Prepared for:
Headquarters, Code DHC-4/ J. McDonald
National Aeronautics & Space Administration
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Grant No. NGL 31-001-005, Supplement 7
15th Semiannual Progress Report
For the period 7/1/69 to 12/31/69

PULSED ELECTROMAGNETIC GAS ACCELERATION

R. G. Jahn, Principal Investigator

Princeton University Account No. 150-6020
AMS Report No. 634n Date: January 1, 1970

PRINCETON UNIVERSITY
DEPARTMENT OF
AEROSPACE AND MECHANICAL SCIENCES

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ABSTRACT

Exhaust velocities far in excess of the Alfvén critical speed are observed in the exhaust of a quasi-steady, self-field MPD accelerator, over a range of arc currents up to 42,000 A. Although the measured velocities correspond roughly to the total electrode voltages, an electrostatic ion acceleration mechanism is not supported by detailed maps of the potential contours within the arc chamber. Rather, it is found that the bulk of the arc voltage gradient, exclusive of the electrode falls, occurs within two diameters of the cathode, and is normal to it. The remainder of the arc chamber, and all of the downstream plasma is nearly equipotential, at a value close to anode sheath potential. Anode fall voltage varies inversely with local current density, implying substantially lower anode losses at higher power arc operation. Minimum anode fall appears to coincide with matched mass flow operation. Bow shocks from small obstacles placed in the exhaust stream indicate supersonic, but not hypersonic flow, and imply ion temperatures of the order of 10 eV. Electron temperatures at the same location appear to be substantially lower.

A range of associated activities are in progress, including development of a technique for monitoring accelerator thrust by internally mounted strain gauges; application of a recently completed 160,000 joule pulse-forming network to extend various quasi-steady experiments into the millisecond range; cataloging of the characteristics of electrolytic pulse-forming networks in quasi-steady accelerator operation; and refinement of the optical methods for plasma flow diagnostics.

CONTENTS

LIST OF ILLUSTRATIONS

CURRENT STUDENT PARTICIPATION

Student	Period	Degree	Thesis Topic
BRUCKNER, Adam P.	1966-	Ph.D. Cand.	Radiation Studies of Gas Accelerating Discharges
CORY, John S.	1969-	Ph.D. Cand.	Velocity Field Determinations in Quasi-steady Accelerators
DI CAPUA, Marco S.	1966-	Ph.D. Cand.	Current-voltage Characteristics of High-current Discharges
FOURNIER, Georges	1969-	B.S.E. Cand.	Optical Spectroscopy of Accelerator Exhaust Flow
FRADKIN, David B.	1969-	Ph.D. Cand.	Spectroscopic Velocity Measurements in Quasi-steady Accelerators
HOUGH, Michael	1969-	B.S.E. Cand.	Mass Spectrometry of Accelerator Exhaust Flow
OBERTH, Ronald C.	1966-	Ph.D. Cand.	Anode Phenomena in High-current Discharges
SABER, Aaron J.	1969-	Ph.D. Cand.	Thrust Measurements on Quasi-steady Accelerators
TURCHI, Peter J.	1963-	Ph.D. Cand.	Cathode Region of a Pulsed Plasma Accelerator
VILLANI, Daniel D.	1969-	Ph.D. Cand.	Power Sources for Quasi-steady Accelerators
WHITE, Fred W.	1969-	M.S.E. Cand.	Propellant Injection Techniques for Quasi-steady Accelerators

I. INTRODUCTION

The major portion of this semiannual report consists of a detailed description of a recent series of experiments on the exhaust flow of our quasi-steady MPD accelerator. Although the measurement of primary interest here is the velocity vector field, other properties of the flow, such as the electron and ion temperatures and the plasma density enter into the interpretation of the primary measurements, and are interesting parameters in their own right. In fact, the complexity of the plasma domain under study is such that no single technique of measurement returns unambiguous results; rather, it is only by the overlapping determinations of several methods that a self-consistent picture of the true situation sharpens into focus. Thus, we report here studies with time-of-flight velocity probes, floating electrostatic probes, Langmuir probes, and some photographic observations, and from them deduce certain properties of the plasma flow in the arc. Portions of this work were reported at the recent contractors meeting,[95] and at the AIAA Space Sciences Meeting;[93,97] other results have been obtained only recently.

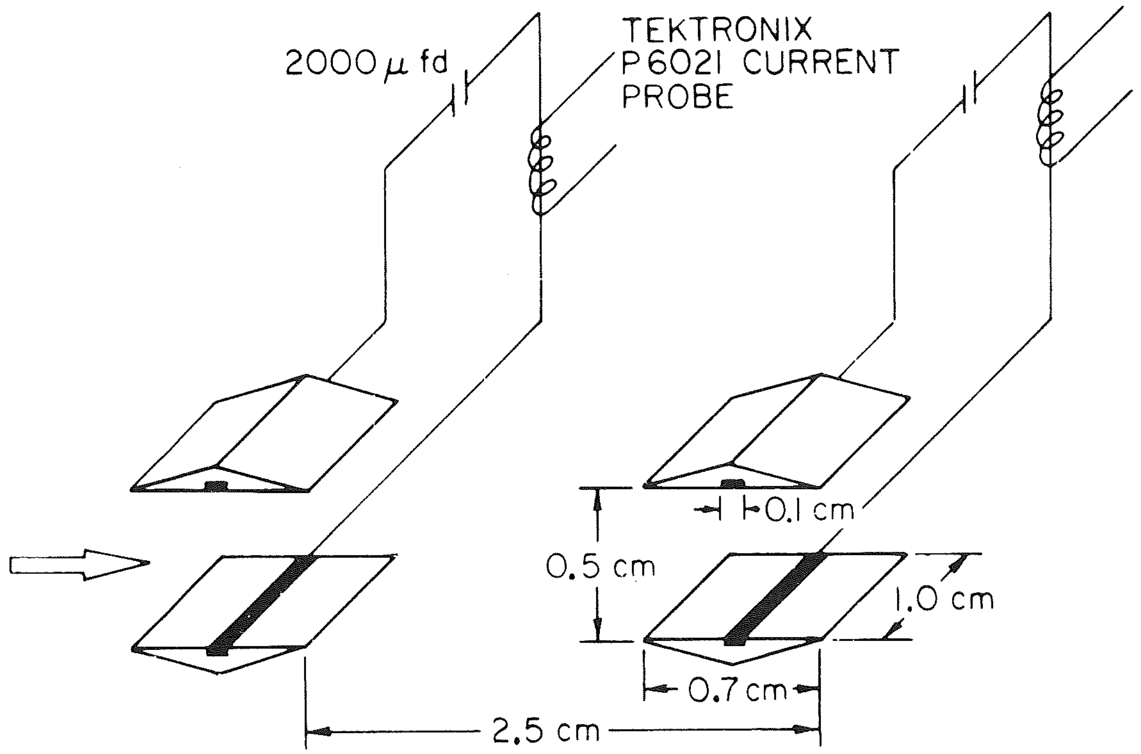
To provide a more complete view of the laboratory activity, the second portion of this report consists of several more concise descriptions of other work in progress, including the completion of our new long-pulse power supply, progress on the internal stress thrust measurement technique, studies of electrolytic capacitor lines and their attendant problems, and a few new diagnostic concepts under development. While none of these merits a major presentation at this time, each plays a significant role in the present course of the laboratory program.

II. ACCELERATION PATTERNS IN THE QUASI-STEADY MPD ARC
(Clark, Oberth, Turchi)

A. VELOCITY MEASUREMENTS

Direct experimental determination of the velocity field in the exhaust plume of a magnetoplasmadynamic accelerator cannot be accomplished by any classical gasdynamic techniques because of the low density, high temperature, nonequilibrium state of the flow. Rather tedious Doppler shift methods have provided isolated data points in a few steady MPD arcs, but attempts to apply these methods to this quasi-steady accelerator have failed so far for lack of sufficient integrated intensity in the shifted lines. Gridded electrostatic ion energy analyzers have proven useful in certain lower power accelerators, but in this device the high plasma density in the exhaust plume forces an unreasonably large expansion of any collected sample before the biasing grids can function properly. One rather simple method for velocity probing that has proven serviceable in this facility, however, involves the use of displaced pairs of biased double electrostatic probes. Passage of local fluctuations in plasma number density, convected on the exhaust stream, are recorded by a biased double probe as a fluctuation in the ion saturation current. Thus, two of these probes, separated a known distance, yield a velocity through the time of flight of these perturbations.[92]

A schematic of the most recent version of this time-of-flight probe is shown in Fig. 1. Each sensor is a 1.0 x 0.1 cm copper surface mounted flush in a small nylon airfoil to keep flow disturbance to a minimum. The two probe circuits are individually biased to 10 V via 2000 μfd capacitors, and their currents, as sensed by Tektronix P6021 probes, are recorded on a dual-beam oscilloscope. The complete probe assembly can be moved in the r − z plane, and its axis can be



SCHEMATIC OF TIME OF FLIGHT PROBE

FIGURE 1
AP 25 · 4561

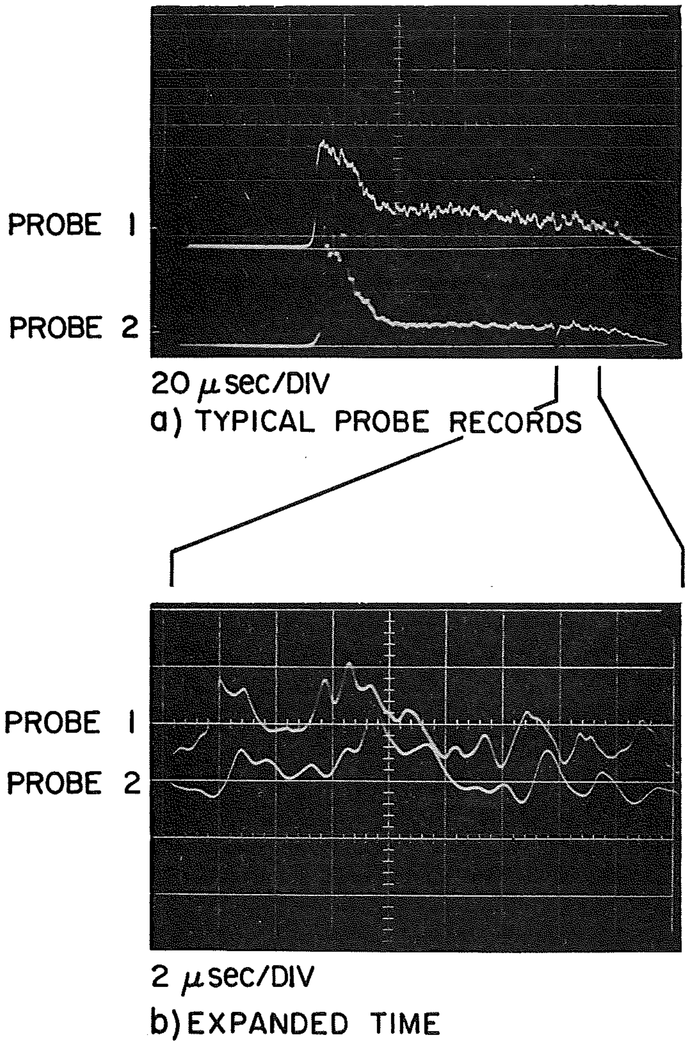
inclined with respect to the accelerator centerline to establish the prevailing flow direction. The probes are cleaned after each shot by allowing a glow discharge to pass between the electrodes for several minutes, thereby improving their high-frequency response and signal reproducibility.

Figure 2a displays typical probe records obtained on the centerline 23.5 cm downstream of the anode face, for a 17.5 kA x 150 μsec driving current pulse and a matched mass flow rate of 5.9 g/sec. The large initial peaks on these traces are associated with the initial starting transient of the accelerator, and the relatively long following plateaus with the quasi-steady acceleration phase. The velocity of the latter is measured by expanding a small segment of these traces on a second oscilloscope, as shown in Fig. 2b and measuring the time displacement between characteristic features of the two probe responses.

The development of the fluctuation velocity along the thruster centerline is shown in Fig. 3 for the 17.5 kA, 5.9 g/sec operation. These data indicate that the plasma leaves the anode orifice with a velocity of about 2×10^4 m/s, negotiates a curious dip in velocity between the 5 cm and 15 cm axial stations, and then continues to accelerate to a value of approximately 2.7×10^4 m/s 30 cm downstream. This latter value is more than three times the Alfvén critical speed, which for argon is 8.7×10^3 m/s, and approximately twice the value calculated from the electromagnetic thrust relation:[100]

$$T = \frac{\mu J^2}{4\pi} \left[\ln \left(\frac{r_a}{r_c} \right) + \frac{3}{4} \right] = \dot{m} v \qquad (1)$$

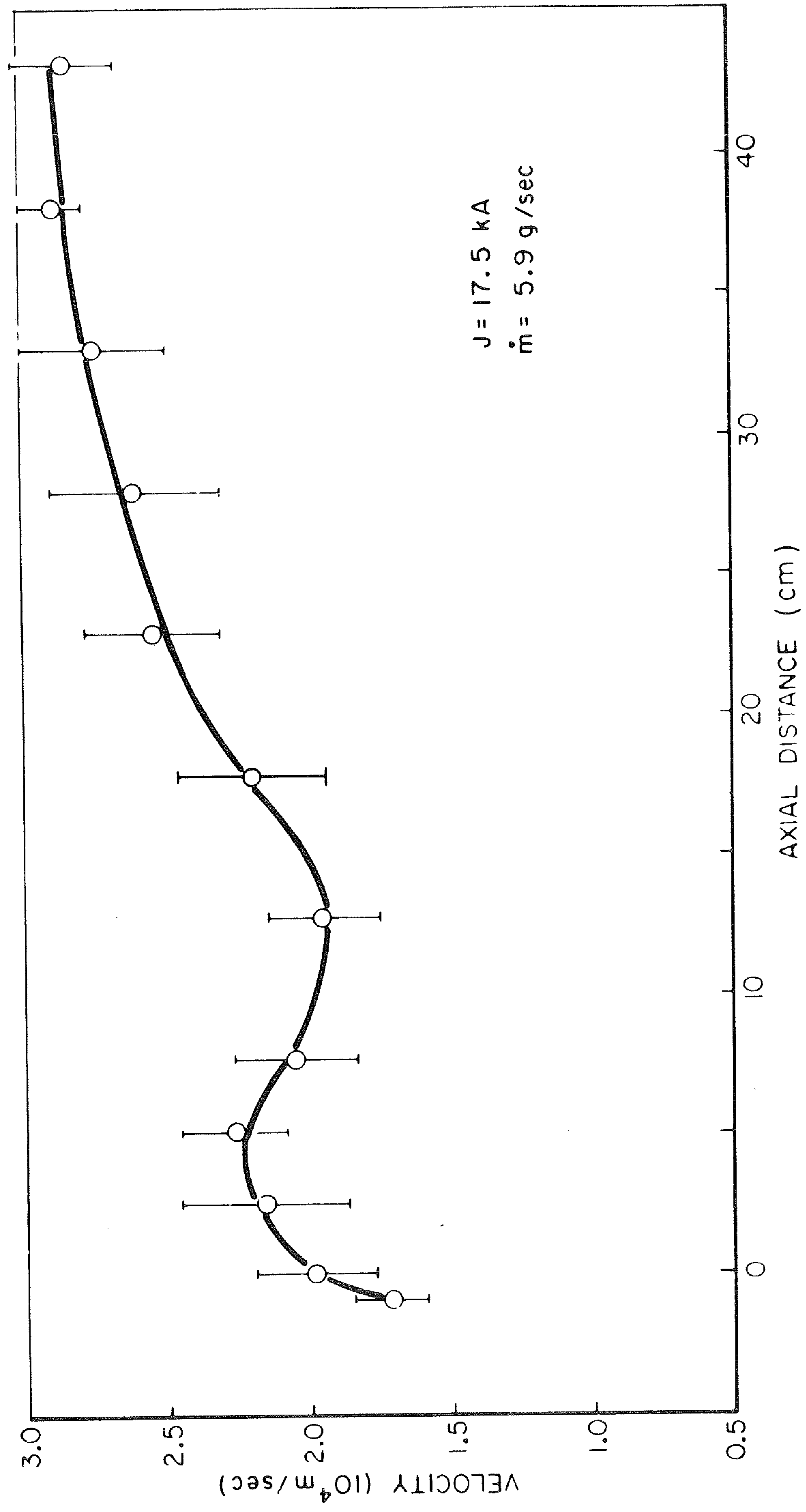
The radial velocity profile at three axial stations is shown in Fig. 4. The profile is seen to be rather steep at



RESPONSE OF BIASED DOUBLE PROBES SHOWING PROPAGATION OF LOCAL FLUCTUATIONS

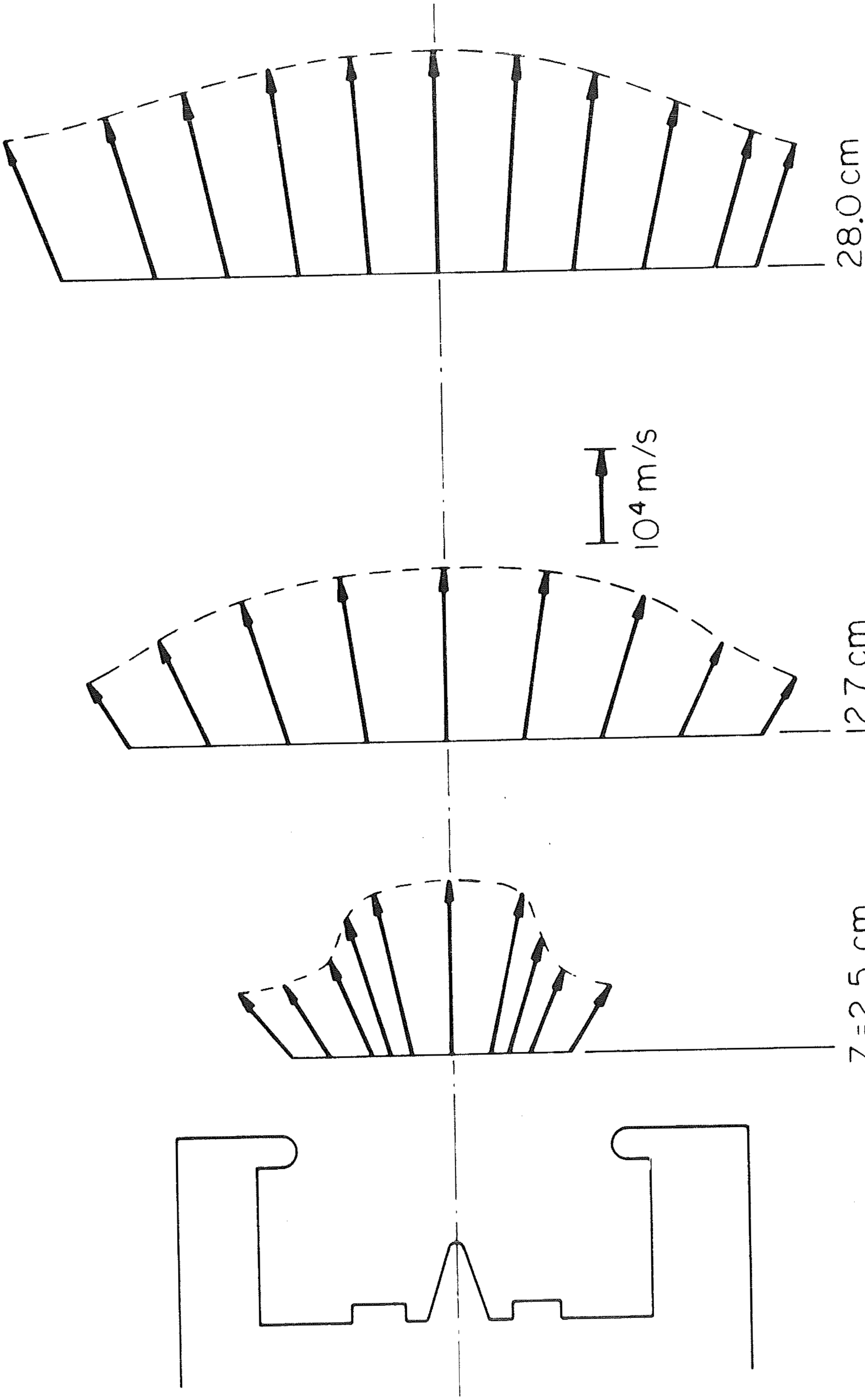
PROBE SPACING = 1.9 cm
J = 17.5 kA , $\dot{m}$ = 5.9 g/sec
Z = 23.5 cm , R = 0

FIGURE 2
AP 25 - 309



CENTERLINE VELOCITY DEVELOPMENT

FIGURE 3
AP 25·4563



VELOCITY PATTERN IN ACCELERATOR EXHAUST.
$J=17,5$ kA; $\dot{m}=5.9$ g/sec ARGON.

FIGURE 4
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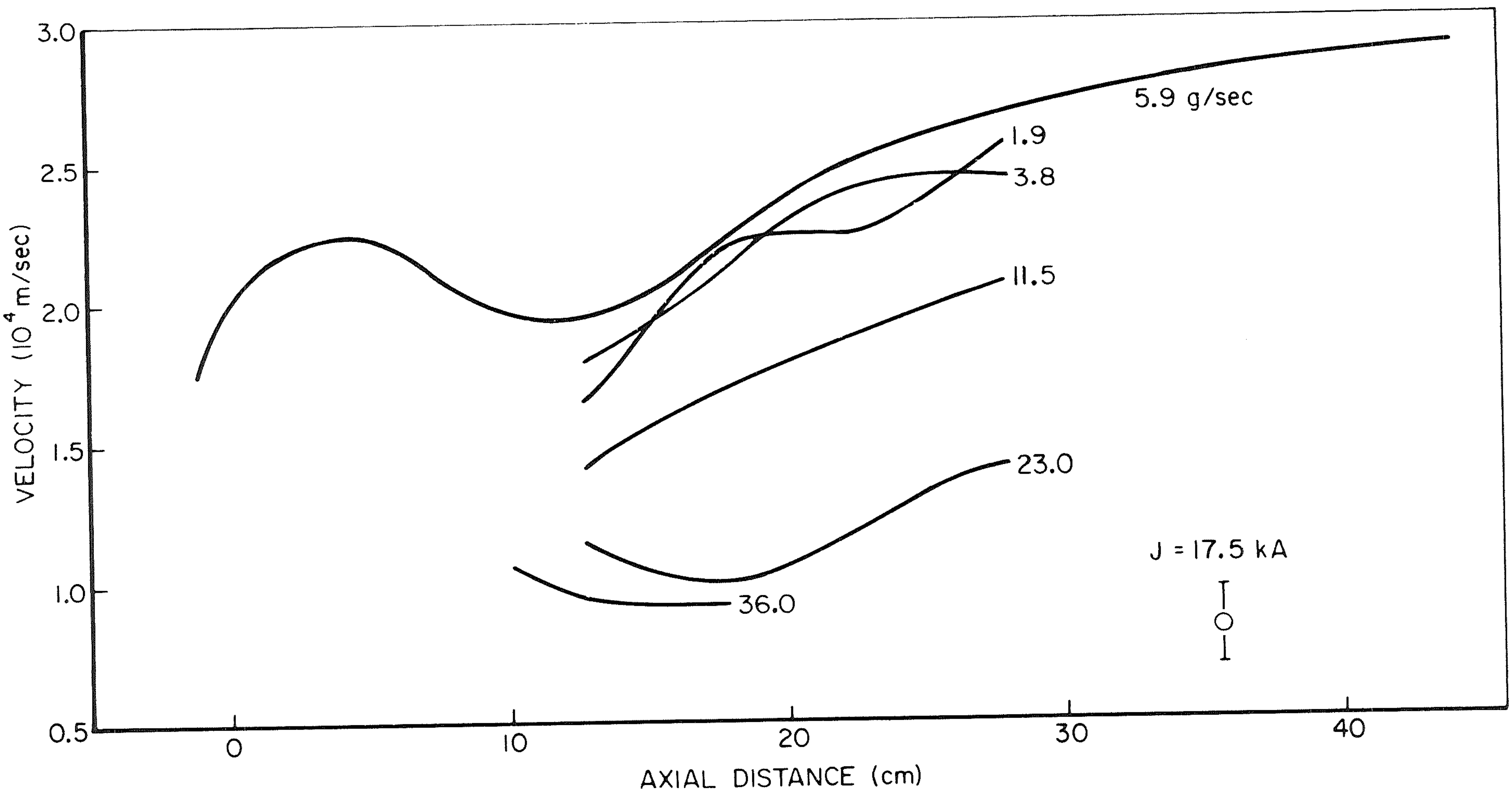
the 2.5 cm location, but to spread rapidly to a more uniform profile at the downstream positions. From these profiles, and estimates of particle densities derived from the magnitudes of the probe current, $n \approx 2 \times 10^{20}$ m^{-3}, a mass-averaged mean velocity is calculated to be about 2.2×10^4 m/sec, a value still substantially greater than the Alfvén critical speed.

The principal concern of such velocity measurements derived from time of flight of plasma fluctuations is that a wave propagation component may be superimposed on the true convective velocity of the flow. For the particular environment downstream of the accelerator, the only relevant wave system would be the so-called ion acoustic mode, an electrostatically coupled longitudinal oscillation which propagates disturbances at a hybrid velocity determined by both ion and electron temperatures.[A-1] Using reasonable estimates of ion and electron temperatures, (see Secs. C and D), this ion acoustic wave speed is approximately 6×10^3 m/s. Thus, even if the measured velocities are in fact the combined streaming and wave velocities, the streaming component must be at least 75 percent of the measured values, still well above the critical speed.

Less detailed surveys of the velocity field have been made at several other arc operating conditions. Downstream centerline velocities for mass flow rates from 1.9 to 36.0 g/sec at a fixed current of 17.5 kA are shown in Fig. 5. The centerline velocity profile for 5.9 g/sec shown in Fig. 3 is repeated here for comparison. These data show that as the mass flow rate is increased above 5.9 g/sec, the velocity is decreased, as would be expected from Eq. (1) if the ions and neutrals were collisionally coupled. However, decreasing the mass flow rate below 5.9 g/sec produces no change in the velocity profile within the measured error brackets, a



CENTERLINE VELOCITIES FOR VARIOUS MASS FLOW RATES

FIGURE 5
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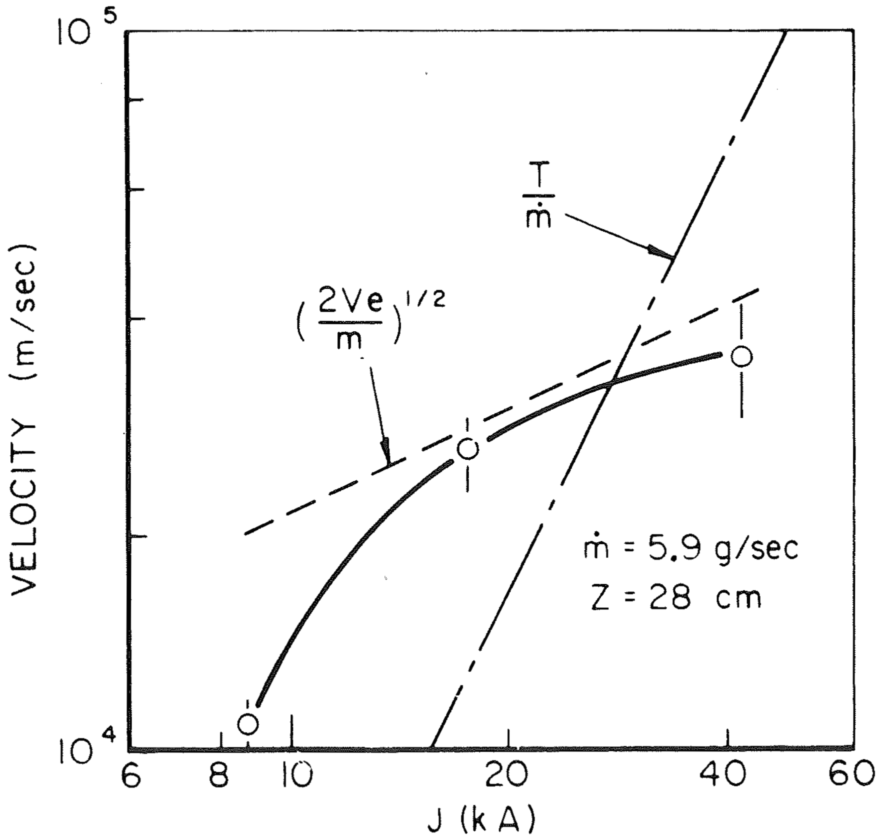
behavior indicative of extraneous mass ingestion. These data thus support the matching of the 5.9 g/sec mass flow rate to the 17.5 kA current level, as previously derived from the terminal voltage data.[87]

The measured velocities at the 28 cm axial position for steady current levels of 8.7, 17.5, and 42.0 kA at a fixed mass flow rate of 5.9 g/sec are shown in Fig. 6. For comparison, this figure also includes the velocity calculated from the electromagnetic relation (1), and the velocity based on kinetic energy equivalent to the observed total electrode voltage. Although this comparison would be more meaningful for mass flow rates matched to the specific current levels as indicated by Fig. 5, it is interesting to note a relatively close correspondence between the measured velocities and $(2Ve/\dot{m})^{\frac{1}{2}}$. This suggests that collisionless ion acceleration in the arc potential field may be a principal element in the acceleration process, a point explored in the following section.

B. POTENTIAL PATTERNS

The rough correlation of the exhaust particle kinetic energies with the discharge terminal voltage suggests that electrostatic processes might play a large role in the acceleration mechanism within the arc. To explore this possibility, maps of floating potential throughout the accelerator were prepared for a representative selection of operating conditions, by point-by-point probing of the discharge with a variety of electrostatic sensors. Although the results of these studies clearly negate any simple electrostatic model of the acceleration process, they provide several other valuable elements of information on the structure of the high-current discharges, particularly in connection with processes near the two electrodes.



CENTERLINE VELOCITY AS A FUNCTION OF ARC CURRENT

FIGURE 6
AP 25-4577

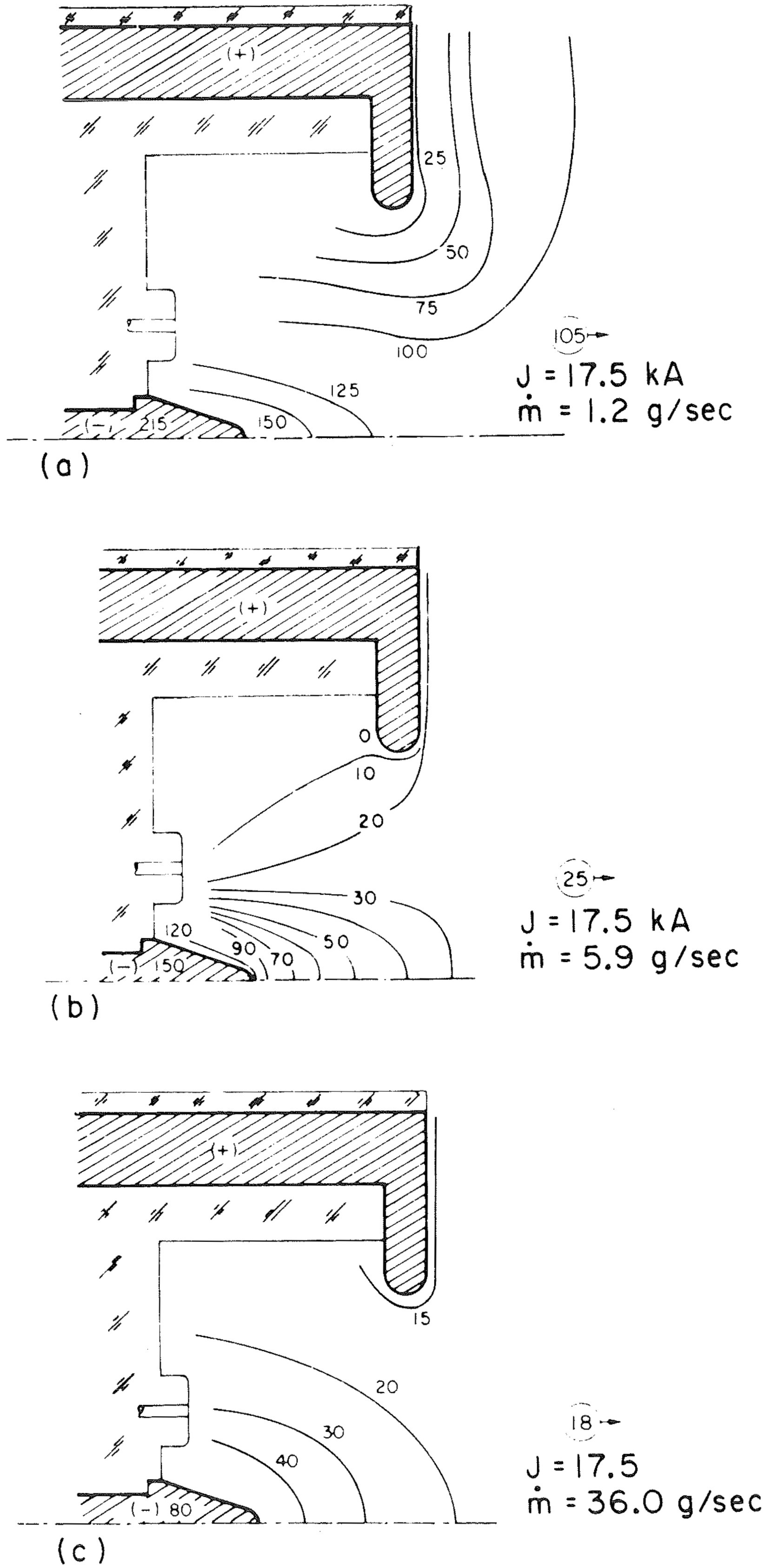
The probes used for these measurements have three configurations of exposed surface: (1) 1/16-in. diam x 1/16-in. high cone; (2) 1/16-in.-diam flat disc; (3) 1/16-in.-diam hemisphere. In most cases the probes are inserted axially upstream into the discharge, in a few cases the probes are inserted radially. Some probes are bent to allow access to regions behind the anode lip. All leads to the probe sensing surfaces are coaxially shielded, and the signals are presented to the oscilloscope via a Tektronix Model 6013A voltage probe of 10^8 ohm impedance. Typical patterns of floating potential derived from these measurements are shown in Figs. 7 and 8, for various conditions of arc current and argon flow rate.

In interpreting these patterns, it should first be recognized that although they are contours of floating potential, they are also good representations of the plasma potential profiles. For the special case of equal argon ion and electron temperatures:[A-2]

$$V_f - V_p = \frac{kT}{e} \ln \frac{j_+}{j_e} \approx \frac{kT}{e} \ln \left(\frac{m_+}{m_e}\right)^{\frac{1}{2}} \approx 5.6 \frac{kT_e}{e} \qquad (2)$$

As indicated in the following section, there is experimental and theoretical basis for estimating electron temperatures around 1.4 eV over most of the chamber and near exhaust field, so that the plasma potential profiles may be displaced some eight volts toward anode potential from the floating values. Any excess of ion temperature above electron temperature, or any ion streaming effects tend to reduce this displacement, so that we may regard the floating potential contours as adequately indicative of the plasma potential variations.

Figure 7b shows the equipotential contours for quasi-steady arc operation at the matched condition of



EQUIPOTENTIAL PROFILES

FIGURE 7

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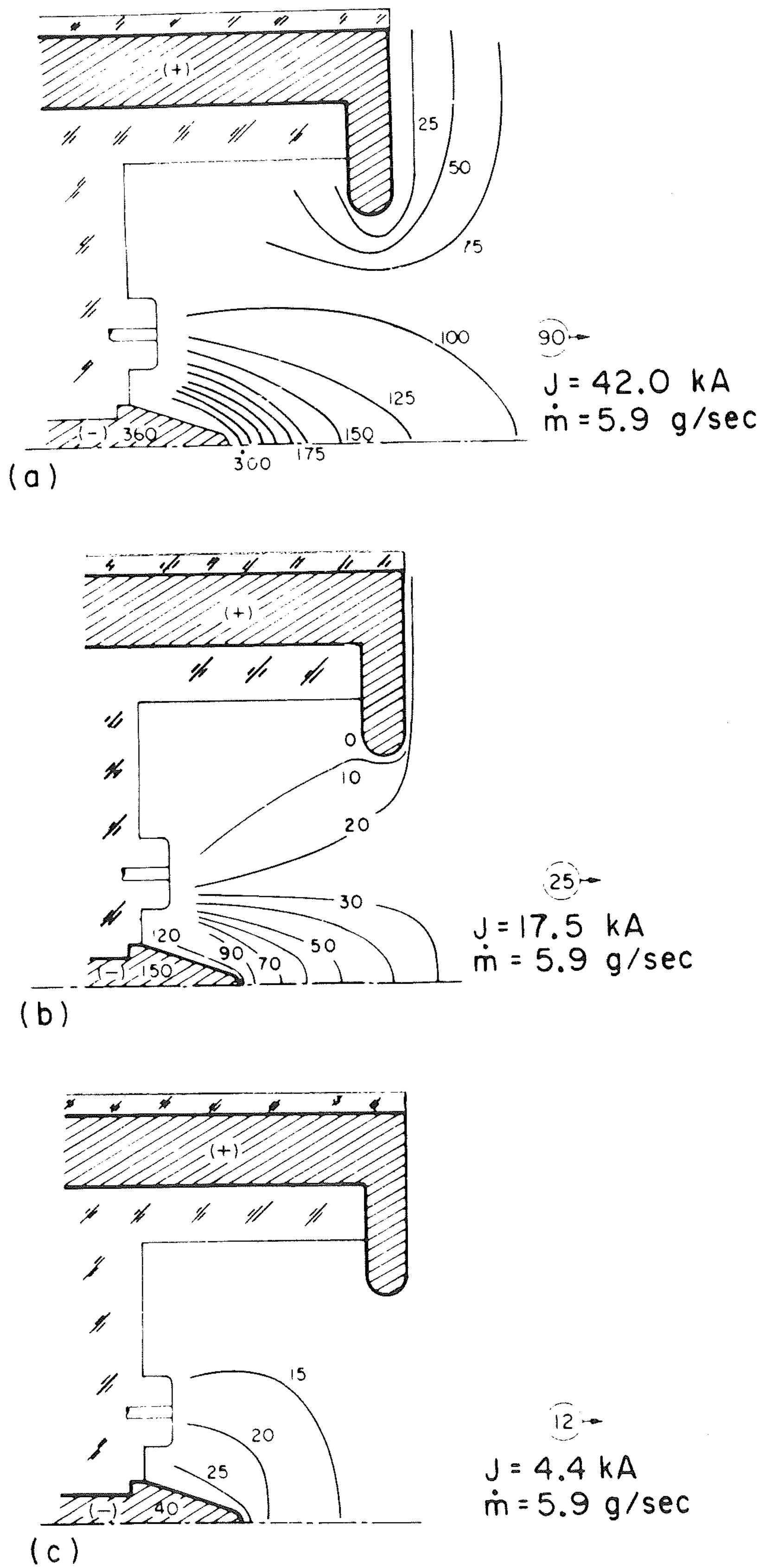


EQUIPOTENTIAL PROFILES

FIGURE 8

AP 25-4581

17,500 A x 5.9 g/sec argon. Several significant features are immediately evident:

1. Downstream potential differs by only 25 V (17 V if 1.4 eV electron temperature correction is applied) from anode potential, and by only 15 V from the region of gas injection. This is an order of magnitude lower than the observed ion kinetic energy in the exhaust stream, and hence voids any simple collisionless electrostatic acceleration model.

2. Anode fall voltage is less than 10 V (or 2 V) over the upstream lip of the anode where current density is a maximum and rises to a somewhat higher value on the downstream face where current density is lower. The dependence of anode fall on current density and the implications for anode losses are discussed below.

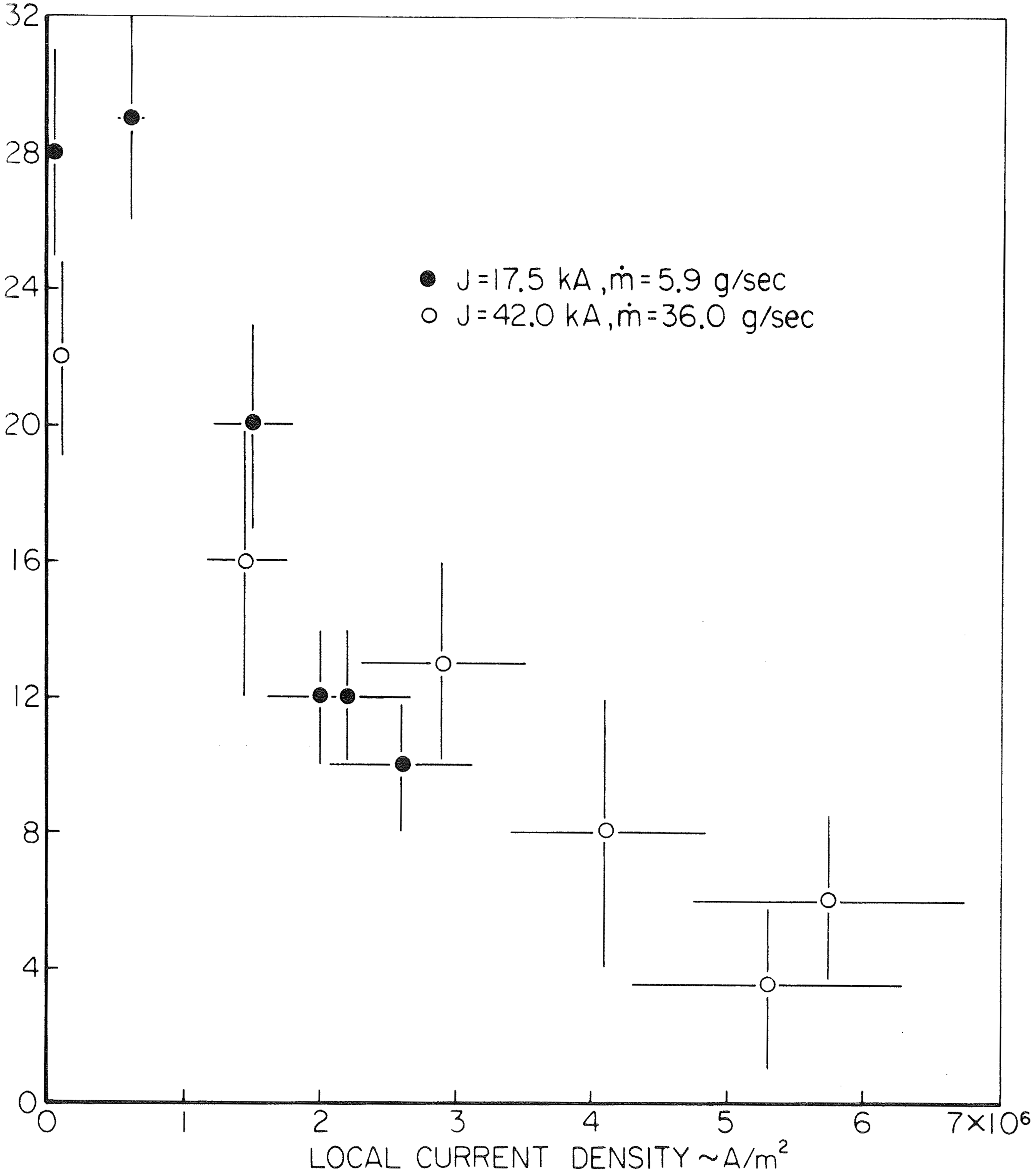
3. The bulk of the potential drop occurs within two diameters of the cathode and is normal to it. Note that this intense field region is directed to decelerate ions attempting to flow downstream, hence cannot aid in a direct electrostatic acceleration process. The significance of this cathode "envelope" region is also discussed below.

4. The gas upstream of the line connecting the injector ports with the anode lip is separated from the downstream flow by about 15 V, which is roughly the ionization potential of argon. This may be coincidental, or it may reflect the ionization process functioning on the cold incoming gas.

5. Other than the regions of anode fall, cathode envelope, and ionization belt just described, the remainder of the field is essentially equipotential,

indicating that the bulk of the energy input to the gas occurs in relatively small regions of the arc, most notably in the cathode envelope.

Although the hypothesis of electrostatic acceleration originally motivating the potential measurements is immediately negated by the character of the profiles, the other aspects of the patterns identified in items 2 to 5 above speak significantly to various features of the arc operation, and bear further discussion. For example, the observed low anode fall, and its inverse dependence on local current density, have major implications for overall efficiency of the accelerator. Steady-flow devices operating in much lower power ranges are known to dissipate large portions of their input power--in some cases 40 percent or more--in heating of the anode. This dissipation is clearly related to the anode fall established by the arc, and any empirical means for reducing the fall voltage should be reflected in higher overall performance. Figure 9 is a graph of measured anode fall at various points along the anode surface versus the current density at the same points computed from measured enclosed current contours.[76] Also included are values found for arc operation at 42.0 kA and a matched mass flow of 36.0 g/sec. Within the accuracy of both experiments, these data define a common functional dependence of anode fall on surface current density which is essentially reciprocal in the form $V_a \approx 3 \times 10^7/j$ (volt/amp/m^2). This criterion could also be expressed on the basis of a constant power density to the anode sheath, $P_a \approx 3 \times 10^7$ (watt/m^2). Integration of these observations over the entire anode surface provides an indication of the total power delivered to the anode sheath. Figure 10 plots this quantity as a fraction of total arc power, versus the arc current, for three values of current and two mass flows. Regardless of the representation



ANODE FALL VARIATION WITH LOCAL CURRENT DENSITY

FIGURE 9

AP 25·4565

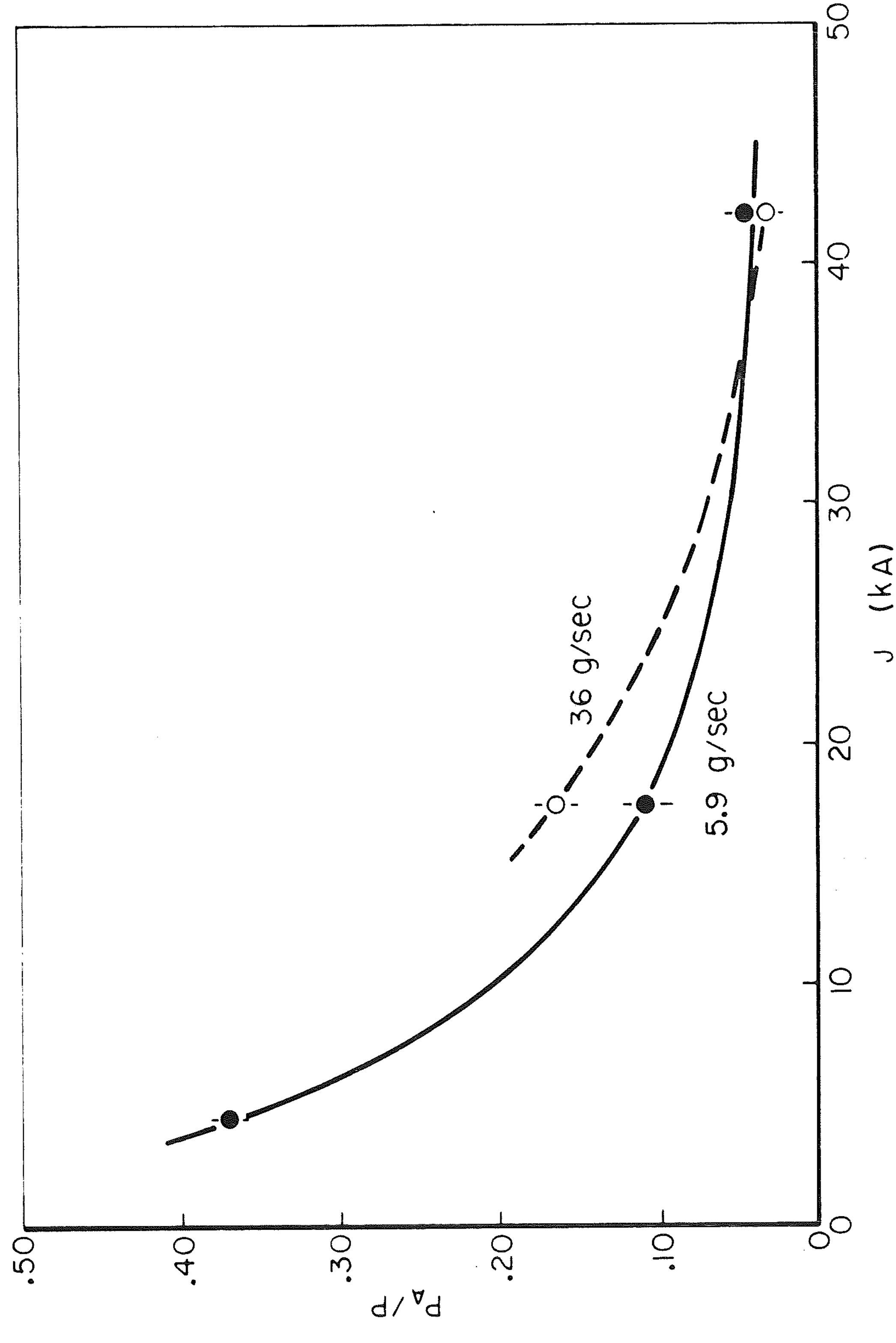


FIGURE 10
AP 25 · 4564

of these data, their implication is clear: over the regime studied, fractional anode loss should decrease significantly with increased arc power.

In constructing Fig. 9 only data obtained from arc operation at "matched" mass flow has been included. If the arc is operated in conditions of mass "starvation" or mass "overfeed," the character of the potential profiles changes substantially, and identification of the true anode fall becomes somewhat ambiguous. For example, Fig. 7a displays the floating potential map for the starved condition $J = 17,500$ A, $\dot{m} = 1.2$ g/sec. Note the following changes from the matched condition of the same current (Fig. 7b): (a) the total arc voltage has increased by 45 percent; (b) the downstream potential has increased by a factor of four; and (c) there is now an envelope of potential gradient extending outward from the anode, as well as from the cathode. It is not clear whether this anode envelope is a functional part of the acceleration process, or whether it is simply a very large anode sheath necessitated by the difficult conduction conditions prevailing in the low density environment. If ion production in the anode sheath is an essential part of the conduction process, the dimensions of the sheath would need to grow as the density dropped. In turn, if all of the power deposited in this large sheath were delivered to the anode, the fractional anode loss in this condition would be quite high.

For comparison, Fig. 7c shows the potential pattern for arc operation at the same current, but with an excessive mass flow of 36 g/sec. Here the total voltage, downstream potential, and anode envelope have all decreased, but in such proportion that the fractional anode fall power is again somewhat higher than for the matched case.

The same changes observed in the potential patterns by varying the mass flow from the nominal value at fixed current can also be produced by varying the current at a fixed mass flow rate of 5.9 g/sec. For example, Fig. 8a shows the equipotentials in a "starved" condition, J = 42,000 A, and Fig. 8c displays the potential pattern in a mass "overfeed" condition, J = 4400 A.

Returning to the nominal case of Fig. 7b, we next consider the cathode envelope region which dominates the entire potential pattern. Exclusive of the cathode fall, some two-thirds of the arc voltage is dropped across this region, and in view of the high-current densities prevailing here, it must be presumed that this zone is primarily responsible for the high exhaust velocities found downstream. Beyond this suspicion, however, no detailed model of the acceleration process is apparent. As previously remarked, the prevailing electric field accelerates positive ions inward, rather than outward. Comparison with the measured current density profiles indicates that total current conduction in this region is largely scalar, even though electron Hall parameters greater than one can reasonably be expected near the cathode shoulder. In some portions of the envelope the electric field could reflect a large $\vec{u} \times \vec{B}$ or motional emf component, but in others, such as near the inlet orifice and along the axis, this component must be small, leaving mainly a resistive component. This in turn implies substantial ohmic heating, and subsequent electrothermal contributions to the overall acceleration process.

In this connection it should be noted that over most of the cathode envelope the self-magnetic body forces have large components directed radially inward which must act to compress the plasma along the axis. Thus it may be that downstream of the cathode tip there exists a region of very hot gas, constrained by the magnetic field and heated by the electron stream which has fallen through the envelope, somewhat akin to the dense plasma focus seen in certain thermonuclear injectors.[A-3] Subsequent expansion of this hot gas in the magnetic nozzle may then provide a significant component of the observed exhaust kinetic energy.

The importance of this electrothermal component to the composite acceleration process could best be assessed by identification of the state of the hot gas zone in question. Unfortunately, this is a hostile environment for most experimental studies. Electric probes, as discussed in the following section, have problems of survival and ambiguities of interpretation. Spectroscopic attempts to assign temperatures by species identification are in progress but have not yet yielded quantitative results. Some support for an electrothermal expansion component may be derived from the centerline velocity profile of Fig. 3 which shows acceleration continuing substantially beyond the limits of the current density pattern, but more detailed diagnostic results are clearly needed.

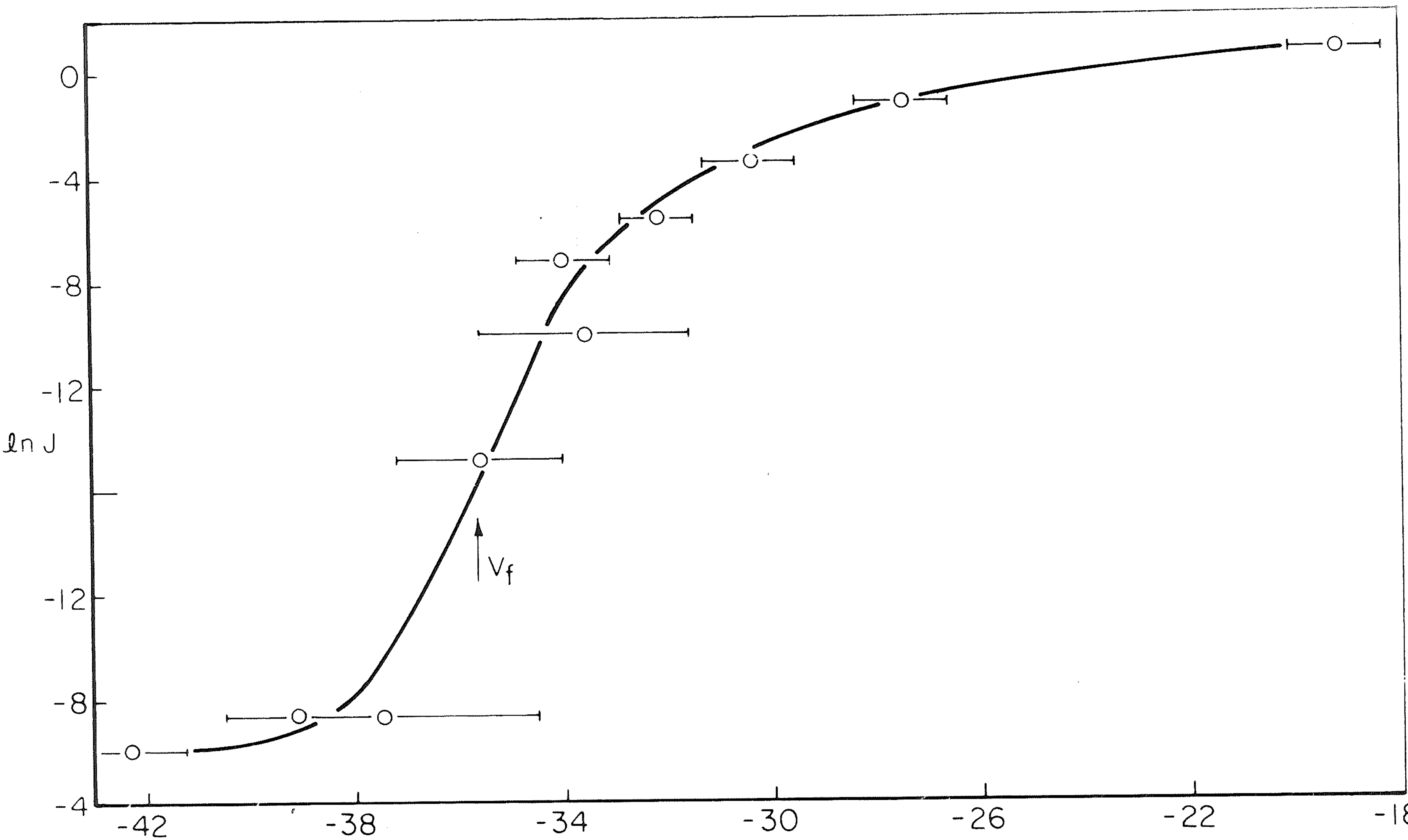
C. LANGMUIR PROBE STUDIES

Interpretation of both the exhaust velocity and the equipotential observations would benefit from some knowledge of the state of the plasma in those regions where the measurements were taken. In principle, information on electron temperatures and densities, and in some cases, ion temperatures can be extracted from conventional Langmuir probing of the flow. In practice this is a somewhat tedious technique which suffers from a variety of experimental complications, such as probe contamination, overheating, and erosion, and analytical ambiguities catalogued in terms of the ratios of probe dimension, mean free path, Debye length, etc.[A-2] In our experiments it has not yet been possible to sustain a sufficiently small probe within the chamber, or immediately downstream of the cathode tip. Some results have been obtained 30 cm downstream of the anode face on the centerline.

The probes employed have cylindrical tungsten tips, 0.003-in. in diam and 0.11-in. long, oriented parallel to the flow axis to minimize streaming effects. This probe radius is less than the anticipated electron-ion mean free path in the region to be probed, and larger than the Debye length. Leads to the probe are coaxially shielded and insulated with mylar tape and epoxy. To trace the electron current branch of the probe characteristic, voltages developed across a succession of resistors from 9.6 to 10^8 ohm are monitored with a Tektronix P6013A probe and displayed on an oscilloscope. To trace the ion current branch, a 45-V battery is added in series with the resistor.

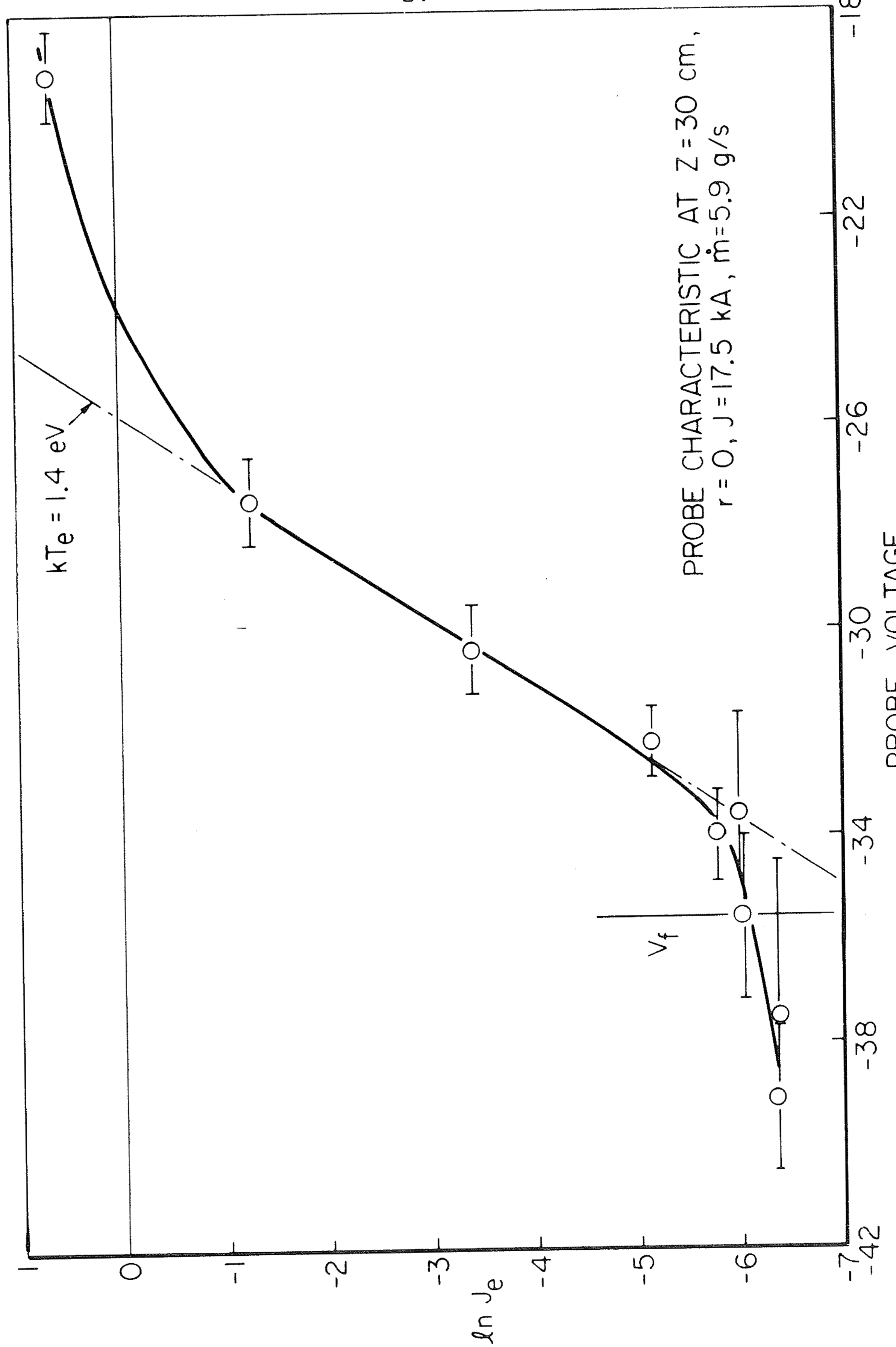
A typical probe characteristic is displayed in Fig. 11. The error bars reflect the shot-to-shot reproducibility of a given data point, which in each case is an average of several values. Note that both negative and positive current saturation has been attained, and while there is considerable uncertainty in the saturation voltages, the magnitudes of saturation currents seem well bounded.

Presuming sheath thickness small compared to the probe radius, data are reduced by the standard procedure of removing the ion saturation current from the total current, plotting the logarithm of electron current vs. probe voltage, (Fig. 12), and identifying the slope of the straight portion as the electron temperature. Deviation from the straight line at the higher voltages is indicative of plasma potential; the lower deviation may reflect a non-Maxwellian tail on the electron distribution function, but is not pursued further here. From the electron current density at the plasma potential the electron density may be computed, and



LANGMUIR PROBE CHARACTERISTIC AT
$Z = 30$ cm, $r = 0$; $J = 17.5$ kA, $\dot{m} = 5.9$ g/sec

FIGURE 11
AP 25-4572



LANGMUIR PROBE ELECTRON CURRENT VARIATION WITH PROBE VOLTAGE

FIGURE 12
AP 25 - 4562

thence, from the ion saturation current, the ion temperature may be estimated. By this route the following properties are deduced:

$$T_e = 1.4 \pm 0.2 \text{ eV}$$

$$n_e = 5.2 \pm 4.0 \times 10^{19} \text{ m}^{-3}$$

$$T_i = (5.6 \pm 0.2) T_e = 8.8 \pm 0.6 \text{ eV}$$

This value of electron density is somewhat lower than that indicated by the double probe observation of Sec. A and, if correct, places the Langmuir probe in a marginal domain. The Debye length consistent with these measurements is 2.7×10^{-6} m, or only a factor of 14 smaller than the probe radius. In this circumstance, sheath thickness may not be negligible, and the values of n_e and T_i would need be revised upward and downward, respectively. Experiments with larger probes to explore this effect are in progress.

The observed electron temperature is typical of discharges of this type where the vulnerability of the electron swarm to inelastic collisions of many types effectively limits their mean random energies to a few eV over a broad range of total plasma energy density. The observation of a substantially higher ion temperature this far downstream lends an element of support to the hypothesis of significant electrothermal conversion, and coincides nicely with the Mach number measurements described in the following section. It also aids in the estimation of the ion acoustic speed necessary for better evaluation of the velocity probe data of Sec. A.

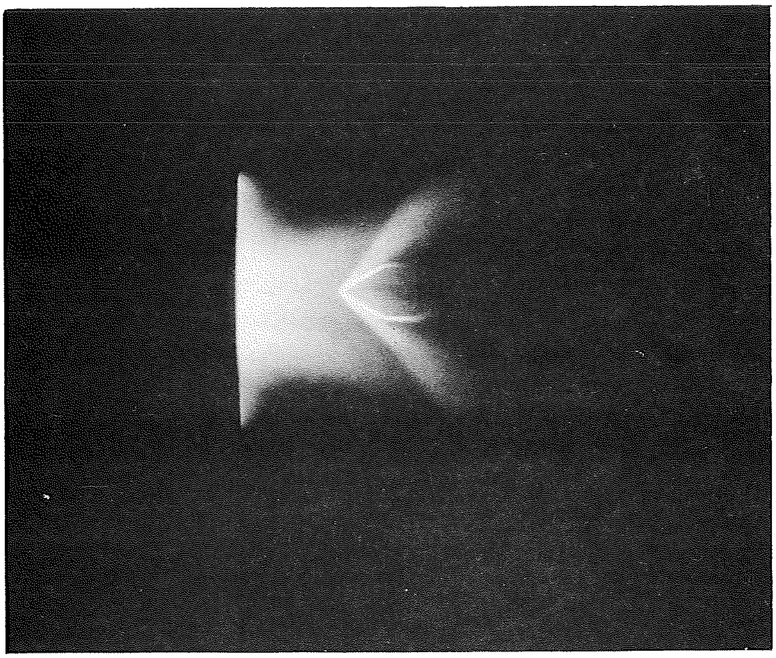
D. MACH NUMBER OBSERVATIONS

Estimates of the Mach number of the exhaust flow can be made from photographic observation of the bow shock waves formed on small wedges inserted along the centerline. Comparison of these values with the measured velocities can then lead to estimates of the local ion temperature. Figure 13 shows a typical photograph of a 30.5° half-angle wedge, 3.8 cm downstream of the anode for the 17.5 kA, 5.9 g/sec operating condition. The photograph was taken from the side of the accelerator (flow from left to right) through a 5 μsec Kerr-cell shutter delayed by an oscilloscope until the quasi-steady acceleration phase was well developed. Photographs taken farther downstream show no shock waves on the wedges, presumably because of inadequate plasma density in the expanded jet.

Deduction of Mach number from the bow shock angles requires knowledge of the effective ratio of specific heats, γ, for the plasma. Although this quantity can be estimated to lie in the vicinity of 1.3 for this medium, it is possible in principle to extract both Mach number and γ information from simultaneous consideration of data from two or more different wedge angles at the same location. When such an approach is attempted, the resulting self-consistent solution consists of a Mach number of about 2.5, but a totally unreasonable value of $\gamma \approx 0.6$. This paradox persists even when the data are taken from two surfaces of a single wedge, inclined at an angle of attack. This problem may alternatively be illustrated by presenting values of Mach number calculated from several different wedge half-angles, δ, shock angles, θ, and an assumed γ of 1.3:

δ	θ	M
10.0°	31.5°	1.9
20.5°	37.5°	2.4
30.5°	43.0°	3.7
40.5°	51.0°	8.1

The wide spread in the calculated Mach numbers, or the γ paradox mentioned above, may be related to the altering of the effective deflection angle by non-ideal flow effects near the



FLOW OVER 30.5° HALF-ANGLE WEDGE AT
Z = 3.8 cm, r = 0; J = 17.5 kA,
$\dot{m}$ = 5.9 g/sec

FIGURE 13
AP 25-310

wedge surface. Specifically, the strong cooling of the flow by the surface, and possible recombination effects may yield a boundary layer with a negative displacement thickness, thereby necessitating a smaller flow deflection than the nominal wedge angle. This effect should be minimized at the smaller wedge angles, since the corresponding shock waves are weaker. Thus, the 10° wedge angle data probably yield the most reliable value of Mach number.

It is now possible to iterate the Mach number and the fluctuation velocity measured at the same position to a self-consistent value of the ion acoustic speed, and thence to an ion temperature. Such calculation yields an ion temperature at this location of about 16 eV, a value not inconsistent with that deduced from the Langmuir probe measurements further downstream in view of the flow expansion indicated by the changes in the velocity radial profiles over this interval.

E. REMARKS

The various items of experimental data presented here by no means provide a complete, self-consistent picture of the quasi-steady arc operation. They do, however, provide certain indications that the operation of self-field MPD arcs in the megawatt range differs in important respects from that at lower powers. First, the Alfvén critical velocity appears not to impose a fundamental limitation on the attainable exhaust speed; achievement of high specific impulse with heavy ions seems straightforward. Second, power loss to the anode, as indicated by the anode fall voltage, becomes proportionately less important in high power operation; this should be reflected in higher overall efficiency. Finally, the portion of the arc in the immediate vicinity of the cathode is indicated as the region of primary energy input, which probably controls the high performance capability of the device.

III. ASSOCIATED EXPERIMENTS

A. THRUST MEASUREMENT (Saber)

It seems possible to measure the thrust of our quasi-steady MPD accelerator by mounting strain gauges directly on portions of the accelerator structure to indicate the local distortion throughout a pulse. The conventional magnetoplasmadynamic model of the accelerator,[61] the observed patterns of current density and electric potential discussed in Sec. II, luminosity photographs of the accelerator operation, and examination of the cathode surface all strongly suggest that most of the thrust is borne by the cathode structure. Therefore, our first attempts at strain gauge monitoring of thrust profiles will concentrate on this element.

When the machine thrusts, three strain waves--distortion, dilatation, and Rayleigh--each with its own propagation velocity, travel down the cathode cylinder. Once the quasi-steady operating mode has been achieved, these strains ideally should reach a pseudo-steady state, until reflected waves return from the supporting structures.

Response of the strain gauges should pass through four phases:

1. Null phase: the thrust pulse has not yet reached the strain gauge although spurious electrical and mechanical signals associated with breakdown initiation and gas injection may appear.

2. Direct phase: the "information wave" passes through the strain gauge, but the reflected waves have not yet returned from the supports.

3. Reflection phase: reflected pulses pass over the gauge, as the state of local stress drives toward an equilibrium.

4. Steady phase: if the thrust pulse remains quasi-steady long enough, stress oscillations subside and local strain reaches a constant value, perturbed only by exterior effects.

With our existing accelerator equipment we can deal only with the first two modes, since the pulse times are inadequate for full stress relaxation in the solid structure. Eventually our long-pulse facility may permit use of phase 4, also.

For the first feasibility tests two piezoelectric strain gauges (BLH:SPB3-12-100-C6) have been mounted on the inside of the cathode cylinder, one with the filament axial and the other with the filament azimuthal, to sense the direct and Poisson stress waves separately. The strain gauges are first mounted on insulating mylar sheets, $\approx$ 0.0075-in. thick, to insulate them from cathode potential, using EP-150 epoxy after roughening the mylar sheet with a knife blade and cleaning with acetone. These assemblies are then installed on the cathode cylinder and connected to Wheatstone bridges and thence to oscilloscopes via 50-ohm coaxial cable (Fig. 14). The location of the gauges, within six inches down the cathode cylinder from the tip provides for attenuation of corner effects in signal transmission from the cathode plate to the cylinder.

The only modification of the accelerator system needed for the feasibility tests is the incorporation of a device to trigger the oscilloscopes before the diaphragm of the shock tube is burst, in order to display as many background effects on the strain gauges during the whole duty period as

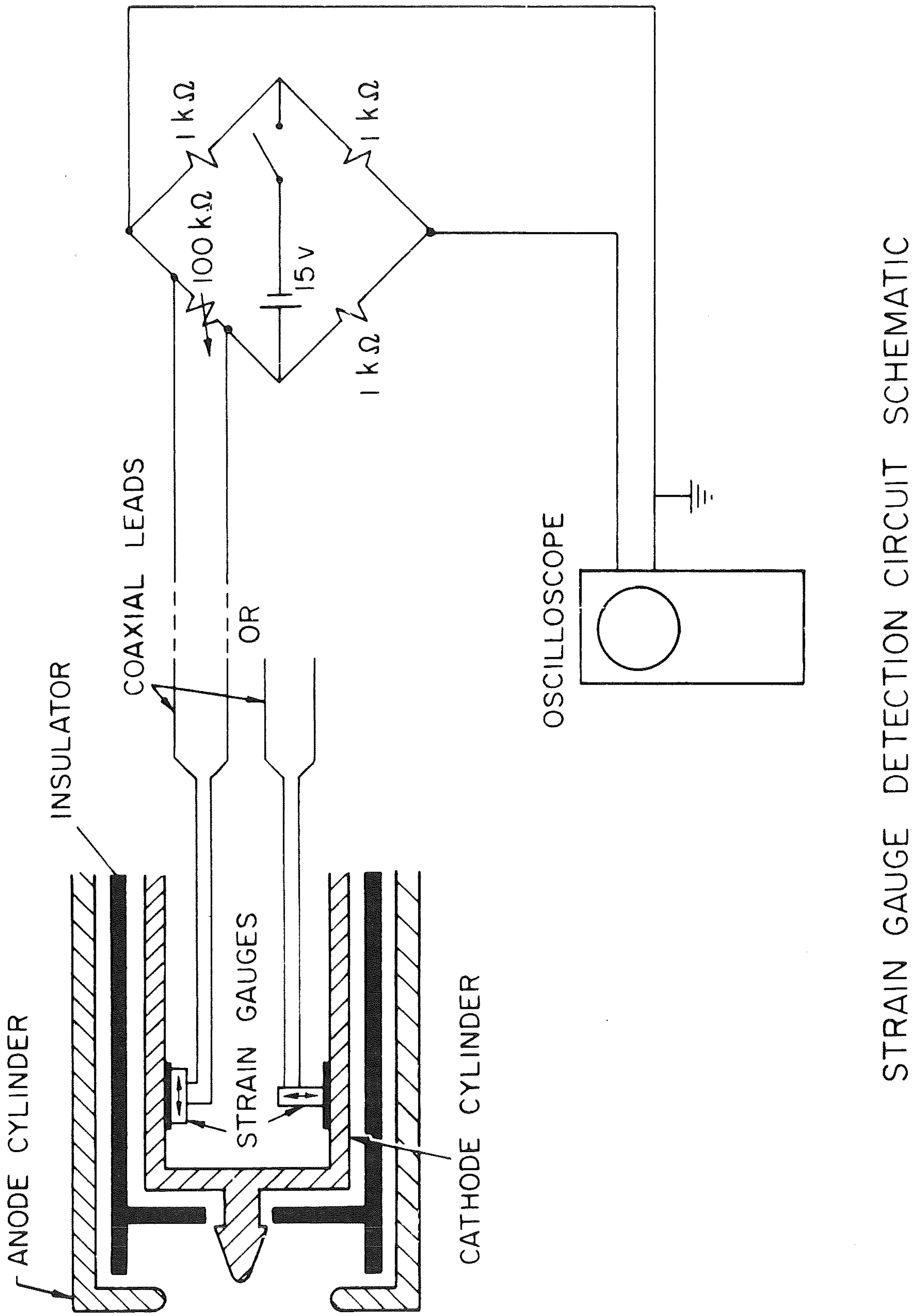


FIGURE 14
AP 25·4579

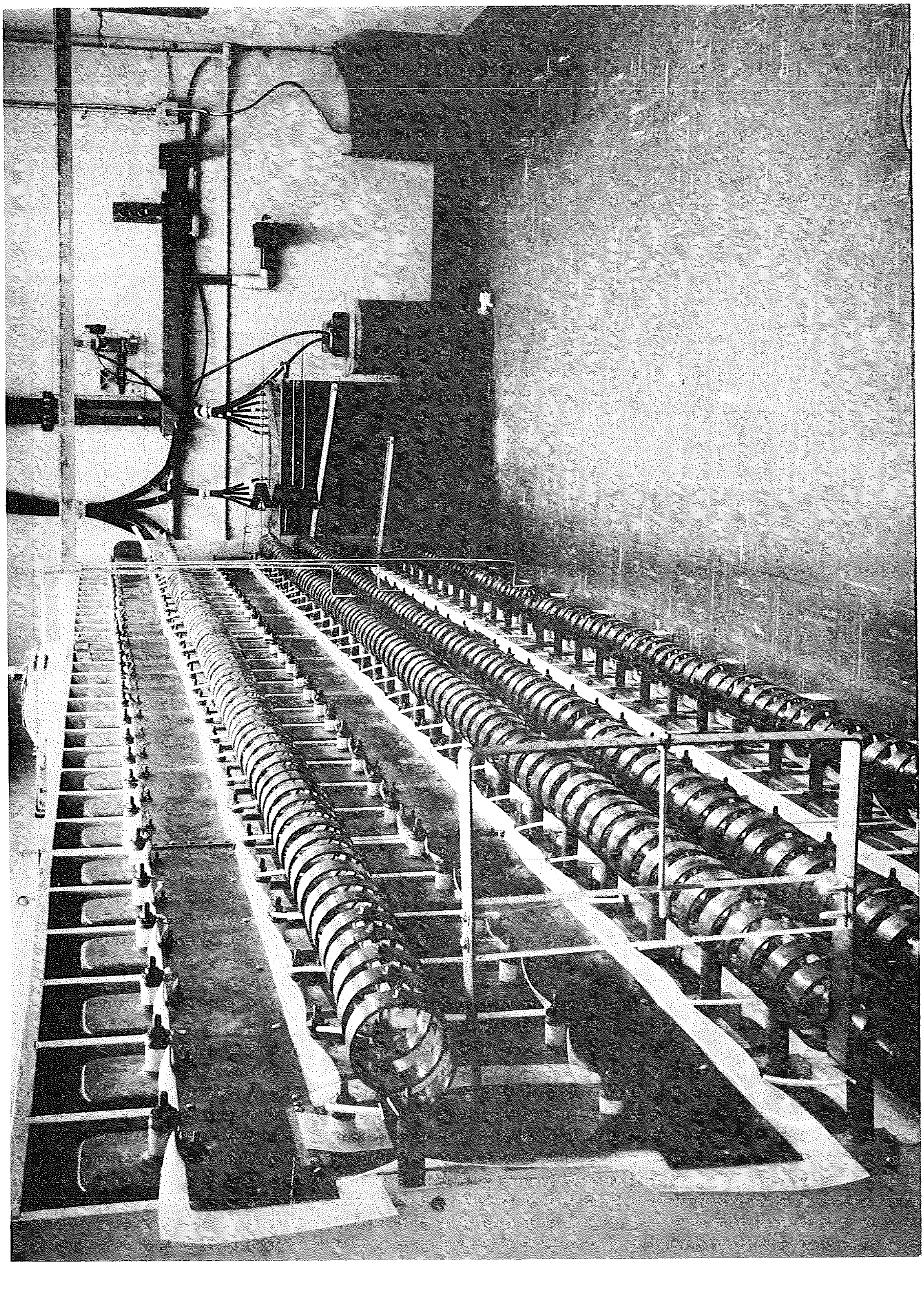
possible. For the present this is done by triggering the oscilloscopes while releasing the arrowhead to break the diaphragm.

The anticipated thrusts lie in a range of about 1 lb. for a total current of 4.4 kiloamps to over 1000 lb. at 140 kiloamps. The corresponding voltage outputs from the Wheatstone bridges to the oscilloscopes range from about 10 microvolts to 10 millivolts, which necessitates particularly careful shielding of the circuitry against spurious pickup. At present preliminary experiments with the gauges in place on the accelerator are in progress to indicate the full magnitude of this problem.

B. LONG-PULSE POWER SOURCE (DiCapua)

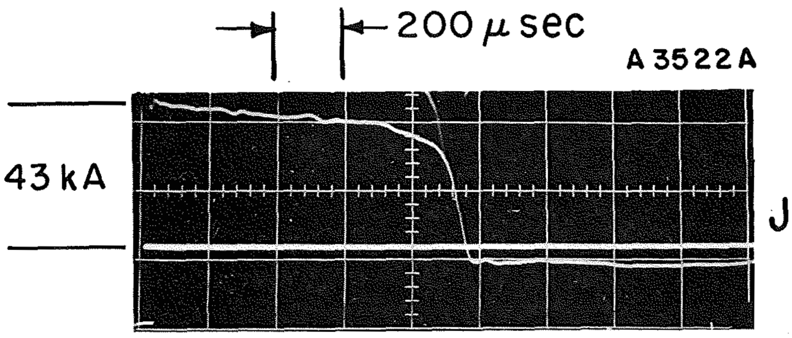
The 160-kilojoule, pulse-forming network described in previous semiannual reports[76,92] is now complete. The network, with the terminating resistors, loaded at full voltage has been discharged across a short circuit load and performs according to specifications. Figure 15 shows the completed network with the interconnecting inductors as well as the terminating resistors and the coaxial cables which feed the accelerator. The current pulse obtained by the series connection of all four lines driving a short circuit load is shown in Fig. 16. Early experiments with this power source switched across the parallel-plate accelerator with ambient argon fill are encouraging in indicating that the long-desired extension of the program of quasi-steady accelerator operation in this geometry to longer pulse times can now be pursued. Figure 17 shows typical terminal voltage traces obtained at both ends of the accelerator.

These early surveys have also indicated a need for redesign of the gas-triggered switch to permit it to handle the longer pulses without excessive interior contamination



VIEW OF 160 KILOJOULE PULSE FORMING NETWORK

FIGURE 15
AP 25 - 314



CURRENT PULSE PROFILE FROM 160 KILOJOULE PULSE FORMING NETWORK THROUGH SHORTED LOAD.

FIGURE 16

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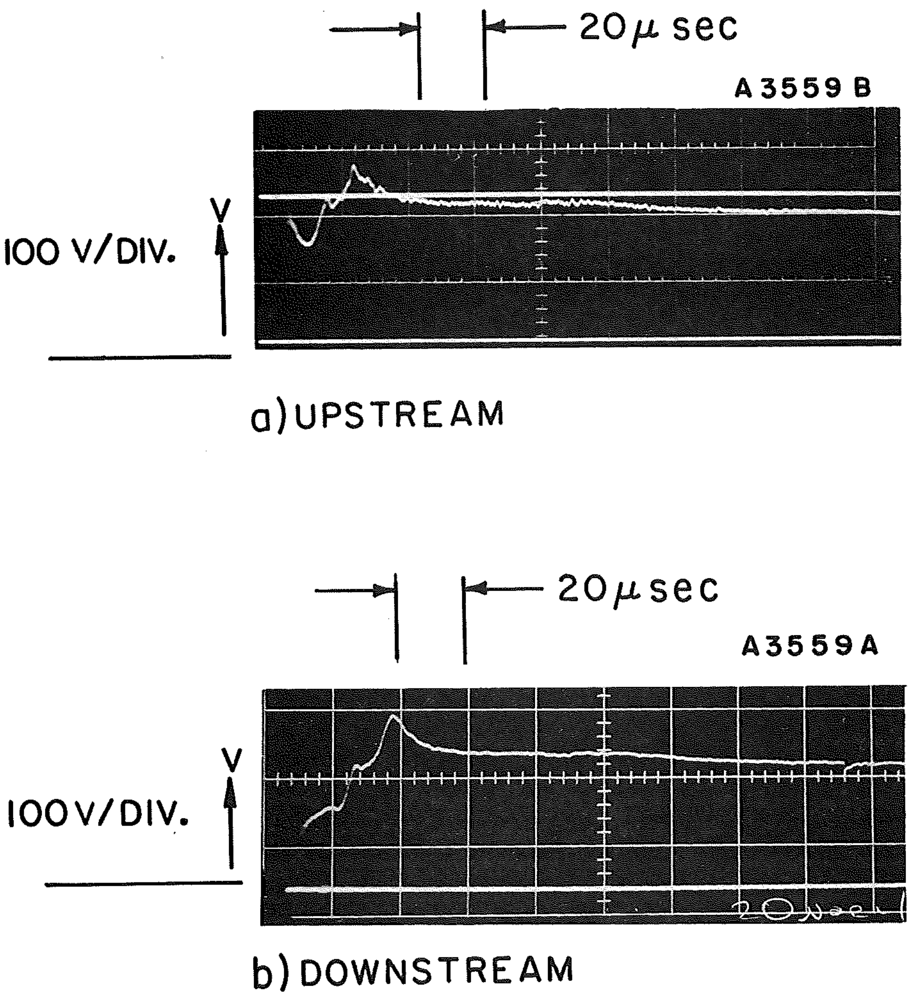
DISCHARGE IN 100μ AMBIENT ARGON



TERMINAL VOLTAGE

FIGURE 17

AP 25•312

and premature breakdowns. At present, this switch reconstruction is in progress, a safety enclosure for the entire parallel-plate facility is being built, and the long line is being applied to the MPD accelerator to provide first indications of the characteristics of operation of that device on the much longer pulses.

C. ELECTROLYTIC CAPACITOR PULSE-FORMING NETWORK (Villani)

The capacitor-inductor, pulse-forming networks used as energy storage units for pulsed plasma accelerator research most commonly employ high voltage, oil-filled capacitors. Recent studies in an associated program[94,98] have identified certain attractive advantages in using low-voltage electrolytic capacitors for this purpose:

1. Electrolytic capacitors have lower specific mass than any other type, by at least one full order of magnitude. Units currently available commercially fall in the range of 0.01 kg/joule and lower.

2. Electrolytic capacitors are commonly available with much higher unit capacitance--above 2000 μfd in many cases. Since the impedance of a pulse-forming network scales inversely with the square root of the unit capacitance, it is much simpler to achieve an impedance match between the network and the 0.005 – 0.010 ohm load typical of an MPD accelerator.

3. Electrolytic capacitors are inherently low voltage devices (< 500 V). Electrolytic networks thus would allow simpler power conditioning equipment to mate them to prime power sources, particularly solar panels.

Electrolytic capacitors also have well-known characteristic disadvantages which have heretofore discouraged their application to space systems, most notably their high internal resistance, high leakage current, high parasitic inductance, low reliability, and unipolar terminal asymmetry. As yet, insufficient study has been made to establish whether these disadvantages or the previously cited advantages prevail for the particular applications of interest here, or whether reasonable improvement in the product can improve this balance. The purpose of the present program is to examine various features of electrolytic capacitor behavior in an MPD pulse line configuration in the hope of clarifying such judgment.

The first studies of this concept involved an electrolytic line driving a pulsed vacuum arc,[94,98] and it was unclear in some cases whether the observed behavior reflected characteristics of the capacitors, or of the vacuum arc discharge. The present study employs a spark-triggered argon discharge in our conventional 4-in. anode diameter MPD configuration, in the hope of distinguishing these causes.

The particular electrolytic capacitors used here are 2200 μfd, 400-V G.E. units borrowed from the neighboring Plasma Physics facility. Tests have been made on selected capacitors to determine individual electrical parameters. True capacitance was found to be somewhat higher than nominal, closer to 2400 μfd. Parasitic inductance was found to range from 20 to 50 nanohenries, compared to the quoted value of 30 nanohenries. The equivalent series resistance when discharged from 20 V into a short circuit was found to be less than 5 milliohms.

A 10-element pulse network has been assembled using unit inductances of about 300 nanohenries. This line is connected to a spark initiated, 4-in. anode diameter calibration accelerator. Current waveform is monitored with a Rogowski coil and a 5.95 millisecond integrator. Voltage across the thruster is tapped by a Tektronix Type P6000 10X attenuator. Typical oscilloscope traces are shown in Fig. 18. The ideal (lossless) impedance of this line should be about 0.014 ohm. Assuming a discharge impedance of 0.005 ohm based on other experiments,[87,100] the ideal waveform should consist of a 10,000 A x 500 μsec rectangular pulse with 35 percent current reversal. Observed behavior is substantially different:

1. The pulse is not at all square; it rises to a maximum in approximately 60 μsec, then begins an almost linear decay to zero current over approximately 1 millisecond.

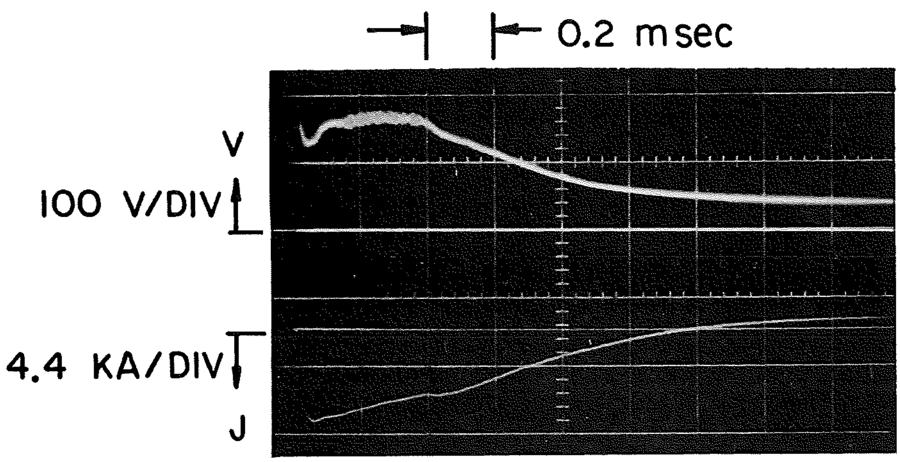
2. There is negligible current reversal and no voltage reversal. The voltage, in fact, does not drop to zero, but to a constant value of about 50 V.

Both of these characteristics were also observed in the earlier experiments with the vacuum thruster, hence may now reasonably be assigned to the capacitors. As in those experiments, it is found here that the waveform can be improved by adjusting the relative sizes of the inductors, leading to the conclusion that it is the parasitic inductance and resistance of the capacitors which distorts the waveform.

The current trace can be integrated graphically and compared with the charge delivered from the capacitors:

$$\int J dt = \Delta q = n C_1 \Delta V \tag{3}$$

to obtain the proper calibration factor for the Rogowski coil. Current and voltage traces may then be multiplied together and integrated graphically to find the total power input to the accelerator. Comparison of this value with the



TYPICAL VOLTAGE AND CURRENT SIGNATURES FROM ELECTROLYTIC CAPACITOR PULSE NETWORK

FIGURE 18
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energy change of the pulse network, computed as

$$\Delta \mathcal{E} = \frac{n}{2} C_1 (V_i^2 - V_f^2) \qquad (4)$$

indicate an energy transfer efficiency of somewhat greater than 80 percent.

D. RADIATIVE PROCESSES IN QUASI-STEADY DISCHARGES (Bruckner)

The previous report[92] summarized preliminary gain coefficient measurements at 4880 Å carried out on the parallel-plate accelerator by means of a pulsed argon ion laser. The search for positive values of gain, corresponding to population inversion in the ionic energy levels of the argon in the discharge, has been continued with an improved detection scheme, namely a two-beam balanced optical system. This utilizes the beam from both ends of the laser and provides for the simultaneous monitoring of the discharge modified laser output, I, and the undisturbed, or reference, laser output, I_o. Experiments have been carried out at various ambient argon fill pressures (25 μ, 50 μ, 100 μ, 200 μ, 300 μ) and three axial positions downstream of the electrode-insulator junction (Δx = 4", 10.5", 17").[92] Previous results at Δx = 4" have been verified and the usefulness of the new technique has been demonstrated. However, positive gain still has not been unequivocally identified at any of the three probing positions or initial fill pressures. One possible reason for this may be the excessive noise output of the two photomultiplier detector tubes in relation to the expected magnitude of the difference signal $I - I_o$. Consequently, the photomultiplier tubes are being replaced by solid-state silicon photodiodes (UDT Type PiN-5) which are much better suited for laser light detection. Another improvement in detection sensitivity, presently being implemented, is the use of a multipass technique for the laser beam which probes the discharge.

Spontaneous emission data again demonstrate the presence of significant amounts of undesirable impurities, especially hydrogen, in the discharge plasma. These interfere not only with the actual detection of population inversion in ionic argon, but also may disrupt some of the excitation mechanisms responsible for the excess populations of the upper energy levels. To alleviate this problem the accelerator is being fitted with a shock tube mass injection system very similar to that used on the quasi-steady MPD arc facility.[87] With a continuous supply of fresh gas for the duration of the quasi-steady discharge, ablation of the electrode and insulator material will be minimized and the concentration of impurity particles hopefully greatly decreased.[70]

So far, only the 4880 Å transition has been investigated for gain effects. There is some evidence, however, that there may be detectable gain on other transitions of singly ionized argon and perhaps on transitions corresponding to higher ionization states.[A-4] These possibilities will be investigated also but will require somewhat modified detection techniques.

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Appendix A: Semiannual Statement of Expenditures

PULSED ELECTROMAGNETIC GAS ACCELERATION
NASA NGL 31-001-005
Supplement No. 7
Princeton Univ. Account No. 150-6020
R. G. Jahn, Principal Investigator
1 July 1969 - 31 December 1969

Direct Costs

I.	Salaries and Wages		
	A. Professional	$21,255	
	B. Students	8,880	
	C. Technicians	9,470	
	D. Supporting Staff	4,437	
			$44,042
II.	Employee Benefits (19% of IA,IC,ID)		6,681
III.	Equipment		0
IV.	Materials and Services		9,343
V.	Travel		1,616
	Total Direct Costs		$61,682

Indirect Costs

VI.	Overhead (68% of I)	$29,949
	Total	$91,631