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**A BIBLIOGRAPHY AND AUTHOR INDEX FOR
ELECTRICAL DISCHARGES IN VACUUM
(1897-1980)**

**H. Craig Miller
Neutron Generator Development
Engineering Operation**

January 29, 1982

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**General Electric Company
Neutron Devices Department
P. O. Box 11508
St. Petersburg, Florida 33733**

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ABSTRACT

This bibliography covers the field of electrical discharges in vacuum, comprising both electrical breakdown in vacuum and vacuum arcs. A brief review section lists some review papers which would be helpful to the novice in this field. The bulk of the paper consists of bibliographic listings, arranged by year of publication and within each year, alphabetically by first author. An author index refers one to all papers authored or coauthored by a particular person. There are 2450 papers listed through December 1980.

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INTRODUCTION

The field of electrical discharges in vacuum has been a subject of intense theoretical and experimental investigation for many years. As a result there has been created a large body of literature in which one might want or need to search. Thus a good bibliography can be a useful tool for workers in this interesting field.

In the last decade and a half there have appeared four bibliographies covering electrical discharges in vacuum. The published indexed bibliography of Hawley and Maitland,¹ though detailed, is now fourteen years old and thus limited to the older literature. That of Bacon, Grissom, Mangan, McClure and Newton² appeared as a Sandia Laboratory report. It was more comprehensive in that it included the entire field of arc discharges, but is now over nine years old. The most current subject bibliography is that of Farrall.³⁻⁵ His original bibliography was complete through February 1972,³ but has been updated twice since then, the latest supplement containing references through November 1975.⁵ Farrall's bibliography is very useful for obtaining references in a particular category of interest, since its entries are cross-referenced under more than 70 categories. The references are listed by author and year, which then allows the interested reader to find the full abstract in Physics or Electrical Engineering Abstracts.

This paper is a revised and updated version of a previously issued bibliography and author index.⁶ It does not contain a subject index. However, it is hoped that the reader will find it useful, especially in conjunction with a subject-indexed bibliography such as Farrall's. The references are first grouped by year, then within a year alphabetically by first author. In addition, an author index is given which will allow you to find all papers with which a given investigator was associated as an author.

REVIEW REFERENCES

The subject of electrical discharges in vacuum is usually broken down into two main categories (with frequent overlapping): (1) Electrical breakdown in vacuum, which is concerned with phenomena before breakdown and at the instant of breakdown, and (2) arcing in vacuum, which considers the phenomena after breakdown has occurred and a (quasi) steady state discharge has been established.

Prebreakdown currents frequently occur in vacuum gaps. These currents fall into two general categories:

- (1) Steady or quasisteady currents emitted from sites on the cathode by means of field emission or thermally-assisted field emission. Such emission sites may be metal projections, interfaces between insulating inclusions and the electrode metal, thin semiconducting patches on the electrode, etc.
- (2) Microdischarges - which are self-limiting bursts of current. They may be caused by small clumps of material being detached from one electrode and crossing the gap to strike the other. They may also be caused by a beam of electrons from the cathode vaporizing a small quantity of material from the surface of the anode. Microdischarges tend to be more common in vacuum gaps with contaminants on their surfaces. Here a microdischarge may occur when a regenerative interchange of charge carriers between sites on the cathode and anode continues until the local contaminant density is reduced sufficiently to stop the interchange.

Sometimes the same vacuum gap will show both types of breakdown phenomena, either concurrently or at different voltage levels.

Prebreakdown currents may lead directly to breakdown. Or they may affect the surfaces of the vacuum gap so as to make subsequent breakdown of the gap either more or less probable. In certain high voltage vacuum devices with low operating currents, such prebreakdown currents can increase to the point where they load the device's power supply sufficiently to prevent proper operation. In such cases the device may be said to have failed even though no breakdown has occurred. Certain types of breakdowns are caused directly by growth of prebreakdown currents. Other types involve different phenomena.

Electrical breakdown in vacuum is usually explained by theories which fall into four main categories:

- (1) "Clump" theories postulate that breakdown is initiated by a particle or "clump" becoming detached from one electrode, then crossing the interelectrode gap and impacting on the other electrode with sufficient energy to trigger a breakdown.
- (2) Interaction theories assume that chain reactions involving electrons, positive ions, negative ions, and photons cause a rapid rise in prebreakdown current which increases until breakdown of the gap occurs.

- (3) Cathodic theories assume that field emission of electrons from projections on the cathode causes heating and vaporization of the projections, leading to the introduction into the gap of a supply of vapor or plasma sufficient to cause breakdown. This vapor (plasma) can be produced either by Joule heating of the projection or by an explosion of the projection.
- (4) Anodic theories actually involve both cathode and anode, since they assume the existence of a beam of electrons emitted from the cathode. This beam impinges upon the anode, producing effects there which ultimately lead to breakdown. In one group of anodic theories the beam heats a small part of the anode surface enough to produce vapor, then ionizes the vapor. This ionized vapor then triggers breakdown of the gap. The second group of theories assumes that the effect of the beam on the anode is to produce (or free) a particle from the anode surface. This particle then is electrostatically transferred to the cathode, where it triggers the breakdown of the anode-cathode gap. This triggering occurs either (a) by the original beam continuing to play on the particle as it traverses the gap, producing sufficient vapor to trigger the breakdown, or (b) by a strong Field Emission discharge between the cathode and the approaching particle, which discharge triggers breakdown of the overall anode-cathode gap.

Of all these theories, only the Interaction theories definitely have been ruled out as applying to clean vacuums and surfaces, though they have significant practical applications in devices such as accelerators. No theory seems to explain all breakdowns, since by an appropriate choice of gap geometry, electrode material, and voltage waveform one can establish a situation where as desired a clump, cathode, or anode process will be the primary cause of breakdown.

The subject of electrical breakdown in vacuum has been thoroughly discussed by Latham in a recent book.⁷ Two other good recent reviews of vacuum breakdown have appeared as chapters in books,⁸⁻⁹ Chatterton's review⁸ (184 references) and Farrall's (160 references).¹⁰ A good review concerned primarily with Explosive Emission is that of Bugaev¹¹ (103 references).

Once the discharge has been fully established the current is normally limited primarily by the external circuitry and a vacuum arc is formed. Most of the work on vacuum arcs has been done on cathode phenomena, since unlike conventional gas arcs the anode is not an active electrode at low currents and the gap (column) phenomena are dependent upon the electrode material and geometry.

The established vacuum arc may be considered as being in a stationary state (quasistatic equilibrium) or it may be considered as a dynamic series of nonstationary phenomena. For example some arc theories consider the cathode current emitting sites to be a succession of nonconnected areas, each site being initiated by an explosive emission event similar to the explosive emission invoked in some vacuum breakdown theories. Others arc theories explain even time dependent phenomena as a comparatively slow evolution of quasistationary states.

In a vacuum arc the emission of electrons from the cathode is usually described by the equations of Thermal-Field Emission. Different materials may be considered as having Thermally-assisted Field Emission or Field-assisted Thermionic Emission. Examples of extremes might be mercury and carbon. An electron emitting site on the cathode and a dense plasma cloud located just above the site comprise what is normally called the cathode spot. Various arc theories add such items as extensions of the plasma region, the presence of a local positive charge accumulation, a hot region next to the present emitting site, craters at the site, etc., but all cathode spot theories include an intense electron emitting site and an adjacent dense plasma cloud.

Excellent reviews of various vacuum arc phenomena have appeared in the compilation of Lafferty.⁹ Kimblin¹² (54 references) and Holmes¹³ (111 references) have considered phenomena at both arc electrodes, for vacuum arcs and also gas arcs. Vacuum arc cathode phenomena have been exhaustively reviewed by Lyubimov and Rakhovskii¹⁴ (191 references), and also by Hantzschel¹⁵ (56 references), while vacuum arc anode phenomena have been discussed by Miller¹⁶ (61 references).

Three complete reviews of the entire subject of electrical discharges in vacuum have appeared in the last decade. The review of Rakhovskii¹⁷ (several hundred references) appeared in 1970 and in English translation in 1973. Slivkov's review¹⁸ appeared in 1972. The compilation of Lafferty et al⁹ is the most recent, appearing in 1980.

The inexperienced reader should consult the review literature first, choosing the reviews that are pertinent to one's particular field of interest. Once a general base of knowledge has been established, the best way to survey the latest work in the field is by attending, or obtaining the proceedings of, the latest conference in the continuing series of International Symposia on Discharges and Electrical Insulation in Vacuum. These have been held every two years, the last conference being at Eindhoven, The Netherlands in 1980. The next conference is scheduled to be held at Columbia, South Carolina, USA in October 1982.

FORMAT

The bibliographic references are arranged by year of publication, and within a year, alphabetically by the first author's surname. A typical entry appears as:

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
76B4	Vacuum Arc	A. Baker C. Dog	J. Phys. <u>7</u> 18-28

The 76B4 index number is formed as follows: The first two symbols are digits indicating the year of publication (1976), the third symbol is the first letter in the (senior) author's name, while the final symbol is a number indicating that this particular paper is the fourth (alphabetically) B paper of this particular year. The title, author, and reference entries are self-explanatory. Journal references normally use Physics Abstracts abbreviations. The inclusive page numbers are usually given, though sometimes only the first page is listed. The year of publication is omitted since this information is inherent in the year groupings. Conference proceedings to which frequent reference is made are normally abbreviated, with a footnote to the first entry giving the complete conference title.

The bulk of the entries have appeared in Physics Abstracts or in major conference proceedings (Discharges and Electrical Insulation in Vacuum Symposia, Phenomena in Ionized Gases Conferences, Gas Discharge Conferences). Some papers fall in neither category, but appear because a copy was available. In a few cases, I could not obtain or consult the original paper, but entered it as it was referred to in another paper to which I did have access.

Coverage of reports is far from complete, since I have primarily listed reports which I possess or to which I had access. Also, if a paper appears to be a published version of an earlier report, then frequently only the published paper is listed. Many reports are available from NTIS (National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161, USA). Such reports are indicated by the expression (NTIS) following the report listing. If the NTIS order reference is different from the report reference, the NTIS reference also appears in the parentheses.

Some documents are available in microfiche format from INIS (INIS Clearinghouse, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria). Such references are indicated by the expression INIS ... (the INIS order reference) following the document listing. INIS normally can supply microfiches of all non-conventional literature (defined by them as everything but books or journal articles) appearing in the abstracting journal INIS Atomindex. Assistance in obtaining access to conventional literature abstracted in INIS Atomindex may be obtained in many countries from the National INIS Liaison Officer in that country.

My American language bias is apparent in several respects. Titles are normally given in English for papers written in another language. Sometimes the subjects covered in a non-English language paper are given instead of the title; this is indicated by placing the subject listing in parentheses.

Entries from Russian journals appearing in English translation (e.g., Zh. Tekh. Fiz. to Sov. Phys.-Tech. Phys.) are referred to as they appear in the translated journal. In case of a conflict between the title as given in the translated paper and that in Physics Abstracts, the title of the paper is preferred. Such differences often occur when different translators prepared the Physics Abstracts entry and the translated journal article. In some cases the translated articles hadn't yet become accessible to me. For such papers the original Russian reference is given, with the title of the translated journal appearing afterwards.

The question of the correct expression of Russian names in English is troublesome because the same Russian name may be written differently in the Latin alphabet depending on the transliteration scheme used (Russian-German, Russian-English, Russian-American English, etc). I prefer to use the transliteration scheme of the American Institute of Physics (Table I) when a choice must be made. This is the scheme I usually use in my author index (so for example В. И. Раховский would be V. I. Rakhovskii). However, for individual entries I use the exact name as given in the entry, so in the references he may appear as W. Y. Rakhovskii or Rakhovsky.

SCHEME OF TRANSLITERATION	
Cyrillic Character	Transliteration
А а	a
Б б	b
В в	v
Г г	g
Д д	d
Е е	e
Ж ж	zh
З з	z
И и	i
Й й	i
К к	k
Л л	l
М м	m
Н н	n
О о	o
П п	p
Р р	r
С с	s
Т т	t
Тс тс	t-s
У у	u
Ф ф	f
Х х	kh
Ц ц	ts
Ч ч	ch
Ш ш	sh
Щ щ	shch
Ъ ъ	" or "
Ы ы	y
Ь ь	' or '
Э э	e
Ю ю	yu
Я я	ya

Table 1. Transliteration Scheme of the
American Institute of Physics

Nevertheless, since authors are people and not just index entries, the final determination of the correct spelling of a name should be made by the person who bears the name. Therefore, if any author whose native tongue uses a Cyrillic or other nonlatin alphabet prefers a different spelling than I have used, I request that they inform me of their preferred spelling.

All authors connected with any of the bibliographic entries are listed alphabetically by surname in the author index. A typical entry appears as:

Baker, A	60F1	70B6	76B4	76N4
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The index numbers indicate all papers for which A. Baker was listed as an author.

In order to allow for future updating and revision, the bibliographic reference and author index sections have consecutive page numbers within each section, but not between sections. Thus the reference section starts with page 101, and the author index with page 401.

This Bibliography contains 2450 references, the latest of which appeared in December 1980. It is planned to keep the bibliography and the author index files reasonably current as a basis for preparing future supplements or revisions. Thus I would appreciate being informed of any omissions or errors which you notice or become aware of.

ACKNOWLEDGMENTS

I particularly want to thank George Farrall for his help. Dr. B. Jüttner has suggested numerous additional references, those improving the coverage of non-English literature being especially appreciated. A listing of all the other people who have assisted me in the formation and maintenance of this bibliography would take several pages and still probably err in omission. Therefore, I express my gratitude to all my colleagues in General Electric, the United States, and abroad, who have sent me copies of their papers or with whom I have had discussions. The efforts and detective ability of a succession of library workers in obtaining items for me were a vital and appreciated part of this work. The contributions of a series of long-suffering typists in reading my writing were also much appreciated.

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ELECTRICAL DISCHARGES IN VACUUM
BIBLIOGRAPHY
(1897-1980)

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
97W1	A New Form of Cathode Discharge and the Production of X-rays Together With Some Notes on Diffraction	R. W. Wood	Phys. Rev. Ser. I <u>5</u> 1-10

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
01E1	The Sparking Distance Between Plates for Small Distances	R. F. Earhart	Phil. Mag. <u>S6</u> <u>1</u> 147-

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
05H1	The Relationship Between P. D. and Spark-length for Small Values of the latter	G. M. Hobbs	Phil. Mag. <u>S6</u> <u>10</u> 617-31
05K1	Short Spark Discharges	C. Kinsley	Phil. Mag. <u>S6</u> <u>9</u> 692-708

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
08E1	Discharge from an Electrified Point and the Nature of the Discharge Occurring through very small distances	R. F. Earhart	Phil. Mag. <u>S6</u> <u>16</u> 48-

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
12R1	Some Applications of the Electron Theory of Matter	O. W. Richardson	Phil. Mag. <u>S6</u> <u>23</u> 594-

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
13C1	A Powerful Rontgen Ray Tube With a Pure Electron Discharge	W. D. Coolidge	Phys. Rev. <u>2</u> 409
13L1	The Effect of Space Charge and Residual Gases on Thermionic Currents in High Vacuum	I. Langmuir	Phys. Rev. <u>2</u> 450
13M1	The Attainment of High Potentials by the Use of Radium	H. G. J. Moseley	Proc. Roy. Soc. (London) <u>A88</u> 471

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
18M1	Extreme Ultraviolet Spectra of Hot Sparks in High Vacua	R. A. Millikan R. A. Sawyer	Phys. Rev. <u>12</u> 167-70

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
20M1	On the Possibility of Pulling Electrons From Metals by Powerful Electric Fields	R. A. Millikan B. E. Shackelford	Phys. Rev. <u>15</u> 239-40

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
22H1	The Dielectric Strength of the Vacuum. Electrostatic Ionization Gradient of Metal Electrodes	J. L. R. Hayden	J. Am. Inst. Elec. Engrs. <u>41</u> 852
22L1	Rontgen Radiation from the Kathode in Autoelectronic Discharge	J. E. Lilienfeld	Physik. Z <u>23</u> 506-11
22R1	Electronic Discharge with Small Distances Between Electrodes	F. Rother	Physik. Z <u>23</u> 423-7

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
23L1	Auto-Electronic Discharge	J. E. Lilienfeld	Z. Physik <u>15</u> 46-50
23M1	The Pulling of Electrons Out of Metals by Intense Electrical Fields	R. A. Millikan C. F. Eyring	Phys. Rev. <u>22</u> 525
23S1	Cold and Hot Electron Discharges	W. Schottky	Z. Physik <u>14</u> 63-106
23S2	Auto-Electronic Discharge	W. Schottky	Z. Physik <u>15</u> 51
23S3	Concerning Cathode- and Anode Fall in Hg, Zn, Cd, and Mg Vacuum Arcs	H. Schüller	Z. Physik <u>14</u> 32-43

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
25C1	The Diffusion of Electrons Against an Electric Field in the Non-Oscillatory Abnormal Low Voltage Arc	K. T. Compton C. Eckart	Phys. Rev. <u>25</u> 139-46
25J1	Significance of Gas Contents of Metals for Some Electric Phenomena	A. Janitzky	Z. Physik <u>31</u> 277
25P1	Cold Electronic Discharge From Mo	R. J. Piersol	Phys. Rev. <u>25</u> 112
25R1	Electric Contact Between Glowing and Cold Electrodes in a Vacuum	H. Rohmann	Z. Physik <u>34</u> 94-102

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
26C1	Auto-Electronic Discharge	K. Cunradi	Ann. Physik <u>81</u> 155-72
26G1	The Emission of Electrons Under the Influence of Intense Electric Fields	B. S. Gossling	Phil. Mag. <u>S7</u> <u>1</u> 609
26H1	Temperature Relations of Photoelectric and Thermionic Emission of Electrons	E. H. Hall	Proc. Nat. Acad. Sci. USA <u>12</u> 486-8
26M1	Laws Governing the Pulling of Electrons Out of Metals By Intense Electrical Fields	R. A. Millikan C. F. Eyring	Phys. Rev. <u>27</u> 51
26R1	Electric Contact of Glowing Platinum in Vacuum	H. Rohmann	Z. Physik <u>36</u> 803-13
26R2	Passage of Electricity Between Platinum Electrodes in a Vacuum	H. Rohmann	Z. Physik <u>39</u> 427-36
26R3	On the Emission of Electrons from Cold Metal	F. Rother	Ann. Physik <u>81</u> 317
26R4	Electrons Emitted From Cold Metal	F. Rother	Physik. Z <u>27</u> 471-2
26S1	Vacuum Switching Experiments	R. W. Sorensen H. E. Mendenhall	Trans. ATEE <u>45</u> 1102-5

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
27D1	Low-Pressure Electric Discharge in Intense Electric Fields	C. Del Rosario	Phys. Rev. <u>29</u> 360
27H1	Escape of Electrons From Metals Under the Action of High Field Strength	G. Hoffman	Ann. Physik <u>82</u> 254-6
27M1	Vacuum Switch	H. E. Mendenhall	Phys. Rev. <u>29</u> 754

<u>Index Number</u>	<u>Title</u>	<u>Author</u>	<u>Reference</u>
28A1	Influence of Anode Heating on the Striking of Metal Arcs	H. Alterthum H. Ewest	Z. Tech. Physik <u>9</u> 221-3
28D1	Effect of Temperature on the Auto-Electronic Discharge	N. A. de Bruyne	Proc. Cambridge Phil. Soc. <u>24</u> 518-20
28D2	Some Experiments on the Auto-Electronic Discharge	N. A. de Bruyne	Phil. Mag. <u>S7</u> <u>10</u> 574
28D3	The Action of Strong Electric Fields on the Current from a Thermionic Cathode	N. A. de Bruyne	Proc. Roy. Soc. (London) <u>A120</u> 423-7
28D4	Low-Pressure Electric Discharge	C. Del Rosario	J. Franklin Inst. <u>205</u> 103
28D5	Low-Pressure Electric Discharge	C. Del Rosario	Phys. Rev. <u>31</u> 154
28E1	Fields Currents From Points	C. F. Eyring S. S. Mackeown R. A. Millikan	Phys. Rev. <u>31</u> 900-9
28E2	Field Currents From Points	C. F. Eyring S. S. Mackeown R. A. Millikan	Phys. Rev. <u>31</u> 914
28F1	Electron Theory of Metals and Thermionic Formulae	R. H. Fowler	Proc. Roy. Soc. (London) <u>A117</u> 549-52
28F2	Electron Emission in Intense Electric Fields	R. H. Fowler L. Nordheim	Proc. Roy. Soc. (London) <u>A119</u> 173-81
28H1	Electron Emission of Cold Metals	W. V. Houston	Z. Physik <u>47</u> 33-7
28H2	Some Characteristics of the Discharge Between Cold Electrodes in a Vacuum	A. W. Hull E. E. Burger	Phys. Rev. <u>31</u> 1121
28L1	Different Types of Field Currents, Their Laws and the Conditions Under Which They Arise	C. C. Lauritsen R. A. Millikan	Phys. Rev. <u>31</u> 914
28M1	Relations of Field Currents To Thermionic Currents	R. A. Millikan C. C. Lauritsen	Proc. Nat. Acad. Sci. USA <u>14</u> 45-9

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53H2	The Mechanism of the Initiation of an Electrical Gas Discharge Under the Influence of a Transverse Magnetic Field in the Pressure Range 10^{-1} to 10^{-8} mm Hg	R. Haefer	Acta. Phys. Austriaca <u>7</u> 251-77
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54K1	On the Electron Emission from Cold Metal Surfaces at Medium Field Strengths	K. Kerner H. Raether	Z. angew. Phys. <u>6</u> 212-3
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