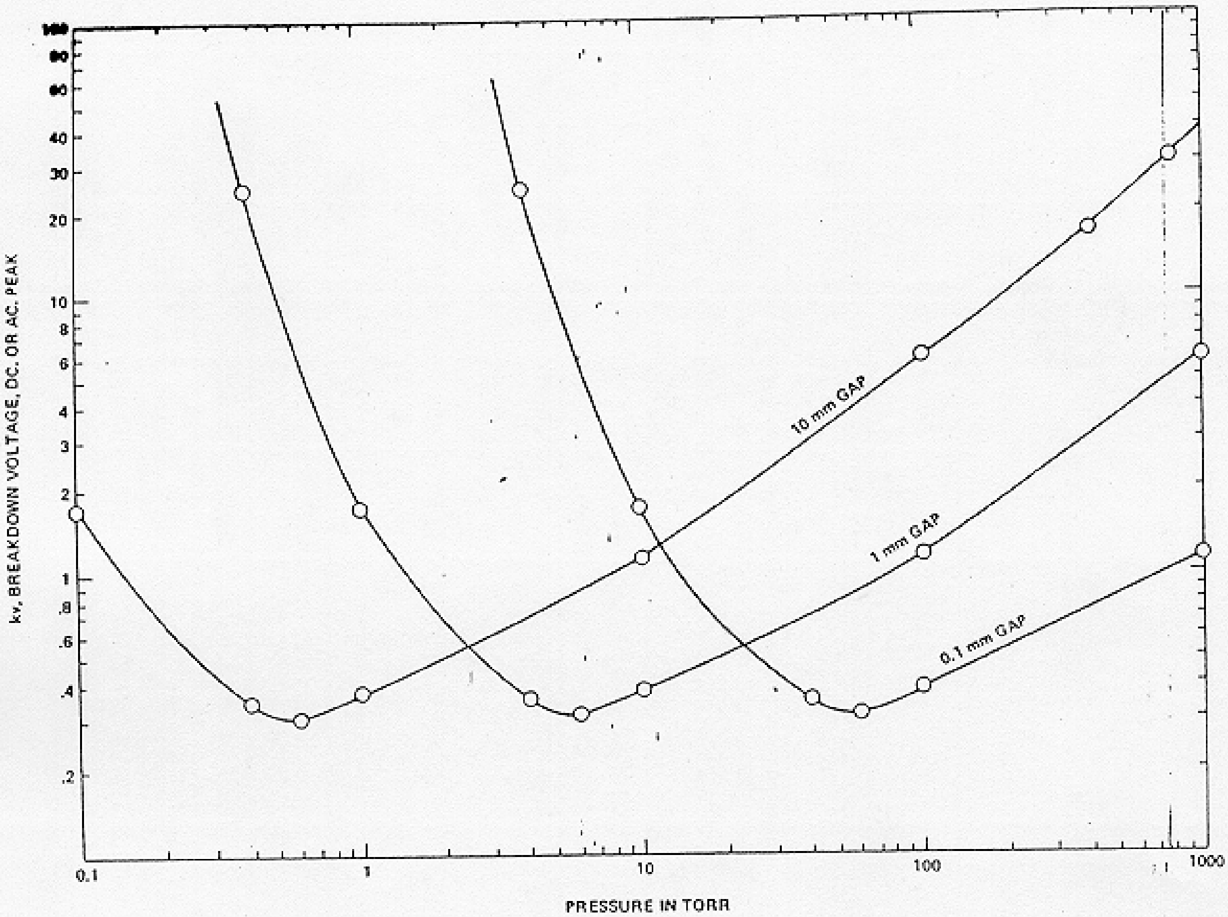


Figure 2. Paschen's Original Curves. Breakdown Voltage in Air as a Function of Pressure. (Iron Electrodes)

2. Analytical Expressions

Paschen's law can be generally expressed as

$$V_s = f(pd)$$

where V_s denotes the spark-breakdown voltage. Using field-intensified ionization theory, a useful equation can be derived to characterize the spark-breakdown phenomenon:

$$V_s = \frac{Bpd}{\ln[\frac{Apd}{\ln(1/\gamma)}]}$$

where A and B are gas related constants, and γ is a gas and conductor-metal related constant. These constants are listed in Table 1 and Table 2.

Table 1

Gas	A	B
Air	14.6	365
N_2	12.39	342
CO_2	20.0	466
H_2	5.0	130
H_2O	12.9	289
He	2.8	34

Data Source: Reference [1]

Table 2

γ Constant

Metal	H_2	He	Air	N_2
Al	0.095	0.021	0.035	0.10
Cu	0.050	....	0.025	0.066
Fe	0.061	0.015	0.020	0.059
Ni	0.053	0.019	0.036	0.077

Data Source: Reference [1]

It is evident from Figure 1 and Figure 2 that the minimum spark-breakdown voltage for iron electrodes in air is about 300 V. The minimum voltage value is different for different gases. We may determine the minimum voltage value for any gas by taking the partial derivative of Paschen's equation with respect to the gap spacing and setting the derivative to zero:

$$\frac{\partial V_s}{\partial d} = 0$$

The minimum voltage can be obtained as:

$$V_{sm} = \frac{B}{A} e \ln\frac{1}{\gamma}$$

where e = 2.718.

Minimum spark-breakdown voltages for different gases and electrode metals may be calculated using the above equations.

Table 3

Minimum Spark-Breakdown Voltage

Gases	Metal	V_{sm} (v)
Air	Cu	250
Air	Fe	265
Air	Al	227
N_2	Al	172
N_2	Cu	203
N_2	Fe	212

It is worth noting that the minimum spark-breakdown voltages listed in Table 3 are independent of the gas pressure. As long as the operating voltage is lower than the minimum spark-breakdown voltage, sparking phenomenon in gases will not occur.

3. Analytical Results

An automated computer algorithm using an iteration scheme to solve Paschen's equation was developed at NASA/GSFC to give the minimum conductor gap spacing requirement in order to avoid spark-breakdown failures. The algorithm was designed such that the minimum gap spacing can be determined under any gas pressure. The following tables listed in the appendix were generated to show the minimum spacing requirements for various conductors in air and nitrogen. Data in the following tables were also plotted in Figures 3 through 8.

Table A-1:	Cu electrodes in air.
Table A-2:	Al electrodes in air.
Table A-3:	Fe electrodes in air.
Table A-4:	Cu electrodes in nitrogen.
Table A-5:	Al electrodes in nitrogen.
Table A-6:	Fe electrodes in nitrogen.

Notes:

(1) All data are based on the pressures of 760, 300, 100, 10, and 1 mmHg.

(2) A safety factor of 2.0 is recommended in determining the minimum gap spacing between conductors. This safety factor can be adjusted by user. Tables A-1 through A-6 have been calculated with a safety factor of 2.0.

4. Discussion

The calculated results in Tables A-1 through A-6 show the effects of different conductors, gases, and pressures on the spark-breakdown voltage. The spark-breakdown voltages shown in the tables have been calculated for values on the right side of Paschen's curve only. Data was plotted from D_{min} (gap spacing when the slope of Paschen's curve is zero) to the minimum distances associated with 600 volts. See Figures 3 through 8.

Paschen's curve (Figure 1) clearly shows data on the left side of D_{min}; in Paschen's original experiment, as the distance decreased beyond D_{min}, the values of spark-breakdown voltages increased. This phenomenon cannot be readily explained by using Paschen's equation. His equation only models his experiment on the right side of D_{min}. It is suspected that at distances less than D_{min}, rarefied gas dynamics theories apply and hence cannot be modeled using Paschen's equation. For practical purposes, conductor distances smaller than the calculated D_{min} values may not be realistic in electronic assemblies. Spark-breakdown voltages corresponding to distances greater than D_{min} can be extrapolated from Tables A-1 through A-6.

Tables A-1 through A-6 also show the effect of pressure on the spark-breakdown voltage. It is apparent that the minimum spark-breakdown voltage is independent of the pressure. For applications where the DC or AC peak voltage does not exceed the minimum spark-breakdown voltage, the gas will not become conductive.

The tables also show the effects of pressure on conductor spacing; when the pressure decreases, the minimum conductor spacing requirements increase, hence, high density electronic assemblies subjected to low pressures require larger conductor spacing.

It is not possible to model the effects of zero or negative pressures because of mathematical singularities. The tables show a trend of the effects of pressure as pressure approaches or nears zero. Minimum design distances can be extrapolated for pressures greater than zero.

Non-uniform electric fields and irregularly shaped conductors can affect the spark-breakdown voltage. The tables in this report are estimates of minimum design distances and are based on Paschen's equation. More accurate conductor design distances can only be derived through experimentation with conductor geometries, gases, and voltages typical of any specific environment.

5. Reference

1. Cobine, J. D., "Gaseous Conductors - Theory and Engineering Applications". Dover Publications, Inc., New York.

6. Appendix (Data for Minimum Gap Spacing Requirements)

Minimum Conductor Distances for Varying Pressures

Conductor: Cu   Gas: Air

Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
250	.018	.046	.140	1.397	13.916
260	.024	.062	.186	1.864	18.646
270	.028	.071	.214	2.143	21.420
280	.031	.079	.238	2.388	23.875
290	.034	.087	.262	2.622	26.240
300	.037	.094	.284	2.849	28.514
310	.040	.102	.307	3.070	30.742
320	.043	.109	.329	3.295	32.925
330	.046	.117	.351	3.513	35.153
340	.049	.124	.373	3.731	37.336
350	.052	.131	.395	3.952	39.519
360	.054	.139	.417	4.170	41.701
370	.057	.146	.439	4.392	43.930
380	.060	.153	.461	4.610	46.112
390	.063	.161	.483	4.834	48.341
400	.066	.168	.505	5.055	50.569
410	.069	.176	.528	5.280	52.797
420	.072	.183	.550	5.504	55.025
430	.075	.190	.573	5.731	57.299
440	.078	.198	.595	5.956	59.573
450	.081	.206	.618	6.186	61.847
460	.084	.213	.641	6.413	64.120
470	.087	.221	.664	6.644	66.440
480	.090	.229	.687	6.877	68.759
490	.093	.236	.710	7.107	71.078
500	.096	.244	.734	7.341	73.397
510	.099	.252	.757	7.574	75.762
520	.102	.260	.781	7.810	78.127
530	.105	.268	.804	8.047	80.491
540	.109	.276	.828	8.286	82.856
550	.112	.284	.852	8.526	85.266
560	.115	.292	.876	8.765	87.676
570	.118	.300	.900	9.005	90.087
580	.121	.308	.924	9.247	92.497
590	.124	.316	.949	9.492	94.952

TABLE A-1

Minimum Conductor Distances for Varying Pressures

Conductor: Al   Gas: Air

Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
227	.016	.042	.127	1.272	12.665
237	.022	.057	.172	1.721	17.243
247	.026	.066	.199	1.994	19.944
257	.029	.074	.223	2.236	22.370
267	.032	.082	.246	2.467	24.659
277	.035	.089	.269	2.691	26.902
287	.038	.097	.291	2.913	29.146
297	.041	.104	.313	3.134	31.343
307	.044	.111	.335	3.352	33.541
317	.046	.119	.357	3.571	35.738
327	.049	.126	.379	3.789	37.936
337	.052	.133	.401	4.010	40.133
347	.055	.141	.423	4.232	42.331
357	.058	.148	.445	4.453	44.528
367	.061	.155	.467	4.678	46.771
377	.064	.163	.490	4.899	49.015
387	.067	.170	.512	5.127	51.258
397	.070	.178	.535	5.354	53.547
407	.073	.185	.557	5.578	55.790
417	.076	.193	.580	5.809	58.079
427	.079	.201	.604	6.039	60.414
437	.082	.209	.627	6.270	62.703
447	.085	.216	.650	6.503	65.038
457	.088	.224	.673	6.737	67.373
467	.091	.232	.697	6.973	69.707
477	.094	.240	.721	7.210	72.088
487	.097	.248	.744	7.447	74.469
497	.101	.256	.768	7.683	76.849
507	.104	.264	.792	7.926	79.230
517	.107	.272	.816	8.165	81.656
527	.110	.280	.840	8.408	84.083
537	.113	.288	.865	8.654	86.509
547	.117	.296	.889	8.896	88.981
557	.120	.304	.913	9.142	91.408
567	.123	.312	.938	9.387	93.880
577	.126	.321	.963	9.636	96.352
587	.130	.329	.988	9.885	98.870
597	.133	.337	1.013	10.134	101.342

TABLE A-2

Minimum Conductor Distances for Varying Pressures

Conductor: Fe Gas: Air

Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
265	.019	.049	.148	1.480	14.746
275	.025	.065	.195	1.959	19.590
285	.029	.074	.224	2.238	22.397
295	.032	.083	.248	2.489	24.887
305	.035	.090	.272	2.725	27.241
315	.038	.098	.295	2.953	29.550
325	.041	.105	.317	3.177	31.768
335	.044	.113	.340	3.401	33.987
345	.047	.120	.362	3.619	36.205
355	.050	.127	.383	3.837	38.378
365	.053	.135	.405	4.058	40.597
375	.056	.142	.427	4.277	42.770
385	.059	.149	.449	4.498	44.988
395	.062	.157	.471	4.716	47.161
405	.064	.164	.494	4.940	49.379
415	.067	.172	.516	5.158	51.598
425	.070	.179	.538	5.382	53.816
435	.073	.186	.560	5.607	56.080
445	.076	.194	.583	5.831	58.298
455	.079	.201	.605	6.055	60.562
465	.082	.209	.628	6.285	62.825
475	.085	.217	.651	6.509	65.089
485	.088	.224	.673	6.740	67.398
495	.091	.232	.696	6.970	69.706
505	.094	.240	.720	7.200	72.015
515	.097	.247	.743	7.430	74.324
525	.100	.255	.766	7.667	76.678
535	.103	.263	.789	7.900	78.987
545	.107	.271	.813	8.133	81.341
555	.110	.279	.837	8.369	83.696
565	.113	.286	.860	8.606	86.095
575	.116	.294	.884	8.848	88.449
585	.119	.302	.908	9.084	90.849
595	.122	.310	.932	9.327	93.248

TABLE A-3

Minimum Conductor Distances for Varying Pressures

Conductor: Cu   Gas: Nitrogen

Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
203	.016	.040	.122	1.216	12.109
213	.022	.055	.168	1.677	16.792
223	.025	.065	.195	1.960	19.593
233	.029	.073	.221	2.214	22.164
243	.032	.081	.245	2.457	24.598
253	.035	.089	.269	2.697	26.940
263	.038	.097	.293	2.930	29.327
273	.041	.105	.316	3.164	31.669
283	.044	.113	.339	3.400	34.011
293	.047	.121	.363	3.631	36.353
303	.050	.128	.386	3.868	38.694
313	.054	.136	.410	4.104	41.036
323	.057	.144	.434	4.341	43.424
333	.060	.152	.458	4.581	45.811
343	.063	.160	.482	4.820	48.199
353	.066	.168	.506	5.063	50.633
363	.069	.176	.530	5.306	53.020
373	.073	.184	.554	5.548	55.500
383	.076	.193	.579	5.794	57.933
393	.079	.201	.604	6.040	60.413
403	.082	.209	.628	6.288	62.892
413	.086	.218	.653	6.537	65.418
423	.089	.226	.678	6.792	67.897
433	.092	.234	.704	7.044	70.423
443	.096	.243	.730	7.299	72.994
453	.099	.251	.755	7.556	75.565
463	.102	.260	.781	7.811	78.137
473	.106	.268	.807	8.072	80.708
483	.109	.277	.832	8.330	83.325
493	.113	.286	.859	8.594	85.943
503	.116	.295	.885	8.855	88.560
513	.120	.303	.911	9.119	91.177
523	.123	.312	.938	9.383	93.840
533	.126	.321	.964	9.650	96.503
543	.130	.330	.991	9.917	99.167
553	.134	.339	1.018	10.190	101.876
563	.137	.348	1.045	10.457	104.585
573	.141	.357	1.073	10.730	107.294
583	.144	.366	1.100	11.003	110.003
593	.148	.375	1.127	11.276	112.758

TABLE A-4

Minimum Conductor Distances for Varying Pressures

Conductor: Al   Gas: Nitrogen

Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
172	.013	.034	.104	1.034	10.287
182	.019	.048	.146	1.465	14.692
192	.022	.057	.174	1.738	17.381
202	.026	.066	.198	1.987	19.884
212	.029	.074	.223	2.227	22.295
222	.032	.082	.246	2.461	24.659
232	.035	.089	.269	2.698	26.978
242	.038	.097	.293	2.932	29.342
252	.041	.105	.316	3.166	31.660
262	.044	.113	.340	3.402	34.025
272	.047	.121	.364	3.639	36.389
282	.051	.129	.387	3.876	38.753
292	.054	.137	.411	4.119	41.164
302	.057	.145	.435	4.356	43.575
312	.060	.153	.460	4.602	46.032
322	.063	.161	.484	4.848	48.489
332	.067	.169	.509	5.094	50.947
342	.070	.178	.534	5.340	53.404
352	.073	.186	.559	5.595	55.907
362	.076	.194	.584	5.844	58.457
372	.080	.203	.609	6.099	61.007
382	.083	.211	.635	6.354	63.557
392	.087	.220	.661	6.609	66.107
402	.090	.228	.687	6.870	68.703
412	.093	.237	.712	7.131	71.299
422	.097	.246	.739	7.392	73.942
432	.100	.255	.765	7.653	76.538
442	.104	.264	.791	7.920	79.227
452	.107	.272	.818	8.188	81.870
462	.111	.281	.845	8.455	84.559
472	.114	.290	.872	8.722	87.248
482	.118	.299	.899	8.995	89.937
492	.121	.308	.926	9.269	92.672
502	.125	.318	.954	9.542	95.407
512	.129	.327	.981	9.815	98.189
522	.132	.336	1.009	10.094	100.924
532	.136	.345	1.037	10.368	103.706
542	.140	.355	1.064	10.647	106.488
552	.143	.364	1.093	10.926	109.316
562	.147	.373	1.121	11.212	112.098
572	.151	.383	1.149	11.491	114.926

TABLE A-5

Minimum Conductor Distances for Varying Pressures

Conductor: Fe   Gas: Nitrogen

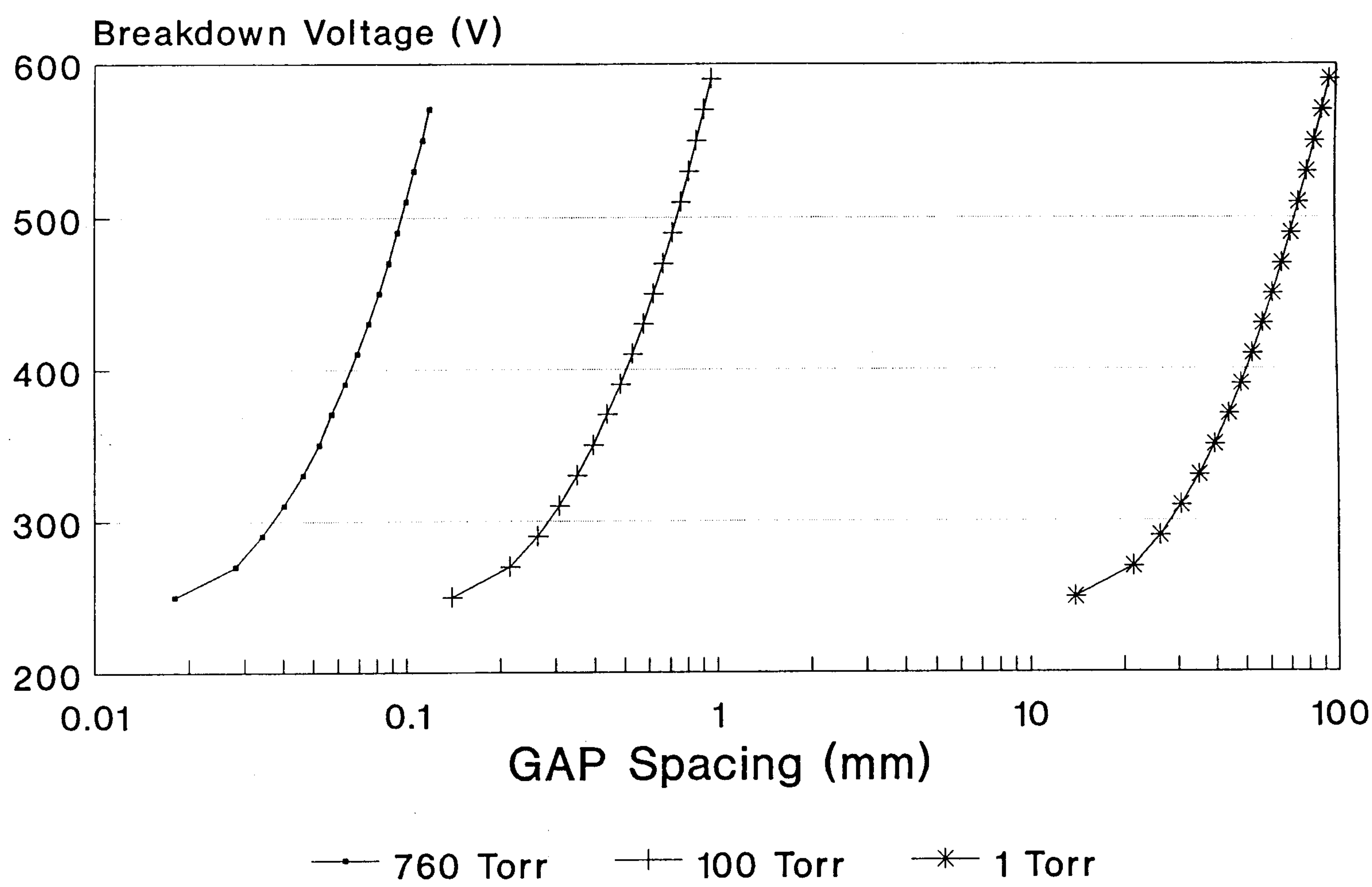
Minimum Design Distance (mm)
(Saftey Factor: 2)

Voltage (V)	760 Torr	300 Torr	100 Torr	10 Torr	1 Torr
212	.016	.042	.127	1.265	12.600
222	.022	.057	.173	1.733	17.363
232	.026	.067	.201	2.018	20.202
242	.029	.075	.227	2.272	22.767
252	.033	.083	.251	2.521	25.194
262	.036	.091	.275	2.758	27.575
272	.039	.099	.299	2.994	29.957
282	.042	.107	.322	3.228	32.293
292	.045	.115	.346	3.461	34.628
302	.048	.123	.369	3.698	36.964
312	.051	.131	.393	3.931	39.299
322	.054	.138	.416	4.165	41.681
332	.057	.146	.440	4.401	44.016
342	.061	.154	.464	4.641	46.398
352	.064	.162	.487	4.881	48.825
362	.067	.170	.512	5.120	51.207
372	.070	.178	.536	5.360	53.634
382	.073	.186	.560	5.605	56.061
392	.076	.195	.585	5.851	58.488
402	.080	.203	.609	6.094	60.961
412	.083	.211	.634	6.342	63.434
422	.086	.219	.659	6.591	65.907
432	.090	.228	.684	6.843	68.426
442	.093	.236	.709	7.095	70.945
452	.096	.244	.734	7.349	73.464
462	.100	.253	.760	7.604	76.028
472	.103	.262	.785	7.859	78.593
482	.106	.270	.811	8.114	81.157
492	.110	.279	.837	8.374	83.722
502	.113	.287	.863	8.635	86.332
512	.117	.296	.889	8.896	88.943
522	.120	.305	.915	9.157	91.553
532	.123	.314	.942	9.421	94.209
542	.127	.322	.968	9.685	96.866
552	.130	.331	.995	9.951	99.522
562	.134	.340	1.021	10.218	102.178
572	.138	.349	1.049	10.485	104.880
582	.141	.358	1.075	10.758	107.582
592	.145	.367	1.102	11.028	110.284

TABLE A-6

Paschen's Curve (Copper Electrodes)

Voltage Breakdown vs Conductor Distance



Gas: AIR

Figure 3

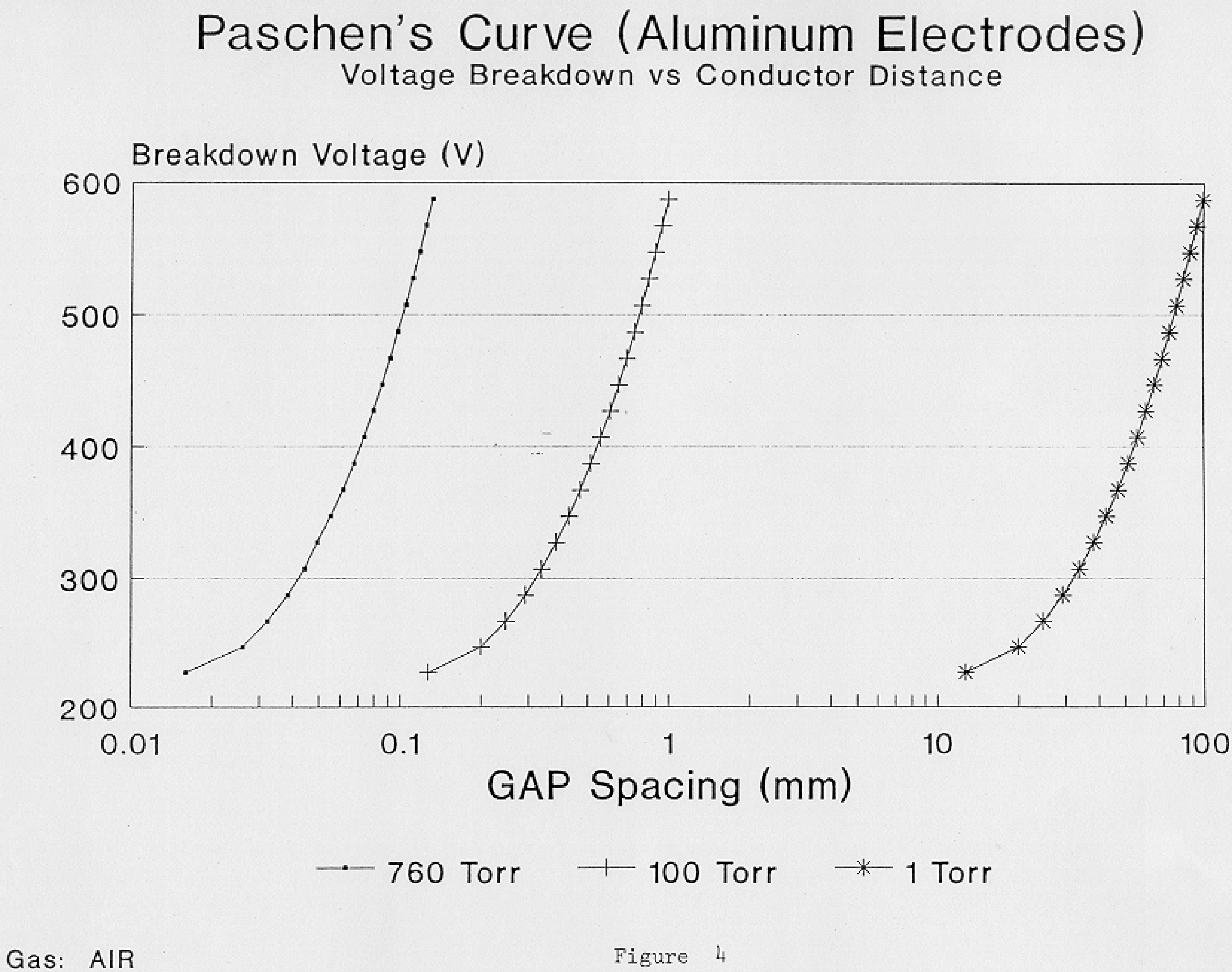

Paschen's Curve (Aluminum Electrodes)
Voltage Breakdown vs Conductor Distance
Breakdown Voltage (V)
600
500
400
300
200
0.01
0.1
1
10
100
GAP Spacing (mm)
760 Torr
100 Torr
1 Torr
Gas: AIR

Figure 4

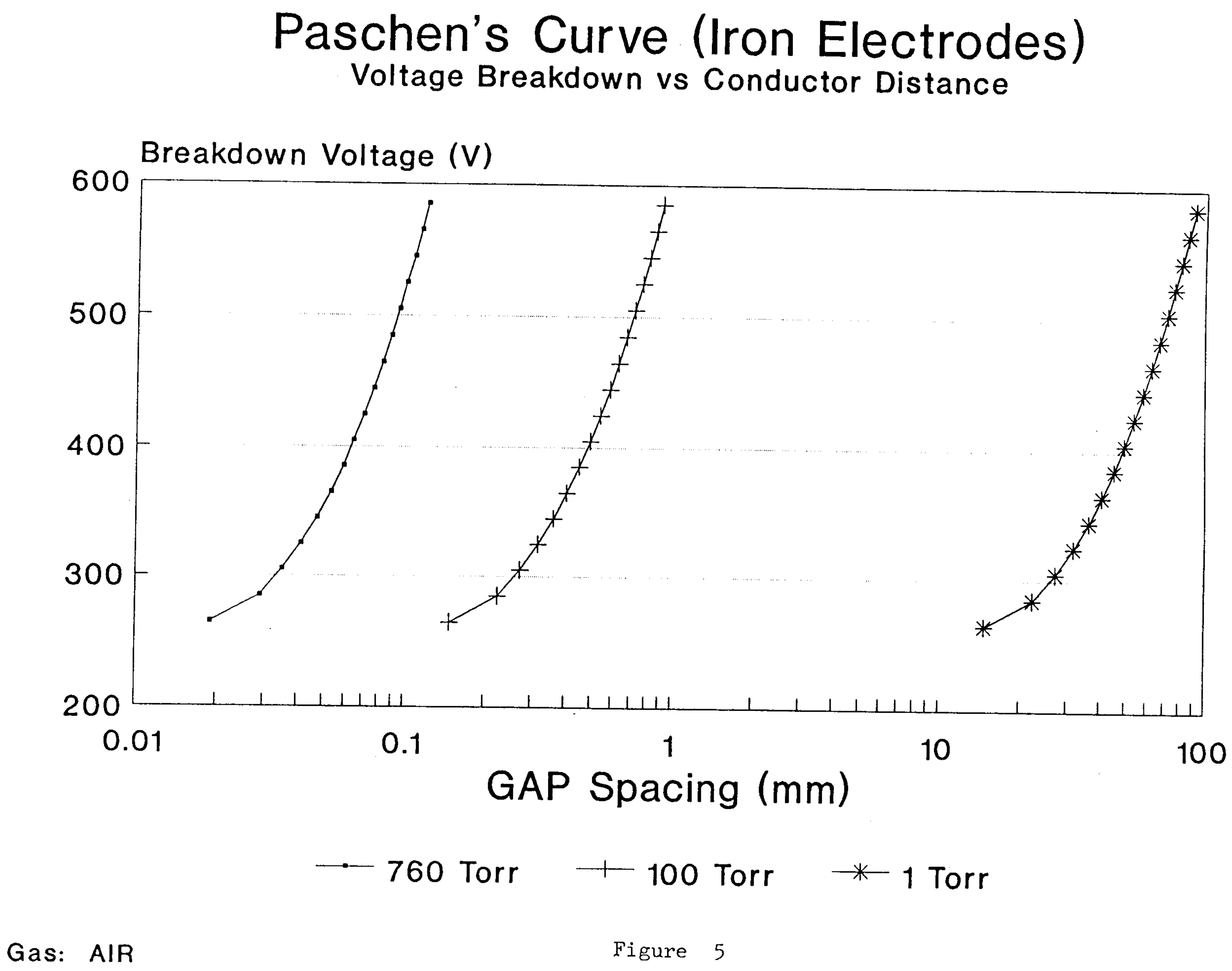

Paschen's Curve (Iron Electrodes)
Voltage Breakdown vs Conductor Distance
Breakdown Voltage (V)
600
500
400
300
200
0.01
0.1
1
10
100
GAP Spacing (mm)
760 Torr
100 Torr
1 Torr
Gas: AIR

Figure 5

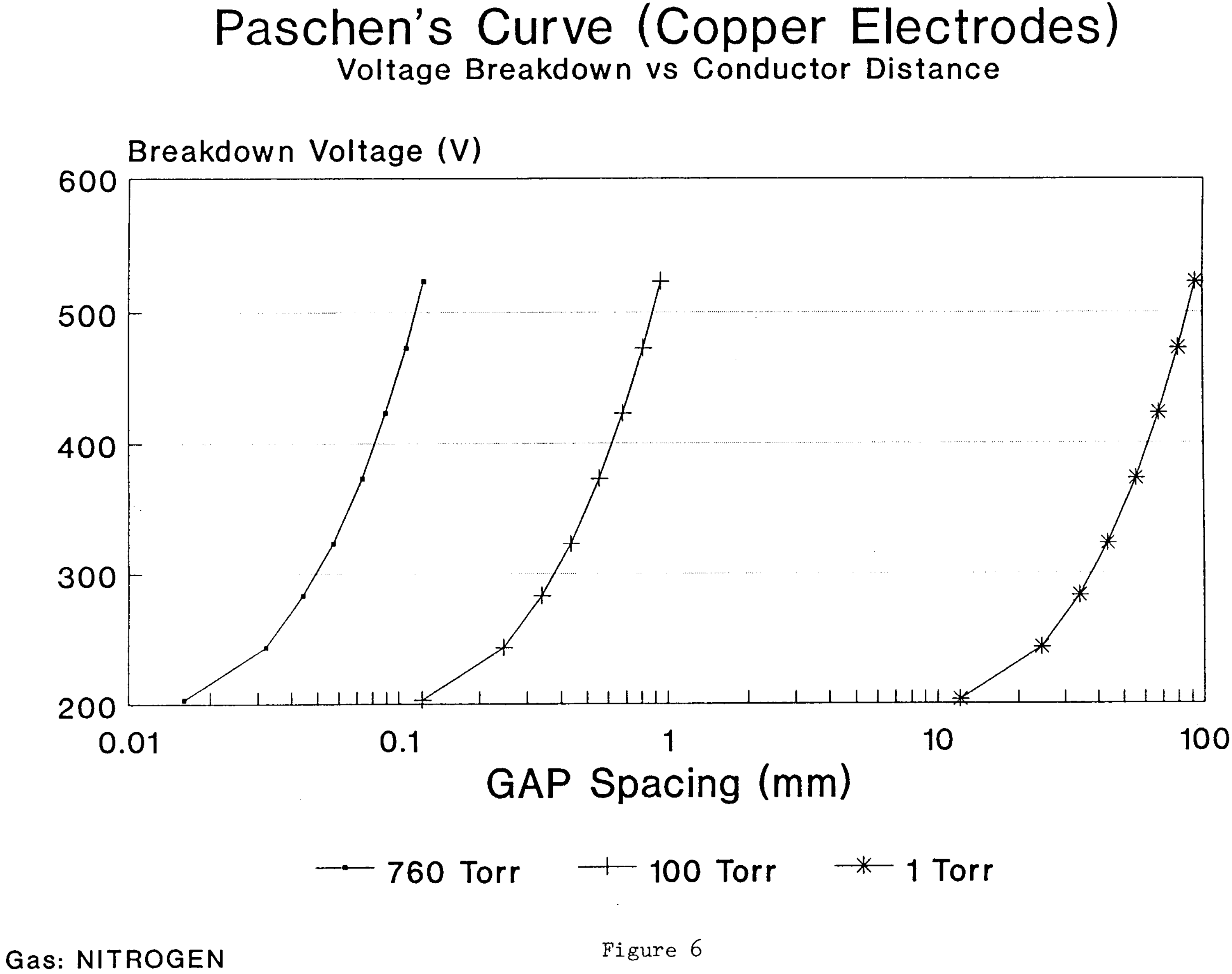

Paschen's Curve (Copper Electrodes)
Voltage Breakdown vs Conductor Distance
Breakdown Voltage (V)
600
500
400
300
200
0.01
0.1
1
10
100
GAP Spacing (mm)
760 Torr
100 Torr
1 Torr
Gas: NITROGEN

Figure 6

Paschen's Curve (Aluminum Electrodes)

Voltage Breakdown vs Conductor Distance

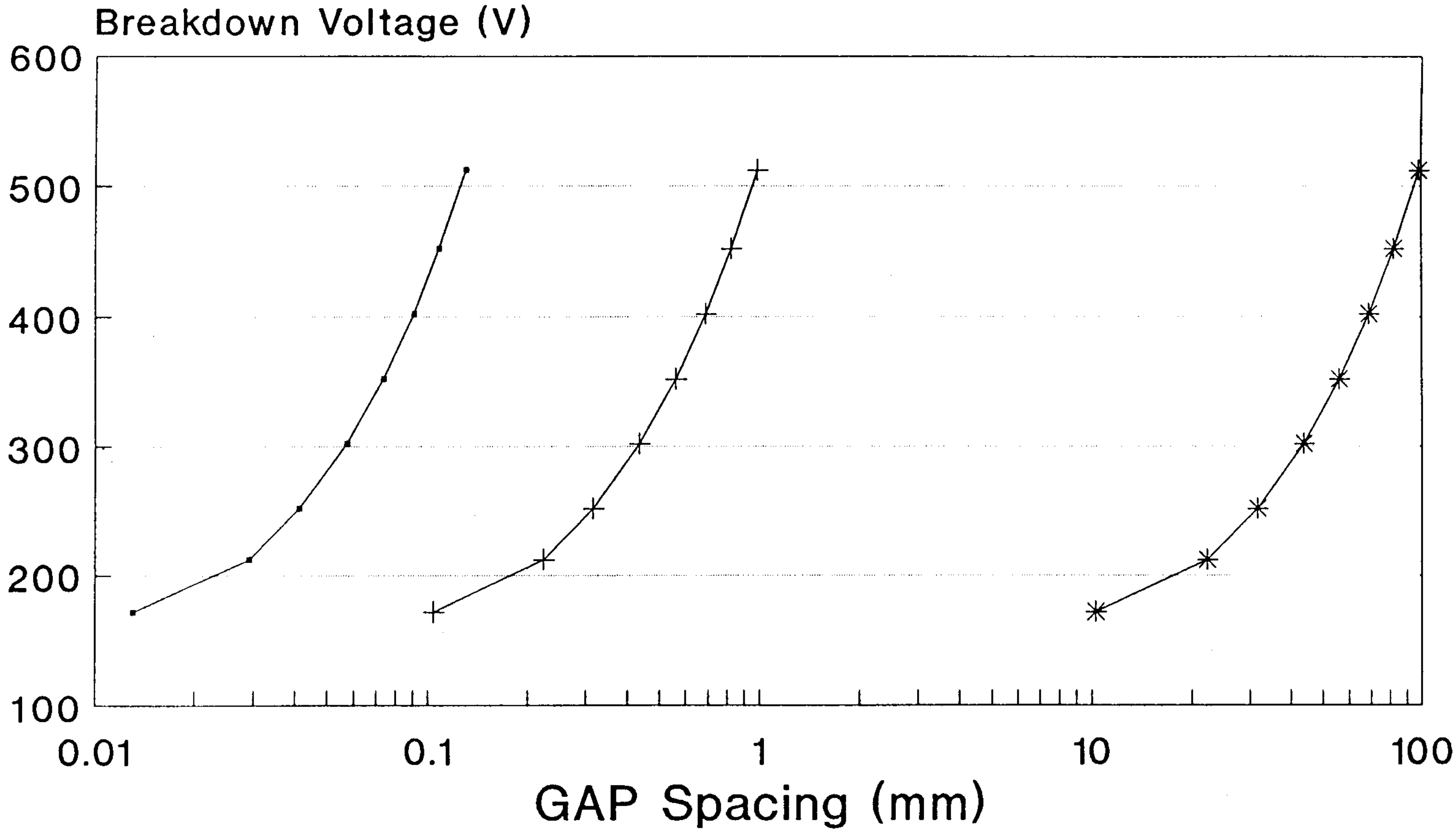


Figure 7

Gas: NITROGEN

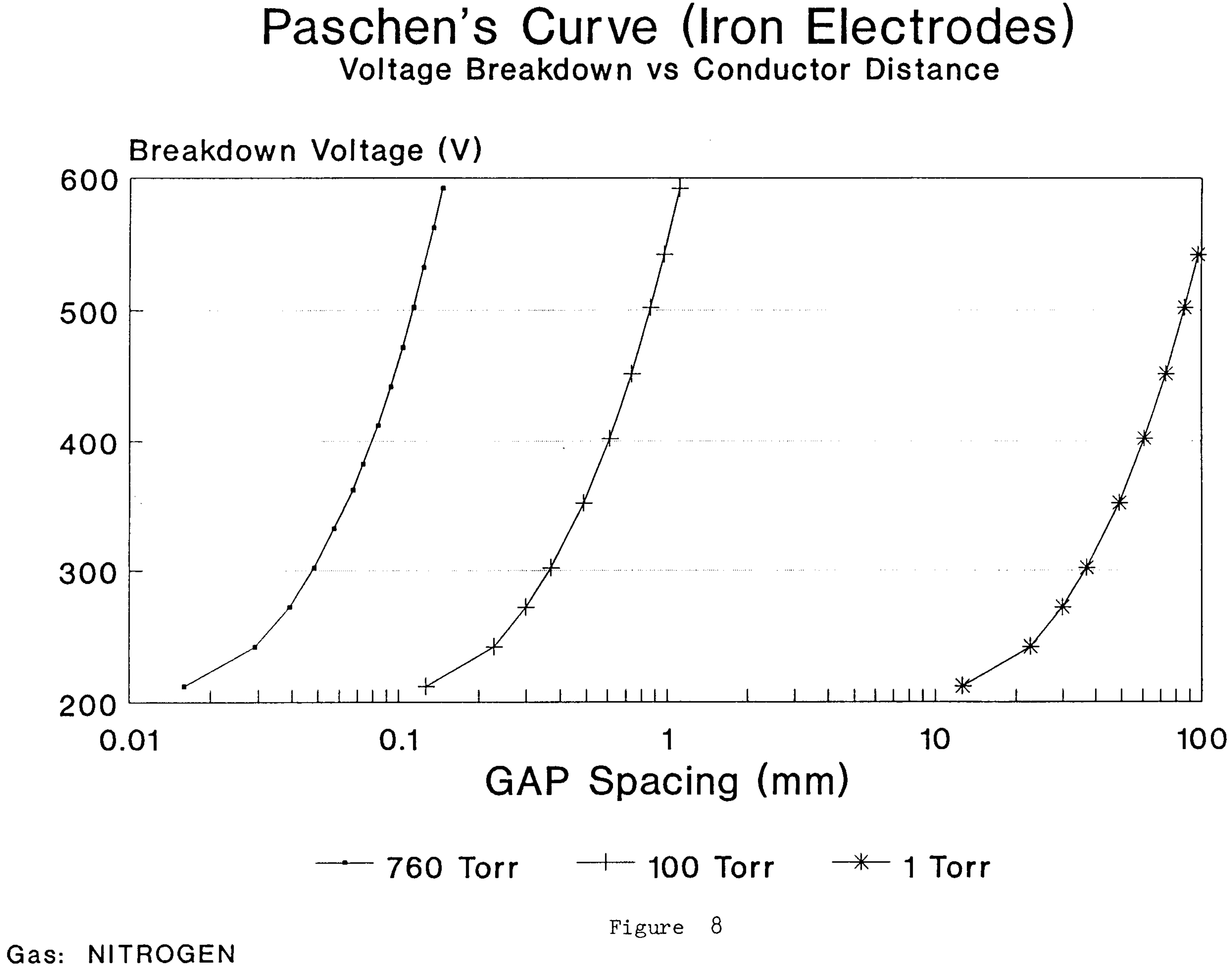

Paschen's Curve (Iron Electrodes)
Voltage Breakdown vs Conductor Distance
Breakdown Voltage (V)
600
500
400
300
200
0.01
0.1
1
10
100
GAP Spacing (mm)
760 Torr
100 Torr
1 Torr
Gas: NITROGEN

Figure 8