Title
DIRECTLY HEATED LANTHANUM HEXABORIDE FILAMENTS

Authors
Leung, K.N.
Pincosy, P.A.
Ehlers, K.W.

Publication Date
1983-12-01

LBL-16797
Preprint c2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

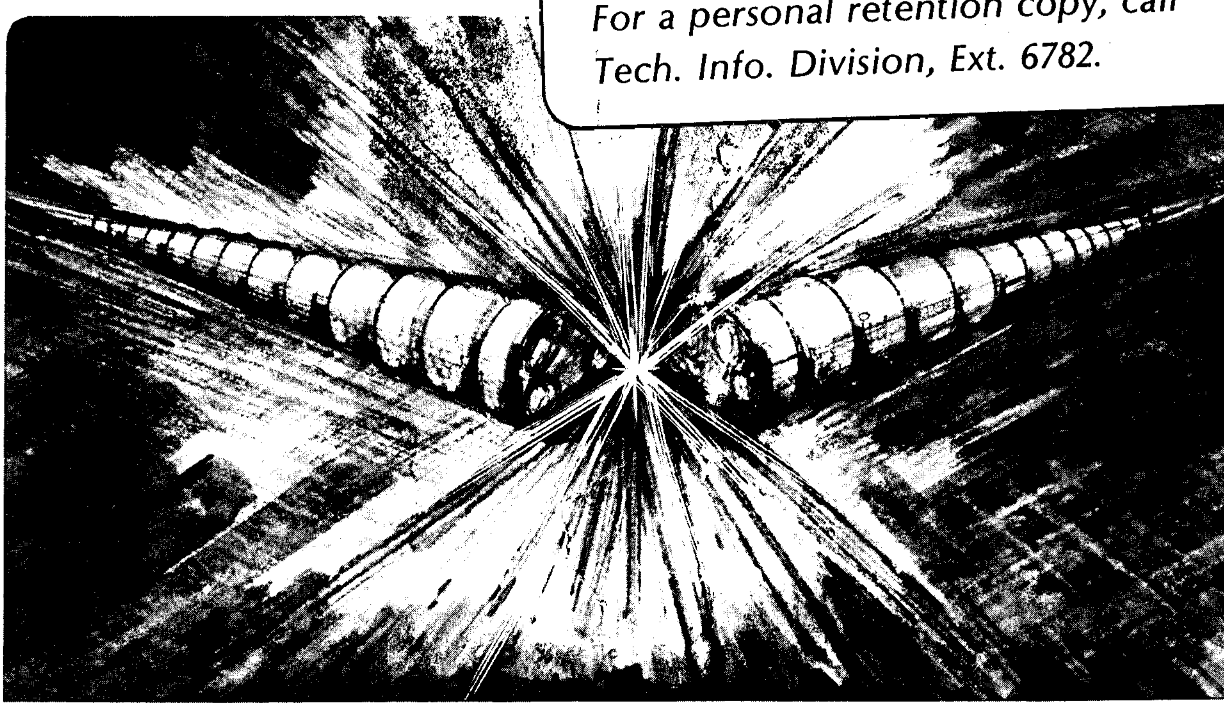
Accelerator & Fusion Research Division

Submitted to Review of Scientific Instruments

DIRECTLY HEATED LANTHANUM HEXABORIDE FILAMENTS

K.N. Leung, P.A. Pincosy, and K.W. Ehlers

December 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-16797

DIRECTLY HEATED LANTHANUM HEXABORIDE FILAMENTS*

K. N. Leung, P. A. Pincosy and K. W. Ehlers

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Some physical properties of lanthanum hexaboride filaments, when operated as cathodes in a gas discharge, are presented. These directly heated hairpin shaped filaments have been tested in different types of ion sources and are shown to be capable of long pulse or cw discharge operations. The design of a shaped lanthanum hexaboride filament for the purpose of further extension of lifetime is also described.

*This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Introduction

It has been known for some time that lanthanum hexaboride (LaB_6) is a good material for use as an electron emitter. It has unusual physical properties such as a high melting point, chemical inertness, low work function, high brightness of emission current and resists erosion under ion bombardment. For this reason, LaB_6 cathodes are now widely used in many branches of modern technology such as electron microscopes, mass spectroscopy, demountable vacuum gauges and thermionic converters.

In 1951, Lafferty investigated the emission properties of a LaB_6 cathode.[1] It was suggested that the high thermionic emission properties of LaB_6 are the result of the diffusion of lathanum atoms through the boron matrix to the surface, where an active layer of lanthanum is constantly maintained.

In most applications, LaB_6 is operated as an indirectly heated cathode, either in the form of a small crystal structure or in some geometric form with a heater behind it. However, there is one disadvantage of the LaB_6 cathode, namely the boron attacks most base materials to which the LaB_6 is attached and forms interstitial boron alloys with the base. When this occurs, the boron framework around the alkaline-earth metal collapses and permits the boron to evaporate. With rhenium as the base metal, this effect is least pronounced. Borides do not react with graphite, and graphite or carburized tantalum has also been used as a base material.

In this paper, a new and simple design is reported in which the LaB_6 is operated as a directly heated "filament" cathode through which an electric current is passed. It is shown that these LaB_6 filaments perform satisfactorily in different types of ion sources where tungsten filaments are normally employed. To further increase filament lifetime, it is easy to properly shape the LaB_6 filament so that uniform electron emission can be obtained from the entire filament surface.

I. Some characteristics of LaB_6 when operated as cathodes

The properties of LaB_6 have been investigated by many authors.[1-3] When heated to a temperature of 1400 C or higher, LaB_6 is a copious emitter of electrons. Normally the emitted electron current density J_e is limited by space charge. But for high extraction electric fields, a saturation current density J_{max} is reached, which is given approximately by the Richardson-Dushman equation,

$$J_{max} = A\,T^2 \exp(-e\phi/ kT) \qquad (A/cm^2) \qquad (1)$$

where T is the cathode temperature in degrees kelvin, $e\phi$ is the work function in electron-volts, k is the Boltzmann constant and A is Richardson's constant. For typical operating temperature of 1900 K, a LaB_6 cathode with $A = 30\ A/cm^2\ deg^2$ and $e\phi = 2.67$ eV, the emission current density is 9 A/cm^2. Similarly a typical tungsten cathode, with $A = 70\ A/cm^2\ deg^2$, $e\phi = 4.55$ eV operates at T = 2700 K, will provide an emission current density of 1.6 A/cm^2. Thus the LaB_6 cathode appears to offer a brightness significantly larger than tungsten cathodes.

LaB_6 is a very hard material and is best cut with a diamond saw. We first tested a very thin strip of LaB_6 (0.4 mm thick, 5 mm wide and 55 mm long) by supporting the two ends with graphite chucks as illustrated in Figure 1. This cathode filament emitted 20 A of electron current when 60 A of dc heater current was passed through it. However, this thin strap cracked as soon as the heater current was turned off. The LaB_6 material has a high coefficient of thermal expansion and the filament chucks do not provide enough tolerance when the contraction occurs. To overcome this problem, rectangular and circular shaped LaB_6 hairpin filaments were fabricated (Figure 2). In these hairpin configurations, the filament can expand and contract freely in a manner similar to regular tungsten hairpin filaments.

When LaB_6 filaments are operated as cathodes in a gas discharge, it is important to know the relationships of the heater current, filament temperature, emission current, and lifetime. The filament heater current characteristics were measured for both the rectangular and circular hairpin geometries by using an optical pyrometer. The cross-sectional area is about 1.6 mm x 3 mm for both filaments. The measured filament temperature is plotted in Figure 3 as a function of the heater current. By balancing the ohmic heating power with radiative losses, the heater current required (neglecting other heating and cooling mechanisms) for the filament to reach an equilibrium temperature T is

$$I_h = \sqrt{\frac{2\varepsilon\sigma}{\rho}} \quad T^2 \sqrt{w\ t\ (w + t)} \qquad (2)$$

Where ε and ρ are the emissivity and resistivity of LaB_6 respectively, σ is the Stephen constant, and w and t are the width and thickness of the filament respectively. The theoretical curve calculated from this equation is also presented in Figure 3. It can be seen that the calculated values agree closely with the experimental measurement.

The emission current density of the LaB_6 filament can be calculated from Equation (1) for various temperatures. Figure 4 shows a plot of the calculated current density as a function of the filament temperature. For comparison, the emission current densities for tantalum and tungsten are also presented in the same diagram. It can be seen that the normal operating temperature for the LaB_6 cathode is much lower than those of tantalum and tungsten. At a given filament temperature, the emission density for LaB_6 is two orders of magnitude higher than that of tantalum and tungsten.

Since the normal operating temperature for a LaB_6 filament is low, one would expect that the evaporation rate for the LaB_6 material is also small. From the published data,[4] the evaporation rates ($gm/cm^2/sec$) for LaB_6, tantalum and tungsten are shown in Figure 5 as a function of the emission current density. For the same emission density, the evaporation rate of tantalum and tungsten are both two orders of magnitude higher than that of LaB_6. Accordingly, the lifetime of a LaB_6 filament (which depends largely on the evaporation rate) should be much longer than that of the tungsten or tantalum filament. In fact, lifetime test have shown that a LaB_6 emitter can last several thousands of hours at relatively low current densities in the range 10 - 20 A/cm^2. With an emission density of more than 50 A/cm^2, the useful life of the Lab_6 can still be greater than 200 h.[2]

A filament cathode operating in a gas discharge is constantly being bombarded by ions. If the rate of sputtering of the filament material by the positive ions is high, then the lifetime of the filament will also be limited. The sputtering rate of LaB_6 and tungsten have been compared under the same environment by Kudintseva et al.[5] and the published data are shown in Figure 6. The loss in weight for the tungsten sample is approximately ten times higher than the LaB_6. Since tungsten is about four times heavier than LaB_6, the volume of LaB_6 material sputtered away by the ions is still a factor of 2.5 less than that of the tungsten.

II. Filament discharge testing

(a) Single LaB_6 filament operation

The discharge characteristics of a single LaB_6 filament (total surface area ≅ 4 cm^2) have been studied in a cylindrical multicusp ion source[7] operated with hydrogen or argon gas. Since LaB_6 attacks metals like copper and molybdenum, the hairpin filament was mounted either on graphite holders (Figure 2(a)) or on molybdenum chucks but with the filament feet wrapped with rhenium foil (Figure 2(b) and (c)). The filament was biased at approximately -80 V with respect to the chamber wall. With a filament heater current of about 125 A and a temperature of 1650 K, the LaB_6 filament should be able to provide 2 A of emission current. However, a steady state discharge current of more than 40 A was obtained from a single rectangular shaped LaB_6 hairpin filament due to the additional heating from ion bombardment. The filament was operated with this discharge current for several hours. When the source was opened, no significant change in the shape or color of the filament was observed.

During the discharge operation, the emission current could be easily regulated by adjusting the filament heater current in a manner similar to the operation of an ordinary tungsten filament. The power consumed in heating the LaB_6 filament was about 150 watts. In comparison, a 10 cm long 0.15-cm diam tungsten filament requires about 1.1 kilowatt of heating power to produce 40 A of discharge current with a discharge voltage of 75 V. Thus the tungsten requires about nine times more heating power than the LaB_6 hairpin filament. Since the cross-sectional area of the LaB_6 filament is larger than the 0.15-cm diam tungsten filament, one would expect that the magnetic field generated at the filament surface by the same amount of heater current is smaller for the LaB_6 filament which in turn will result in a less effective containment of the emitted electrons. Thus, the LaB_6 filament may generate less plasma density fluctuation when it is heated by an alternating current.

(b) Multiple LaB_6 filament operation

In some applications, such as the neutral beam injection systems in fusion research, hundreds of amperes of electron emission current are required for the operation of the ion source with pulse length in tens of seconds. If tungsten filaments are used as the cathode, a large number of filaments are required and their lifetime is always limited due to evaporation and arc spotting.

In order to test multiple filament operation, eight circular shaped LaB_6 hairpin filaments were installed in the Berkeley 10 x 10 cm^2 multicusp (bucket) source as illustrated in Figure 7. The filaments were mounted in the molybdenum chuck slots with a rhenium foil interface between the LaB_6 and the molybdenum. Each of these circular hairpin filaments required ~130 A of heating current in order to obtain 55 A of emission per filament when operating in an emission limited basis in a hydrogen plasma. According to the data shown in Figures 3 and 4, 130 A will not produce a temperature high enough for 50 A of emission. The fact that 50 A of emission was attained from each filament suggests that additional heating power comes from ion bombardment heating as was indicated in the single filament experiment in Sec. II(a).

The source operation of the above conditions was similar to arc discharges using 0.15-cm diam tungsten filaments. A discharge voltage of 100 V and current of 430 A produced an extractable ion current density of 220 mA/cm^2 during 7 seconds of discharge time. The oscilloscope trace in Figure 8 shows that the ion current density is constant in time. The preheat filament current is reduced at the moment when the arc discharge is turned on so as to compensate for the additional current heating due to the arc discharge current which passes through the filament..

In this measurement, the pulse length was limited to 10 seconds or less due to inadequate cooling of the source chamber. However, the set of LaB_6 filaments can be operated with longer pulses or even cw if the discharge chamber is properly designed for high power loading and the vacuum system is adequately pumped. When the discharge test was over, the filaments were found to be in-tact. For a short distance of about 0.5 cm from the chuck, the filament showed a brownish color compared to the normal violet LaB_6 color. Otherwise the filaments appeared to be free of contamination.

(c) LaB_6 filament in a Penning type source

In 1963, Ehlers et al. developed a direct extraction negative ion source which is still widely used in cyclotrons.[7] This source is operated as a hot cathode Penning-type gas discharge. The filament cathode is a 3.8 mm thick tantalum plate and is heated with a direct current of 380 A to the required temperature. In normal source operation, the filament is biased at ~300 V with respect to the anode. Thus the part of the filament exposed to the plasma is always severely sputtered by the positive ion bombardment.

Eventually, the source ceases to function when a hole is developed in the tantalum filament in line with the arc column.

We have tested a LaB_6 filament in this type of Penning source operated with a hydrogen plasma. The filament was mounted on the copper holders with a piece of rhenium foil sandwiched in between as shown in Figure 9. It was operated continuously for three hours with an arc voltage of 250 V and an arc current of 2 A. The heater current required was about 120 A. The plasma was very stable and no adjustments had to be made to the arc or heater power supply during the discharge process. When the filament was examined after the test, no significant erosion marking due to sputtering could be observed on the surface. We are planning to conduct more filament lifetime tests in this type of ion source in the near future.

III. Shaped LaB_6 filament

In a high density discharge plasma where the filaments emit a significant electron current density, the temperature distribution along the filament is non-uniform. The result is that only a small part of the filament provides the bulk of the emission current and hence the lifetime of the filament is reduced. One method of solving this localized emission problem is the use of a filament with a variable cross-sectional area. For this application, the LaB_6 can be cut in different geometrical shapes much easier than regular tungsten material.

Consider a rectangular LaB_6 filament with uniform thickness t but with a variable width w. When this filament is operated as a cathode in a discharge, it will be heated by ohmic dissipation and by plasma ion bombardment of the surface and cooled by electron emission and by radiation. If heat conduction to the filament chucks is neglected (this assumption is valid for areas a few filament widths away from the chucks), then the power balance equation can be written as

$$\frac{\rho}{t}\left(I_d - j_e\int_o^x 2[w(x) + t]dx\right)^2 + 2V_a j_i[w(x) + t] =$$

$$2\varepsilon\sigma T^4[w(x) + t] + 2V_w j_e[w(x) + t] \qquad (3)$$

where V_w is the work function, j_i is the local plasma ion density, I_d is the discharge plus heater current, V_a is the cathode voltage, ρ is the electrical resistivity, ε is the emissivity, T is the temperature and j_e is the emitted electron current density. The width variation of the filament (proceeding from the negative leg where the width is the largest) can be approximated by a third order polynomial

$$w(x) = w_o + ax + bx^2 + cx^3$$

and the coefficients w_o, a, b and c can be evaluated in terms of the above defined parameters by using Equation (3). Then, the proper shape of the tapered filament can be determined. The only problem associated with the tapered filament is that it will have longer thermal equilibration time than a regular LaB_6 hairpin filament.

We have fabricated a tapered LaB_6 filament and we anticipate that its lifetime will be about three times longer than one with uniform width. The test of this new filament is in progress and the results will be reported in the near future.

Acknowledgments

We would like to thank D. Moussa for technical assistance. This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

1. J. M. Lafferty, J. Appl. Phys. 22, 299 (1951).
2. H. Ahmed and A. N. Broers, J. Appl. Phys. 43, 2185 (1972).
3. S. P. Gordienko, E. A. Guseva and V. V. Fesenko, Teplofiz. Vys. Temp. 6, 821 (1968).
4. Walter H. Kohl, Handbook of Materials and Techniques for Vacuum Devices, Reinhold Publishing Corporation, New York (1967).
5. G. A. Kudintsva, A. I. Mel'nikov, A. V. Morozov and B. P. Nikonov, Thermoelectroniye Katody, Sec. 5, p. 309 (Energia Publishing House, 1966).
6. K. W. Ehlers and K. N. Leung, Rev. Sci. Instrum. 50, 1353 (1979).
7. K. W. Ehlers, Nucl. Instrum. Method 32, 309 (1965).

Figure Captions

Figure 1 A thin strap of LaB_6 filament.

Figure 2 Rectangular and circular shaped LaB_6 hairpin filaments mounted on graphite holders (a) and on molybdenum chucks (b) and (c).

Figure 3 The measured LaB_6 filament temperature as a function of the heater current. The solid line is the theoretical curve calculated from Equation (2).

Figure 4 The calculated emission current density as a function of the filament temperature for LaB_6, tantalum and tungsten.

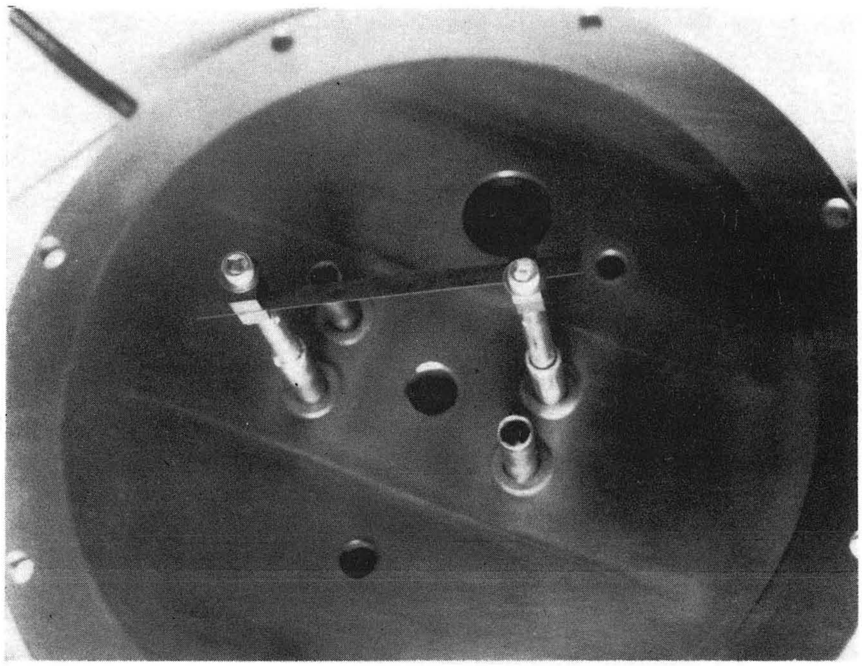
Figure 5 The evaporation rate of LaB_6, tantalum and tungsten as a function of the emission current density.

Figure 6 The sputtering-rate curves for LaB_6 and tungsten presented in Reference 5.

Figure 7 (a) The top, and (b) the side view of eight LaB_6 filaments mounted on the molybdenum chucks of a multicusp ion source.

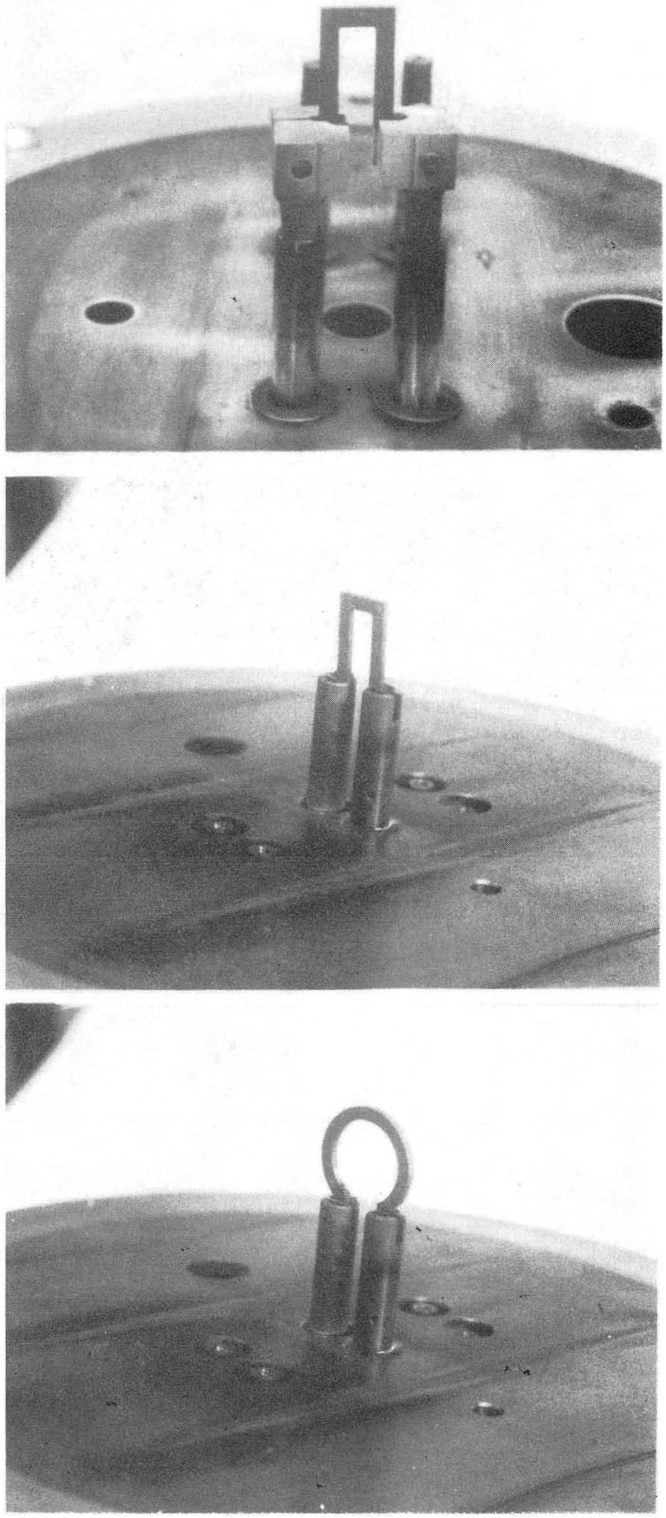
Figure 8 Oscilloscope traces showing the arc voltage, arc current and ion current density during a 7 s pulse discharge operation.

Figure 9 A LaB_6 filament installed inside the Ehlers' type Penning source.



XBB 830-8715

Fig. 1



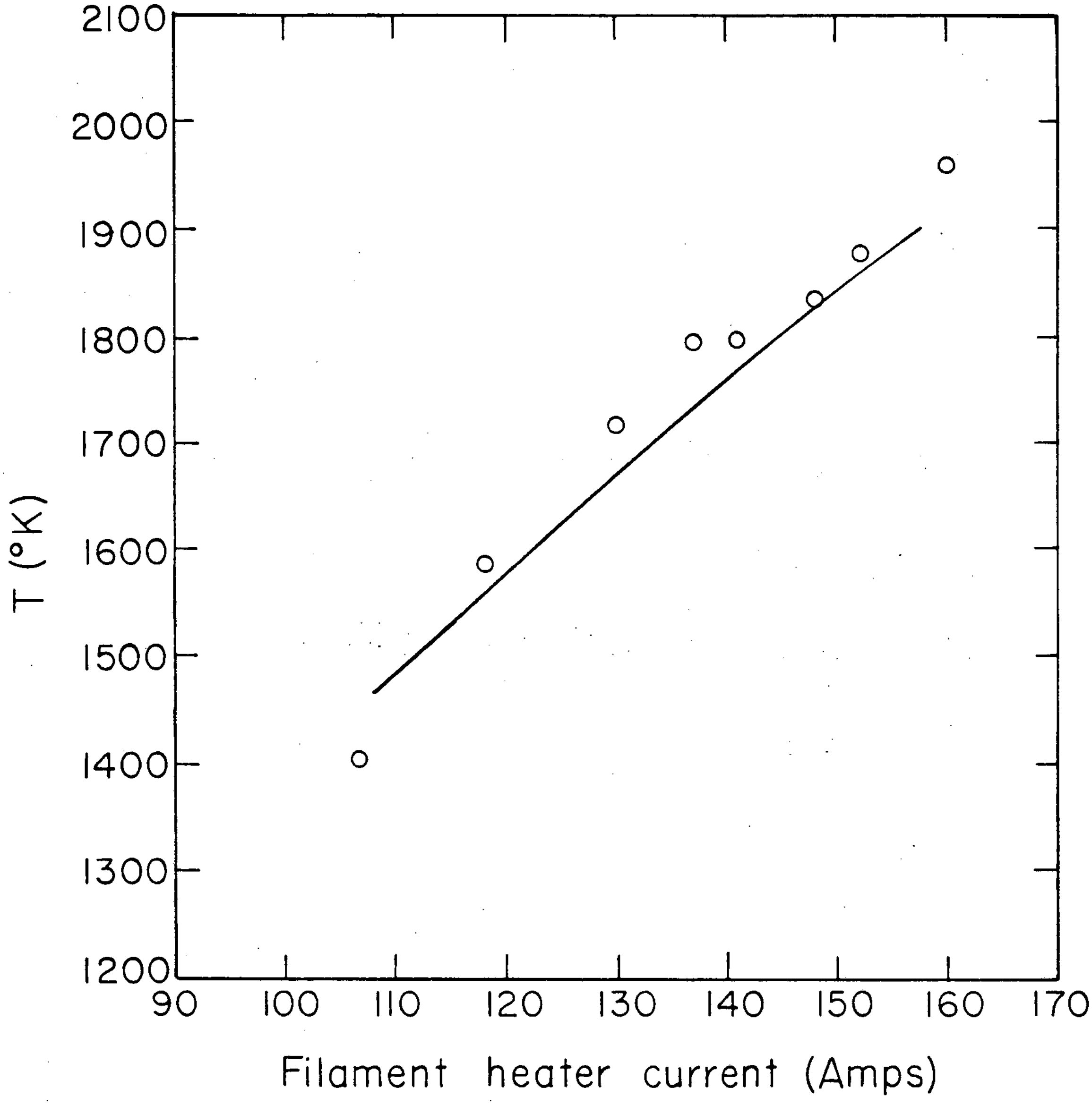
(a)

(b)

(c)

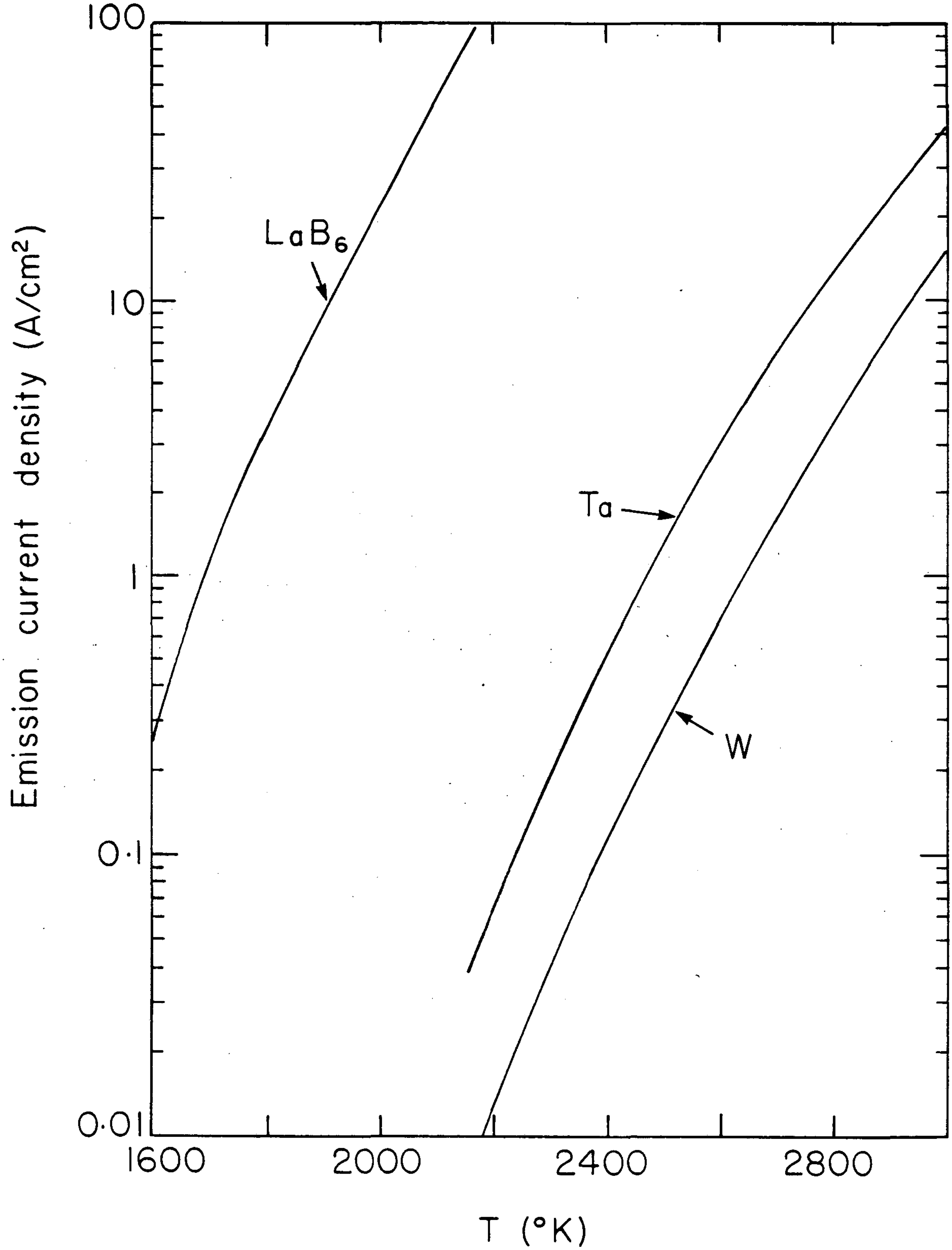
XBB 841-424

Fig. 2



XBL 839-11661

Fig. 3



XBL 839-11662

Fig. 4

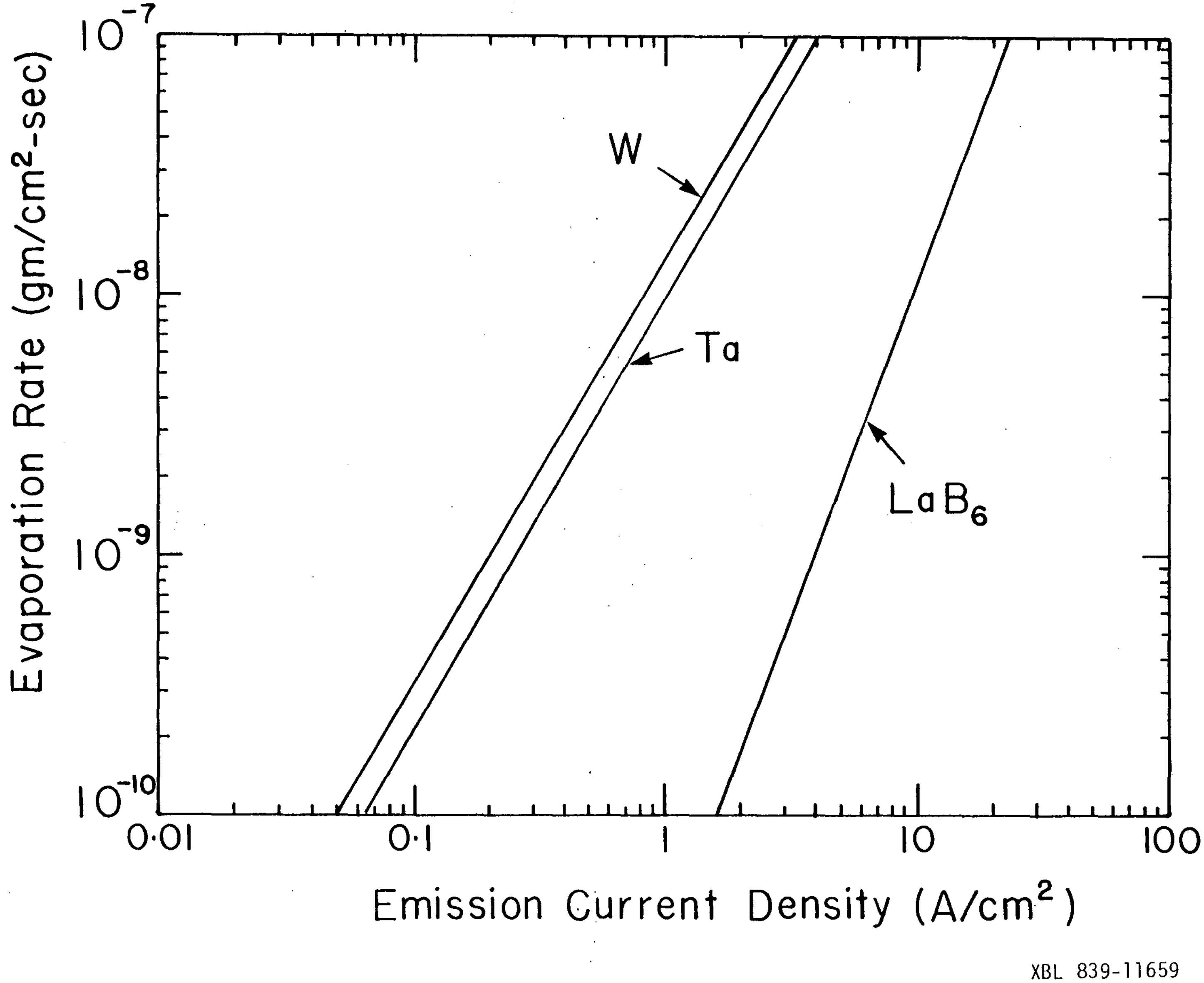
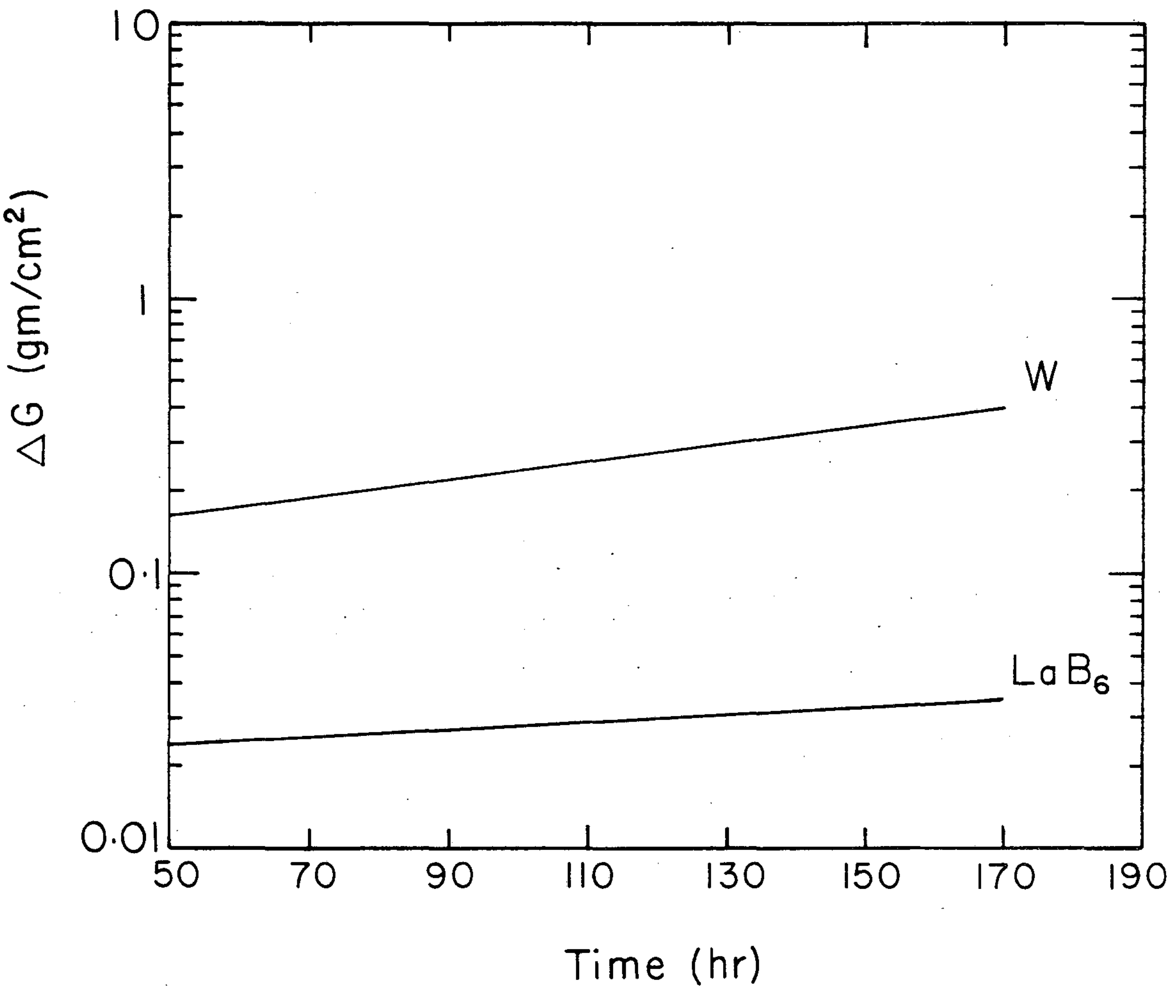
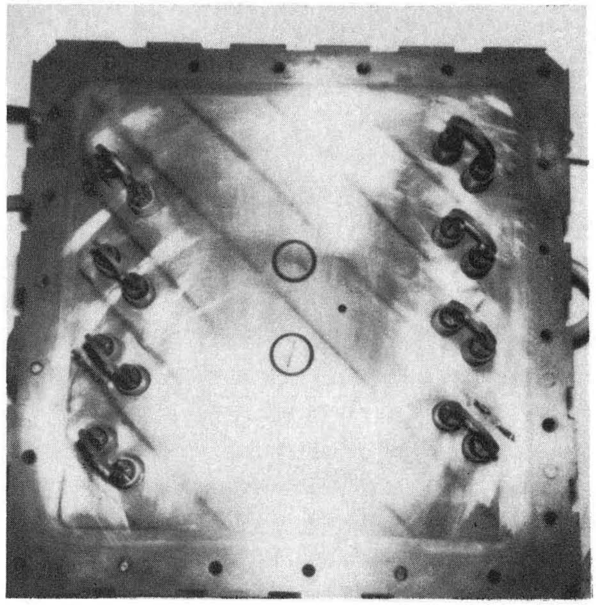

W
Ta
LaB_6
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0·01
0·1
1
10
100
Evaporation Rate (gm/cm²-sec)
Emission Current Density (A/cm²)
XBL 839-11659

Fig. 5



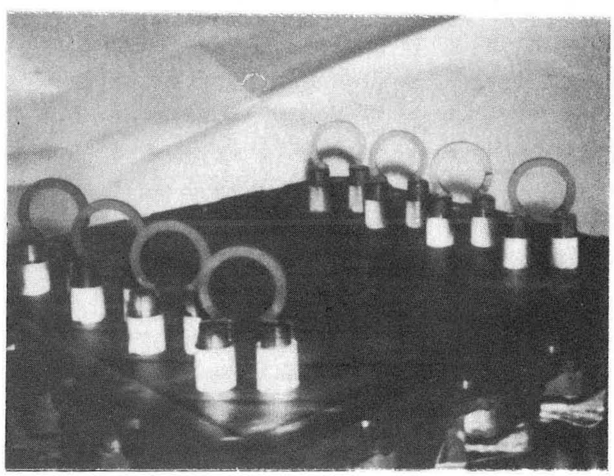
XBL 839-11660

Fig. 6



CBB 836-5372

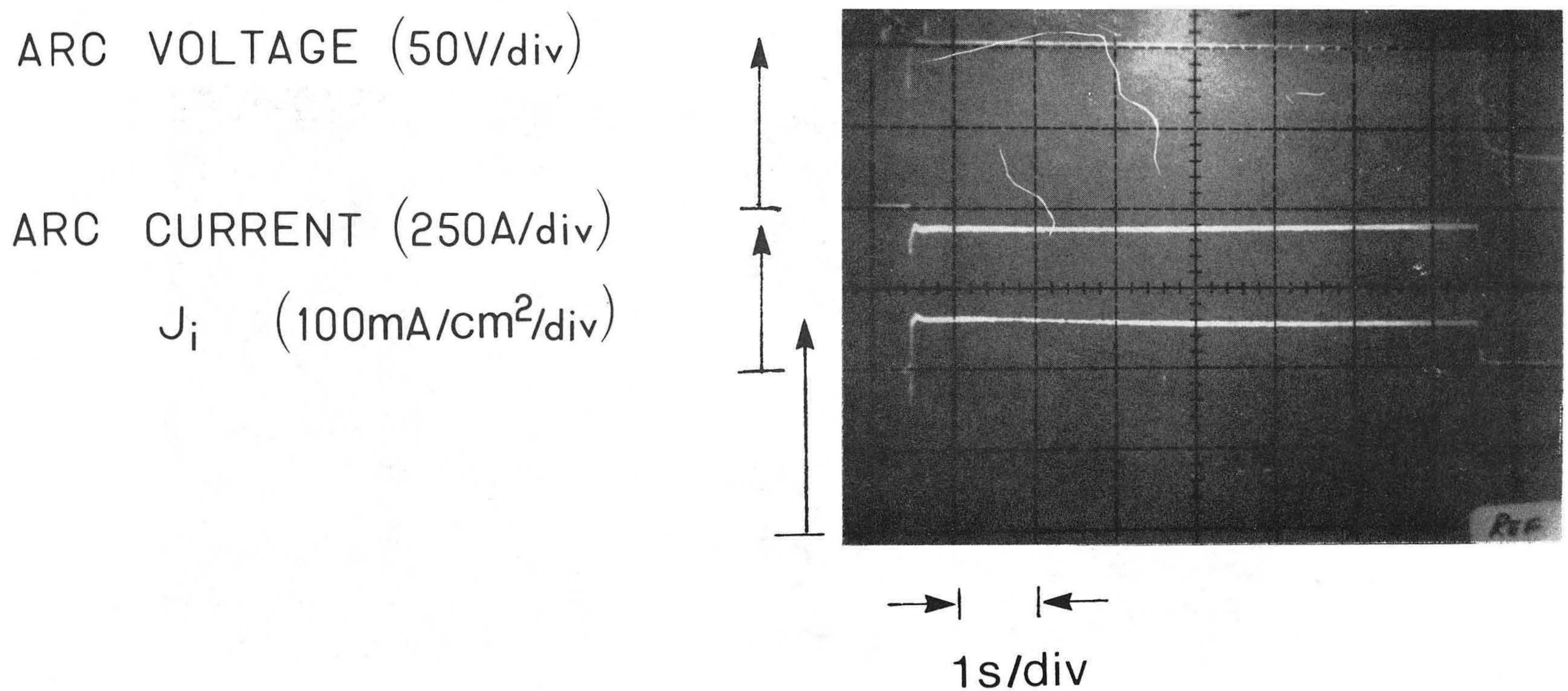
(a)



CBB 836-5370

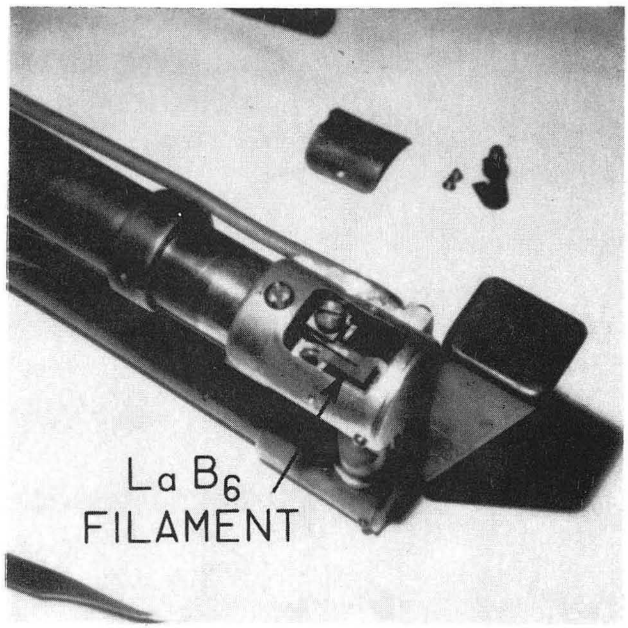
(b)

Fig. 7



XBB 830-8714

Fig. 8



CBB 839-8389

Fig. 9

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720