ELECTRON EMISSION FROM CONDUCTORS SUBJECTED TO INTENSE, SHORT-PULSE ELECTRIC FIELDS

R. D. Scarpetti, D. A. Goerz, P. R. Bowen, R. L. Hodgin, K. C. Wong
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

P.D'A. Champney
Pulse Sciences, Inc.
14796 Wicks Blvd.,
San Leandro, CA 94577

Abstract

We studied electron emission from metal electrodes subjected to electric fields ranging from 0.5 to 2.5 MV/cm for pulse durations of 3 to 10 ns. We used two high-voltage pulsers for these tests: a 500- to 700-kV, 72-Ω pulser that generated a 3-ns gaussian pulse; and a 2-MV, 60-Ω pulser that generated a 10-ns flat-top pulse with a 1-ns risetime. The high voltage levels allowed emission studies using electrode spacings of several millimeters to several centimeters. Our studies emphasized bare and anodized aluminum surfaces having surface finishes that ranged from rolled stock to machined finishes of 2-400 μin. roughness. We also investigated polished stainless steel and brass. Emphasis was on first-shot performance with subsequent pulses applied to check for possible conditioning. The background pressure was typically 5 x 10^{-5} Torr.

Our studies showed that for 10-ns pulse lengths, anodized aluminum surfaces could hold off more than twice the electric field strength of bare aluminum surfaces without appreciable electron emission. Anodized surfaces performed well at 1.0-1.5 MV/cm, while bare surfaces emitted at 0.5-0.7 MV/cm. For the shorter, 3-ns pulse lengths, anodizing was less effective at improving suppression of electron emission, while surface finish became the important factor. Electrodes with surface finishes of 40-μin. or better roughness performed well at field strengths of up to 2.4 MV/cm. The behavior of velvet cloth as an emitter was also investigated using the 3-ns pulser. We found that velvet would emit within 3 ns at field strengths approaching 100 kV/cm.

Introduction

The understanding of electron emission in a vacuum is important for two different applications: first, to improve the insulating quality of vacuum gaps, making it possible to design higher-energy-density devices and lower-inductance systems having faster risetimes; and second, to improve the electron-emission characteristics of cathode materials at lower applied electric fields leading to brighter, lower-emittance cathodes that turn on more quickly and with better uniformity. The emphasis of the work described here in on suppressing electron emission to improve high-voltage holdoff. However, we also studied the emission characteristics of velvet at low electric fields.

Electron-field emission was first treated by R. Fowler and L. W. Nordheim[1] in 1928 in terms of a quantum mechanical tunelling phenomenon. Electrons near a material surface must overcome the potential barrier, the material work function, in order to escape. An externally applied electric field lowers the barrier slightly. More importantly, it gives the barrier a finite width, which allows the electrons to tunnel through. Here we will just touch upon the theory of electron emission. There are many good articles addressing electron emission, and the reader is referred to several summary articles.[2,3,4]

Electron-emission studies fall into two main categories. The first approach uses point emitters made of materials such as single-crystal tungsten having a tip radius of several microns. If the dimensions of these points are accurately measured, both the emitting area and the electric field enhancement are well known. Because of the large enhancement factor associated with these cathodes, high electric fields are achievable using low-voltage, fast-rise-time pulsers. The second approach is to use broad-area emitters. Electrodes in this geometry are generally smooth, nearly flat, and have diameters up to many centimeters. Because enhancement is small, high-voltage pulsers are required to obtain the high electric fields. These pulsers usually have risetimes of tens of nanoseconds. Results from experiments using point emitters have in general given excellent agreement with the Fowler-Nordheim equation, but the behavior of the large-area cathodes follows the F-N curves, but only if the electric fields are 10 to 1000 times higher. To account for this discrepancy, current theory states that emission starts from microscopic protrusions, or whiskers, on the electrode surfaces, which enhances the E-field by the necessary 1-3 orders of magnitude. A more recent explanation suggests that emission occurs because of dielectric inclusions and scratches, or begins along grain boundaries. This theory came about after microscopic comparisons of the surface showed emission sites occurred not at the expected whiskers, but rather at the scratches, grain boundaries, and inclusions. Tests done on electrodes having deliberately inbedded dielectric inclusions show that electron emission occurs at much lower fields than expected.

Early on, it was observed that the turn-on time or when electron emission begins depends on the magnitude of the applied electric field. It is believed that when surfaces are subjected to intense fields, electrons are emitted from whiskers on that surface at extremely high-current densities. The emitter tips experience rapid Joule heating and explode, forming a plasma that results in large emitted currents. The turn-on time was related to the emitted current density, and hence the electric field, by the relation $t_{bd} \propto 1/j_e^2 \propto 1/E^3$, where t_{bd} is the delay time between the application of the electric field and the start of explosive electron emission.

Most of the published work to date has dealt with point emitters, or broad area cathodes with electrode spacings less than 0.1 cm, and well-conditioned electrodes. This paper reports on tests of broad-area cathodes with greater electrode spacings. The emission characteristics have been measured for electrodes subjected to electric fields ranging from 0.5 to 2.5 MV/cm from high-voltage pulses ranging from 3 ns FWHM to 10 ns in duration.

Description of Pulsers

Two high-voltage pulsers were used in this investigation. One produced a 2-MV, 10-ns flattop pulse with a 1-ns risetime; the other produced a 550- to 700-KV, 3-ns Gaussian pulse.

The 10-ns Pulser

This pulser is located at Sandia National Laboratory in Albuquerque, NM, and was designed and built by Pulse Sciences, Inc. We were permitted to use the machine for several (long, hard, weekend!!) days to conduct these experiments. The output of the 60-Ω pulser was nominally plus or minus 2 MV, with a risetime of 1 ns and a pulsewidth of 10 ns. The front end of the pulser, along with a typical output pulse, is shown in Fig. 1. The vacuum coaxial line is about 6-ns long, and the inner conductor has a diameter of about 10 cm. The test electrodes were attached to the end of this center conductor and faced a flat ground plane that also served as the major current diagnostic (see Fig. 1). The electrodes were approximately 10 cm in diameter to match the center conductor dimensions and minimize any impedance change. The test electrodes were 10-cm long with the front edge machined with a 1.27-cm radius to minimize electric field enhancement at the edge.

Diagnostics. The diagnostics included a capacitive voltage probe and a thin-foil current monitor flush mounted to the outer wall of the

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14. ABSTRACT
We studied electron emission from metal electrodes subjected to. electric fields ranging from 0.5 to 2.5 MV/cm for pulse durations of 3 to 10 ns. We used two high-voltage pulsers for these tests: a 500- to 700-kV, 72-Q pulser that generated a 3-ns gaussian pulse; and a 2- MV, 60-Q pulser that generated a 10-ns flat-top pulse with a 1-ns risetime. The high voltage levels allowed emission studies using electrode spacings of several millimeters to several centimeters. Our studies emphasized bare and anodized aluminum surfaces having surface finishes that ranged from rolled stock to machined finishes of 2-400 pin. roughness. We also investigated polished stainless steel and brass. Emphasis was on first-shot performance with subsequent pulses applied to check for ~ossible conditioning. The background pressure was typically 5 X 10- Torr.

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coaxial line. The probes were located 180° apart at the same axial location, about 5 in. from the electrode. A second thin-foil current monitor incorporated into the anode consisted of an ATJ graphite insert around which an annular resistive foil current monitor was located. The monitor has a 300-ps response time and a time constant of 230 ns. Its sensitivity ranged from several hundreds of amperes to 30 kA, which allowed it to handle the full space-charged limited current. We measured chamber pressure using an ionization gauge located in the direct vicinity of the test electrode. For these tests, with electrode spacings of 1.2 to 4.2 cm, the applied electric field ranged from 500 kV/cm to 2.0 MV/cm.

The 3-ns Pulser

The pulser shown in Fig. 2 was designed and built at LLNL. The pulser is an addition to a short-pulse electron beam machine, the Febetron 206.[5] We converted the 600-keV, 6-kA electron beam into a voltage pulse by having the electron beam current impinge upon the center conductor of a 72-Ω coaxial vacuum transmission line. This current pulse produces a voltage wave given by $I(t) \times Z_{line}$. We chose the 72 Ω because it was considerably less than the 100-Ω diode impedance to minimize the formation of a virtual cathode between the output window of the diode and the center conductor current collector. We used existing stainless-steel tube sections, 8.5 cm in diam., for the outer conductor of the transmission, and 2.54-cm-diam. stainless-steel bar stock served as the center conductor, which was supported by two lexan insulators having 30-deg angles. No special care was taken to shield the triple points at the center conductor, and no flashover occurred. We fixed the two insulators to the center and outer conductors to avoid shifting of the insulators and center conductor with respect to the outer conductor. We positioned one insulator slightly greater than one pulse width away from the test electrodes to avoid any voltage doubling at the insulator that could cause a flashover. We purposely placed the second insulator close to the other end of the line so that it would see both the incident and reflected waves causing it to flashover and produce a single pulse rather than a chain of pulses. This technique worked very well.

The test electrodes were 1 in. in diameter and 0.75 in. long and were attached to the end of the center conductor. The pulser produced a maximum open-circuit output voltage of 700 kV of 3.0-ns FWHM, having a 1.3-ns risetime. A comparison of the electron current out of the Febetron (as shown in the operations manual) with the actual pulser voltage (as shown in Fig. 3) shows that the two matched well.

Diagnostics. The diagnostics included a capacitive voltage probe located midway down the transmission line to monitor both the incident and reflected voltage pulses and another located within 120 ps of the test electrode to monitor the actual voltage as seen at the electrode. We calibrated the probe at about 5.1 V/100 kV with a time constant of 200 ns. We determined the response and sensitivity of all probes using a 2-kV, 1-ns risetime pulser. A shielded Faraday probe served as the main current diagnostic and measured the actual current emitted from the cathode electrode. The probe consisted of a 0.233-Ω, 1.5-ns transmission line. A 25.4-μ-thick aluminum foil cap isolated the probe center conductor from the electrode and any capacitive current flowed along the outside of the aluminum foil, while any electrons emitted from the cathode passed through the thin foil and set up a voltage wave that traveled down the line. The line was terminated in 50 Ω, resulting in nearly full reflection of the incident wave. The reflected signal showed up 3.0 ns later and slowly decayed. The probe could detect emitted current of less than 5 A, corresponding to less than 2 A/cm^2. The maximum current, determined by the breakdown of the low-inductance vacuum insulator located at the foil end of the probe, was about 6.0 kA. The probe had a sliding O-ring seal to permit adjustment of the probe position, setting the electrode gap spacing and hence the applied electric field. The probe's frequency response was estimated to be about 1 GHz.

For these tests, the chamber pressure was mid 10^{-5} Torr and was measured by an ionization gauge located in the direct vicinity of the electrodes. A turbomolecular pump used for pumping was attached symmetrically to the pulser line. To cause minimal perturbation to the voltage wave, the actual pump went out through a set of 2-mm holes arranged in a honeycombed fashion.

The test emphasis was to study the emission behavior of unconditioned surfaces, i.e., first-shot behavior, bare and anodized surfaces, having surface finishes ranging from electropolished SS and 2-μin. finishes to more than 400-μin. finishes. On subsequent shots, we focused on examining the effects of conditioning.

Test Results

Behavior of Electrodes Subjected to a 10-ns Pulse

Figure 4 shows the measured emission current on the first shot vs electric field strength for aluminum electrodes with various surface preparations. Bare aluminum performed poorly compared to anodized aluminum. Aluminum coated by the type III[6] anodizing process performed best, emitting 5-30 A/cm^2 at field strengths of 1.0 to 1.4 MV/cm. Surfaces coated by the Type II process or anodized with the Type III process followed by a Type II process performed better than bare metal, emitting 25-100 A/cm^2 also at field strengths of 1.0 to 1.4 MV/cm. Bare aluminum emitted as much as 50 A/cm^2 at 0.7 MV/cm. For all cases, the time between the onset of the voltage pulse and the onset of detectable electron emission stayed fixed at about 4 ns. This delay was easily determined by measuring the time between the appearance of the electrode displacement current caused by the voltage rise and the appearance of the emitted current.

Variations in the substrate finish from 4 μin. to 63 μin. and variations in anodized layer thickness had, at best, a weak effect on electrode behavior. This is in agreement with earlier results[7] using a 50-ns, 500-kV pulser.

The performance of bare aluminum degraded after the first shot when it was subjected to fields of 0.5 to 0.9 MV/cm for 10 ns. The increased emission on subsequent shots is shown in Fig. 5, along with a comparison of the emission from bare aluminum when subjected to a 50-ns pulse as studied by Frazier.[7]

Unlike bare surfaces, conditioning of the anodized surface occurs with repetitive high-voltage pulsing.

The conditioning, shown in Fig. 6, is likely caused by a cleaning up of the electrode surface by the desorption of surface gases due to the previous pulse.

Behavior of Electrodes Subjected to a 3-ns Pulse

The electrodes tested included bare and anodized aluminum having surface finishes of 2 μin., 44 μin., and rolled stock finishes; stock brass surface; and polished stainless steel. We obtained the stock surface by "cookie cutting" the electrode out of rolled plate and machining all but the electrode area facing the anode.

The first shot data of the emitted current density vs the applied electric field plotted in Fig. 7. The 2-μin. anodized aluminum performed well, emitting 320 A/cm^2 at 2.4 MV/cm, which corresponds to 1.7% of the possible space-charge-limited current; the stock anodized electrode performed almost as well, emitting 400 A/cm^2 at 2.3 MV/cm (2.2% of the space-charge-limited current). The 400-μin. bare aluminum performed worst, emitting 2263 A (58% of the space-charged limited current) at 0.9 MV/cm. Other high emitters included the 44-μin. bare aluminum and the stock brass electrodes. There is an improvement with anodizing and, as expected, the surface finish is also important.

Conditioning occurred on subsequent shots. For all cases, the emitted current dropped with increasing shot number at the same applied field. When the field was increased, the emitted current increased but then decreased on the next shot. This was likely caused by a cleanup of the surface by the removal of absorbed and adsorbed gases on the bare metal surface and in the porous oxide coating.

The results of a series of shots made using a polished stainless-steel electrode are show in Fig. 8, clearly showing conditioning. The first shot at 2.4 MV/cm resulted in 600 A emitted, while only four shots later, 80 A were detected at 2.4 MV/cm.

Occasionally, a two-pulse burst was made when the first insulator failed to flashover with the doubling of the voltage pulse. The pulses occurred separated by the wave round-trip transit time in the pulser of approximately 10 ns. This resulted in a dramatic increase in

the emitted current. The result of a two-pulse burst is as follows. The first pulse produced a 1.7-MV/cm electric field and resulted in an emitted current of 193 A. Ten-ns later, a second, reduced voltage pulse arrived, producing a field of 500 kV/cm, and 1200 A were emitted. The first pulse produced a cathode flare partially filling the gap with plasma, and this resulted in a greater emission on the second pulse. This behavior was first studied by Mesyats et al.[8] using needle cathodes and a voltage of 30 kV.

Velvet (Cloth Fiber) Cathodes at Low Electric Fields

Velvet cathodes were found by Alder et al[9] to be very good emitters at electric fields of 100 kV/cm. They found that the emission from the fiber cathode matched the 30-ns rise time of the voltage pulse. We studied the behavior of velvet cathodes to determine how well they would emit when subjected to the 3-ns FWHM pulser. We attached the velvet to a stainless-steel electrode using transfer tape keeping it flush with the electrode surface. We tested several rayon-cotton mixes as well as several colors, and they all behaved similarly. With a 0.5- to 1-cm spacing, the field was varied from 700 kV/cm to 85 kV/cm by adjusting the pulser charge voltage. The ratio of emitted current to the space-charge limit current is shown in Fig. 9. Note that we obtained full space-charge limited current for fields above 400 kV/cm. At these levels, the emitted current followed the 1.3-ns rise time of the voltage pulse. Below 400 kV/cm, emission from the velvet lagged the voltage pulse until, at about 100 kV/cm, we detected no current (i.e., less than 5 A). When we sprayed the velvet with a graphite spray, we detected 30 A at 95 kV/cm.

Summary

For 10-ns-duration pulses, anodized aluminum surfaces perform better than bare metal surfaces. Bare aluminum degrades after the first shot at field strengths less than 1.0 MV/cm, while anodized surfaces condition on subsequent shots at fields from 1.0 to 1.4 MV/cm. Variations on substrate finishes and anodizing layer thickness had a weak effect on electrode behavior.

For 3-ns pulses, anodizing improves electrode performance, but has a lesser effect than at longer pulse lengths. Surface finish is also important. Conditioning is seen on both bare and anodized surfaces for these short pulses.

Velvet cathodes "turn-on" in less than 1.3 ns at fields greater than 400 kV/cm. At field strengths of less than 100 kV/cm, no emission was detected from velvet. Spraying the velvet with graphite resulted in electron emission at 95 kV/cm.

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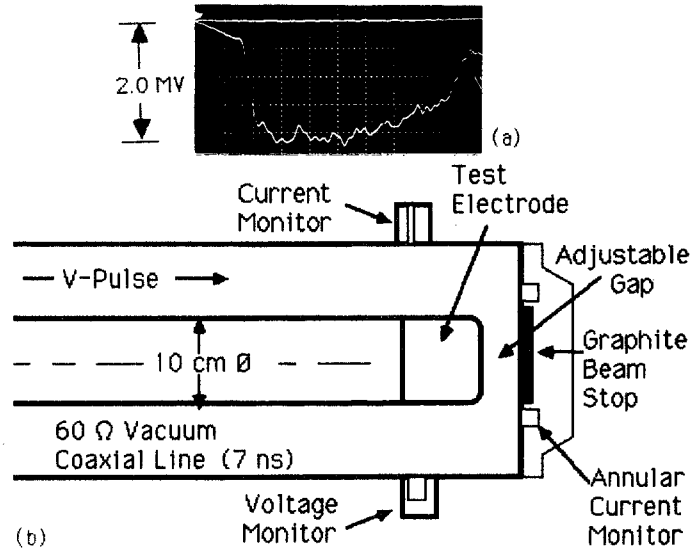

Fig. 1. Experimental setup. (a) Voltage waveform 2-ns/div; (b) output transmission line of the 10-ns pulser.

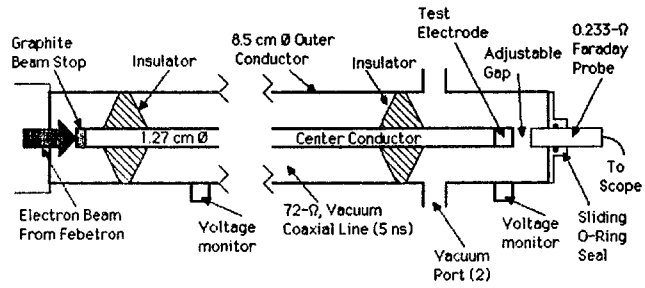

Fig. 2. Experimental setup of the 3-ns pulser.

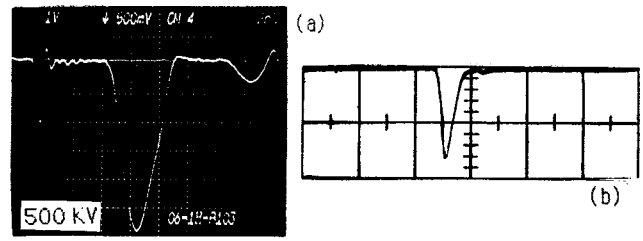

Fig. 3. The 3-ns pulser output voltage. (a) 2-ns/div matches nicely to the input current waveform; (b) 10-ns/div.

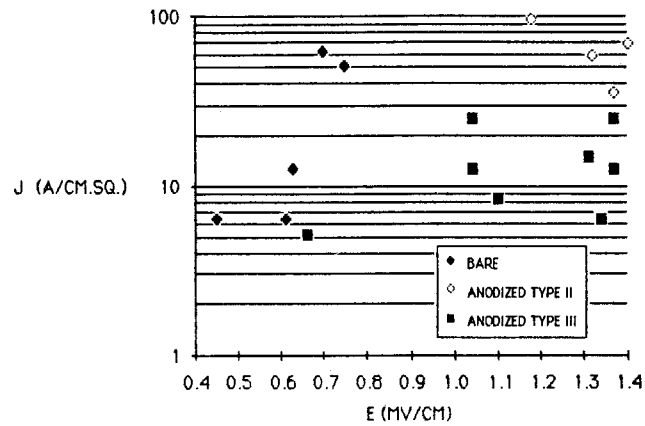

Fig. 4. First-shot data for electrodes subjected to the 10-ns E-fields. Type III anodized aluminum performs best.

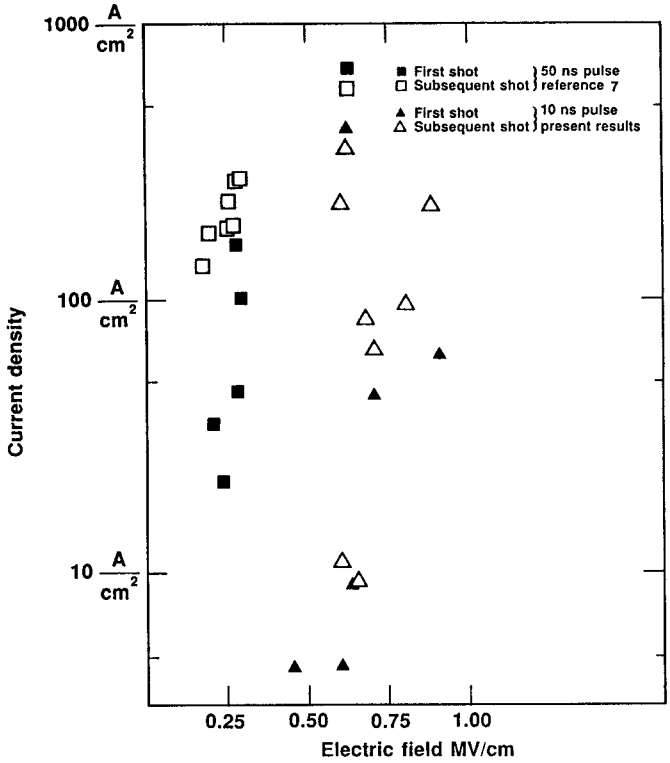

Fig. 5. The performance of bare aluminum surfaces degrades on subsequent shots when it was subjected to fields of 0.5 to 0.9 MV/cm for 10 ns. This is compared with 50-ns-pulse results.

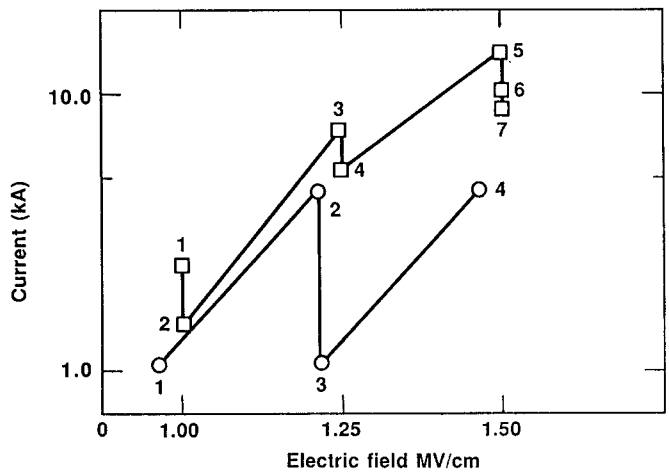

Fig. 6. Conditioning occurs for anodized surfaces when subjected to fields of 0.9 to 1.5 MV/cm for 10 ns.

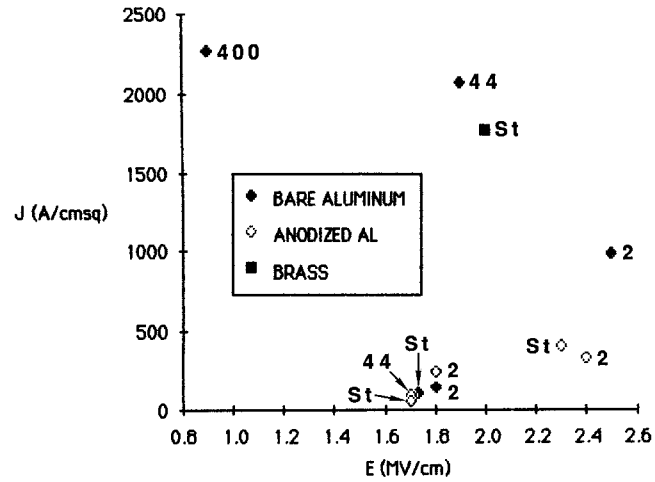

Fig. 7. First-shot data for electrodes subjected to the 3-ns E-fields. Numbers denote surface finish; St denotes stock surface.

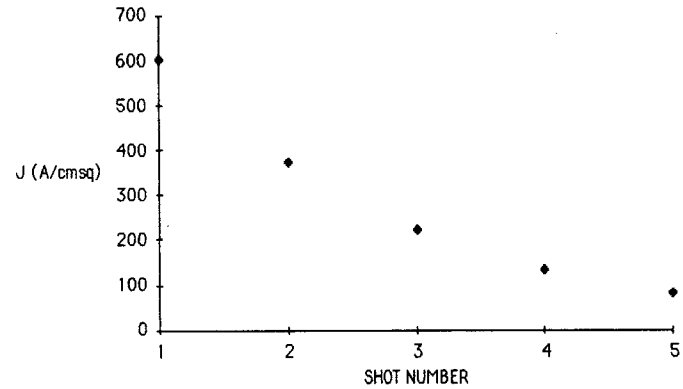

Fig. 8. Conditioning of polished stainless steel subjected to repetitive 3-ns pulses at 2.5 MV/cm.

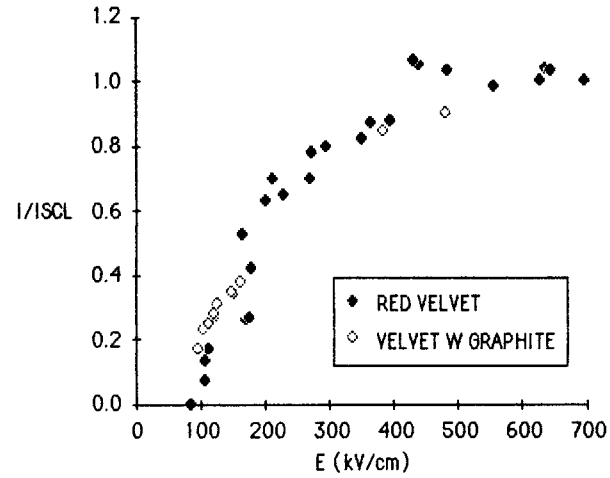

Fig. 9. Performance of velvet cloth cathode subjected to a 3-ns voltage pulse.