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FROM: Edward Vendell, Principal Investigator for NASA Grant NGR-45-002-014, Utah State University, Logan, Utah, 84321

SUBJECT: Final Report covering period from Oct. 1, 1969 to April 1, 1970.

TITLE: "A Theoretical Study of Hall Parameter Measurements with an Immersible Three-Coil Conductivity/Velocity Plasma Probe."

RESEARCH OBJECTIVE

A three-coil plasma probe has been designed and successfully tested in a low-density argon plasma stream in the absence of externally applied electromagnetic fields by Rossow, Posch, Vendell, and Cook.[1,2*] The purpose of the present research is to determine if the same instrument can be used to take meaningful conductivity and velocity data in a plasma when the only externally applied field is a large d.c. magnetic field.

SUMMARY OF WORK ACCOMPLISHED

An attempt to theoretically analyze the performance of the three-coil probe in the presence of a large (10^{-1} tesla) applied d.c. magnetic field was abandoned due to large cross-coupling effects with the small (10^{-7} tesla) sinusoidal alternating (100kHz) magnetic field associated with the primary coil of the probe. However, as described in a previous status report, experimental probe data, taken in an argon plasma near the exit plane of a 5 cm-by-5 cm crossed field MHD accelerator at the Ames Research Center, indicates that the three coil instrument can be used to measure the Hall Parameter although the data scatter and lack of independent correlation leaves something to be desired.

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* Superscript numbers refer to REFERENCES CITED on page 7.

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Centerline probe conductivity data taken in the absence of an applied field by R.E. Posch using three different primary coil frequencies (43.2 kHz, 100 kHz, 214 kHz) and four different probe heat shields (10° cone-cylinder, 4 mm-o.d.; 10° cone-cylinder, 6 mm-o.d.; 15° cone-cylinder, 4 mm-o.d.; blunt 6 mm-o.d.) differed by less than 4% at an arc current setting of 600 amps and an argon mass flow rate of 3.65 gm/sec. Thus, when the applied d.c. magnetic field is zero, the probe conductivity data are highly replicable. *

In an effort to obtain independent velocity data corroboration, J.R. Jedlicka and R.E. Posch obtained simultaneous velocity data using the three-coil probe and the time-of-flight method described in Ref. 3. Although probe velocity measurements were repeatable to within 10% when the applied magnetic field was zero, the corresponding time-of-flight data varied by as much as 50% in an apparent random manner. In half of the runs the probe velocity values were bracketed by the range of the time-of-flight data; in the remaining runs the probe data were below the time-of-flight range.

By assuming that the probe data were taken in an equilibrium argon plasma and that the static pressure in the data survey plane was uniform and equal to that maintained in the MHD accelerator exhaust plenum chamber, E.W. Vendell and Arun K. Gambhir, a graduate student at Utah State University, used the experimental conductivity and velocity profiles and integrated over the jet cross-section to obtain the mass flow rate for three arc-current settings. The resulting values differed from each other by less than 10% and were 18% higher than the value predicted by a conventional gas flow meter. This work is described in detail below. Because there is some possibility that this agreement was fortuitous, additional confirming tests were contemplated, but these were subsequently cancelled after several MHD equipment failures. At the present time the configuration of the magnetic field in the Ames 5 cm-by 5 cm MHD accelerator is being extensively modified and the new coils will be water-cooled.

MASS-FLOW RATE CALCULATIONS

As noted above, these calculations by Vendell and Gambhir are based on the assumption of an equilibrium argon plasma and

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* These results also seem to preclude the existence of strong shocks in the plasma jet caused by the presence of the immersible three-coil probe.

a uniform static jet pressure equal to that maintained in the MHD accelerator exhaust plenum chamber (P_{box} = 3.6 X10^{-3} atm). Based on considerable experience with this accelerator, J. R. Jedlicka has stated that the assumption of equilibrium is reasonable. Regarding the second assumption, the theoretical equilibrium electrical conductivity curves for argon by Ahtye[4] indicate that, for the same value of conductivity in the temperature range expected in these experiments, a ten-fold change in pressure is accompanied by only a 7% change in temperature. Thus, for temperatures less than about 9000° K, conductivity, σ, is a much stronger function of temperature than of pressure. Therefore, the second assumption also seems reasonable.

Figs. 1, 2, and 3* are reproductions of typical conductivity, σ, and conductivity-velocity, σU, profiles taken as the three-coil probe was swept through the free plasma jet in about 0.1 sec. and approximately 10 cm from the accelerator exit plane. Using these same profiles, centerline values for σ and U were computed using the method described in Ref. 2. The resulting σ and U values agreed within 5% of data taken under identical conditions on at least three other days.

Figs 4, 5, and 6 are velocity profiles obtained by dividing ordinate values of the σU-profiles by the corresponding ordinate values of the σ-profiles in Figs. 1, 2, and 3, respectively. It is interesting to note that all three velocity profiles display a curious local relative maximum velocity about 3 cm from the jet axis and the magnitude of this peak is approximately the same in all three figures. As Figs. 1, 2, and 3 indicate, the magnitude of the possible data reading error increases as the edge of the jet is approached, and this fact may be used to argue that the local velocity peaks don't exist. However, the fact that the maximum does occur in all three profiles suggests the possible existence of a supersonic compression or expansion wave even though the luminosity of the plasma jet precluded visual observations of well-defined wave patterns.

Fig. 7 is a graph of σ as a function of temperature, T, for the constant and uniform data plane static pressure of 3.6X10^{-3} atm. and is based on Fig. 6 in Ref. 4. Each σ and U profile was arbitrarily divided into eight concentric cylindrical regions. Since the conductivity in each region was known from the probe data, the corresponding temperature was read from Fig. 7. Mass density was then computed using this temperature and compressibility factors from Fig. 14 of Ref. 4. Then the mass flow rate was

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* Data taken by R.E. Posch and J.R. Jedlicka.

computed and plotted for each subdivision and was graphically integrated as an approximation to the integral

$$\dot{m}_{total} = {}_0\int^R 2\pi\rho\ \hat{\rho} U d\rho$$

where $\dot{m}_{total}$ is the total mass flow rate, R is the jet radius, ρ is the radial coordinate, and $\hat{\rho}$ is the mass-average density. The results of these calculations are presented in the following table.

I_{arc} (amps)	$\sigma_{\mathbb{C}}$ (mho/m)	$U_{\mathbb{C}}$ (km/sec)	$\dot{m}$ (gm/sec) (three-coil probe)	$\dot{m}$ (gm/sec) (rotameter)
600	1220	4.49	4.3	3.65
400	1050	3.78	4.3	3.65
200	715	3.02	3.94	3.65

It should be noted that the values given above for σ and U were repeatable to within 6% for at least three separate test runs some of which occurred in different calendar months using different three-coil probes.

Although the agreement indicated in the table above is encouraging, there is still the possibility of a fortuitous set of data and further confirming tests are being planned.

TIME-OF-FLIGHT CORRELATION

As a typical illustration of the lack of correlation between simultaneously-recorded time-of-flight and probe velocity data, consider the results of Run No. 56 (January 21, 1970, $\dot{m}$ = 3.65 gm/sec, I_{arc} = 400 amps, no applied fields, argon gas).* The centerline velocity, $U_{\mathbb{C}}$, measured by the three-coil probe was 3.67 km/sec. However, there were more than 20 useable time-of-flight data records and the corresponding values of $U_{\mathbb{C}}$ varied in an apparently random manner from 4.09 to 6.06 km/sec. These

* Data recorded by R.E. Posch and J.R. Jedlicka; data reduction by R.E. Posch.

results seem to confirm the following statements from Ref. 3

> "However, it has generally been concluded by various persons interested in the development of instrumentation that for some reason such (time-of-flight) measurements are very poor indicators of jet velocity."

> "The intermingling of fast and slow moving features in the luminosity of a plasma jet verifies that any simple measurement of the velocity of these fluctuations will fail to reveal the gas dynamic velocity."

CONCLUSIONS AND FUTURE PLANS

In July 1970 a final definitive test of the three-coil probe in the 5 cm-by-5 cm MHD accelerator will be conducted to confirm the use of probe data for computing mass flow rate and to resolve data scatter occurring when a magnetic field is applied. It is believed that these new data together with past results will be the bases for a publishable paper.

Although this research failed to solve the analytical problem posed in the original research proposal and although it is not yet clear that the probe can be used with confidence for the direct measurement of the Hall Parameter, it is claimed that this NASA grant resulted in the following positive benefits.

1. Part of the funds were used to support a graduate and undergraduate student at Utah State University.

2. As mentioned above, the magnetic field configuration of the Ames 5 cm-by-5 cm accelerator is now being revised in an effort to minimize the undesirable effects of the circulating currents discussed in Ref. 5. The success of this work can be judged by comparing new probe data with the data obtained for the present research contract using the old field geometry.

3. This research indicates that time-of-flight velocity measurements are very difficult to interpret and that the three-coil instrument provides more reliable velocity data by which the efficacy of an accelerator can be ascertained.

In conclusion, the principal investigator wishes to express his appreciation to NASA for the opportunity to perform this important research.

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EWV:jm

cc: Winnie M. Morgan
Rudolph E. Posch
Vernon J. Rossow

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(1) Rossow, V.J. and Posch, R.E.: "Coil Systems for Measuring Conductivity and Velocity of Plasma Streams." Rev. Sci. Instr. Vol. 37, No. 9, (1966), 1232-1242.

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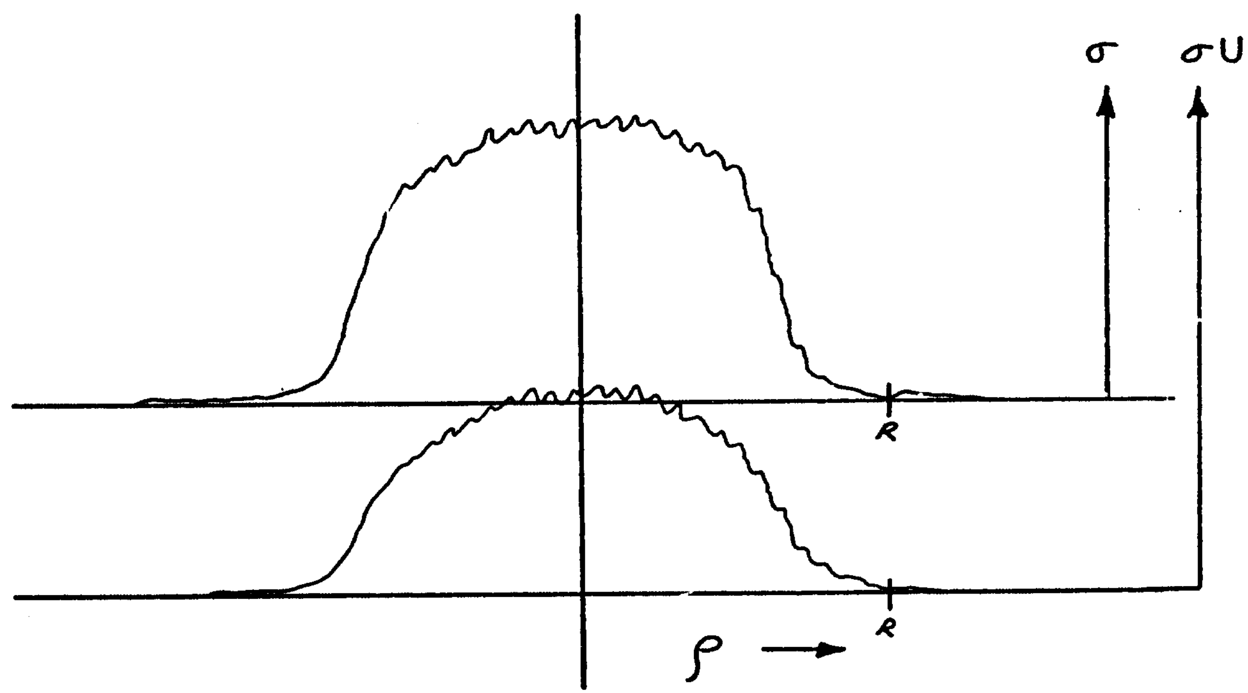

FIGURE 1. TYPICAL THREE-COIL DATA RECORD OF CONDUCTIVITY, σ, AND CONDUCTIVITY-VELOCITY, σU, AS A FUNCTION OF RADIAL JET POSITION, ρ. THIS TEST, RUN NUMBER 55, OCCURRED ON JANUARY 21, 1970, AT AN ARC CURRENT OF 200 AMPS AND A MASS FLOW RATE OF 3.65 GM/SEC. (DATA BY POSCH AND JEDLICKA)

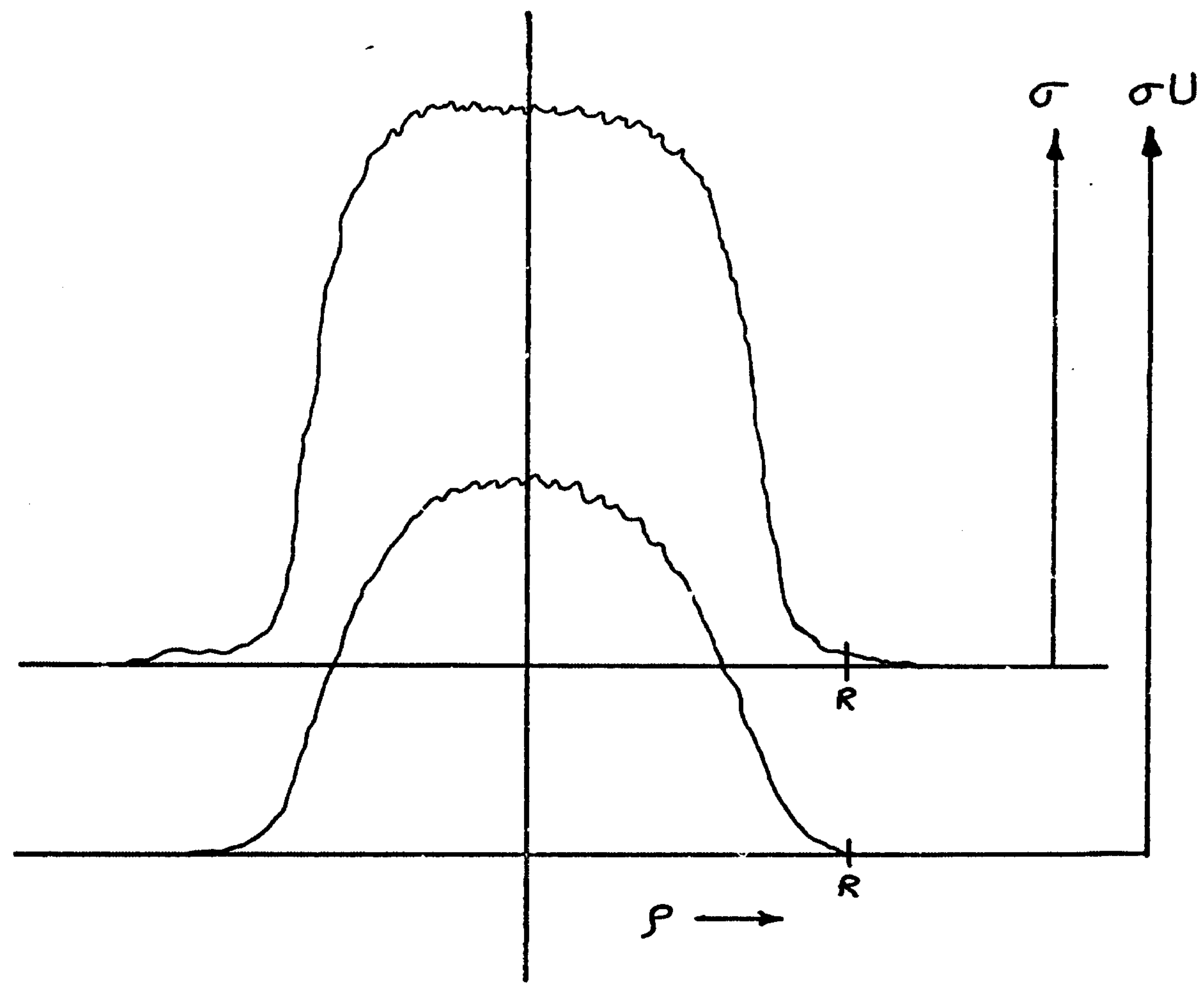

FIGURE . TYPICAL THREE-COIL DATA RECORD OF CONDUCTIVITY, σ, AND CONDUCTIVITY-VELOCITY, σU, AS A FUNCTION OF RADIAL JET POSITION, ρ. THIS TEST, RUN NUMBER 53, OCCURRED ON JANUARY 21, 1970, AT AN ARC CURRENT OF 400 AMPS AND A MASS FLOW RATE OF 3.65 GM/SEC. (DATA BY POSCH AND JEDLICKA)

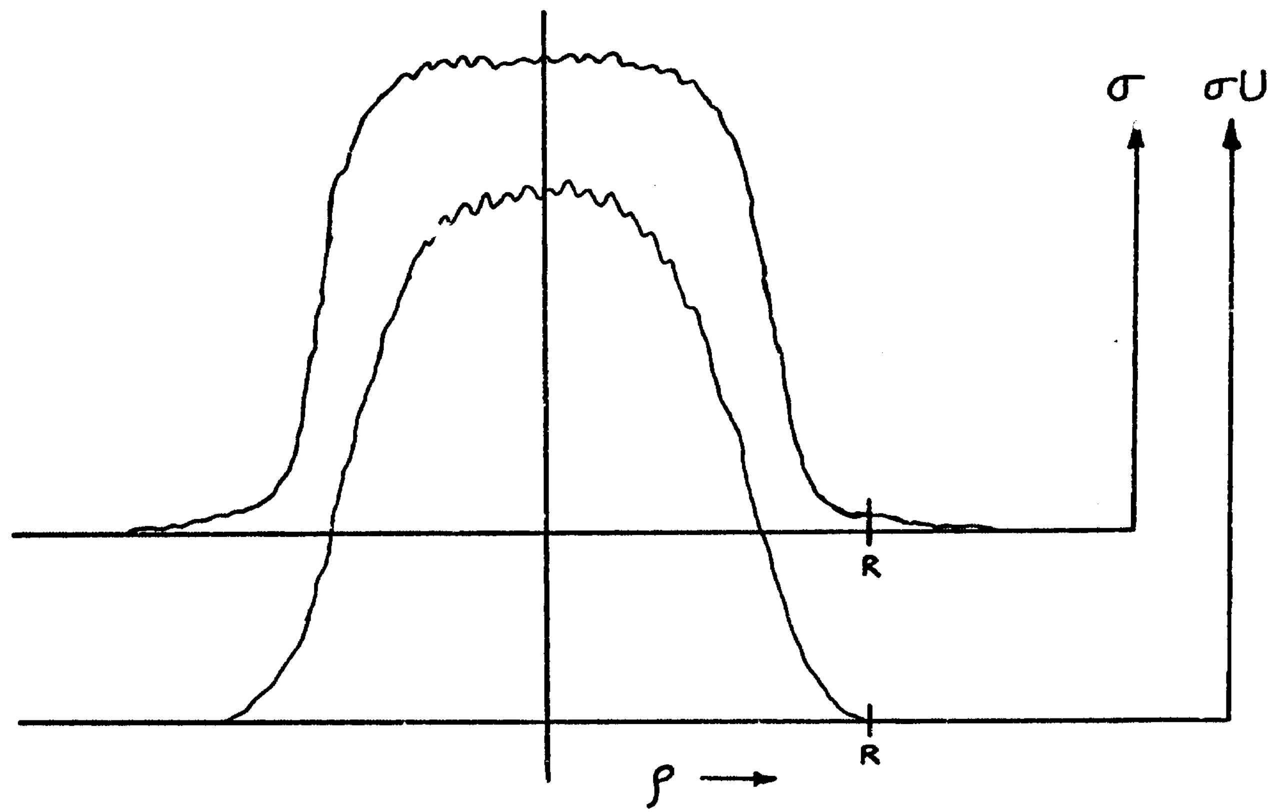

FIGURE 3. TYPICAL THREE-COIL DATA RECORD OF CONDUCTIVITY, σ, AND CONDUCTIVITY-VELOCITY, σU, AS A FUNCTION OF RADIAL JET POSITION ρ. THIS TEST, RUN NUMBER 60, OCCURRED ON JANUARY 21, 1970, AT AN ARC CURRENT OF 600 AMPS AND A MASS FLOW RATE OF 3.65 GM/SEC. (DATA BY POSCH AND JEDLICKA)

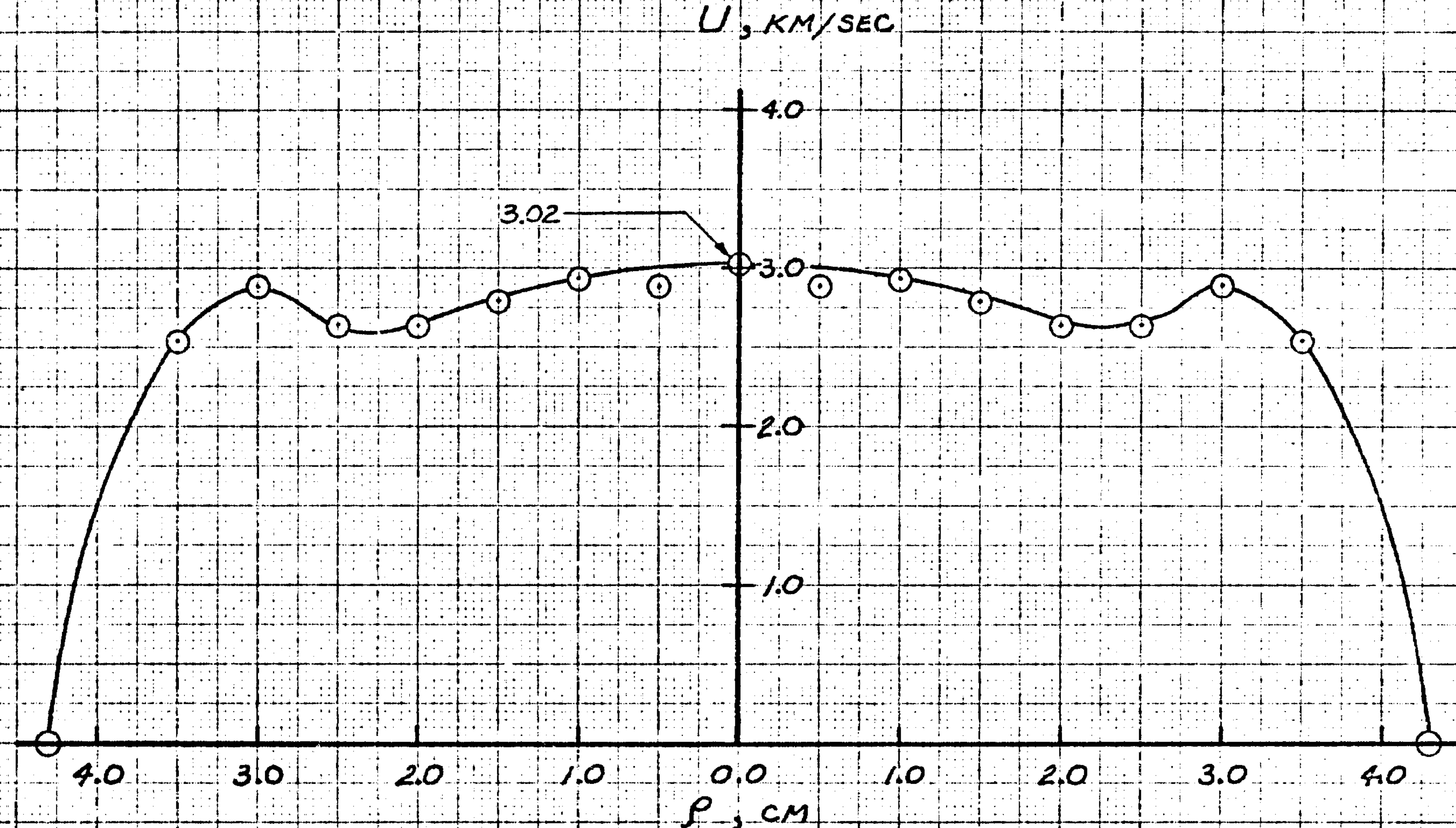

FIGURE 4. PLASMA JET VELOCITY PROFILE OBTAINED FROM THE DATA OF FIGURE 1

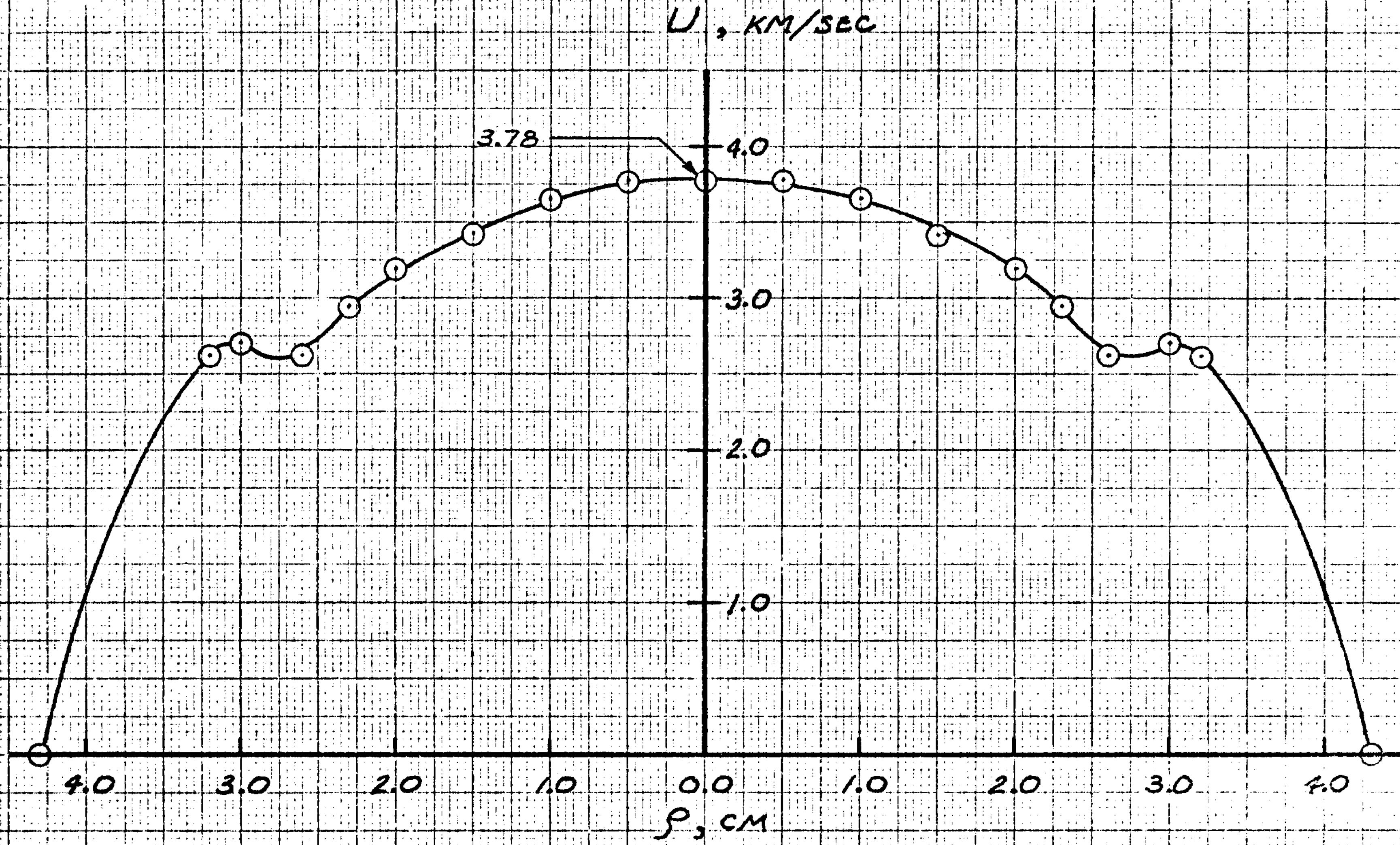

FIGURE 5. PLASMA JET VELOCITY PROFILE OBTAINED FROM THE DATA OF FIGURE 2.

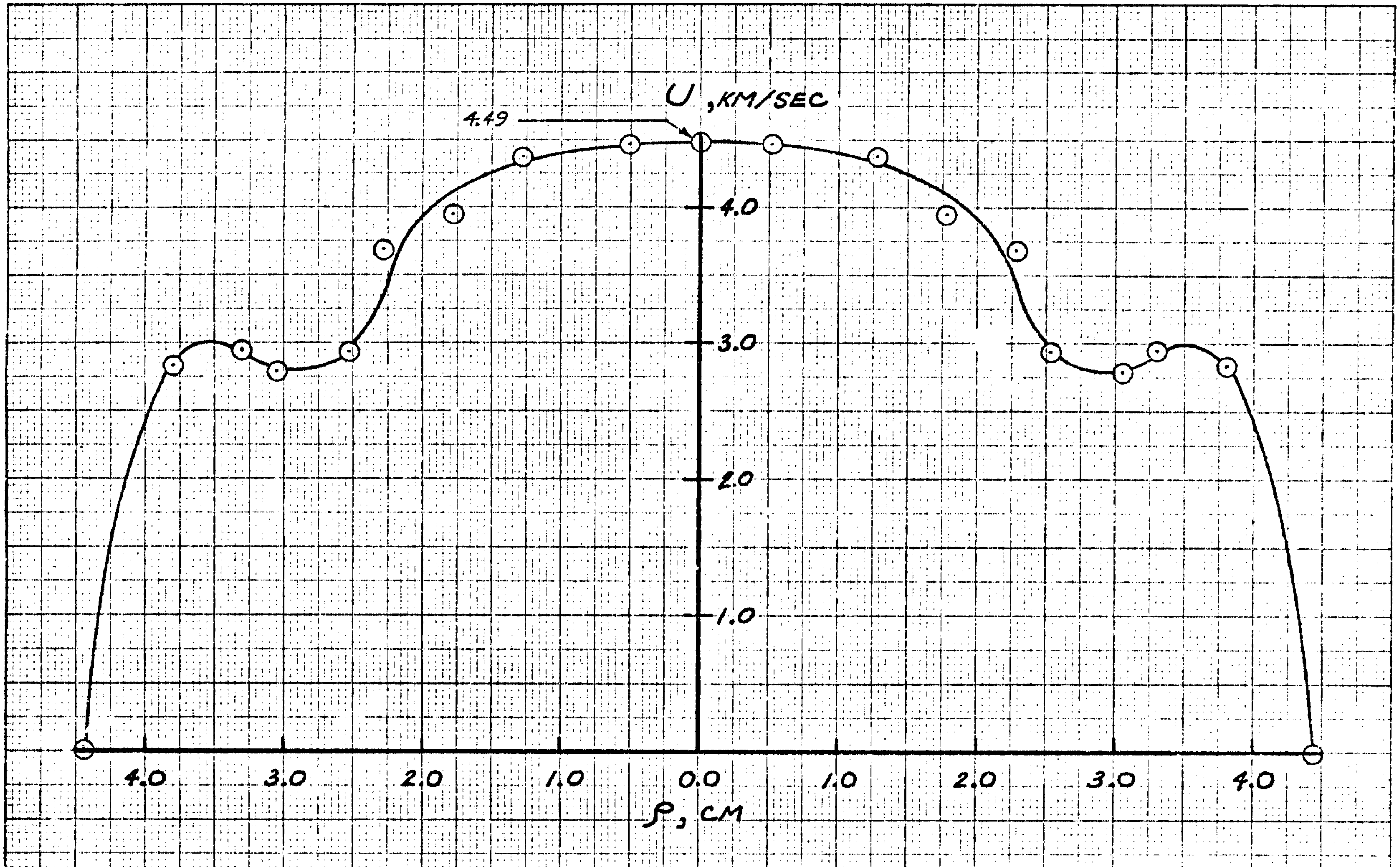

FIGURE 6. PLASMA JET VELOCITY PROFILE OBTAINED FROM THE DATA OF FIGURE 3.

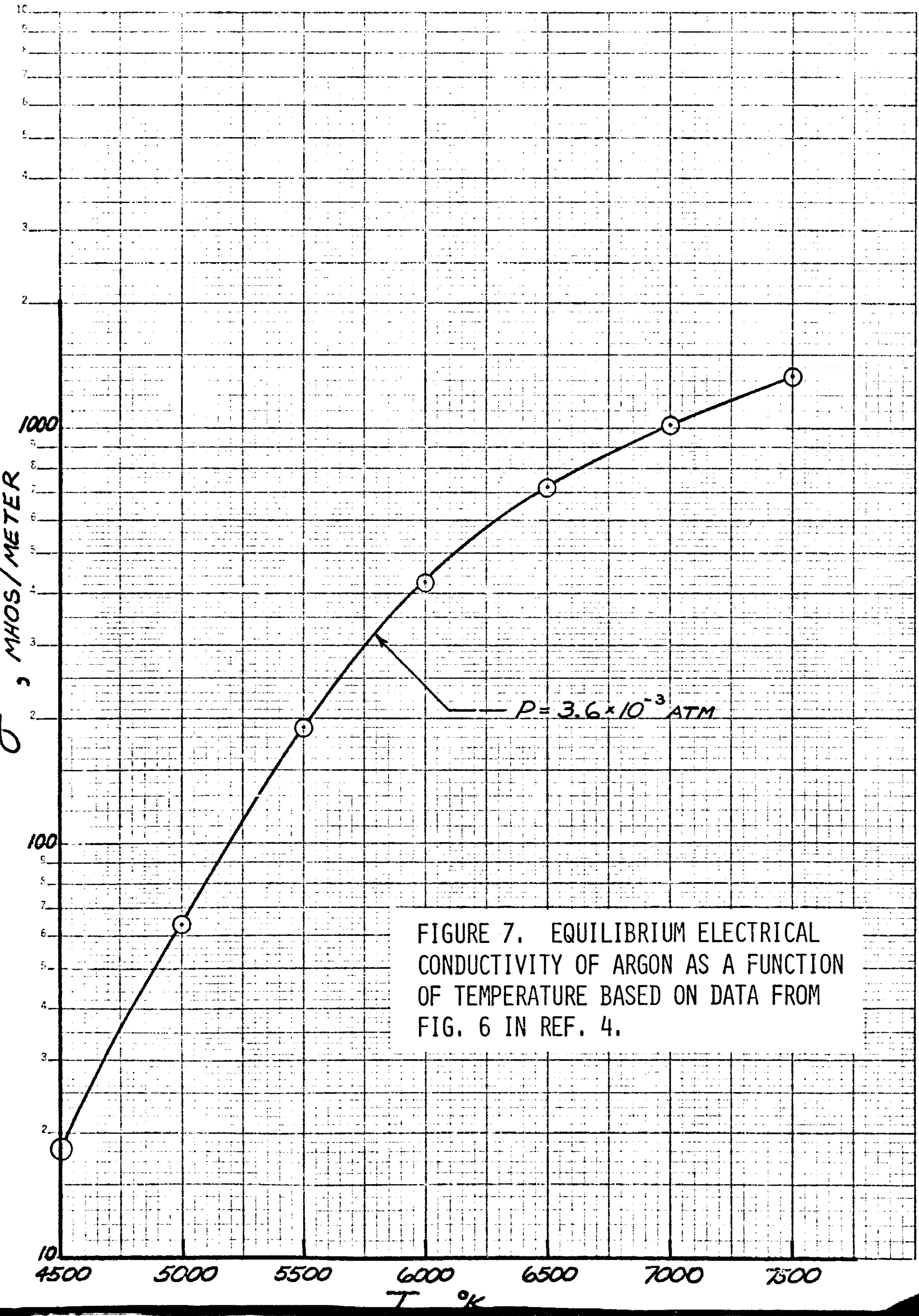

FIGURE 7. EQUILIBRIUM ELECTRICAL CONDUCTIVITY OF ARGON AS A FUNCTION OF TEMPERATURE BASED ON DATA FROM FIG. 6 IN REF. 4.