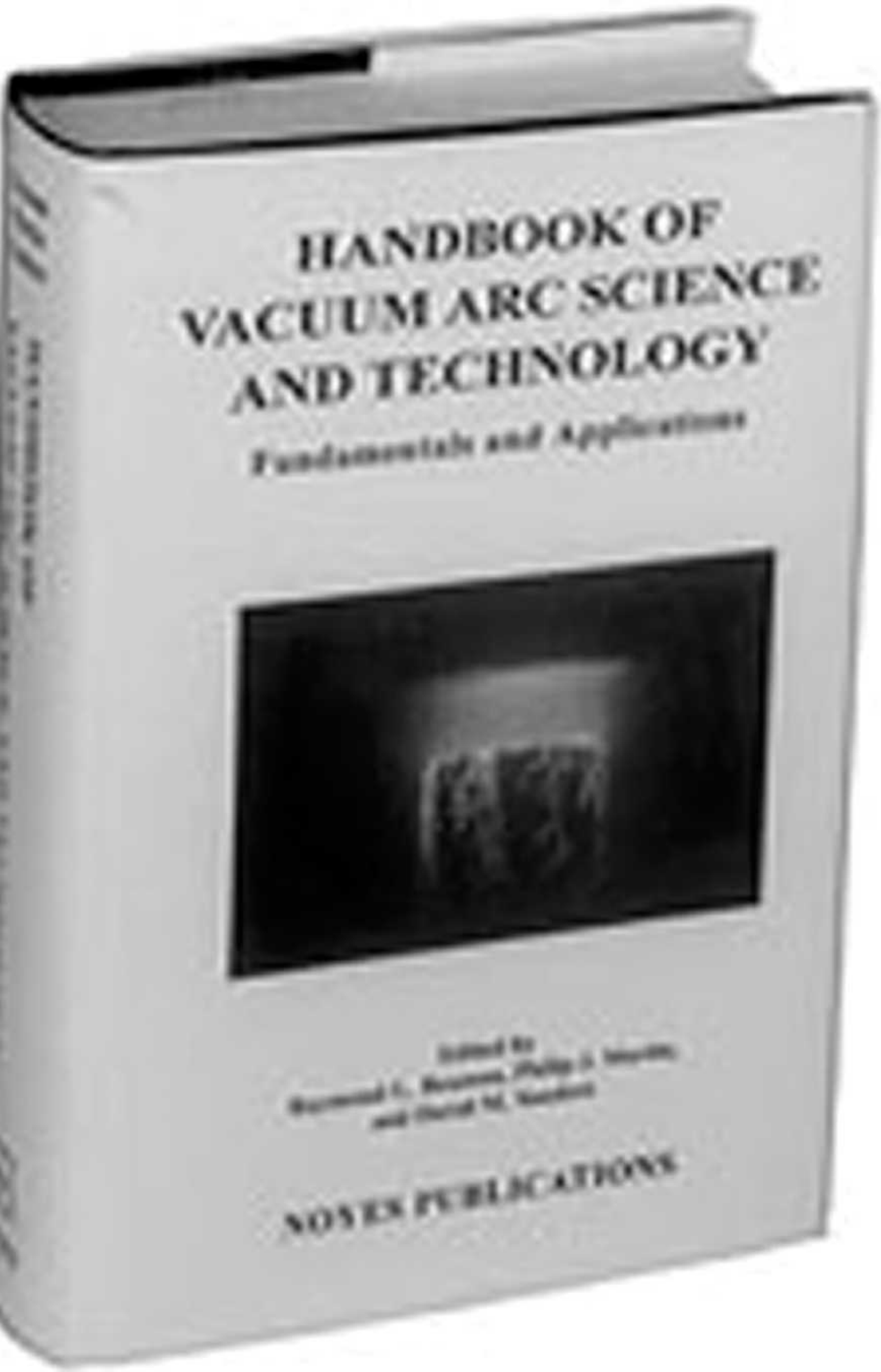

# HANDBOOK OF VACUUM ARC SCIENCE AND TECHNOLOGY

*Fundamentals and Applications*

Edited by
Raymond L. Boxman, Philip J. Martin,
and David M. Sanders

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## Fundamentals and Applications

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np
NOYES PUBLICATIONS
Park Ridge, New Jersey, U.S.A.

Library of Congress Catalog Card Number: 95-22677
ISBN: 0-8155-1375-5
Printed in the United States

Published in the United States of America by
Noyes Publications
Mill Road, Park Ridge, New Jersey 07656

10 9 8 7 6 5 4 3 2

Library of Congress Cataloging-in-Publication Data

Handbook of vacuum arc science and technology : fundamentals and applications / edited by Raymond L. Boxman, Philip J. Martin, David Sanders
p. cm.
Includes bibliographical references and index.
ISBN 0-8155-1375-5
1. Vacuum arcs. 2. Vacuum arcs--Industrial applications.
3. Plasma (Ionized gases) I. Boxman, R. L. II. Martin, Philip J.
III. Sanders, David (David M.)
QC705.H36 1995
537.5'3--dc20 95-22677
CIP

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# Foreword

The electric arc may be defined as a discharge of electricity between two electrodes in a gas or vapor that has a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor. The arc is a self-sustained discharge capable of supporting large currents by providing its own mechanism for electron emission from the negative electrode. Nature has provided us with the electric arc in the form of lightning since time immemorial, but it was not until the development of the voltaic pile that the arc was first studied in the laboratory by Sir Humphrey Davy around 1810.

An arc may be initiated either by a spark or glow discharge, or by the separation of a contact between two electrodes carrying an electric current. When the contact breaks, the current flowing through the electrodes melts and vaporizes the last small point of contact, leaving a metal vapor discharge which can develop into an arc if the resistance of the external circuit is low. An arc may exist in an ambient of either high or low gas pressure or only in the vapor of its volatilized electrodes.

Nature apparently never anticipated an arc in a vacuum environment. This is a contrivance of man. The term *vacuum arc* is a misnomer. What is really meant by a *vacuum arc* is a metal vapor arc in a vacuum environment. However, since the term *vacuum arc* is in common usage and has been accepted in the literature, it is retained here, and is the subject matter of this book. A vacuum arc, then, burns in an enclosed volume that prior to ignition is a high vacuum. A characteristic feature of such an arc is that after ignition it produces its own vapor by consumption of its cathode and sometimes its anode if the energy density is high enough. The vapor is partially ionized, providing a conducting plasma to achieve the current transport between the electrodes.

Certain fundamental processes occur in all types of electrical discharges including arcs. These individual processes have been investigated since about

1895 and continue to the present day, filling many volumes. The important ones have been summarized in Ch. 1 and serve as an introduction to phenomena occurring in arcs.

Phenomena that lead to vacuum arc ignition have been the subject of much study and are summarized in Ch. 2. Once the vacuum arc is established, one can clearly distinguish phenomena that occur at the cathode and at the anode and in the plasma occupying the space between the electrodes. The phenomena in these three regions have also been the subject of much study and are fully addressed in Chs. 3, 4, and 5. However, because these phenomena are exceedingly complex and interrelated, there are no general theories that completely describe the vacuum arc or predict its behavior.

Arcs have been in use since the time of Thomas Edison when electric power first became commercially available. All switches and circuit breakers depend on establishing and quenching the electric arc. It was Dr. Joseph Slepian, consulting engineer, Westinghouse Research Laboratories, who said in effect that if Nature had not thrust the arc upon us, it would have been necessary for man to invent it, or some more expensive and complicated equivalent device to interrupt current in high-powered electric circuits.

The first commercial applications of the *vacuum* arc, however, did not occur until the early part of the 20th century with the invention of mercury-pool discharge devices. These were the mercury-arc rectifier and the Cooper Hewitt mercury-vapor lamp. The next major commercial application of vacuum arcs did not occur until nearly sixty years later with the invention of the high-power vacuum circuit breaker. The high dielectric strength of a vacuum and the fast deionization time of a metal vapor in a vacuum makes the vacuum arc an ideal circuit breaker. However, the simplicity and elegance of reliably interrupting large alternating currents in high voltage circuits by separating two metal contacts enclosed in a vacuum took some thirty-five years from the time of conception to a finished product because of a lack of supporting technologies in vacuum and metallurgical processing. This work has been described in a book published in 1980 by John Wiley & Sons entitled Vacuum Arcs, Theory and Application, edited by J. M. Lafferty. Since then, vacuum arcs have been used for thin film deposition, metal coatings, and metallurgical processing. The latest advances are all fully described in Chs. 6 and 7. This book concludes with an update on vacuum switches and triggered vacuum gaps in Chs. 8 and 9.

This comprehensive treatise on vacuum arcs should be useful not only as a reference book, but as a text for the student in a formal classroom or for self study.

November, 1995 James M. Lafferty
Schenectady, New York

# Preface

## DEFINITION, PHENOMENA, AND APPLICATIONS

The vacuum arc is a high current, low voltage electrical discharge between two electrodes situated in a vacuum ambient. Vacuum *per se* cannot support a high current discharge at low voltage. A conducting medium is required, which the arc itself supplies in the form of a highly ionized plasma of vaporized electrode material, produced by an intensive interaction of this plasma with the electrodes. As Dr. Lafferty points out in the preceding foreword, a more accurate description of this phenomena would be a "metal vapor arc in a vacuum environment," but economy of words as well as accepted usage endow us with the more compact term *vacuum arc.*

In most vacuum arcs having currents less then a few kA, the production of plasma is localized at one or several minute locations on the cathode, known as cathode spots. The highly luminous cathode spot is the most strikingly visible and highly studied aspect of the vacuum arc. In addition to providing the conducting medium, the cathode spots also supply the mechanism for releasing electrons from the generally cool electrode. With all of the arc current concentrated in minute areas, local conditions of extremely high temperature and electrical field prevail, whereas if the current was distributed uniformly neither sufficient electron nor plasma production could occur. While the exact mechanism of the cathode is still a matter of investigation, the properties of the plasma it produces are well documented, and extraordinary. The metal vapor produced from the cathode spot is almost fully ionized, and multiply ionized species are common, particularly for the more refractory cathode metals. The ions are highly energetic, with kinetic energies typically of 50–150 eV, even though the discharge voltage is only around 20 V. This translates to a plasma flow velocity on the order of 10 km/s away from the cathode spots. And a copious quantity of plasma is produced. The convected ion current in the plasma jet is approximately 10% of the arc current.

The cathode plasma jets expand in all directions, and some fraction of the plasma makes contact with the anode. Electrical current is provided by a flow of electrons from the cathode to the anode which is significantly faster than the velocity of the ions, which have the same charge density and flow in generally the same direction. The plasma flow, as well as the electrical current flux, can be profoundly influenced by magnetic fields, either self-produced by the arc current, or externally imposed. The ion and electron flux at the anode heats it, and under appropriate conditions the anode may become a source, or even the dominant source, of plasma. Anodic vaporization may be localized in the form of an anode spot, which may occur in high current transient arcs, or over extended regions of the anode, in long duration arcs on anodes which are thermally isolated.

The unique properties of the vacuum arc have important technological applications. High current switching requires a medium which can change its state between conducting and non-conducting under controllable conditions. Vacuum is a good insulator, and the metal vapor plasma produced in the vacuum arc, as well as the metal arc electrodes, are good conductors. Conduction can be initiated, or *switch closing* accomplished, by bringing the electrodes into contact, or by initiating a vacuum arc between electrodes with a vacuum gap between them, by the imposition of high voltage, either directly or through a trigger electrode in close proximity to one of the electrodes, or by the injection of plasma using an external source (typically surface flashover between two closely spaced electrodes) or pulsed laser irradiation of one of the electrodes.

Switching from the conducting to the insulating state (accomplishing *switch opening)* is more of a technical challenge. Separating electrical contacts in vacuum (or in any medium) when high current is flowing also generates an arc and its conducting plasma, and thus the conducting state is continued. In the vacuum arc, the conducting medium is generated by the arc itself, and this can occur only when electrical current is flowing. If the current momentarily reaches zero, plasma production ceases, and the metal vapor condenses very rapidly onto the cool electrodes and walls of the vacuum vessel. Because of the high velocity of the plasma, the time required for the plasma to reach a cool surface on which to condense is very short (typically a microsecond), while the thermal time constant of the minute cathode spots is extremely short (typically a nanosecond). Thus current interruption can be effected when the current reaches zero, whether naturally in an AC circuit, or when momentarily forced to zero with a commutation circuit. In addition, the imposition of a magnetic field transverse to the arc axis will impede the current flow, and can be used as part of a commutation scheme.

The large flux of electrode material produced by the vacuum arc lends itself to a range of technological applications. In a metallurgical process known as vacuum arc remelting, a metal ingot is suspended over a water-cooled mold in a vacuum vessel, as a vacuum arc is run between the ingot, serving as cathode, and the mold. The ingot material is transported to the mold in the form of vapor and droplets, which condense and solidify. By transporting the material to the mold on a drop by drop basis and rapidly cooling it, the grain size of the resultant cast ingot can be controlled, and the macrosegregation of the various elements constituting an alloy metal can be prevented. In another metallurgical process known as vacuum arc degassing, molten metal in an evacuated ladle serves as one of the arc electrodes. Heating at the surface, and arc-induced stirring, are effective in purifying the metal by liberating volatile materials, including sulfur and dissolved gases, into the vacuum chamber, from whence they are pumped out.

The metal vapor plasma flux produced by the arc will condense on any cool surface and form a coating. While this is a nuisance in switch applications as it will short circuit unprotected insulating walls, the phenomena is used to advantage in vacuum arc deposition. The cathodic plasma jets form a unique deposition medium characterized by nearly full ionization, high ion energy, and a high flux. The high ionization facilitates controlling the energy of the depositing ions by biasing the substrate which has a strong influence on the microstructure of the coating, while the high energy results in self-cleaning the substrates of contaminants by ion sputtering, and a dense deposition. The high flux results in a high deposition rate which is economically favorable. The largest commercial application combines a titanium plasma jet with a low pressure nitrogen gas to form coatings of TiN, a hard, gold colored material which increases the service life of drills and other cutting tools by factors of 3–100.

The various components of the plasma can also be used separately. Electrons can be extracted from the plasma, particularly from the expanding cathode spot plasma during the high voltage electrical breakdown process, and form a very "bright" electron source. Intense x-rays are emitted when these electrons strike the anode before the collapse of the high voltage, and from intense plasma balls which can form near the anode in very high current, short duration (100 kA, 100 ns) discharges. The ions can also be extracted and accelerated, and used for ion implantation.

## Historical Notes

Applications have been intertwined with basic studies of the vacuum arc from its very beginning. The first published paper on vacuum arcs, or vacuum sparks, was by Arthur Wright.[1] Wright was one of the first batch of three American recipients of a Ph.D. degree in science from an American institution (Yale College). He studied under Prof. Sloan, the first American professor of science at a U.S. university, and later became his son-in-law. In the 1870's Wright applied the repetitive output of a spark coil circuit to a pair of electrodes in an evacuated tube, noted the formation of a coating near the cathode, and studied its optical properties. We can only surmise from the currents and voltages typically available in such apparatus that cathodic arc deposition occurred, rather than sputtering, as oscillographic recording of the arc voltage was, of course, not available in his day.

Thomas Edison applied for a patent on vacuum arc deposition in 1882. He was apparently unaware of the previous work (a phenomena which reoccurred repeatedly during the next century), and correspondence was exchanged with the patent examiner during the course of ten years, until finally the patent was issued for much narrower claims than originally requested.[2] The issued patent[3] was confined to the use of a continuous vacuum arc, which Edison differentiated from the previous pulsed discharge, which he dismissed as being only a laboratory curiosity, while the continuous arc could be applied industrially. Edison's intention was to use vacuum arc deposition as part of a process for producing master molds for duplicating "phonograms." Acoustical waves were recorded mechanically on wax cylinders. Edison proposed first depositing a coating of a conductive metal such as copper onto the wax cylinder with the acoustical impressions, and then building up the thickness of the coating using electrochemical deposition. The wax could then be removed by melting, and the remaining metal shell could be slit into three longitudinal sections having the acoustical impressions on their inner surface. These sections would then form a mold for impressing the acoustical record on additional wax cylinders.[4] We don't have any knowledge, however, of whether this scheme was ever implemented for production.

Vacuum arc deposition was reinvented several times in the ensuing decades. Many authors mentioned the possibility of using the vacuum arc as a deposition technique, but the first modern study of the properties of the coatings produced was conducted at the Tokyo Institute of Technology[5] in the 1960's. The Japanese knew at least indirectly of Edison's work, which was mentioned briefly in a letter published by one of the modern pioneers of physical vapor deposition, L. Holland,[6] who felt that Edison's arc was not a true vacuum arc, due to the limited vacuum technology available then. We now know that the main cathodic processes would be approximately the same for Edison's vacuum and a modern vacuum, since the pressure in the cathode spot plasma is probably several times atmospheric pressure. Vacuum arc deposition was first implemented industrially in the former Soviet Union in the 1970's.[7] There is no evidence that the Soviet workers were aware of the previous work. Nor was this author aware of the Soviet or other previous work when he and his colleagues at Tel Aviv began studying vacuum arc coatings in the 1980's.

Vacuum arc switching was first studied by Sorensen and Mendenhall[8] at the California Institute of Technology in the 1920's. Though current interruption was successfully demonstrated, the technology did not exist for producing a sealed vacuum switch, and the installation of vacuum pumps on each switch in the field was certainly not practical. Improvements in glass-to-metal seals, and gas-free metals, led to the commercial production of low-current sealed switches in the 1950's by the Jennings Radio Manufacturing Company and by Allis Chalmers Manufacturing Company, and high current vacuum interrupters by the General Electric Company in the 1960's.[9] Today vacuum switchgear is manufactured worldwide, and is favored for distribution circuit breakers because of its compact size and minimum need for auxiliary equipment and maintenance.

## OUR 'VAST' UNDERTAKING

The motivation for writing *Vacuum Arc Science and Technology* (VAST), and the way the editors and authors approached the task, stems from the following considerations: *(1)* The last general text published on the subject in English (*Vacuum Arcs, Theory and Applications,* edited by J. M.

Lafferty, published by Wiley, 1980) is now out of print, and much has been learned in the decade since its publication which hadn't been digested in the form of a text. Many of us who must guide newcomers to the field, either as teachers or technical managers, have felt the need for a revised text for neophytes, as well as a reference for researchers and practitioners. *(2)* Studies of vacuum arcs in recent times have, to a large degree, been driven by their applications. This has resulted in a large degree of segregation of the researchers and practitioners involved according to their application, and only a limited amount of cross-fertilization of knowledge and ideas.

The objective of this text is to bring together in one place a unified, up-to-date presentation of the science and the industrial art of vacuum arcs. In Part I, the basic physics of vacuum arcs is presented. It is assumed that the reader has a rudimentary knowledge of electrical discharges or plasma physics, but Ch. 1 presents a tutorial which summarizes the key principles which will aid engineers with an application background, or anyone wishing a brief refresher, to get started with the meatier material which follows. How vacuum arcs start is presented in Ch. 2. Cathode spots, which play a central role in almost all vacuum arcs and their applications, are exposed in Ch. 3. This chapter is one of the longest in the text, both because of its central importance, and because of the vast amount of research conducted on this topic. Processes occurring in the interelectrode plasma as it propagates towards the anode are discussed in Ch. 4. Anode phenomena, in particular anode spots, are the subject of Ch. 5.

Part II is devoted to the various applications of the vacuum arc. It is assumed that the reader has some rudimentary knowledge of each application, but each chapter is provided with an introduction and reference citations to bring a newcomer to a particular field up to speed. Ch. 6 is devoted to vacuum arc deposition, and Ch. 7 to vacuum arc metallurgy, particularly vacuum arc remelting. Chapter 8 discusses the application of vacuum arcs to switching in power transmission and distribution applications. And finally Ch. 9 discusses pulsed power applications. Pulsed power refers to the use of extremely high powers, from megawatts to terawatts, but for very brief times, typically nanoseconds to microseconds. Vacuum arcs are used in this context as a switching media, and as electron, ion, and x-ray sources.

Assembling material and writing text on such a wide spectrum of subtopics in a reasonable amount of time was beyond the ability of this writer. The text before you now is a team effort of 24 contributing editors and authors, residing in 7 countries on 4 continents, and speaking five different native tongues. Coordination between us was facilitated by the modern technological miracles of fax, internet, and computer diskettes. Our intention is to present a coherent and readable text (rather than a series of articles) which will help the neophyte acquaint himself with vacuum arcs, and serve as a reference text for the veteran researcher. Our task is now finished, and now, dear reader, the task of judging our effort is before you. We hope you will find the reading of this text enjoyable, and its study rewarding.

Tel Aviv, Israel Raymond L. Boxman
October, 1995

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# Part I

# Fundamentals of Vacuum Arc Science and Technology

# 1

# Electrical Discharges and Plasmas—A Brief Tutorial

*Raymond L. Boxman*

## DEFINITIONS AND PURPOSE OF THE CHAPTER

An *electrical discharge* is the passage of an electrical current through a medium or device which is normally insulating. An example is lightning, where the medium is air, which under normal conditions is a very poor conductor. However, when a sufficiently high voltage or electrical field is applied, *breakdown* occurs, and the medium changes state from an insulator to a conductor. Some fraction of the atoms and molecules present in the medium become ionized, forming a *plasma*, and the electrical current is conducted by the movement primarily of free electrons, with some contribution by ion movement.

In *tenuous* electrical discharges, some external excitation (e.g., radiation, cathode heating, etc.) may be applied in order to maintain the conducting state. In the vacuum arc discharge featured in this text, the processes involved in the passage of the electrical current also maintain the medium in the conducting state, and the discharge is termed *self-sustained.*

Electrical discharges have found technological applications in fields as diverse as welding and lasers. The optimal application of the discharge requires understanding the internal workings of the discharge, and the properties of the plasma it produces. This is especially true of the vacuum arc discharge, and the next four chapters are devoted to that purpose. These chapters presuppose a basic knowledge of electrical discharges and plasmas on the part of the reader. The present chapter is presented on behalf of readers whose backgrounds are more oriented to the applications of vacuum arcs, and may vary from electrical power systems to metallurgy. The intention of this chapter is to explain some of the basic concepts of plasmas and electrical discharges. The presentation is, for the most part, informative and conceptual, concentrating on presenting results and their qualitative physical explanations, rather than attempting to derive the results from first principles. More rigorous treatments may be found in the cited references.

## COLLISION PROCESSES

Collisions between particles, and in particular between electrons and atoms and ions, play a crucial role in electrical discharges, determining the electrical conductivity and often the degree of ionization. In this section, the basic nomenclature of collision processes will be explained, and qualitative explanations will be offered for the behavior of collision processes of particular interest in vacuum arcs.

### Hard Spheres: Cross Section, Mean Free Path, Collision Frequency

The simplest model of a collision to understand is that of elastic collisions between two "hard" spheres, such as billiard balls. In the hard sphere collision model, a collision occurs if the projected path of the center of the test particle passes within a distance $R_1 + R_2$ of the center of the target particle as illustrated in Fig. 1, where $R_1$ and $R_2$ are the radii respectively of the target and test particles. The closest distance between the projected undisturbed trajectory of the test particle and the target is called the *impact parameter b*. In the hard sphere model, if $b > R_1 + R_2$ the test particle misses, and no collision occurs. The area projected by the target particle to the test particle is called the *collision cross section*, and for hard spheres is given by $\sigma = \pi(R_1 + R_2)^2$.

In a plasma, we are generally concerned with a population of targets, with a density of $n$ particles per unit volume. If we consider a thin slab of plasma of thickness $dx$ and area $A$, the slab contains $nA\,dx$ target particles, thus projecting an area of $\sigma nA\,dx$, and the probability of the test particle suffering a collision passing through this slab is the ratio of the projected area of the targets to the area of the slab, or $\sigma n\,dx$ (Fig. 2). The probability of traveling a distance $x$ without suffering a collision is given by $e^{-(\sigma n x)}$. The average distance that the test particle travels between collisions is termed the *mean free path*, and is given by $\lambda_c = 1/(\sigma n)$. If the test particle has an average scalar velocity of v, it will suffer $v/\lambda_c$ collisions per unit time, and thus the *collision frequency* is given by $\nu_c = v\sigma n$.

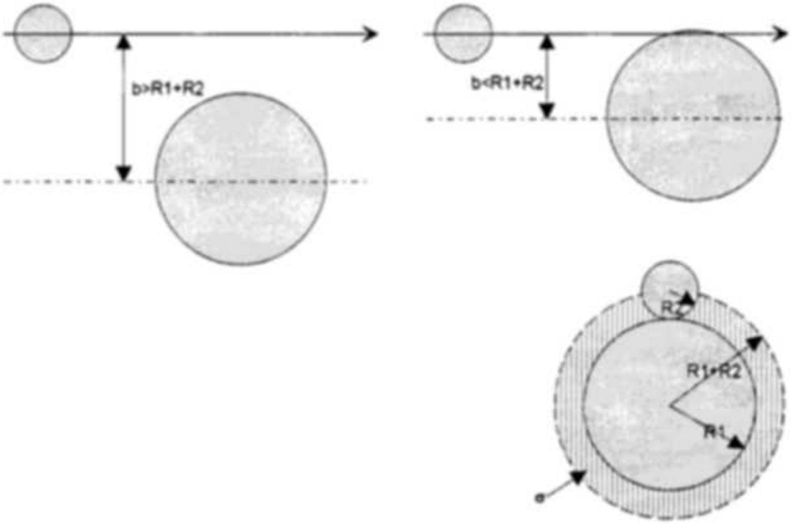

**Figure 1.** Hard sphere collision model. If impact parameter $b$ is larger than the sum of the radii of the test particle and target, $R_1$ and $R_2$ respectively, no collision occurs, while a collision does occur if $b < R_1 + R_2$. Target radius $R_1$ and test particle radius $R_2$ together determine the collision cross section $\sigma$ *(lower right)*.

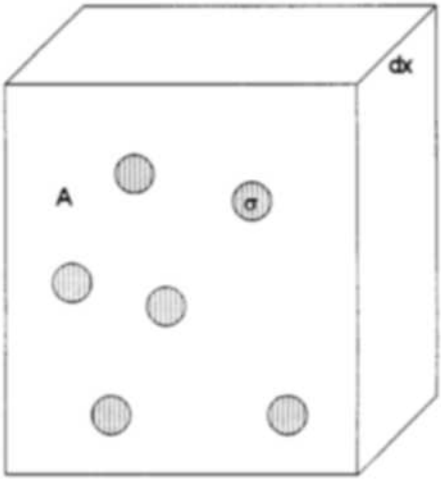

**Figure 2.** Probability of collision in a slice of gas is equal to the ratio of the cross section area of all of the targets in the slice, $n\sigma A\,dx$, where $n$ is the density of target particles, to the area of the slice, $A$.

## Collisions with Real Atoms and Ions

The collisions of particular interest in electrical discharges are between electrons, and ions and atoms. These collisions are more complicated than the billiard ball collisions in that *(i)* the interaction is not confined to a sharply defined region, and *(ii)* the interaction between these particles is by means of the electric field exerted by one particle on the other. In the case of the electron-ion collision, the fields follows Coloumb's law, and the force between the particles varies as $1/r^2$, where r is the distance between the two particles. In the case of the electron-atom collision, the approaching electron produces a Coloumbic field in the vicinity of the target atom, which polarizes the atom—i.e., the electron cloud of the atom is pushed away from its equilibrium position to the side opposite the approaching electron, by an amount which is proportional to the electron's electric field, which varies as $1/r^2$. The resulting dipole produces a field which is proportional to the dipole moment, and varies as $1/r^3$. Thus the force on the oncoming electron varies as $1/r^5$. In both of these cases, the test particle will suffer some deflection, even for an arbitrarily large impact parameter, and thus a simplistic calculation of the collision cross section yields an infinite result.