THIRD QUARTERLY REPORT

THE STUDY OF PLASMA - BOUNDARY INTERACTIONS

(1 March 1968 through 31 May 1968)

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National Aeronautics and Space Administration
Contract NASA-1703

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SPACE SCIENCES INCORPORATED

301 BEAR HILL ROAD, WALTHAM, MASSACHUSETTS, 02154

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ABSTRACT

The arc velocity of a rotating plasma is determined experimentally using the back emf and the time of flight methods. The measurements are made for several electrode materials and gases over a wider range of arc parameters. These measurements indicate that the arc velocity is inversely proportional to the gas pressure which can be described by a power law relation. This is not in agreement with the ionization limiting velocity concept. Further the arc velocity is found to be independent of the magnetic field when determined by the back emf method whereas the time of flight method shows that the velocity increases with the increasing magnetic field. The dependence of arc velocity on the magnetic field, as obtained by the time of flight method, suggests that the measured threshold and the saturation effects in the electrode drag force cannot be explained in terms of the possible threshold and saturation effects in the plasma velocity.

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1. INTRODUCTION

This report covers the Third Quarter of the program to study the plasma boundary interactions.

It has been noted earlier that the emphasis in this program has been on the investigation of plasma velocity and its dependence on arc parameter. This information is necessary for the interpretation of electrode drag measurements and for the understanding of the plasma acceleration mechanism.

Several methods have been used to determine the plasma velocity in the accelerators. For example the back emf and the time of flight methods have been the most popular techniques because of their simplicity. These methods although extensively used for the determination of plasma speed, yield results which are inconsistant and difficult to interpret. For instance, the back emf method gives a velocity which is about two orders of magnitude higher than the velocity obtained by the time of flight method. Also the back emf method indicates that in the range of experiments, the arc velocity is independent of the magnetic field whereas the time of flight method shows that the arc velocity increases with the magnetic field. To understand these difficulties and to obtain the plasma velocity by an independent method, a Doppler Shift system has been developed.

In the published literature two physical models have been proposed to describe the physics of plasma propulsion. The concept of ionization limiting velocity has been suggested by Lin[1] to explain the plasma velocity measurements of Fahleson[2] and of Alfven[3]. According to this concept the plasma velocity is given by the ionization potential of the gas. If this were the case, one should find the plasma velocity to be independent of the magnetic field, arc current and the gas pressure etc. Some experiments however, indicate that the plasma velocity depends strongly on the arc parameters.

The other model for the plasma propulsion is based on the snowplow concept. Accordingly it is assumed in this case that the mass overtaken by the moving plasma is accumulated within it and subsequently moves along with it, hence the nomen "snowplow." This model is quite successful in predicting current sheet trajectories for a variety of pulsed plasma accelerators over a broad range of operation. This model predicts that the plasma velocity should decrease with the increasing gas pressure with a slope of $p^{-1/4}$. The validity of this model in the case of a continuously rotating plasma still remains to be studied. In the present research program these and other models are being evaluated and being studied analytically to interpret the results of the experiments.

This report deals with the study of plasma velocity in a continuously rotating arc. While the Doppler Shift system for the measurement of a radiating particle velocity is being developed and the parts are being fabricated, additional measurements of plasma velocity are made using the back emf and the time of flight methods. The velocity measurements described in Section 2 of this report cover a wider range of arc currents and gas pressures for several electrode materials and plasma gases. The arc velocity is measured as a function of the magnetic field in order to study the possible threshold and saturation effects in the plasma velocity. This possibility originates from the observed threshold and saturation effects in the measured electrode drag forces. From the results of the present experiment it is concluded that the threshold and saturation in the electrode drag are not related to the plasma velocity and may be due to the threshold in the momentum accommodation coefficient or in the particle flow to the electrode. Further experiments to clarify this aspect would be of value in the understanding of this complex phenomena.

2. EXPERIMENTAL PROGRAM

The need of plasma velocity measurement in the JxB coaxial accelerator has been discussed earlier[4,5]. Some measurements of the plasma velocity made by 1) the back emf and 2) the time of flight methods were presented in the Second Quarterly Progress Report of this program[6].

The velocity determined by the back emf method was found to be in the order of magnitude agreement with the ionization limiting velocity. The velocity measurements however, indicated that for the same arc conditions the velocity obtained by the back emf method was about two orders of magnitude higher than the velocity obtained by the time of flight method.

To better understand these observations, further measurements of arc velocity are made using both the back emf and the time of flight methods. In this study the effect of cathode material, plasma gas, arc current and gas pressure on the arc velocity is determined experimentally.

2.1 Arc Velocity Measurement Using the Back emf Method

The back emf method of determining the arc velocity was described in the Second Quarterly Progress Report. Figure 1, showing the schematic of the apparatus for measuring the arc voltage as a function of the magnetic field, is reproduced here for the sake of completeness of this report.

Using this experimental setup the dependence of arc voltage on the transverse magnetic field was studied for copper cathode in argon for a number of arc currents and gas pressure. Figures 2 and 3 show the arc voltage measurement as a function of the magnetic field for 30 and 50 amp arcs respectively. The magnetic field was varied from 700 to 1500 Gauss.

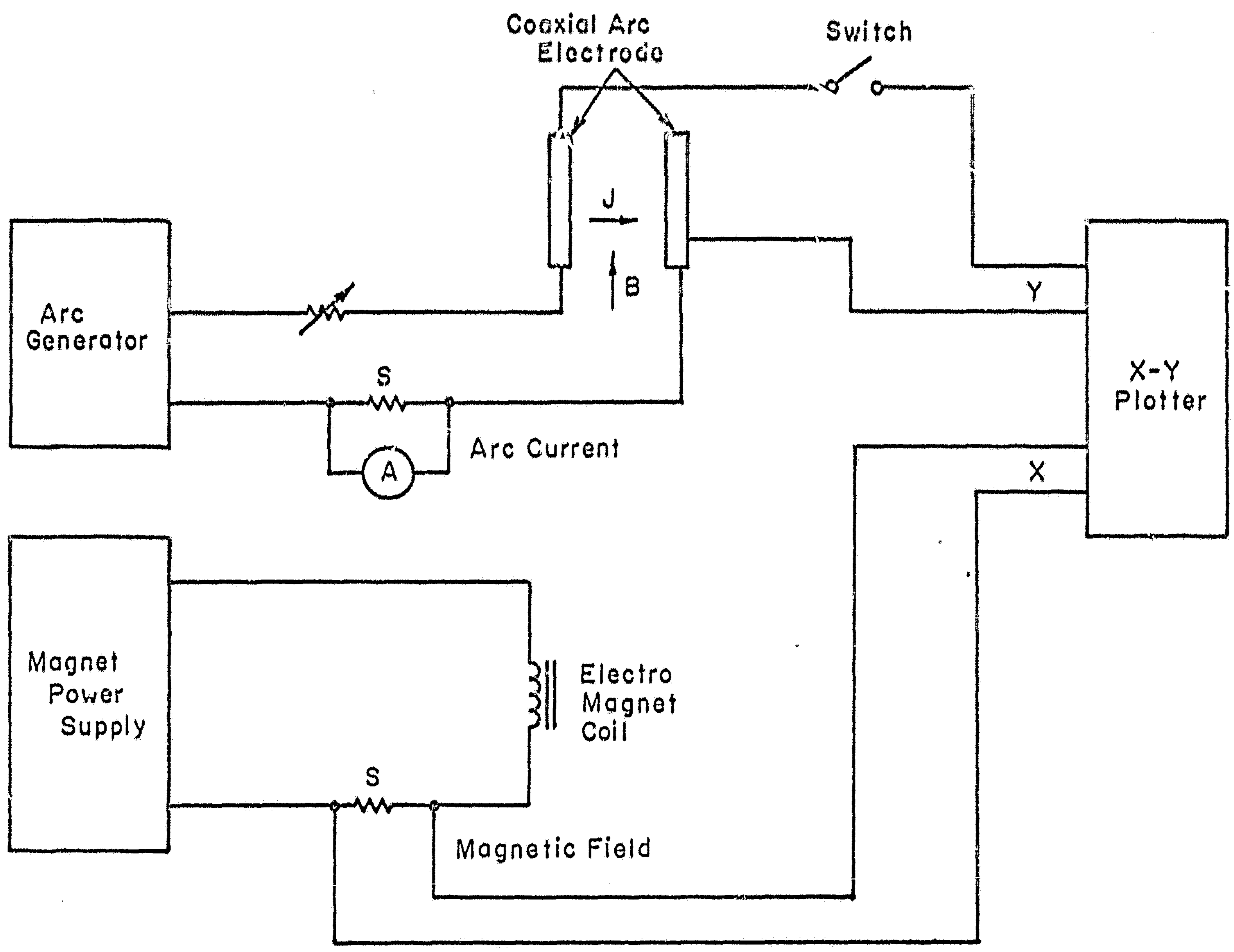

FIGURE 1.

SCHEMATIC OF THE APPARATUS FOR MEASURING THE ARC VOLTAGE AS A FUNCTION OF MAGNETIC FIELD.

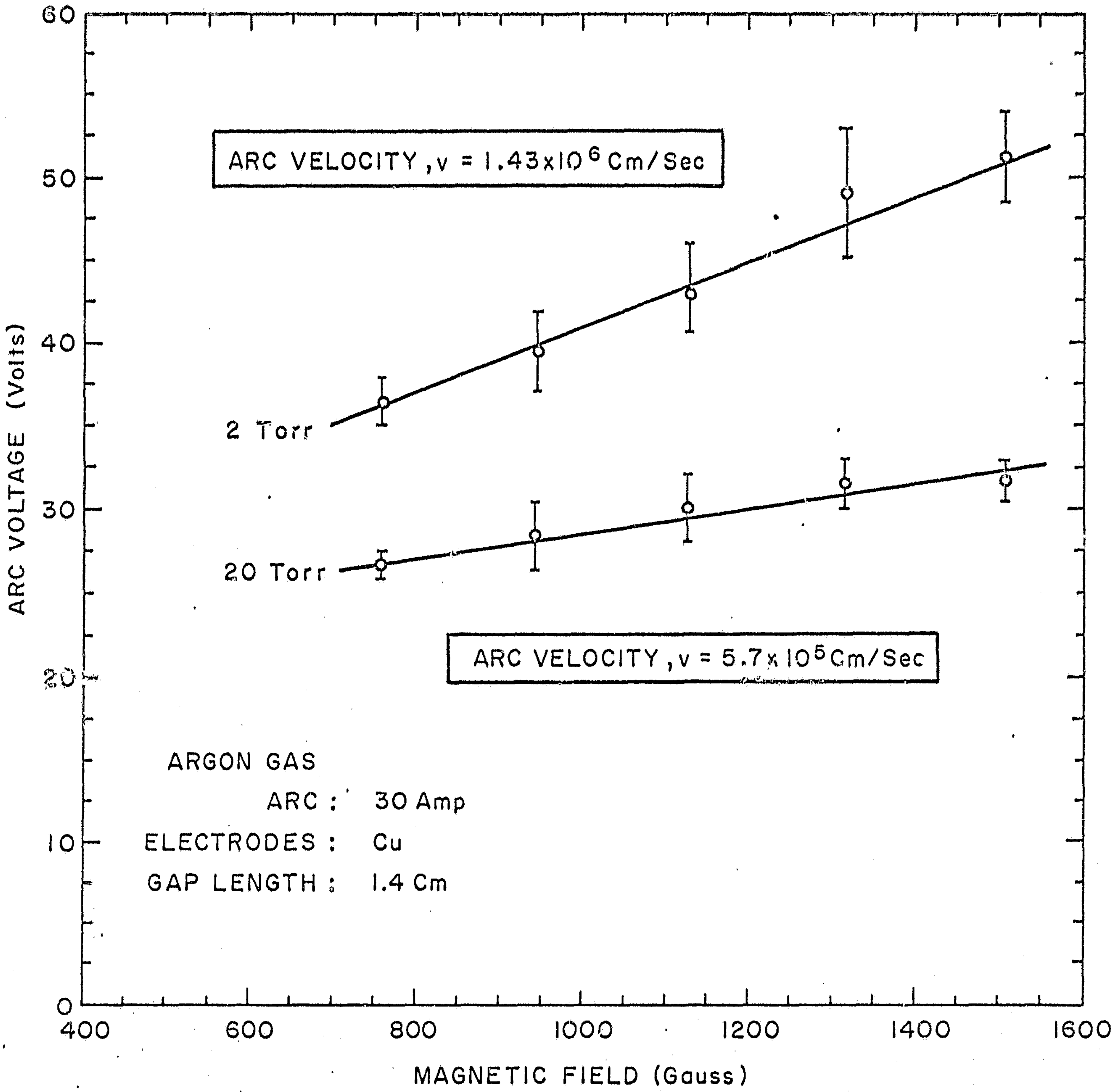

FIGURE 2.

DEPENDENCE OF ARC VOLTAGE ON MAGNETIC FIELD AT FIXED ARC CURRENT OF 30 Amp.

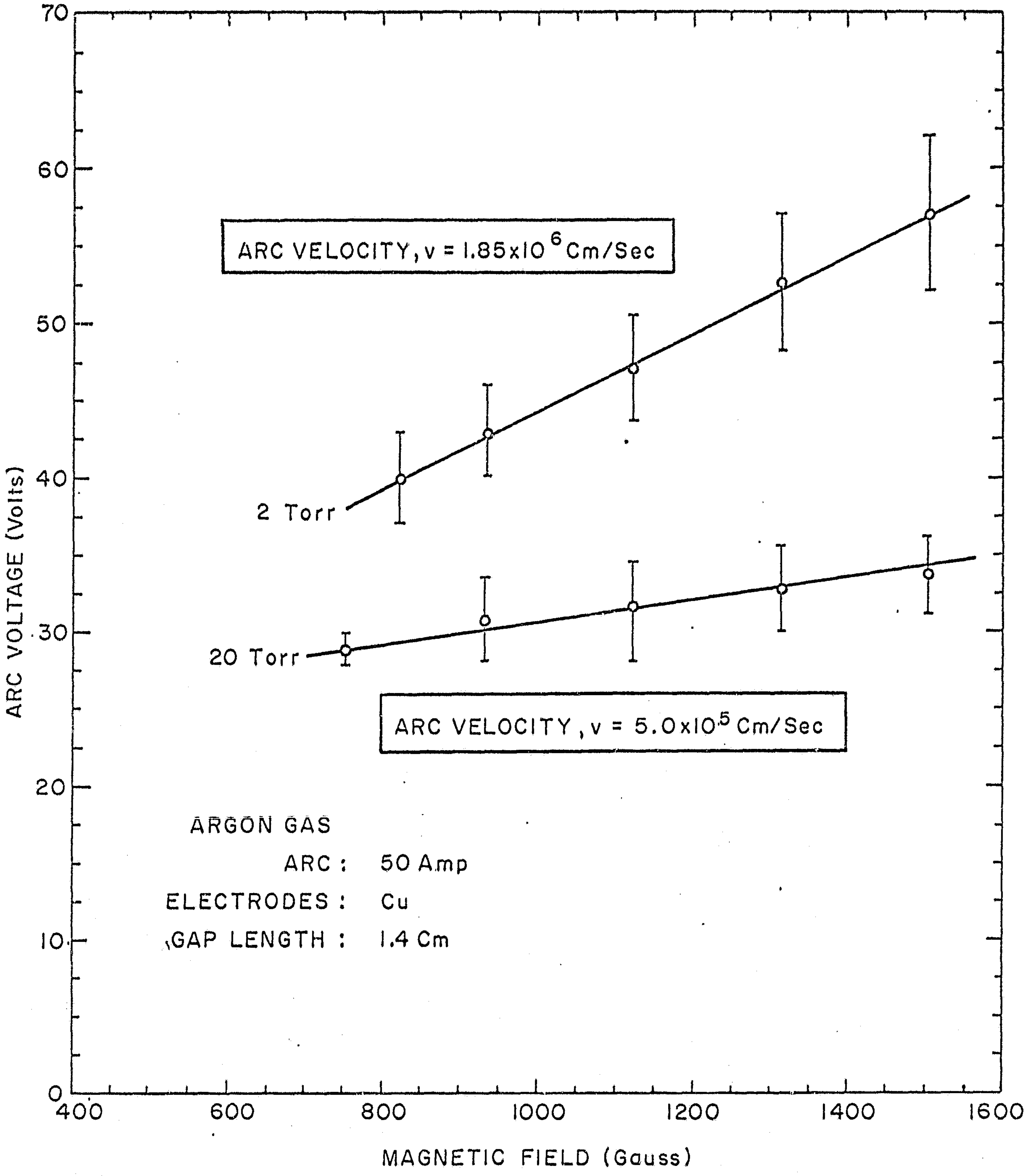

FIGURE 3.

ARC VOLTAGES vs. MAGNETIC FIELD
AT HIGHER ARC CURRENT (50 Amp.)

The arc velocity is deduced from this data using the expression

$$v = \frac{1}{\ell} \frac{dV}{dB}$$

where ℓ is the gap length between the electrodes and dV/dB represents the change of arc voltage with the magnetic field.

Within the accuracy of these measurements, it is noted from these figures that the arc velocity at higher pressures (20 Torr) is lower than the velocity at lower pressures (2 Torr). At 20 Torr the arc velocity does not appear to depend on the arc current, however at 2 Torr the higher arc current gives higher arc velocity. Furthermore these velocities are in the order of magnitude agreement with the arc velocities with molybdenum cathode indicating that the cathode material does not significantly affect the plasma velocity.

Figures 4 and 5 show the dependence of arc voltage on the magnetic field in helium at 100 and 0.5 Torr respectively. This data was taken for a fixed arc current of 50 amp. The cathode material in this case was molybdenum.

The arc velocities deduced from these measurements are 7.6×10^5 and 3.7×10^6 cm/sec at 100 and 0.5 Torr respectively. Once again the arc velocity is found to be inversely proportional to the gas pressure.

The data in Figure 6 indicates the dependence of arc velocity on the helium gas pressure as obtained by the back emf method. This data was taken at a fixed arc current of 50 amp. This data suggests a power law dependence between the arc velocity and the gas pressure of the form

$$v \propto p^{-1/3} \quad \text{(for Helium)} .$$

A comparison of this power law relation with the snowplow model and the ionization limiting velocity concept in helium is illustrated in Figure 7.

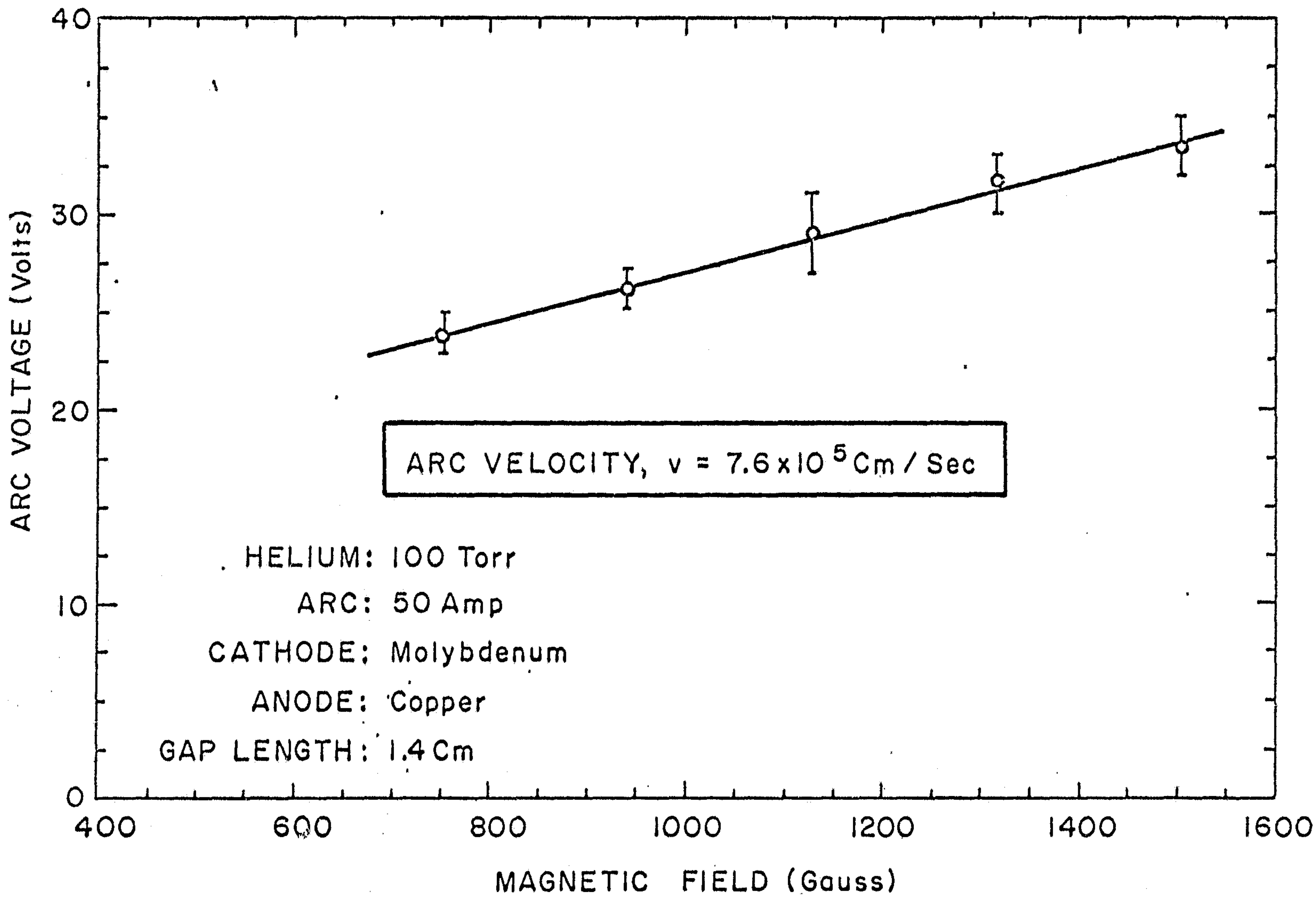

FIGURE 4.

DEPENDENCE OF ARC VOLTAGE ON THE MAGNETIC FIELD IN HELIUM AT 100 TORR.

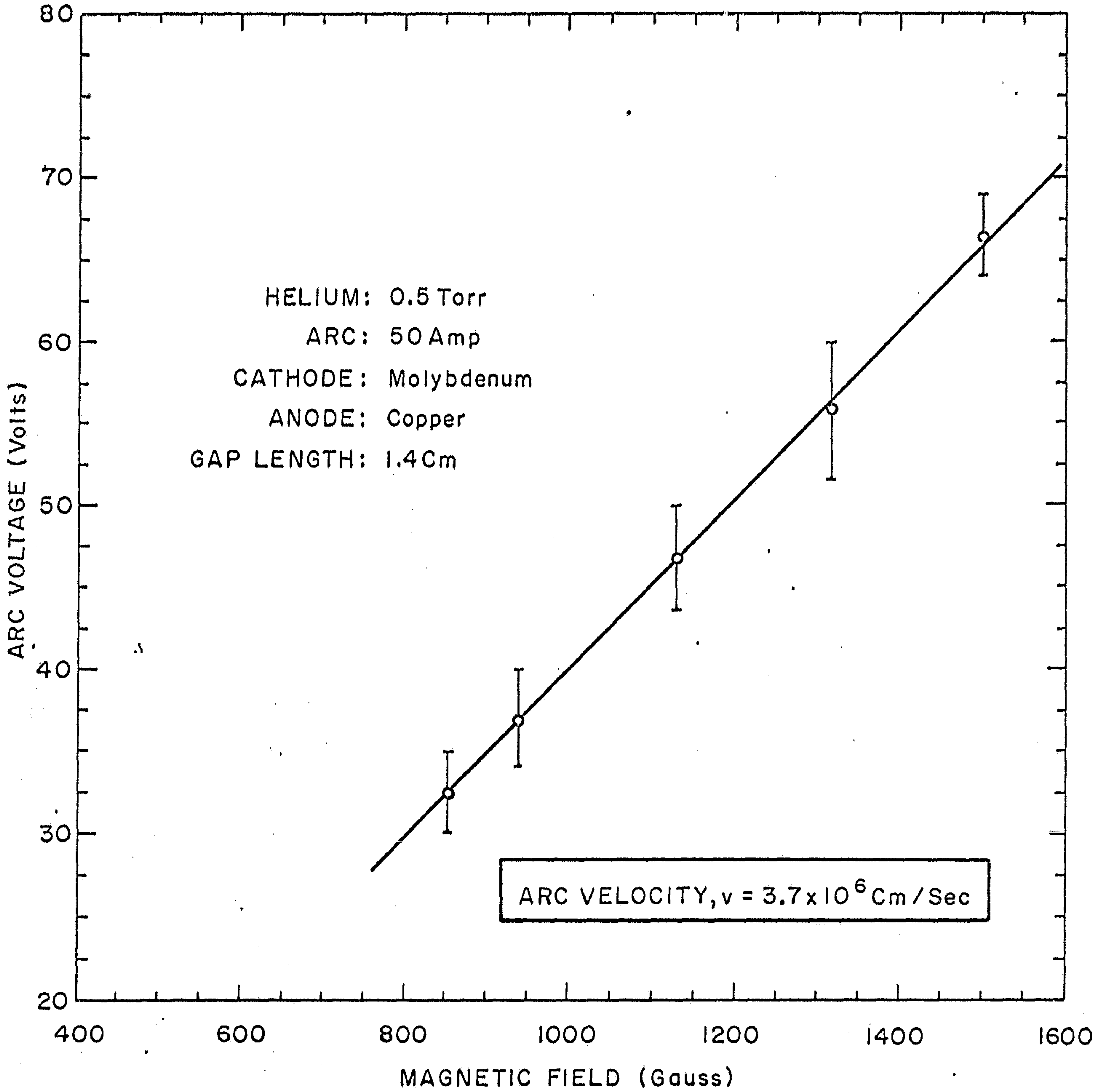

FIGURE 5.

DEPENDENCE OF THE ARC VOLTAGE ON THE MAGNETIC FIELD IN HELIUM AT LOWER PRESSURES (0.5 Torr).

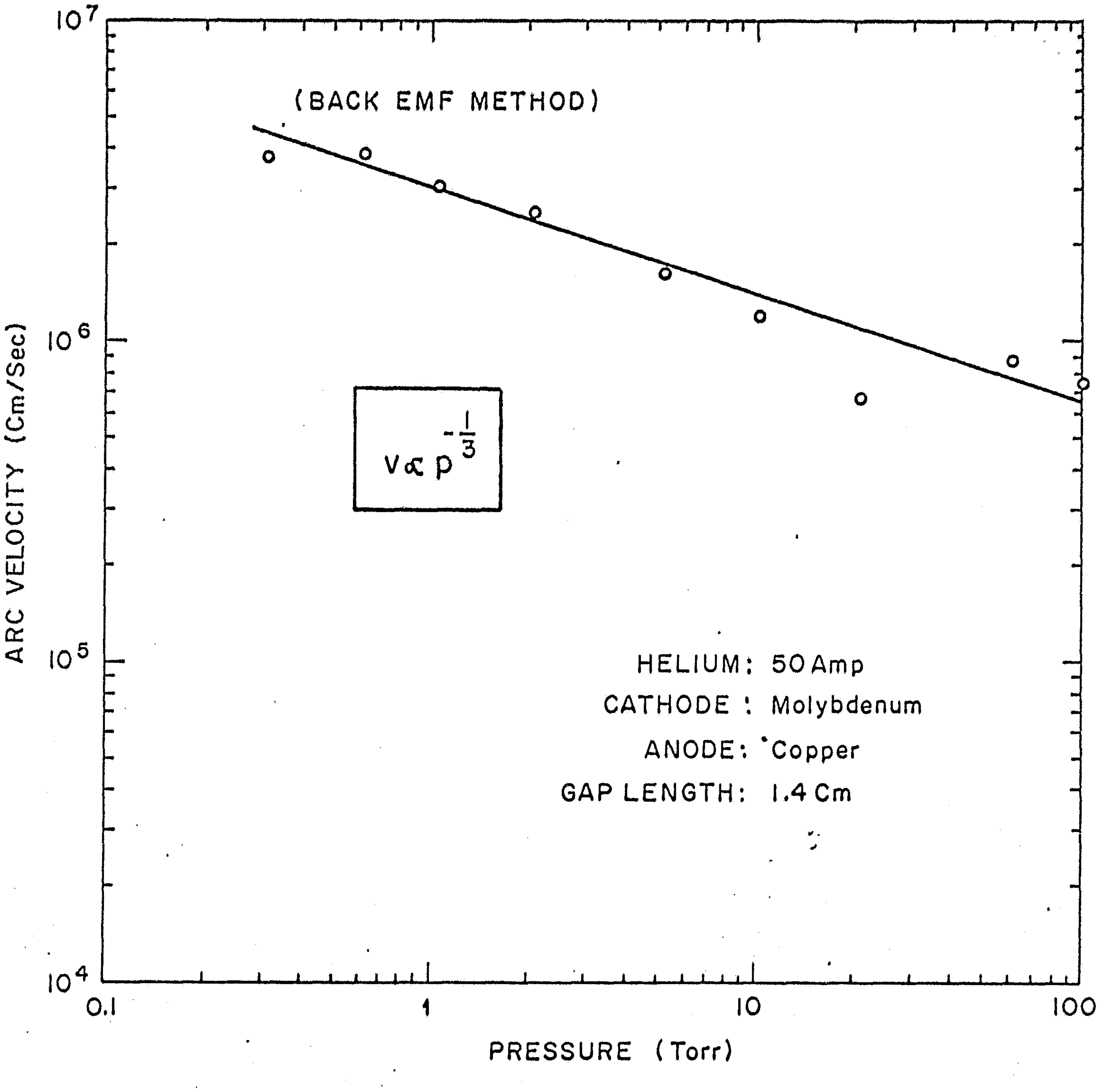

FIGURE 6.

DEPENDENCE OF ARC VELOCITY ON GAS PRESSURE IN HELIUM AS DETERMINED BY THE BACK EMF METHOD.

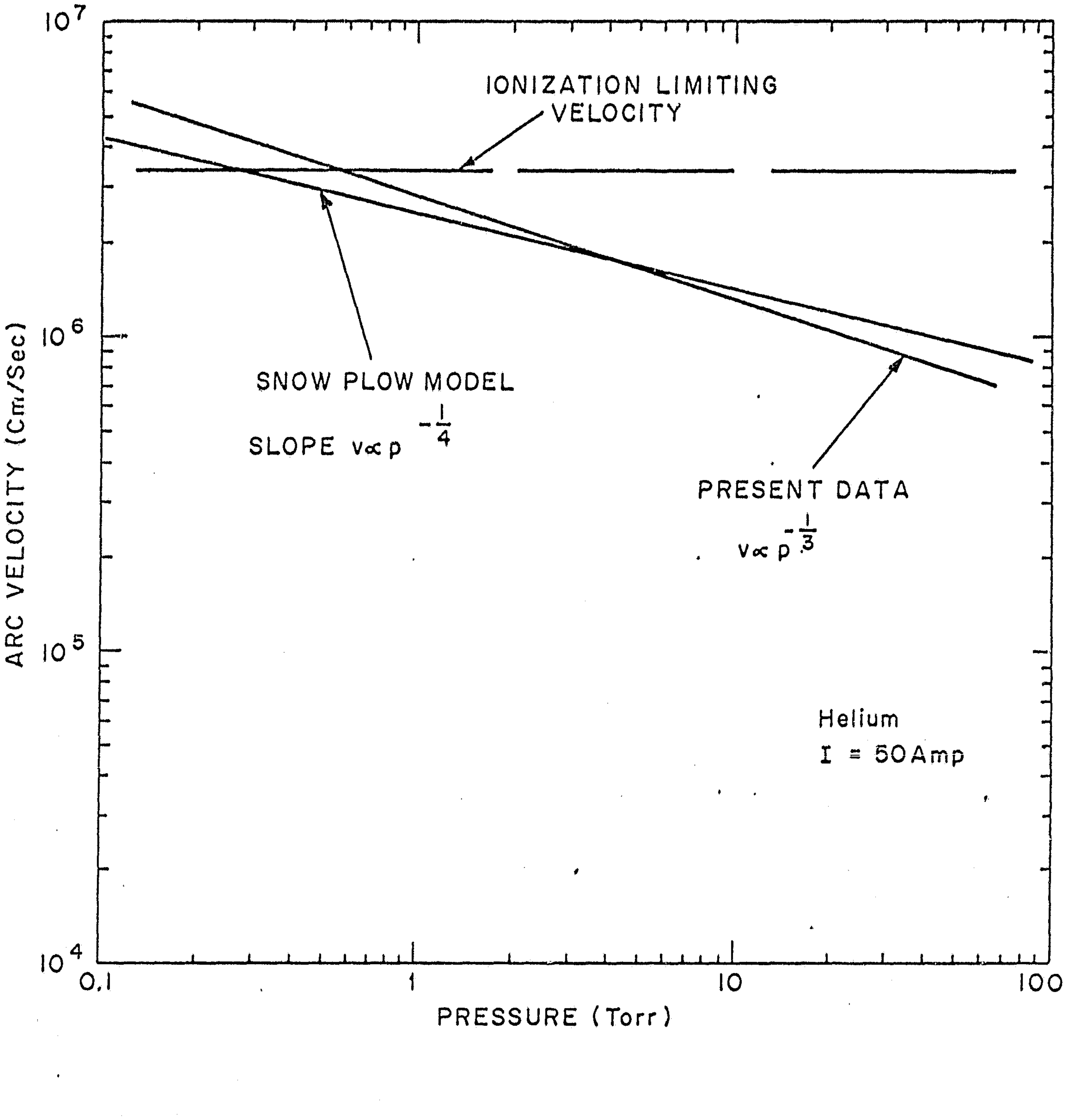

FIGURE 7.

COMPARISON BETWEEN SEVERAL PHYSICAL MODELS SHOWING THE PLASMA VELOCITY DEPENDENCE ON GAS PRESSURE IN THE CASE OF HELIUM.

The dependence of arc velocity on gas pressure in argon is given in Figure 8. Here again the data indicates a power law relationship of the form

$$v \propto p^{-1/2} \qquad \text{(for Argon)}.$$

Figure 9 compares the measured arc velocity dependence in argon gas pressure with the snowplow and the ionization limiting velocity models.

Both Figures 7 and 9 indicate that the experimental data may be considered to support the snowplow or a similar model for plasma velocity but not the ionization limiting velocity concept.

In Figure 9 is also included the arc velocity measurements of Lie et al[7]. They used optical methods to determine the velocity of a pulsed plasma accelerator. The plasma in their device is accelerated by discharging a high voltage capacitor bank in a coaxial structure. The plasma speed reported by them is about an order of magnitude higher than the ionization limiting velocity. Their measurements indicate that the velocity is related to the gas pressure by a power law of the form

$$v \propto p^{-1/4},$$

which is in agreement with the slope predicted by the snowplow model.

Further the measurements of arc velocity by the time of flight method show that the velocity of a self accelerated pulsed plasma[7] is about 200 times higher than the velocity of a continuously rotating plasma in a transverse magnetic field. In both cases, however, the plasma velocity is inversely proportional to the gas pressure.

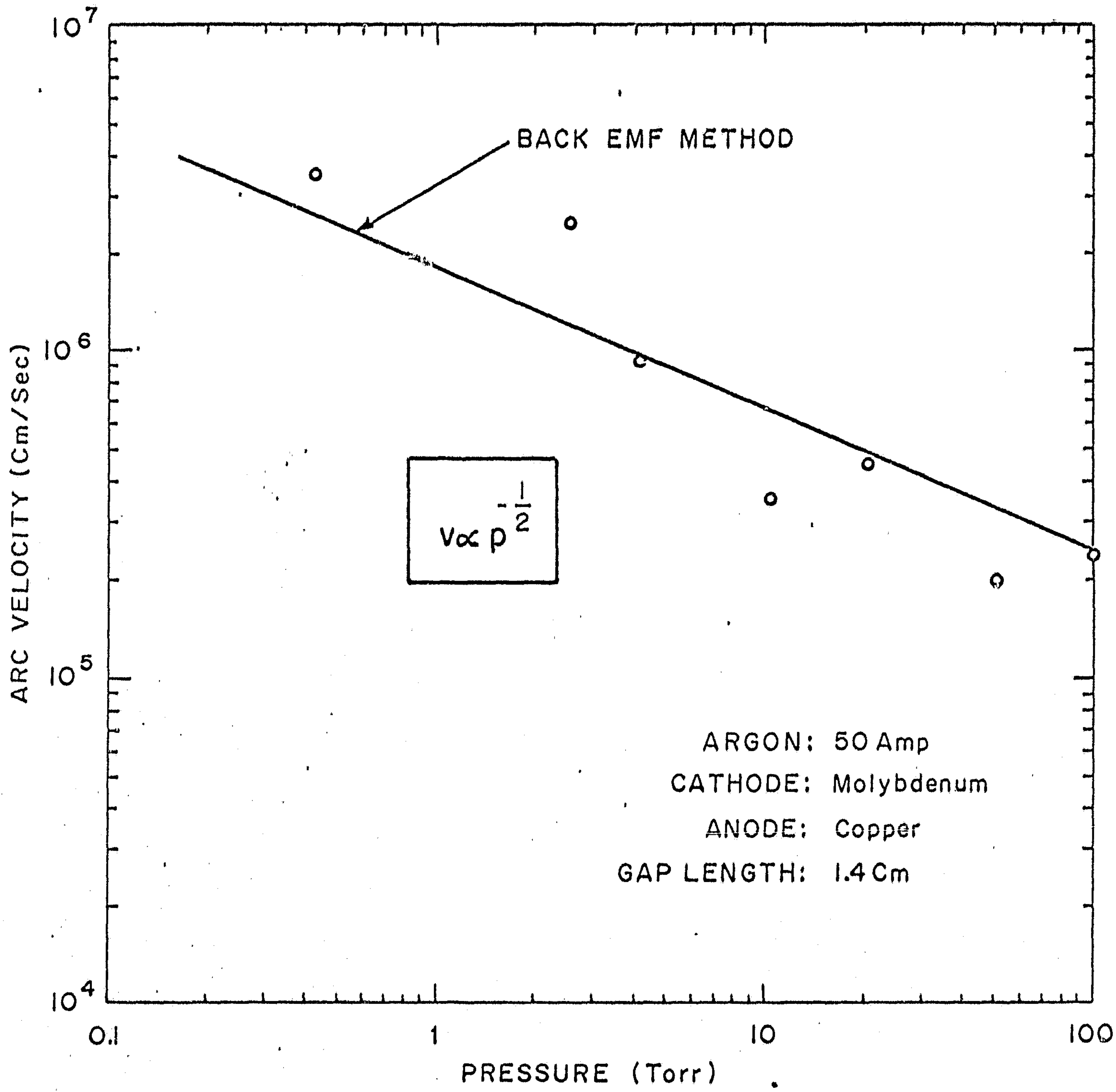

FIGURE 8.

DEPENDENCE OF ARC VELOCITY ON GAS PRESSURE IN ARGON.

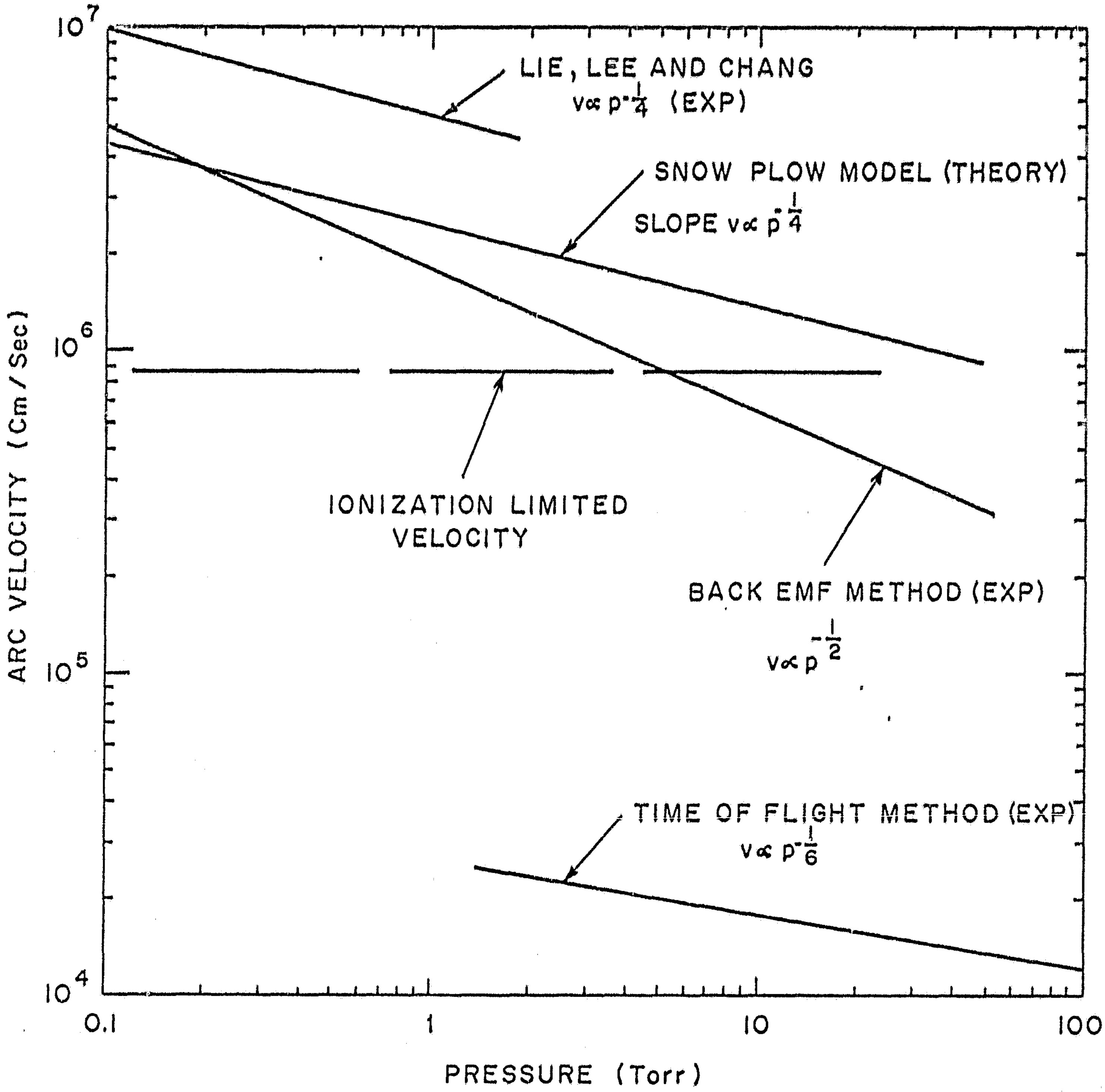

FIGURE 9.

ARC VELOCITY DEPENDENCE ON GAS PRESSURE IN ARGON AS PREDICTED BY VARIOUS PHYSICAL MODELS.

2.2 Plasma Velocity Measurement Using the Time of Flight Method

During this period of investigation, additional measurements of the arc velocity using the time of flight method are also made. Once again the system used for these measurements is reproduced in Figure 10 to make this report self contained. In this case the plasma rotation frequency is measured with a frequency counter at fixed arc currents, gas pressure and magnetic field. The arc velocity is obtained from the measured frequency using the expression

$$v = 2\pi rf$$

where f is the frequency at a radial distance r.

Figures 11, 12 and 13 show the variation in arc velocity as a function of arc current at various gas pressures. For the sake of clarity the data is presented in separate figures for each gas pressure. A constant magnetic field of 750 gauss was applied in all cases. These figures indicate that in the range studied the arc velocity increases slightly with the arc current.

Figure 9 compares the dependence of the arc velocity on the gas pressure in argon as determined by the back emf and the time of flight methods. Although there is a difference of about two orders of magnitudes in the absolute value of the arc velocity, both methods indicate a decrease in arc velocity at higher gas pressures.

Table 1 summarizes the results of the arc velocity measurements as determined by the two methods.

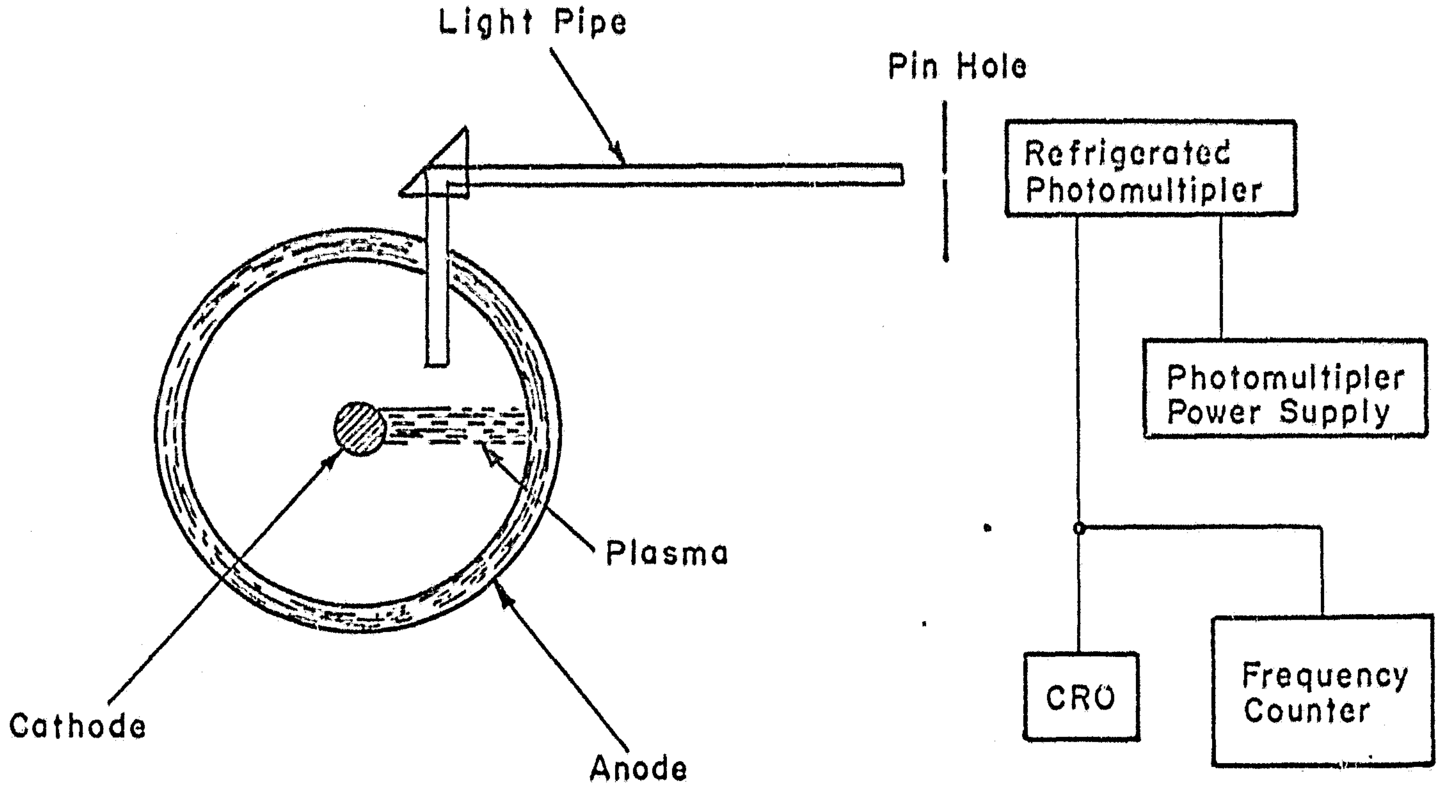

FIGURE 10.

EXPERIMENTAL SETUP FOR PLASMA ROTATIONAL FREQUENCY MEASUREMENT.

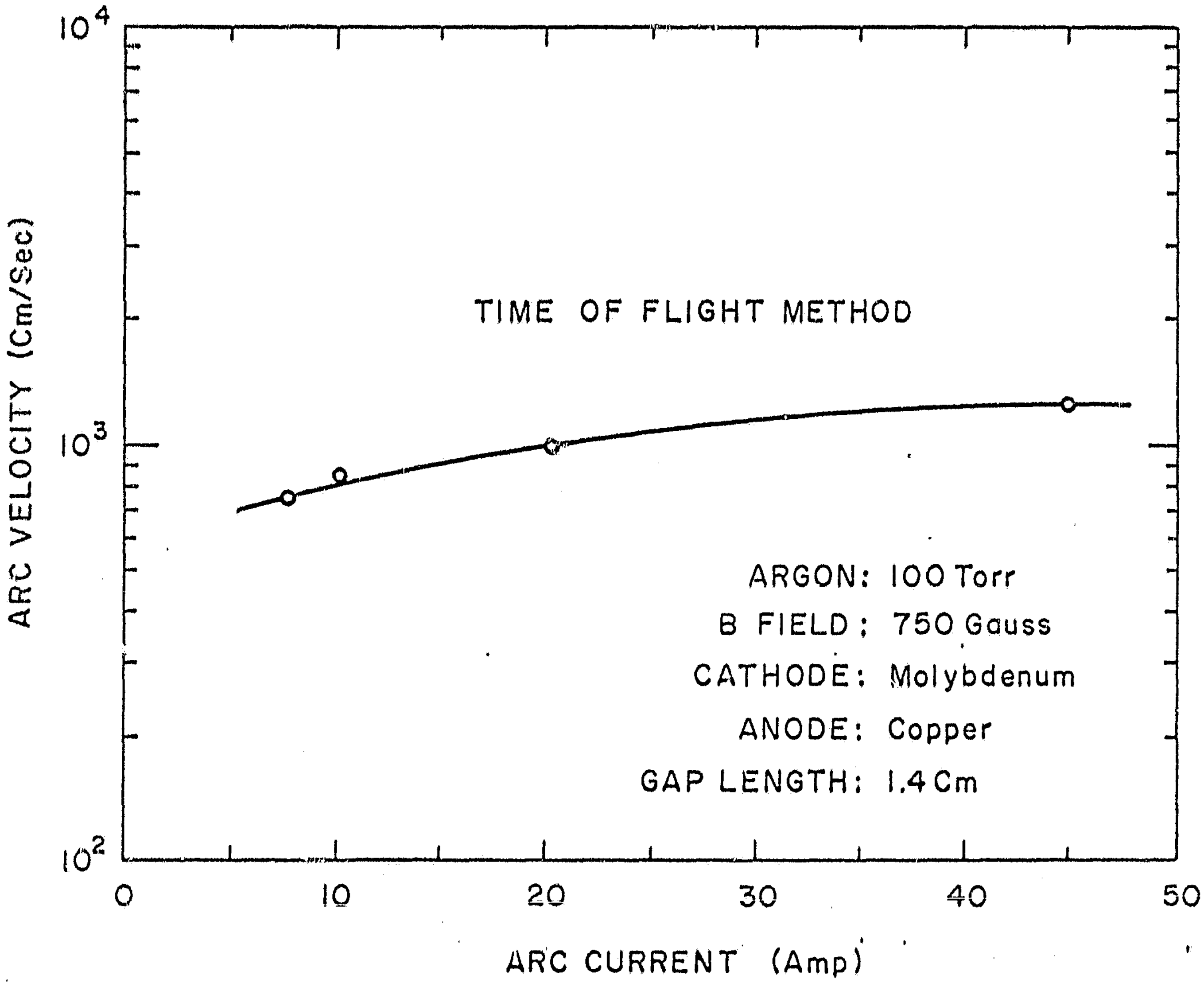

FIGURE 11.

DEPENDENCE OF ARC VELOCITY ON ARC CURRENT AT 100 TORR IN ARGON.

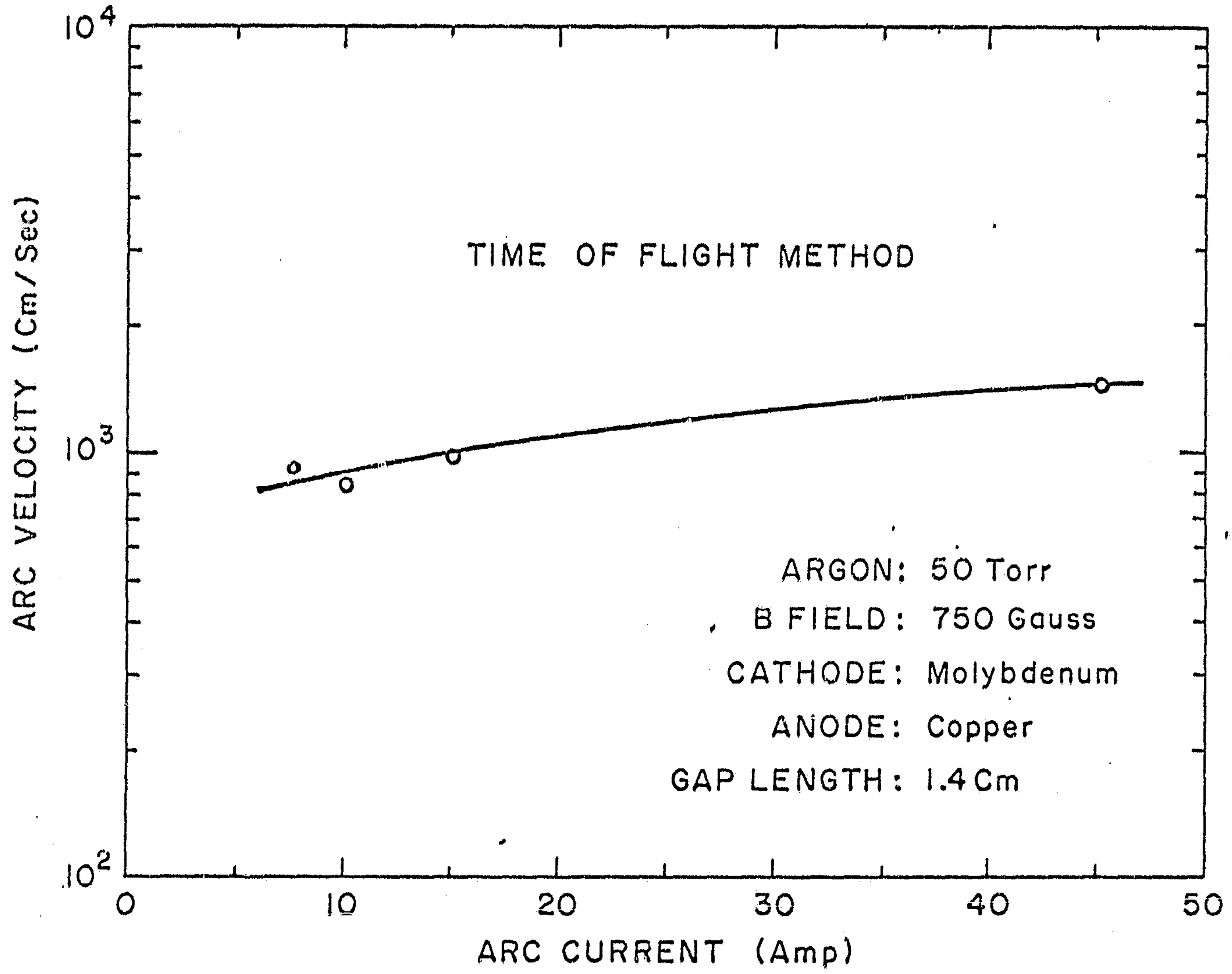

FIGURE 12.
ARC VELOCITY vs. ARC CURRENT IN ARGON AT A PRESSURE OF 50 TORR.

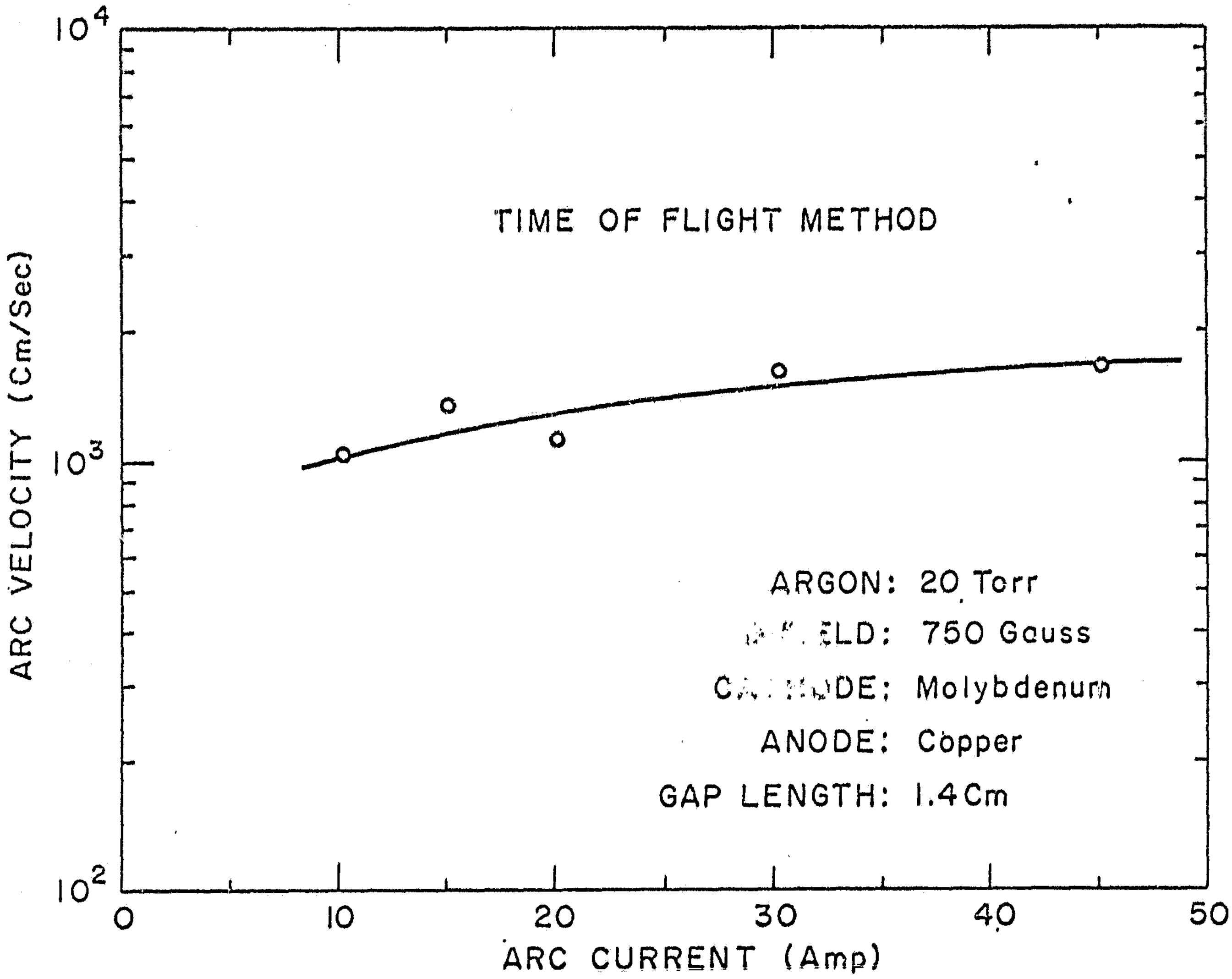

FIGURE 13.

ARC VELOCITY vs. ARC CURRENT IN ARGON AT A PRESSURE OF 20 TORR.

TABLE 1

COMPARISON OF ARC VELOCITY AND ITS DEPENDENCE ON ARC PARAMETERS AS STUDIED BY THE BACK EMF AND THE TIME OF FLIGHT METHODS

1.	Arc velocity is in the order of magnitude agreement with the ionization limiting velocity.	1.	Arc velocity is about two orders of magnitude smaller than the ionization limiting velocity.
2.	Arc velocity is independent of magnetic field.	2.	Arc velocity increases with the magnetic field.
3.	Arc velocity increases slightly with the arc current.	3.	Arc velocity increases slightly with the arc current.
4.	Within the accuracy of this test the arc velocity does not depend on the cathode material.	4.	———
5.	Arc velocity increases with decreasing gas pressures.	5.	Arc velocity increases as the gas pressure decreases
6.	The arc velocity is found to be higher in helium than in argon.	6.	———

2.3 Dependence of Arc Velocity Magnetic Field

The measured drag force on the electrodes of a coaxial plasma accelerator has shown a complex behaviour, consisting of a threshold and a saturation effect both as a function of the magnetic field and arc current[4]. These measurements suggest that there may be a threshold either in the tangential velocity, or in the particle current flow to the electrode or in the tangential momentum accommodation coefficient. These possibilities need further investigation in order to understand the observed phenomena. Towards this end the arc velocity is measured as a function of the magnetic field using the time of flight method.

Figure 14 shows the dependence of the arc velocity and the cathode drag force on the magnetic field. The velocity data presented in this figure was obtained with a photomultiplier and a frequency counter. The back emf method gives a value of arc velocity is independent of the magnetic field in this range. The ionization limiting velocity and the velocity by the back emf method for this case are 8.7×10^5 and 2.5×10^6 cm/sec respectively.

The tangential drag force data presented in Figure 14 are reproduced from the earlier electrode force measurements on the cathode of a JxB accelerator[4]. From this figure it is noted that although there is a threshold and a saturation effect in the cathode drag force, the arc velocity increases monotonically with the magnetic field in this range. Thus it is inferred that the threshold and saturation effects as seen from the electrode drag measurements do not arise due to the dependence of the arc velocity on the magnetic field. This reduces the possibilities of a threshold in the particle current flow to the electrode or in the tangential momentum accommodation coefficient. Investigation of this phenomena with the help of direct experimental measurements should lead to further clarification.

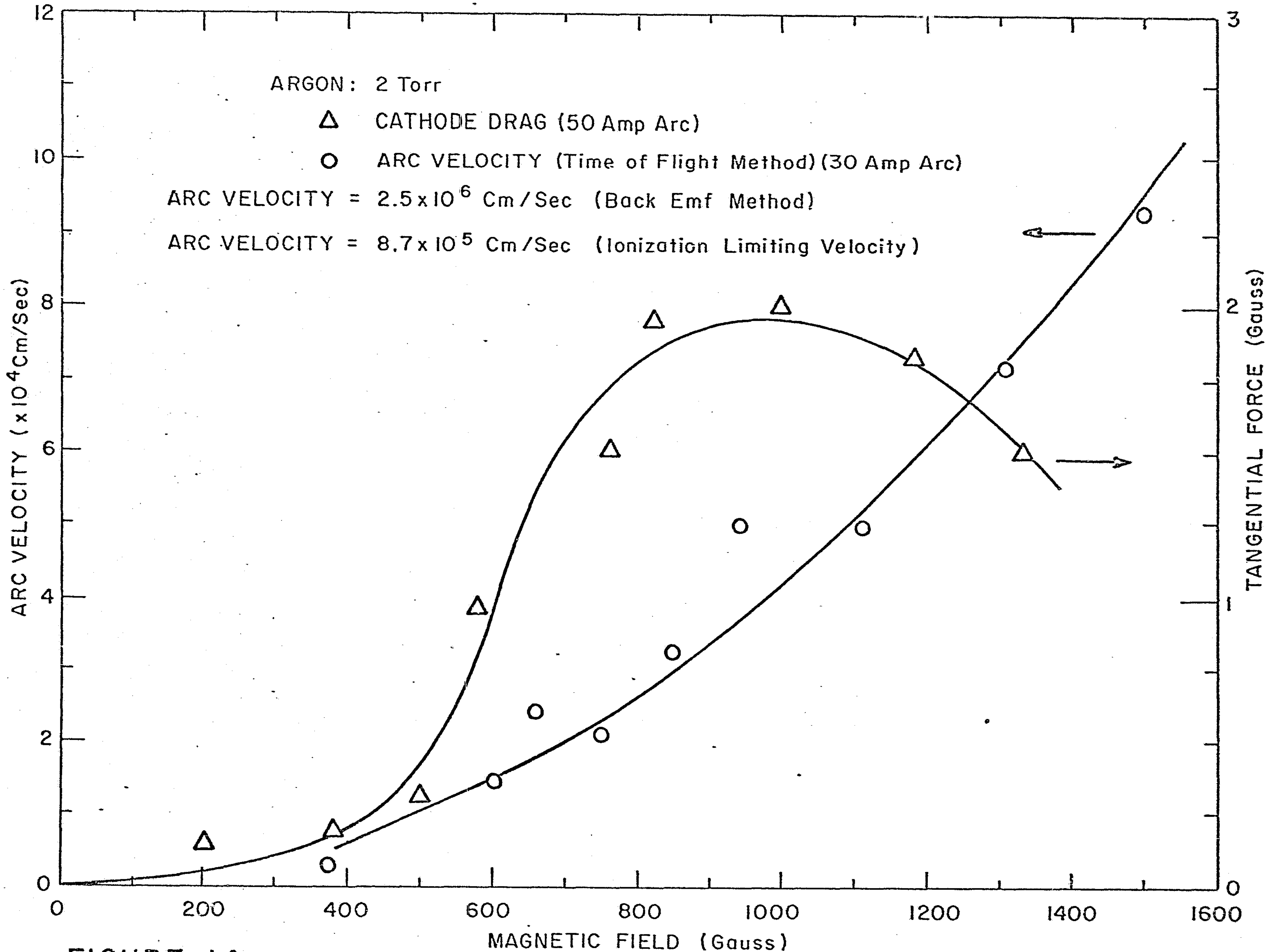

FIGURE 14.
DEPENDENCE OF ARC VELOCITY AND CATHODE DRAG FORCE ON THE MAGNETIC FIELD.

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