GENERAL ELECTRIC
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THE PLASMA ELECTRON BEAM SOURCE AND ITS APPLICATION TO VACUUM METALLURGY

by

M. A. Cocca and L. H. Stauffer*

Report No. 63-RL-3380 M July 1963

CLASS 1

*Advanced Technology Labs.

SCHENECTADY, NEW YORK

GENERAL ELECTRIC
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July 1963

Published by
Research Information Section
The Knolls
Schenectady, New York

ABSTRACT

Some time ago the Advanced Technology Laboratories announced development of an electron beam cathode which was capable of generating a beam in a low-pressure inert gas atmosphere. The cathode can generate a beam without being heated to temperatures at which electron emission would occur, but instead draws upon a gas plasma as a source of ions that cause electron emission.

The first part of this report summarizes the results of experiments conducted at Advanced Technology Laboratories aimed at gaining a fundamental understanding of the electrical properties and behavior of the cathode. The remainder of the report sets forth the results of metallurgical processing experiments which serve to provide a measure of the processing capabilities of the apparatus.

High-intensity electron beams were generated, producing beam power levels of over 30 kw. The cathode is rugged, simple, and versatile and, as a process tool, provides the inherent advantages of hot cathode electron beam devices without some of the limitations, in performing a variety of processing operations including melting, welding, sintering, and heat treating.

Manuscript received June 20, 1963.

THE PLASMA ELECTRON BEAM SOURCE AND ITS APPLICATION TO VACUUM METALLURGY

M. A. Cocca and L. H. Stauffer*

INTRODUCTION

Technological advances in the last decade have created a demand for metals and alloys that will provide high strength at high temperatures. Elements such as molybdenum, columbium, tantalum, and tungsten and their alloys are finding increased uses in a broad variety of applications, such as structural components in missile and space vehicles. The refractory and reactive properties of these materials require process equipment which provides high temperatures and controlled environments. One process which has come into prominence which embodies the aforementioned conditions uses electron beams as the energy source. Beams having energies of 10 to 100 kv or more are finding increased application where very high power densities are needed. For melting, refining, and heat treating of refractory metals in vacuum, electron beams can deliver kilowatts of highly concentrated beam power to the workpiece.[1, 2] In welding applications these beams deliver several tens of thousand kilowatts per square inch[3] of concentrated energy at a focal spot a few mils in diameter. Such beams are generated by electron guns employing heated cathodes of tungsten or some other good thermionic emitter. The guns use electrostatic lens systems for forming the beam and may employ additional electrostatic or magnetic lenses to further concentrate it into a small focal spot.

Generally, hot cathode guns are limited to operation at pressures of 10^{-4}† torr or less, for various reasons. In the highly concentrated electron beams, space charge spreading becomes a problem and mutual repulsion of electrons in the beam tends to limit the current density which can be achieved in the normal high vacuum environment. In addition, the hot cathode and other components, such as filaments, are run at extremely high temperatures and are susceptible to oxidation, contamination, and possible total failure if pressure bursts occur in the system. Such pressure bursts are frequently encountered due to removal of gaseous impurities from the material being treated.

Within the past year the General Electric Company and the Martin Company independently announced developments in the field of cold cathode electron guns which may have wide applications in science and industry.[4, 5] These electron beam sources use a cold cathode in the form of a hollow perforated cylinder or sphere with a small circular hole from which the beam emerges. They do not operate in a high vacuum as does a hot cathode. Instead, an inert gas such as argon or helium is employed at low pressure (10^{-3} to 10^{-2} torr or higher). On

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† 10^{-3} torr = 1 micron.

application of a high d-c potential, a well-collimated electron beam is formed in the low-pressure gas atmosphere. A proper, though not critical, range of adjustment of gas pressure and cathode voltage is required to maintain collimation and stability in the beam. Depending on cathode design, beam currents may range from milliamperes to amperes with cathode potentials of 10 to 20 kv or more.

This report will describe the results of experiments conducted to better understand the physical properties and operational characteristics of the cathode, and also the results of preliminary experiments which utilized a plasma electron beam cathode in metallurgical applications in order to appraise its applicability to materials processing.

BASIC EXPERIMENTS

Preliminary experiments were carried out with a demountable apparatus, schematically illustrated in Fig. 1. Cathodes of various sizes, made of perforated sheet or wire mesh, have been tested. Copper, aluminum, stainless steel, and molybdenum cathodes have been tried in several inert gases. Collimated electron beams can be readily produced with all of these metals in helium or argon. For very high beam currents, stainless steel or molybdenum mesh is preferred because it can better withstand the heating due to positive ion bombardment.

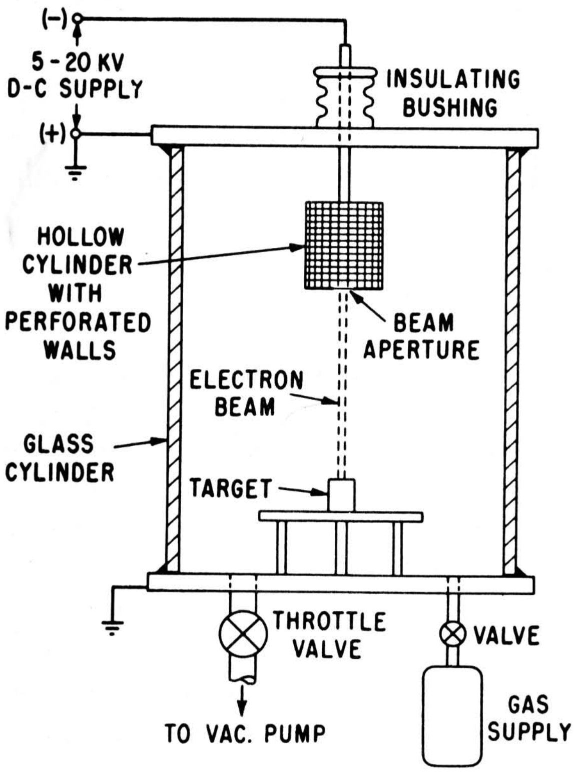

Fig. 1 Schematic of experimental assembly.

Most of the experiments were done at moderate power inputs (500 to 1000 watts) with cylindrical cathodes about 1 inch in diameter. The largest cathode tested was 3 inches in diameter and 4 inches high with a 5/16-inch aperture. This cathode was used for melting experiments that are described in a later portion of the report.

BEAM FORMATION

Formation of the plasma electron beam is associated with the interaction of ionized regions inside and outside the cathode with electric fields between its perforated surface and the plasma boundaries. Positive ions formed in the beam path by electron collisions with gas atoms play an important role in beam collimation by neutralizing the negative space charge which would otherwise cause beam spreading.

Figure 2 shows an experimental cathode made of 40-mesh, 10-mil stainless steel screening emitting a self-collimating electron beam in helium at approximately 15 microns pressure.

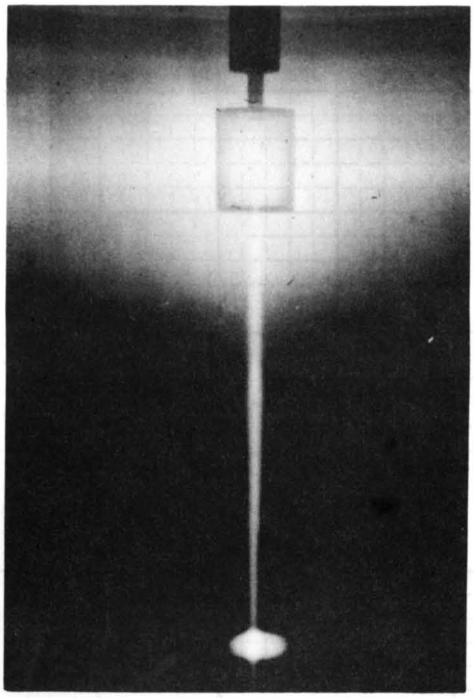

Fig. 2 Electron beam emerging from cathode with no external focusing.

This cylindrical cathode measures 1 1/8 by 1 1/2 inches and has a 1/4-inch beam exit aperture. A stainless steel stem extending through an insulating bushing supports the cathode from an aluminum cover plate which, with other parts of the system, acts as the anode. This cover plate together with a large glass cylinder forms a bell jar to which selected gases can be admitted at pressures in the micron range. An oil diffusion pumping system is used to evacuate the chamber.

When the gas pressure and cathode voltage are adjusted properly, the beam mode of operation sets in and the electron beam path is marked by the luminosity of excited atoms in its path. Ordinarily, the gas density is too low to cause appreciable scattering of the beam. Beams up to 30 inches in length have been produced by this method with little spreading. The focusing effect of positive ions in the beam path is an important factor in maintaining collimation.[6] Typically, the beam cross section is about the size of the exit aperture, although it can be made smaller by adjustment of pressure and cathode voltage.

At pressures and voltages outside the range of the beam mode a more or less diffuse glow discharge is obtained. In argon the beam mode is most easily supported at pressures from 3 to 10 microns with applied voltages from 5 to 10 kv depending on gas pressure and cathode characteristics. In lighter gases such as hydrogen and helium the beam mode is obtained at higher pressures (10 to 100 microns). Beam currents range up to 2 amperes for a 3-inch cathode in argon with 20 kv applied. Divergent or convergent beams may be obtained by adjusting the gas pressure or cathode voltage.

In general, it was found that larger cathodes can produce higher beam currents at higher voltages before instability is encountered. The beam current increases with voltage until a runaway buildup of current sets in. At this point, a more or less homogeneous glow discharge replaces the beam mode. This is illustrated by the volt-ampere characteristics of Fig. 3. For these measurements, a 5800-ohm ballast resistor was placed in series with the cathode to stabilize the discharge.

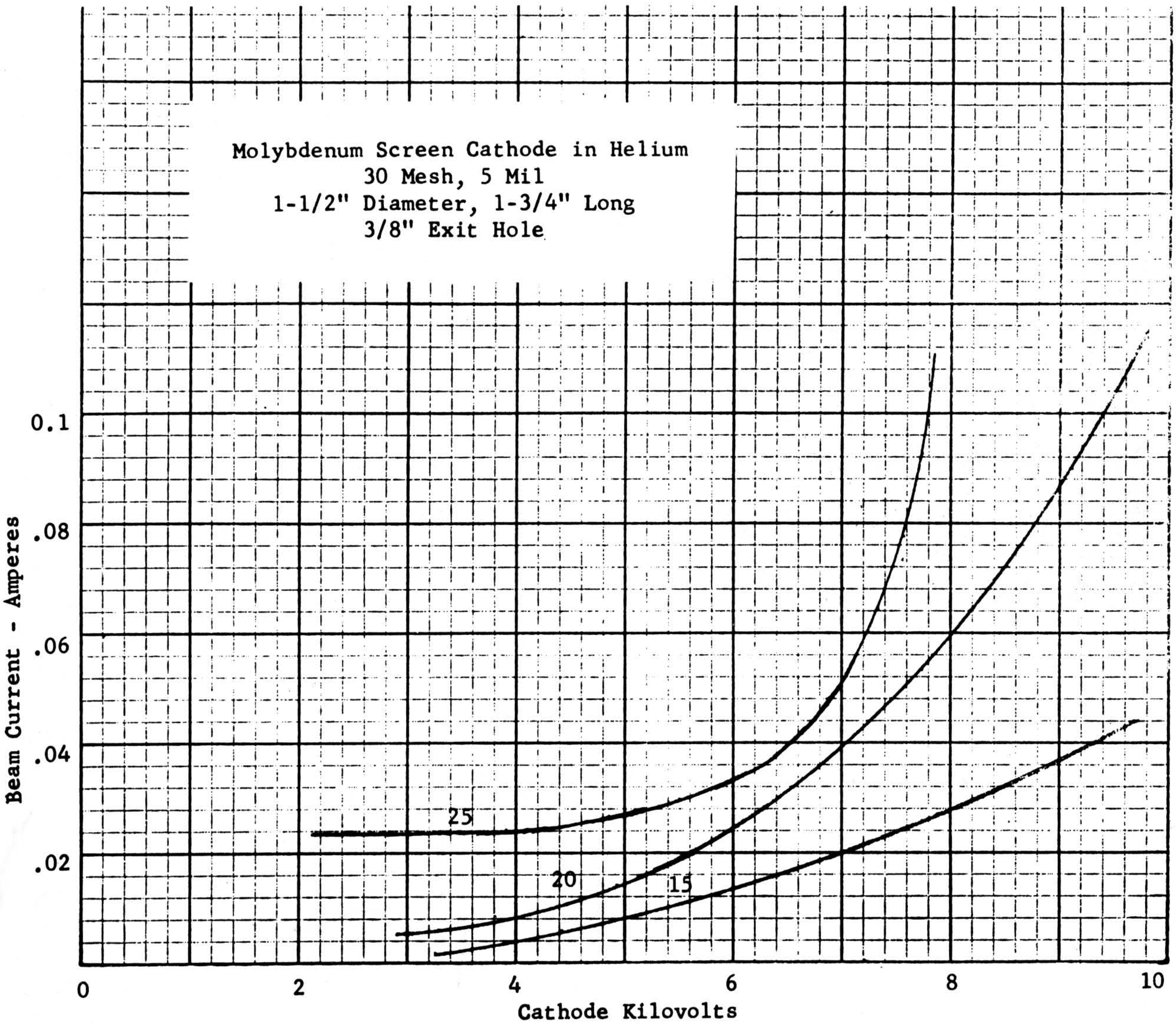

Fig. 3 Current-voltage characteristics for the beam mode at various pressures. Attached numbers give helium pressures in microns.

CATHODE CONSTRUCTION

Several different cathode designs have been used successfully. Some of them are shown in Fig. 4. For power levels of 2 kw or less a cylindrical cathode made from perforated stainless steel sheet has been found convenient. Construction is very simple, the parts being cut to shape and assembled by spot welding. Cathodes are supported by a coaxially shielded lead as shown in Fig. 5 in order to prevent a discharge from the supporting high-voltage rod. High-power cathodes are usually made from molybdenum wire mesh using solid sheet molybdenum end plates. Assembly is by means of spot welding, using tantalum foil between the molybdenum parts to facilitate the welding. Two interesting variations are shown in Fig. 4, a long, slotted cylinder, and a squirrel-cage type. The cylinder was used to produce a sheet beam for use in a plasma ionization experiment, while the squirrel-cage construction was a prototype for

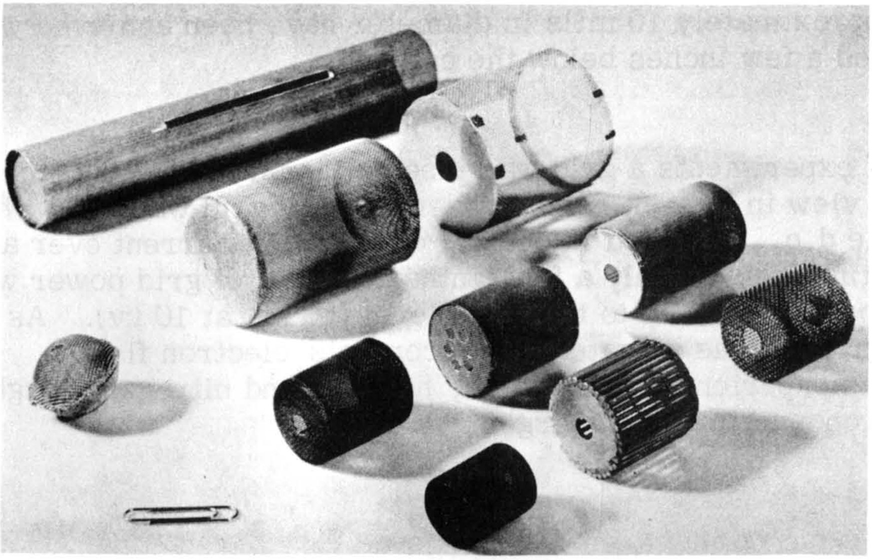

Fig. 4 Cathodes made of wire mesh and thin perforated sheet metal.

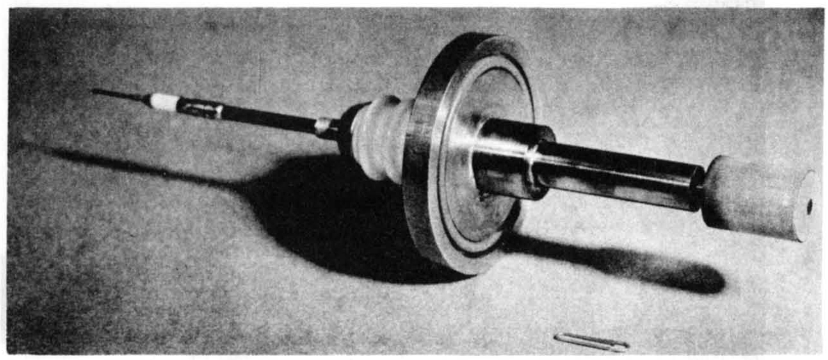

Fig. 5 Cathode assembly with sealing flange and bushings.

a water-cooled cathode for extremely high power operation, using tubing instead of rods.

BEAM FOCUSING

With no auxiliary focusing the spot size of the electron beam can be varied from less than 1/8 inch to as large as desired by adjusting the cathode potential over a range of a few per cent at any given pressure. The self-focusing property of the plasma electron beam is due to the combined action of two factors: positive ion space charge near the aperture and in the beam path, and the electrostatic lensing property of an aperture separating regions of different potential gradients.

Beam focusing is dependent upon cathode voltage and variation in voltage gradients in the plasma surrounding the cathode. A more detailed explanation of this and other beam characteristics is given by Stauffer et al.[4, 7]

To achieve adjustable beam focusing without the necessity of changing the cathode voltage, and hence the electron velocity, a simple magnetic lens may be used. Because the beam is already collimated, or slightly divergent, the lens need not be a strong one. Only a few hundred ampere turns are needed to focus the beam. Spot sizes approximately 10 mils in diameter have been achieved with a short solenoid supported a few inches below the cathode.

GRID CONTROL

In one series of experiments a grid was inserted inside of the cathode as is shown in the exploded view in Fig. 6. A molybdenum wire grid was used which, when biased with variable d.c., resulted in control of the beam current over a wide range without affecting focus. Only a few tenths of a watt of grid power was required to control the beam power up to the 5-kw level (50 ma at 10 kv). As in an electronic tube, the grid acts as a "gate" which controls electron flow. Similar grid behavior was experienced with argon, helium, and nitrogen though control action is most pronounced with the argon.

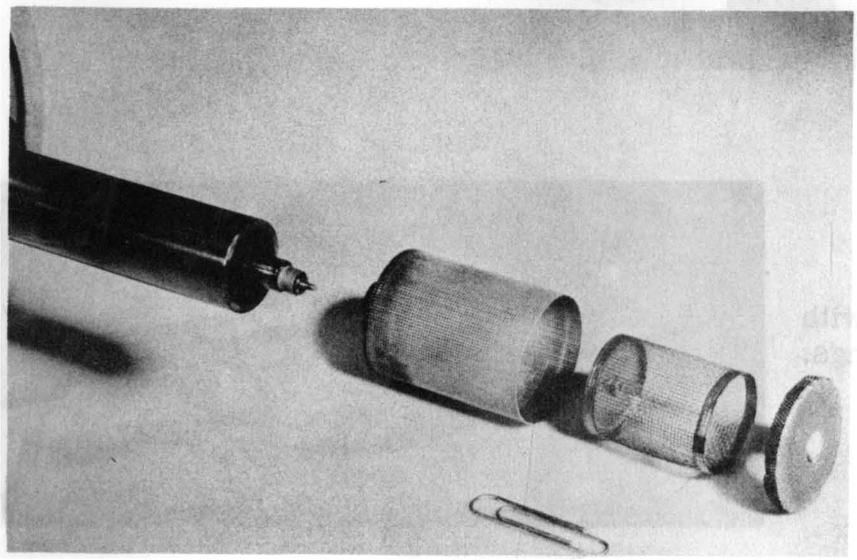

Fig. 6 Exploded view of grid-controlled cathode assembly.

ORIGIN OF ELECTRONS

Because the cathode operates at temperatures too low for appreciable thermionic emission, other mechanisms must be looked for to explain the origin of the beam. While the plasma inside the cathode may supply a small fraction of the electrons most of them must come from the inner cathode surface. This is borne out by observed suppression of the beam current on application of a negative grid potential. Most of the electrons from the inside of the cathode are suppressed when a negative bias of 8 volts is applied. This suggests that low-energy secondary electrons produced by high-energy ion bombardment or photoelectrons (or both) make up the bulk of the beam current.

Cathodes with oxide films or other deposits become clean after a few minutes of operation. This indicates that positive ions drawn out of the surrounding sheath are accelerated to high velocities and, by entering the perforations and the aperture, bombard both the inside and outside surfaces of the cathode. Foreign surface layers are quickly removed from the cathode surfaces by the impact of ions from the discharge. More important, however, is the possibility for a single energetic ion to remove one or more electrons from metals such as molybdenum.[8] This together with photoelectrons ejected by the spectrum of ultraviolet light emitted by the discharge may well account for the entire cold emission from the cathode. Also it should be pointed out that the cathode is subject to a flux of soft x-rays from the target which could account for considerable photoemission.

Even though the combined areas of all of the perforations or mesh openings total many times the area of the beam aperture, only a small fraction of total cathode current is accounted for by electrons escaping through these small openings. These electrons are accelerated outward from the cathode and, by collisions, ionize the surrounding gas. A continuous supply of positive ions is thus maintained. A large portion of the electrons are not stopped by gas collisions and these strike the walls. This is evidenced by fluorescence and slight heating of the glass walls in the bell jar experiments.

Experiments with apertures of different sizes, and with multiple apertures in a single cathode, have shown that the beam seeks out the largest aperture and that emission from other apertures is suppressed. Once the external beam is established its space charge constricts the boundaries of the cathode dark space near the aperture and enhances the field strength to extract electrons from the internal plasma. While there is a continuous replenishment of electrons to the internal plasma from the cathode walls, the space charge balance remains on the positive side when the beam mode predominates.

APPLICATIONS

The unique characteristics possessed by this type of electron gun in considering its potential process applications are:

1. Insensitivity to contamination.
2. Ability to operate in a partial vacuum (pressures to 100 microns in hydrogen or helium).
3. Grid control of beam intensity.
4. Self-focusing properties.
5. Good depth of focus.
6. Ruggedness and simplicity.
7. Design flexibility to provide various beam configurations.

Some of its characteristics may also be listed as disadvantages:

1. Gas pressure and cathode voltage must be regulated.
2. Chamber walls must be spaced several cathode diameters from the cathode.

Among the obvious applications are electron beam welding, melting, and refining of refractory materials and chemical processing. Other possible applications such as microwave generation by plasma interaction, light source excitation, and ionization of gases are being explored.

For welding, the plasma electron gun offers the advantage of a long beam with a small angle of convergence which can be focused on remote parts of the work with less interference than would be encountered with a highly convergent beam with less depth of focus. Beam control by biasing the grid in combination with a variable focus magnetic lens provides for independent adjustment of total beam power and power density at the focal spot. By operating at voltages below 25 kv only soft x-rays are generated that are absorbed by relatively thin metal or glass walls.

To provide additional flexibility for the cathode in applications where large gas pressure fluctuations occur or where different gases are used over the work, a differential pumping arrangement may be employed. Figure 7 shows one possible arrangement in which the beam passes through two small apertures which have higher impedance to gas flow than the pumping outlets. Gas, sufficient to sustain the discharge, is admitted into the upper chamber in which the cathode is located. This arrangement would be equally useful for melting, zone refining, or sintering operations.

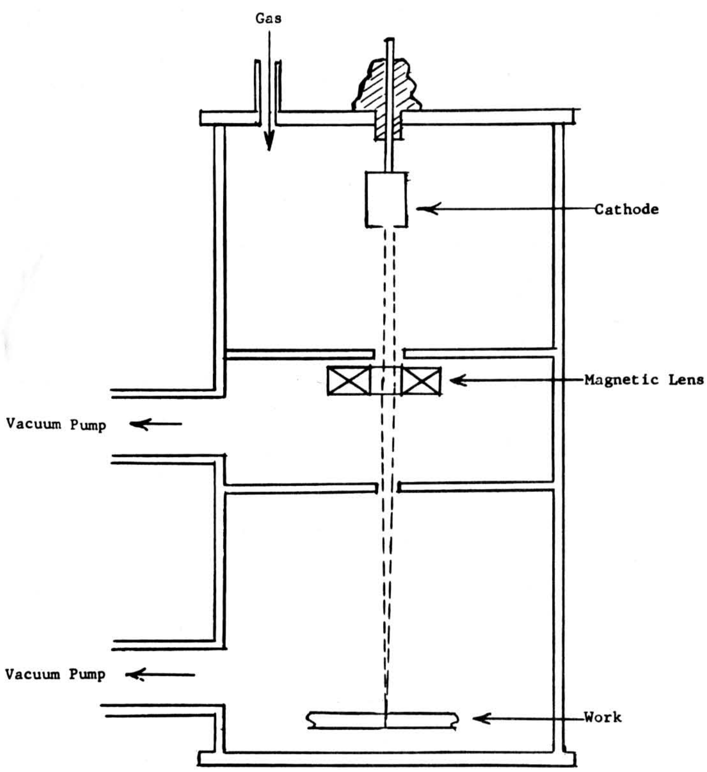

Fig. 7 Pressure stabilization by differential pumping.

MELTING EXPERIMENTS

To determine feasibility of using the plasma electron beam for metallurgical process applications requiring higher power levels, a number of melting experiments were conducted. A conventional electron beam melting furnace in use at the Research Laboratory was temporarily converted to accommodate the plasma cathode. As shown in Fig. 8, the conventional gun was removed from the water-cooled furnace chamber. A cover plate in the top of the chamber was fitted with a porcelain bushing which supported a

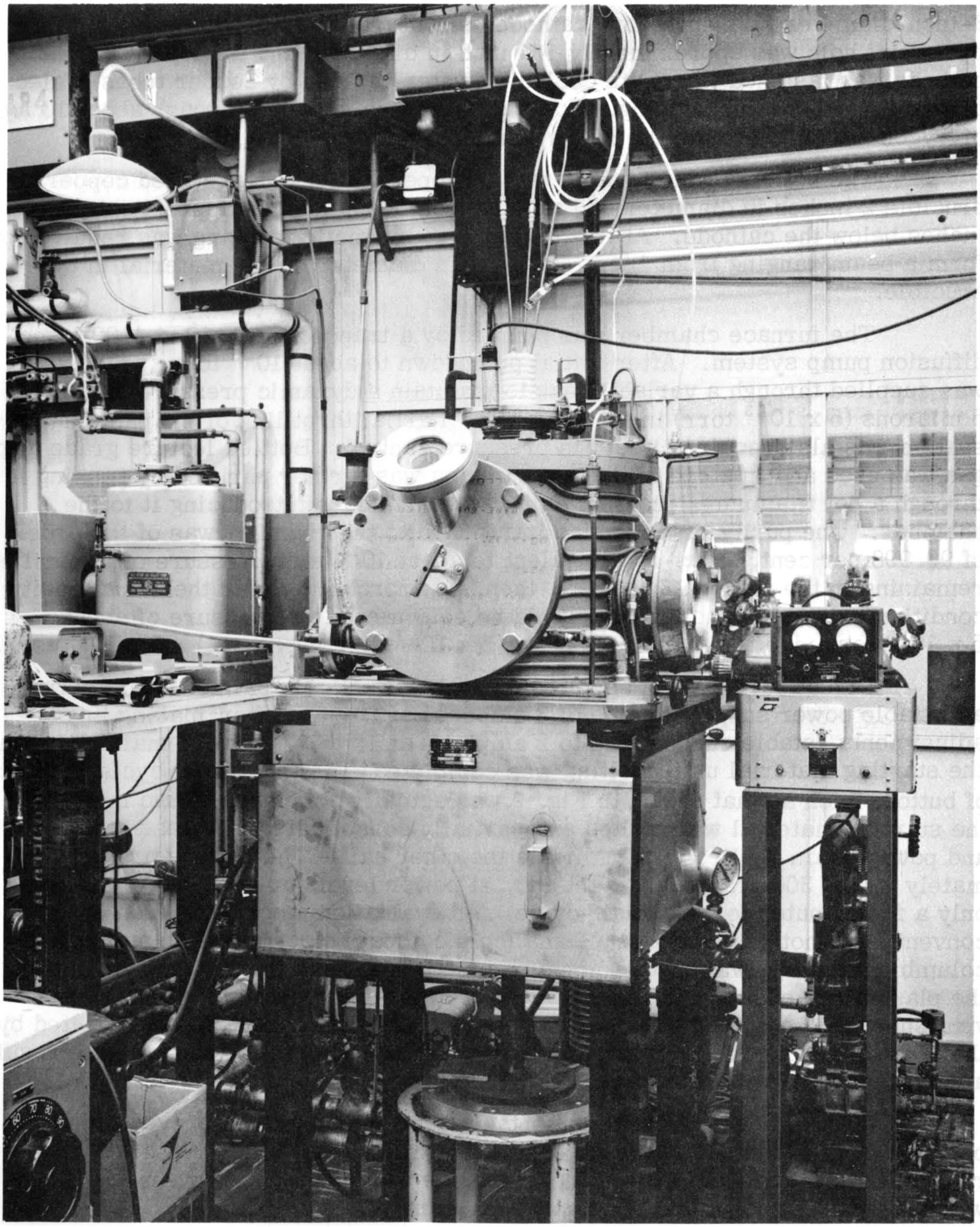

Fig. 8 Electron beam melting furnace chamber equipped with plasma cathode.

3-inch-diameter by 4-inch-long cathode, similar to that shown in Fig. 5. The beam exit hole was approximately 1/4 inch in diameter and the top end of the cathode was fastened to a plate cooled by water carried by copper tubes sealed through the insulating bushing. Cooling water was supplied through about 10 feet of Tygon tubing to isolate the high voltage.

The bottom of the furnace was equipped with a water-cooled copper crucible 2 inches in diameter and about 1 inch deep, located approximately 14 inches below the cathode. At this distance no magnetic focusing was required to form a beam ranging from 1/4 to 3/4 inch in diameter on the material in the crucible.

The furnace chamber was pumped by a trapped and baffled 4100 l/sec diffusion pump system. After initial pumpdown to about 10^{-5} torr, argon gas was supplied through a variable leak to maintain a dynamic pressure of about 5 microns (5×10^{-3} torr) in the chamber. Partial throttling of the pumping system was also required to attain pressure control. Bottled lecture grade argon gas was used and in some of the experiments was further purified by passing it through a hot titanium-zirconium chip furnace, before introducing it to the chamber. The purity of the gas as introduced to the chamber was of the order of 99.998 per cent, which is equivalent to about 10^{-2} torr pressure of impurities remaining in the gas.[9] In theory, then, an approximation of the actual purity condition existing in the furnace would be equivalent to a pressure of about 5×10^{-5} torr, i.e., (10^{-2} torr purity) (5×10^{-3} torr pressure) = 5×10^{-5} torr.

Direct current was supplied through a 1200-ohm ballast resistor from an adjustable power supply capable of 3 amperes at 20 kv. After making initial adjustments, stable currents up to 2 amperes at 15 to 17 kv were maintained on the starting material until melting was completed. A single-melt cycle in the case of buttons such as that shown in Fig. 9 was actually composed of two melts, i.e., the starting material was melted and partially consolidated. It was turned over and power again applied to consolidate the other half. The buttons are approximately 200 to 300 grams in weight and, at power levels up to 30 kw, required only a few minutes for each half-cycle. An evaluation and comparison of the conventional (hot cathode) and plasma (cold cathode) electron beam melted columbium buttons was made to obtain some measure of the relative ability of the plasma cathode to consolidate and/or refine. Buttons melted by the conventional E.B. process are identified with prefix "EB" whereas those melted by the plasma (cold cathode) beam are designated by the prefix "CC." These results are discussed in a later section.

It should be noted that under the conditions described above, ion bombardment of the cathode was sufficient to raise it to a dull red heat. After removal from the furnace the cathode surface was found to be bright and clean with no signs of erosion or other physical damage.

In another melting experiment with this equipment, molybdenum buttons were melted. These melts were made in the lower power equipment described earlier and shown in Fig. 1. The buttons were melted on a relatively massive, uncooled tungsten hearth. Buttons were of the order of 3/4 inch in diameter by

Fig. 9 Plasma electron beam melted columbium button.

1/4 inch thick after melting and were held molten in each case for 3 to 4 minutes. These buttons were not double melted as were the columbium samples. The argon gas used in the apparatus was of the same purity as that used in the large-scale experiments. About 2.5 kw of power were required to melt the buttons.

MELTING RESULTS

Figures 10 and 11 are photomicrographs of two as-cast columbium buttons, EB-59 and CC-1, respectively. As is evident the two structures are comparable, both being fairly clean in appearance and having quite large grains. In order to better appraise the differences between as-cast materials, analyses were obtained for the interstitials, oxygen, nitrogen, hydrogen, and carbon. These results are given in Table I. It should be pointed out that the starting material used for EB-59 and CC-1 was the same, and its analysis as given by the supplier is listed in Table I. Both of these buttons had been subjected to a number of low-pressure melt cycles in the conventional electron beam apparatus.

Fig. 10 EB-59, columbium, as-cast. 100X

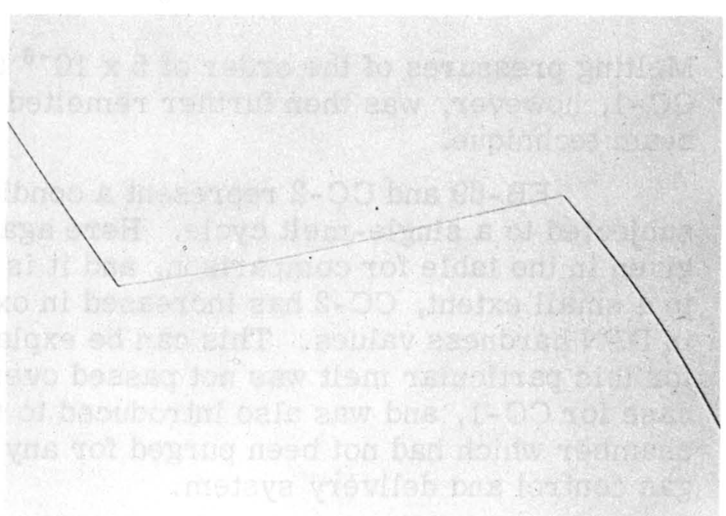

Fig. 11 CC-1, columbium, as-cast. 100X

TABLE I

Analysis of Plasma Electron Beam Melted Cb

Sample No.	Melting Mode	Interstitials O	N	H	C	Hardness DPN*
EB-59	Conventional	6	12	0	18	56-60
EB-69	Conventional	34	23	0	<10	61-65
CC-1	Cold cathode	37	25	0	<16	54-58
CC-2	Cold cathode	123	70	0	10	80-89
Starting material (EB-59 and CC-1)		<50	50	5	<30	69-64
Starting material (EB-69 and CC-2)		38	41	<10	60	NA

*All hardnesses are result of six or more readings per sample.

Melting pressures of the order of 5 x 10^{-6} to 5 x 10^{-5} torr were the norm. CC-1, however, was then further remelted (on both sides) by the plasma electron beam technique.

EB-69 and CC-2 represent a condition where both buttons were only subjected to a single-melt cycle. Here again the starting material analysis is given in the table for comparison, and it is seen that although EB-69 was refined to a small extent, CC-2 has increased in oxygen and nitrogen content as well as in DPN hardness values. This can be explained on the basis that the argon used for this particular melt was not passed over hot Ti-Zr chip retort, as was the case for CC-1, and was also introduced to the furnace through an intermediate chamber which had not been purged for any length of time prior to its use in the gas control and delivery system.

The molybdenum samples Mo-1 and Mo-2 were analyzed for interstitials, and the results are shown in Table II along with starting material analyses.

TABLE II

Analysis of Plasma Electron Beam Melted Mo

Sample No.	Interstitials O	N	H	C
Mo-1	5	4	1	11
Mo-2	10	5	2	10
Mo-1 SM*	7	2	1	10
Mo-2 SM†	14	6	1	12

*Starting material--vacuum arc-melted ingot

†Starting material--sintered powder billet

The low level of impurities in the case of the Mo-2 starting material was rather surprising. Retention of purity in the case of both Mo-1 and Mo-2 is evident. In all instances, i.e., both Cb and Mo buttons, the results obtained indicate that with a purified gas as a plasma medium, the plasma electron beam is capable of providing process purity conditions which are quite adequate for a variety of applications. At the levels of interstitials shown, and considering limits of error of analytical techniques, the limited data are not considered conclusive evidence that the plasma electron beam process is capable of refining conditions comparable to those available at extremely low pressure in hot cathode equipment. Rather, besides purity of the gas employed, the degree of refinement attainable is as much a function of the type and amount of the impurities (e.g., relative levels of carbon and oxygen), the amount of superheat applied, time at temperature, and the nature and pressure of the gas used in the process.[10, 11] In addition, however, the process provides an additional degree of flexibility in that various process conditions (other than that of basic refining) are attainable, since any one of a variety of gases may be used as the plasma medium.

WELDING EXPERIMENTS AND RESULTS

In order to further appraise the potential applications of the plasma beam apparatus, numerous experiments were performed of the welding and cutting type. Although the experiments were relatively simple as regards fixturing and beam control aspects, penetration and fusion welds were made on a variety of materials. One of the first materials used was René 41. As evidence of the capability of the plasma electron beam to effect a sound weld, photomicrographs of a conventional electron beam weld and a plasma electron beam weld are shown in Figs. 12 and 13. The plasma electron beam weld was made on sheet approximately 0.030 inch thick in the low-power apparatus described earlier and under essentially the same operational conditions. Mechanical property measurements of the plasma beam welds have been obtained and representative results of those of René 41 are given in Table III. These were found to be comparable to those obtained by other welding

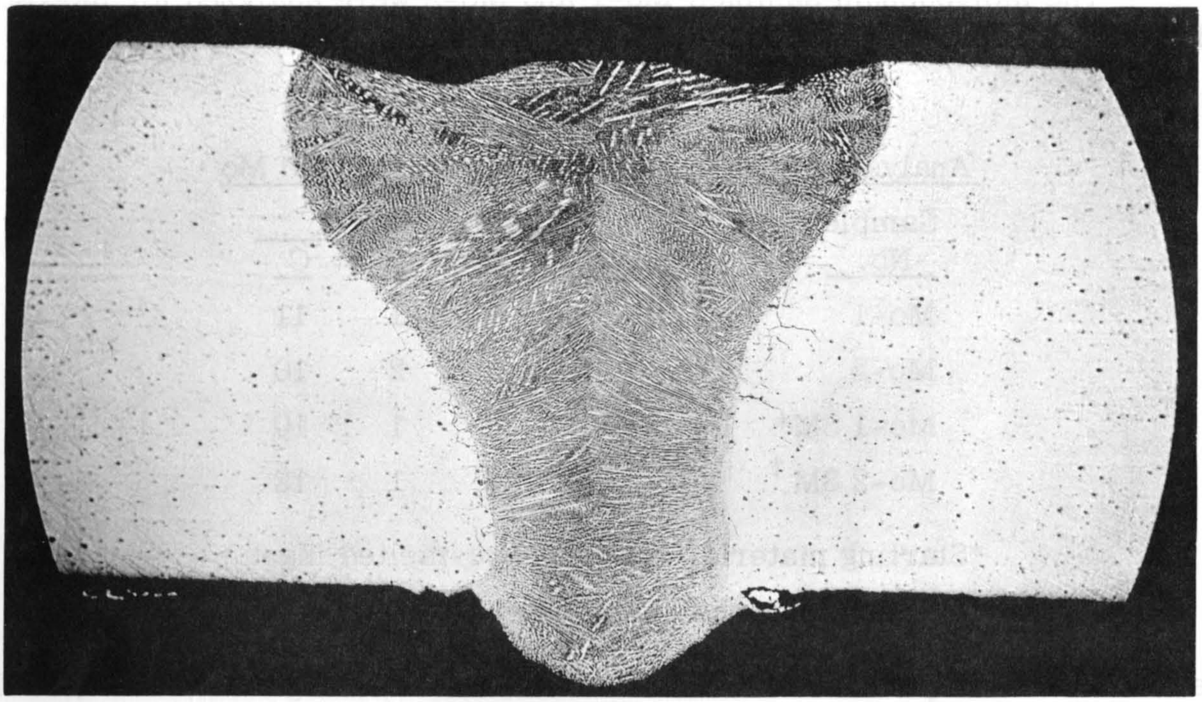

Fig. 12 René 41 sheet--conventional E.B. weld. 50X

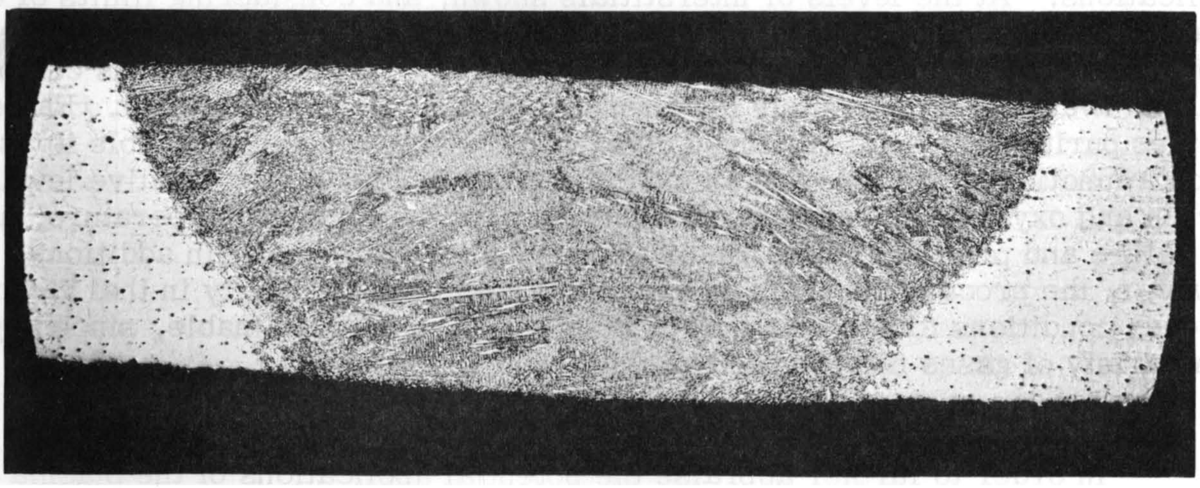

Fig. 13 René 41 sheet--plasma E.B. weld. 50X

TABLE III

Mechanical Properties of Plasma Electron Beam Welded René 41

Sample	U. T. S. (ksi)	0.2% Y. S. (ksi)	% El.
Parent metal	131.8	116.2	6
	134.5	117.6	7
Weld-1	136.3	128.8	2.0
	139.0	129.5	2.5
Weld-2	135.6	126.7	3.0
	135.3	125.3	3.5

Weld-1: Solution treated, welded, solution treated, and aged.

Weld-2: Solution treated, welded, direct age. Both samples broke in parent metal.

techniques. Further studies and comparisons are being conducted on a variety of materials.

The foregoing weld evaluations and results were made and supplied by R. Kutchera, General Electric Company, Evendale, Ohio.

CONCLUSIONS AND FUTURE DEVELOPMENTS

This development has demonstrated that the perforated hollow cathode, when provided with an internal control grid, can generate well collimated and precisely controlled electron beams of high intensity. Because a high vacuum environment is not required and, because the cathode is simple and rugged and operates at low temperature, it is well suited to applications requiring a concentrated heat input. On the basis of the data presented and observations of the beam in operation, it is apparent that the device can readily be applied to a variety of metallurgical process applications. It has demonstrated the capability of performing these functions and at the same time providing an atmosphere condition that is conducive to maintaining or effecting high purity in the material being processed. In operations where the evolution of gaseous reaction products is considerable or different gases from those used as ionized mediums are desired, compartmenting and separate pumping arrangements can be provided. In all instances because of the operational pressures employed, the equipment necessary to do this can be of relatively unsophisticated design.

The nature of the plasma beam cathode operation is conducive to a variety of cathode designs, the construction being simple and straightforward. As a consequence, a variety of beam configurations is readily effected depending upon the process application and its requirements.

Also, other applications are opened by the addition of grid control of the beam. Circuitry applications such as new types of oscillators, amplifiers, and control circuits are definitely possible. While the more obvious applications are being developed, others, possibly more important, await a better understanding of the basic mechanisms of this type of electron beam formation.

ACKNOWLEDGMENTS

The assistance and suggestions of K. L. Boring, R. A. Robbins, and A. C. Rockwood in performing the various experiments are gratefully acknowledged. The authors also wish to thank R. Kutchera, L. J. E. D., Evendale, Ohio, for providing the data on the René 41 weld evaluation.

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TECHNICAL INFORMATION SERIES

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AUTHOR	SUBJECT CLASSIFICATION	NO.
Cocca, M. A. Stauffer, L. H.	electron beams; vacuum metallurgy	63-RL-3380 M DATE July 1963

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The first part of this report summarizes the results of experiments conducted at Advanced Technology Laboratories aimed at gaining a fundamental understanding of the electrical properties and behavior of the cathode. The remainder of the report sets forth the results of metallurgical processing experiments which serve to provide a measure of the processing capabilities of the apparatus.

High-intensity electron beams were generated, producing beam power levels of over 30 kw. The cathode is rugged, simple, and versatile, and as a process tool, provides the inherent advantages of hot cathode electron beam devices without some of the limitations, in performing a variety of processing operations including melting, welding, sintering, and heat treating.

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

INFORMATION PREPARED FOR:

SECTION: Materials Application and Evaluation

DEPARTMENT: Metallurgy and Ceramics Research; Advanced Technology Labs.