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HIGH VOLTAGE BREAKDOWN STUDY

HANDBOOK OF VACUUM INSULATION

Prepared by:

M. J. Mulcahy and P. C. Bolin

ION PHYSICS CORPORATION

BURLINGTON, MASSACHUSETTS

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13. ABSTRACT

The "Handbook on Vacuum Insulation" discusses the factors influencing breakdown in high voltage vacuum devices. The data on the factors, interactions and theories on vacuum breakdown are interpreted and presented in a manner so as to be useful in the design of microwave and modulator tubes that must operate at voltages greater than 100 kV. It is produced as part of a 5-year program, which was carried out at Ion Physics Corporation, to investigate, under controlled conditions and using factorial design and analytical techniques, vacuum breakdown up to 300 kV for conditions pertinent to high power vacuum tubes. It draws not only on this program but also on an updated review of vacuum insulation/discharge literature.

The handbook is intended both as an introduction to, and realistic appraisal of, the use of vacuum as the insulating medium for high voltage and high power tubes. As such, it contains general discussions and recommendations pertaining to factors, levels, combinations and interactions of same, preparation, conditioning and operating procedures, etc., without, however, going into engineering and manufacturing details, discussion of which are best given in individual tube handbooks.

The handbook first describes briefly the experimental program. This is followed by an introduction to the basic phenomena of vacuum insulation and a short review of the major theories of vacuum breakdown. The factors of practical import which influence insulation of metal electrodes in vacuum are then discussed in some detail. A final section briefly discusses the role of solid dielectrics in vacuum insulation.

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Factors Influencing Vacuum Breakdown						
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Criteria for Vacuum Breakdown						
Optical and X-Radiation						
Partial Pressure and Gap Current						
Factorial and Statistical Design						
Microdischarges						
Electric Field Enhancement and Etching						
Electron Beam Heating						
Conditioning Procedures						
Energy Conditioning and Diversion						
Magnetic Field and Series Resistance						
Barium Contamination						
Electrode Materials and Surface Properties						
Electrode Firing and Gas Content						
Breakdown Voltage and Voltage Collapse						
Time Effects and Pulse Breakdown						
Electrode Gap and Area Effects						
Pressure and Temperature Effects						
Dielectric Coatings						
Insulator Flashover and Grading						
Field Emission Theory of Vacuum Breakdown						
Particle Exchange Theory of Vacuum Breakdown						
Clump Theory of Vacuum Breakdown						

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HANDBOOK OF VACUUM INSULATION

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PURPOSE

The factors influencing breakdown in high voltage vacuum devices will be discussed. Data and concepts will be presented which should be useful in the design of microwave and modulator tubes that must operate at voltages greater than 100 kV.

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1. INTRODUCTION

Ideally, vacuum is the best voltage insulator, with stress levels up to 10^7 V/cm limited only by emission from electrode surfaces. In practice, stress levels fall orders of magnitude short of this level, and vacuum insulation has been used only where its physical properties are essential - for example, in the control and acceleration of charged particles to high energies. Recent developments and consequent requirements of high power radar, high energy particle accelerators, and space exploration have enhanced the importance of vacuum insulation. Its more important applications include:

(1) High Power High Voltage Vacuum Tubes

(2) Acceleration Tubes

(3) X-Ray and Field Emission Tubes

(4) Electron Microscopes

(5) High Quality Capacitors

(6) Circuit Breakers

(7) Electrostatic Particle Separators

In all cases, one of the prime performance limiting factors is breakdown of vacuum insulation. It is not surprising, therefore, that vacuum breakdown and the factors which affect it, have been the subject of extensive investigation over the past 40 years. Unfortunately, for most of this time, these investigations, as evidenced from the resulting literature, produced a wide divergence in both the data and the theories which were generated from the data. Indeed, it was not until relatively recently that a measure of coordination and rationalization of data and theories has been achieved, and this only for voltages below 100 kV. At the higher voltages needed for very high voltage high power vacuum tubes used in many high power radar systems, serious problems have been and are encountered both in the design and reliable operation of the tubes. Accordingly, over the last five years a controlled factorial program investigating vacuum breakdown up to 300 kV under conditions pertinent to high power vacuum tubes has been carried out by Ion Physics Corporation for ARPA and the USAECOM. The present "Handbook of Vacuum

Insulation" is produced as part of this program. It draws upon experimental work, the literature dealing with vacuum insulation, and meetings with personnel concerned with high voltage insulation and discharges in vacuum, and in particular with high voltage vacuum tubes. The handbook is intended both as an introduction to, and realistic appraisal of, the use of vacuum as the insulating medium for high voltage and high power tubes. As such, it contains general discussions and recommendations pertaining to factors, levels, combinations and interactions of same, preparation, conditioning and operating procedures, etc. without, however, going into engineering and manufacturing details, discussion of which are best given in individual tube handbooks.

It is important to recognize, at the outset, that a thorough understanding of high voltage vacuum insulation and the mechanisms of breakdown is, to some extent, incomplete. Indeed, several different mechanisms can explain most experimental effects, and those mechanisms are complex, depending as they do on the properties of a surface-to-vacuum interface. However, mean stress levels of 100 kV/cm can be reliably obtained with vacuum insulation and it is possible to improve this by an order of magnitude under certain conditions.

In order, the remainder of the handbook first describes briefly the experimental program. This is followed by an introduction to the basic phenomena of vacuum insulation and a short review of the major theories of vacuum breakdown. The factors of practical import which influence insulation of metal electrodes in vacuum are then discussed in some detail. A final section briefly discusses the role of solid dielectrics in vacuum insulation.

2. HIGH VOLTAGE VACUUM BREAKDOWN PROGRAM

2.1 Introduction

The experimental program underlying this handbook is briefly described in this section. Detailed results can be found in Quarterly Progress Reports[1] and the Final Report[2] - "High Voltage Breakdown Study." The primary effort was to identify and study the factors of practical import which influence the breakdown voltage of approximately uniform-field vacuum gaps of .25 to 3.0 cm. Factorial design[3] was chosen as an experimental technique because it provides a powerful tool for the analysis of the results and enables information to be derived from a minimum number of experiments on both the effects of individual factors and on the degree of interaction among factors -- the latter proved to be of great importance in vacuum breakdown.

Six major experimental blocks based on factorial design investigated the factors of electrode material, electrode geometry, gap length, conditioning, discharge energy, electrode gas content, surface finish, transverse magnetic field, gas exposure and barium contamination. The experiments were performed in a clean, baked vacuum at 10^{-8} torr. The effects of most of the factors were complex; significant interactions between factors were common. Conditioning was one of the most important factors and, when high energy (up to 6750 J) discharges were used, anode material became the dominant factor in determining breakdown voltage. The breakdown voltage for a wide range of anode materials (Cu, Ni, SS, Al, Pb, and Ti-7 Al-4 Mo) was found to correlate with physical properties of the anode.

2.2 Prebreakdown Phenomena

The initial experiment[4] explored prebreakdown phenomena in an attempt to discover criteria for incipient breakdown. Current, pressure surges, optical and X-radiation were monitored -- none provided a reliable indicator of incipient breakdown. For unbaked electrodes, pulsed self-extinguishing discharges ("microdischarges") preceded steady field emission

currents. Release of gas (N_2 and H_2) was often found prior to breakdown. Conditioning by controlled evolution of gas was found to yield higher breakdown voltages than spark conditioning.

2.3 Seven Factor Experiment

Anode and cathode material, anode and cathode surface finish, anode and cathode geometry and bakeout were investigated as factors at two levels each in a fractional factorial design of 32 treatments.[5] Both anode and cathode material were important, with Ti-7 Al-4 Mo better than OFHC copper. Electrode surface finish was not significant after several breakdowns. Electrode geometry was significant, with spherical anodes having a higher breakdown voltage than uniform field electrodes. Finally, bakeout of the entire system was important and the rather high apparent scatter in the factorial analysis could be attributed to lack of control of gas content of the electrode materials. Breakdown voltage was found to vary as the square root of the gap and the maximum prebreakdown current was often inversely proportional to the square root of the gap.

2.4 Electrode Size and Gas Content

Observations of gas release prior to breakdown led to the design of the next experiment[6] which investigated, in a three factor design, the effects of firing the anode or cathode electrodes in either vacuum or hydrogen at 900°C. Two sizes of uniform field electrodes were used and the effect of gas content was found to depend both on gap and electrode size. These results led to the hypothesis that breakdown is initiated by a beam of field emitted electrons which heats up the anode to a temperature at which gas is evolved copiously into the gap. The gas accumulates and ionizes in the beam at an average rate depending on both electrode geometry and gap length. At a critical gas density the process becomes unstable and breakdown occurs. This mechanism has been theoretically developed by Watson.[7]

2.5 Five Factor Full Factorial Experiment

The next experiment,[8] of five factors (32 treatments), was designed to explore in more detail the phenomena and mechanisms described above. The factorial results, while fitting into the expected pattern, proved so complex as to preclude any simple description. Electrode material and size were most important with copper better than aluminum and small anodes (1.28" dia) better than large (4" dia). A transverse magnetic field of 100 to 400 G was found to raise the breakdown voltage for small gaps (<.75 cm) and lower it (~20%) for large gaps (>.75 cm). Averaged breakdown voltages from a large number of tests showed that the dependence of breakdown voltage on gap was linear for small gaps (<.75 cm) and as the square root of the gap for large gaps (>.75 cm). Exposure to gas, at pressures up to 15 psia, of electrodes which had been conditioned to high breakdown voltages reduced the breakdown voltage severely if the gases were subject to contamination (factory atmosphere); for pure gases (O_2, N_2) the reduction in breakdown voltage upon exposure was slight and transient.

2.6 Energy Conditioning Study

The energy conditioning study investigated in detail conditioning with discharges, having available energy levels of from ~ 50 J to 6750 J over a range of electrode materials and sizes for uniform field geometry. Further control of discharge characteristics was provided by series resistance variations (from 25 ohms to 30 kilohms), and a fast crowbar which could divert energy from the vacuum gap within 500 ns of the initiation of the discharge.

The average initial breakdown level was about 140 kV for a 0.75 cm gap. High impedance conditioning raised the average breakdown voltage to 200 kV. Moderate energy conditioning with 1 kilohm series resistance and 0.15 μF capacitive energy storage reduced this to 187 kV. The scatter, as measured by the standard deviation, increased from 4.5% to about 14%. High energy discharges (total series resistance of 25 ohms with a .15 μF capacitive energy storage) simulated failure of a high power vacuum tube under operating conditions. The overall average breakdown voltage dropped to 145 kV with

occasional values as low as 35 kV. Reconditioning was generally possible.

It was found that anode material became a dominant factor when discharge energy was high. Anodes of Ti-7 Al-4 Mo, nickel and stainless steel, after an initial sharp drop in breakdown voltage upon introduction of high energy discharges, improved in holdoff as a result of approximately 50 to 100 high energy discharges. Cathode material was not important and a copper cathode opposite a Ti-7 Al-4 Mo anode held 300 kV across a .75 cm gap (4" dia uniform field electrodes). Examination of electrodes after testing revealed an extensive transfer of anode material to the cathode in form of a condensed film and discrete droplets. The anode surface was severely eroded and melted.

Linear multiple regression analysis was used to correlate physical properties of anode material with the maximum breakdown voltage during an extended high energy discharge series for anodes of copper, aluminum, nickel, Ti-7 Al-4 Mo, and 304 stainless steel. Melting point temperature (T_m), specific heat (C_p) and density (D_m) were found to give the most reasonable fit to an equation of the form:

$$V_{Breakdown} = A\, T_m^{\,a}\, C_p^{\,b}\, D_m^{\,c} \qquad (1)$$

A maximum breakdown voltage of 72 kV was predicted for a lead anode -- the experimental value was found to be 76 kV.

2.7 Barium Contamination Study

High voltage vacuum tubes, which use a thermionic cathode of the Barium Oxide type to supply the necessary electrons, are usually limited to lower electric stresses than tubes not subject to the decomposition and evaporation products from this heated cathode. The most probable explanation for this lowering of operating stress is the reduction of work function of the metal surfaces when barium and/or barium oxide is deposited. This would lead to higher prebreakdown currents and lower breakdown voltages than for the uncontaminated case, and has been demonstrated at voltages below 100 kV by Brodie[9]. The effects of barium contamination at higher voltages have been

studied in an experiment with uniform field electrodes of copper, nickel, Ti-7 Al-4 Mo, and stainless steel fired in vacuum, baked and conditioned prior to contamination from a typical heated Barium Oxide thermionic cathode.

It was found that the effect of barium contamination of the anode was negligible. Cathode contamination caused a drop in breakdown voltage of as much as 50%. Prebreakdown current was sometimes increased and, in general, breakdown occurred at lower total current levels than before cathode contamination. In most cases conditioning with either low (10 J) or high (6750 J) energy discharges restored breakdown voltage and prebreakdown current to levels typical of uncontaminated electrodes. However, in several cases, high energy discharges transferred to contaminated cathodes anode material which did not adhere as well as is usual on clean cathodes. This layer then fractured to form large (~ 1 mm), and sharp field enhancing projections which led to low breakdown voltages (40 kV at .75 cm), and high prebreakdown currents.

2.8 Major Conclusions

Factors, such as electrode geometry, and the processing of materials have a complex influence on vacuum breakdown. Conditioning was the most significant factor, especially for high energy discharges. Anode material was then a crucial factor with refractory metals (Ti, Ni, SS) better than non-refractory metals (Cu, Al, Pb). Barium contamination of the cathode lowered breakdown voltage and, under high energy discharges, led to permanent damage due to poor adhesion of transferred anode material. The breakdown voltage varied linearly with gap up to ~ 7mm, and as the square root of the gap above ~ 7 mm. Anode gas evolution due to field emission beams and particle extraction from thermally softened anode regions were indicated as breakdown mechanisms.

2.9 References

(1) Quarterly Progress Reports #1 - #19; Research and Development Technical Report ECOM-00394-1-19; "High Voltage Breakdown Study" - Ion Physics Corp., Burlington, Mass., Contract # DA-28-043-AMC-00394 (E), 16 November 1964 through 15 November 1969.

(2) Final Report; "High Voltage Breakdown Study" Research and Development Technical Report ECOM-00394, Ion Physics Corp., Burlington, Mass., M. J. Mulcahy, P. C. Bolin, W. R. Bell, A.S. Denholm, F. J. McCoy, G. K. Simcox, M. M. Thayer, F. Y. Tse, and A. Watson.

(3) Davies, O. L., The Design and Analysis of Industrial Experiments, Hafner, N.Y., (1963).

(4) Watson, A., et al, 2nd Intl. Sym. on IHVV, p. 103, Boston, (1966).

(5) Mulcahy, M. J., et al, 2nd Intl. Sym. on IHVV, p. 117, Boston (1966).

(6) Watson, A., et al, 3rd Intl. Sym. Discharges & Elec. Insl. in Vac., p. 151, Paris, (1968).

(7) Watson, A., 3rd Intl. Sym. Discharges & Elec. Insl. in Vac., p. 193, Paris, (1968).

(8) Bell, W. R., et al, 17th Quart. Prog. Rept. High Voltage Breakdown Study, Ion Physics, (Aug. 1969).

(9) Brodie, I., J. Vac Sci. Tech. 2, p. 249 (1965).

3. BASIC PHENOMENA OF VACUUM INSULATION AND BREAKDOWN

3.1 Introduction

Vacuum insulation exists when the mean free path for electrons is much greater than the interelectrode distances. This occurs in normal apparatus at pressures below 10^{-3} torr. Then, the usual charge multiplication processes are impossible and other mechanisms lead to conduction and breakdown. The proceedings of three recent international symposia[1,2,3] on vacuum insulation contain both up-to-date information on, and discussion of the various mechanisms. Here, only the major phenomena are described.

The primary prebreakdown conduction process in vacuum is field emission of electrons from the negative electrode (cathode). When a high electric field is applied to a vacuum-metal interface, the surface potential energy barrier is thinned sufficiently so that free electrons in the metal can tunnel through and escape into the vacuum (see Figure 3-1). Fowler and Nordheim,[4] in 1928, derived the following equation to describe field emission:

$$I = A E^2 e^{-B/E} \tag{1}$$

where:

E = Electric field strength

A = Constant, depending on emitting area

B = Constant, depending on work function ϕ of the metal surface

The exponential term is dominant, and a typical voltage (field-current) measurement of field emission from a tungsten needle which had been etched to a very sharp point is given in Figure 3-2. Appreciable currents are produced by fields of the order of 3×10^7 volts/cm. In the normal vacuum breakdown experiment with broad area electrodes, field emission currents appear at macroscopic fields around 10^5 volts/cm. This disparity is resolved by introducing a field enhancement factor β which raises the mean field (given by $\frac{V}{d}$) to the true field at the emitting site. In some cases, this enhancement

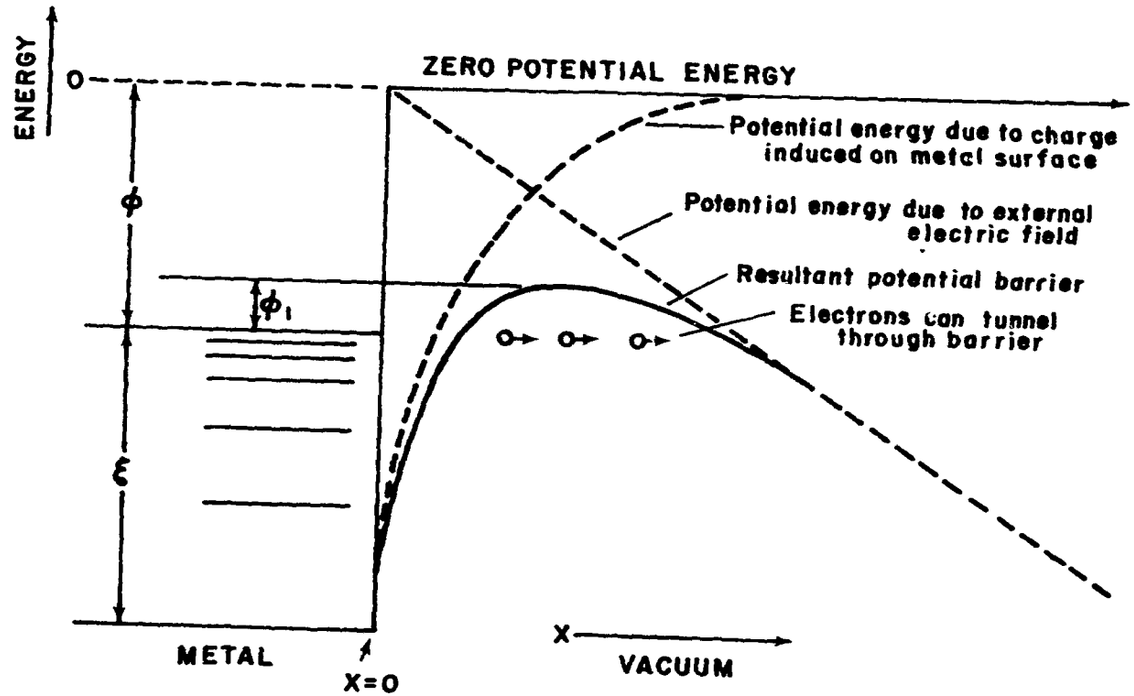

Figure 3-1. Field Emission Tunneling of Potential Energy Barrier at Metal Surface

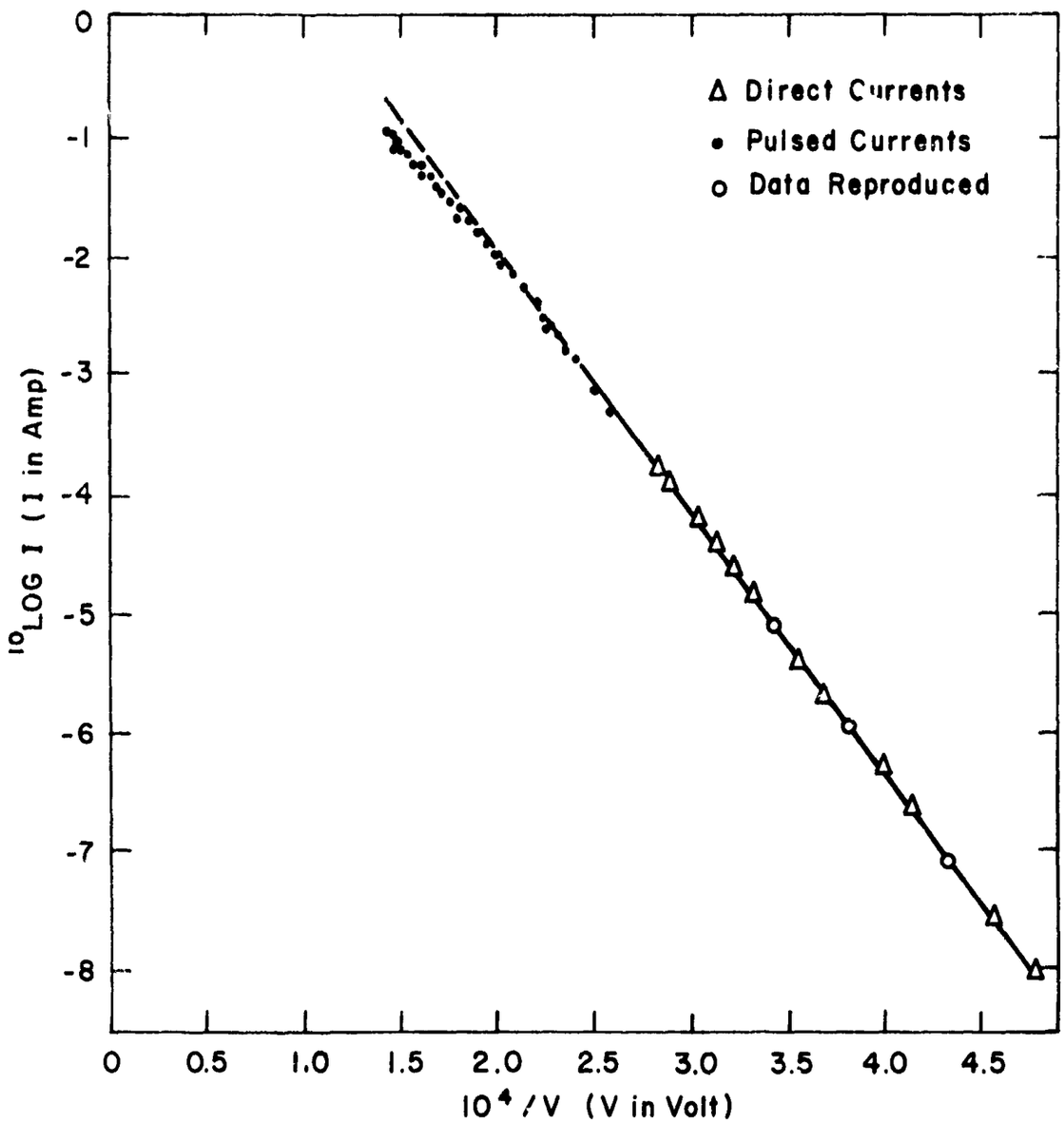

Figure 3-2. Fowler-Nordheim Plot of Voltage and Current for Field Emission from Tungsten Emitter with Space Charge Deviation at Large Currents (After Dyke, et al[5])

1-4240

can be identified with micron sized projections on the cathode surface (see Figure 3-3). These projections, or whiskers, are not to be confused with usual surface irregularities. Whiskers are much smaller, and their origin is not certain in all cases. There is considerable evidence that electrical stress of the electrode surfaces is a prerequisite for their appearance. A typical field enhancement factor is around 100.

In addition to steady currents due to field emission, transient pulses of current termed microdischarges may also occur. These have amplitudes of μA to mA level and duration of 100's μs to ms and are self extinguishing. The voltage across the gap is reduced by only a few percent for each microdischarge. Microdischarges are thought to arise from the regenerative exchange of positive and negative ions, thus occurring more readily in contaminated systems. The voltage threshold for their appearance can be raised by repeated discharges. A typical microdischarge waveform is given in Figure 3-4.

Other phenomena associated with electrical stress in vacuum are production of gamma radiation by electron impact with the anode, visible and infrared radiation, gas evolution from the electrodes, ionization of residual gases, and transport of electrode material -- primarily from anode to cathode. It is useful to remember that almost all of these phenomena occur at the vacuum-metal interface. This surface is complex and in continuous change due to variations in the ambient vacuum and the applied electrical stress.

3.2 Theories of Vacuum Breakdown

Field emission considerations would place a limit on vacuum insulation strength of about 3×10^7 volts/cm. Even under ideal conditions, vacuum gaps often fail to sustain fields of more than 10^6 volts/cm. This failure to achieve the theoretical strength of vacuum, and the usual experimental finding that the field at breakdown decreases as the gap separation and total voltage increase, have stimulated many experimental studies. Breakdown, which is the complete collapse of voltage across the gap, involves a sudden transition (often in less than 100 ns) from limited prebreakdown currents of 10^{-12} to 10^{-3} amperes, to a low voltage arc of hundreds or thousands of amperes, whose

Figure 3-3. Microprojection (Whisker) Produced After Electrically Stressing on Optically Flare Stainless Steel Surface (after Little and Whitney[6])

2-1410

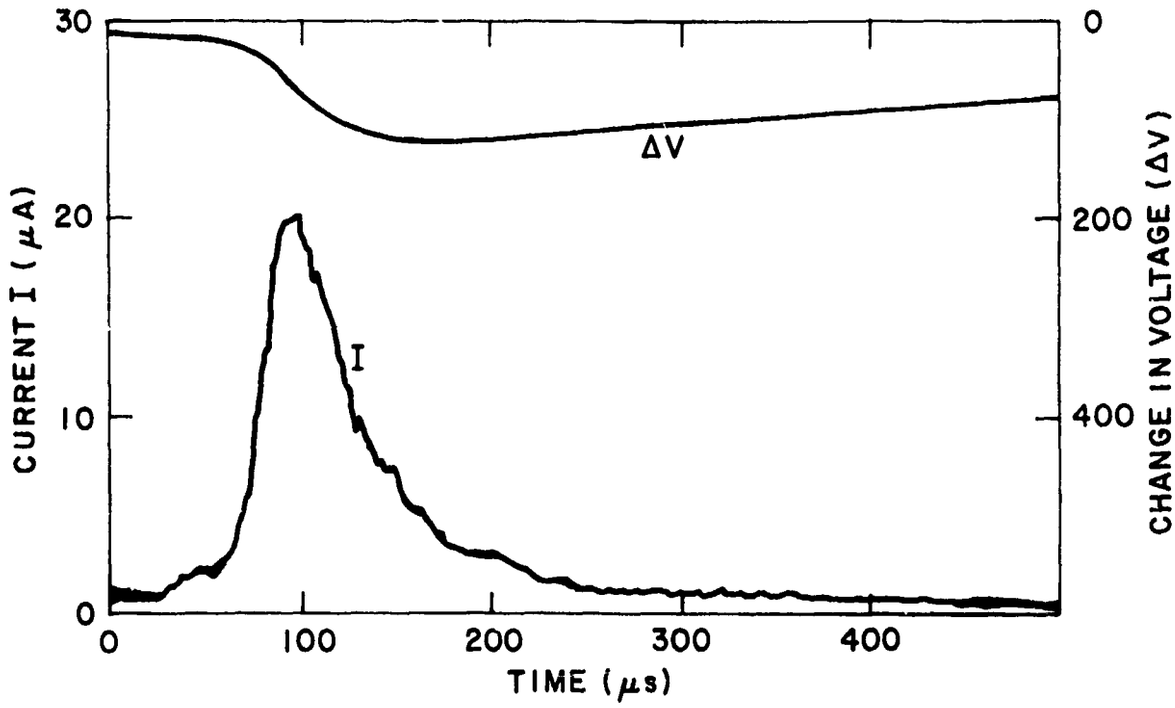

Figure 3-4. Microdischarge - Voltage and Current for Steel Electrodes, 1 mm Gap, 22 kV (After Boersch et al[7])

1-4241

magnitude and duration are limited only by the external electric circuit. A wide variety of mechanisms have been proposed in attempts to explain practical experience with vacuum insulation. These reduce, essentially, to three major types of instability mechanisms for explaining vacuum breakdown.

3.2.1 Field Emission[8,9]

Field emission currents from a cathode protrusion (whisker) resistively heat the protrusion. The electron beam also heats the opposite anode surface. When a critical current density is reached, the top of the protrusion may melt or explode (Figure 3-5), initiatiating breakdown. Alternately, heating of the anode may first lead to breakdown through generation of gas at the anode (Figure 3-6). Which mechanism occurs first is a function of gap, surface condition, and electrode materials. The critical field has been measured to be 6×10^7 V/cm (Figure 3-7) and the crossover between cathode and anode dominated breakdown is around 1 mm (Figure 3-8).

3.2.2 Particle Exchange

Electrons, positive ions and negative ions due to secondary emission processes could lead to breakdown if the exchange between electrodes becomes unstable. Positive ions, produced by electrons, would themselves produce more electrons and so on, as shown in Figure 3-9 . Photons might also participate. The process would be unstable if coefficients for the production of particles exceeded unity. While the measured coefficients do not seem adequate, the introduction of negative ions into the mechanism appear to give overall coefficients close to unity at total voltages above 250 kV.

3.2.3 Clump Hypothesis[10]

Electrostatic surface forces might tear a particle of electrode material away from the electrode surface. The charged particle would be accelerated across the gap, gaining an energy equal to its charge times the total voltage across the gap. Upon impact, if the energy exceeded a critical value, localized heating would produce a vapor cloud sufficient for breakdown

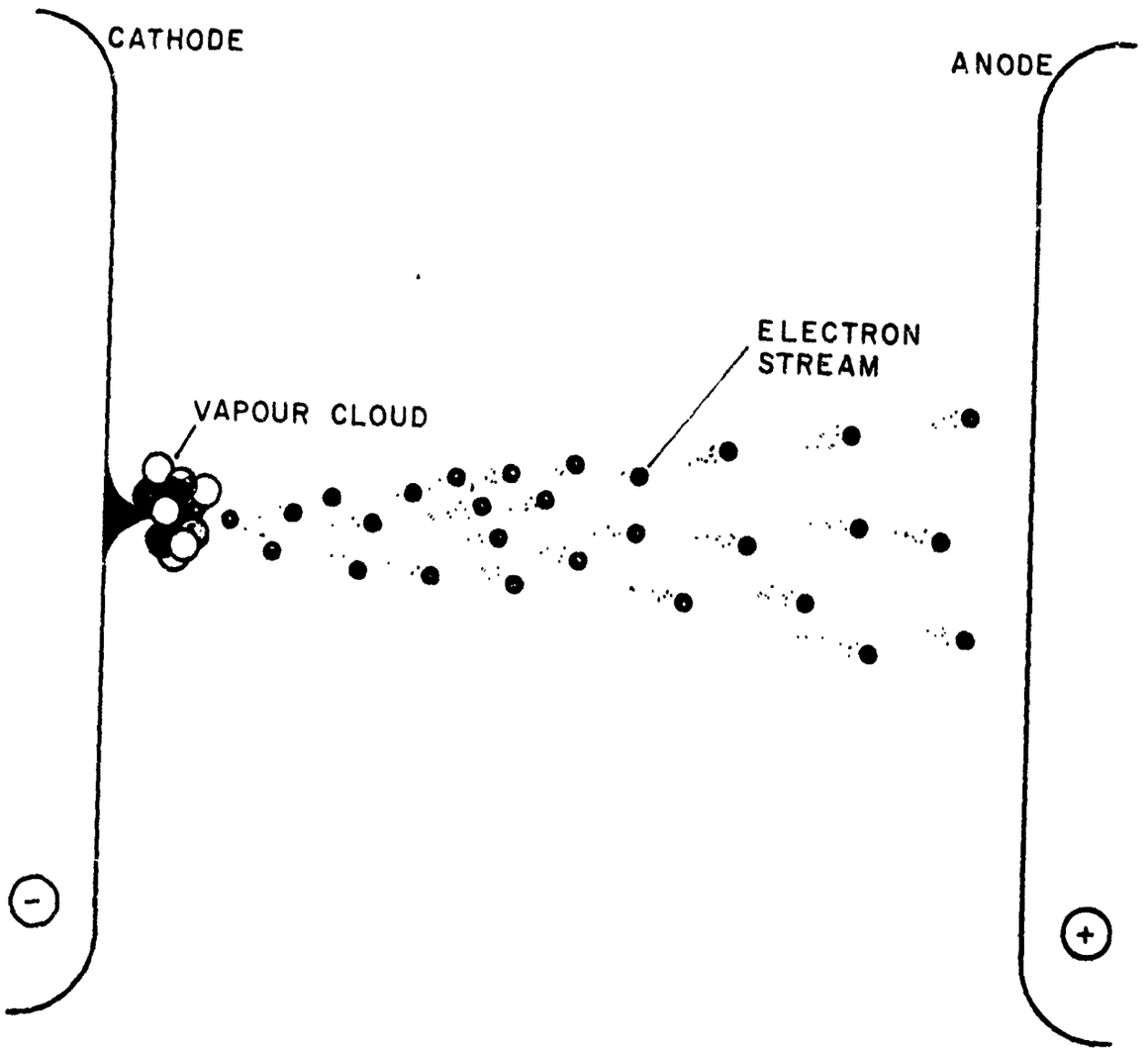

Figure 3-5. Cathode Dominated Field Emission Initiation Breakdown[11]

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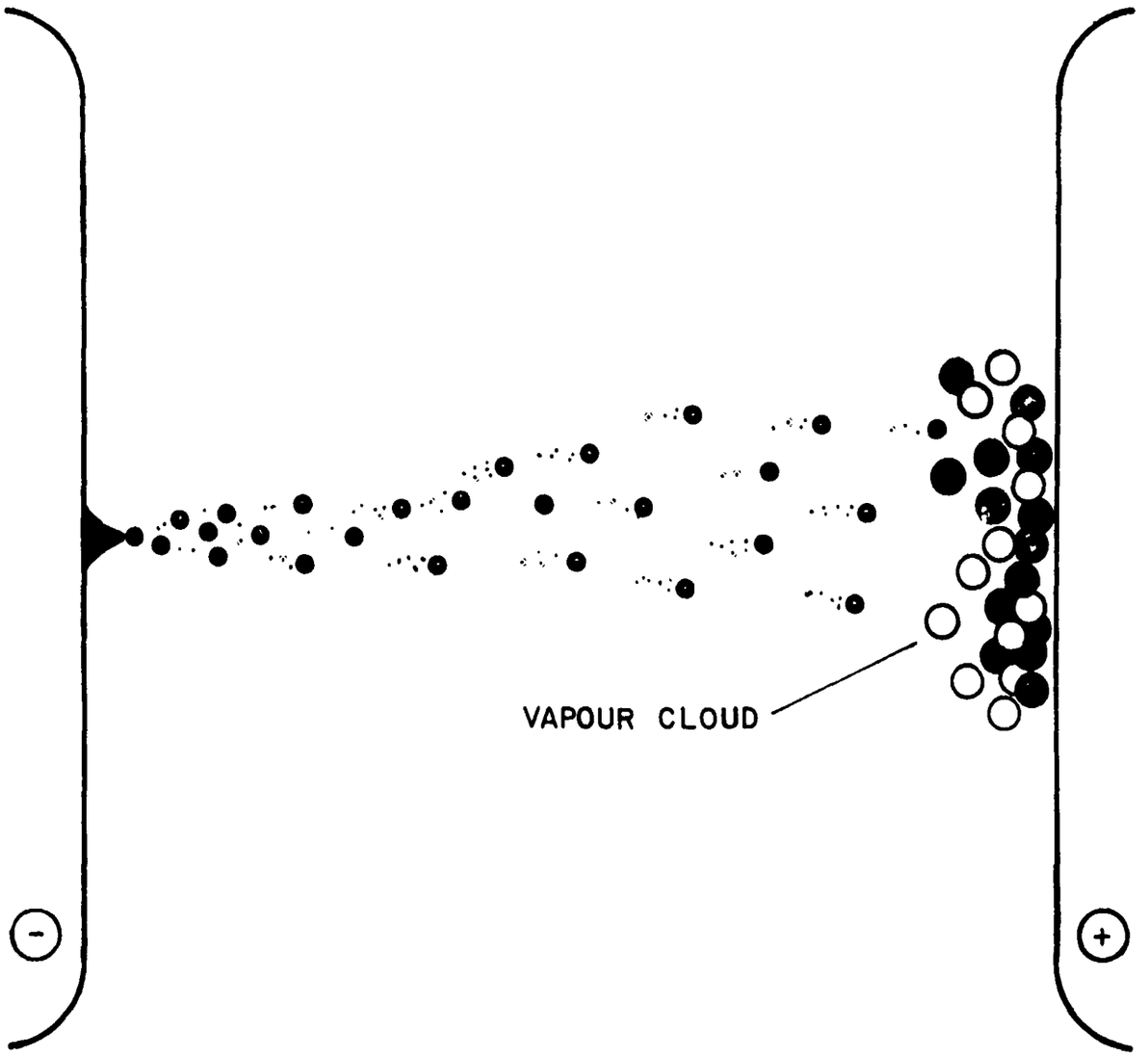

Figure 3-6. Anode Dominated Field Emission Initiated Breakdown[11]

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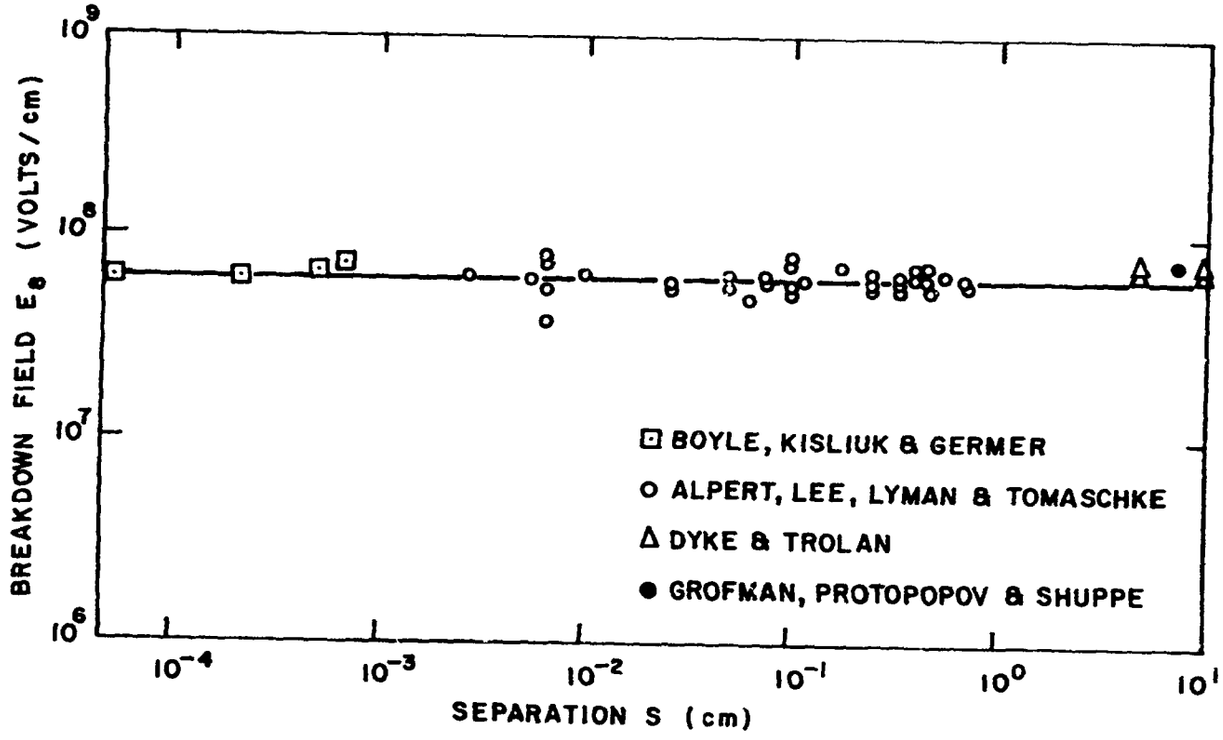

Figure 3-7. Critical Electric Field at Breakdown vs Gap Separation (After Alpert[8])

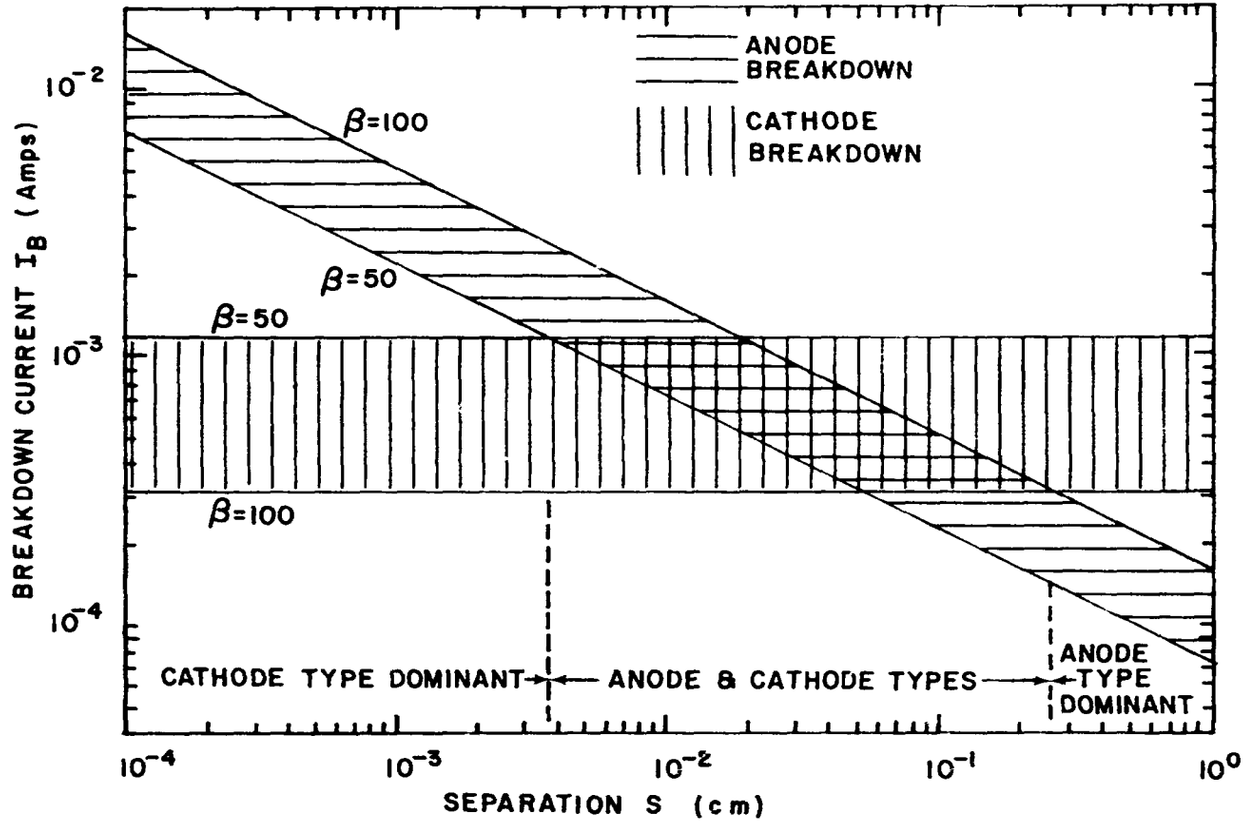

Figure 3-8. Theoretical Anode and Cathode Dominated Regions of Field Emission Initiated Breakdown (After Utsumi[10])

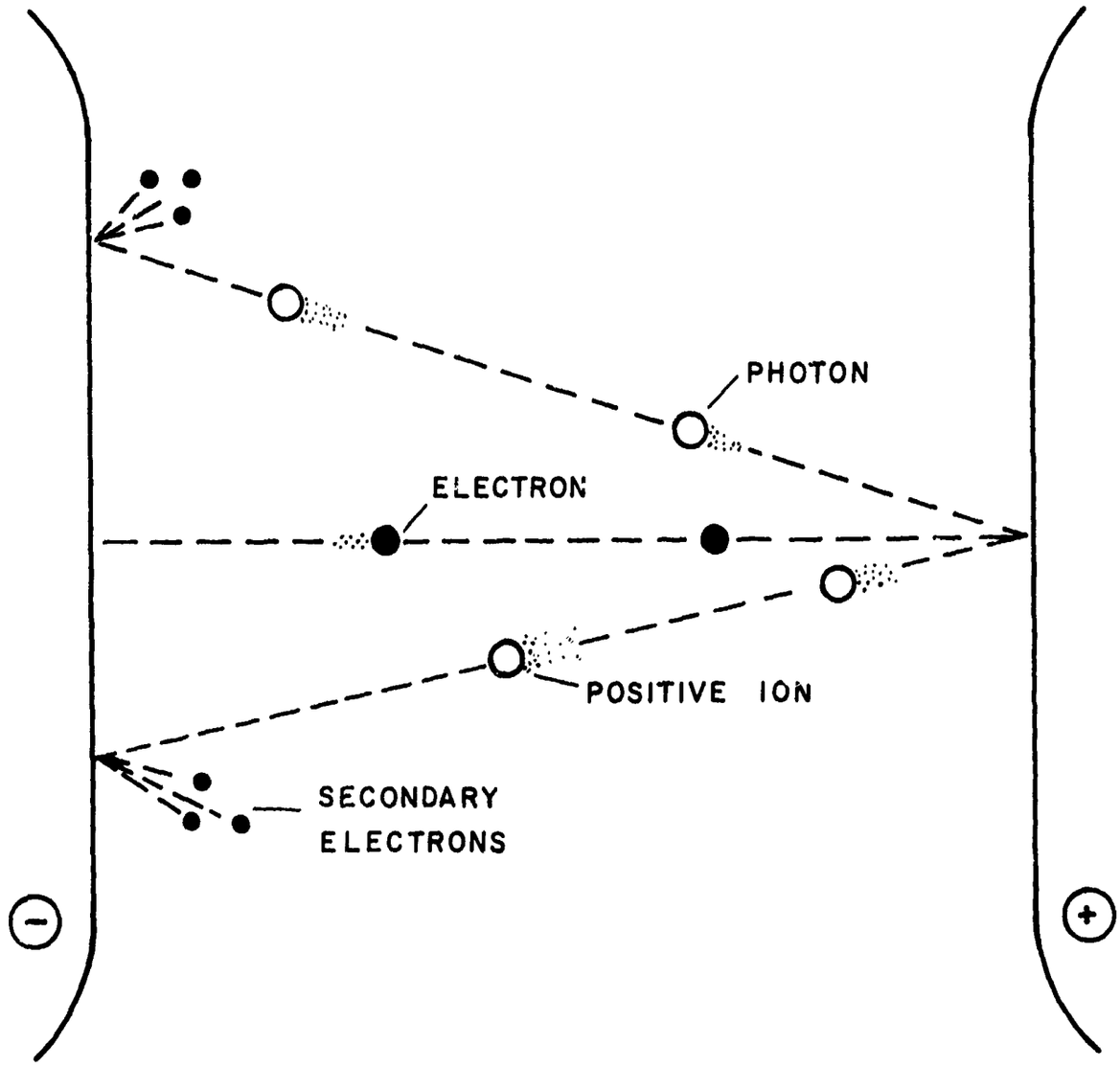

Figure 3-9. Elementary Particle Exc. ange Mechanism of Vacuum Breakdown[11]

1-4246

(Figure 3-10. For uniform field configurations, the predicted dependence of breakdown voltage upon gap is $V = kd^{1/2}$; this is often observed at large gaps (>5 mm) and high voltages (100 kV) as shown in Figure 3-11, and was observed throughout the experimental program.

3.2.4 Discussion

At small gaps (< 1 mm) and voltages below 100 kV, field emission initiation of breakdown has considerable theoretical and experimental support. At larger gaps and higher voltage, there is little agreement as to precise mechanisms, with all three theories having some support. In order to explain experimental results it is usually necessary to elaborate and sometimes combine the above theories. An additional difficulty arises because the physical parameters used in the theories (such as work function, surface structure, etc.) are not subject to direct observation. Thus, it is often difficult to apply any of the theories in a practical situation.

3.3 References

(1) Proceedings of the First International Symposium on the Insulation of High Voltages in Vacuum, MIT (October 1964).

(2) Proceedings of the Second International Symposium on Insulation of High Voltages in Vacuum, MIT (September 1966).

(3) Proceedings of the Third International Symposium on Discharges and Electrical Insulation in Vacuum, Paris (September 1968).

(4) Fowler, R. H. and Nordheim, L., Proc. Roy. Soc. 119, A, p. 173 (1938).

(5) Dyke, W. P. and Trolan, J. K., Phys. Rev. 89, 799 (1953).

(6) Little, R. P. and Whitney, W. T., J. Appl. Phys. 34, 2430 (1963).

(7) Boersch, H., Hamisch, H. and Wiesner, S. Z. angew., Phys. 13, 450 (1961).

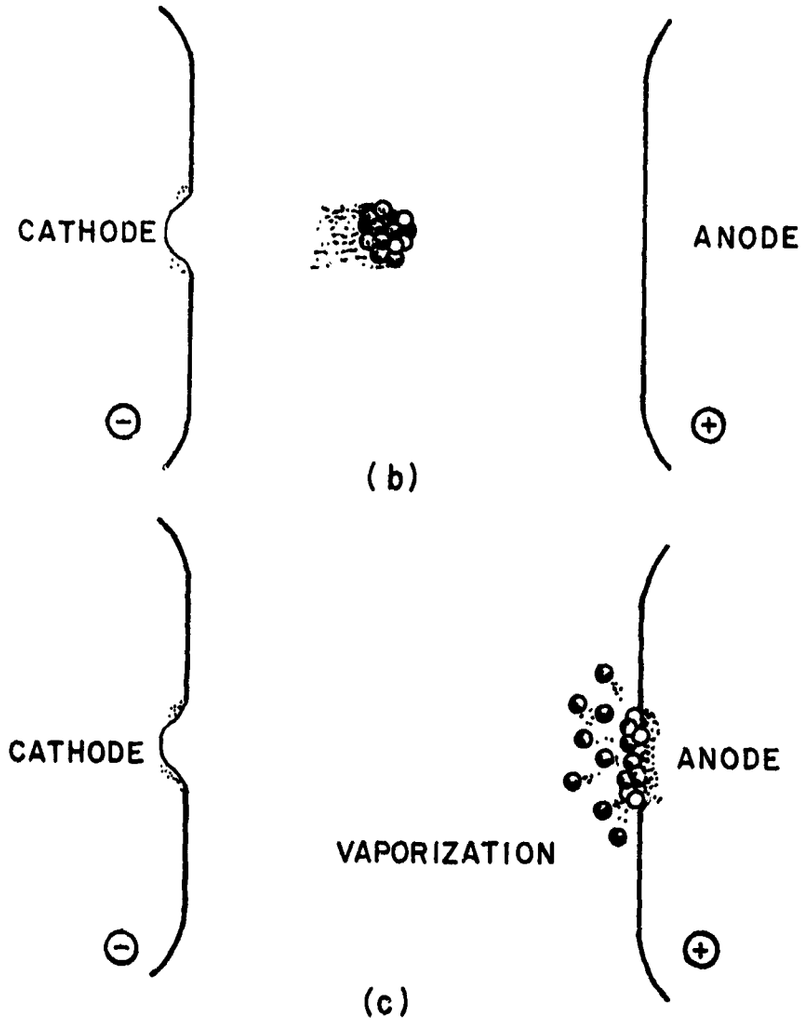

Figure 3-10. "Clump" Mechanism of Vacuum Breakdown[11]

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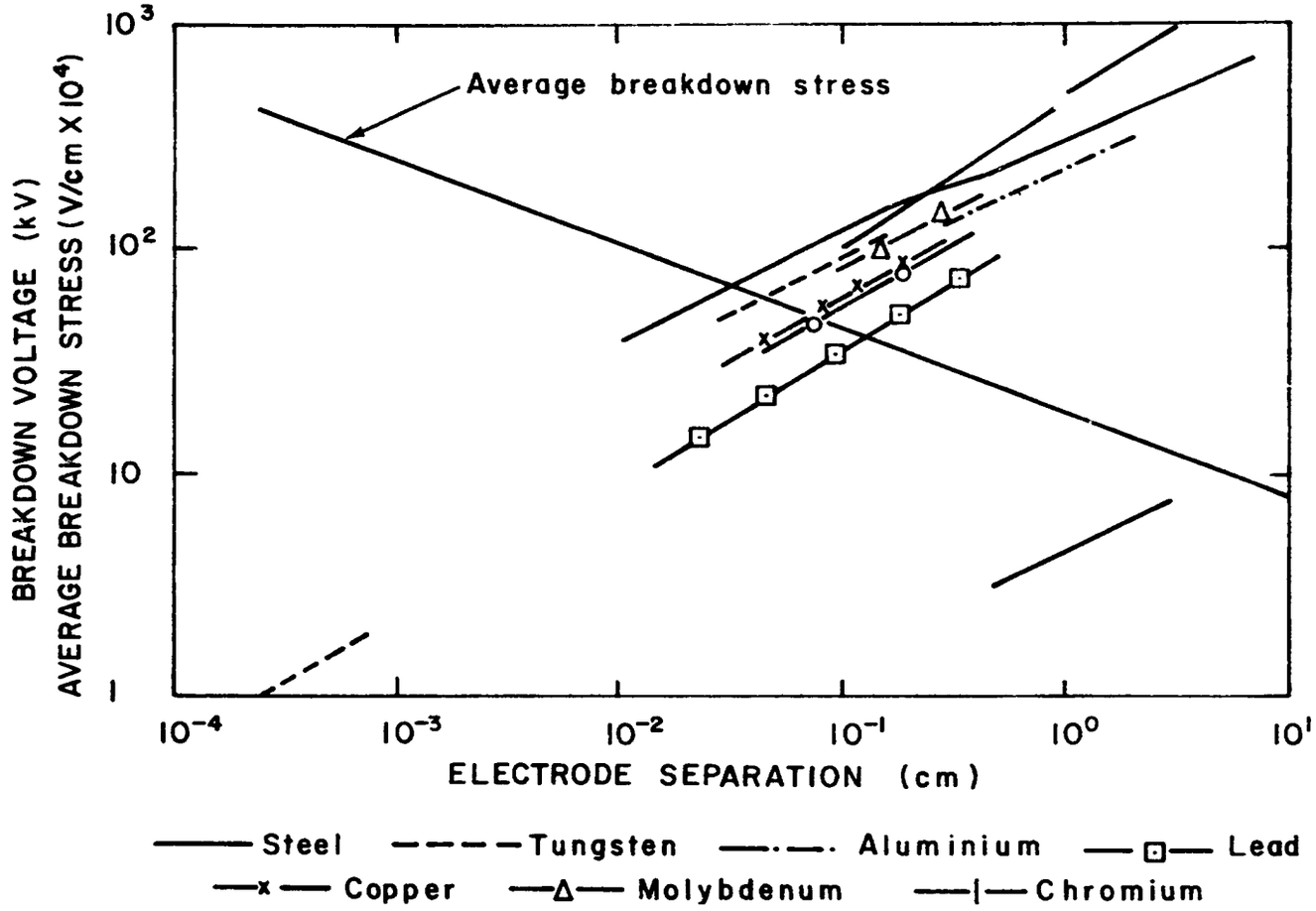


Figure 3-11. Breakdown Voltage vs Gap for Various Electrode Materials Demonstrating Approximate Fit to $V_{BD} = kd^{1/2}$ as Predicted by Clump Hypothesis (After Hawley[11])

(8) Alpert, D., "Electrical Breakdown in Ultra-High Vacuum", The Twenty-Sixth Annual Conference on Physical Electronics (March 1966).

(9) Utsumi, T., "Physical Processes in Electrical Breakdown in Vacuum," Tech. Report No. RADC-TR-66-712, Cornell University (January 1967).

(10) Cranberg, L., J. Appl. Phys. 23, 518 (1952).

(11) Hawley, R., "The Electrical Properties of High Vacuum," Chapter 4 in High Voltage Technology, Ed. L. L. Alston, Oxford University Press, London (1968).

4. FACTORS IN VACUUM INSULATION BETWEEN METAL ELECTRODES

4.1 Introduction

Practical utilization, and indeed, successful controlled experimentation depends to a large extent on awareness of all the factors which influence the performance of a physical system. In vacuum insulation, this is especially true; much of the unreliability and divergence of data commonly encountered is due to incomplete specification of the important parameters. Therefore, it is worthwhile to consider the entire range of factors in an organized manner. Table 4-1 gives a classification of factors known to be critical in vacuum insulation. Inflexible factors are ones which can be varied only during construction of the insulation system; flexible factors can normally be varied during testing and operation.

These factors cannot be considered independently of one another. In vacuum insulation the effect of one important factor generally depends upon the state or level of the other factors. For example, in the experimental program it was found that final processing in terms of vacuum or hydrogen firing would raise or lower the breakdown voltage as a function of electrode material, electrode shape and size, and the gap. The existence of such interactions means that simple prescriptions for achieving high breakdown voltages are very difficult, if not impossible. Thus, in any given situation careful consideration of all the pertinent factors is a requisite, and, even then, experimentation and tests may well be required to obtain optimum performance. Because of these interactions the factors are presented or considered in groups. For example, the influence of the external electric circuit is so closely related to conditioning that one cannot be adequately analyzed without the other.

4.2 Electrode Material

Electrode material is most important, with both anode and cathode material having an influence. In high energy discharge cases, the anode material is especially critical; this is discussed in section 4.3. An approximate

Table 4-1. Factors Important in Vacuum Insulation

Inflexible Factors	Flexible Factors
Electrodes-Cathode and/or Anode	Environment
Material	Residual Gas Pressure and Species
Surface Finish	Contaminant
Final Processing	Magnetic Field
Bakeout	Radiation
Dielectric Surface Films	
Geometry	External Electric Circuit
Shape	Impedance
Size (Area)	Available Energy and/or Current
	Voltage Application Rate
Vacuum Chamber	Electrode Temperature
Material - Metal or Dielectric	Electrode Spacing
Chamber Geometry - Size	
Bakeout	Conditioning - Electrical Stress History of the Electrodes

ranking in order of increasing excellence is:

C, Be, Pb, Al, Cu, Ni, Fe, SS, Ti, Ta, Mo, W

Consistent and reliable performance of these metals as vacuum insulation electrodes requires that pure and/or standard raw stock be used.

However, a more detailed examination of the electrode material influence in vacuum breakdown in practical situations reveals the important role of interactions with surface finish, final processing, and bakeout. Surface finish is in itself of minor importance, but can appreciably affect the degree of cleanliness that is achieved. For example, the use of oils and buffing compounds in giving the electrode surfaces their final finish has been found to leave behind organic contamination that is practically impossible to remove. Thus, it is recommended that finishing techniques such as the use of abrasive paper with water be considered. In the "High Voltage Breakdown Study" a 600 grit finish was found to be adequate, in that the performance achieved with it was indistinguishable from that achieved with 1.0 micron finish.

Final processing includes cleaning and, for optimum performance, some form of heat treatment in a controlled atmosphere that stabilizes the gas content and surface properties of the electrodes. In the experimental program, both vacuum and hydrogen firing were found to be useful, with temperatures up to 900 °C.

After assembly of the system, e.g., modulator tube (with care being taken to avoid dust particles which are detrimental to high withstand voltages), evacuation and bakeout should be carried out. While the latter is not essential and sometimes impossible, it is beneficial, both in terms of increased breakdown voltages and consistency of results.

Often, due to system requirements not directly related to the insulation of high voltages, different materials are used for cathode and anode. For example, in most high power vacuum tubes copper is used as the anode, because of its high thermal capacity and conductivity, while a high temperature material such as nickel or tungsten is used for the cathode material. It is important to recognize that, in vacuum breakdown, material transfer from one electrode to the other generally takes place. In some cases, but in particular

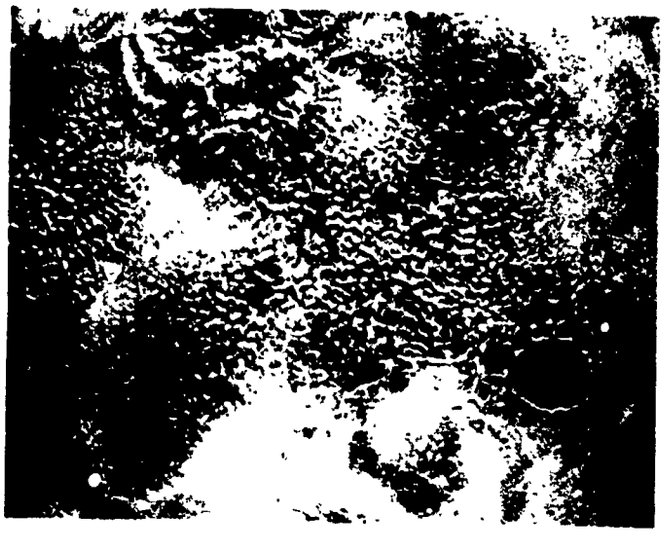
when the discharge energy is high, there is extensive transfer of anode material to the cathode. This complicates the interpretation of the factor of electrode material, and introduces that, which causes prime concern in vacuum insulation -- the fact that the properties of a vacuum gap can be expected to change with use.

4.3 Conditioning

The electrical insulating properties of electrodes in a vacuum are strongly dependent on previous operating history. It is usually found that the voltage hold-off of electrodes in a vacuum can be substantially improved by allowing repeated breakdowns or passage of appreciable prebreakdown current. This behavior is termed "conditioning" and is of necessity a consideration in any vacuum insulation study or application. It has also been called aging, spot-knocking, formation, or training.

Conditioning occurs due to changes in the surface states of the electrodes. These changes may be brought about by: mechanical deformation due to high electric fields; bombardment of the anode by field emission electron beams; sputtering of cathode protrusions by ionized residual gases; and possibly by the energetic impact of charged macroparticles detached from one electrode by electrostatic forces and accelerated across the gap. In addition, breakdown is a localized discharge that releases energy which disrupts the electrode surfaces. The most common conditioning technique is to repeatedly allow the gap to break down. Each discharge is normally limited in energy (and peak current) by a high series resistance (of the order of megohms). In this case, the breakdown voltage rises smoothly to a plateau in from 10 to 100 or more breakdowns.

Typical results of conditioning are shown in Figure 4-1; the anode is burned, eroded, and melted, while the cathode exhibits craters and deposits of anode material. These are extreme results of conditioning; with very low energy discharges the effect of thousands of breakdowns may be invisible to the naked eye. Figure 4-2 shows the surfaces of a copper anode and cathode after conditioning. The anode surface has been etched by electron bombardment,



Anode - Treatment e - 10X

Cathode - Treatment c - 10X

Figure 4-1. Typical Anode and Cathode Surface Change Features

2-1243

(a) Grain Structure Revealed by Electron Bombardment (~ 49 X)

(b) Severely Eroded Region (~ 40 X)

(c) General View of Crater (~ 20 X)

(d) Detail of Crater (~ 75 X)

Figure 4-2a. Surface Changes on Copper Anode Due to Many Low Energy Discharges

2-1457

(a) General View of Cathode Surface (~10X)

(b) Detail of Cathode Surface Showing Crater and Protrusions (100X)

(c) Detail View with Tips of Protrusions in Focus (100X)

(d) Detail View with Surface in Focus - Note 600 Grit Polishing Marks (100X)

Figure 4-2b. Surface Changes on Copper Cathode Due to Many Low Energy Discharges[20]

2-1464

revealing the grain structure. The cathode surface was generally undisturbed, but in the central regions protrusions consisting of transferred anode material can be seen.

Most high voltage, high power vacuum tubes operate with considerable energy available to any discharge. Thus, the effect of a spurious breakdown may be catastrophic, leading to low breakdown voltages, high prebreakdown currents, loss of vacuum, or mechanical damage. It is generally not economical to operate high voltage electron tubes at voltages so low that breakdown will never occur (see Section 4.6). Therefore, the effects of high energy discharges must be considered. The typical response of electrodes to discharges of different energy levels is given in Figure 4.3 and is discussed in some detail, due to the importance of the factor of conditioning. A summary of energy conditioning performance with a copper anode, obtained by using the average values of breakdown voltage over eight tests, will serve as a basic model.

The average initial breakdown voltage of unconditioned electrodes was ~ 140 kV (187 kV/cm). High impedance conditioning (HIC), i.e., 90 discharges with 30 kilohms series resistance raised the average breakdown voltage to 200 kV. Prebreakdown current (as indicated in Figure 4-3 by the voltage at which 10^{-6} amperes flowed) diminished. The next moderate energy conditioning (MEC) series of 90 discharges, with 1 k-ohm series resistance and 0.15 μF capacitive energy storage, reduced the average breakdown voltage to 187 kV, and the scatter, as measured by the standard deviation, increased from 4.5% for HIC to 14% for MEC. Prebreakdown current levels, however, were not appreciably affected by the increase in discharge energy.

Next, a limited number of high energy discharges (series resistance 0 ohms at the high voltage bushing, 25 ohms at the 0.15 μF capacitor bank) sharply reduced breakdown voltage, increased scatter, and led to very high prebreakdown current levels. The overall average breakdown voltage was 145 kV, with occasional values as low as 35 kV. Subsequent reconditioning with moderate energy discharges brought the average breakdown voltage to 201 kV.

High impedance conditioning with energy storage produced little scatter ($\sigma < 4\%$) and high average levels of breakdown voltage (220 kV).

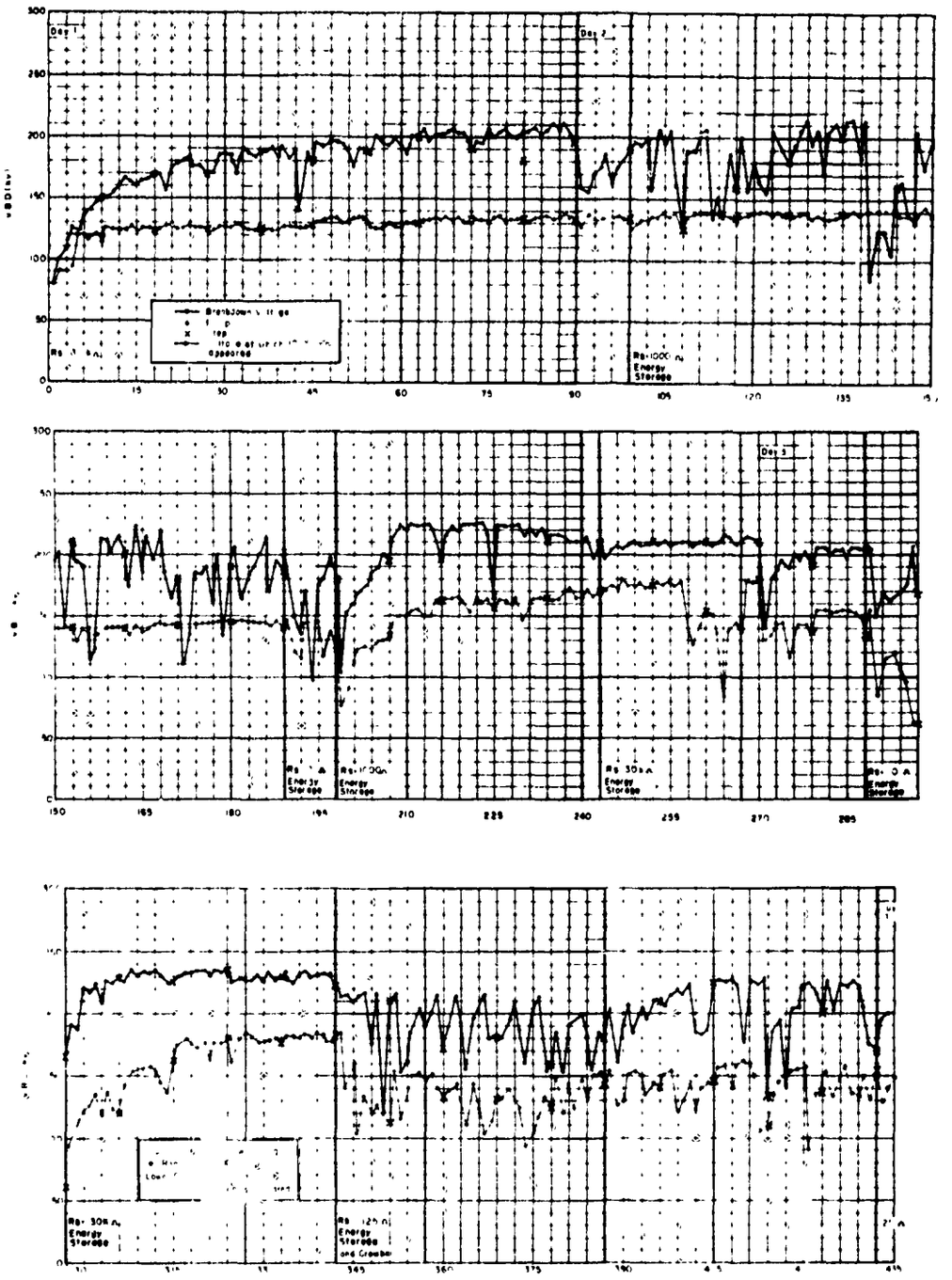


Figure 4-3. Typical Energy Conditioning Curve.

Conditioning Curve (Breakdown Voltage vs. Breakdown Sequence) for 4" dia. Uniform Field Electrodes at .75 cm Gap - Copper Anode - Ti-7 Al-4 Mo Cathode Showing Effect of Changes in Series Resistance (R_S), Energy Storage (.15 μF Capacitor Bank), and Crowbar (< 500 ns to Diversion) - From the "High Voltage Breakdown Study".

Measurements of the breakdown current pulse showed that a series impedance of 30 k-ohms was sufficient to isolate the gap from capacitive energy storage in the power supply circuit. A second high energy discharge series reduced the average breakdown voltage to 151 kV; however, high impedance conditioning quickly restored the breakdown voltage to the former level of 200 kV. Fast crowbarring (diversion within 500 ns) with 125 ohms series resistance and 0.15 μF energy storage was only partially effective and the average breakdown voltage dropped by 10% to 201 kV with the scatter increased to 15%. Thus, significant damage occurs within the first microsecond of the discharge.

Simultaneous measurement of discharge current and gap voltage showed that the current rose rapidly ($> 2 \times 10^{10}$ A/s) with relatively slow collapse of voltage across the gap (about 100 ns for 0.75 cm gap). Thus the initial phase of the discharge appears to have a high impedance (~ 1000 ohms). This accounts for the observation that most of the discharge damage occurs during the first microsecond.

A copper anode opposite a nickel cathode progressively deteriorates as a result of 220 high energy discharges. The average breakdown voltage drops from 220 kV to 140 kV and the prebreakdown current increases (voltage for 10^{-6} amperes decreased from ~ 160 kV to ~ 60 kV). The basic factorial study was extended to include anode material as a factor at six levels (Cu, SS, Ni, Pb, Al and Ti-7 Al-4 Mo). Differences in breakdown voltages for the various materials was minor for low and moderate energy discharges, but major differences were found with high energy discharges.

Copper, aluminum and lead anodes deteriorated in insulating ability as a result of high energy discharges. Stainless steel (type 304), nickel, and Ti-7 Al-4 Mo anodes, after the usual sharp drop in breakdown voltage, upon introduction of high energy discharges, soon conditioned to breakdown voltage levels higher than before high energy conditioning. Cathode material was not important and a copper cathode opposite a Ti-7 Al-4 Mo anode held 300 kV across a 0.75 cm gap. Examination of typical electrodes revealed an extensive transfer of anode material to the cathode as discrete droplets and a condensed film. The anode surface was severely melted and eroded.

Linear multiple regression analysis was used to correlate physical properties of anode material with the maximum breakdown voltage during an extended high energy discharge series for anodes of copper, aluminum, nickel, Ti-7 Al-4 Mo, and 304 stainless steel. The cathode in most cases was Ti-7 Al-4 Mo. Melting point temperature, specific heat and density were found to give the most reasonable fit (index of determination > 0.95) as shown in the curve of Figure 4-4. A maximum breakdown voltage of 72 kV was predicted for a lead anode, the experimental value was 76 kV.

This curve provides a way of ranking the performance of anode materials for high energy applications. The curve uses maximum breakdown voltages - average and minimum values follow the same trends.

The observation that significant damage occurs during the first microsecond means that protection of the vacuum gap by series impedance or crowbarring must limit the energy flow very rapidly. Thus, crowbarring for diversion within 500 ns was not fast enough to adequately protect the electrodes in the experimental study. Addition of inductance, or more series resistance, would slow the energy input enough so that crowbarring in times of the order of a microsecond should be effective.

The energy conditioning behavior described above, especially the critical dependence on anode material, suggests a breakdown mechanism in which the thermal interaction of field emission beams with the anode surface is important. It has been suggested that breakdown might occur when a metallic particle is electrostatically extracted from a region of the anode which has been weakened due to field emission beam heating. The extracted particle is accelerated across the gap in the beam, partially vaporized while in transit, and finally its energetic impact on the cathode precipitates breakdown.

In summary, high energy discharges can be endured by a vacuum gap without permanent damage. Refractory anode materials are especially tolerant of high energy discharges. The close correlation between thermal properties of anode material and breakdown voltage provides a practical means of ranking anode materials, and estimating the breakdown voltage to be expected in high energy applications.

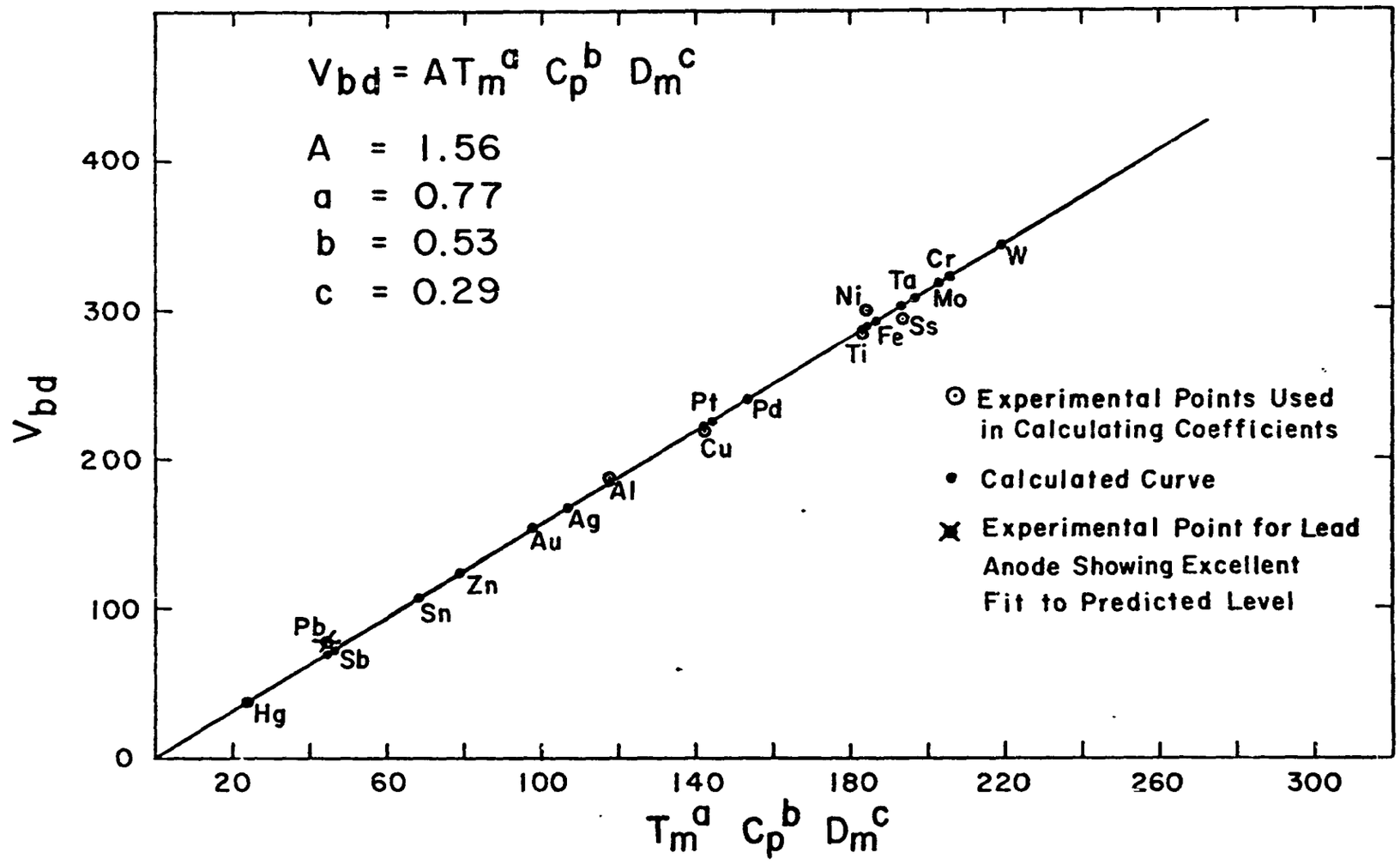


Figure 4-4. Correllation Between Anode Material Physical Properties and Breakdown Voltage During High Energy Discharge Conditioning. From the "High Voltage Breakdown Study".

Another conditioning technique which requires times of the order of days is to increase the applied voltage very slowly, keeping the prebreakdown current and pressure level of evolved gases at some arbitrary low level. This can produce higher conditioned levels than are achieved by sparking as shown in Figure 4-5. The deliberate introduction of gas during conditioning is discussed in Section 4.5.

Less widely used techniques which, in some applications, have been found useful are heating of the electrodes to a high temperature, or a low pressure gas glow discharge. These are especially applicable in systems subject to organic contamination.

The change in insulation strength from the level of first breakdown to final fully conditioned level is often more than a factor of two. There are some few applications where even one discharge cannot be tolerated, and spark conditioning is ruled out -- the initial breakdown value is then the only one of interest. In general, however, conditioning is acceptable, and it is the most widely used technique for improving the insulation performance of vacuum gaps.

4.4 Electrode Spacing

The variation of breakdown voltage with electrode spacing has been extensively investigated. For small gaps (< 5 mm), the dependence is approximately linear. With large gaps (> 5 mm), the breakdown field strength decreases as the gap increases, resulting in a "total voltage effect" in which the breakdown voltage increases as some fractional power of the gap (usually from 0.4 to 0.7). Figure 4-6 due to Trump[1] is typical and gives this effect for a 1 inch diameter steel sphere opposite a plane. Figure 4-7 from the experimental study illustrates the linear and square root regime for uniform field electrodes with a lead anode. This total voltage effect is probably a result of charged particles being able to gain an energy equal to the product of their charge times the gap voltage, since collisional losses of energy are very unlikely.

For small gaps, up to 1 mm or so, field emission initiation of breakdown as discussed in Section 3.2.1 can explain vacuum breakdown. At larger

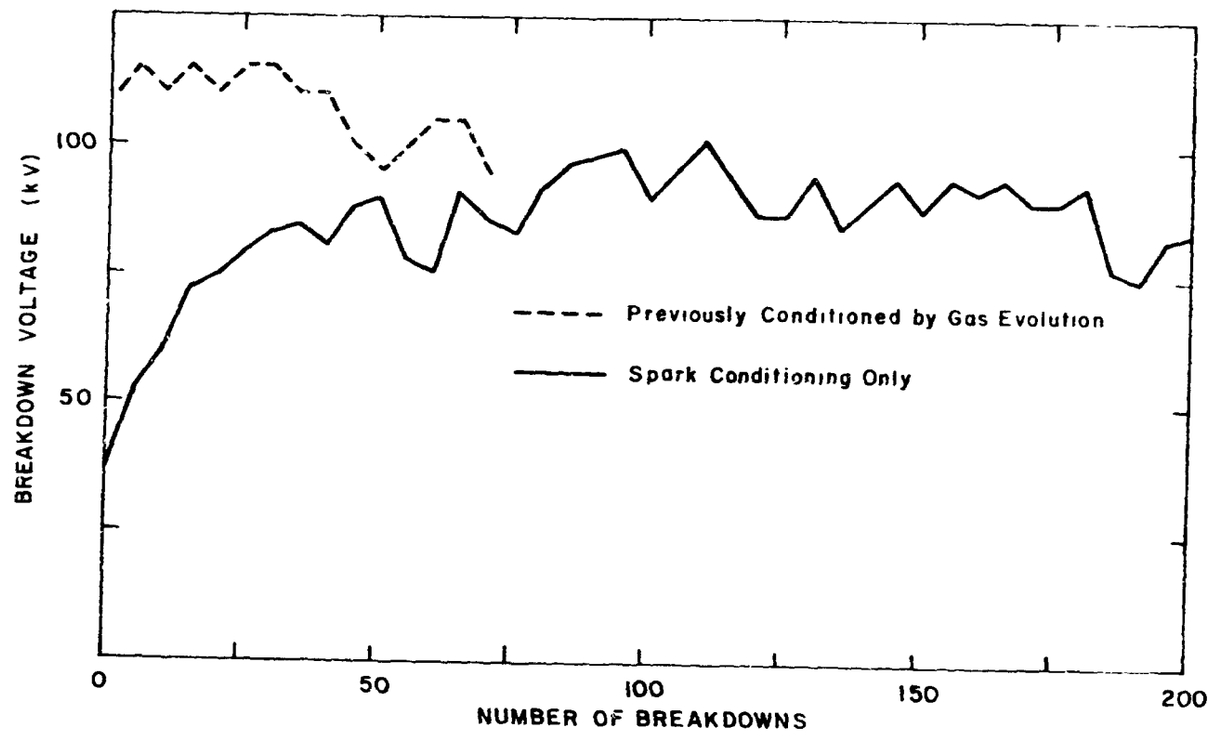


Figure 4-5. Effect of Gas Evolution Conditioning - 3/32 Inch Gap From the "High Voltage Breakdown Study".

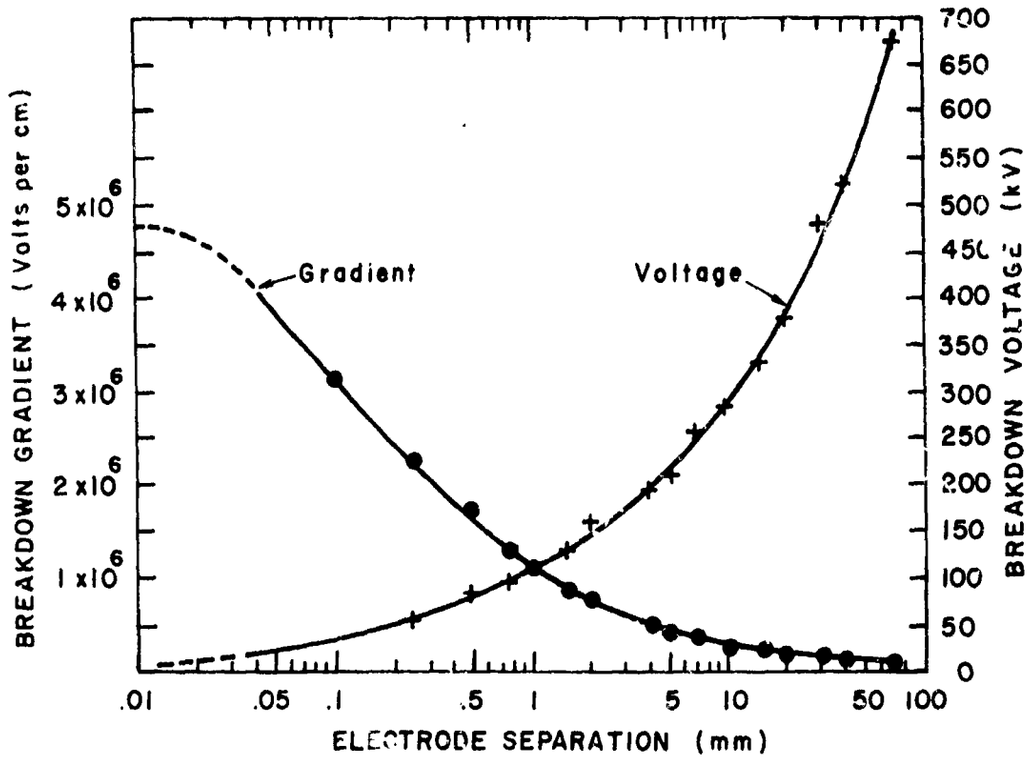


Figure 4-6. Breakdown Voltages and Gradients Between 1-Inch Stainless Steel Ball and 2-Inch Steel Disk in Vacuum[1]

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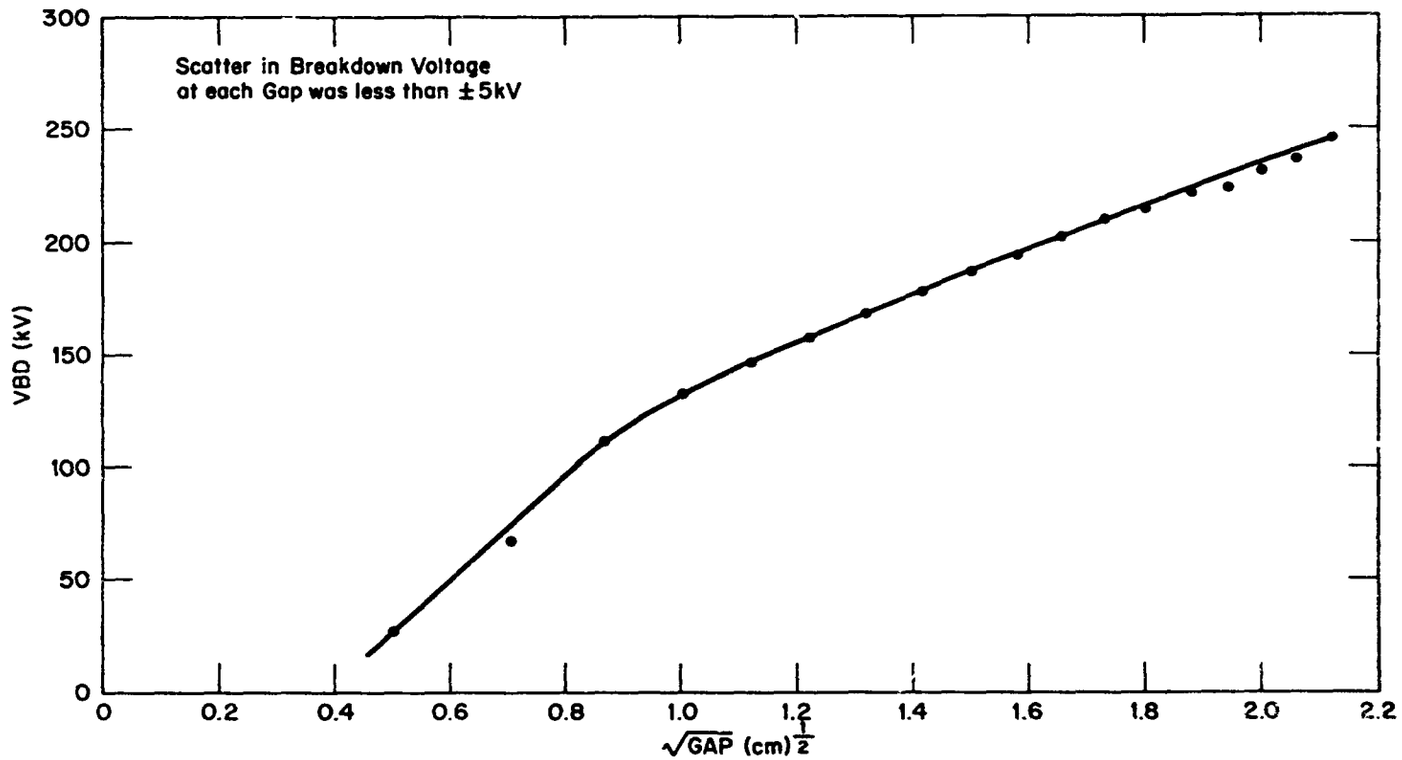

Figure 4-7. Breakdown Voltage versus Square Root of the Gap - 4-Inches Diameter Bruce Profile Electrodes - Lead Anode and Ti - 7 Al - 4 Mo Cathode - After Conditioning - Low Energy Discharges - Points are the Average of Nine Breakdowns.

gaps, and higher voltages, there is presently no commonly accepted and comprehensive theory of breakdown. In many instances several mechanisms are involved, and which happens first or predominates depends upon the experimental parameters of each situation.

An interesting technique for increasing breakdown voltage by taking advantage of the high dielectric strength of small gaps is to break the total gap into shorter sections by means of metal equipotential planes. Ten gaps of 1.0 mm might easily withstand 50 kV each for a total of 500 kV, while a single gap of 10 mm cannot be expected to withstand more than 200-300 kV. Of course some space is lost to the equipotential planes, and, both in dc and fast pulse applications, fixing the potential of each plane is difficult. Also, the vastly increased surface area makes it more difficult to obtain a clean vacuum and introduces an area effect. However, in applications where potentials of millions of volts must be insulated by vacuum, as in acceleration tubes, the breaking up of the interelectrode space into short segments has been found to be indispensible.

4.5 Electrode Geometry

Electrode geometry in terms of shape and size (area) is more important than might be expected. While it is difficult to separate the effects of area and shape, the general trend is for small areas to support much higher stresses than large areas - thus, for uniform field geometry, the breakdown voltage decreases as electrode area increases, as shown by McCoy[2] (Figure 4-8). Increasing curvature of spherical electrodes, while producing a higher maximum stress, reduces the active area so much that the breakdown voltage for a given gap increases, as shown by Rabinowitz[3] (Figure 4-9). In the experimental study a decrease in electrode area by a factor of ten was accompanied by a 10-20% increase in breakdown voltage.

A reasonable design criterion for vacuum insulation is to minimize the highly stressed surface area - even at the expense of increasing the maximum electric field.

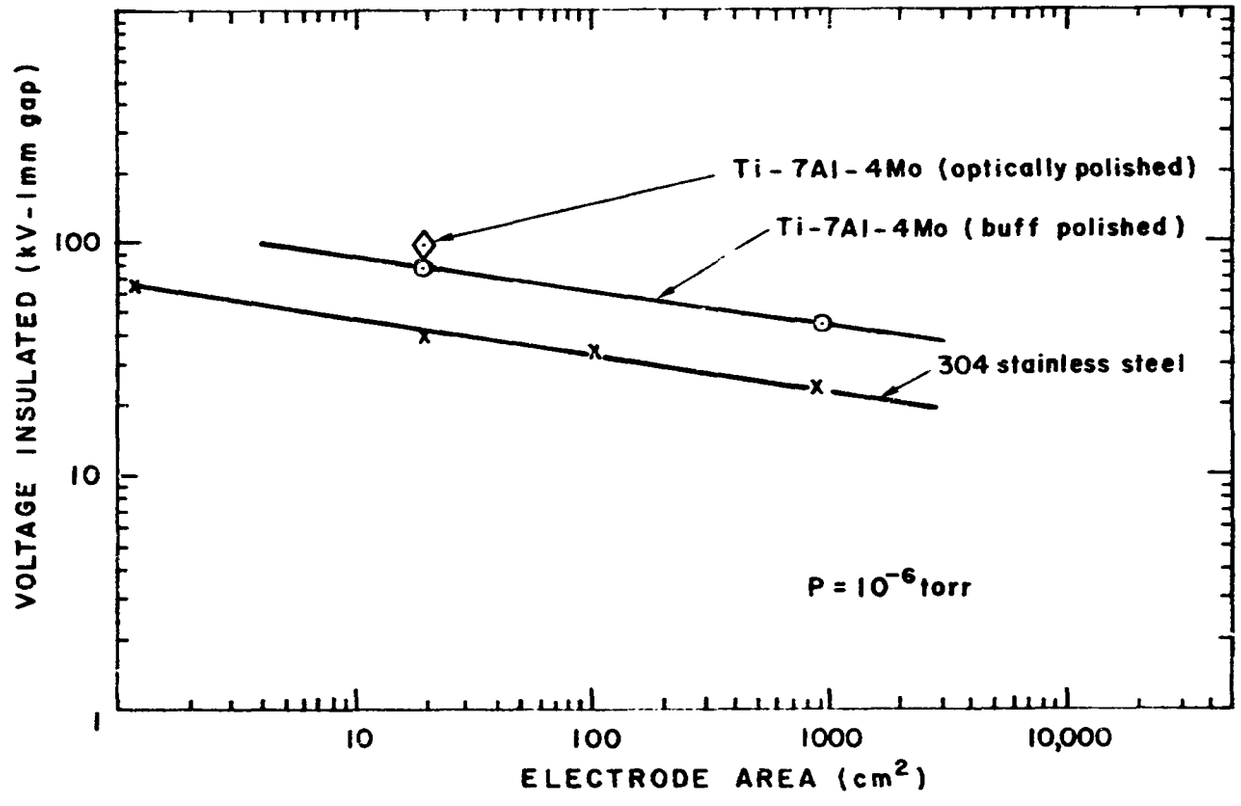

Figure 4-8. Electrode Area Effect (After McCoy[2])

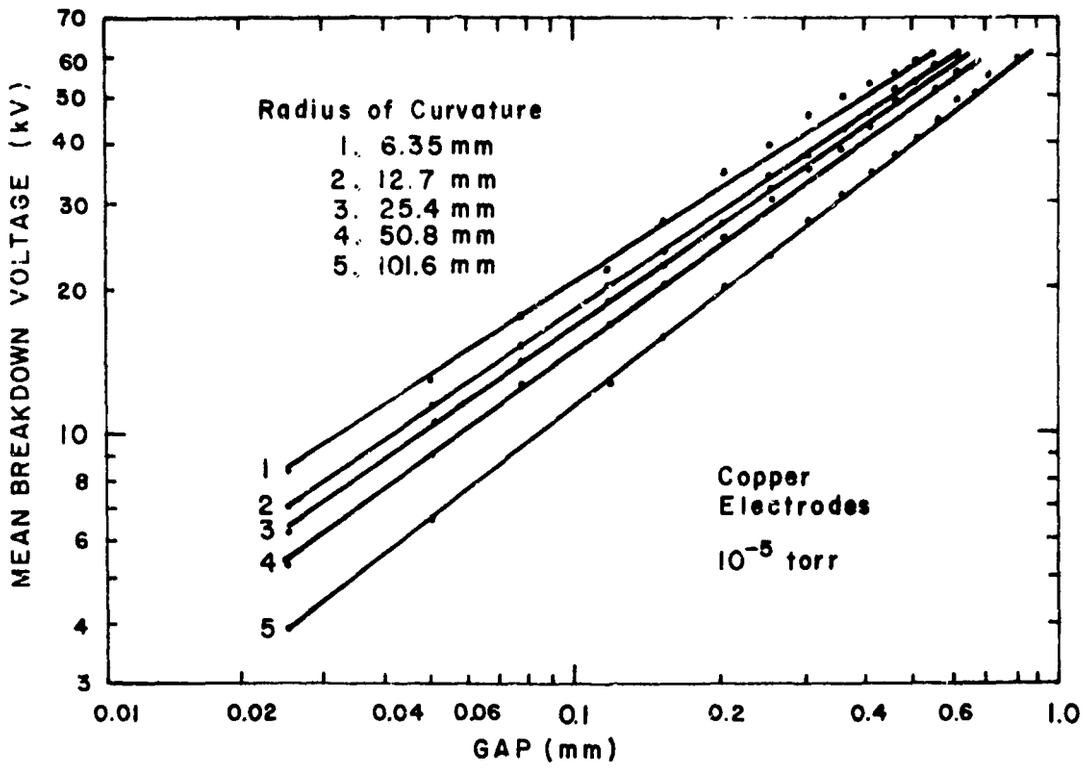

Figure 4-9. Curvature Effect for Conditioned Copper Electrodes(3)

1-4250

The reasons for an "area" effect have not been conclusively identified. One explanation is statistical in nature, postulating that a given unit area has a certain probability of breakdown, so that the greater the number the more chance there is for breakdown. Another explanation is simply that it is more difficult to prepare large surface areas with the same precision and cleanliness as small surface areas. Yet another, is gas release during voltage application and variations in pumping conductance.

4.6 Time Effects

Most of the vacuum insulation studies to date have been for dc voltage conditions. Recently, however, pulsed voltage applications have increased in scope and importance. There is every indication that this will continue in the future. The same is true of ac applications. Some relevant studies are reported below.

Even in the dc case, time is important since, for a given electrode system at some stage of conditioning, there is a definite relationship between breakdown rate and stress level. Thus, Figure 4-10 shows that a 0.75 cm uniform field gap will sustain 245 kV if ~ 1 breakdown/minute is acceptable; whereas it will sustain only 220 kV if there is a requirement for zero breakdown in a time period of many hours. This is for the case of continuously applied voltage.

Time is also important, even when there is no electric stress on the electrodes. In most vacuum systems or tubes long periods of time (hours to days) without electric stress will result in de-conditioning of the electrodes. Then, some degree of conditioning will be required to again reach previous operating voltage levels.

Impulse breakdown in the microsecond range has been investigated at up to 500 kV by Smith[4] with 1/4000 μs pulses. Breakdown was found to occur in either an abrupt localized spark after ~ 20 μs or a diffuse glow-like discharge with slow current rise, also at about 20 μs. A particle exchange mechanism is suggested for the second type. Breakdown stress levels in this experiment were about 100 kV/cm, which is not particularly high, and is

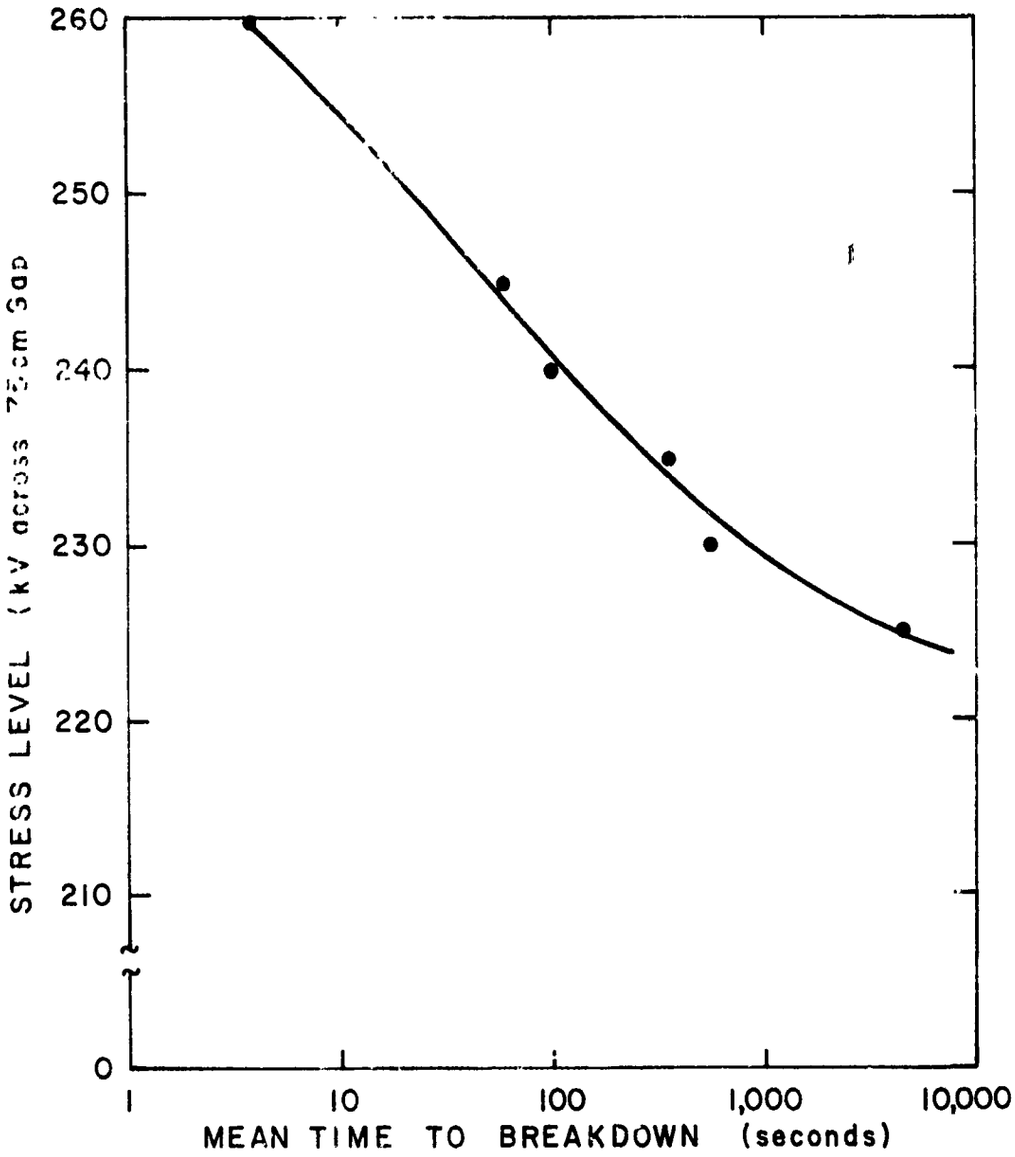

Figure 4-10. Typical Withstand Properties of High Impedance Conditioned Vacuum Gap - 4 Inch Diameter Uniform Field Nickel Electrodes. From "High Voltage Breakdown Study".

1-42-8

evidence that the breakdown mechanism is probably very similar to that found under dc conditions.

Nanosecond pulse breakdown has recently been extensively studied for moderate voltages by Wolff[5] and Mesyats.[6] It was established that, for nanosecond pulses, breakdown is cathode dominated. Breakdown could occur in 0.15 ns if a sufficient overvoltage were available. Figure 4-11 summarizes the major observations of the experiments of Mesyats.

RF breakdown has been theoretically and experimentally investigated by Kustom[7] and it was tentatively concluded, over the frequency range 60 Hz to 21.5 MHz, that the breakdown voltage was independent of frequency (Figure 4-12). This indicated a cathode vaporization mechanism for the small gaps of this study.

If the secondary emission coefficient of the electrode surfaces is greater than one, vacuum breakdown may occur due to a process termed "multipacting." If the gap, field strength and frequency of applied voltage are such that an electron emitted from one electrode while it was negative arrives at the other electrode while it is negative, then the secondary electrons emitted will be accelerated across the gap to arrive at the first electrode when it is again negative, producing more secondary electrons. This chain of events is rapidly repeated leading to a great increase in the electron current until breakdown occurs.

4.7 Environmental Effects in Vacuum Breakdown

The vacuum environment is important primarily in relation to its effect on electrode surfaces. Thus, residual gases at pressures less than 10^{-5} torr appear to have no effect on vacuum breakdown, but there is evidence that even very slight traces of organic contamination on the electrode surfaces are detrimental. For this reason the use of contamination-free vacuum systems is recommended. All particles of dust should be excluded. The deliberate introduction of gas for use as a conditioning process is discussed in Section 4.8.

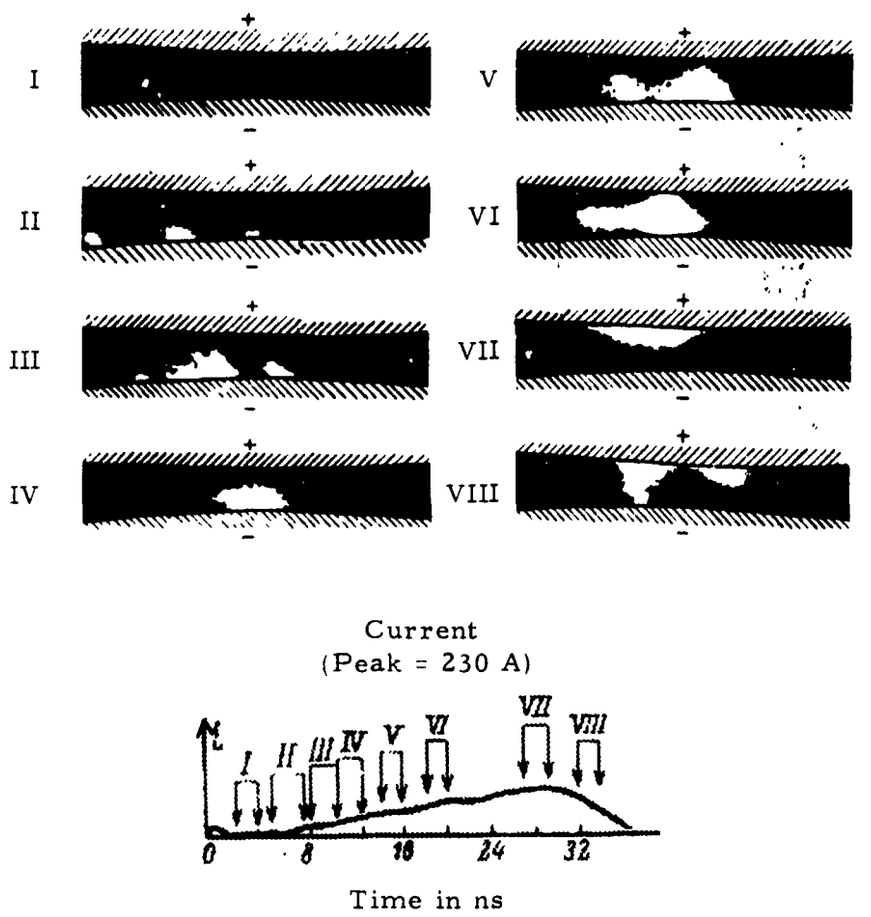

Figure 4-11. Development of Gap Luminosity in Nanosecond Breakdown of Vacuum Gaps[6]

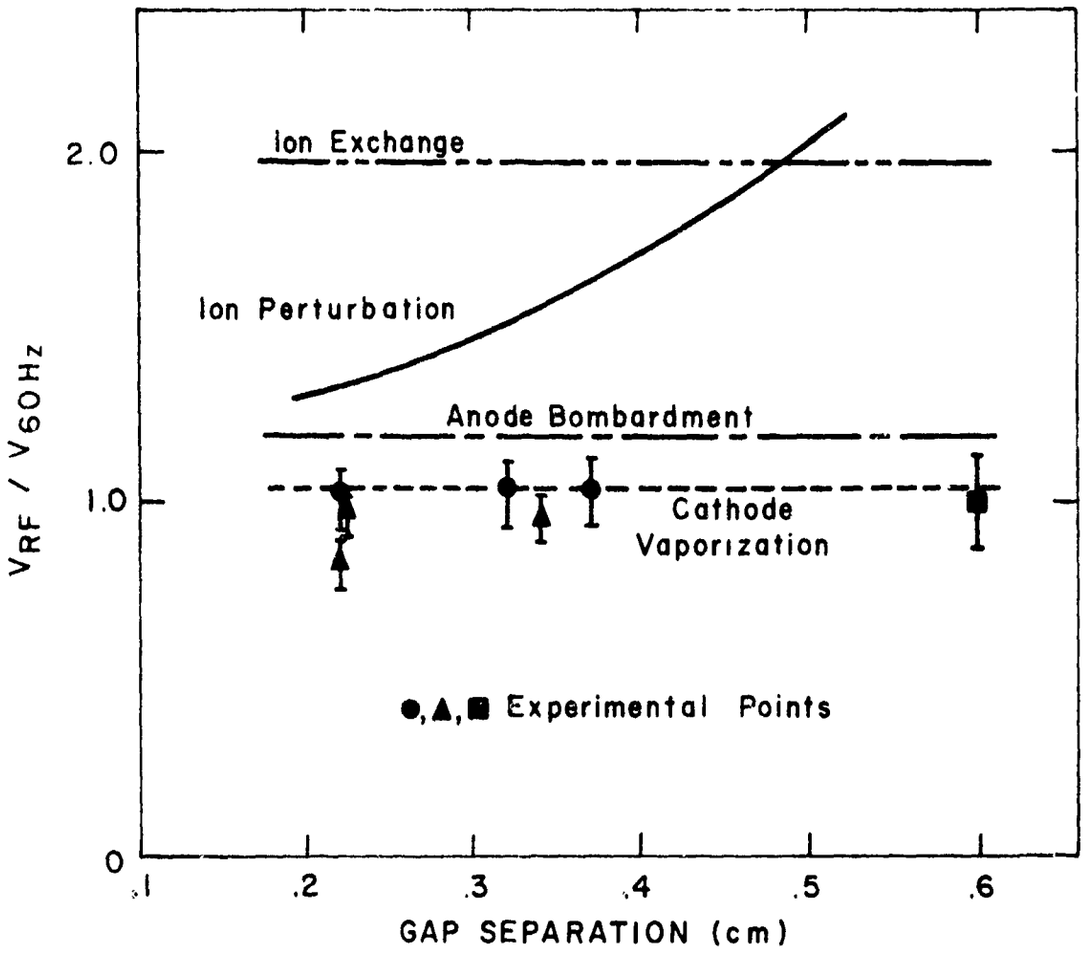

Figure4-12. Comparison of Vacuum Breakdown at 21.5 MHz to 60 Hz for Tungsten Electrodes; Theoretical Curves included[7]

1-4259

Magnetic field is another environmental factor. In the experimental study weak magnetic fields (to 500 gauss), transverse to the electric field, had the effect of slightly lowering breakdown voltage for gaps greater than 1.0 cm, and raising the breakdown voltage slightly for smaller gaps. In a study by Pivovar[8] at lower voltages, a strong magnetic field was applied which prevented field emitted electrons from reaching the anode. This raised the breakdown voltage, but did not appreciably change the voltage at which microdischarges (see Section 3.1) occurred. Thus, there is evidence that magnetic fields will affect the breakdown voltage of vacuum gaps, but the effects were not strong. When a dielectric surface is present in the high field regions of the vacuum system, the effects of a magnetic field are much more severe. This will be discussed in Section 5.

The environment of a vacuum gap in an electron tube may contain sources of contamination. For example, the glass walls of a typical tube may produce small dielectric particles which can induce discharges if they migrate to the highly stressed electrodes. In many tubes a barium oxide thermionic cathode is used. High voltage vacuum tubes with a barium oxide thermionic cathode are usually limited to lower electric stresses than tubes without such a cathode.[9] This lower operating stress is most probably due to the reduction in work function of metal surfaces when barium and/or barium oxide is deposited, which, in turn, leads to higher field emission currents and lower breakdown voltages. Thus, contamination from a barium oxide cathode is an important factor in high voltage vacuum tube performance.

Brodie[10] found that barium contamination of nickel electrodes reduced the breakdown field, and increased field emission currents by several orders of magnitude. Conditioning, by low energy discharges at a 0.5 mm gap, restored the breakdown field to its original level, but the emission current was then greater by a factor of over 15. These effects were conclusively related to the deposition of barium on the tips of whiskers, in an experiment with a cylindrical projection tube. Barium decreased the work function of the emitting tips and, thus, increased field emission currents. Conditioning, then, destroyed the emitting sites which had been rendered unstable by increased

emission. This explanation is supported by considerable experimental evidence that vacuum breakdown, at a small gap (0.5 mm), is usually due to the explosive vaporization of field emitting protrusions on the cathode when the current density exceeds a certain critical value.

In the experimental study electrodes of copper, nickel, stainless steel and Ti-7 Al-4 Mo were tested at high voltages. It was found that the effect of barium contamination of the anode had a negligible effect, but was more serious for the cathode. Differences among the metals tested were slight.

Initially, for copper electrodes there was only a slight change in breakdown voltage upon exposure. Sixteen hours of exposure to the barium oxide cathode run at a high temperature resulted in a progressive decline in breakdown voltage as conditioning proceeded. Prebreakdown currents were erratic and breakdown usually occurred at less than 10^{-6} A. Rapid sparking (several discharges per second) proved very effective in reconditioning the gap. After 13 exposures to various levels of barium contamination, each followed by conditioning, the 10 cm diameter OFHC copper electrode had a breakdown voltage of 225 kV for the 0.75 cm gap, with 10^{-6} A of prebreakdown current at 205 kV. This is as good as is found with uncontaminated electrodes.

When stainless steel (304) and nickel electrodes were subjected to high energy discharge conditioning (0.15 μF of capacitive energy storage with 25 ohms series resistance), the breakdown voltage initially dropped but later recovered to higher values (~ 300 kV for a 0.75 cm gap) than before high energy discharges. However, when contaminated from the barium oxide cathode, these electrodes were severely and permanently degraded by high energy discharges. This was due to the poor adhesion of impacted anode particles on the contaminated cathode. The anode material transferred by breakdown did not remain flat on the cathode but was pulled away by the electric field to form large (~ 1 mm) and sharp projections, as shown in Figure 4-13.

Barium contamination is potentially a serious problem in vacuum insulation. Proper conditioning can alleviate its bad effects in most cases, but when high energy discharges occur, barium contamination (and other types of contamination as well) may lead to permanent damage due to poor adhesion of

(a) General View of Broken and Pulled Away Coating of Anode Material on Cathode (~ 5X)

(b) Detail of the Edges of Fractured Coating (~ 10X)

Figure 4-13. Damage on Nickel Cathode due to Fracture of Coating of Anode Material (Nickel) - Lack of Adhesion is due to Barium Contamination

2-1426

particles transferred by breakdown from the anode to the cathode.

4.8 Dielectric Coating of Electrode Surfaces

Thin dielectric films on the cathode surface, if properly applied, can substantially enhance the insulation performance of a vacuum gap. A typical comparison from an extensive study by Jedynak[11] is given in Figure 4-14. The coating is effective in decreasing field emission currents and increasing the breakdown voltage. A good coating can withstand sparks, and indeed, benefits from spark conditioning. The use of anodized aluminum cathodes in large electrostatic particle separators has been highly developed at CERN by Rohrbach and Germain[12] - the effective field strength attainable in the gap was increased by a factor of two. Comparative results gathered from a number of investigations[13] are given in Figure 4-15. Included are results obtained with metal oxides and fluorides, SiO_2, organic films, and epoxies. In almost all cases, electrode systems with dielectric coated cathodes perform better. The dielectric coating acts to inhibit field emission from the cathode; this, in turn, raises the breakdown voltage. An anode coating is usually detrimental.

4.9 The "Pressure Effect" in Vacuum Insulation

The residual gas pressure and species has no effect at pressures below 10^{-5} torr. However, at pressures just below the glow discharge threshold, there occurs an unexpected peak in the vacuum insulation strength. Figure 4-16, due to Cooke[14], gives this effect for a range of gaps. The breakdown voltage increases by a factor of from 1.5 to 7 as the pressure approaches 10^{-2} torr. In addition to an improvement in breakdown voltage, the prebreakdown conduction current is usually decreased by several orders of magnitude. This "pressure effect" can be explained by assuming that residual gas in the gap is ionized locally by electrons in the high electric fields near emitting cathode points. The ionized molecules bombard and sputter the point, blunting it, and leading to decreased emission and higher breakdown voltages.

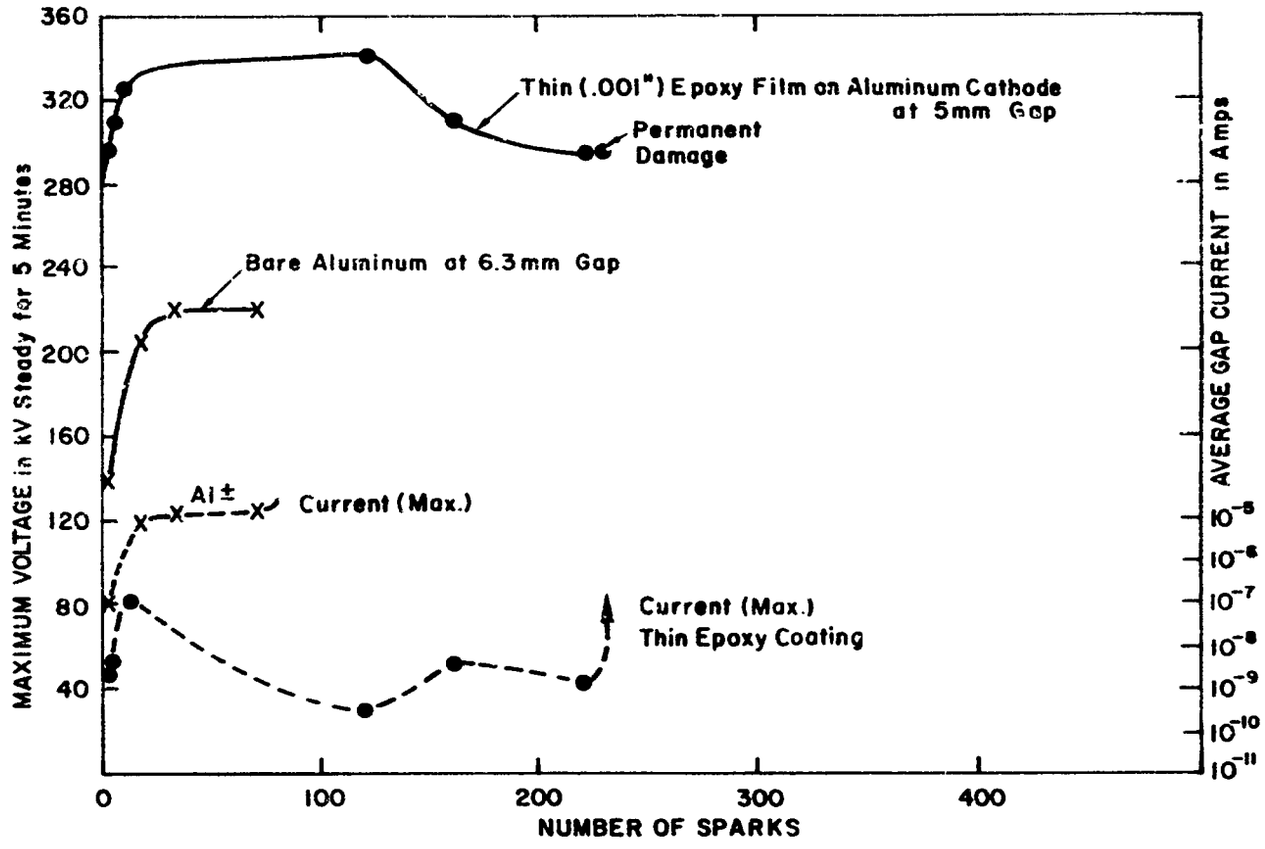

Figure 4-14. Improvement in Breakdown Voltage and Prebreakdown Current Levels with Thin Epoxy Film on Cathode[11]

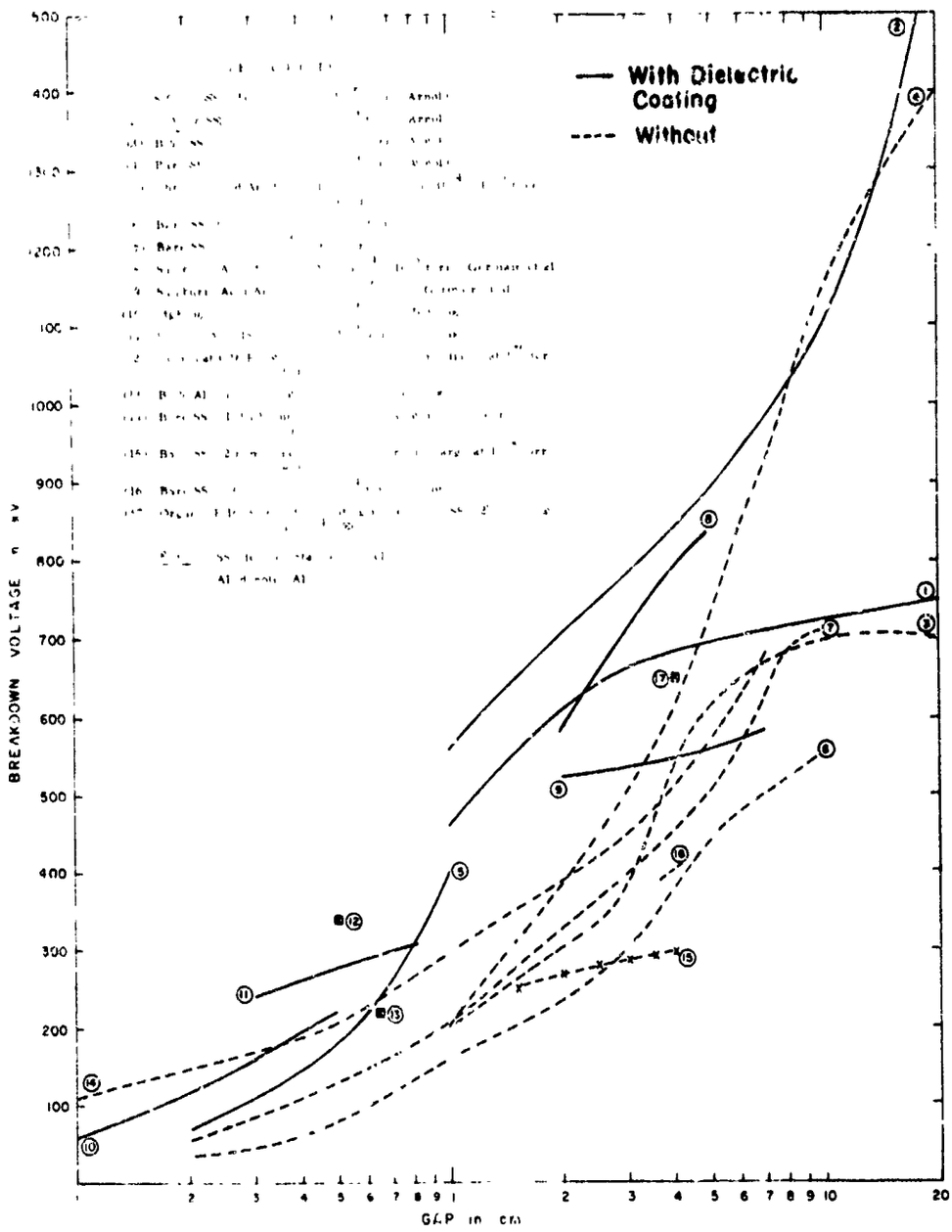

Figure 4-15. Comparisons of Breakdown Voltage vs Gap for Electrode Systems With and Without Dielectric Coated Cathodes[13]

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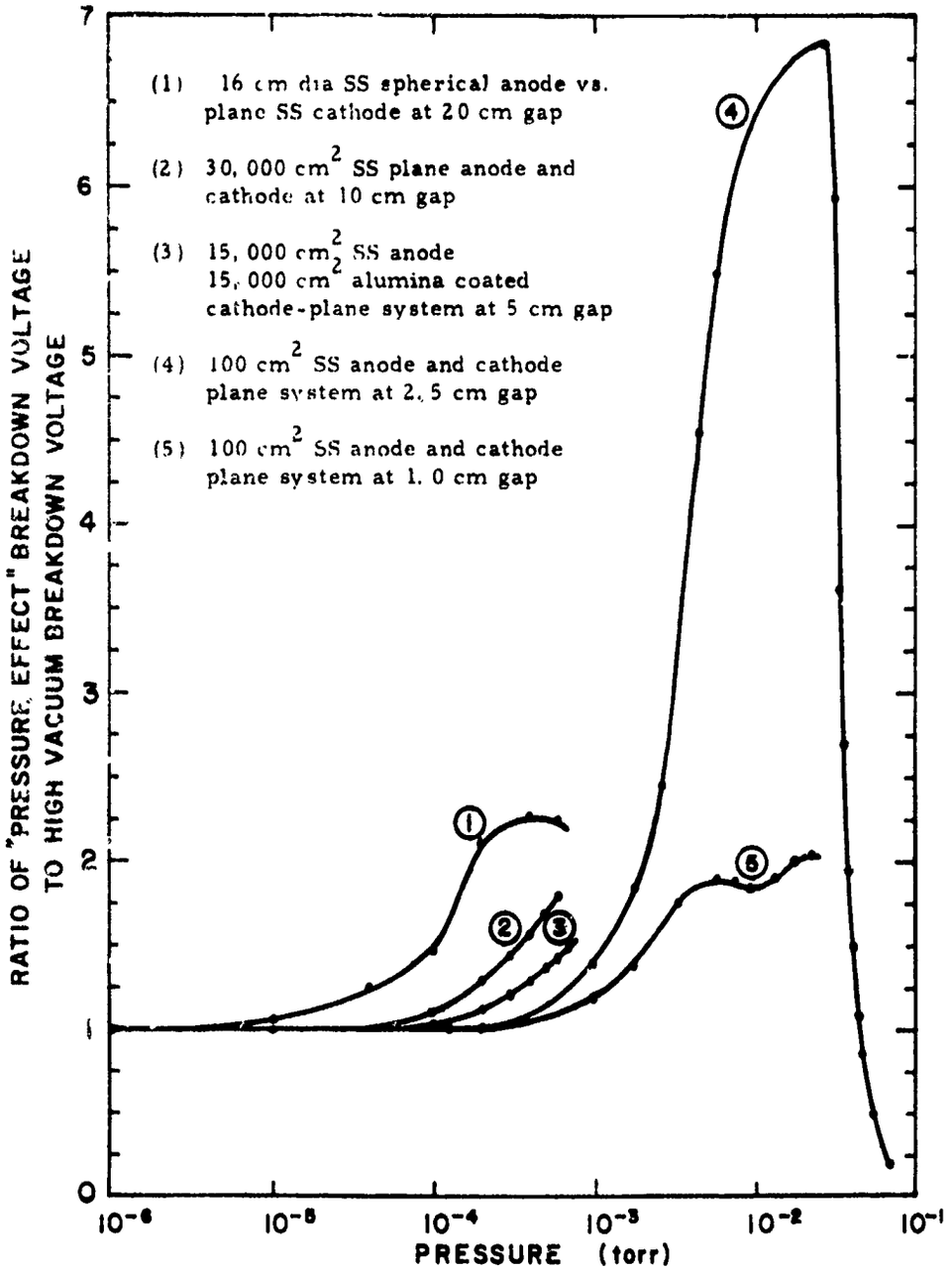

Figure 4-16. Pressure Effect for Various Electrode Systems[14]

1-4256

Recently, Ettinger and Lyman[15] have demonstrated a "gas conditioning" procedure which can be used to reduce prebreakdown current and raise breakdown voltage. In this technique, an inert gas is introduced and prebreakdown currents of 50 μA drawn for many hours, with the voltage being slowly raised. The result is a cathode surface that is more stable, and with less emission than would be the case for electrodes conditioned by sparking. Again, the mechanism is thought to be selective sputtering of cathode protrusions. This is similar to conditioning by prebreakdown current used in the experimental study and discussed in Section 4.3.

4.10 Electrode Temperature

The effect of heating the anode or cathode electrode has been investigated by Slivkov[16] with pulsed voltages (1.5/50 μsec wave). There was no appreciable affect up to ~ 400°C. Above this temperature anode heating reduced breakdown voltage while cathode heating increased the breakdown voltage. Improvement in breakdown voltage was less than 20% in general, and reduction of breakdown voltage at temperatures up to 800°C was not more than 40%.

The prebreakdown field emission currents from the cathode can deliver considerable energy to the anode, raising it to high temperatures if it is not well cooled and the currents are high. For example, in the experimental study currents of 2 mA at 200 kV were not uncommon. The power input to the anode was thus 400 watts, and under these conditions the anode was heated to the point of glowing. Even so, the breakdown voltage did not decrease by over 40%. However, in a practical application it would be desireable to insure that anode cooling is adequate.

Cooling of electrodes to cyrogenic temperatures has been found[17, 18] to decrease prebreakdown currents and increase breakdown voltage. However, these results were preliminary, and further investigation is necessary before general substantiation of this method of improving the dielectric performance of vacuum gaps.

4.11 Conclusions Regarding Factors in Vacuum Insulation

After many decades of investigation and use, the factors and mechanisms important in vacuum insulation are now generally recognized and partially understood. With continued growth in the number and scope of the applications of vacuum insulation, it can be expected that, in the near future, a more complete theory of vacuum breakdown will emerge.

Already, the application of dielectric coatings to cathode surfaces and use of the optimum pressure for vacuum insulation has enabled substantially improved performance to be achieved where these techniques are possible.

The crucial role of conditioning as a means of producing stable electrode surfaces is now receiving critical attention. Many of the new metals developed for other uses have proved to be excellent for vacuum insulation. Progress along these lines can be expected to continue, and enable stress levels of hundreds of kV/cm to be routinely and reliably achieved with vacuum insulation. Table 4-2 summarizes the more important factors that have been considered in this handbook.

4.12 References

(1) Trump, J. G. and Van de Graaff, R. J., J. Appl. Phys. Vol. 18, No. 3, 327-332 (March 1947).

(2) McCoy, F. J., Electrostatic Generator Quarterly Reports, Contract No. AF33(615)-1168, Ion Physics Corporation, Burlington, Mass. (1964).

(3) Rabinowitz, M., Proceedings of the First International Symposium on Insulation of High Voltages in Vacuum, p. 119, Boston (October 1964).

(4) Smith, W. A., Mason, T. R. and Childs, T. L. K., Proceedings of The Third International Symposium on Discharges and Electrical Insulation in Vacuum, p. 203, Paris (September 1968).

Table 4-2. Factors and Effects in Vacuum Insulation

FACTOR	EFFECT ON BREAK-DOWN VOLTAGE	INTERACTS WITH:	RECOMMENDATIONS
ANODE MATERIAL	Refractory metals have higher B.D.V.'s than non-refractory metals.	Conditioning, Discharge Energy, Gas Content	Use refractory metals: especially when high energy discharges are to be endured.
CATHODE MATERIAL	Cu better than Al. No significant difference between Ni, Ti, SS.	Gas Content, Anode Material - with many moderate or high energy discharges the cathode becomes covered with a layer of anode material.	Some improvement can be obtained with high strength cathode materials.
CONDITIONING	Increases B.D.V. by more than a factor of 2 in most cases.	Discharge Energy, Anode Material	Conditioning technique is very important. If high energy discharges are possible, conditioning should use high energy, discharges and a good anode material.
GAP	B.D.V. is proportional to: Gap below .75 cm, to $\sqrt{\text{Gap}}$ above .75 cm	Gas Content, Geometry	When appropriate break a large gap into a series of small gaps.
GEOMETRY OF ELECTRODES	Spherical or curved surface better than flat surfaces. Small areas better than large areas.	Gas Content, Polarity	Use geometries which minimize highly stressed area, even if this increases the maximum electric field.

Table 4-2. Continued.

FACTOR	EFFECT ON BREAK-DOWN VOLTAGE	INTERACTS WITH:	RECOMMENDATIONS
SURFACE FINISH	Not significant if surface is reasonably smooth and clean.	Contamination.	Do not expend effort beyond that which produces a clean and reasonably smooth surface.
GAS CONTAMINATION	Pure gases have a negligible effect, but gases with dust and organic contamination reduce the B.D.V.	Degree of Conditioning; exposure seldom reduces B.D.V. to below unconditioned level.	Avoid exposure to contaminated gases.
BARIUM CONTAMINATION	Temporary reduction in B.D.V. that can be conditioned away.	Cathode (lowered B.D.V. only when on Cathode), Conditioning, High Energy Discharge.	Proper conditioning techniques can minimize degrading effects.
MAGNETIC FIELD	Lowers B.D.V. for gaps <.75 cm - raises B.D.V. for gaps >.75 cm.	Gap	Avoid magnetic field in highly stressed regions.
PROCESSING BAKEOUT (GAS CONTENT)	Bakeout increases B.D.V. and improves consistency.	Electrode Material and Geometry	Hydrogen or vacuum firing of electrodes can be beneficial. Complete system bakeout is useful.
TIME	The longer the period of application of stress the more likely a low breakdown voltage.	Conditioning, Contamination	Minimize time at highest stress but do not leave without stress or deconditioning may occur.

Table 4-2. Concluded.

FACTOR	EFFECT ON BREAK-DOWN VOLTAGE	INTERACTS WITH	RECOMMENDATIONS
PREBREAKDOWN CURRENT	High prebreakdown currents can heat anode and lead to breakdown.	Gap, Magnetic Field, Conditioning, Electrode Material	When possible, condition to produce low prebreakdown currents.
DIELECTRIC COATINGS	Cathode coatings can raise B. D. V. significantly.	Polarity - Anode coating usually detrimental; conditioning	Apply a thin dielectric film to the cathode when possible.
PRESSURE	As the glow discharge pressure range is approached the B. D. V. goes through a maximum.	Geometry; Conditioning	When possible, use "high" pressure operation or conditioning.
ELECTRODE TEMPERATURE	Heated cathodes may raise B. D. V.; heated anodes lower B. D. V.; cryogenic cooling may raise B. D. V.	Polarity; Contamination	More investigation of this factor is required.

(5) Wolff, H., Juttner, B. and Rohrback, W., Proceedings of the Third International Symposium on Discharges and Electrical Insulation in Vacuum, p. 209, Paris (September 1968).

(6) Mesyats, G. A., Bugaev, S. P., Iskolsdskii, A. M. and Proskurovskii, D. I., Soviet Physics, Tech. Phys., Vol. 12 (June 1968) (English Translation).

(7) Kustom, R. L., Proceedings of the Third International Symposium on Discharges and Electrical Insulation in Vacuum, p. 223, Paris (September 1968) and "The Electrical Breakdown of Vacuum Insulated Electrodes Under Radio Frequency Stress," Proceedings of the 1969 Particle Accelerator Conference, p. 556, Washington, D. C.

(8) Pivavar, L. I., et al, Sov. Phys., Tech. Phys., 2, 909 (1957).

(9) Doolittle, H. D., Machlett Cathode Press, 21, No. 1, pp. 2-15 (1964).

(10) Brodie, I. J., Vacuum Science Technology, 2, p. 249 (1965).

(11) Jedynak, L., J. Appl. Phys. Vol. 35, No. 6, 1727-1733 (June 1964).

(12) Germain, C., Jeannevot, L., Rohrback, F., Simon, D. and Tingnely, R., Proceedings of the Second International Symposium on Insulation of High Voltages in Vacuum, p. 279, Boston (October 1969).

(13) Bolin, P. C. and Trump, J. G., Proceedings of the Third International Symposium on Discharges and Electrical Insulation in Vacuum, p. 50, Paris (September 1968).

(14) Cooke, C. M., Proceedings of the Second International Symposium on Insulation of High Voltages in Vacuum, p. 181, Boston (September 1966).

(15) Ettinger, S. Y. and Lyman, E. M., Proceedings of the Third International Symposium on Discharges and Electrical Insulation in Vacuum, p. 128, Paris (September 1968).

(16) Slivkov, In. N., Sov. Phys., Tech. Phys. 4, p. 1359 (1959).

(17) Looms, J. S. T., Meats, R. J. and Swift, D. A., Brit. J. Appl. Phys. (J. Phys. D), Vol. 1, Ser. 2 (1968).

(18) De Geeter, D. J., AEC-NASA Tech. Brief #66-10499 (November 1966).

5. SOLID DIELECTRICS IN VACUUM INSULATION

5.1 Introduction

Solid dielectrics are almost invariably required in vacuum insulation systems to support electrodes, or to lead high voltages into the vacuum from some other insulating medium. In some cases, the vacuum chamber itself is of a dielectric material. Since the vacuum flashover voltage of a solid dielectric is much lower than either its volume puncture strength or the breakdown voltage of an equivalent vacuum gap, the details of solid insulator design and placement are critical factors in practical systems.

5.2 Grading and Mechanisms of Flashover

Grading techniques often break the insulating length into short, independent and uniformly stressed sections. Thus, the flashover characteristics of solid dielectrics have been extensively studied only for samples of the order of 1 to 3 cm long. These are usually placed between uniform field electrodes. It has been found that the surface discharge originates from the negative junction of metal, solid dielectric and vacuum. At this "triple point," field enhancement (due to imperfect metal-dielectric contact and the different dielectric constants of a solid dielectric and vacuum), leads to electron emission; this, in turn, charges in a non-uniform way, the surface of the solid dielectric; charge multiplication along the surface may occur; gas may be evolved and ionized; finally flashover results.

5.3 Techniques for Increasing Flashover Voltage

Intimate contact between the solid dielectric and the metal electrodes and proper shaping of the negative junction can raise the flashover voltage of a given material. The usual techniques rely on either shielding of the negative triple point to reduce field stress, or on shaping of the insulator to minimize the deleterious effects of electron emission from the negative triple point. Figures 5-1 and 5-2 show various shielding methods investigated by Finke[1] and Shannon, et al[2]. Certain of Shannon's insulator shapes are designed so

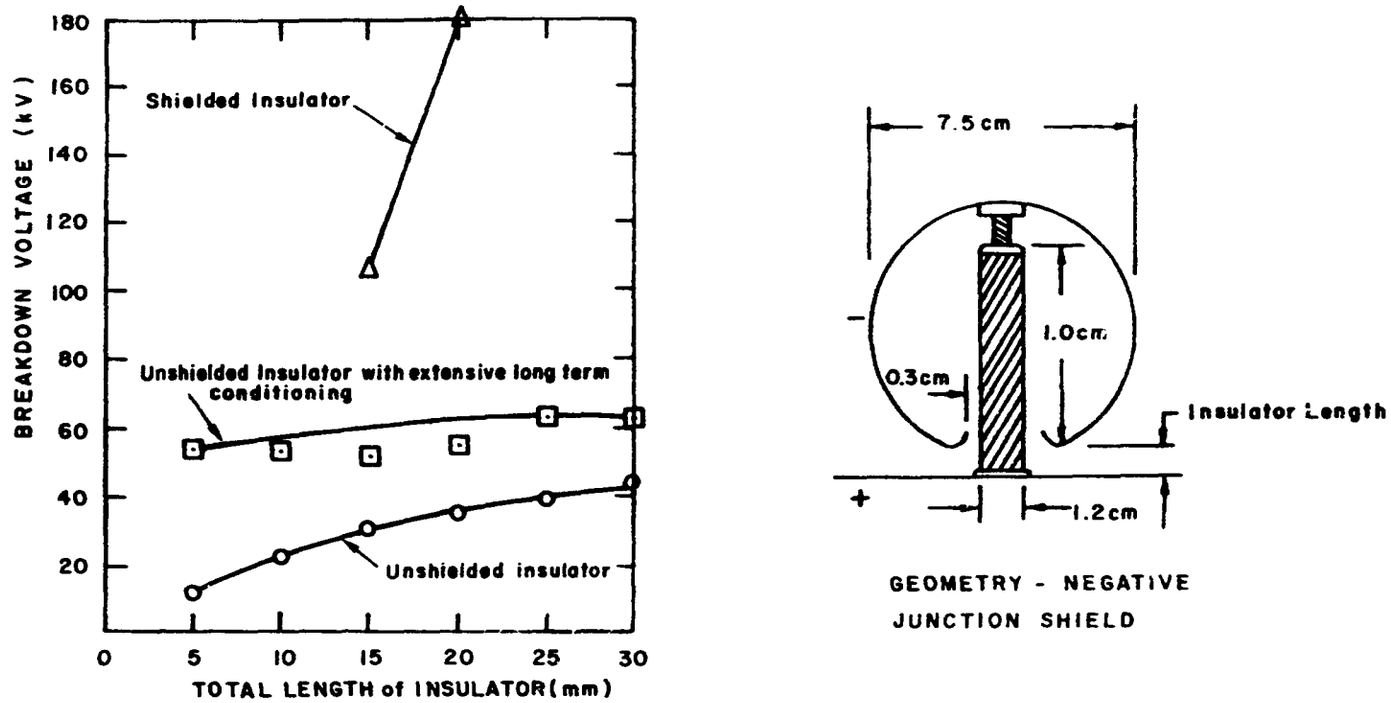

Figure 5-1. Effect of Shielding Negative Junction with Re-Entrant Sphere Flashover Voltage of Standoff Insulation (from Finke[1]).

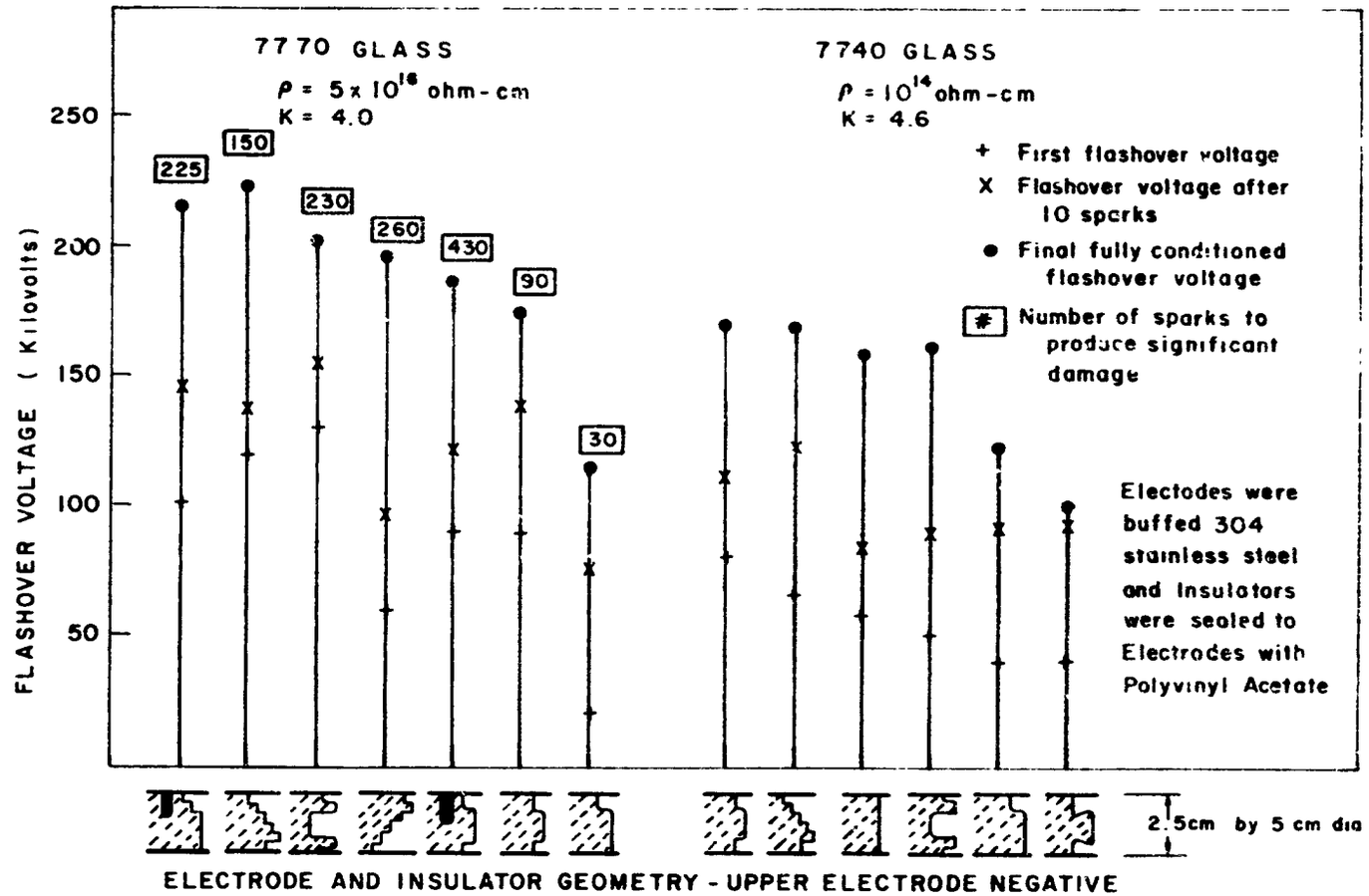

Figure 5-2. dc Flashover of Glass Insulators of Various Shapes (from Shannon, et al[2]).

that the initial emission from the negative junction charges the insulator in such a way that the electric stress on the junction is reduced. Figure 5-3 from Watson[3] shows the effect of removing the insulator surface from interaction with emitted electrons. In this case, for 30 ns pulses, the improvement in flashover voltage is as much as a factor of 4.5.

Other factors which strongly influence the flashover voltage are solid dielectric material, residual gas pressure, voltage pulse length and conditioning. Representative flashover stress levels for various levels and combinations of these factors are given in Table 5-1. The effects of material and voltage pulse length are very evident - - dc stress levels for good materials were limited to about 90 kV/cm, while for short pulses (< 100 ns) the stress level can go as high as 260 kV/cm. In the experimental study it was found that a weak (~ 250 gauss) magnetic field parallel to solid dielectric surfaces led to flashover at very low stresses.

At the very high voltages (millions of volts) used in dc nuclear particle accelerators it has been found necessary to, not only break the total insulation length into many short sections, but also to insure that charged particles which may be in the gap, do not gain too high an energy before colliding with an electrode or insulator surface. The use of small and tapered holes between sections is useful and an "inclined field" principle originated by Van de Graaff, et al[8] can be applied.

5.4 References

(1) Finke, R. C., Proceedings of the Second International Symposium on Insulation of High Voltages in Vacuum, MIT, Boston, p. 217 (September 1966).

(2) Shannon, J. P., Philp, S. F. and Trump, J. G., Journal of Vacuum Science and Technology, Vol. 2, No. 5, p. 234 (September-October 1965).

(3) Watson, A., J. Appl. Phys. 28, 2019-2023 (1967).

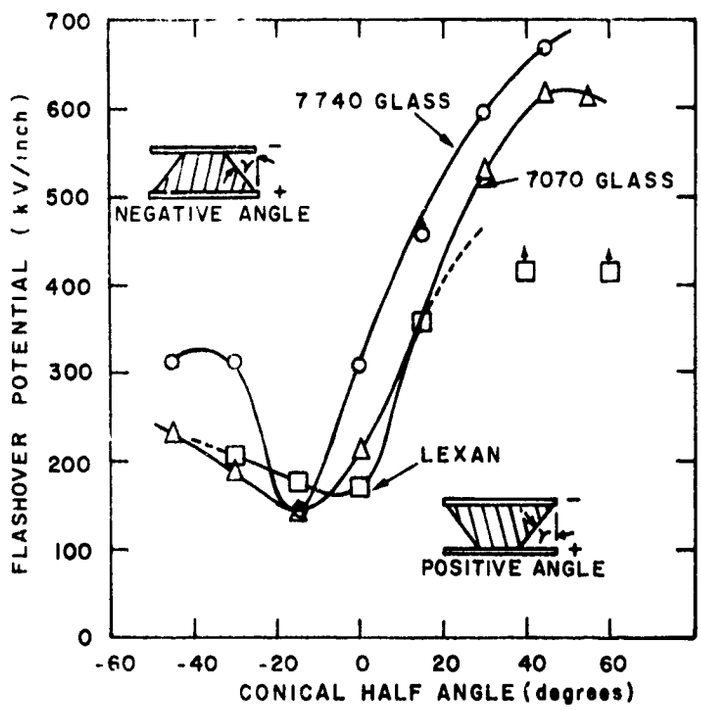

Figure 5-3. Effect of Insulator Geometry on Fast Pulse (30 ns) Vacuum Flashover of Glass and Lexan (from Watson[3]).

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Table 5-1. Representative Flashover Gradients for Laboratory Samples.

Type of Voltage	Material	Flashover Gradient (kV/cm)	Length of Sample (cm)	Diameter of Sample (cm)	Details of Design (Negative Junction, Pressure)	Reference
dc	Pyrex 7770	88	2.5	5.0	Internal Negative Junction Shield	2
dc	Pyrex 7770	48	2.5	5.0	Step in Insulation at Negative Side	2
dc	Pyrex 7740	40	2.5	5.0	Step in Insulation at Negative Side	2
dc	Porcelain	30	1.9	3.8	10^{-4} torr	4
dc	Alumina	90	1.9	3.8	10^{-4} torr	4
dc	Soda Glass	18	2.25	1.25	Ends not Recessed	5
40 μs	Steatite	42	1.17	5.5	10^{-4} torr, Ends not Recessed	6
40 μs	Zircon	34	1.17	5.5	10^{-4} torr, Ends not Recessed	6
800 ns	Polyethylene	140	0.95	2.54	45-Degree Angle at Negative Junction	7
800 ns	Perspex	120	0.95	2.54	45-Degree Angle at Negative Junction	7
30 ns	Pyrex 7740	260	0.95	2.54	45-Degree Angle at Negative Junction	3
30 ns	Epoxy	163	0.95	2.54	45-Degree Angle at Negative Junction	3
30 ns	Lexan	>163	0.95	2.54	45-Degree Angle at Negative Junction	3

(4) Srivastava, K. D., Proceedings of the Eighth Electrical Insulation Conference, 68C6-EI-28, p. 14-20, Los Angeles, California (December 1968).

(5) Gleichauf, P. H., Jr., J. Appl. Phys. 22, pp 535-541 and 766-771 (May-June 1951).

(6) Kofoid, M. J., Trans. AIEE, USA, Part III, 79, pp 991-1004 (1960).

(7) Smith, I. D., Proceedings of the First International Symposium on Insulation of High Voltages in Vacuum, p. 261, MIT, Boston (October 1964).

(8) Van de Graaff, R. J., Rose, P. H., and Wittkower, A. B., Nature 195, 1292 (1962).