HIGH VOLTAGE VACUUM INSULATION: The Physical Basis

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Preface

The aim of this book is to provide a contemporary "introduction" to the physics and technology of high-voltage vacuum insulation; to this end, it gives a concise account of the basic physical concepts, together with a detailed source for further specialised reading. Each chapter deals with a specific aspect of the subject and, as far as possible, has been written as a self-contained entity with inclusive referencing. Whilst the book is chiefly directed towards the research worker or development engineer, its format makes the text equally suitable for use as a basis for "special topic" lecture courses at either under-or postgraduate level within Electrical Engineering or Applied Physics departments of universities or polytechnics.

In the opening chapter, the reader is given a general perspective of the electrical insulating properties of the vacuum gap, together with a brief historical survey of the main developments in the identification of the fundamental physical processes that ultimately determine its performance. This is followed in chapter 2 by a detailed account of the design criteria for practical high voltage electrode pairs and how their operational characteristics are influenced by such basic parameters as their material, geometry,separation and surface preparation. The central chapters (3 to 6) of the book are devoted firstly to an analysis of the theoretical models that have been evolved to explain how the electrical breakdown of a gap is initiated, and secondly, to a review of the corroborative experimental evidence that has been obtained from controlled laboratory simulation studies. Attention is then directed in the penultimate chapter(7)towards a very important series of experimental investigations that have used diagnostic techniques to identify the physical processes that actually occur in normal operational gaps; in particular, it highlights a number of sophisticated systems that have recently been developed for making in situ dynamic studies of phenomena. The final chapter opens with a discussion of the practical implications of some exciting new findings that have emerged from these latter studies,and concludes with an objective assessment of the "present state of the art" that integrates the well established concepts presented in the earlier chapters of the book with some new but relatively undeveloped ideas. It should be noted that this treatment deliberately omits any consideration of the properties of the high current arcs that characterise the post-breakdown regime, since this topic is adequately dealt with in the literature on plasma physics. An appendix has however been included that outlines the essential details of the associated breakdown phenomenon that can result from a "flashover" across the internal vacuum surface of the glass or ceramic insulators that invariably support high voltage electrodes.

Whilst most of the cited references have been taken from well known scientific periodicals, a considerable number have also been drawn from the Proceedings of the International Symposium on "Discharges and Electrical Insulation in Vacuum" - subsequently abbreviated as Proc. DEIV. These were initiated in 1964 at the Massachusetts Institute of Technology (Proc. DEIV-I) with subsequent two-yearly symposia being held at various other international centres in North America, Europe and the U.S.S.R. Since these proceedings have provided a regular up-dating of the major developments in the field, they could be a valuable source of detailed information for the reader who wishes to pursue the subject beyond the introductory level provided by this text.

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My thanks are also due to Sylvia Wallace for her patience and co-operation in the typing of both the draft and final copy of the manuscript.

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Author's Notes

1. Although SI units have been used consistantly throughout this book, it will be noted that "pressure" has been expressed in terms of the millibar, where 1 mbar $\equiv 10^2$ Pa. This choice is based on the current policy of vacuum equipment manufacturers who calibrate their pressure monitoring systems in the mbar since this unit is similar in magnitude to the more familiar *"torr"* (i.e. 1 torr = 133 Pa $\sim$ 1 mbar).

2. As already stated in the Preface, reference has frequently been made to papers appearing in the two-yearly Proceedings of the International Symposium on Discharges and Electrical Insulation in Vacuum. For simplicity, this source has been abbreviated to Proc. I, II ... IX-DEIV where I (1964) and II (1966) were held in the U.S.A. at M.I.T., III (1968) in Paris, IV (1970) at Waterloo, Canada, V (1972) in Poznam, Poland, VI (1974) in Swansea, UK, VII (1976) in Novosibirsk, USSR, VIII (1978) in Albuquerque, USA,and the most recent IX (1980) in Eindhoven, The Netherlands.

Similarly, in the Appendix, reference is frequently made to papers taken from the Annual Reports on Conferences on Electrical Insulation and Dielectric Phenomena held at the National Academy of Science, Washington, D.C., USA; these have been abbreviated Ann. Rpt. CEIDP.

Symbols and Abbreviations

SYMBOLS

A_e	effective emitting area of a micropoint electron source
α_v	pulse over-voltage coefficient
β	geometric enhancement factor of the electric field at a micropoint electron source
C	specific heat
C_c	Cranberg constant
γ	electron penetration depth
D	microcrater diameter
d	electrode separation (i.e. electrode gap)
δ_e	secondary electron yield coefficient
E	macroscopic electric field in an electrode gap
E_b	macroscopic d-c breakdown field
E'_b	macroscopic pulse breakdown field
E_c	critical microscopic field defining whether a breakdown event is cathode or anode initiated
E_g	microscopic electric field in the gap between a microparticle and an electrode
E_ℓ	microscopic field defining the onset of space-charge limited emission
E_m	microscopic field at the surface of a microemitter
E_o	operational macroscopic gap field
e	electronic charge
ε	dielectric constant
F_d	microparticle detachment force
F_{vw}	Van der Waals adhesive force

h	height of a microprotrusion
I	the prebreakdown current flowing across a high voltage gap
I_o	modified Bessel function
i_{EE}	"explosive" electron emission current
i_F	generalised field electron emission current from a single emitter
i_{OF}	low-temperature field electron emission current from a single emitter
i_{TF}	high-temperature field electron emission current from a single emitter
i_p	photomultiplier current
j_F	generalised field electron emission current density
j_{OF}	low-temperature field electron emission current density
j_{TF}	high-temperature field electron emission current density
K	Thermal conductivity
k	Boltzmann's constant
M_p	microparticle mass
μ_o	Fermi energy at $T = 0$
$\mu(T)$	chemical potential
ρ	density
ρ_t	tunnelling resistivity
Q_p	microparticle charge
Q_T	total charge transferred between a microparticle and an electrode
q_i	impact ionisation charge
R_a	radius of anode "hot-spot"
R_g	"Gaussian" radius of electron beam cross-section
R_p	microparticle radius
r	tip radius of microprotrusion
s	thickness of ambient oxide film on an electrode surface
σ	surface charge density
σ_y	yield strength of electrode material
T	temperature
T_b	temperature at the base of a microprotrusion

T_e	electron temperature
T_i	Nottingham inversion temperature
T_p	phonon temperature
T_r	temperature at the tip of a microprotrusion
$T(r,x)$	temperature distribution in an anode "hot-spot"
T_{oo}	temperature at the centre of an anode "hot-spot"
t	time
t_b	total breakdown time
t_c	contact time of a bouncing microparticle
t_d	breakdown delay time
t_p	pulse length
t_t	transit time of a microparticle across an electrode gap
τ	charge relaxation time
τ_A	thermal response time of an anode "hot-spot"
τ_c	thermal response time of a cathode microprotrusion
τ_γ	heat spread parameter in an anode "hot-spot"
τ_s	characteristic tip-sharpening time
τ_t	time constant of charge exchange process occurring during the bouncing impact of a charged microparticle
U_k	kinetic energy of a microparticle
V	externally applied d-c gap voltage
V_{ac}	externally applied a-c gap voltage
V_b	d-c breakdown voltage of a gap
V_b'	pulse breakdown voltage of a gap
V_{ip}	externally applied impulse gap voltage
V_o	operational voltage of a gap
V_p	potential of a charged microparticle relative to an electrode
v	microparticle velocity
v_c	critical microparticle impact velocity for plastic deformation of electrode
v_f	cathode flare velocity
v_i	impact velocity of a microparticle
W	total power in an electron beam
w	power density of an electron beam

$\Omega(T)$	electrical resistivity
Z	atomic number

ABBREVIATIONS

EEE	Explosive electron emission
EHT	Extra high tension
FEE	Field electron emission
FL	Fermi level
F-N	Fowler-Nordheim
HV	High Voltage
I-V	Current-voltage characteristic
M-FEE	Metallic field electron emission
SEM	Scanning electron microscopy
T-F	Thermally assisted field emission
UHV	Ultra high vacuum

Contents

1 Introduction

1.1. The Breakdown Phenomenon

Although vacuum is used extensively for the insulation of high voltages in such devices as X-ray tubes, electron microscopes, power vacuum switches, particle accelerators and separators etc., the reliability of its performance is limited by the operational risk of an unpredictable "sparking" or "arcing" between the high voltage electrodes, when the insulating capability of the vacuum gap is suddenly lost and "electrical breakdown" is said to have occurred. For some devices, such as sealed-off high voltage vacuum diodes with oxide cathodes, a breakdown event is likely to be an irreversible process and catastrophic from both the operational and financial points of view since, not only will the cathode probably be damaged, but the high voltage gap is subsequently likely to break down at a very much lower voltage: at all events, the future performance of the device will almost certainly be permanently impaired. In other applications however, such as vacuum switches and particle separators, occasional breakdown events, although undesirable, can generally be tolerated without disasterous consequences, provided special precautions are taken; for example, by controlling the energy that is available in the external circuitry for dissipation in a gap during a breakdown event. Not surprisingly, this practical limitation of the insulating capability of vacuum has had a profound influence on the design of high voltage vacuum equipment: in the short term, the problem is conventionally tackled by such empirical and often expensive procedures as maximising the dimensions of vacuum gaps, using special electrode materials and surface polishing techniques, or incorporating sophisticated electronic protection circuitry. For the long term, there has been a considerable research investment directed towards obtaining an understanding of the fundamental physical processes that give rise to breakdown, so that by taking informed precautions the insulating capability of high voltage vacuum gaps can be improved. It is with the details of this research programme and the technological implications of its findings that this book is principally concerned.

The most serious hazard in the early applications of vacuum insulation was the presence of excessive residual gas, which manifested itself either directly as a relatively high ambient pressure in the gap, probably little better than $\sim 10^{-6}-10^{-5}$ mbar, or indirectly as transient pressure bursts caused by the thermal desorption of gas from the electrodes and vacuum chamber walls by localised electron or ion bombardment processes. Thus, if the local pressure p in the gap approaches a value where the mean free path of electrons becomes less than the dimension of the electrode gap d, the necessary conditions will be created for avalanche ionisation and the spontaneous establishment of an arc between the electrodes. This situation has been quantified as the well known Paschen Law [1], which defines the sparking or breakdown potential V_b in terms of a function of the product pd whose detailed form can be found, for example, in the writings of Von Engel [2], Morgan [3] and Llewellyn-Jones [4] on the electrical properties of low pressure ionised gases. However, as a result of the many advances that have taken place in high vacuum technology, where it is now standard practice to use baked-out vacuum systems in which ambient pressures of $< 10^{-7}$ mbar can be guaranteed, this mechanism of electrical breakdown is no longer regarded as a threat and, accordingly, will receive no further treatment in this text.

Thus, whilst the use of relatively gas-free ultra high vacuum (UHV) conditions greatly improves the high-voltage insulating capability of a vacuum gap, its electrical breakdown is still ultimately initiated by some form of discharge process arising from the creation of an ionisable medium in the gap. Since this can now only be derived from an increase in the local metal vapour pressure, it follows that any physical explanation of this form of breakdown must be based upon electrode surface processes that lead to the vaporisation of electrode material.

1.2. Historical

The breakdown phenomenon was first investigated scientifically by Wood [5] in 1897 and somewhat later by Earhart [6], Hobbs [7] and Millikan and Sawyer [8]. From these early studies it was established that, even prior to breakdown, a vacuum gap has a small but finite conductivity as evidenced by the flow of "prebreakdown" currents whose magnitude increased rapidly with increasing gap voltage until breakdown occurred. For mm gap separations, it was found that the corresponding breakdown field was typically $\sim 10^8$ Vm^{-1}, although it depended somewhat on the electrode material. A further observation of considerable practical significance was that the breakdown voltage was independent of pressure in the range 10^{-8} - 10^{-5} mbar. Millikan and Sawyer [8] also discovered that the voltage hold-off capability of a given gap can be significantly improved if it is subjected to an initial "conditioning" procedure (see Section 2.3) whereby the voltage is increased in small steps such that all major prebreakdown current instabilities are allowed to decay before the next voltage increment is applied. In 1920, Millikan and his subsequent co-workers [9-11] embarked on a decade of study into the source of the noisy but reversible component of the prebreakdown currents that flow between a pair of broad-area high voltage electrodes. They established that they were electronic and originated from a cold emission process (now known as field electron emission FEE) at isolated points on the surface of the cathode which gave rise to complementary fluorescent spots on the anode. At this time, these emission sites were assumed to be localised regions of the electrode surfaces where there was either an "effective" reduction in the work function through the Schottky effect [12] at field-enhancing microfeatures associated with the intrinsic microscopic roughness of electrode surfaces, or to a "real" reduction in the work function due to the presence of isolated chemical impurities. The noisy nature of the currents was attributed to the back-sputtering of ions produced by electron collision processes in the gap. Millikan and Lauritsen [11] also established that this prebreakdown current I had a well-defined empirical dependence on the gap field E such that a graph of log I versus 1/E gave a reversible straight line, i.e.

$$I = A \exp\left(-\frac{B}{E}\right)$$

where A and B are constants. It was found however that the slope B and intercept A of such plots were very sensitive to the electrode surface conditions. Other early workers of note whose principal concern was with the origin and role of these highly localised cold emission processes included Hull and Burger [13], Snoddy [14], Beams [15] and Ahearn [16]. The initial conclusion to emerge from their studies was that breakdown was due to the intense localised heating and consequent vaporisation of the anode by the bombardment of electrons emitted from these point sources. However, Ahearn [16] extended the understanding of the phenomenon by considering the possibility of breakdown being cathode initiated following the field-induced rupture of current emitting projections.

One of the first really comprehensive investigations into how the operational breakdown voltage of a gap depends on such practical parameters as the electrode material, surface preparation and gap spacing etc. was undertaken by Anderson [17] in 1935. Although the general practical conclusions to emerge from this and many subsequent studies of its kind will be reviewed in chapter 2, special mention should be made in this historical context of Anderson's identification of the 'total voltage effect'.

This is associated with large cm-gap regimes supporting hundreds as opposed to tens of kilovolts, where it is found that breakdown tends to be voltage rather than field-dependent and not apparently related to the prebreakdown electron emission currents which are frequently absent or negligible in such regimes, i.e. where the macroscopic gap fields are significantly lower than those existing in the earlier mm-gap studies of cold emission processes. To illustrate this distinction, it can be pointed out that, whereas it is possible for a 0.5 mm vacuum gap to support $\sim$20kV without breaking down, a 10 cm gap will support less than 1MV. Another important observation associated with this type of large-gap breakdown event was that electrode material is transported across the gap, apparently arbitarily from either the cathode or anode. In these early experiments, this phenomenon was investigated by using dissimilar electrodes, say copper and aluminium, so that optical spectroscopy techniques could be used to identify the presence of traces of a "foreign" element on a given electrode. Although it was concluded from these findings that there was evidently some additional electrode surface process which was common to both cathode and anode, no satisfactory physical explanation for it emerged until 1952 when Cranberg [18] proposed his "clump" hypothesis. This breakdown model introduced for the first time the concept that loosely adhering microscopic particles ("clumps", or nowadays more frequently referred to as "microparticles") may be torn from an electrode surface by the applied field and, because of their charge, accelerated across the gap to impact on the opposite electrode as high velocity microparticles, causing localised fusion and vaporisation of electrode material that is sufficient to trigger the breakdown of the gap. The immediate appeal of this simple mechanism was that it provided an explanation of why breakdown events are unheralded, independent of the prebreakdown current and can result in material transfer between electrodes. There have subsequently been many refinements and developments of the original model: for example, there is the "trigger discharge" model of Olendzkaya [19], whereby a charged microparticle can give rise to a local breakdown initiating discharge between itself and an electrode at very close distances of approach. As a result, the concept of microparticle initiated breakdown is now firmly established and will be discussed at length in chapter 4. Apart from these theoretical considerations, there have also been extensive laboratory simulation studies using artificially generated microparticles to verify many of the theoretical predictions: in fact, chapter 6 is devoted to a full review of these investigations.

At about the same time that Cranberg proposed his microparticle initiated breakdown mechanism, Dyke and his co-workers in America [20-22] made the next major contribution to the subject with their publication of the first quantitative results from a controlled laboratory study on the electron emission induced breakdown mechanism identified by earlier workers. The approach followed by this group, which will be fully described in chapter 5, was to simulate the field emitting micro-protrusions thought to be present on broad-area electrodes by laboratory-etched micropoint emitters similar to those used in the field emission microscope pioneered by Müller [23]. With the much improved vacuum conditions available at that time, they were able to use such emitters to study the breakdown characteristics of a well defined point-plane diode and establish that there is a critical emission current density of about $1 \times 10^{10} Am^{-2}$ at which the emitting surface becomes thermally unstable, cathode material is vaporised and breakdown is consequently initiated. The relevance of these studies to the understanding of the breakdown mechanisms operating in a broad-area gap situation was further emphasized by the electron optical profile imaging of the surfaces of miniature electrodes by Bogdanovskii [24] in 1959, and later for broad-area electrodes by Little and Smith [25] and other workers, that positively confirmed the existence of micro-protrusions having a sufficiently "sharp" geometry to produce the required geometrical field enhancement for FEE to occur. Based on information of this kind, Tomaschke and Alpert [26] were then able to show that the measured macroscopic breakdown field of a thoroughly out-gassed broad-area tungsten gap corresponded to a microscopic breakdown field of $\sim 6\text{-}7 \times 10^{9} Vm^{-1}$ at the tip of a tungsten microprotrusion; i.e. in agreement with the value quoted earlier that was measured directly using control micropoint emitters.

By the mid 1960's it had been recognised that a given field emitting microprotrusion would also give rise to an associated anode "hot-spot" where the electrode surface becomes locally heated by the bombardment of the fine pencil of electrons emitted by the cathode protrusion. Thus, if the local power density of the beam reaches some critical value, it is possible for anode material to be vaporised and hence the initiation of an arc between the electrodes. Such a mechanism is conventionally termed "anode-initiated" breakdown, as opposed to "cathode-initiated" breakdown when the microprotrusion itself becomes thermally unstable. In order to be able to predict which of these initiating mechanisms is most likely to precipitate the breakdown of a gap, unified theories were developed firstly by Chatterton [27] and Slivkov [28] in 1966 and in a somewhat more complete form by Carbonnier et al [29] in 1967, which established the critical initiating criteria for the two mechanisms in terms of the gap field, the electron emitting properties of the microprotrusion, the cathode and anode thermal diffusion characteristics and finally, the material constants of the electrode material. The general qualitative conclusion to emerge from these theories is that a sharp thin microprotrusion will give rise to "cathode-initiated" breakdown whilst a more blunted geometry will favour the "anode-initiated" mechanism: for a quantitative evaluation of the criteria, the reader is referred to chapter 3. It must