# Vacuum Arcs

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***Abstract*— Vacuum arcs and their applications are discussed. A brief history of vacuum arcs is presented. Cathode phenomena, column phenomena, and anode phenomena in vacuum arcs are summarized. Applications of vacuum arcs-especially vacuum interrupters (vacuum circuit breakers (VCB), vacuum switches) and vacuum arc generated coatings are given. Those readers desiring further information on specific topics are referred to several excellent books.**

***Index Terms*— Anode phenomena, cathode phenomena, coatings, column phenomena, vacuum arcs, vacuum interrupters.**

## I. Introduction

THE term "Vacuum Arc" is an oxymoron or contradiction in terms! Vacuum designates a volume with a pressure lower than its surroundings. It can be low or moderate, as in a suction cup attach to a smooth surface. It can be an ultrahigh vacuum, containing surfaces which must remain clean for hours or days. An arc implies the presence of current carriers (electrons, ions, charged particles), which would adversely affect a vacuum. The actuality is that the term "vacuum arc" by convention means an arc between electrodes in a vacuum ambient where the conducting particles are supplied by the electrodes–primarily the cathode for lower current arcs, with a significant contribution from the anode for higher current arcs.

Arcs (lightning) occur in nature, but man-made arcs only began in the 1700s, when apparatus capable of producing the currents required for arcing was invented and Anders gives an excellent review of the history of arcs [1, pp. 7–63]. Arcs can occur in gases, liquids, and solids, though in the latter cases, they transform the liquid or solid into vapor. Vacuum arcs are characterized by a positive voltage-current characteristic, that is, for a vacuum arc an increase in arc current is accompanied by an increase in arc voltage, as seen in Fig. 1.

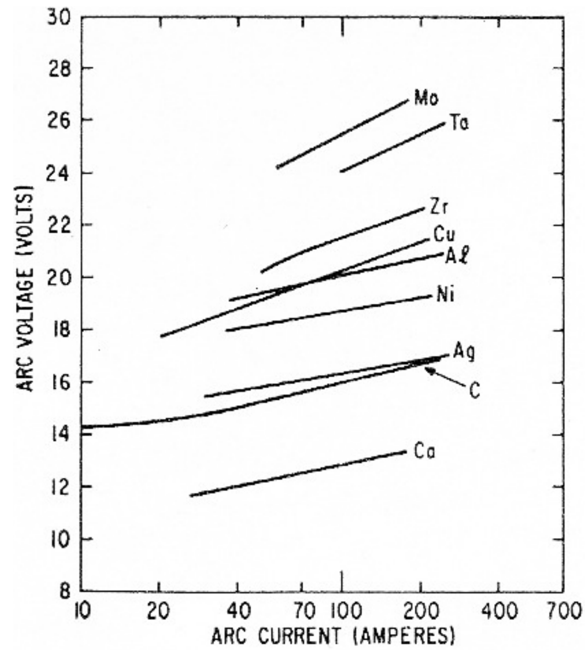


Fig. 1. Vacuum arc characteristics.

Vacuum arcs required the development of apparatus capable of pumping volumes to pressures sufficiently low that arcs could not occur in the gaseous ambient. The first published paper which describes a vacuum arc is that of Wood [2].

Excellent discussions of the work on vacuum arcs beginning in the 1920 s which ultimately led to the first successful vacuum circuit breakers (VCBs) (vacuum interrupters) are given by Lafferty [3, pp. viii–xiii] and Slade [4, pp. xix–xviii]. In summary, in the early 1920s, Millikan at Cal Tech observed that a vacuum gap could sustain a high voltage, which lead to the invention of the vacuum switch. General Electric continued this work, finally developing commercial vacuum switches using tungsten electrodes. At this time (the 1930s), only tungsten could be made sufficiently gas free. Strong glass-metal seals and sealed-off bottles (to enclose the electrodes), which could maintain a good vacuum for years, were also not available but development continued. The invention of FERNICO[1] allowed the construction of strong vacuum bottles; improved materials meant the bottles could maintain good vacuum for years, and zone-refining produced electrodes with sufficiently low gas content. Thus, by the late 1950s, commercial VCBs became available.

In the 1950s, Dyke and coworkers began investigating electrical discharges in clean ultrahigh vacuums. In the 1970s, Jüttner and coworkers investigated nanosecond discharges with high spatial resolution. Such techniques allowed basic data to be obtained about details of vacuum arcs, especially cathode spots.

More vacuum arc history will appear in appropriate sections, Vacuum arcs normally start in one of three ways.

1) Electrodes are separated while a current is passing through them.
2) An arc is triggered by an external third electrode or laser.
3) A high enough voltage is applied to the vacuum gap to initiate vacuum breakdown.

Manuscript received 7 October 2022; revised 30 December 2022; accepted 9 January 2023. Date of publication 10 July 2023; date of current version 22 August 2023. The review of this article was arranged by Senior Editor M. T. Domonkos.

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPS.2023.3261779.

Digital Object Identifier 10.1109/TPS.2023.3261779

[1]Trademarked.

TABLE I
CATHODE SPOT TYPES

| Name | MFS | GS | GSHC | GSI |
|---|---|---|---|---|
| | Moderate fast spot (Type 2) | Group Spot | High Current-Group Spot | Intense Arc Group Spot |
| Motion | Fast | Slow | Slow | Very Slow |
| Velocity (m/s) | 10 | ≤ 0.1 | ≤ 0.1 | ~0 |
| Current (A) | < 300* | >300* | >1000* | >1000 |
| Existence Time (µs) | < 10 | 100-1000 | >100 | > 1000 |
| *Depends on cathode material – see Table 2 | | | | |

TABLE II
SPOT SPLITTING CURRENTS (AVERAGE) FROM [5, TABLE3, PP. 92]

| Cathode Material | Spot Current (A) |
|---|---|
| Mercury | 0.6 |
| Cadmium | 12 |
| Zinc | 15 |
| Bismuth | 4 |
| Lead | 7 |
| Indium | 16 |
| Silver | 80 |
| Aluminum | 40 |
| Copper | 85 |
| Chromium | 40 |
| Iron | 80 |
| Titanium | 70 |
| Carbon | 300 |
| Molybdenum | 150 |
| Tungsten | 270 |

VCBs typically use the first method. For 2, the third electrode is usually near the cathode, often within it but electrically isolated by an insulator. In this case, an external triggering circuit is used to start the arc. Initiation of a vacuum arc by high voltage is usually undesirable, resulting from a failure of vacuum insulation. Vacuum arc initiation, including some uncommon ways, has been extensively discussed by Anders [1, pp. 250–255], Boxman et al. [5, pp. 53–59], Beilis [6, pp. 143–149], Mesyats [7, pp. 265–268], and especially Lafferty [3, pp. 81–119].

Papers concerning vacuum arcs have appeared in IEEE TRANSACTIONS ON PLASMA SCIENCE since it began publication in 1972. At present, probably more vacuum arc papers are published in it than in any other journal. The primary conference on vacuum arcs (and vacuum breakdown) is the International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV) which has been held biannually since 1964. Most ISDEIV Conferences have resulted in Special Issues pertaining to Vacuum Arcs.

## II. CATHODE PHENOMENA

### A. Cathode Spots

The arc current flows to the cathode (negative electrode) through small bright spots called cathode spots. Anders defined types 1 and 2 cathode spots. Type 1 spots tend to clean the surface, so with sufficiently long arc durations type 2 spots dominate. Most investigations of cathode spots since 1980 have been on type 2 spots [1, pp. 128–131].

Various investigators have defined additional categories of cathode spots, considering the effects of background gas, magnetic fields, and gap geometry [5, pp. 78], [6, pp. 199–200]. I consider only spots on clean surfaces. My choices of spot types are shown in Table I, which is based on a table by Beilis [6, Table 7.10, pp. 200].

A cathode spot has a maximum current depending on the electrode material, see Table II. At higher currents additional cathode spots form. Because of their positive $V$–$I$ characteristic, cathode spots readily burn in parallel in higher current arcs. Initially, multiple cathode spots tend to burn as individual spots. As more and more cathode spots form, their plasma fluxes tend to merge to produce a group spot. While the group spot velocity appears low, the velocities of the individual cathode spots remain high. But as the number of cathode spots continues to increase, their mutual interaction becomes greater, and a High Current Group Spot forms where the individual. Spots are no longer apparent. The Intense Arc Group Spot is present in the Intense Arc Mode, where strong erosion occurs at the cathode and thermionic emission can become important.

Materials are ordered by increasing boiling point. Thermal conductivity may also be a factor [5, pp. 92].

Cathode spot parameters may be divided into four groups as follows.

1) Quantities accessible without microscopic spatial resolution: arc voltage $V_A$ amplitude and $\Delta V_A$ noise, erosion rate $E_r$, arc lifetime $\tau_l$, emitted light, ejected droplets, and total flux of emitted ions (ion current $I_i$, and charge $Z$). A temporal resolution of $>10$ $\mu$s may be sufficient because the most pronounced fluctuations of these qualities occur with frequencies $<100$ kHz.

2) Quantities measurable with modest special resolution ($\geq 0.1$ mm): spot velocities, plasma density and temperature outside the spot, energy and charge of plasma ions, and number of spot fragments. Time resolution will be as in (1).

3) Quantities requiring spatial resolution $\leq 0.1$ mm without time resolution: crater size, surface melting depth.

4) Quantities requiring spatial resolution $\leq 0.1$ mm and time resolution $<100$ $\mu$s: spot diameter, surface temperature, plasma density and temperature within the spot, spot formation time, spot residence time current density, self-magnetic field, elementary displacement step, and gross erosion rate [5, pp. 74–75].

Cathode spots produce melted craters. They also tend to move as a random walk but can be forced to move in a linear fashion by an external magnetic field, which allows measurements of the melted craters and the subsequent tracks produced by the moving spots, as can be seen in Fig. 2.

Cathode spots contain smaller spots, often called cells [1, pp. 48–49, 126–728] [6, pp. 176–187]. They have finite lifetimes. New cells tend to appear on the edge of the cathode spot, thus determining their directions of motion. The terms spot fragment, cell, and emission center used by various authors are equivalent.

A sketch of a cathode spot is shown in Fig. 3.

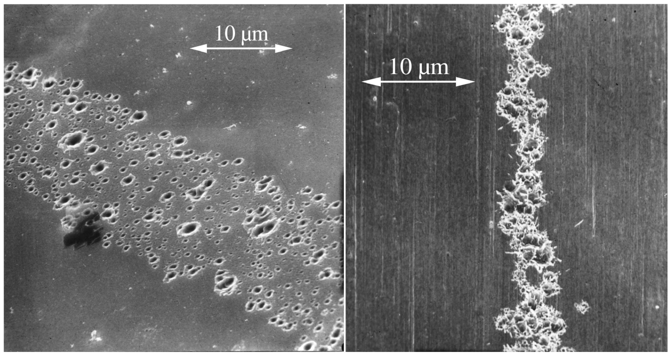


Fig. 2. "Track of erosion craters left by spots of type 1 (left) and type 2 (right): a TMF was applied to "drive" apparent spot motion leaving a rather straight trace. (Photos courtesy of B. Jüttner)" [1, Fig. 3.14, pp. 112].

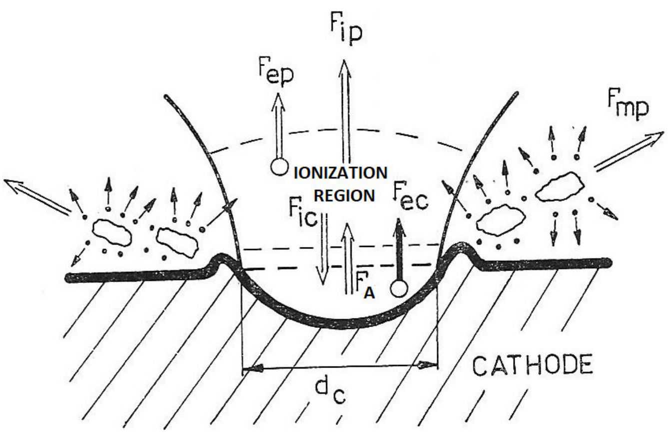


Fig. 3. F are the fluxes, subscripts ip and ep are ion and electron fluxes from the ionization region to the plasma, iC is the ion flux to the cathode, eC is the electron flux from the cathode to the ionization region, A is the atom flux from the cathode to the ionization region, and mp is the flux of macroparticles. Macroparticles are often liquid and emit vapor as they travel.

### B. Cathode Flux

At first current densities in vacuum arcs were thought to be $\sim 10^6$ A/m$^2$. Estimated values increased with the development of more precise time and spatial measurements. Measurements suggested that current densities were higher for short (ns) arcs. Probable current densities for $t > 1$ $\mu$s are $\sim 10^{12}$ A/m$^2$ [5, pp. 47–49] [6, pp. 201–205].

Direct measurements in the 1930s showed that the ion and neutral particle flux from the cathode had a significant velocity $\sim 10^4$ m/s. Atoms from a thermal source would require unrealistic temperatures of $5 \times 10^5$ K, so the flux was probably ions, but no mechanism was known to give the ions the kinetic energies required [8], [9], [10]. Beilis presents more details [6, pp. 320–331].

Work in the 1960s in the Soviet Union [11], [12] and the United States [13] measuring the individual ion masses and potentials firmly established that cathode ions have the kinetic energies required for the observed velocities. More detail is given in [6, pp. 354–360]. An extensive table of charge state distributions is given in [14].

Arc lifetimes strongly depend on arc current [5, pp. 114–118] [6, pp. 166–176], as shown in Fig. 4. This has implications for the performance of vacuum interrupters, as will be discussed later.

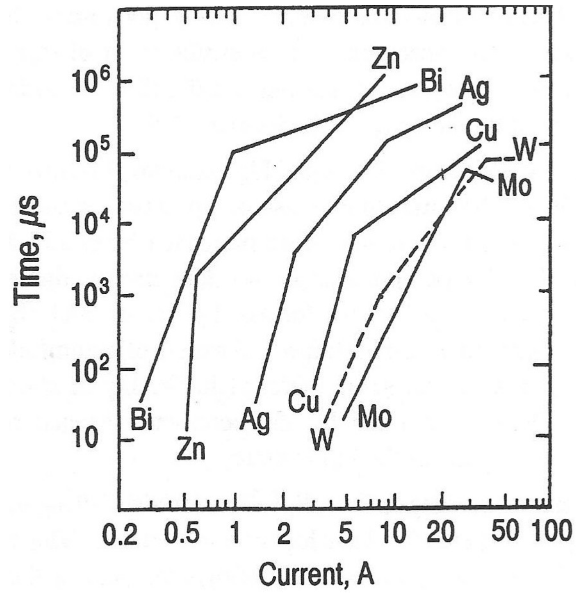


Fig. 4. Mean arc lifetime as a function of current (Farrall) [5, Fig. 25, pp. 116].

### C. Cathode Spot Theory

Prof. Beilis, who has worked on cathode spot theory for over 50 years [15], presented a critical history of cathode spot theories [16] [6], [15, "Cathode Spot Theories, History and Evolution of the Mechanisms," pp. 545–598].

Mesyats explained electrical breakdown in vacuum as being initiated by "ectons," electrical explosions of microprotrusions on the cathode [7, Ch. 7, "The Simplest Models of the Ecton," pp. 112–123]. He used ectons to explain cathode spots [7, Ch. 22, "The Ecton Mechanism of a Vacuum Arc," pp. 368–388]. Mesyats listed the processes occurring during the ignition, death, and reignition of a cathode spot.

1) Onset of explosive electron emission (EEE) and the appearance of an ecton.
2) Appearance of a liquid-metal pool on the cathode.
3) Cathode plasma pressure on the liquid metal in the pool.
4) Appearance of a jet of liquid metal.
5) Cessation of EEE and the completion of the ecton operation.
6) Onset of the ionic phase of the cycle (hot-cathode arc).
7) Explosion of the new jet and the onset of a new cycle.

It should be borne in mind that the above processes are not sequential in time. For instance, processes 1 to 4 occur during the electronic portion of the cycle [7, pp. 371].

Anders also discussed ectons [1, 3.4.7 EEE and Ecton Mode, pp. 109–111]. He states "For fragments of spot type 2, i.e., emission sites on clean metal cathode surfaces, the formation of microprotrusions is not difficult to recognize when investigating the crater traces left by the microexplosions" (see Fig. 2, right). "The microexplosion produces a thin layer of molten cathode material, which yields high plasma pressure. The liquid material is ejected from the explosion crater and is rapidly quenched, producing microprotrusions, which can serve as new ignition points. One of them will be most suited to go through thermal runaway, leading to the next microexplosion. According to this picture, the location of the next explosion is displaced by about one crater radius from the location of its predecessor. It is common for this spot type that long chains of craters are formed" (see Fig. 2, right) [1, pp. 112].

Anders showed that treating cathode spots as fractal (self-similar at any scale) can be quite useful [1, 3.5 Fractal Spot Model, pp. 112–146], [17]. Stating "The simple question 'What is a cathode spot?' does not have a simple answer but the definition 'A cathode spot is an assembly of emission centers showing fractal properties in spatial and temporal dimensions' captures the essential elements. Each ignition event and resulting emission center may be described as an elementary step, corresponding to a sequence of emission stages, which includes the explosive or 'ecton' stage in the Mesyats framework. The assembly of fragments exhibits fractal properties, and the individual steps are the small-scale, short-time cutoffs of spatial and temporal self-similarity" [1, pp. 128].

Beilis presented a mathematically closed cathode spot theory [6, Ch. 16, Gas Dynamic Theory of Cathode Spot Mathematically Closed Formulation, pp. 599–667], then extended it to a physical closed theory [6, Ch. 17, Kinetic Theory. Mathematical Formulation of a Physically Closed Approach, pp. 669–723]. He stated, "The goal of any complete spot theory is to indicate mechanism that can determine the difference between non-equilibrium and equilibrium regions and to understand the charge particles' motion near the surface…a system of equations is presented… modeling the ion motion to the cathode allowed to close the problem in comparison to previously published approaches. The mathematical formulation allowed using parameters relatively well measured to determine the spot parameters, which cannot be measured (without any data given previously arbitrary). Such model and, respectively, system of equations will be defined as *mathematically closed*.

Let us introduce the following definition by the term 'cathode spot' the entire small region in both the plasma and the metal in which these two minute sub-regions support the current conductivity between the highly conductive cathode body and low conductive adjacent dense plasma will be understood. The specifics of *the arc spot we now define as phenomenon, which arise as a result of local intense heating of the cathode*, in comparison to other discharges for example glow discharge" [6, pp. 599].

Beilis predicts the following cathode spot behavior. Consider a spot (cell) initially operating on the surface of a bulk cathode. With time the cathode erodes, and a crater is formed so that the spot becomes embedded deeper in the body and 3-D heat losses increase. The heat loss in the bulk increases and the voltage required to compensate for the loss reaches such high values that a new spot appears at a neighboring protrusion, where the voltage and heat conduction energy can be smaller. The current in the new spot increases while the current in the old spot drops to zero. This causes apparent spot motion, i.e., one spot dies and a new spot is ignited at a nearby location. Fig. 5 shows the splitting of a dying spot, with the ignition of a new spot, which grows and survives. The theory predicts current fluctuations and continuous spot death and formation, but with continuity of arc current (quasi-steady behavior by the presence of non-stationary spots).

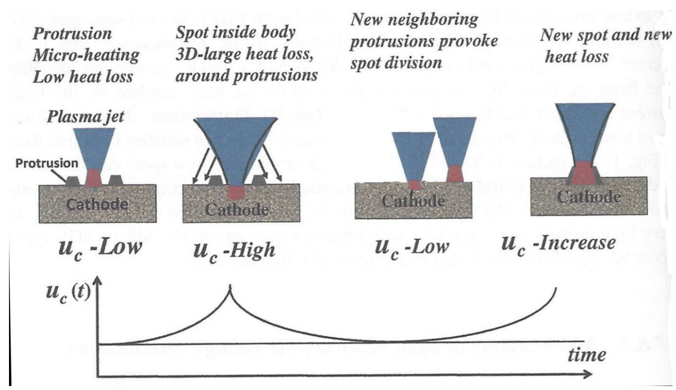


Fig. 5. Cathode spot formation and associated voltage (modified from Beilis [6, Fig. 17.40, pp. 716]).

Cathode spot theoreticians mainly divide into two groups: Group 1 (Mesyats) thinks the cathode spot (cell) current ceases, but after a very short (ns) interval a new cathode spot ignites, probably on a microprotrusion on the edge of the old spot's crater. Group 2 (Beilis) thinks that as the cathode spot current decreases to a low level, a new spot ignites, again most likely on a crater edge microprotrusion, followed by an extinction of the old spot (cell). One group prefers a continuous series of EEE events, and the other, a continuity of current (quasi-steady-state).

The cathode is separated from the arc column by a transition layer (cathode sheath). The interaction between the cathode and the column is discussed by Beilis [6, Ch. 5, Basics of Cathode-Plasma Transition. Application to the Vacuum Arc, pp. 112–139].

## III. Column Phenomena

At low currents, only a single cathode spot is present. The flux from the cathode to the anode consists of electrons, ions, and probably some atoms. However, the density of particles in the interelectrode gap is so low that little visible light is emitted. As the current increases to a maximum for a single spot (value dependent on cathode material Table II, typically 50–100 A) the spot splits into two. Each spot and the associated flux (plasma jet) operate independently. As the current increases further, eventually a point is reached where the plasma jets from the individual spots merge and the individual spots converge and form a group spot. The characteristics of the group spot depend on the overall current as described earlier when discussing Table I.

The interelectrode gap region now emits light, and this region is usually described as the arc column. Heberlein and Gorman investigated the appearance of the column as a function of arc current and gap length in a classic paper [18], summarized in Fig. 6. They noted "Because the time parameter is eliminated in this representation of arc appearance, the validity of this diagram is limited" [18, pp. 286]. But its overall placing of regions should be valid, shifting to shorter gaps and lower currents as arcing time increases.

The diffuse arc in Fig. 6 would correspond to a diffuse arc at the cathode. The higher current regions beyond the diffuse arc region probably involve group spots on the cathode. At small gap lengths with high currents (the Constricted Column region), severe erosion would occur at the cathode.

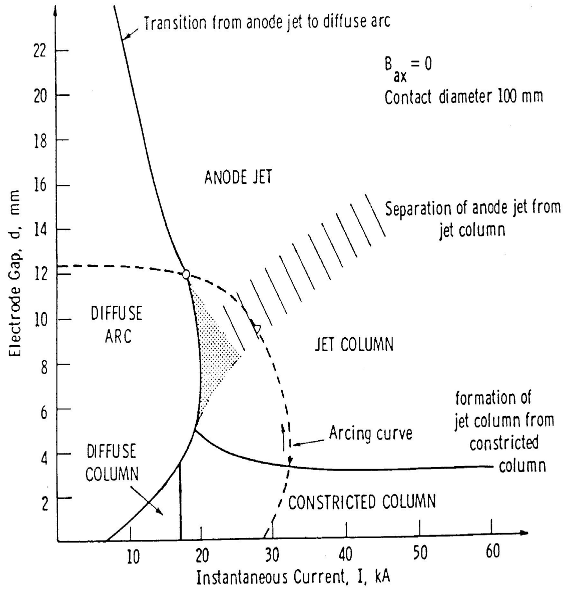


Fig. 6. "Physical arc appearance as a function of current and electrode gap, for one half-cycle of arcing, 50–60 Hz, electrode diameter 100 mm, Isep > 7 kA" [18, Fig. 7].

For low currents (individual spots), the density of the cathodic plasma flux would decrease as $1/d^2$, where $d$ is the distance from the cathode. For group spots, the density would decrease as $1/d^{\alpha}$, where $\alpha < 2$ and depends on the gap geometry.

The ion energies mentioned previously were measured well away from the cathode (dc arcs, time-integrated measurements [13]). This was because the ions are generated in the micrometer-sized active volume of the cathode spot, but the available apparatus did not have the high time and space resolution required for localized measurement. The measurements are still reasonably accurate because the ion energy distributions stabilize very quickly as they leave the cathode spot. Calculations based upon local or partial Saha equilibrium match the measured distributions quite well [1, pp. 182–189]. Some measurements were made on ions which had passed through a central hole in the anode. Such ions had energies like those measured radially [13]. Hence, ion energies in the column of the arc should be the same as those measured for the cathode flux.

Some neutrals are present in the arc column. Possible sources are as follows.

1) Sputtering at cathode and anode.
2) Vapor from craters of previous cathode spots.
3) Evaporating macroparticles.

More details are given in [1, pp. 210–214].

Good discussions of the arc column (interelectrode plasma) are given by Anders [1, 4 The Interelectrode Plasma, pp. 175–225] and Slade [4, 2.3.2 The Plasma between the Cathode Spot and the Anode, pp. 161–173; 2.4 The Columnar Vacuum Arc, pp. 173–179]. Basic plasma parameters pertinent to the vacuum arc are discussed by Beilis [6, pp. 3–36, 101–113].

## IV. Anode Phenomena

Initially, there were thought to be only three modes in a vacuum arc.

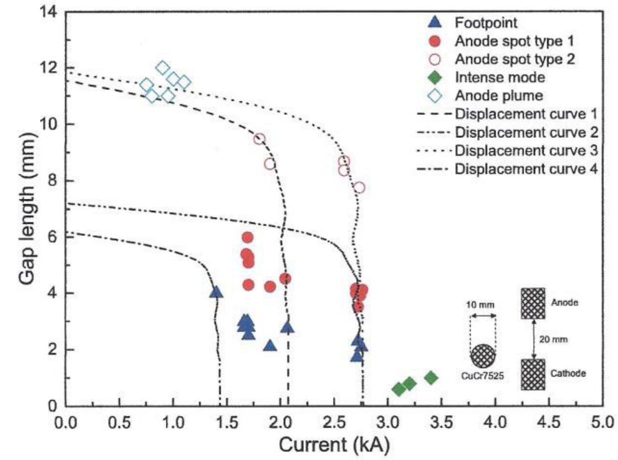


Fig. 7. "Existence areas of high-current anode modes as a function of gap length and current. Note that for each shot only the threshold currents are marked by symbols..." [29, Fig. 8]. Four pulsed dc current versus time traces are shown.

1) A low current diffuse arc mode, where the anode functioned only as a recipient for the cathode flux. Even if the anode were made of a different material from the cathode, the cathode flux condensing on the anode surface would make the anode surface the same as the cathode.

2) As the current increased the cathode would develop more cathode spots and eventually a group spot, then enough energy would be absorbed by the anode to create an anode spot, a hot, bright, evaporating source of vapor.

3) At small gaps the proximity of the anode spot would supply additional energy to the cathode, causing it to profusely lose material, thus creating the intense arc mode.

But in the 1970s evidence appeared for additional modes. Zalucki and Kutzner observed diffuse arcs with a return flux from the anode [19], [20]. Kutzner later concluded that the most probable explanation was sputtering at the anode [21].

Several investigators in the 1970s and early 1980s established the presence of small bright spots on the anode which were not anode spots [22], [23], [24]. It was shown that their results agreed, though they gave different names to their spots, the name "footpoint" was chosen for their spots and this additional anode mode [25].

In the 2010s, researchers in Germany and Russia working with CuCr electrodes observed two additional modes-a plume mode in the footpoint region and a second anode spot mode (Type 2) [26]. Type 2 anode spots develop from, and have a higher voltage than, type 1 anode spots. Recent work indicated that the plume mode can also accompany the Type 2 anode spot mode [27].

Anode spots are discussed by Liu et al. [38, pp. 1–88].

Various workers have plotted the presence of various anode modes in a current versus gap figure, usually along a current versus time trace (displacement curves, which show gap length as a function of time). An example is given in Fig. 7. Such diagrams were helpful in preparing a sketch of Anode Spot Modes-Fig. 8.

Fig. 8 shows a generic sketch. Higher ac frequencies or shorter pulse lengths would move the diagram to the left, and more refractory contact materials would move it to the right. Any actual device or experimental setup allows numbers to

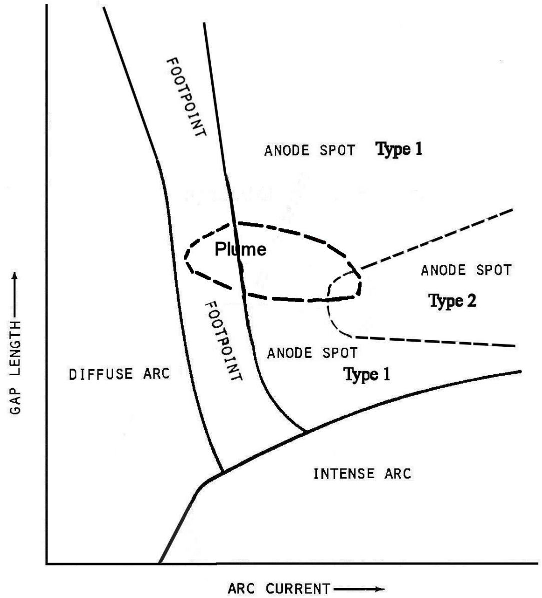


Fig. 8. Anode modes as a function of current and gap length [30, Fig. 19].

be placed on the gap length and current axes. It has been pointed out by Zhang et al. [28] that anode current density is what determines the actual mode present, but for any particular setup, the current is much more readily obtained and suitable for determining modes.

The Anode Spot Type 2 region is outlined in dashes, because they have been seen only with CuCr electrodes. The Plume region is also outlined in dashes because plumes have been seen with CuCr electrodes, but only in special cases with copper. "…such plumes appear at copper electrodes only above heat-insulated protrusions…or around flying droplets…" [26]. They further conclude that this fact indicates that the surface evaporation rate plays a key role in plume appearance. The interior of the plume is primarily anode atoms, with the surface of the plume being mostly ions of anode material. A recent paper has treated the plume surface as an electric double layer [27].

The characteristics of the various anode modes are presented in Table III and Fig. 9.

Anode modes are discussed in detail in [30]. More details on anode phenomena are presented by Boxman et al. [5, Ch. 5, Anode Phenomena, pp. 308–364] and most recently by Beilis [6, Ch. 14, Anode Phenomena in Electrical Arcs, pp. 496–542], which also discusses anode phenomena in gaseous arcs.

TABLE III

CHARACTERISTICS OF VARIOUS ANODE MODES *ANODE GAINS MATERIAL, SO EROSION IS NEGATIVE **CATHODIC EROSION INCREASES WITH CURRENT *** SPUTTERING OCCURS AT ANODE, SO ANODE COULDGAIN OR LOSE MATERIAL

| Mode | Arc voltage | | Luminous areas on anode | | | | Erosion | |
|---|---|---|---|---|---|---|---|---|
| | mean | Noise | # | size | bright-ness | temp | Anode | Cathode |
| Diff-use (1) | low | low | - | - | - | < melt | neg* | slight ** |
| Diff-use (2) | low | low | - | - | - | < melt | *** | slight ** |
| Foot-point | med - high | med to high | 1 pos few | small | moderate | melt | low to mod | slight |
| Plume | med | medium | 1 | med plus in gap | moderate | melt | mod | slight to low |
| AS 1 | med - high | med | ~ 1 | med to large | bright | boil | mod high to high | low to mod |
| AS 2 | high | med | 1 | large | bright | boil | high | mod to high |
| Intense | low-med | low | 1 | large | bright | boil | high | high |

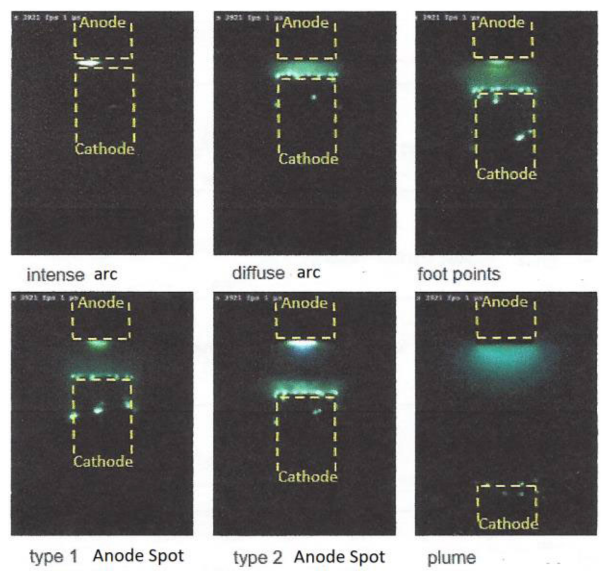


Fig. 9. Photos of different discharge modes. CuCr50/50 electrodes, 10-mm diameter. Maximum current ~1.8 kA, pulsed dc 25 ms [from 27, Fig. 3].

## V. APPLICATIONS

### A. Vacuum Interrupters

Vacuum interrupters may be divided into two classes - vacuum switches, which mainly connect and disconnect loads, therefore only need relatively low (~kA or less) current interrupting capability, and VCBs, which can also connect and disconnect loads, but whose primary purpose is to protect circuits, thus must be capable of interrupting fault currents of ~10 kA or greater [5, pp. 620].

Vacuum switches are well-suited to frequent switching operations. Such duties include motors, shunt capacitor banks, shunt reactors, and arc furnaces. "The ideal material for vacuum switch contacts must satisfy several requirements simultaneously. The gap must have rapid recovery of electric strength immediately after arcing and a high ultimate breakdown strength. The contacts must not weld while carrying high momentary currents or when closing in on a short circuit. This requires that their electrical resistance should be low, which also minimizes heating during the flow of normal continuous current. Finally, the arcs drawn between the electrodes must be stable at low currents to prevent the generation of overvoltages by current chopping. Since each of these characteristics requires, in general, the exploitation

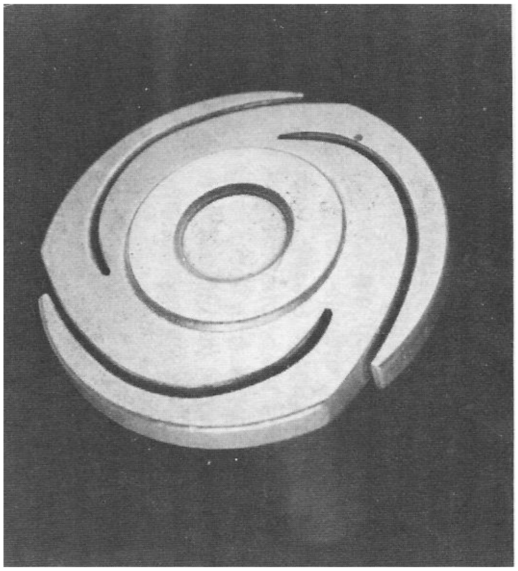

Fig. 10. Spiral contact [3, pp. 333].

of different physical properties of the contact material, these demands are not easily satisfied simultaneously and in some instances may even be contradictory” [3, pp. xii].

Contact materials for vacuum switches include W for high-voltage, low current switching. Other applications require contacts of two or more materials. WC-Ag is used for motor applications. Applications such as capacitor bank switching with high inrush currents often use contacts of W-Cu. The advantages\disadvantages of Cu-Cr, Ag-WC, and Cu-W are tabulated by Slade [4, Table 2.10, pp. 245]. Vacuum switches are discussed in detail by Slade [4, Ch. 5, Application of Vacuum Interrupter for Switching Load Currents, pp. 401–480].

Because VCBs have the additional requirement of interrupting fault currents they generally use contacts composed of two metals. The first successful VCBs used Cu-Bi. “. . . a two-phase alloy of copper with a few percent of bismuth. In the liquid phase the bismuth is soluble in the copper, but on solidification it precipitates out in the grain boundaries and on the surface of the copper. Since the bismuth is virtually insoluble in the copper the high conductivity of the copper is retained. The bismuth precipitate in the copper grain boundaries hardens the alloy and produces a weak brittle weld interface that is easily broken on impact by the circuit breaker opening mechanism. Finally, the presence of the high vapor pressure bismuth during arcing reduces current chopping” [3, pp. viii].

Work on contact materials for VCBs continued. CuCr was first investigated in England, then further developed by Westinghouse into a practical material for use in their VCBs [4, pp. 224–234]. CuCr contacts are now generally preferred for use in VCBs. Vacuum interrupter contact materials are discussed in detail by Slade [4, 3.2 Vacuum Interrupter Contact Materials, pp. 220–245].

The first VCBs used spiral contacts (see Fig. 10).

When spiral contacts open on short-circuit currents an anode spot quickly develops. Anode spots tend to severely erode the anode surface. The geometric design of the spiral contact causes the current to flow through the contact in such a way as to generate a significant transverse magnetic field (TMF). This causes the arc to rotate around the contact, thus continuously moving to a cooler area of the anode surface. This movement significantly reduces the anode erosion, thus improving the VCBs interrupting capability and the VCBs operational lifetime.

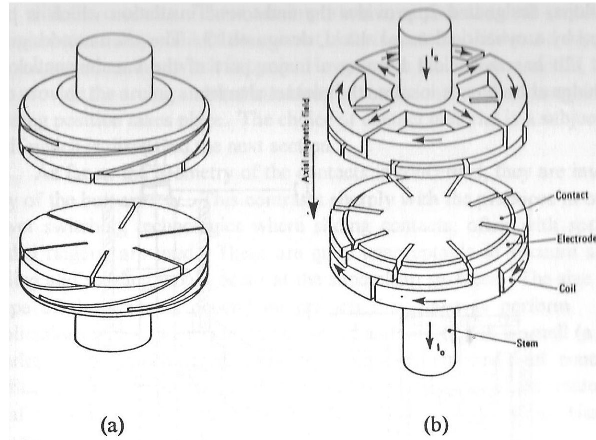


Fig. 11. Electrodes designed to produce AMFs [5, pp. 611]. (a) Electrode design 1 [5, p.623 Ref.27]. (b) Electrode design 2 [5, p.623 Ref.28].

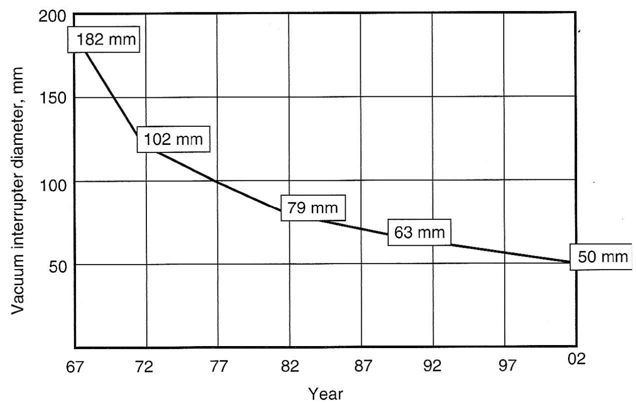


Fig. 12. Reduction of the vacuum interrupter diameter from 1968 to 2002 for the 15-kV, 12-kA rating [4, Fig. 3.1, pp. 220].

Another common contact design produces an axial magnetic field (AMF), as shown in Fig. 11. The AMF keeps the arc in the diffuse mode until higher currents, thus reducing the erosion caused by high-current arcs. Both TMF and AMF designs are in wide use. Contact designs are discussed by Slade [4, 3.3 The Contact Structures for the Vacuum Interrupter, pp. 245–283].

VCBs have been significantly improved over the years. For example - the reduction in size of standard VCBs (Westinghouse/, Eaton), is illustrated in Fig. 12. New designs for higher voltages and currents have appeared.

The speed with which VCB contacts separate is called the opening velocity. When contacts part while carrying current the last points in contact carry a very large current density and vaporize to form a plasma bridge. At low to medium currents, this quickly transforms into a diffuse arc. At high currents it transforms into an intense arc, severely eroding both electrodes. As the gap increases the arc will transform into a diffuse or footpoint mode, and possibly to an anode spot mode, depending on the gap and instantaneous current. For high peak currents and low opening velocities, the arc will spend much time in the intense arc mode, but not in an anode spot mode. At high opening velocities, the arc will spend little or no time in an intense arc mode, but much in an anode spot mode. Designers of VCBs consider these opposite behaviors in choosing the opening velocities for particular applications. It was shown theoretically [31] and confirmed experimentally [32], [33], [34], [35] that starting with a high opening velocity to avoid the intense arc mode, but then shifting to a low velocity to minimize time in an anode spot mode significantly decreases the time a VCB spends in a highly erosive mode. Details on designing such opening characteristics for VCBs are given in Liu et al. [38, 4.1 Determination of Opening and Closing Velocities, pp. 220–252]. Greenwood [5, 8 Vacuum Switching of High Current and High Voltage at Power Frequencies, pp. 590–624] and, especially, Slade [4, Part 2 Vacuum Interrupter Application, pp. 321–612] provide additional details on VCB applications. Liu et al. [38, Ch. 4, VCBsat Transmission Voltage Level, pp. 219–302] discuss Transmission Voltage Level VCBs.

Triggered vacuum gaps (TVGs) are related devices that are normally open, but close to carry high currents when triggered TVGs are used in Pulsed Power applications [5], [9, Pulsed Power Applications, pp. 625–699].

## B. Coatings

Vacuum arcs produce copious quantities of metallic vapor plasma, which can condense to form high-quality coatings on substrates. "When the plasma ions arrive at a surface, they do so with considerable kinetic energy. which is typically in the range 22–150 eV without bias. A bias voltage can increase this energy even further/energetic condensation involves subsurface processes when the arriving ions displace surface and near surface ions to come to rest below the surface. Shallow ion implantation or "subplantation" occurs, leading to dense and hard coatings that are generally under high compressive stress. Hardness and compressive stress are related. Excessive compressive stress is detrimental because it can lead to catastrophic failure of the coating by delamination. Stress control becomes paramount for high-performing coatings. This can be addressed by utilizing the high degree of ionization: biasing the substrate is very efficient and giving ions controlled, high energy capable of generating small collision cascades in the subsurface layer of the solid. Stress can be relieved through atom rearrangement facilitated by the short period of high mobility. This is best controlled by sophisticated biasing techniques, such as pulse biasing with optimized pulse duration and duty cycle. One can maximize stress relief while maintaining an overall high level of hardness and elastic modulus" [1, pp. 363]. A detailed discussion about cathodic arc coatings, macroparticles, and coating applications is given by Anders [1, pp. 265–490].

"Macroparticles are formed at cathode spots, together with electrons and ions. They are commonly called macroparticles because they are very massive compared to ions and electrons...The size distributions can be fit by power laws, which is another indication for the self-similar nature of cathode processes" [1, pp. 265] (see Fig. 13).

A sketch of macroparticle (MP) generation is shown in Fig. 14. "Macroparticles form when the layer of liquid cathode material (in black) yields to the plasma pressure. As the illustration suggests, many macroparticles are preferentially ejected under 5°–30° angle to the cathode surface. Just-ejected macroparticles or nonlinear wave of the liquid may rapidly cool down and freeze at the crater rim, forming microprotrusions that can serve as field-enhancing objects for the ignition of the next emission site. There is also a large fraction of micro particles ejected in a direction close to the surface normal" [1, pp. 266–67].

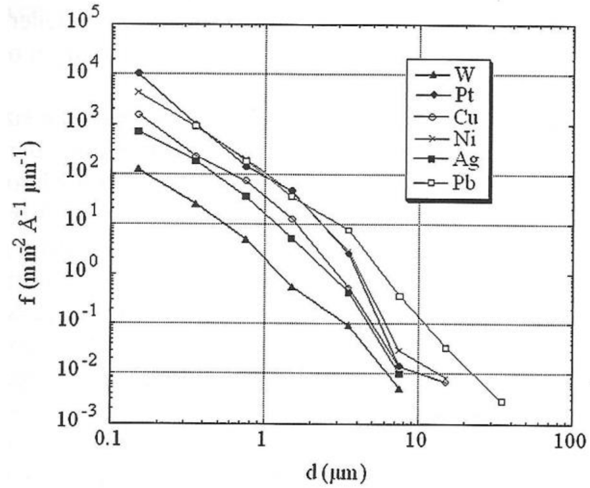


Fig. 13. "Size distribution functions for macroparticles collected on axis of a pulsed cathodic arc source in vacuum. The functions are normalized as number and size class per area and film thickness, the arc current was 200 A" [1, Fig. 6.4, pp. 269].

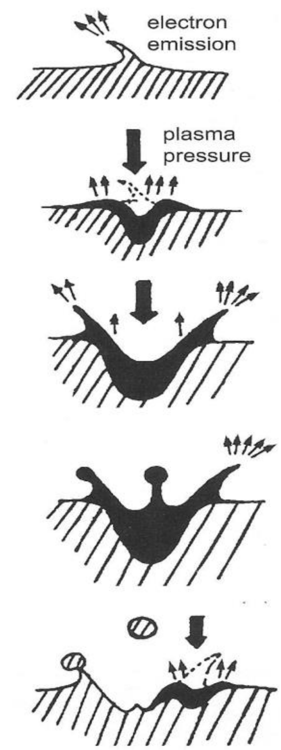


Fig. 14. Sketches illustrating microparticle generation because of plasma pressure on the liquid cathode material, adapted from an original by Burkhard Jüttner [1, Fig. 6.2, pp. 267].

This implies that larger particles tend to flow near the cathode while smaller particles tend to flow toward the anode.

"The most common and successful approach to deal with the infamous macro particle issue is to utilize curved macroparticle filters. Filters are used to separate and remove macroparticles from the cathodic arc plasma, thereby greatly improving the quality of cathodic arc thin films and coatings" [1, pp. 299]. Such filters typically use both electric and magnetic fields.

Cathodic arcs in a gaseous ambient can be used to deposit hard coatings (such as TiN, TiCN, CrN) on cutting tools and wear parts, often without filtering [36].

Coatings can also be produced using the anode of a vacuum arc. "A different vacuum arc plasma source is based on the *hot anode vacuum arc* (HAVA)... where metallic plasma is produced by the evaporation of anode material. In this arc mode, the arc current heats the anode until its temperature reaches sufficiently high values so that the anode surface becomes an intensive source of vapor. The HAVA plasma is diffusely attached to the hot electrode surface and metallic plasma has not contaminated the droplets as in conventional cathode spot or anode spot vacuum arcs. Therefore, cleaner coatings could be attained. The HAVA occurs when the anode is more volatile and smaller than the cathode" [6, pp. 937].

"Hot refractory anode vacuum arc (HRAVA). In this discharge, material evaporated from the cathode is transported to the refractory anode. As the arc developed. two phenomena were observed: 1) anode heating; 2) condensation of the cathode material at initial stage when the anode was cold and the arc operated in multi cathode spot mode; and 3) re-evaporation of the cathode material deposited on the hot anode from on the developed stage of the arc.

As the HRAVA evolves, the anode is significantly heated (~2000 K), and an intensely radiating plasma plume is created at the anode surface, expanding with time in the axial and radial direction. Spectroscopically, the plume radiates lines of the cathode material. The HRAVA plasma is sufficiently hot and dense to result in the evaporation of the macroparticles produced by the cathode spots during their passage through the interelectrode gap. Thus, the radial expanding HRAVA plasma"(see Fig. 15). "...has the potential to be used as macroparticle-free plasma source in technological applications, and in particular in thin film deposition" [6, pp. 938].

"Vacuum arc with blackbody assembly (VABBA). In this arc mode..., the material eroded from the cathode spots as plasma jets containing macroparticles impinges on a cup-shaped refractory anode, which almost encloses the volume bounded by it, a water-cooled cylindrical cathode and a planar BN insulator ring separating the cathode from the anode. The arc simultaneously heats the anode. Initially, when the arc is cold, cathodic plasma material condenses on the anode. With arc time, when the anode is sufficiently hot, the condensed material is re-evaporated from the anode. In steady state, a dense high-pressure plasma is formed within the enclosed volume. In the closed VABBA configuration, the plasma expansion is not free. Part of the particles and arc energy returned and dissipated in the cathode. Therefore, the effective cathode voltage is twice that measured in the HRAVA...or in the free burning conventional cathodic arc. The VABBA acts toward the plasma and MPs somewhat analogously to how a "blackbody" acts toward photons, i.e., not permitting condensation, while allowing a flux to escape through small apertures. The escaping plasma forms an expanding flow. ...The material efficiency using VABBA can be quite high, due to utilization of the most of eroded cathode included

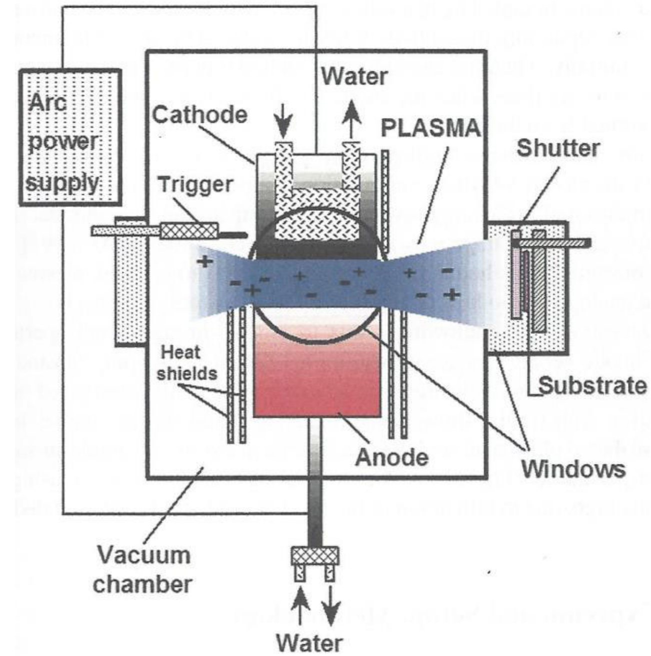


Fig. 15. "Schematic presentation of the radially expanding HRAVA plasma, which has the potential to be used as macroparticle free plasma source" [6, Fig. 22.4, pp. 939].

the MPs" [6, pp. 940]. For more details, see Beilis [6], [22, Vacuum Arc Plasma Sources. Thin Film Deposition, pp. 933–1001]. An older, but comprehensive, presentation of vacuum arc coatings is [6, 6 Coatings From The Vacuum Arc, pp. 367–551].

### *C. Other Applications*

C1 Space Thrusters (Micro-propulsion). Vacuum arc thrusters for micro-propulsion are interesting for orbital maneuvering of small spacecraft (<10 kg). The typical vacuum arc thruster uses a coaxial design, with a central cathode surrounded by an insulator and an anode. Gas dynamic calculations indicate that cathode plasma is accelerated to supersonic velocity within 2–3 times the cathode spot radius, so that very small and lightweight devices can be built Beilis [6, pp. 1005, 1007]. Recent measurements of the plasma jet momentum in vacuum arc thrusters [37] agreed with the results of Tanberg [8], obtained 90 years earlier, illustrating the value of knowing the history of vacuum arcs.

C2. Vacuum Arc Metal Processing. "The most commonly used vacuum arc process, vacuum arc remelting (VAR), uses an arc between a massive source electrode, which is cast using another metallurgical process, and a water-cooled mold. The consumable electrode is suspended over the mold and acts as the arc cathode. Heating by the arc transfers material to the mold on a drop by drop basis, which improves the grain structure and uniformity of the cast ingot, while the vacuum environment removes gases and volatile contaminants" [5, pp. 532].

## VI. Future

Excellent work continues to be done in this field. I would like more experimental observations of vacuum breakdown and arcing in long gaps (>30 cm).

## VII. Conclusion

The captivating subject of vacuum arcs was revealed. A brief history of vacuum arcs was presented. Cathode phenomena (especially cathode spots), column phenomena, and anode phenomena (especially anode modes) in vacuum arcs were discussed in moderate detail. Applications of vacuum arcs-especially vacuum interrupters (VCBs, vacuum switches) and vacuum arc-generated coatings were given.

## Acknowledgment

Comments and suggestions by Prof. Isak Beilis, Dr. Paul Slade, and especially Prof. Raymond Boxman significantly improved this article.

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