EXPERIMENTAL AND THEORETICAL RESEARCH ON PLASMA SHEATHS AND BOUNDARY LAYERS AROUND STAGNATION POINT ELECTRODES

SEMI-ANNUAL PROGRESS REPORT NO. 2

1 January 1965 to 30 June 1965

NASA Grant NSG 724

Prepared for:

National Space and Aeronautics Administration

Office of Grants and Research Contracts

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SUMMARY

During the time covered in this report the construction of the experimental apparatus has been essentially completed. Considerable effort has been devoted to calibrating and debugging the experimental apparatus, with the result that the arc jet was virtually contamination-free and steady state. Preliminary data have also been obtained in terms of spectrum and probe and electrode characteristics. A modest, but highly promising theoretical analysis has also been undertaken.

I. Introduction

This report describes the work performed during the second six months (1 January 1965 to 30 June 1965) of the two-year program entitled "Experimental and Theoretical Research on Plasma Sheaths and Boundary Layers Around Stagnation Point Electrodes" sponsored by the Office of Grants and Research Contracts, National Space and Aeronautics Administration. The NASA Technical Advisor is Mr. Howard Stine, NASA Ames Research Laboratory.

Personnel currently engaged in this research are: Professor Michael Ming Chen, Chief Investigator; Mr. Elihu Zimet, graduate student; and Robert L. Stevenson, undergraduate assistant.

II. Experimental Program

As described in the previous report (#1) the experimental technique consists of placing the test electrode in the pre-ionized gas jet of a conventional arc heater. Spectroscopic, voltage-current, and other diagnostic measurements would then be carried out for the plasma boundary layer around the test electrode. The current status of the program is described below.

A. The Arc Jet

The plasma source consists of a conventional coaxial arc jet. A 2% thoriated tungsten rod with a conical tip serves as the cathode, located immediately at the entrance of the nozzle. The interchangeable nozzles consist of a 0.1-inch diameter constant area section followed by a 7° or 15° expansion. They are cooled by a water jacket and serve also as the anode of the arc discharge. When the arc jet is operating stably (see below), the arc discharge takes place between the cathode tip and somewhere in the supersonic region of the anode. The discharges appear to be uniform and no distinguishable anode spot can be seen.

Since arc jet devices often exhibit instabilities, considerable effort has been devoted to ascertain that no undesirable instabilities or oscillations exist in the plasma stream. This was done by monitoring the electrical signals, i.e., the current and voltage measurements, at various current levels and flow rates. Some representative results of the oscilloscope tracings are shown in Figures 1 and 2. In Figure 1 the flow rate is kept constant while the arc current is gradually increased from 30 amps to 72 amps. It is seen that at 30 amps the arc discharge exhibits fairly large fluctuations at low frequency. Both the voltage and current fluctuations are of the order of 10%, at about 200 cycles per second. It is not too clear what the cause of this oscillation is. The frequency, however, appears to be consistent with those which can be obtained by assuming that a kink or screw instability as proposed by Chen[2] exists in the arc column, which moves through the nozzle with the flowing gas.

When the arc current is increased, as can be seen by the 60.5 amp and 72 amp photographs, the oscillation gradually disappears until it is consistently below 1/2 %. This level is considered satisfactory for the intended experiments.

Figure 2 shows the influence of flow rate when the arc jet is operated at the same current. It is seen that for the ranges of flow rates shown, it has very little effect on the inherent oscillations of the arc jet.

In order to gain some qualitative insight of the frequencies involved in those oscillations, the bottom two pictures in Figure 2 are taken with a relatively fast sweep speed. It is seen from the single sweep oscilloscope that the oscillations are basically random, although it shows an obvious emphasis at a single frequency. This is made particularly clear in the multiple sweep picture, triggered by a given slope for the voltage curve. It is seen that the period of the oscillation is of the order of 10 microseconds, giving a frequency of roughly 100 kilocycles.

While these oscillations are insignificant in view of the intended experiments, a modest effort is being made to understand their origin so that their amplitude can be reduced further.

B. Spectroscopy

Preliminary spectroscopic data have been obtained and two typical spectra are shown in Figures 3 and 4. These are shown with the slit focussed in the center of the jet in front of the first electrode. A relatively wide slit was used, resulting in the characteristic triangular line-shape with a base of roughly 4 Angstroms. A careful identification of the lines in the entire visible spectrum (not shown) showed only argon lines, indicating that the arc jet is spectroscopically pure. This agrees with the observation that except for "new" cathodes, there are no distinguishable erosions of the cathode tip.

In view of the fact that spatial accuracy is important for the proper mapping of the temperature field in the vicinity of the test electrode, it was decided that a motor-driven standing table be constructed. Therefore, no spatial scans were included in this report.

C. Electrical Characteristics of the Electrode

Extensive current voltage characteristics have been obtained for a test electrode of 1/8-inch diameter, made from 2% thoriated tungsten. The test electrode is mounted flush inside a 3/8-inch outside diameter boron nitrite tube. The test current is applied between the test electrode and the arc jet anode. In order to avoid uncertainties caused by the arc jet anode fall, the test electrode potential is measured with respect to a reference probe placed outside the shock layer of the test electrode, drawing a constant 1 mA electron current.

When the test electrode is used as a negative probe, the voltage current characteristics are similar to the saturation ion current of electrostatic probes. The saturation-ion current observed is of the order of 1 amp. This value is consistent with the expected ion concentration in the plasma stream.

When the test electrode is used as an anode or positive probe, the current voltage characteristics do not follow the straight line expected from the usual electron current portion of probe theory. Some typical results are shown in Figure 5. It is seen that plotted on a semi-log paper, the curve shows no straight line portion and therefore it is not possible to interpret the slope as an indication of electron temperature. Tentatively, this behavior is attributed to the existence of an electron temperature gradient and the change of sheath thickness as a function of applied voltage. Clearly, a detailed interpretation of the structure of this curve would be an important portion of our future research program.

Efforts to draw more than the saturation ion current when the test electrode is negative generally resulted in erratic behavior accompanied by rapid electrode erosion. It is believed that the high thermal conductivity of the boron nitrite installation prevented the test electrode tip from reaching thermionic emission temperatures. Effort to overcome this difficulty is being made.

III. Theoretical Program

In order to gain some elementary understanding of the mechanism of current constriction on electrode surfaces, a simple stability theory has been developed. This approach bypasses the difficulty of satisfying the partial differential equations of conservation for the three-dimensional plasma and solid half-spaces. Rather, assuming a uniform one-dimensional discharge, we inquire under what conditions can such a discharge be stable.

The instability mechanism to be invoked in the present theory is that due to the coupling of the plasma energy equations with equations governing electrical conduction. In the simplest form, this instability can be explained by considering electrical conduction in a gas whose electrical conductivity increases rapidly with temperature. If a perturbation exists in the form of a local hot spot, the hot spot may disappear in time due to heat conduction, or may intensify due to increased Joule heating, which is a result of the higher electrical conductivity. The latter case represents an instability which may grow until an entirely different discharge configuration with localized current is obtained. Similar processes may occur in the vicinity of electrodes, although they can no longer be expressed in such simple terms due to the additional complications of sheath and emission characteristics.

In order to bypass the multitude of theoretical complications which surround the solid plasma interface and fluid mechanical boundary layer, and place the emphasis only on the instability aspects of the problem, we restrict our attention to the simple problem of a motionless plasma between two plane surfaces. Either or both of the surfaces could be an electrode surface. Other major assumptions are:

(1) Except in the sheaths, the plasma is considered to obey the simple Ohm's Law, with electrical conductivity dependent on temperature only. This assumption can easily be modified to include the case of non-equilibrium ionization by considering tensor conductivities.

(2) Radiation and convective heat loss in the plasma are considered negligible, with heat transfer governed by Fourier's Law of heat conduction. Thermal conductivity shall be considered temperature dependent, but $\frac{k}{\rho C_p}$ shall be assumed constant.

(3) Effects of electrode sheath are assumed to be expressible as boundary conditions to the plasma current and energy equations in the

form: $j_n = j_n(\phi_s, n_s, T_s, T_c)$ and $q_n = q_n(\phi_s, n_s, T_s, T_c)$ with known partial derivatives. The subscripts n, s, and c refer to the normal flux, sheath edge, and cathode surface, respectively.

The analysis follows the procedure of a typical stability problem. First, a solution for the uniform case, consisting of one-dimensional problem in y only, is obtained with appropriate boundary conditions. Next, linearized perturbation equations are investigated in terms of a perturbation solution periodic in x and z. The growth rate of this perturbation is then used as an indication of instability.

At the time of this report, solutions to the differential equations are still being sought. However, examination of the equations yield the following qualitative conclusions:

(1) The important parameter, in terms of the model presented above, which determines whether a uniform discharge is possible is

$$\left(\frac{d\sigma}{dT}\right) \frac{h^2 j^2}{K\sigma^2} ,$$

where h can be interpreted generally as a characteristic thickness of the plasma slab. When this parameter exceeds a critical value, uniform discharge is not likely.

(2) From the former instability parameter, it can be concluded that as a rule weakly ionized gases are less likely to yield uniform gas discharges at the same current level.

(3) The critical value of the stability parameter is strongly affected by the electrode sheath boundary conditions. For an emitting electrode, the conditions are such that thermionic emissions tend to yield a more uniform discharge.

These conclusions are seen to be in agreement with qualitative trends. Investigations along these lines will be continued and reported in the future.

IV. Financial Condition

As of 30 June 1965, about 45% of the total funds have been expended. The rate of expenditure has been roughly in agreement with the original cost estimate.

V. Future Plans

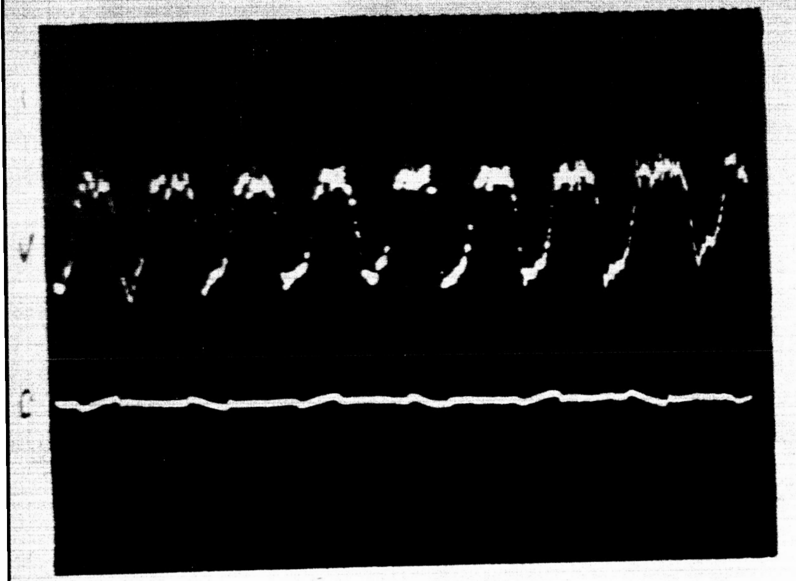
In the immediate future, effects will be concentrated in increasing the test metal surface temperature and in obtaining a spectroscopic mapping of the plasma environment. Solutions to the differential equations in connection with the stability theory shall also be attempted.

REFERENCES

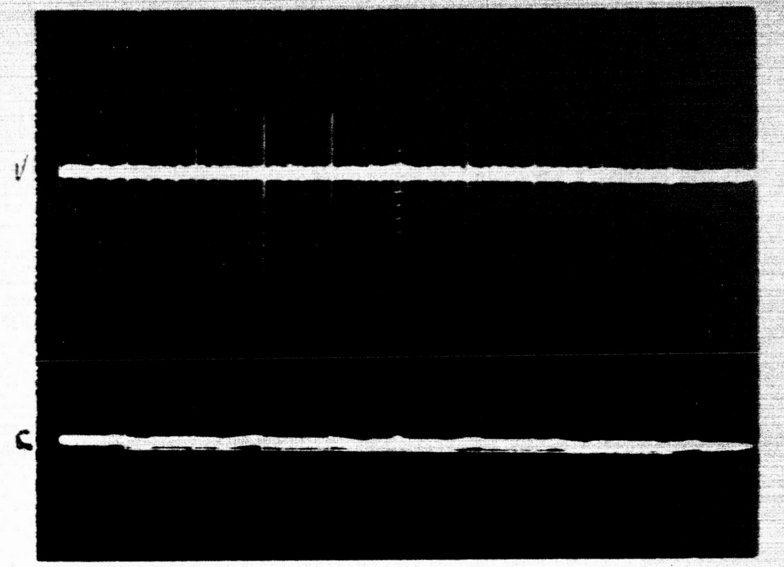
1. "Experimental and Theoretical Research on Plasma Sheaths and Boundary Layers Around Stagnation Point Electrodes," Semi-Annual Progress Report No. 1, for period ending 31 December 1965, by Michael M. Chen.

2. "Validity Conditions of Transport Property Measurements Using Arc Columns," by M. M. Chen, AIAA Paper 65-541.

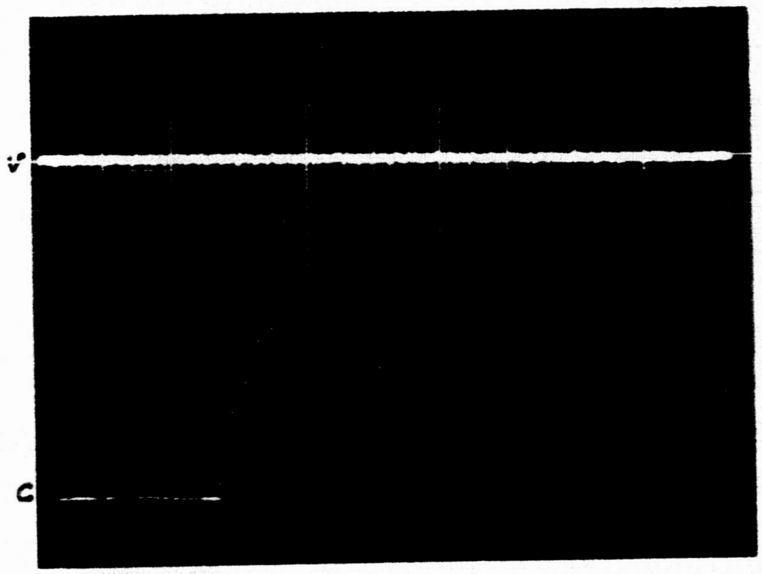
Flow Rate 0.30 CFM   Sweep Speed 5 m sec/div



50 Amps 10 mv/div
35.5 Volts 2 volts/div



60.5 Amps 2 mv/div
22 Volts 2 volts/div

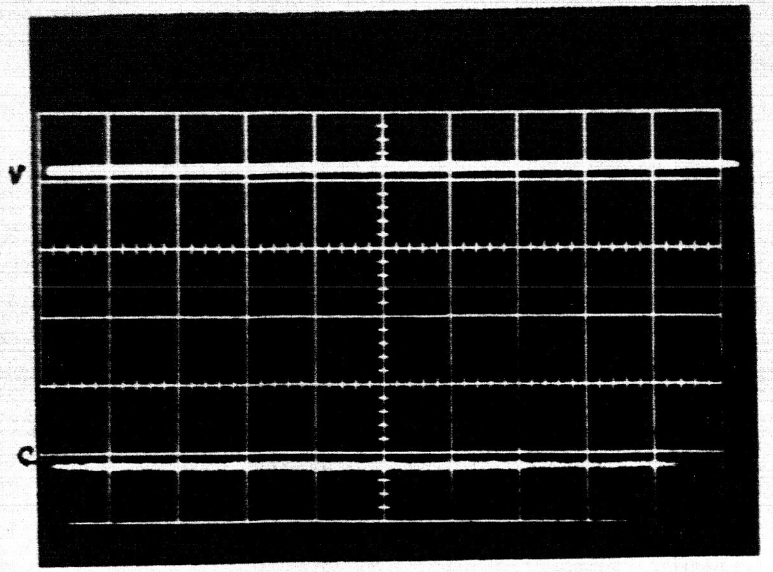


72 Amps 2 mv/div
21 Volts 2 volts/div

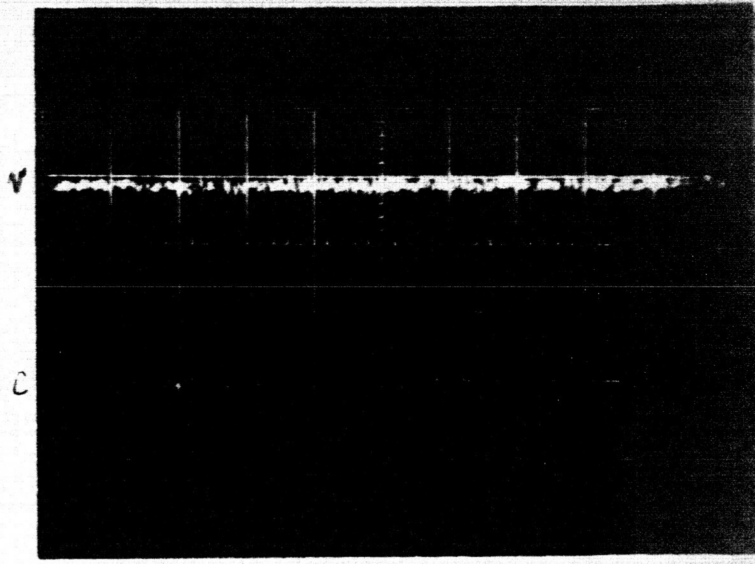
Note: 50 mv shunt for amperage reading.
150 AMPS

FIG 1

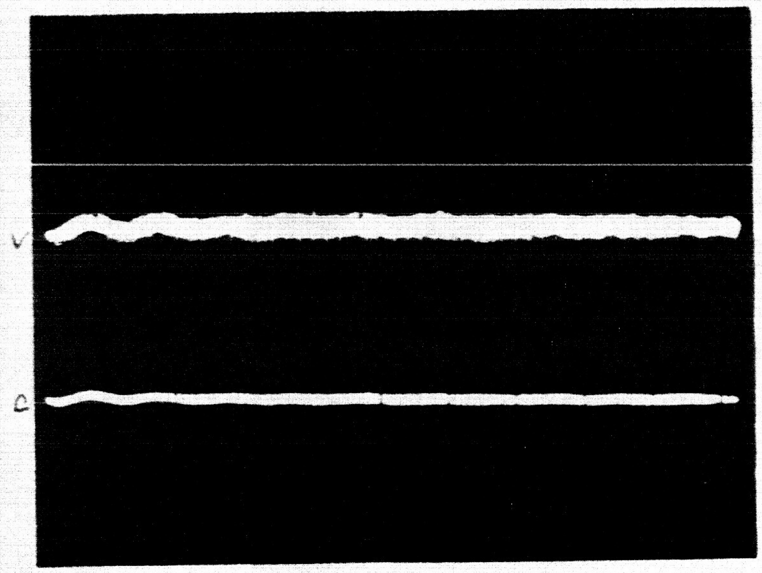
80 Amperes 21 volts to nozzle



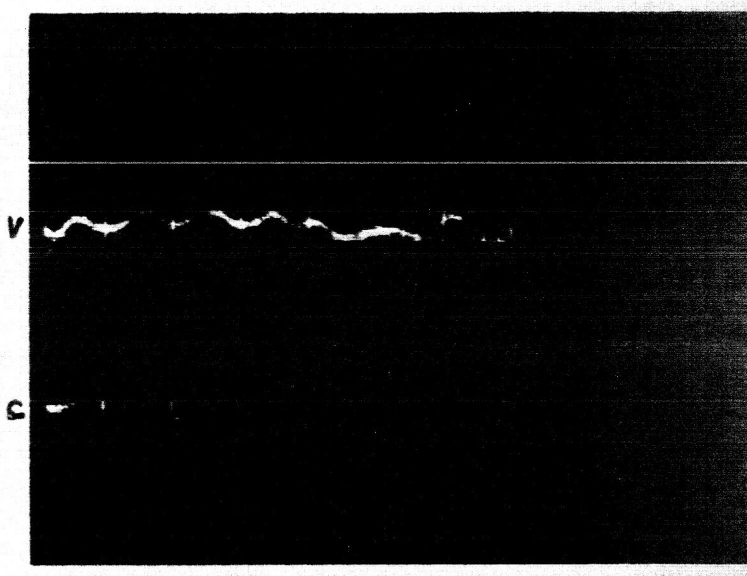
0.2 cfm 2 mv/div current
2 volts /div voltage
10 mm sec/div



0.3 2 mv/div current
1 volt/div voltage
5 m sec/div



0.45 cfm 2 mv/div current
1 volt/div voltage
10 mm sec/div
multiple sweep



0.45 cfm 2 mv/div current
1 volt/div voltage
10 mm sec/div
single sweep

Note: 50 mv shunt for amperage reading.
150 AMPS

FIG. 2

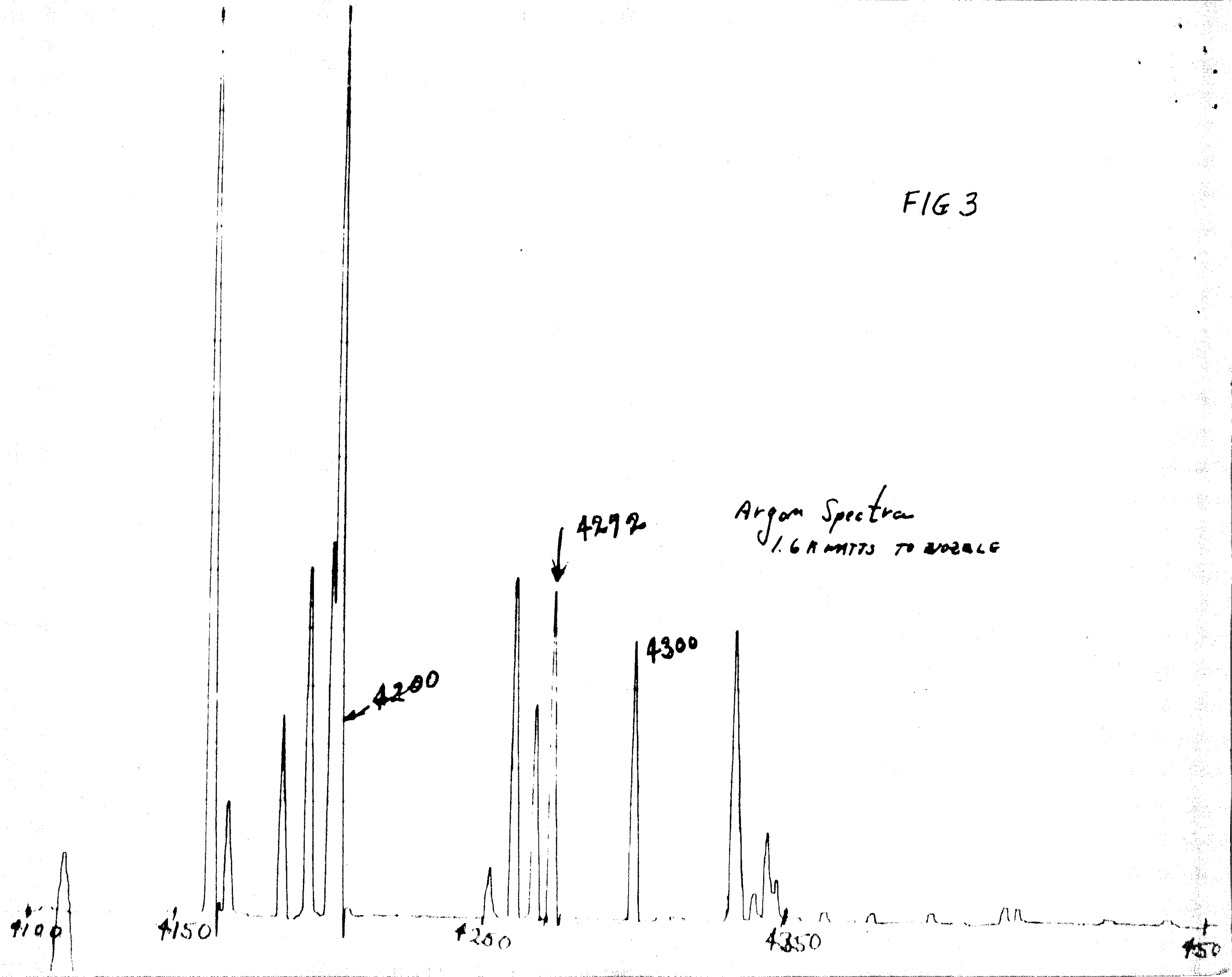
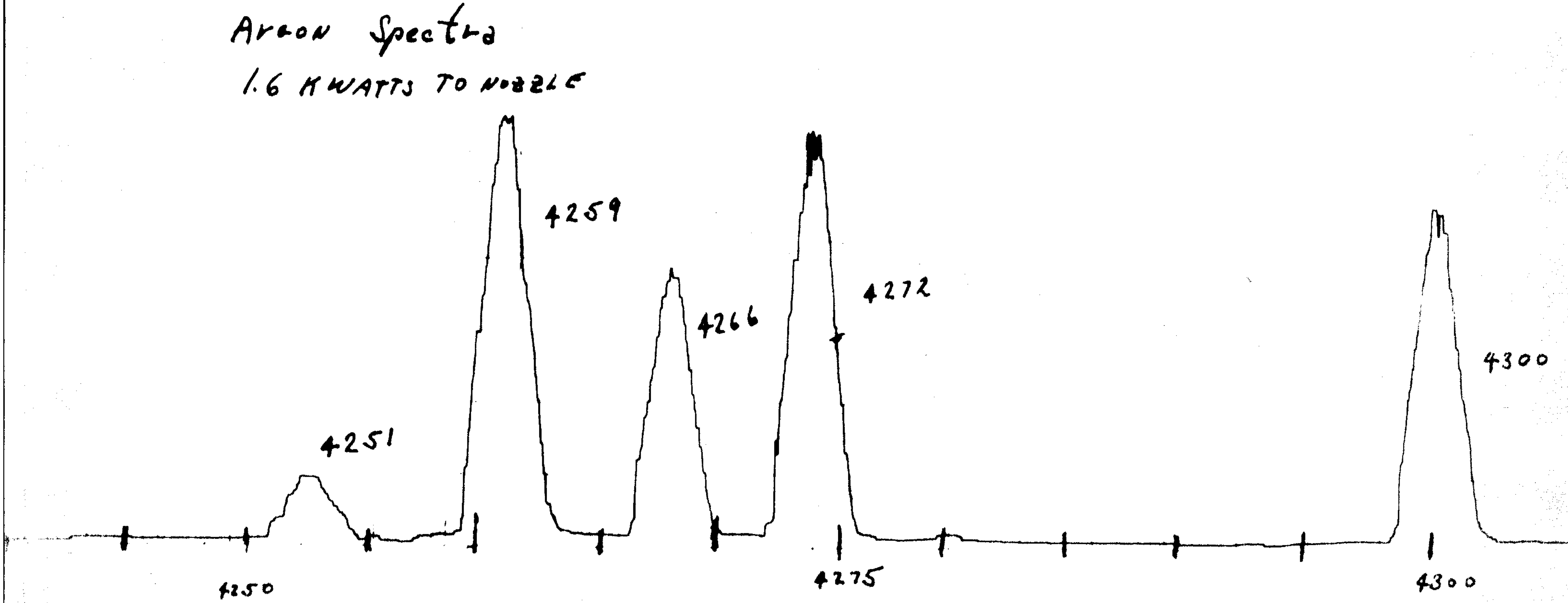

Argon Spectra
1.6 K WATTS TO NOZZLE
4292
4200
4300
4100
4150
4250
4350

FIG 3

FIG 4



Argon Spectra
1.6 KWATTS TO NOZZLE
4251
4259
4266
4272
4300
4250
4275
4300

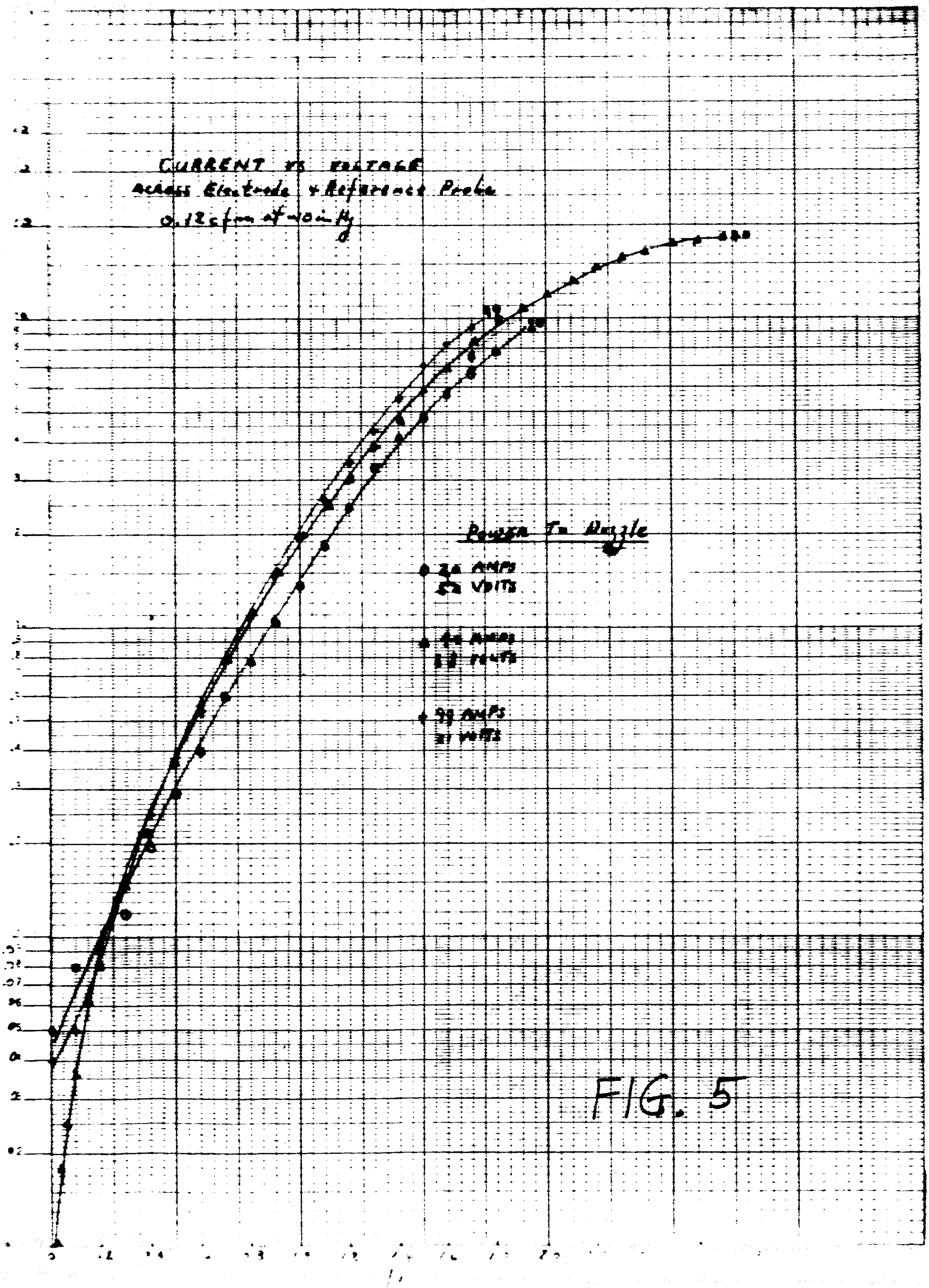

CURRENT VS VOLTAGE
Across Electrode + Reference Probe
Power To Nozzle

FIG. 5