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A BIASED ELECTROSTATIC PROBE IN A CONTINUUM REGIME

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Samuel Lederman and Yoel Avidor

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POLYTECHNIC INSTITUTE OF BROOKLYN

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ABSTRACT

The current collection of cylindrical negatively biased electrostatic probes in a continuum plasma regime is experimentally investigated. The effects of plasma flow, length-to-diameter ratio, diameter, and angle of attack of the probes with respect to the moving plasma are found to be rather strong. It is found that the current collection of the probe increases with the angle of attack, with the decrese of the fineness ratio l/ρ, and with the decrease of the diameter of the probe.

† This research was supported by the National Aeronautics and Space Administration under Grant No. NsG-409.

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SECTION I

INTRODUCTION

The biased electrostatic probe has recently become a very important tool in the hands of scientists concerned not only with the diagnostics of plasmas in laboratory environment but also with plasmas encountered in space, e.g., around reentering vehicles. The renewed interest, in this type of probe, which belongs to one of the oldest diagnostic instruments for ionized gases, can be attributed to its simplicity of construction and operation and its enormous dynamic range. The interpretation of the probe's signals is quite difficult and not perfectly understood. Since on reentry one might expect the operation of a probe to span the whole range of plasma regimes from the free molecular through the transitional to the continuum, an understanding of the operation of a probe in each regime is of prime importance.

The problem considered here is the operation of electrostatic cylindrical probes in the continuum plasma regime. One aspect of the problem is the effect of fineness ratio, that is, the ratio of length of the probe to its radius, on the current collected by the probe. Another aspect is the effect of the radius of cylindrical probes in a continuum regime and the effect of angle of attack on current collection by electrostatic probes. A conventional shock tube was used to generate a slightly ionized gas flow. A rake of cylindrical probes, having various lengths and diameters, was used to investigate the effect of fineness ratio and probe radius on the current collected by the probe. In addition to this, a rake of cylindrical probes of different angles of attack ($0-90^{\circ}$) with respect to the flow direction, was used to investigate the effect of angle of attack on current collection by the cylindrical probes.

In this report the theory of cylindrical probe operation in the continuum plasma regime at rest developed by Zakharova et al. (Ref. 1) was used to reduce the collected current data under flow conditions. A comparison between the theoretically predictable current density in a plasma at rest with the experimentally obtained current densities in a moving plasma was made. Furthermore, an experimental determination of the current density dependence on fineness ratio and on probe radius was obtained.

SECTION II
STATEMENT OF THE PROBLEM

The use of electrostatic probes for plasma diagnostics is based essentially on the interpretation of the current collected by a probe in terms of the unperturbed plasma properties. A large volume of work has been accumulated over the years, since the original work of Langmuir, dealing with the theoretical aspects of probe operation. Recent investigations reported in the literature (Ref. 2-9) dealing with electrostatic probes are limited mostly to low density plasmas. Both cylindrical and spherical probe configurations were treated. In these the probe dimensions, radius of cylinder or sphere, are small compared to the mean free path and thus the ions or electrons attracted to the probes experience no collisions. Recent contributions, both theoretical and experimental, of probe operation in the collisionless free molecular plasma regime established the electrostatic probe as one of the more important diagnostic instruments. Since in practical applications the plasmas are not always free molecular and collisionless, a real need exists for a probe applicable to a continuum regime, i.e., where $r_p >> \lambda$. A survey of the literature (Ref. 1, 10, 11, 12) reveals a much more limited field of available theoretical or experimental data in this regime. Most of the available theoretical work pertaining to this regime, with the exception of the work by V.M. Zakharova et al, deals exclusively with spherical probes. Almost all, including V.M. Zakharova, treat the problem of current collection by probes in the continuum regime in a plasma at rest.

In this work the current collection of cylindrical probes is investigated. Attention is directed towards the effect of probe length to diameter ratio and the effect of the probe diameter on the collected current. In the collisionless free molecular plasma regime it was shown experimentally (Ref. 8, 9) that a theory developed for cylindrical probes in a plasma at rest can successfully be used in a flowing plasma as long as the probe is long and its axis coincides with the direction of motion. With the above in mind an attempt was made at applying the theory of V.M. Zakharova, developed for a stationary plasma, to a plasma in uniform motion. The only assumptions made in the development of the continuum theory of Zakharova was that the plasma was quasi-neutral and that the bias was negative and sufficiently large relative to the floating potential. The relation between the electron density and the collected current density by a cylindrical probe in this regime is, according to Zakharova, as follows:

$$n_i = 5.\,10^{30} \frac{J_i R_p}{\lambda_{i-n} T_e} \sqrt{T_i M_i} \;\ln \frac{\ell}{R_p X_o} \quad [el/m^3] \tag{1}$$

where

$$X_o = (1 + u)\ (1 + 0.05u)$$

and

$$u = 2.3.\,10^{-2} \left(\frac{V_i \lambda_{i-n}}{J_i^2 A}\right)^{1/5} \frac{1}{R_p}$$

R_p probe radius $[m]$

J_i current density $[A/m^2]$

λ_{i-n} mean free path $[m]$.

n_i free stream ion density $[el/m^3]$

T_e electron temperature [^oK]

T_i neutral and ion particle temperature [^oK]

M_i ion molecular weight [kg]

ℓ length of probe [m]

V_i probe potential [Volts]

A Atomic weight

The validity of the above formulation in a steady state continuum plasma regime was verified by the authors of Ref. (1) in a mercury argon and neon discharge. In order to see how this formulation can predict the current collected by probes in a flowing ionized medium as a function of the fineness ratio and radius as compared to the behavior predicted by Eq. (1) in a stationary plasma, the following relations were found. In the case of two probes of different length,

$$\frac{J_i}{(J_i)_r} = \frac{\ell n \frac{\ell_r}{(X_o)_r R_p}}{\ell n \frac{\ell_i}{(X_o)_i R_p}} \qquad (2)$$

r = reference

and in the case of two probes of the same length but different radii,

$$\frac{(J_i)_r}{J_i} = \frac{R_p}{(R_p)_r}$$

SECTION III

EXPERIMENTAL FACILITY.

(A) The Shock Tube

The experiments described in this investigation were conducted in a conventional pressure driven shock tube. A schematic diagram of the experimental apparatus is given in Fig. 1. The shock tube is of a constant area variety, 6 in.

in internal diameter. It consists of a driver, double diaphragm holder, driven section, an appropriate vacuum and pressure manifold system and instrumentation ports. The driver is 6 ft. long; the driven section is 34 ft. long, and made of five sections connected by means of flanges, vacuum proved by O-rings, and matched in such a way that no discontinuities on the inside of the tube exist. The driven and driver tubes were fabricated from 4340 steel alloy. The test section is located at the downstream end of the driven section. The driven section is terminated by a dump tank, 14 in. in diameter and 14 ft. long. The dump tank is placed on a carriage and connected to the driven section by a flange so that access could be provided to the test section. The pressure and vacuum manifold consists of copper tubing and copper pipe, respectively. Two mechanical vacuum pumps are used to obtain the necessary vacuum. The shock tube is rated for 3000 psia pressure. The leak rate of the driven section is relatively low. It amounts to about 1μHg/minute.

(B) Instrumentation and Diagnostic System

The instrumentation can be subdivided into three parts. The first one consists of the various pressure monitoring devices described in (C). The second is the shock velocity measuring system which consists of the ionization probes and a time interval unit. The third part consists of Tektronix 565 oscilloscopes equipped with Polaroid cameras. This kind of recording system is used because of the very short duration of a tests (0.1-0.5 millisecond).

The diagnostic system used in this investigation consists of a rake of cylindrical Langmuir probes of variable length and diameter. A typical probe and its circuit is shown in Fig. 2. All probes were biased at -9 volts for ion collection. The probes were made of a Tungsten wire, insulated with thin-walled Teflon, and then inserted into a stainless steel tube. "Plug-in" type probes were used in all tests, allowing easy replacement. The diameter of the probes was varied from 0.127 mm to 1.58 mm and ranged in length from 2.5 to 127 mm. Special care was taken in measuring the length and diameter of the probes. The ratio of length to probe radius was from 10 to 400.

Two rakes of probes were used in this investigation. The first one, Fig. 3, was used to determine the ion density profile behind the incident shock. Because of this, the probes located near the wall were spaced 1/8" apart (all probes were 0.508 mm in diameter and 25.4 mm long). The second rake, Fig. 4, was used with probes of different radius and length. The rakes were connected to a cylinder having a sharp leading edge. This whole unit was placed at the test section and became an integral part of the shock tube.

In the tests discussed in this work, argon was mixed with 5-10% air. This was done in order to improve test reproduction (in terms of ion density level) which was poor because of varying impurity levels of the driven argon due to leaks in the system. It was decided to utilize the temperature of argon behind the incident shock to ionize the air mixed with the argon. In the range of temperatures and pressures these tests were conducted, the number density of Ar^+ and NO^+ were calculated for each test, and it was found that the number density of NO^+ is as much as two orders of magnitude higher than that of Ar^+. This being the case in what follows, the argon ions were neglected and the ionized gas was treated as if only NO^+ ions were present.

(C) Test Procedure

Before conducting a test, the following series of operations were performed. The driver and driven tubes, separated by a double diaphragm, were evacuated by mechanical vacuum pumps. A Veeco Electronics Thermocouple Cell Vacuum Gauge monitored the evacuation to pressure of about 10μHg. The driven tube was then pressurized with air and argon to the test pressure. The pressure was measured by a Baratron Type 77 capacitance gauge, manufactured by MKS Instruments, Inc. The valves on the driven section were closed and the driver was then charged with helium to the required pressure as measured on a Heise gauge. At the same time the double diaphragm was charged with helium to half the driver pressure. After setting the recording oscilloscopes, the diaphragm was ruptured by bleeding the helium from the double diaphragm section. The signal from a pressure transducer located on the driven section near the double diaphragm was used to trigger the oscilloscopes.

(D) Shock Velocity Measurements

The measurements of the shock velocity is of great importance in shock tube studies. In the ideal situation, one can determine the properties of the test gas in a shock tube if the initial pressure and temperature of the driven gas are known, and the shock velocity is measured. The shock velocity in this shock tube is measured by means of ionization probes. For shock Mach numbers above 4.0 in argon, the increased temperature behind the shock front gives a sufficient increase in ionization and gas conductivity to permit use of simple ionization probes. The probes were located near the test section of the shock tube and were 3.5 ft. apart. The time was recorded by a Time Interval Unit, Model 5262-A, manufactured by Hewlett Packard.

SECTION IV
EXPERIMENTAL RESULTS

Experimental data were obtained for shock Mach numbers varying between 6.4-8.2, and driven pressures of 0.11 Torr (0.1 Torr argon + 0.01 Torr air) and 1.05 Torr (1.0 Torr argon + 0.05 Torr air). The driver pressure in all these tests was kept constant at 200 psia.

The ion density profile behind the incident shock was determined experimentally, using a rake of Langmuir probes, Fig. 3, aligned parallel to the flow direction. The rake consisted of identical probes. Fig. 5 presents the ion density distribution in the test section of the tube. It is evident that the ion density distribution is uniform over about 70% of the diameter of the shock tube. This uniform region was used for the investigation of biased electrostatic probe characteristics in a continuum plasma regime.

Figs. 6 through 10 show the effect of fineness ratio (ℓ/R_p) on current density collection obtained in this investigation. In each of these figures the experimental data was obtained by fixing R_p and varying ℓ. Two sets of probes, each with a different radius (0.254mm and 0.508 mm) were used. Each set consisted of six probes having different lengths. For a given test, six probes of one set were installed in the shock tube. The recorded current density of each probe in this test was then normalized with respect to the current density collected by the reference probe in these tests. The reference probe was always the longest probe, and for a given set it was the same probe in all tests.

A comparison between experimental current densities under flow conditions and the theoretically predicted based on Eq. (2) valid under stationary conditions is also presented. As can be seen, the experimental curves fall above the steady state predictions.

The maximum fineness ratio (ℓ/R_p) for the probes having a radius R_p=0.508mm was only 250 compared to 400 of the probe of radius R_p=0.254, because of the limitation on maximum probe length imposed by the length of the flowing plasma slug.

Since the tests were conducted in a continuum regime, at Mach numbers ranging from 1.3 to 1.5, oblique shocks could form at the tip of the different probes;

this could adversely affect the uniformity of the flow in the test region of the shock tube and thus affect the collected probe currents. To check this, the location of probes was changed, and it was found experimentally that the effects, if present, were negligibly small.

Fig. 11 presents the effect of the radius of the cylindrical probes on current collection. This data was obtained, using a set of five probes of different radius, ranging from 0.0635 mm to 0.79 mm, and having the same fineness ratio $\ell/R_p = 50$. The current density collected by any of the probes in a given test was normalized with respect to the current density collected by the probe having the largest diameter in this test. This reference probe was the same for all tests. The theoretical current ratio based on Eq. (3) was also plotted. In this case the experimental current density was found to be lower than predicted by Eq. (3).

Fig. 12 represents a typical oscillogram of the ion current collected by the probes. The ion density was obtained from this collected current, using Eq. (1). The following assumptions were made when using this formula:

(i) $T = T_e$

(ii) M_i is the molecular weight of NO^+ (in the range of pressures and temperatures of the tests conducted, $Ar^+ << NO^+$).

Fig. 13 presents the effect of angle of attack on current density. This data was obtained with probes of same length and diameter, having different angle of attack with respect to the flow direction. The reference probe is the one with zero angle of attack. The data presented show the large effect of angle of attack on the probe's current density in a continuum, flowing plasma. Current densities to probes at an angle $\alpha = 90^{\circ}$ were more than seven times higher than to probes at zero angle of attack.

In Figs. 14 and 15, ion densities measured by electrostatic probes are compared with the expected theoretical values of electron densities. Certain assumptions were made in calculating these values of ion densities. Since a mixture of argon and air was used as the working gas, it was assumed that the air reaches thermal equilibrium with the argon behind the incident shock, and that the ionized particles are predominantly NO^+. The last assumption was found to be fairly good. A calculation of the number densities of Ar^+ and NO^+ in the range of temperatures and pressures used in this investigation confirmed this.

The theoretical values of ion density, assuming only the ionization of the air, are presented in a shaded region because of the uncertainty of the initial amount of air in the driven section of the shock tube at each test. (The system was generally evacuated to 10-20μHg.)

The agreement between the experimental results obtained from electrostatic probes and the theoretical values of ion number density is fairly good, taking into account two facts; the first one concerning the uncertainty involved in calculating the ion-neutral mean free path (λ_{i-n}), since no data on collision cross sections between NO^+ and argon atoms was available. The second fact is the uncertainty involved in determining the shock Mach number.

SECTION V
CONCLUSIONS

1) It was found that application of the theory of cylindrical probe operation in the continuum plasma regime developed by V. M. Zakharova et al, provides a satisfactory method of data reduction for a flowing plasma.

2) It was also found that the current density of the probe increases with decreasing fineness ratio.

3) The current density dependence on radius variation was found to increase with decreasing radius.

4) The current density of the cylindrical probe is very sensitive to angle of attack.

SECTION VI
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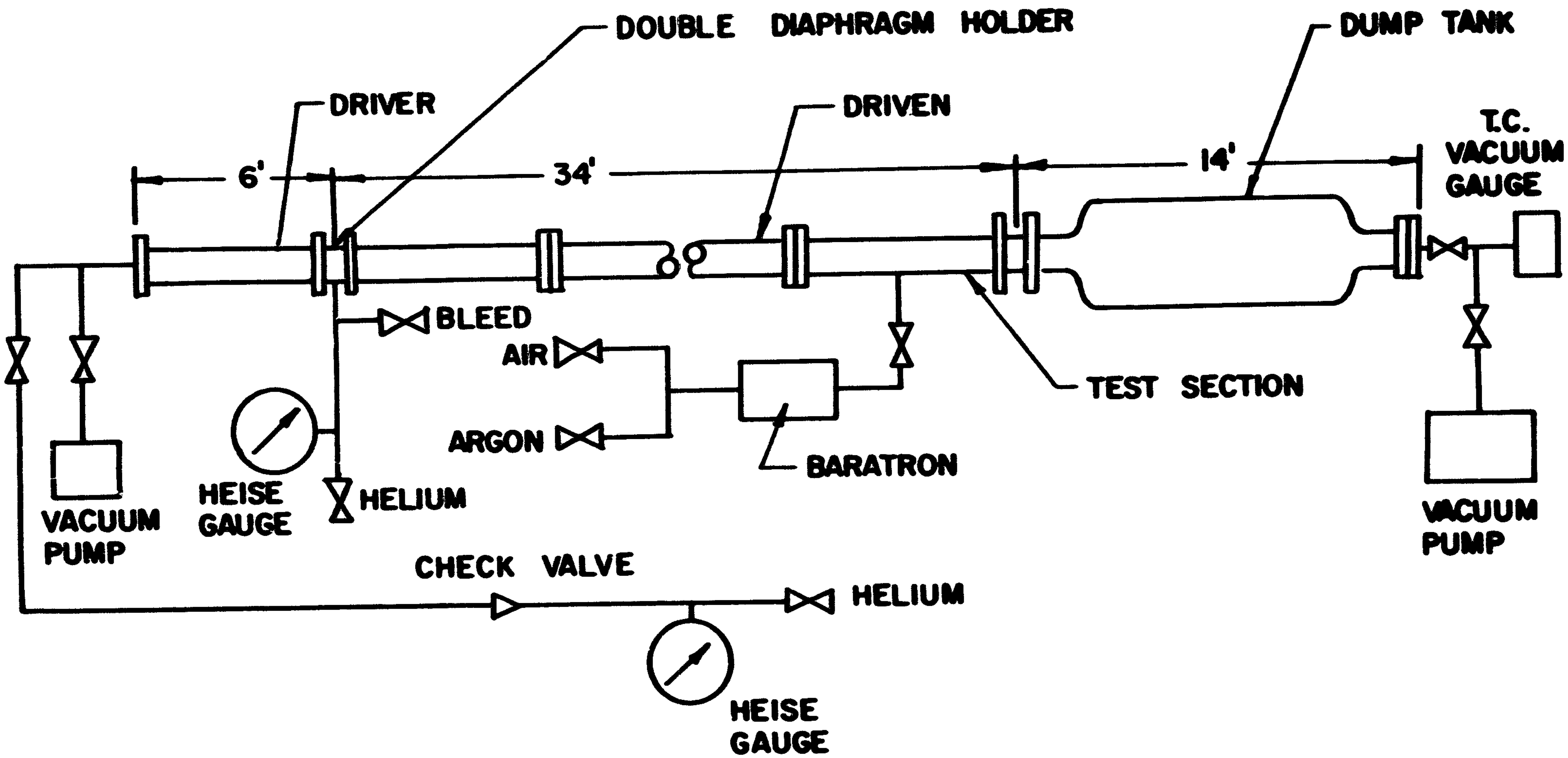

FIG. 1 SCHEMATIC DIAGRAM OF THE SHOCK TUBE

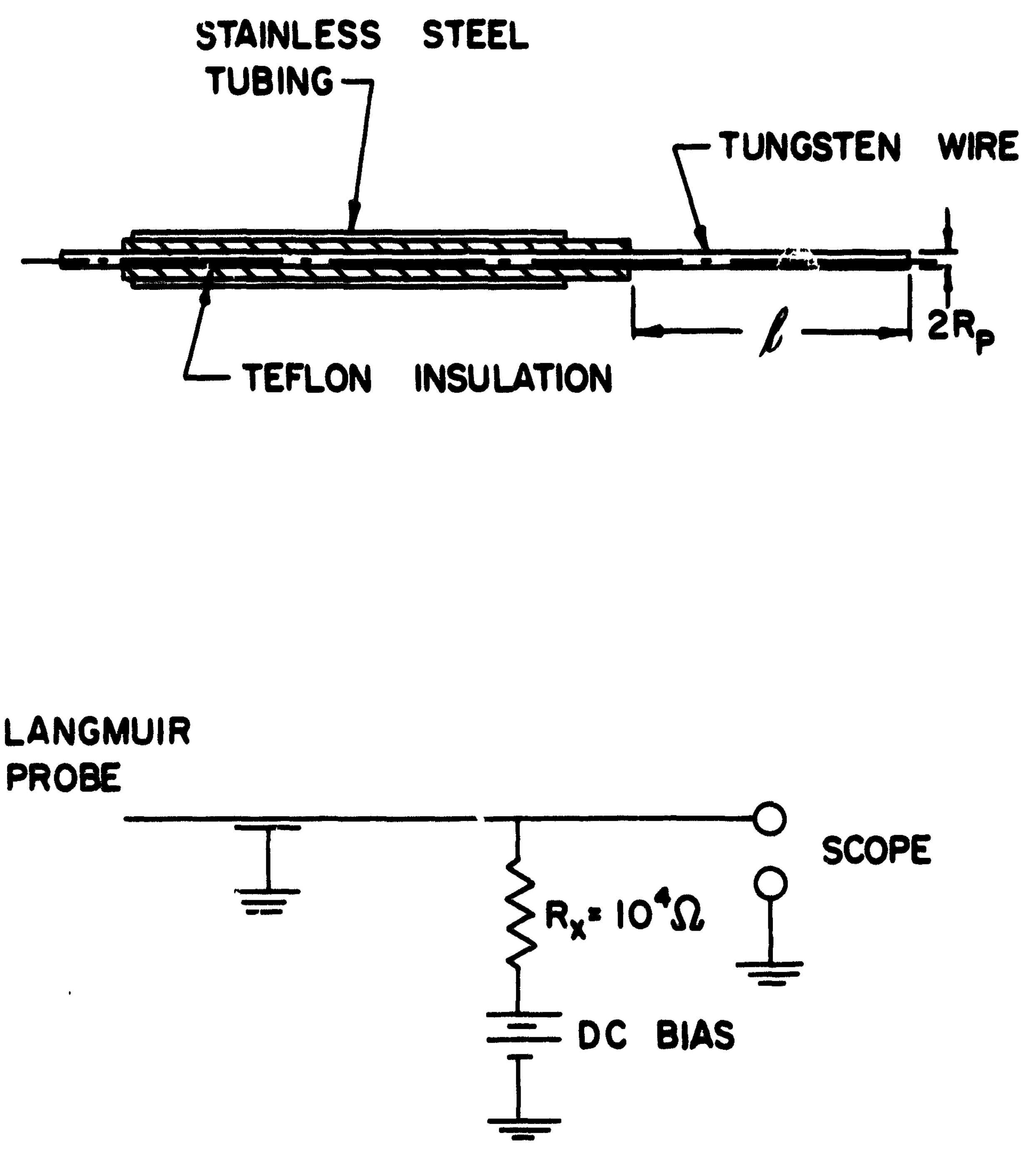

FIG. 2 LANGMUIR PROBE CONSTRUCTION AND CIRCUIT

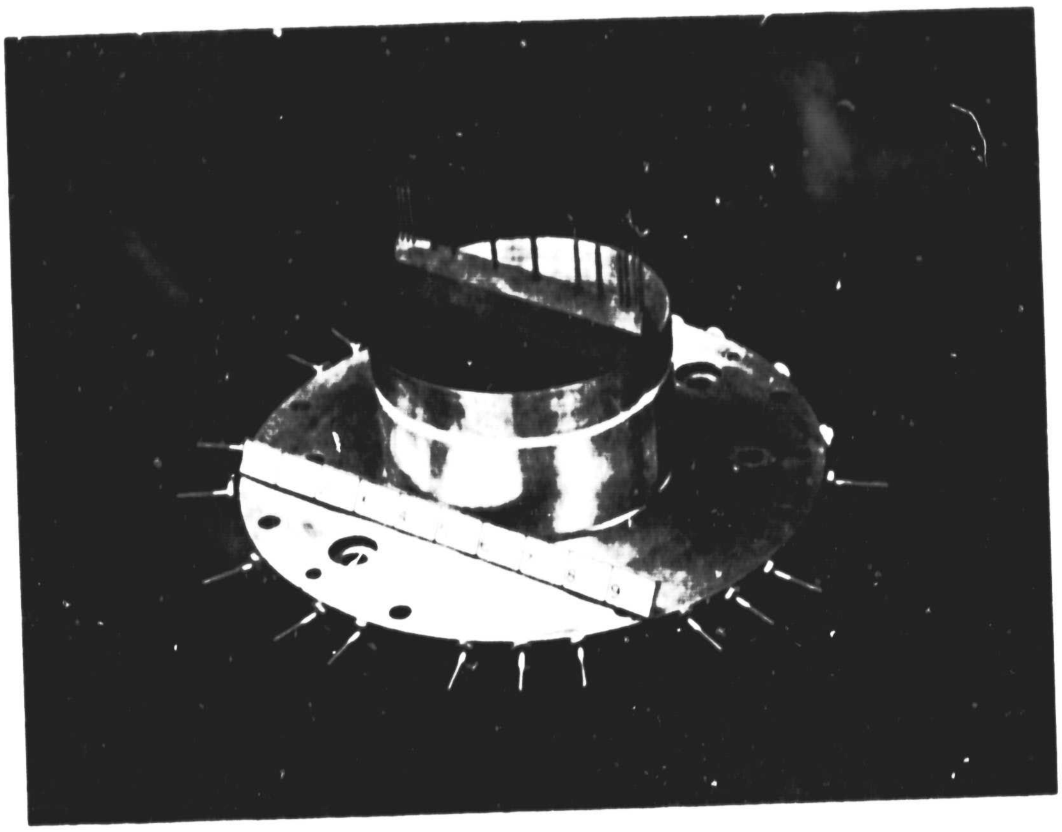

FIG. 3 RAKE OF PROBES

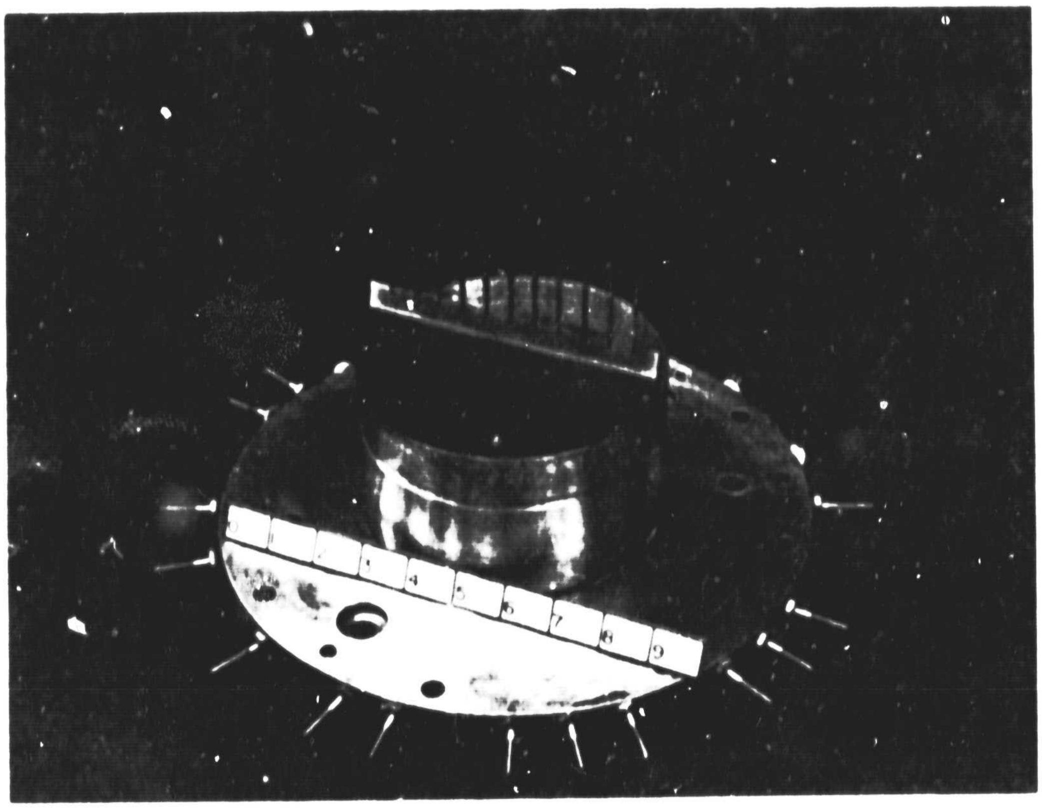

FIG. 4 RAKE OF PROBES

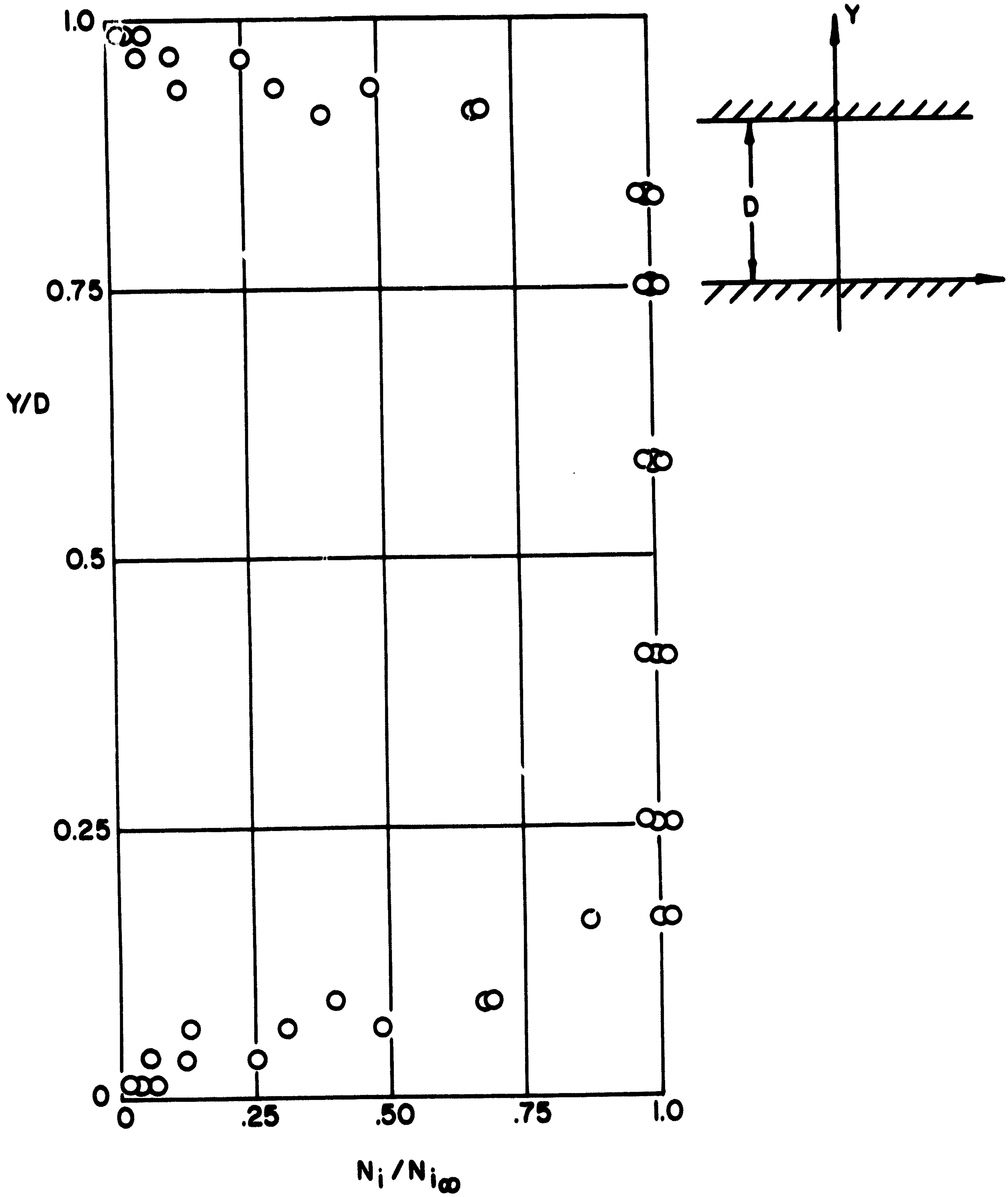

FIG. 5 ION DENSITY PROFILE BEHIND INCIDENT SHOCK

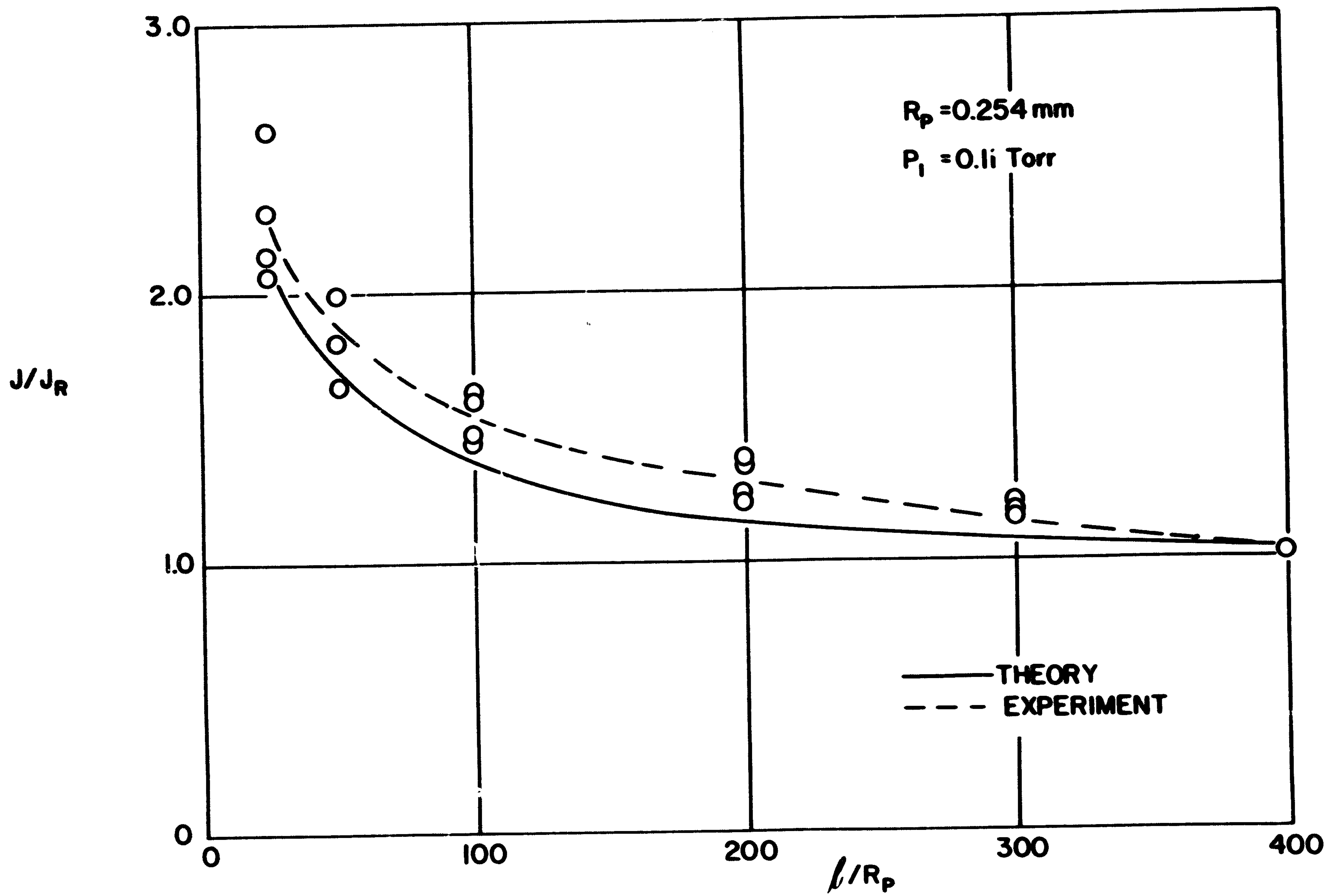

FIG. 6 NON DIMENSIONAL CURRENT DENSITY VS FINENESS RATIO

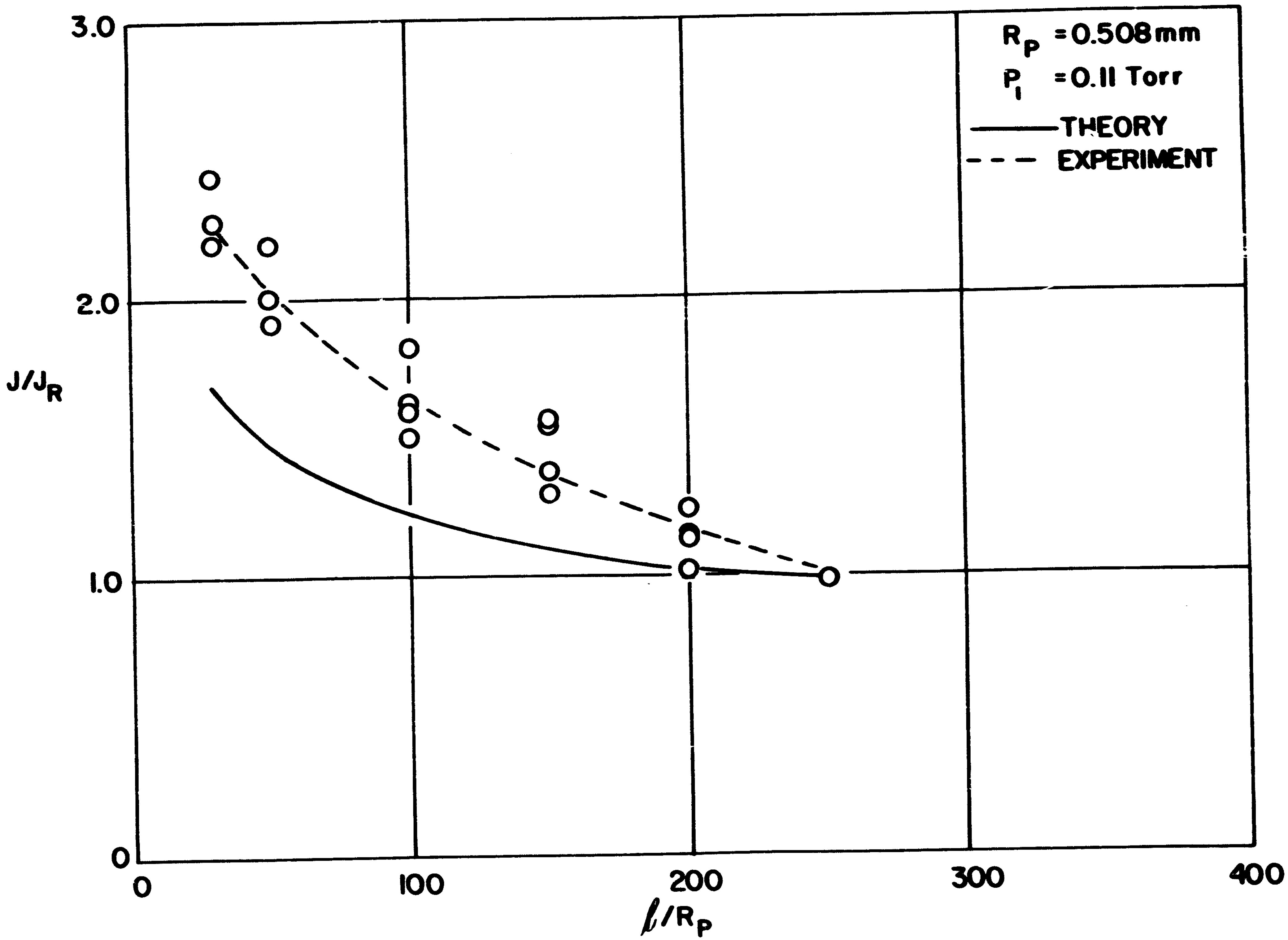

FIG. 7 NON DIMENSIONAL CURRENT DENSITY VS FINENESS RATIO

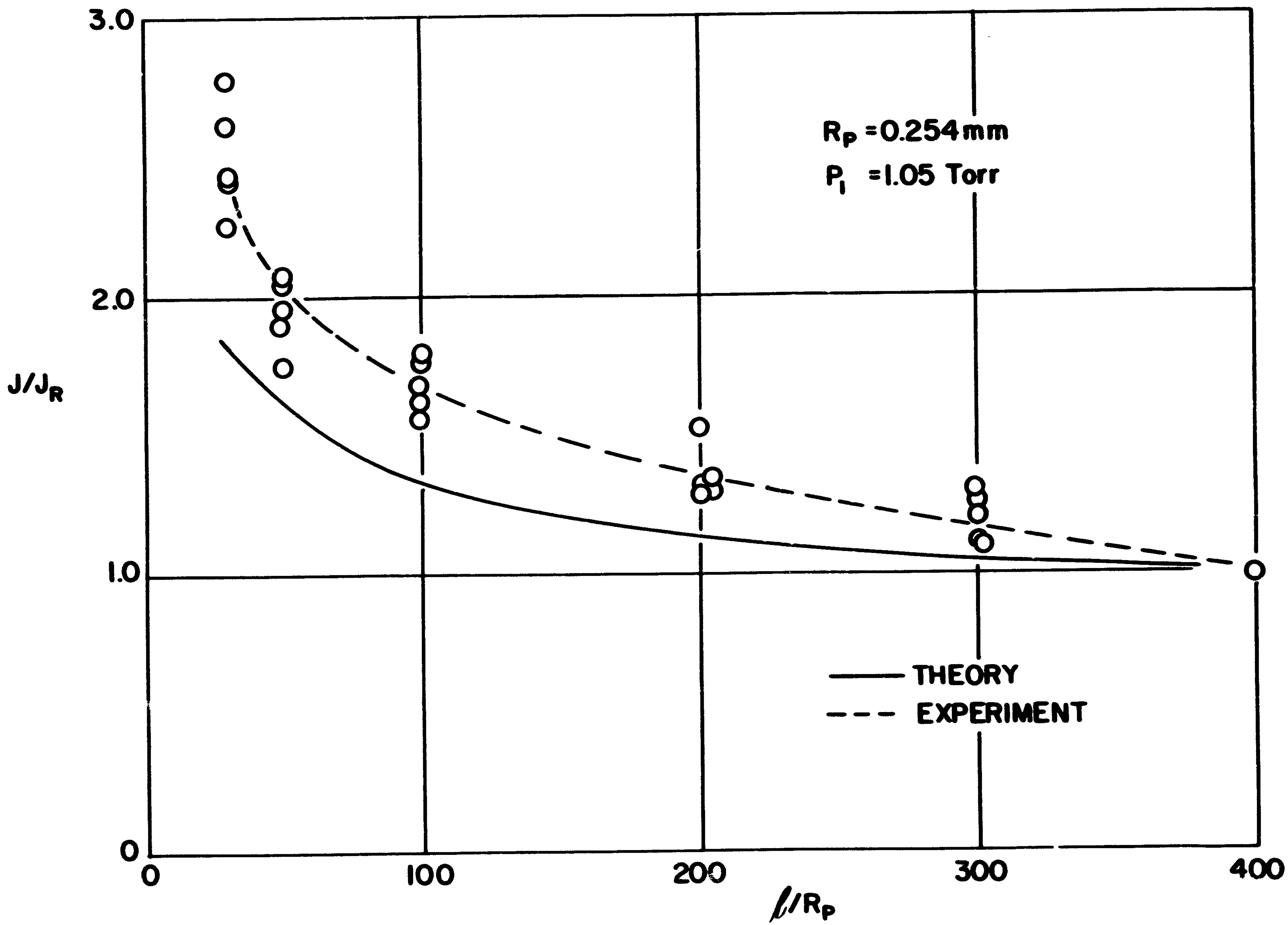

FIG. 8 NON DIMENSIONAL CURRENT DENSITY VS FINENESS RATIO

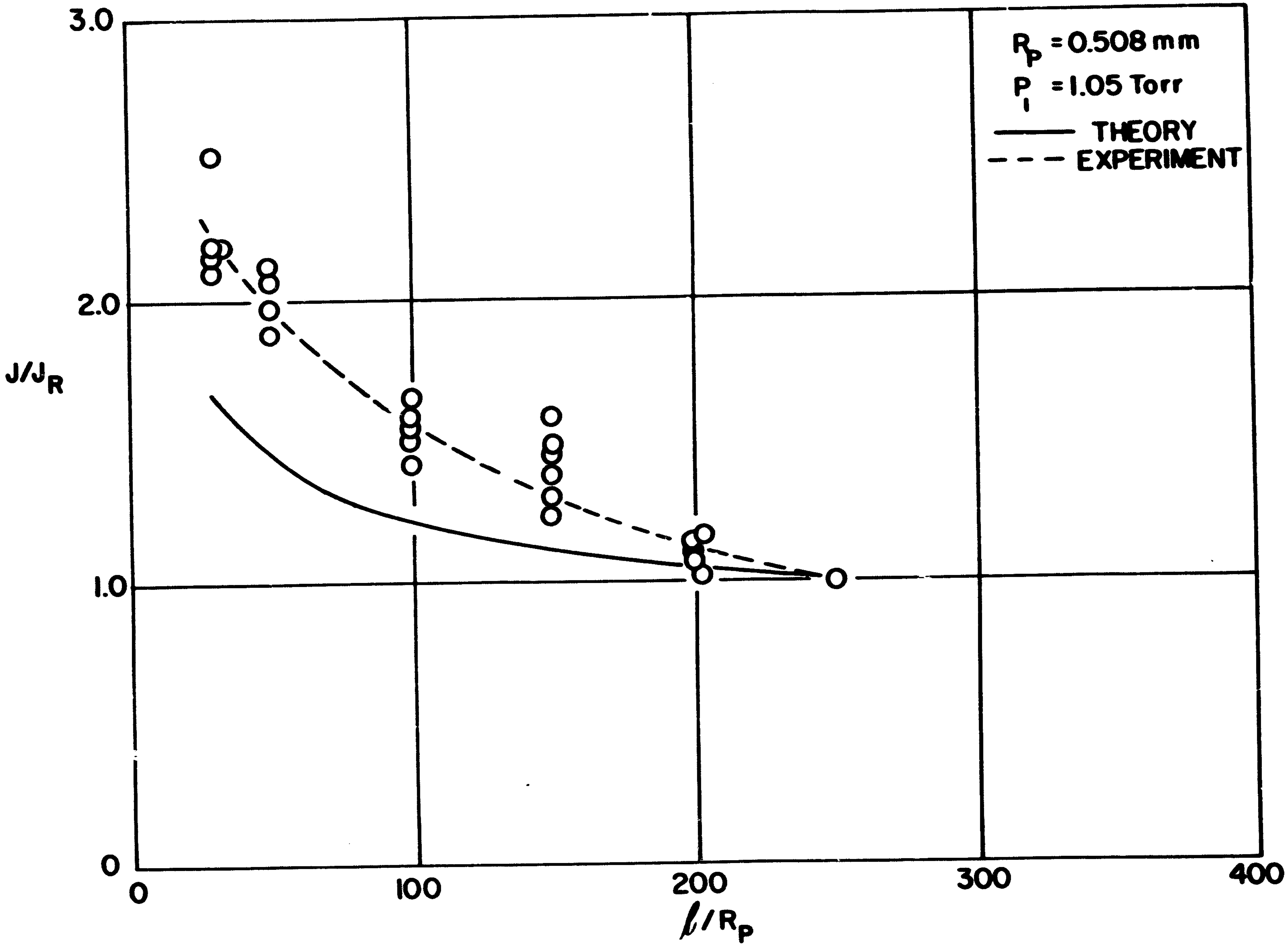

FIG. 9 NON DIMENSIONAL CURRENT DENSITY VS FINENESS RATIO

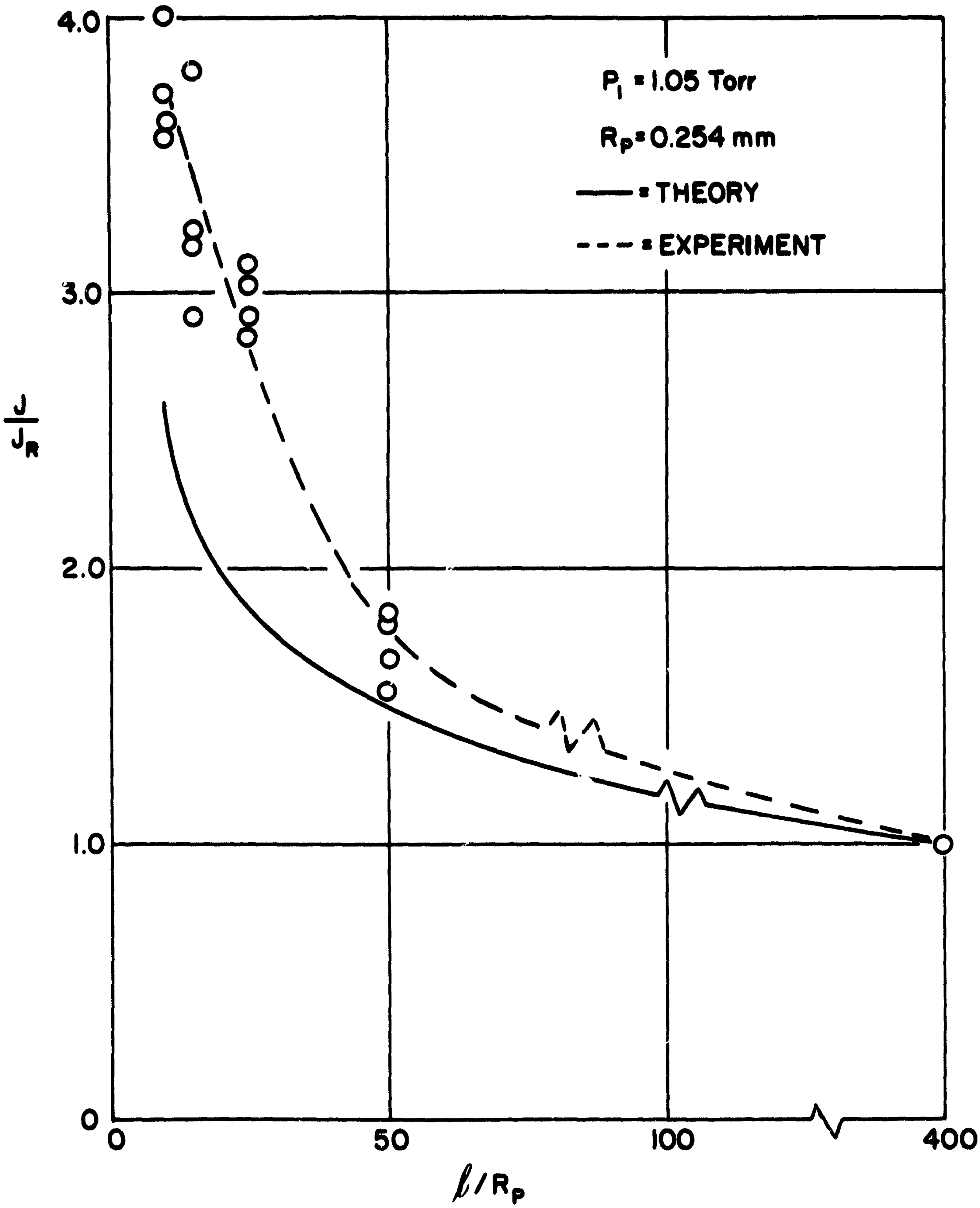

FIG. 10 NON DIMENSIONAL CURRENT DENSITY VS FINENESS RATIO

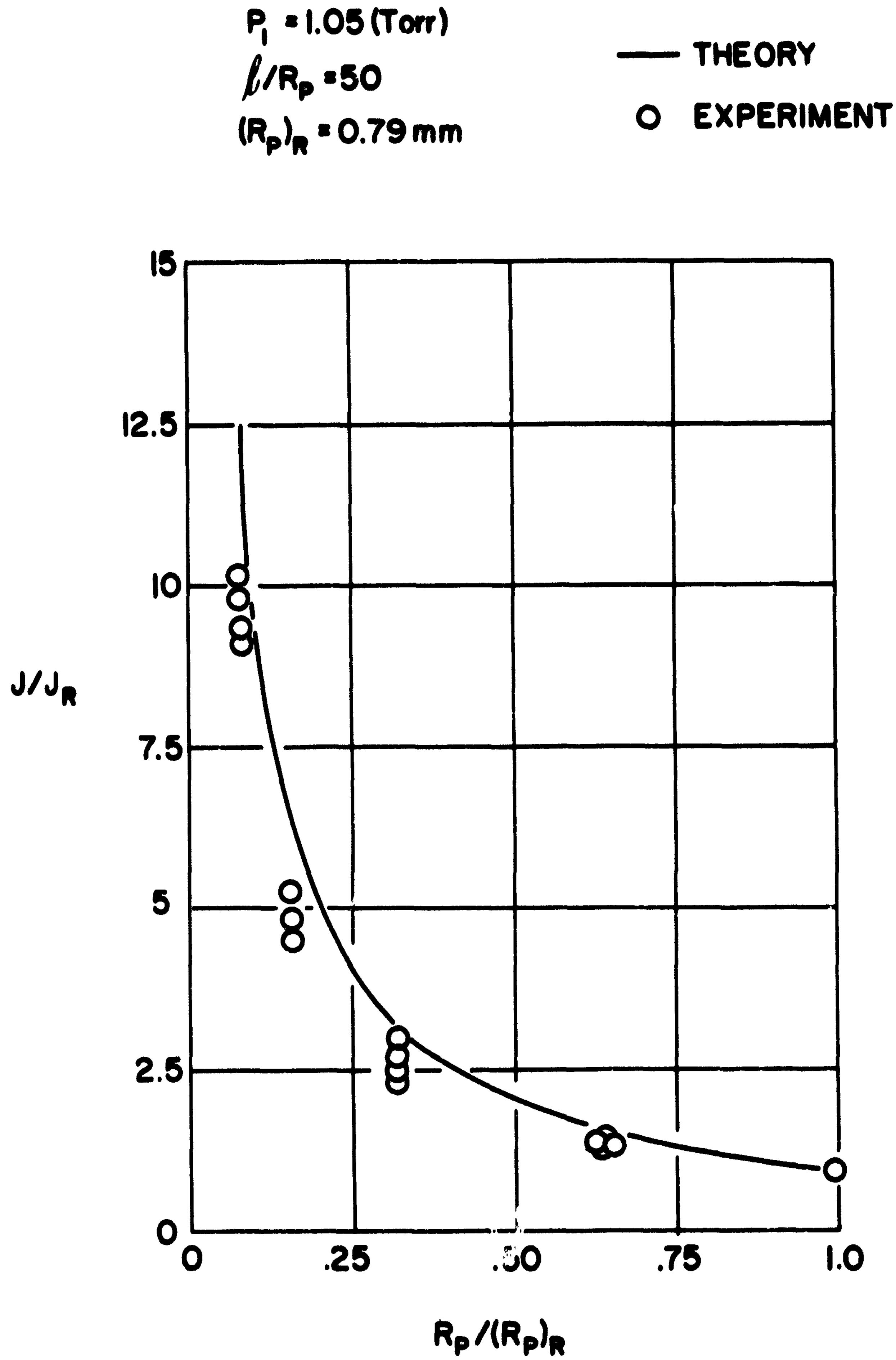

FIG. 11 NON DIMENSIONAL CURRENT DENSITY VS NORMALIZED PROBE RADIUS

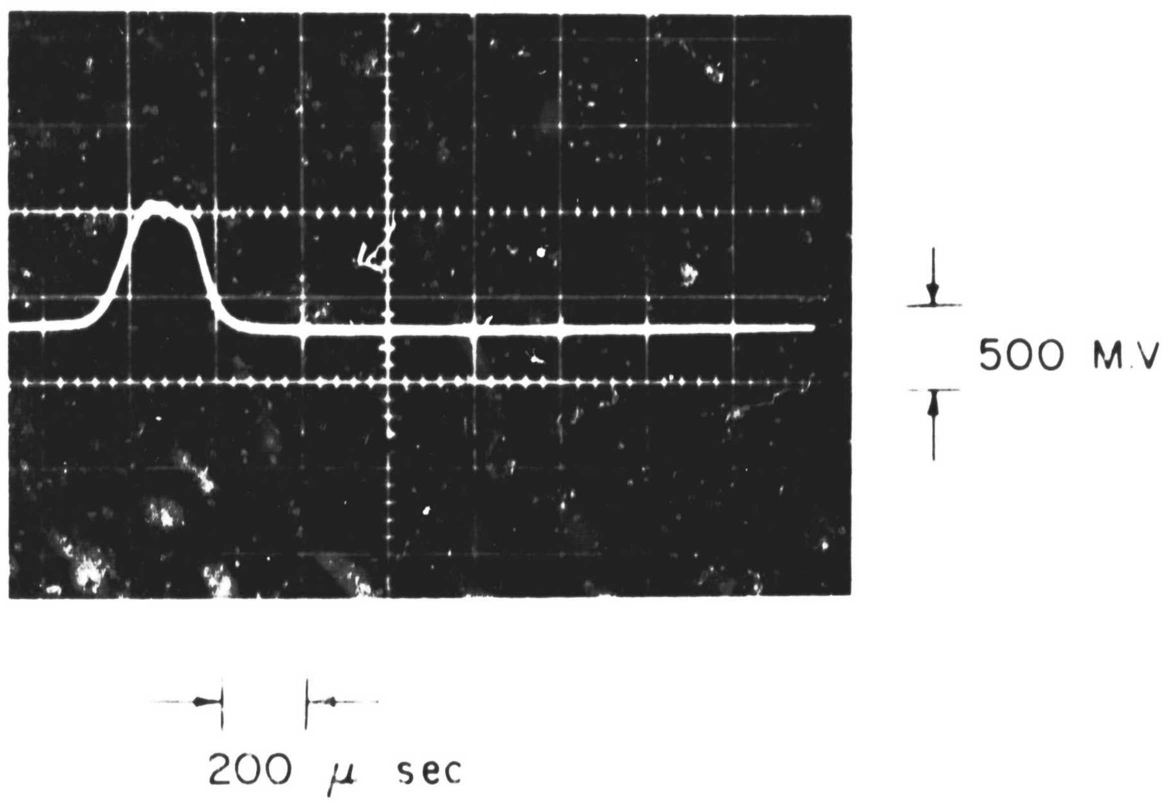

FIG. 12 ION CURRENT OSCILCGRAM

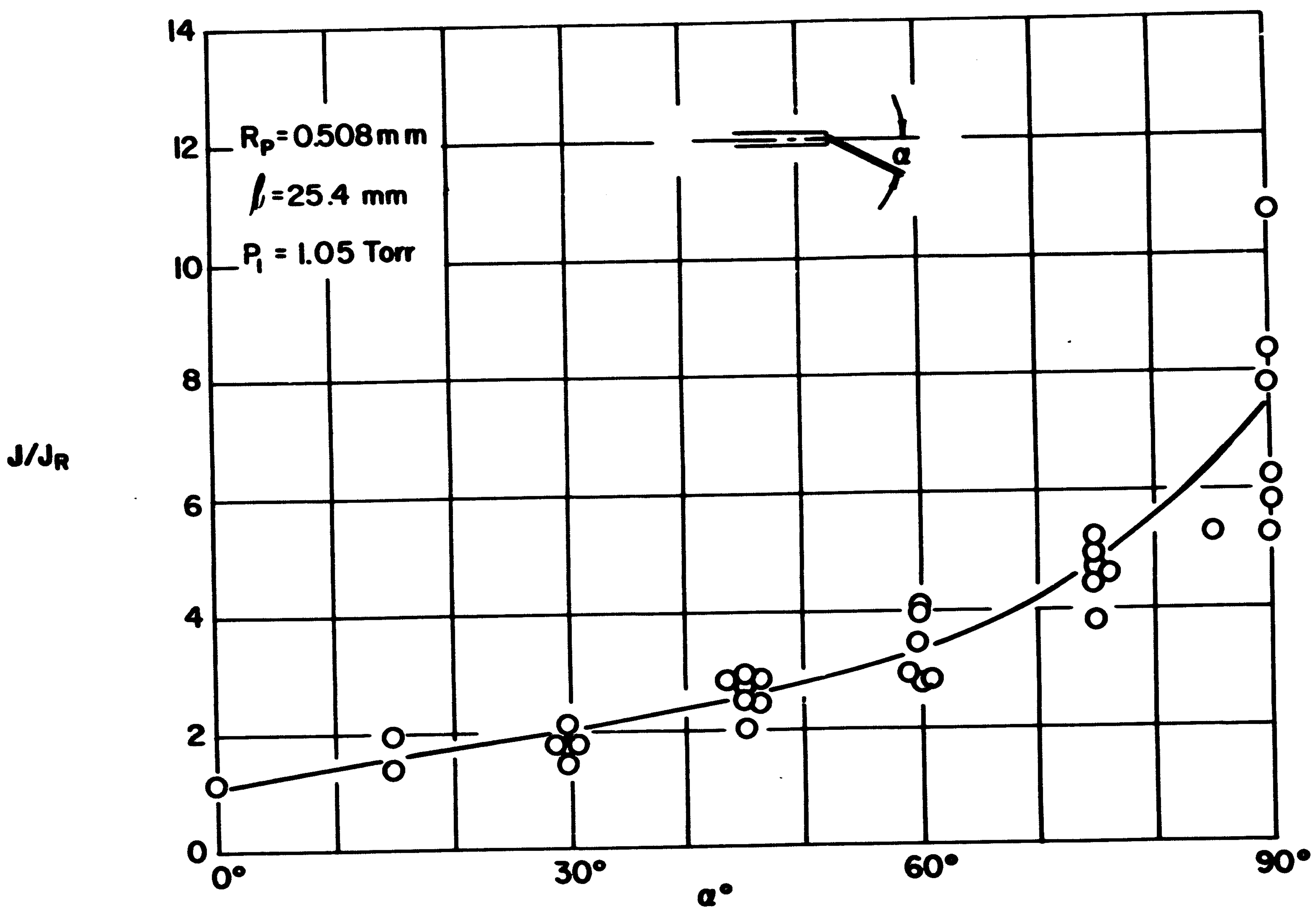

FIG. 13 NON DIMENSIONAL CURRENT DENSITY VS ANGLE OF ATTACK

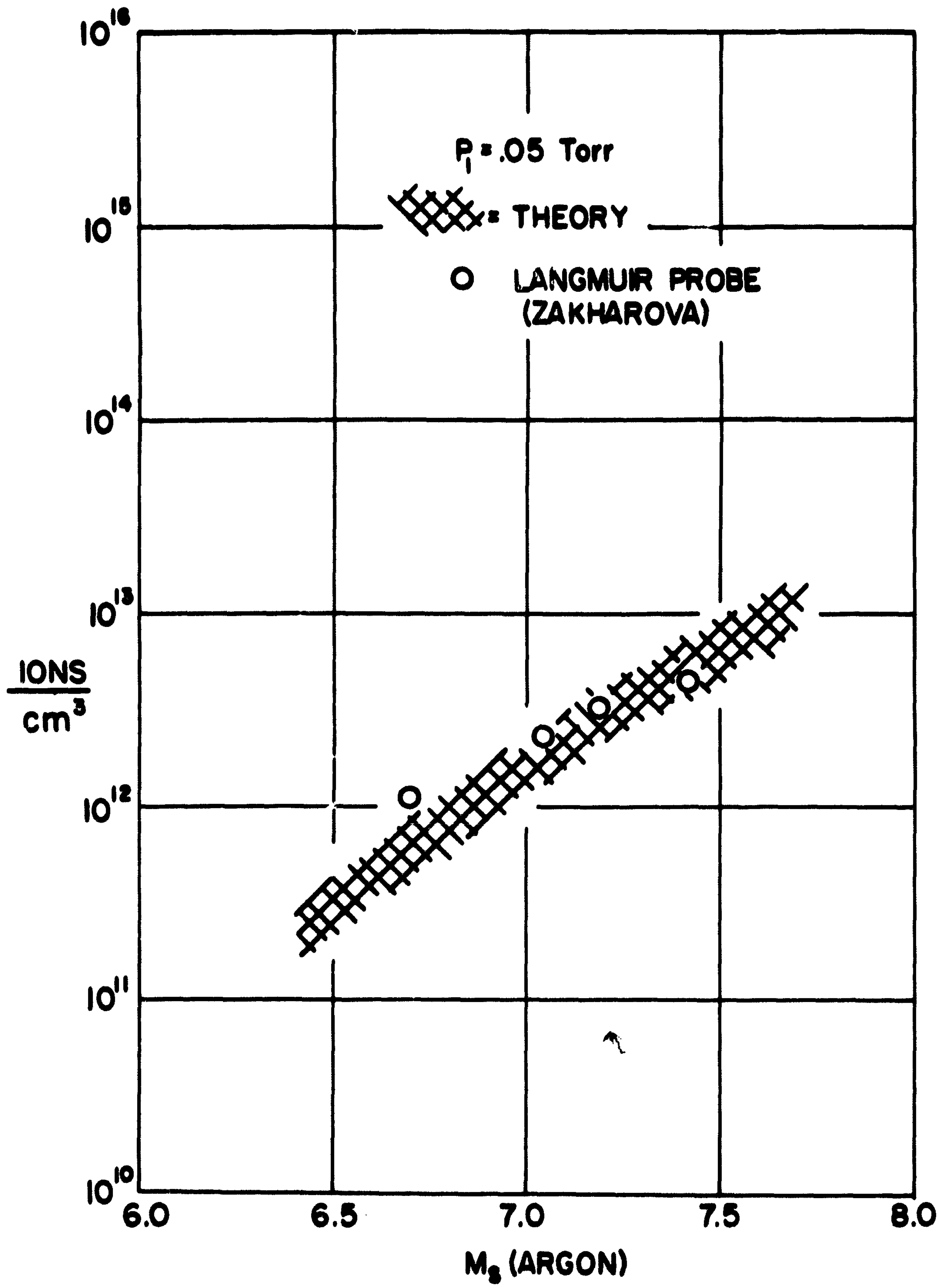

FIG. 14 ION DENSITY VS MACH NUMBER

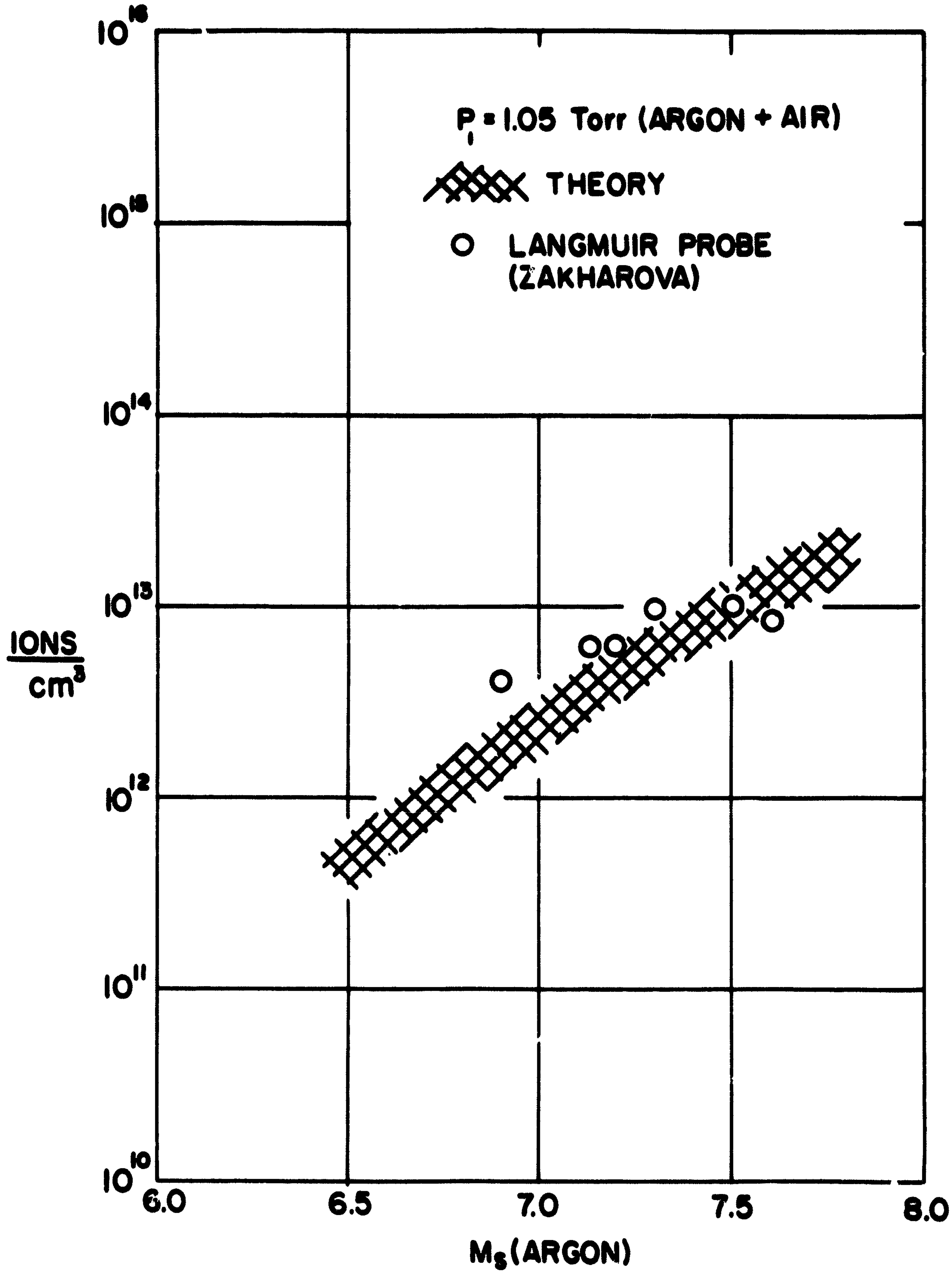

FIG. 15 ION DENSITY VS MACH NUMBER