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## DISTRIBUTED ARC SOURCES *(by Vladimir I. Gorokhovsky, Vladimir P. Polistchook, Ivan M. Yartsev, and Joseph W. Glaser)*

### Introduction

As discussed earlier in this chapter, vacuum arcs can be classified by the mean temperature of the source electrode. In the case where the source electrode is the cathode and where its mean temperature is low (less than 1000 K), random rapidly moving cathode spots with a current density > $10^4$ A/cm$^{-2}$[1][2] are observed. These spots vaporize the cathode material with the resultant vapor used to produce coatings with varying compositions and for a variety of purposes.[3] These cold-cathode vacuum-arc produced coatings usually contain macroparticles of the electrode material with sizes between 1 and 10 μm. Electromagnetic filters have consequently been developed which intercept most of these macroparticles, making nearly macroparticle free coatings possible.[4]-[6]

When the mean electrode temperature is raised above approximately 1520 K, the arc spot becomes diffuse and stationary,[7]-[9] the electrode current density drops to 10–100 A/cm$^2$ and the arc discharge stops producing macroparticles. Another advantage of this type of discharge is that the arc can be more easily controlled as compared with a cold cathode arc.

Two types of diffuse arcs are found, depending upon the polarity of the electrode which is consumed. Positive electrode arcs are called *anodic* and negative electrode arcs, *cathodic*, independent of their discrete or distributed nature. The electrode heating which is necessary to generate distributed arcs can be achieved by the discharge itself in the case of a

distributed cathodic arc or by means of an auxiliary power source. In general, obtaining a vacuum arc on a hot evaporated anode is more straightforward than on a hot evaporated cathode; however, the degree of ionization for cathodic arcs, whether discrete or distributed, is typically higher.

## Distributed Cathodic Arcs

**Arc Description and Classification of Electrode Materials.** A distributed cathodic arc[10][11] occurs when the average cathode temperature is larger than some critical value. The arc vapor is composed of cathode material since anode erosion is negligible. The basic difference between this vacuum arc and cold cathode arcs is the lower average cathode current density (typically 1–100 A/cm$^2$ vs. $10^4$ A/cm$^2$). Because of this lower current density, distributed arcs do not exhibit the high frequency oscillations in discharge voltage and chaotic cathode spot motion characteristic of cold cathode discrete arcs. In Ref. 12, Anders, et al. propose a classification scheme based on phenomena observed in the near cathode region of the vacuum arc. Among these phenomena, evaporation and electron emission from the cathode surface are important for the existence of the arc. The working medium is produced as a result of evaporation. The current continuity at the cathode surface is maintained by the emission. References 2 and 7 suggest a correlation between these two processes based on the dimensionless atom-electron ratio, $\xi$. This parameter represents the ratio of the thermally evaporated atom flow and thermionic electron flow and is the maximum achievable value of the cathode ion current fraction.

The parameter $\xi$ is a material-dependent parameter which can be used for the qualitative analysis of specific properties of the near-cathode region. This parameter is generally useful for all types of vacuum arcs on evaporated cathodes as described in Ref. 13, but is particularly useful in predicting the behavior of distributed arcs where a value close to unity suggests arc stability.

Figure 1 shows the dependence of the atom-electron ratio with temperature for a number of cathode materials.[14] Note that the value of $\xi$ varies over a wide range for these materials. With the exception of carbon, materials with $\xi$ much different than 1 exhibit a strong temperature dependence.

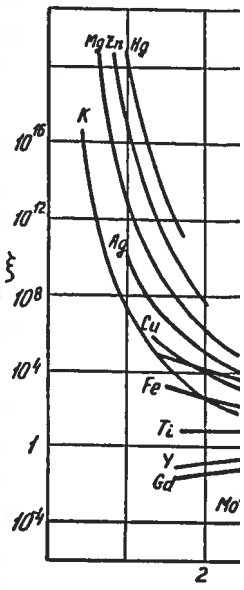


**Figure 1.** Effect of temperature on the

An analysis of the current indicates that the ratio of ion an unity to achieve stable arc behavi the value of $\xi$ approaches this higher temperatures. Also from are seen:

1. *Materials with* $\xi <$ Ta, Nb, Mo) and sc These materials are which effectively op more than $5\times10^3$ K required for heating external medium. Fc current or an excess is supposed. Beca calculating the cath problem, a model v

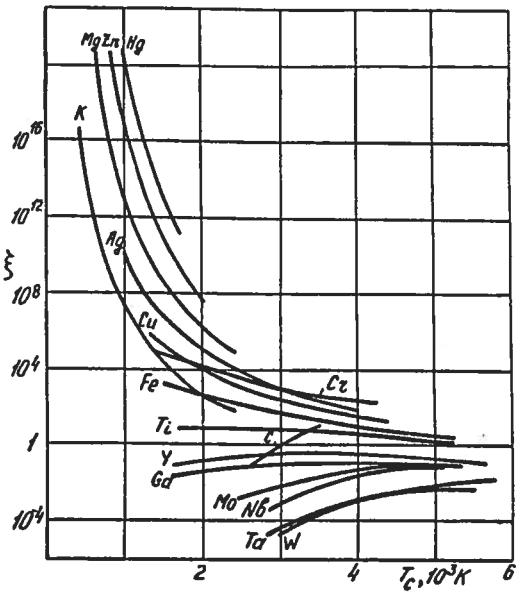


**Figure 1.** Effect of temperature on the atom-electron ratio for different cathode metals.

An analysis of the current and energy balance on the cathode surface indicates that the ratio of ion and electron current must be approximately unity to achieve stable arc behavior. Figure 1 shows that for most materials the value of $\xi$ approaches this optimal value of unity asymptotically at higher temperatures. Also from Figure 1, three classes of cathode material are seen:

1. *Materials with $\xi < 1$.* Examples include refractory (W, Ta, Nb, Mo) and some rare-earth metals (Gd and La). These materials are widely used as thermionic cathodes which effectively operate when the external pressure is more than $5 \times 10^3$ Pa. The ion flow to the cathode required for heating is provided via ionization of the external medium. For these materials, some deficit of ion current or an excess of electrons emitted from the cathode is supposed. Because of this, difficulties arise when calculating the cathode heat balance. To solve this problem, a model which postulates the existence of a

potential minimum near the cathode of the discharge has been proposed.[15] The excess quantity of electrons emitted from the cathode can then return back to the cathode.

2. *Materials with $\xi > 1$.* These include most low melting-point metals $T_m < 2000$ K (Zn, Hg, K, Ag, Cu, Fe, Cr). Since $\xi > 1$, there is a large cathode current deficit which substantially complicates the understanding of the near-cathode vacuum arc process. Models explain the cathode electron current deficit by citing thermal-field emission (see Ch. 3, section "Theory of Cathode Spots").
3. *Materials with $\xi = 1$.* For some metals, for example Ti, the value of $\xi$ has only a weak dependence on the temperature and is approximately equal to unity. Carbon is different than most materials showing both positive and negative values of $\xi = 1$ as seen in Figure 1. Since values of unity for $\xi$ can be easily achieved for these two elements, they make excellent candidates for distributed arc sources.

**Typical Experimental Conditions.** References 9, 10, 14, and 16 describe several experimental arrangements used to determine vacuum arc properties originating from an evaporated hot cathode. In general, the electrode material being melted is placed in a special crucible having a vapor pressure much lower than that of the cathode material in order to avoid contaminating the coating with crucible material. In addition to the vapor pressure difference, it is important that the crucible material not be dissolved by the cathode material in cases where the latter is molten during the arcing process. Table 1 summarizes results for a variety of electrode materials.

The temperature necessary for the formation of a distributed cathodic arc can be achieved by preheating the cathode to the required temperature by means of an external source or by configuring the source so that the arc itself heats the electrode. In the former case, the required voltage is applied in stages with the cold cathode discrete spots moving more slowly and growing in size as the cathode is allowed to heat up. As this is occurring, many macroparticles are generated and a shutter is necessary to protect parts during this stage. When the cathode temperature exceeds a critical value, which is a function of $\xi$, the cathode spots disappear and a diffuse current

Table 1. Experimental Conditions and Characteristics of Vacuum Arcs on Evaporated Cathodes

| Ref | Cathode material | Arc current | Arc voltage | Gap length | Cathode temperature | Cathode current density | Cathode erosion | Vapor pressure | Electron concentration | Electron temperature | $\xi$ | Heating Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | V | cm | K | A/cm$^2$ | g/s | Torr | cm$^{-3}$ | eV | | W |
| 11 | Cr, Cu, Mo | 40-400 | 12-14 | 10 | ~$2\times10^3$ | 10-100 | $2\times10^{-3}$-$2\times10^{-2}$ | >1 | $1\times10^{13}$ | 2-4 | $1\times10^4$ | - |
| 10 | Cr | 12-33 | 40-50 | 200 | ~$2\times10^3$ | 1-5 | - | >1 | >$2\times10^{12}$ | | $1\times10^4$ | <$2.5\times10^4$ |
| 3,15 this work* | Gd | 2-200 | 3-100 | 1-20 | >$1.8\times10^3$ | 1-30 | $10^{-4}$-$10^{-2}$ | >$1\times10^{-3}$ | $10^{12}$-$10^{14}$ | 1-7 | ~0.05 | ~$1\times10^3$ |

**Table 1.** Experimental Conditions and Characteristics of Vacuum Arcs on Evaporated Cathodes

| Ref | Cathode material | Arc current | Arc voltage | Gap length | Cathode temperature | Cathode current density | Cathode erosion | Vapor pressure | Electron concentration | Electron temperature | ξ | Heating Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | V | cm | K | A/cm$^2$ | g/s | Torr | cm$^{-3}$ | eV | | W |
| 11 | Cr, Cu, Mo | 40-400 | 12-14 | 10 | ~$2x10^3$ | 10-100 | $2x10^{-3}$-$2x10^{-2}$ | >1 | $1x10^{13}$ | 2-4 | $1x10^4$ | - |
| 10 | Cr | 12-33 | 40-50 | 200 | ~$2x10^3$ | 1-5 | - | >1 | >$2x10^{12}$ | | $1x10^4$ | <$2.5x10^4$ |
| 3,15 | Gd | 2-200 | 3-100 | 1-20 | >$1.8x10^3$ | 1-30 | $10^{-4}$-$10^{-2}$ | >$1x10^{-3}$ | $10^{12}$-$10^{14}$ | 1-7 | ~0.05 | ~$1x10^3$ |
| this work* | | | | | | | | | | | | |
| " | La | 2-40 | 3-50 | " | >$1.8x10^3$ | 1-10 | $10^{-4}$-$10^{-2}$ | >$1x10^{-3}$ | | | ~0.05 | " |
| " | Ti | 3-15 | 10-30 | " | >$2x10^3$ | 1-10 | $1x10^{-4}$ | $1x10^{-2}$ | | | 5-10 | $4x10^2$-$1x10^3$ |
| " | Cr | 3-15 | 10-30 | " | >$2x10^3$ | 1-10 | | 1 | | | $1x10^4$ | $4x10^2$-$1x10^3$ |
| " | C | 1-30 | 20-100 | 5 | ~$3x10^3$ | 1-100 | $5x10^{-4}$-$5x10^{-3}$ | 1-10 | | | ~1 | (1-2)$x10^3$ |
| 17 | Ti | 0.1-12 | 4-12 | 7 | >$2x10^{-3}$ | 1-50 | - | $1x10^{-2}$ | | | 5-10 | 0-200 |

* This data has not been formally published but is an extension of the work discussed in ref. 15.

spot discharge occurs. It is possible to facilitate such discharges by increasing the cathode thermal insulation. If an external heating source is used, it is possible to avoid the macroparticle formation stage completely by waiting to apply the arc current until the electrode is at the temperature necessary for a distributed discharge.

Anodic arcs have some of the same thermal balance considerations as cathodic arcs. To prevent a current contraction on the anode and to ensure the stable operation of the arc under comparatively low arc voltage, the anode size and location must be chosen carefully. Operating parameters and other experimental conditions are also presented in Table 1.

**Arcs on Cathodes with Low Atom-Electron Ratios ($\xi < 1$).** For this class of materials, the predominant heating mechanism, if external heating is not employed, is the return of ions back to the cathode during arcing. This is described in more detail in a hydrodynamic model proposed by Bronin, et al.[8] External heating can be used to more easily control plasma properties.

This effect is shown in Figures 2a and 2b where the deposition rate increases with heating power. However, arc efficiency as evidenced by the electron temperature and ion saturation current are inversely related to heating power. In fact, as heater power is decreased, the arc changes to a self-sustaining mode at which point cathode heating losses and evaporation account for approximately 25% of the discharge power. The remainder goes to plasma generation and acceleration.[2]

Vasin et al.[10] discuss distributed arcs on a Mo cathode with $\xi = 10^{-2}$ and Refs. 2 and 14 discuss arcs on cathodes made from Gd and La with $\xi = 5\times10^{-2}$–$10^{-1}$. The arc behavior for Gd and La was qualitatively the same. In Refs. 2 and 14, the arc was ignited in a water-cooled metallic chamber evacuated to a pressure of $10^{-2}$–$10^{-3}$ Pa ($10^{-4}$ to $10^{-5}$ torr). Figure 3 shows a typical coating arrangement using an evaporated hot cathode.[17] Here, the vacuum arc is located between the electron beam heated cathode (source) and an anode ring located under the cathode crucible.

Goedicke, Scheffel, and Schiller[18] have devised a process which uses a cathodic arc source to excite vapor produced by electron beam evaporation. The arc generated in this manner is found to be a diffuse arc discharge formed at the cathode surface. They have called this deposition technique *spotless arc activated deposition* (SAD). Deposition rates between 10–100 μ/m have been observed without the production of macroparticle droplets. The dual crucible arrangement shown in Figure 4 has been proposed for reactive deposition of poorly conductive or insulating layers.

In this arrangement, the crucibl
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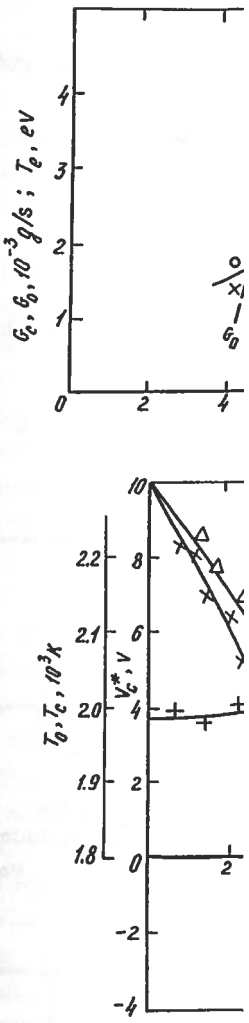


**Figure 2.** *(a)* Values of $T_e$ (electron
cathode evaporation with arc), for $I$ =
arc; Gd cathode. *(b)* The influence of
evaporated cathode at $I$ = 50 A.

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In this arrangement, the crucibles are alternately heated by a swept electron beam gun. Since the vapor emitting surfaces themselves act as the electrodes, problems associated with currently used insulator deposition techniques are avoided. Table 2 compares typical characteristics of their process with those of e-beam (EB) evaporation and cold cathode (CC) arc evaporation.

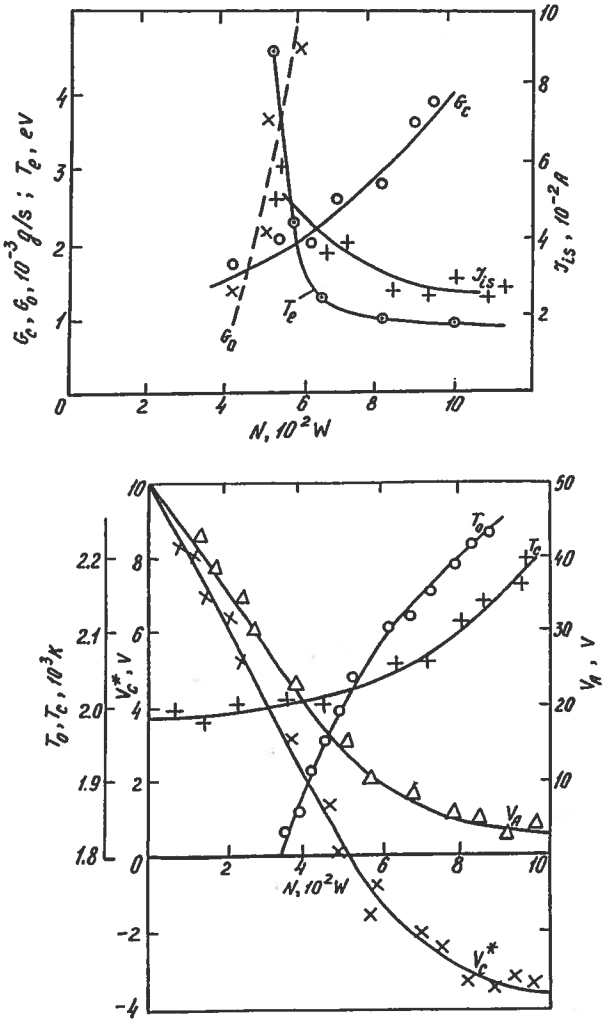


**Figure 2.** *(a)* Values of $T_e$ (electron temperature), $J_{iS}$ (ion saturation current), $G_c$, (rate of cathode evaporation with arc), for $I$ = 50 A; $G_0$, rate of the cathode evaporation without arc; Gd cathode. *(b)* The influence of heater power on the arc characteristics for a Gd hot evaporated cathode at $I$ = 50 A.

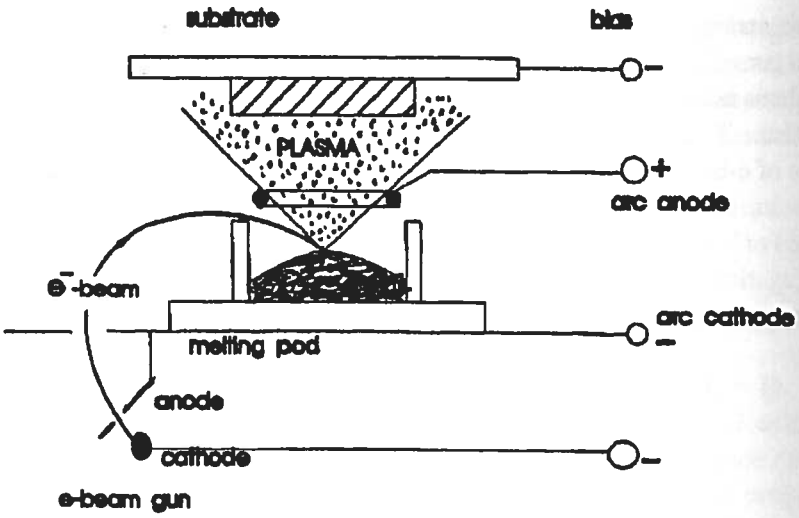


**Figure 3.** Arrangement used for coating deposition:[17] *(1)* cathode crucible; *(2)* anode ring; *(3)* electron beam; *(4)* substrate.

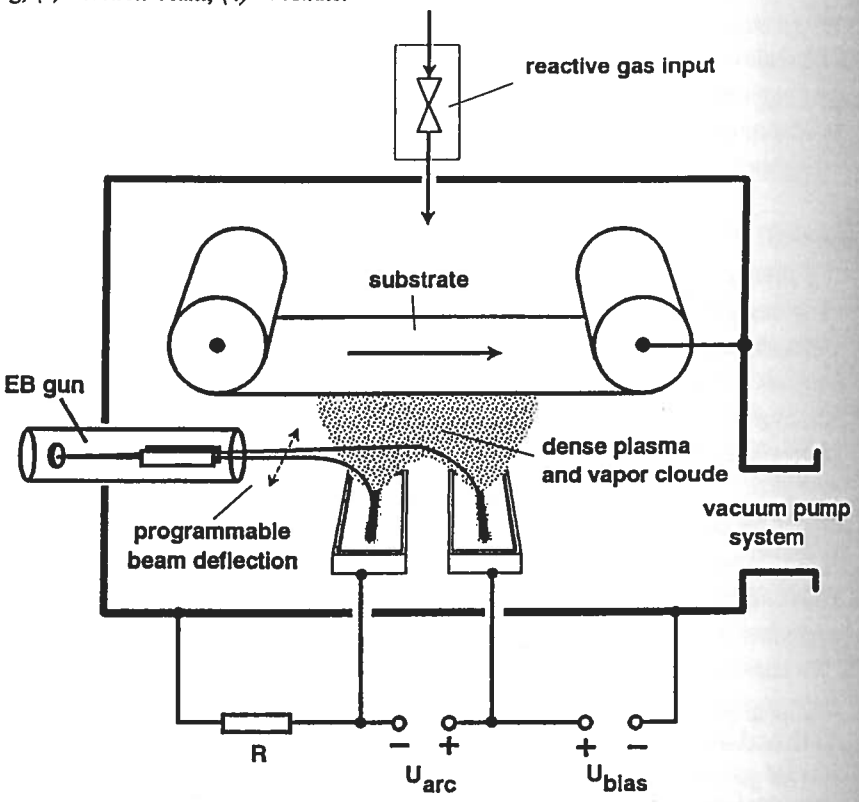


**Figure 4.** Schematic arrangement for the two-crucible spotless arc activated process.[18]

Table 2. Comparison of Proce

| | |
|---|---|
| Vapor generation | by EB h |
| Plasma generation | by spot |
| Arc current | 100–20 |
| Arc current density | $10^1$–10 |
| Arc voltage | 6–40 V |
| Evaporation rate | 10–100 |
| Metal deposition rate | 10–100 |
| Degree of ionization | 10–50% |
| Bias current | 10–400 |
| Droplets | No |

The apparatus used by C material was placed into a therm vacuum-melted pure Mo with electron beam gun was used to distance between electrodes wa initiated via the electric breal cathode temperature $T_c$ = 180C

For materials where $\xi <$ nism which provides cathode c spot on these cathodes, it is ne thermionic current from the cat current. Secondly, the vapor cc than some critical value, typi insulated cathodes. The first transfer, the second is respon layer. It should also be note pressure at which this discharg Pa for Gd and La to 100 Pa fo

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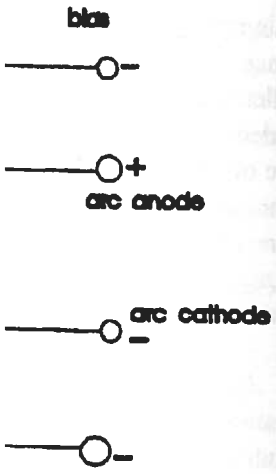
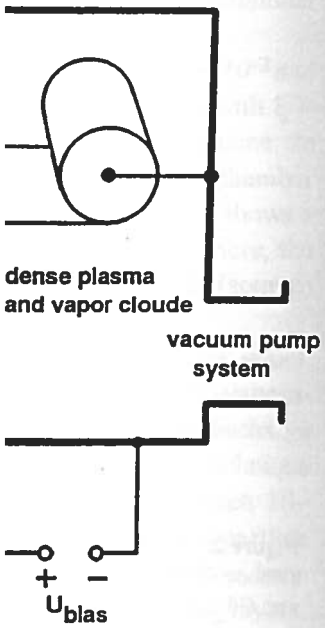



*(1)* cathode crucible; *(2)* anode

eactive gas input




tless arc activated process.[18]

Table 2. Comparison of Process Parameters[18]

| | SAD | CC | EB |
|---|---|---|---|
| Vapor generation | by EB heating | in arc spot | by EB heating |
| Plasma generation | by spotless arc | in arc spot | |
| Arc current | 100–2000 A | 50–500 A | |
| Arc current density | $10^1$–$10^3$ A/cm² | $10^4$–$10^8$ A/cm² | |
| Arc voltage | 6–40 V | 20–30 V | |
| Evaporation rate | 10–100 g/m | 0.1–1 g/m | 10–100 g/m |
| Metal deposition rate | 10–100 μ/m | 1–10 μ/m | 10–100 μ/m |
| Degree of ionization | 10–50% | 10–90% | <0.1% |
| Bias current | 10–400 A | 10–80 A | $<10^{-2}$ A |
| Droplets | No | Some | Yes |

The apparatus used by Gorokhovsky is shown in Figure 5. Cathode material was placed into a thermally insulated crucible which was made from vacuum-melted pure Mo with a cathode surface area of 5 cm². A 1-kW electron beam gun was used to heat the cathode up to $(2–2.4)\times10^3$ K. The distance between electrodes was varied between 2 to 20 cm. The arc was initiated via the electric breakdown of the cathode material vapor at a cathode temperature $T_c$ = 1800 K. The breakdown voltage was ~100 V.

For materials where $\xi < 1$, thermionic emission is the main mechanism which provides cathode current transfer. In order to obtain a diffuse spot on these cathodes, it is necessary to satisfy two conditions. First, the thermionic current from the cathode must be approximately equal to the arc current. Secondly, the vapor concentration near the cathode must be greater than some critical value, typically between $10^{13}$–$10^{14}$/cm³ for thermally insulated cathodes. The first condition provides for the cathode current transfer, the second is responsible for the production of the cathode arc layer. It should also be noted that as $\xi$ increases, the minimum vapor pressure at which this discharge may be observed also increases (from 0.11 Pa for Gd and La to 100 Pa for Cr).

**Carbon and Titanium Cathodes.** Figure 1 shows the unique dependence of the atom-electron ratio on temperature for carbon and titanium arcs. High temperature arcs of titanium and carbon were studied using the arrangement shown in Figure 6.[2] A 5 cm cylindrical cathode of carbon or titanium was placed in a water-cooled copper crucible. Cathode heating was accomplished using an electron beam with a diameter of 5–10

cm and power of 1–2 kW (i.e., 3–20 times larger than that from the arc). Focusing and scanning of the electron beam on the cathode surface was provided by computer-controlled magnetic lenses. The arc-produced vapor was subjected to an opposing magnetic field created by a pair of magnetic coils placed in a coaxial electron beam. The water-cooled enclosure of these coils also served as an anode for the arc plasma originating at the crucible-cathode. The substrate was placed on a carousel-shaped substrate holder which was RF heated. The arc could be started by introducing gas near the substrate holder.

When the cathode temperature exceeded a critical value, the vacuum arc spot became stationary and diffuse. Based on the evaporation rate, the cathode temperature was estimated to be between 2900–3200 K. When the depth of the erosion crater became sufficiently large, the stability of the arc discharged degraded. To prevent this and to provide a more constant rate of cathode erosion, the heating electron beam was swept. Figure 7 shows that the voltage-current characteristics for carbon and titanium cathodes are similar.

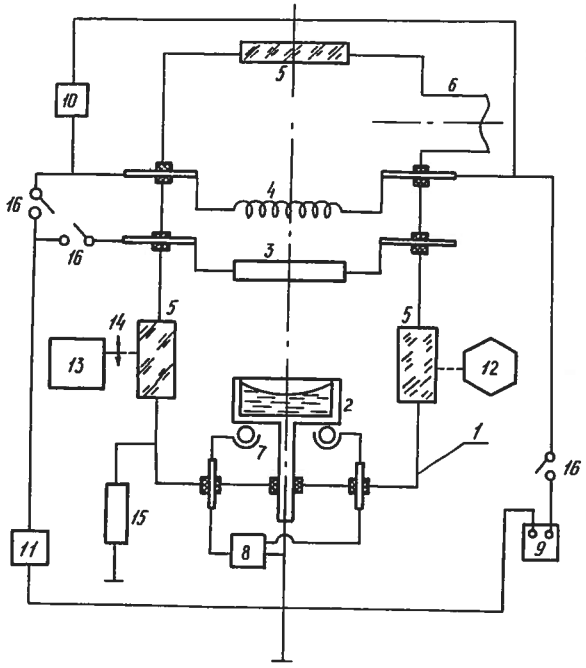



**Figure 5.** Experimental arrangement: *(1)* vacuum chamber; *(2)* electrode crucible; *(3)* anode; *(4)* tungsten electrode; *(5)* optical window; *(6)* vacuum pumping system; *(7)* electron beam heater; *(8)* high voltage source; *(9)* AC current source; *(10)* filament current source; *(11)* DC current source; *(12)* pyrometer; *(13)* monochromator; *(14)* lens; *(15)* electric resistance; *(16)* electrical key.

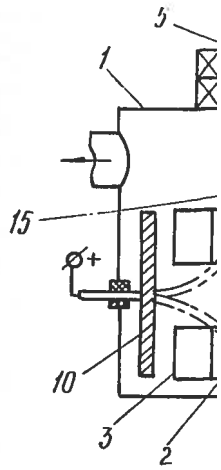



**Figure 6.** THERMION-500 SHC ap
crucible; *(3)* steering coil; *(4)* electron l
scanning lens; *(8)* plasma source with c
auxiliary anode-ionizator; *(11)* substrate
a hot cathode; *(14)* arc column using a
field.

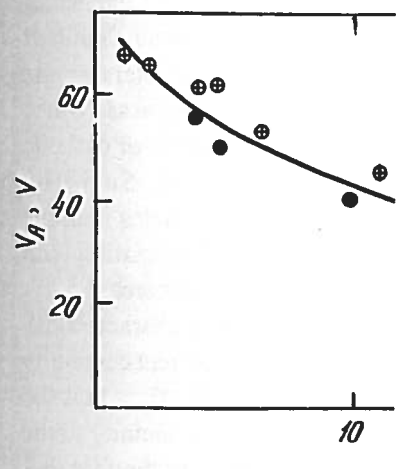



**Figure 7.** Voltage-current characteristi
or titanium (⊕) at an electron beam cu

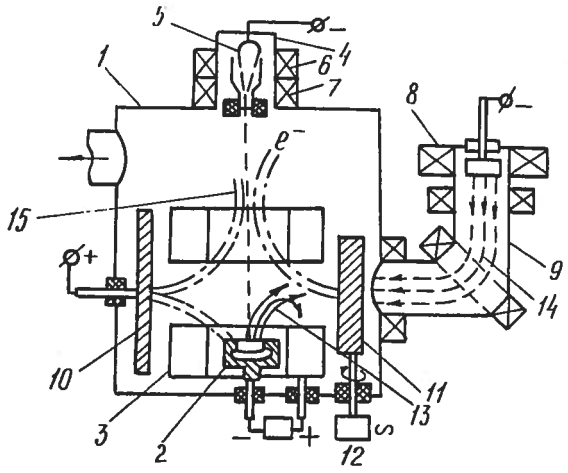



**Figure 6.** THERMION-500 SHC apparatus: *(1)* vacuum chamber; *(2)* water-cooling crucible; *(3)* steering coil; *(4)* electron beam gun; *(5)* gun cathode; *(6)* focusing lens; *(7)* scanning lens; *(8)* plasma source with cold cathode; *(9)* angular macroparticles filter; *(10)* auxiliary anode-ionizator; *(11)* substrate holder; *(12)* HF- generator; *(13)* arc column using a hot cathode; *(14)* arc column using a cold cathode; *(15)* force lines of opposing magnetic field.

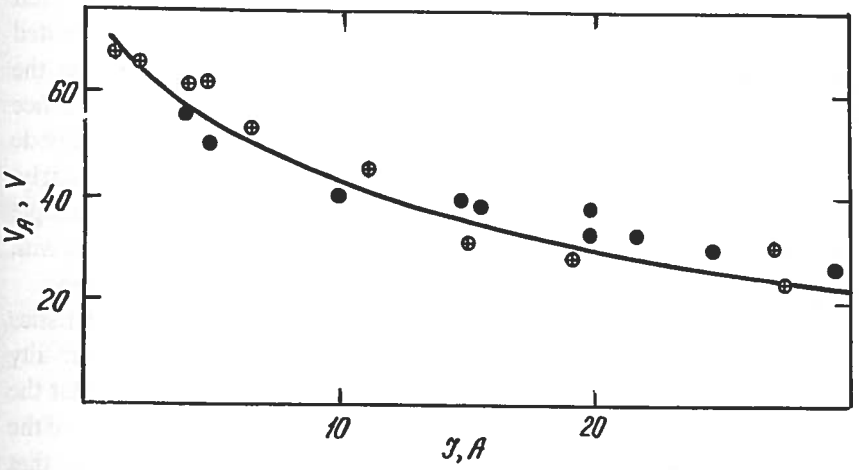



**Figure 7.** Voltage-current characteristics of the evaporated hot cathode using carbon (●) or titanium (⊕) at an electron beam current of 0.3 A.

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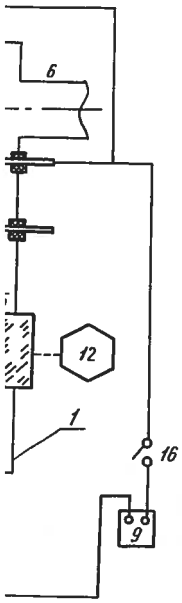


ıamber; *(2)* electrode crucible;
*(6)* vacuum pumping system;
.C current source; *(10)* filament
er; *(13)* monochromator; *(14)*

**Arcs on Cathodes with High Atom-Electron Ratios ($\xi > 1$).** Vacuum arcs with diffuse current transfer were produced using an evaporated hot cathode of chrome[9][10] and copper.[10] According to the data presented in Figure 1, at a characteristic temperature $T_c = 2000$ K, the value $\xi$ is equal to $10^4$ for copper and chrome cathodes. In this section, chrome vacuum arcs are discussed.

In Refs. 9 and 10, a chrome cathode was placed in a thermally insulated Mo crucible. A cold cathode vacuum arc was initiated with the arc gradually heating the chrome cathode. When the average temperature reached ~2000 K, the vacuum arc transformed into a diffuse arc. In this mode, the current was varied between 40 to 400 A. In this range, arc current and voltage oscillations were not observed.

Measurements of arc voltage $V_A$, cathode erosion $G_c$, ion current to the collector $I_i$, and degree of plasma ionization $\alpha$, were monitored and compared with cold cathode generated arcs. Results are shown in Fig. 8, where the hot cathode arcs have lower arc voltages which are almost independent of discharge current. On the other hand, plasma characteristics such as the ionization factor, depend significantly upon this current. Most significantly, the *ionization increases with the current* for the hot cathode while it remains practically constant in the case of the cold cathode arc.

For each cathode spot, the degree of ionization is practically independent of arc current, $I_a$, since $I_a = n_s I_s$. Here $n_s$ is the number of elemental cathodic arc spots, and $I_s$ is a constant determined by the plasma jet emitted from the cathodic arc spot. It is dependent upon such parameters as the target material, pressure, target surface temperature, and roughness. Since a cold cathode generated arc is composed of a constant number of cathode spots, the degree of ionization is a constant as shown in Fig. 8. Similarly, and as shown in Table 2 and Fig. 8, a distributed arc (which contains multiple elemental cathodic arc spots) shows an increase in degree of ionization with current, and hence the number of elemental cathode spots, is increased.

A concern is the lack of a model from which the operating characteristics of this type of source may be understood. The key problem is current continuity for cathode types with $\xi > 1$. Puchkarev, in Ref. 16, hypothesizes that the high ionization rate may be achieved if a potential hump in the vicinity of the cathode exists. Alternatively, in Ref. 12, reference is made to the fact that the higher ion formation rate can be bound up with the surface ionization of metastable chrome atoms which come to the cathode surface with an excitation potential of 2.54 eV. These problems indicate that the list of cathode materials where $\xi > 1$ and on which diffuse arcs can occur may be limited.

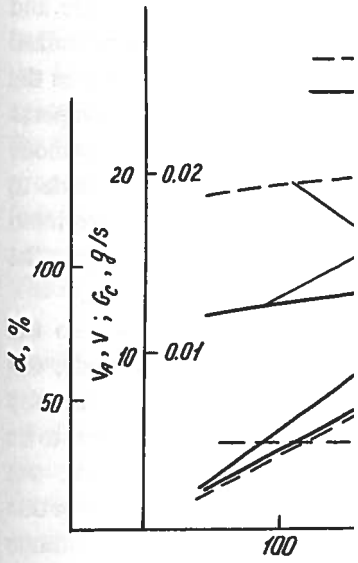


**Figure 8.** Values of arc voltage, $V_A$, cathode: *(1)* cold cathode; *(2)* hot ca

**Arcs on Hot Evaporated An**

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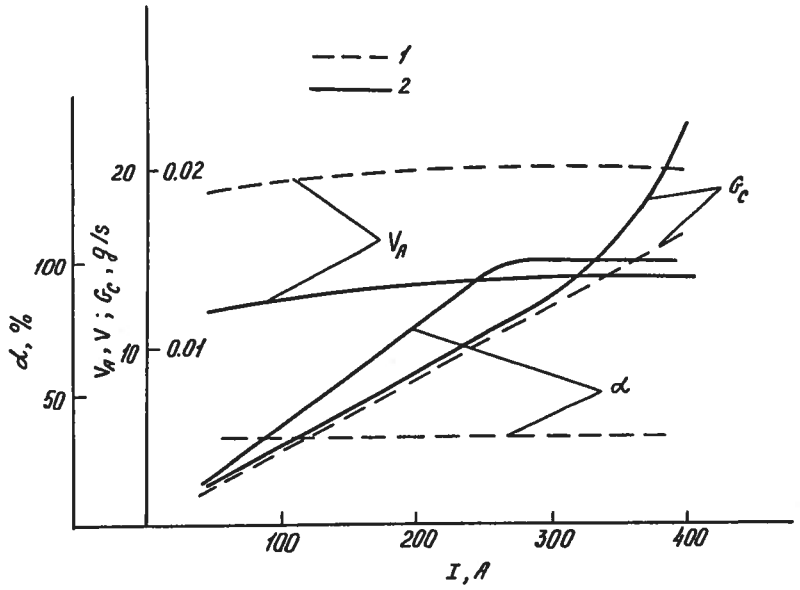


**Figure 8.** Values of arc voltage, $V_A$, cathode erosion, $G_c$, and ionization a for a chromium cathode: *(1)* cold cathode; *(2)* hot cathode.

## Arcs on Hot Evaporated Anodes

To produce a vacuum arc on an evaporated hot cathode, it is necessary to satisfy some specific requirements which depend significantly on the cathode material properties. Vacuum arcs on evaporated hot anodes are, however, less sensitive to the working electrode properties. In these arcs, the generation of the main plasma-forming medium occurs by evaporation of the anode material. Current transfer to the anode is diffuse with a relatively low average current density (1–100 A/cm$^2$). The transition requires that a large portion of the anode be heated to high temperature which can be achieved by either thermally insulating the anode or by external heating.

A vacuum arc on a hot evaporated anode occurs if the discharge current exceeds some critical value. A decrease in both the anode temperature and arc current signifies that critical values of the temperature or the anode material saturated vapor pressure exist. Conversely, when the anode temperature and vapor pressure are less then these values, this type of arc cannot exist. For a chrome self-sustained arc,[10] $I = 15$ A, $T = 1900$ K and $p = 0.5$ torr; cathode heating improves the operational parameters so that the

critical current decreases to 5 A. Similarly, the critical temperature and pressure also decrease. A decrease in pressure also decreases the ionized vapor concentration throughout the electrode gap and, in particular, in the vicinity of the cathode surface. As a result, the critical values for temperature and pressure are, to a large extent, determined by the near-cathode conditions and by the plasma concentration necessary for the cathode to operate in the arc regime. The placement of the electrodes has a profound effect on the existence of the vacuum arc on the anode. In fact, moving the anode beyond certain limits (see below) causes the arc to extinguish.

Sanders[19] has classified the anodic arc source according to the method by which ionization electrons are supplied: hollow cathode, cathodic, and hot filament. The hollow cathode arrangement described by Dorodnov,[20][21] Fig. 9, operates as a self-sustaining arc. The material to be evaporated forms the anode and is located within a hollow cathode. As discussed above, placement of the electrodes is critical to the viability of this form of vacuum arc. Thus moving the anode beyond the hollow cathode region will cause the arc to extinguish.

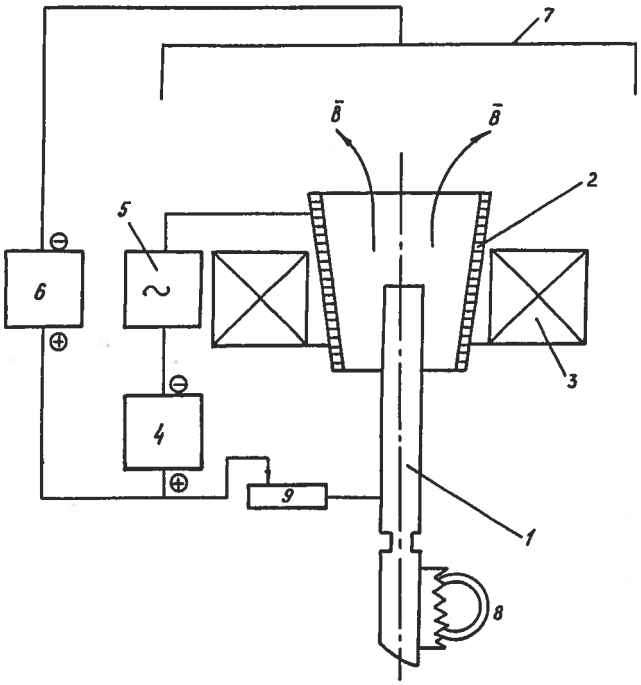


**Figure 9.** Hot anode experimental arrangement: *(1)* anode; *(2)* hot hollow cathode; *(3)* solenoid; *(4)* arc current source; *(5)* cathode filament heater; *(6)* source of shift potential; *(7)* ion collector; *(8)* anode displacement; *(9)* electrical resistor.

The anode material ev
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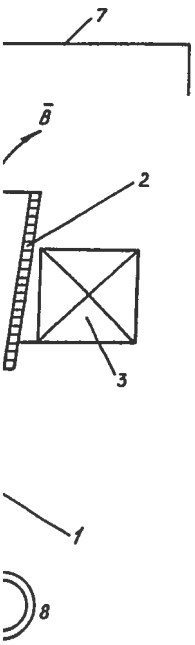


de; *(2)* hot hollow cathode; *(3)*
ter; *(6)* source of shift potential;
esistor.



The anode material evaporates by a low voltage (10–50 V), high current (~100 A) electron beam which, along with electrons trapped within the hollow cathode, ionize the vapor. Since voltages are relatively low, sputtering of the cathode is minimized. Dorodnov reports using this source for Cr, C, Mg, Ti, Mo, Si, Ge, and Cu.[21] Saenko[22][23] used this source to process substrates with diameters up to 150 mm. Derkach and Saenko[22] incorporated a divergent plasma lens which resulted in a 150 mm diameter copper vapor plasma with an ion-component beam uniformity of about 2%. The deposition rate was reported to be approximately 100 nm/s.

Operationally, a cathode made of tantalum, carbon, or tungsten was resistively heated to some working temperature. After the arc reached its operating regime, the filament would be turned off and a self-sustained arc on the hot anode was obtained. Typically the source material would be placed in a refractory crucible. The properties of arcs on the anodes made from various materials were qualitatively the same. Dorodnov[21] suggests using a hearth made of the same material as that being evaporated in order to overcome crucible contamination. For vapors originating from sources which sublime (e.g., carbon), actively cooled supports outside of the heat affected zone have been used.

Using laser absorption spectroscopy, Glaser et al.[24] was able to demonstrate that vapor emanating from an anodic arc source was comprised predominantly of single charge state ions. Two arrangements were investigated: one using a resistance source heater similar to that discussed by Dorodnov and a second which used an electron beam to heat the source material. The experimental arrangement is shown in Fig. 10 and the results shown in Table 3. Note that the actual mechanism by which the source is heated does not significantly affect either the resultant vapor fraction ionized or its distribution.

The approach taken by Ehrich et al.[25]-[27] used a cathodic arc to supply ionization electrons to the vapor stream (Fig. 11). In this arrangement, they deposited Cu and Zn films at rates between 23–65 nm/s (below that reported by Dorodnov). The films were found to be homogeneous with film purities up to 99.9% and within 10% of the bulk material density.[26] They reported an ion temperature of approximately 0.7 eV at plasma densities between $10^{15}$–$10^{17}$ /m$^3$.[27] Overall, compact films with physical properties close to that of the bulk materials were produced by this technique. Contamination of the deposited material due to cathodic bombardment was eliminated through the use of shielding (Fig. 11).[27] This along with source contamination from the containment vessel are issues that need to be addressed when designing this type of arc source.

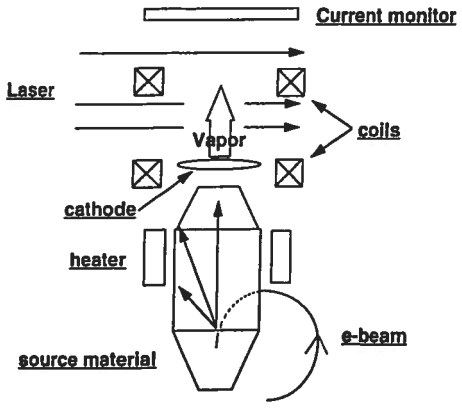


**Figure 10.** Electron beam heated anodic arc source.

**Table 3.** Source Comparison Results

| | Ion Fraction | |
|---|---|---|
| Specie | filament | e-beam |
| Cu | 0.28 | 0.32 |
| $Cu^{+1}$ | 0.70 | 0.64 |
| $Cu^{+2}$ | <0.02 | 0.04 |
| Ce | 0.03 | 0.04 |
| $Ce^{+1}$ | 0.86 | 0.86 |
| $Ce^{+2}$ | 0.11 | 0.12 |

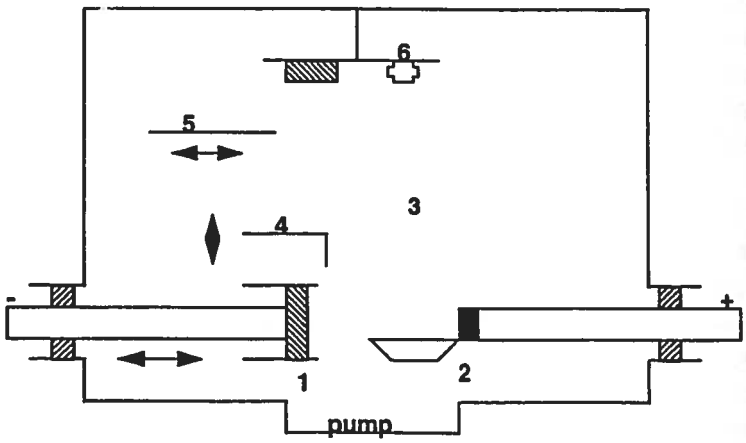


**Figure 11.** Arc discharge apparatus (following Mausbach, et. al.[27]): *(1)* moveable cathode with a cylindrical shield; *(2)* tungsten anode crucible containing the material to be evaporated; *(3)* expanding plasma; *(4)* movable cathodic shield; *(5)* substrate shutter; *(6)* masked substrate and diagnostics.

In Ref. 28, Ehrich repo
including Pb, Zn, Pt, Mo, Si a
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Figure 14 shows an ap
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In general, the relative
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In Ref. 28, Ehrich reports results from about 20 different materials including Pb, Zn, Pt, Mo, Si and C. The cold cathode was a disk made of carbon, pure materials or alloys. The characteristic arc voltage was about 20 V and was found to be almost independent of the electrode-cathode distance. Similar results were reported by Dorodnov in Ref. 21, where an arc could be observed when the arc current and, hence, the anode temperature, exceeded some critical value. For a thermally insulated copper anode, this value was 20 A. Ehrich reported that the electron temperature decreased with the distance from the anode. For an aluminum anode with an arc current of 25 A, the temperature fell from 1 eV near the anode to 0.5 eV at 30 cm away. The measured directed ion energy in the arc plasma was ~5 eV. Thus, ions with high kinetic energy, observed in a cold cathode vacuum arc, are not observed in anodic arcs. The measured ion temperature of 0.7 eV is several-fold greater than the anode temperature. The reason for these high values is not completely clear. The measured plasma ionization factor was independent of distance from the anode while the concentration of particles was inversely proportional to this distance squared. Figure 12 shows that as the deposition current $I$ is increased, the deposition rate, $d$, also increases while plasma flow ionization is decreased. The increase of $d$ indicates an increase of both the anode evaporation rate and its temperature. If anode cooling is incorporated, i.e., the anode temperature is reduced while keeping the current constant, then, as shown in Fig. 13, the deposition rate and the anode evaporation rate will decrease while the ionization fraction will rise. Thus, the thermal conditions of the anode, which determine its temperature for a given value of current, and hence the vapor density, significantly influence the vacuum arc plasma parameters. These conditions also determine the minimal critical current of the arc. For instance, for the data shown in Figs. 12 and 13, enhanced anode cooling results in an increase in the critical current, from 20 to 30 A.

Figure 14 shows an apparatus based on the hot filament concept for coating deposition.[29] Here, the anode material is evaporated via an electron beam. A thermionic cathode, located outside the substrate holder, supplies the ionization electrons for activation of the vapor and the DC arc.

In general, the relatively low (as compared with the cathodic arc technique) evaporation rate, short run times, as well as issues associated with filament lifetime, have hindered the commercial development of the anodic arc source.

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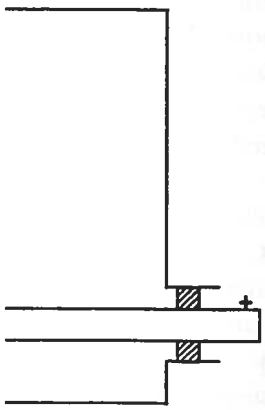


bach, et. al.[27]): *(1)* moveable
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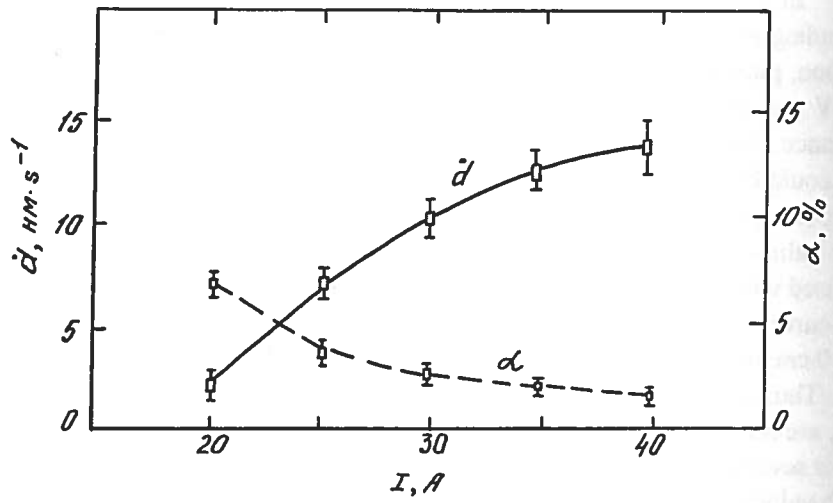


**Figure 12.** Degree of plasma ionization, $a$, and film deposition rate, $d$, for a copper anodic arc with poor anode cooling.

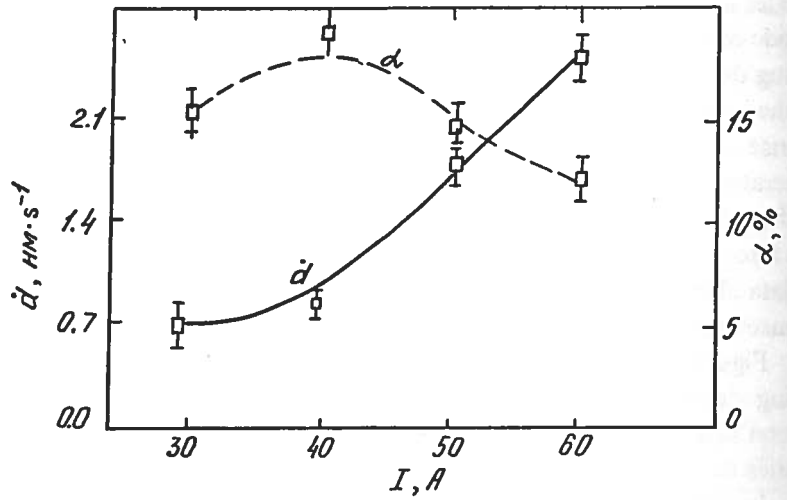


**Figure 13.** Degree of plasma ionization, $a$, and rate of deposition film, $d$, for a copper anodic arc with good anode cooling.


**Figure 14.** Hot filament source[29] substrate holder, magnetic coils

## Non-Coating Applications

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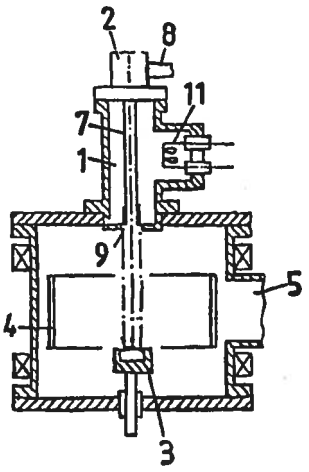
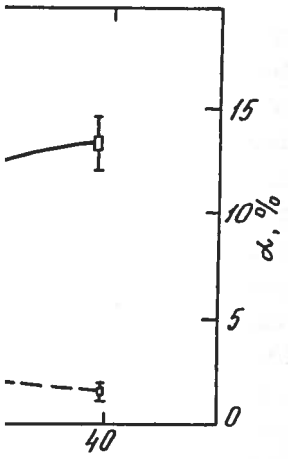



**Figure 14.** Hot filament source[29]: anode crucible, thermionic cathode, electron beam, substrate holder, magnetic coils

## Non-Coating Applications

The utility of the anodic arc lies in its ability to generate a field of predominately mono-charged ions without macroparticles. This flow of single charge state ions facilitates deposition by allowing greater control of deposition energies. This may be contrasted to the cathodic arc where multiple charge state ions exists . Deposition onto a charged substrate, in the case where multiple charge state ions exists, may result in sputter damage to the substrate. Since the charge state distribution in the anodic arc is nearly single-valued, substrate sputtering can readily be controlled. Similarly, the mono-charged nature of the anodic arc generated ions simplifies stream focusing and control. This facilitates their use in such areas as materials processing and as plasma sources in space research. An evolving area is elemental and isotope separation.[30][31] Geva et al.[30] have demonstrated a 300% enrichment of a Cu/Zn system using a 4 m long, 30 cm diameter vacuum chamber operated at $10^{-6}$ torr. Post et al.,[31] using neon gas, was able to isotopically enrich neon using a source similar to that used by Dorodnov. In Ref. 9, indirect heating of the chrome cathode by means of

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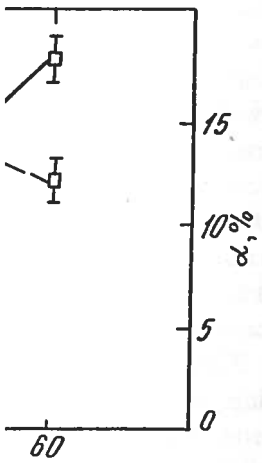


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a 25-kW RF generator was used. A non-self-sustained discharge on a hot cathode with a 200 cm interelectrode gap was placed in a longitudinal magnetic field with maximum strength of ~5000 G and used to separate chrome isotopes. As the arc current was varied from 10 to 70 A, the voltage varied only slightly, 50–55 V. When subjected to an external magnetic field, the arc plasma bent with a radius of 1.5–4 cm. Values of electron concentration in the plasma varied from $10^{12}$ cm$^{-3}$ for $I = 15$ A to $10^{13}$ cm$^{-3}$ for $I = 70$ A. The ion temperature in the plasma was estimated to be about 0.19 eV, close to the cathode temperature estimated to be ~2000 K.

Distributed arc sources, with either a hot anode or a hot cathode, produce plasmas with complementing properties to cathode spot arc sources. Macroparticle contamination is avoided without the use of throughput-reducing magnetic filters. The ion directed energy, ion thermal energy, ionization fraction, and minimum arc current are generally lower than in cathode spot arc sources, while higher evaporation rates can be achieved at the same power input. The distributed arc must be oriented vertically for most materials which are evaporated from molten sources, and avoiding crucible material contamination of the coating requires careful crucible design or material choice. While commercial applications predominately use cathode spot sources, continued research and development is apt to increase the applications of the distributed sources.

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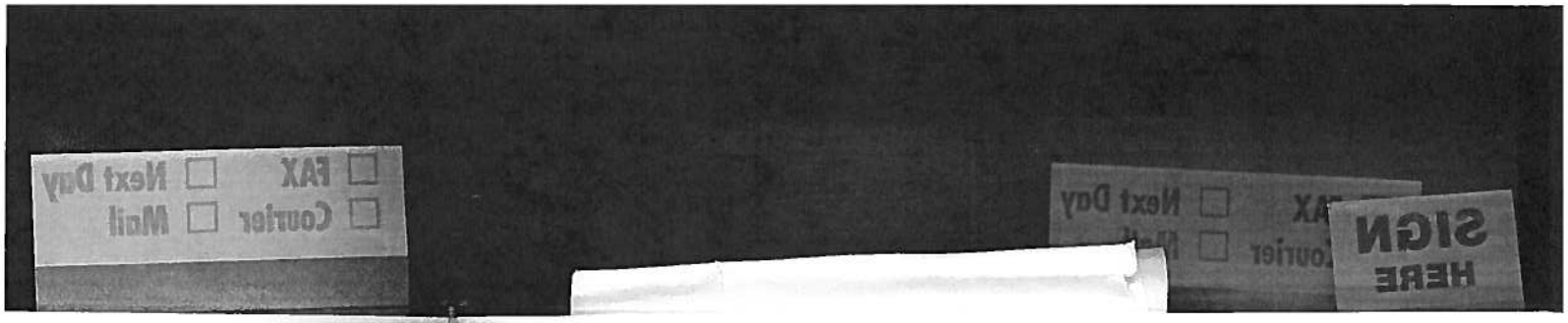

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## PULSED ARC SOURCES *(by Ian Brown)*

Vacuum arc technology can be embodied in DC arc source facilities, discussed in the preceding sections, and their well-known applications for coating processes, or at the other end of the spectrum, in pulsed sources that allow fine control over the deposition flux and thus the formation of metallic thin films and multilayers with thickness and composition tailoring down to the monolayer level. Pulsed arc technology is particularly simple and inexpensive and has found application for surface and thin film research involving the preparation of small experimental samples, as the setup time required is minimal and the amount of material consumed is insignificant. Such plasma guns can in general be physically small which is an advantage for deposition in confined spaces and allows a number of guns to be clustered together.

Repetitively pulsed sources are normally operated at low duty cycle and the mean electrical power input and heat removal requirements are much reduced compared to DC sources. Generally, they are driven by a capacitor discharge although a switched DC supply is sometimes used, too. These thermal and electrical aspects provide a rough demarcation between *pulsed* and *DC* sources typically at pulse widths of order 0.1–1 second or less. Other aspects might determine shorter pulse widths, and duty cycle plays a role, too—it's a "soft" boundary. Pulsed vacuum arc plasma sources have been made with pulse widths from sub-microsecond upwards. The physics of plasma generation at the cathode spots is basically the same for pulsed and DC sources but there are some interesting differences.

### Source Design

*Arc Geometry.* Wherea
source design, this is not so fo
(length/diameter > 1, or *rod sh*
diameter < 1, or *hockey-puck*
the duty cycle and intended in
source might be omitted com
rectly. Thus a pulsed source
The small size and cylindrical
pulsed sources, of course, an
have been made, too. The ca
same, however, and for the
generation rate is the same fo
DC source. It is not possible t
by arc current, (limited by the
are operated in a repetitively p
tion rate and the mean plasma
important to be clear about w

*Arc Circuitry.* A simp
and straightforward means o
might be needed for specific a
capacitance might be replaced
to provide a constant-current
ance might typically be one to
10 μs to 1 ms is conveniently
so is sometimes included to ke
early-time part of the curren
current. The line is charged b
1 kV, depending on the line, a
cycle requirements. Alternat
power supply can be used to
satisfactorily, too. For sub-n
of coaxial cables could be m
pulse line approach is simp
switching approach can provi
duration). In any case, consi
line and the arc source. A sc
has been used[1] is shown in
pulse produced in Fig. 2.