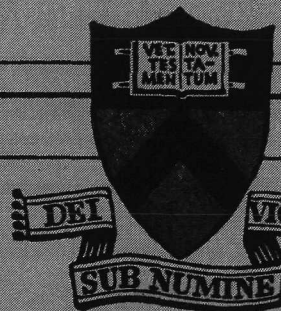


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PULSED ELECTROMAGNETIC GAS ACCELERATION

1 July 1971 to 31 December 1971

Semi-annual Report 634r



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PULSED ELECTROMAGNETIC GAS ACCELERATION

1 July 1971 to 31 December 1971

Semi-annual Report 634r

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January 1972

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## ABSTRACT

Photographs of the exhaust plume of a pulsed MPD discharge through selected narrow band spectral filters reveal a species structure related to the location of the argon mass injection ports. This species structure provides the key to interpretation of time-resolved interferometric velocity measurements in the exhaust. The resulting exhaust velocity increases monotonically from 8500 m/sec at a position 5 cm downstream of the anode face to 16,500 m/sec 40 cm downstream. The latter value is approximately twice the Alfvén critical speed for argon.

The growth of the axial electric field near the downstream face of the anode indicates that the discharge operates in a "starved" mode for values of  $J^2/\dot{m} \gtrsim 35 \text{ kA}^2\text{-sec-g}^{-1}$ . Data from biased double probes imply an electron temperature of 0.8 eV in the exhaust plume and can be used to determine the plasma flow direction. Two of these probes separated a known distance yield a time-of-flight velocity in agreement with the interferometric velocity. Initial experiments indicate that the fractional power to the anode, measured directly by thermocouples, decreases as the input power increases.

Other experimental programs related to MPD arc discharges continue: tungsten hollow cathode characteristics are compared to tungsten solid conical cathodes; a range of mass pulse profiles are mapped for a turbo-gas injector; an improved piezoelectric pressure probe is calibrated for impact pressure measurements in the exhaust; a study is initiated on the optimum propellant injection geometry; an efficient method of synchronizing mass and current pulses is detailed; and a new technique for extracting a plasma sample from the exhaust plume is outlined.

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# CURRENT STUDENT PARTICIPATION

| Student               | Period            | Degree          | Thesis Topic                                                         |
|-----------------------|-------------------|-----------------|----------------------------------------------------------------------|
| BOYLE,<br>Michael J.  | 1968-1969<br>1971 | Ph.D.<br>Cand.  | Velocity and Acceleration<br>Patterns in the MPD<br>Exhaust          |
| BRUCKNER,<br>Adam P.  | 1966-             | Ph.D.<br>Cand.  | Time-Resolved Spectro-<br>scopy of the MPD Exhaust<br>Plume          |
| CORY,<br>John S.      | 1969-1971         | Ph.D.           | Mass, Momentum and Energy<br>Flow from an MPD Accel-<br>erator       |
| DI CAPUA,<br>Marco S. | 1966-1971         | Ph.D.           | Energy Deposition in<br>Parallel-Plate Plasma<br>Accelerators        |
| DUTT,<br>Gautam S.    | 1971-             | Ph.D.<br>Cand.  | Impact Pressure Measure-<br>ments in the MPD Exhaust<br>Flow         |
| HIXON,<br>Todd L.     | 1970-             | A.B.<br>Cand.   | Ultra-Violet Spectro-<br>scopy Studies of MPD<br>Discharge Plasmas   |
| HOUGH,<br>Michael E.  | 1969-1971         | B.S.E.          | Mass Spectrometry of<br>Accelerator Exhaust<br>Flow                  |
| PARMENTIER,<br>Noël   | 1970-1971         | M.S.E.          | Quasi-Steady MPD Arc<br>with Hollow Cathode                          |
| SABER,<br>Aaron J.    | 1969-             | Ph.D.<br>Cand.  | Thrust Measurements on<br>Quasi-Steady Acceler-<br>ators             |
| VILLANI,<br>Daniel D. | 1969-             | Ph.D.<br>Cand.  | MPD Discharge Studies<br>with Solenoid Valve<br>Injection System     |
| WHITE,<br>Fred W.     | 1969-             | M.S.E.<br>Cand. | Propellant Injection<br>Techniques for Quasi-<br>Steady Accelerators |



## I. INTRODUCTION

During the past six months, three thesis programs have been completed. The first of these, a Ph.D. dissertation by J. S. Cory, examined mass, momentum, and energy flows in the MPD exhaust as determined by piezoelectric pressure probes and velocity measurements. The parallel-plate accelerator was used by M. S. Di Capua in his Ph.D. thesis on the initial division of energy input by the discharge into kinetic and thermal modes. The third, an MSE thesis by N. Parmentier, was an experimental investigation of the feasibility of using a hollow cathode in the quasi-steady MPD arc. In addition to these, A. P. Bruckner is in the final stages of completing his Ph.D. thesis on the structure of the MPD exhaust plume.

Much of the material contained in these theses will be presented in two separate papers at the forthcoming Electric Propulsion Conference at Washington, D. C. on April 16-18. Therefore, this semi-annual report will be confined to a rather complete review of all programs in progress. The first section displays the species distribution in the exhaust for various operating conditions along with selected velocity profiles, which will comprise the major portion of the Ph.D. thesis of A. P. Bruckner. In the second section, the results of various experiments on the pulsed MPD discharge are reported, including a summary of all reliable velocity data, the use of the axial electric field near the anode to determine "starved" arc operation, diagnostic studies in the exhaust plume with a biased double probe, and preliminary experiments to measure directly the power deposition in the anode. Other related or supporting programs in various stages of completion are presented in the final section. These include a comparison of tungsten hollow cathode operation with that of a tungsten solid conical cathode, a catalog of mass pulse profiles

available with the turbo-pulse gas injector, calibration procedures for determining the long and short time characteristics of piezoelectric probes, the initial steps in a program to improve the propellant injection geometry, additional considerations for synchronizing current pulses to mass pulses, and a new technique for extracting and subsequently analyzing a sample from the MPD exhaust plume.

## II. MPD EXHAUST PLUME STRUCTURE (Bruckner)

### II-A. Introduction

Optical spectrometric investigations of the MPD exhaust plume have been pursued in two different but complementary approaches. The first involves extensive photography of the plume through selected spectral filters in an effort to determine the distribution of various molecular, atomic, and ionic species in the exhaust flow at various operating conditions. The second is a continuation of the time-resolved velocity and temperature measurements of ionized argon in the plume by means of the scanning Fabry-Perot interferometer.<sup>123</sup> Since the results of the filter photography are basic to the interpretation of the Fabry-Perot data, they will be discussed first.

### II-B. Species Structure of the Exhaust Flow

#### Filter Photography

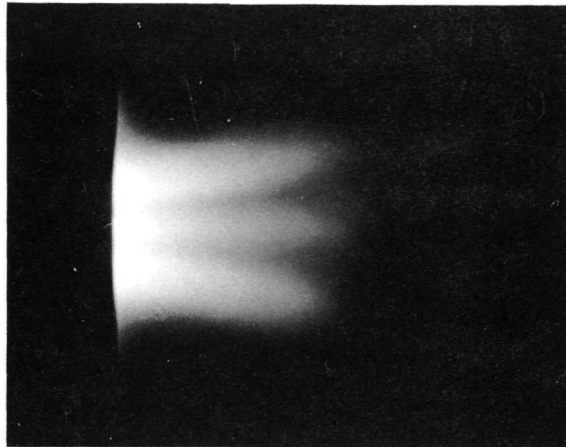
An unusual six-jet structure of singly ionized argon in the exhaust plume was discussed briefly in our previous report.<sup>123</sup> This distribution of AII was at first hypothesized on the basis of results from the Fabry-Perot spectrometry and was subsequently confirmed by photographing the discharge through a narrow band 4880 Å interference filter at various lines of sight. Figure 1 displays the results obtained at the matched operating condition of 16 kA and 6 g/sec argon.

The six jets of argon are azimuthally in line with the six mass injection orifices and appear to remain discrete far down the plume.

It was suggested in our previous report that the core of the exhaust and the gaps between the argon jets are occupied by products ablated off the Plexiglas base plate in

I 8957

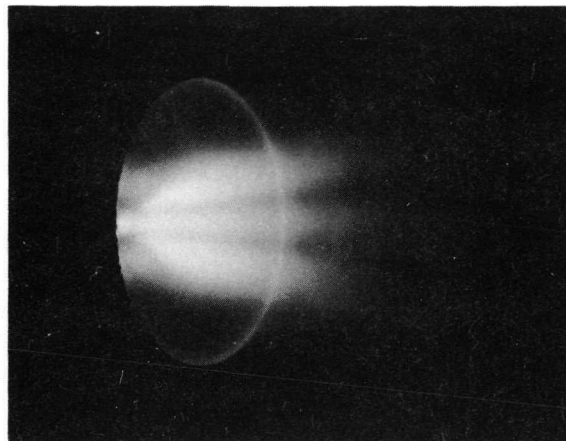
a)



SIDE VIEW

I 8960

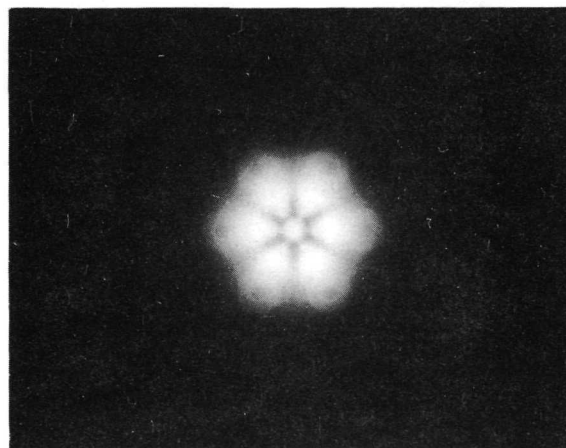
b)



PERSPECTIVE VIEW

I 7618

c)



END VIEW

DISCHARGE AT  $4880 \text{ \AA}$  SHOWING DISTRIBUTION  
OF  $\text{Al II}$  IN THE EXHAUST PLUME  
 $J=16 \text{ kA}$ ,  $\dot{m}=6 \text{ g/sec}$ .

FIGURE I  
AP25-P 428

the arc chamber. Since Plexiglas is a polymer of methyl methacrylate,  $C_5H_8O_2$ , its ablation should yield carbon, hydrogen, and oxygen in various states. Indeed, spectrographic surveys<sup>105,109,131</sup> have demonstrated an abundance of  $C_2$ , CII, H, and OII in the discharge. The predicted distribution of these ablated species has been verified by photographing the discharge through suitable spectral filters which render some of these species visible. The species CII and  $C_2$  are revealed by an interference filter centered at  $5910 \text{ \AA}$ , with a bandwidth of  $75 \text{ \AA}$ . Prominent in this bandpass are the  $5889.97 \text{ \AA}$  and  $5891.65 \text{ \AA}$  lines of CII and the tail of the  $C_2$  band system with its head at  $6191.2 \text{ \AA}$ . Side, perspective, and end-on views of the discharge in this spectral region are shown in Fig. 2. Current and argon mass flow are 16 kA and 6 g/sec respectively. It can be seen, by comparing this figure with Fig. 1, that these products of ablation are found precisely in those regions of the chamber and exhaust where argon is absent, and vice versa.

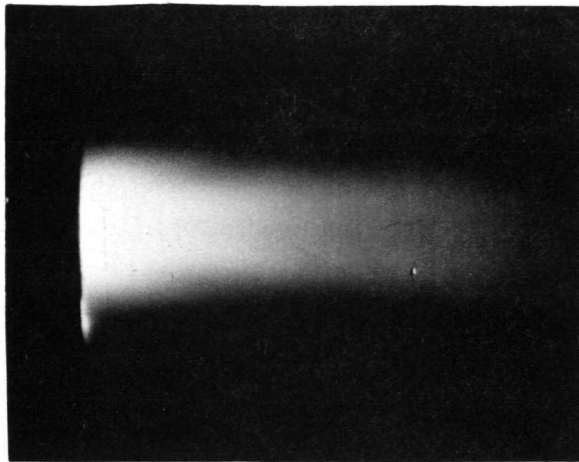
With the aid of detailed spectroscopic investigations,<sup>131</sup> the following additional conclusions can be drawn:

- 1) Molecular carbon ( $C_2$ ) is confined within the arc chamber and is found predominantly in the luminous star-shaped region (Fig. 2c) which extends about a cathode length from the Plexiglas base plate. There is also some  $C_2$  present in a thin layer along the circular side wall of the chamber and just inside the anode lip. However, there is no  $C_2$  in the exhaust plume itself, downstream of the cathode tip.

- 2) The prominent axial jet seen to issue from the chamber in the photographs (Figs. 2a and 2b) consists of singly ionized carbon, CII. This specie is also found in the luminous star above the base plate, but occupies primarily the annular space between the cathode and the six injectors. The distribution of CII in the exhaust plume has itself a star-shaped cross section<sup>131</sup> similar to the luminosity at the baseplate.

6  
I-8067

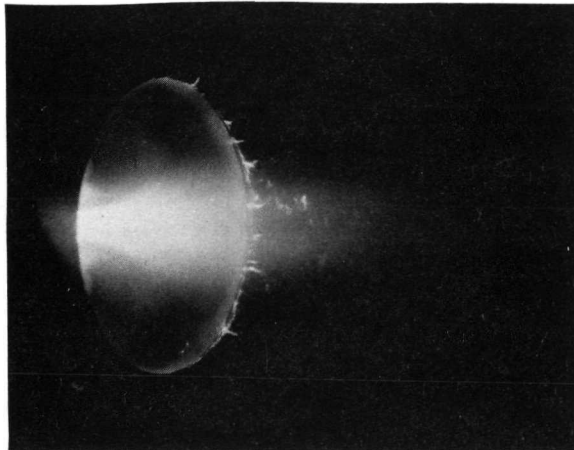
a)



SIDE VIEW

I 8237

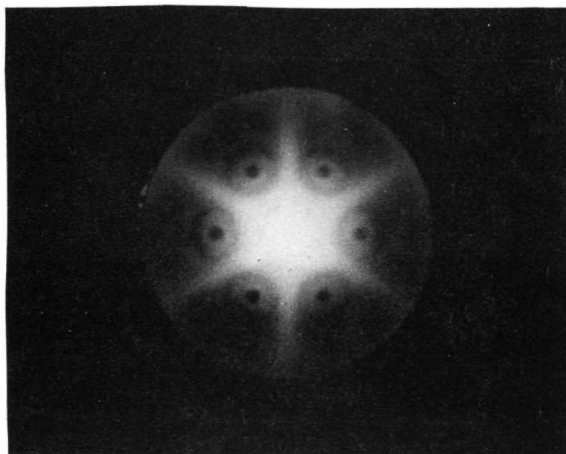
b)



PERSPECTIVE VIEW

I 8910

c)



END VIEW

DISCHARGE AT  $5910 \text{ \AA}$  SHOWING DISTRIBUTION  
OF  $\text{CII}$  AND  $\text{C}_2$ .  $J=16 \text{ kA}$ ,  $\dot{m}=6 \text{ g/sec}$ .

FIGURE 2  
AP25-P429

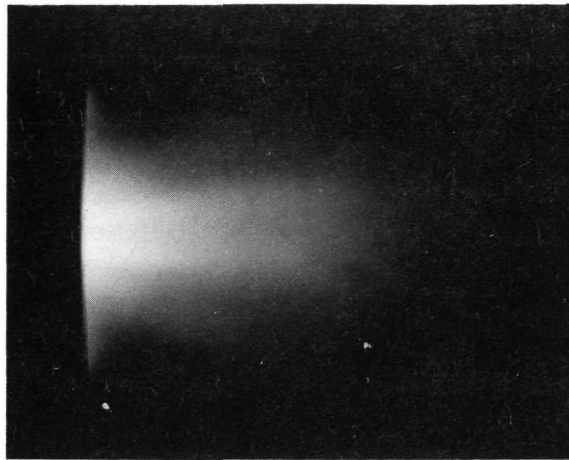
It fills the core of the exhaust flow and the gaps between the argon jets. It is apparent that diffusion times of CII, AII, and hence OII, are too slow to allow mixing of these species for at least three or four anode orifice diameters downstream of the exit plane.

Photographs through a red filter, centered on  $6580 \text{ \AA}$ , with a  $90 \text{ \AA}$  bandwidth, which reveals the  $6562.82 \text{ \AA}$   $H_{\alpha}$  line of hydrogen and the  $6578.03 \text{ \AA}$  and  $6582.85 \text{ \AA}$  lines of CII show that hydrogen is present throughout virtually the entire exhaust plume, even within the argon jets, and that it expands radially far beyond the visible limits of the argon and carbon (Fig. 3). The photographs clearly exhibit the bright core of CII and the fainter but extended plume of H. The pervasive presence of hydrogen in the exhaust is a consequence of its very low atomic weight and corresponding high diffusivity. The presence of even relatively small amounts of ionized hydrogen, would significantly affect every process that involves the diffusion of positive charges in the plasma (Section III-C).

#### Flow Visualization

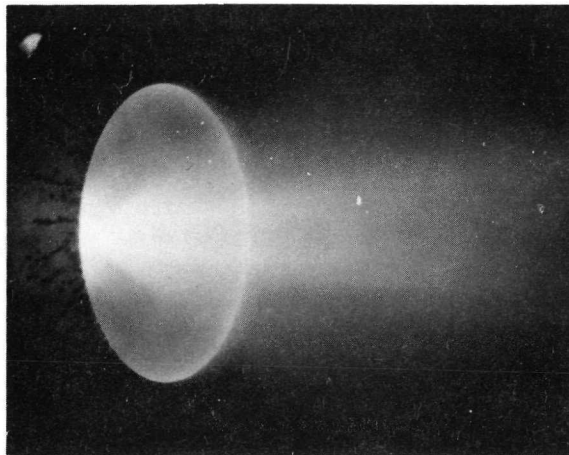
Of great importance in the interpretation of the Fabry-Perot data, to be discussed in a later section, is the correlation of the observed luminous patterns with the actual flow field in the exhaust, i.e.: do the argon "jets" correspond to the actual flow direction in these jets? A simple test is to place a spherical body in one of the argon "jets" and note the direction of the resulting bow shock. To a first approximation this will reveal the local flow direction. Figure 4a displays the results of just such an experiment photographed at  $4880 \text{ \AA}$ . Here an 8 mm O.D. spherical bulb blown on the end of a 5 mm O.D. pyrex tube is immersed in the upper near luminous jet and produces a distinct bow shock. The bisector of the shock appears to be parallel to

a)



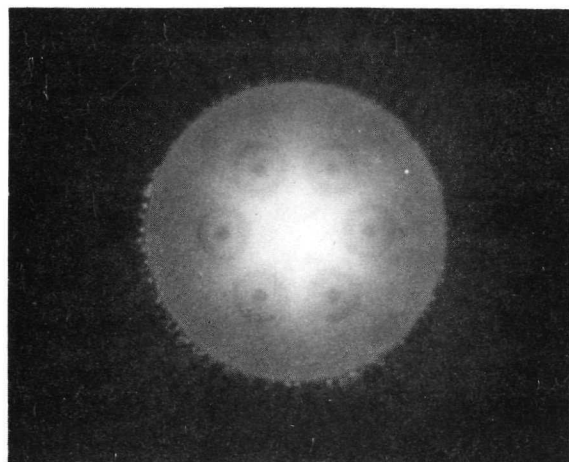
SIDE VIEW

b)



PERSPECTIVE VIEW

c)



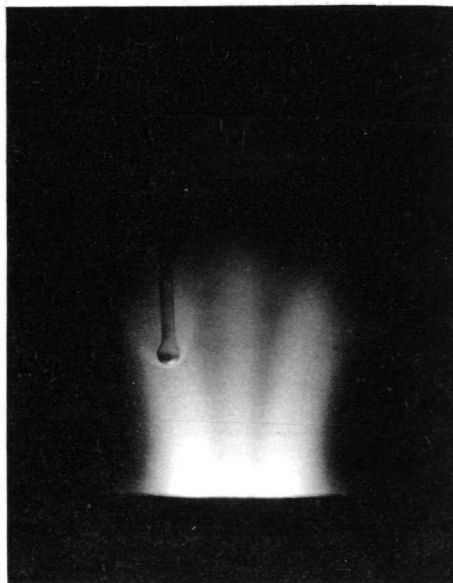
END VIEW

DISCHARGE AT  $6580 \text{ \AA}$  SHOWING DISTRIBUTION  
OF H AND C II IN THE EXHAUST PLUME  
 $J = 16 \text{ kA}$ ,  $\dot{m} = 6 \text{ g/sec}$

FIGURE 3  
AP25-P430



I-8060

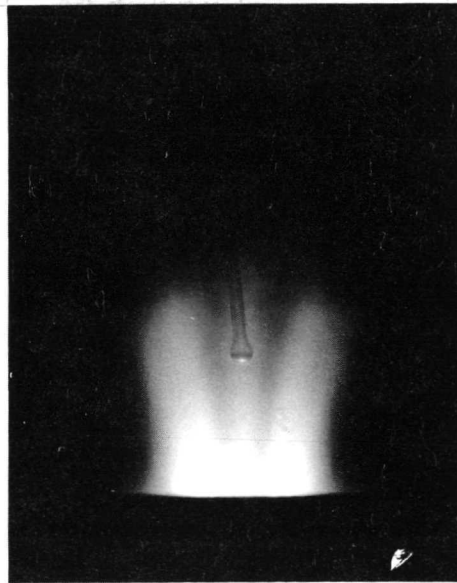


PROBE IN  
UPPER NEAR  
ARGON JET

0 5  
SCALE (cm)

a)

I-8056



PROBE ON  
AXIS

b)

AI FLOW (4880 Å)

I-8066

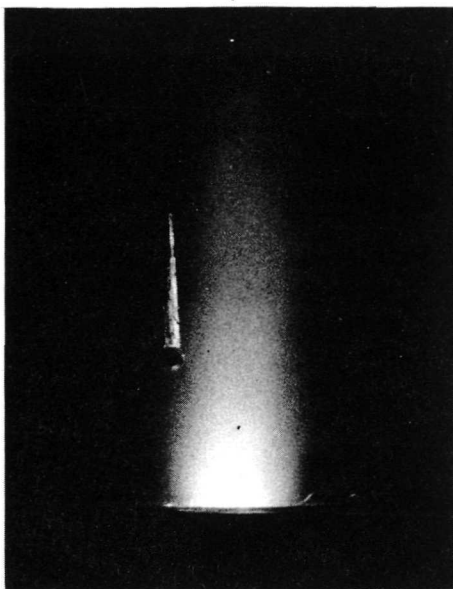


PROBE ON  
AXIS

c)

CII FLOW (5890 Å)

I-8229



PROBE IN  
UPPER NEAR  
ARGON JET

0 5  
SCALE (cm)

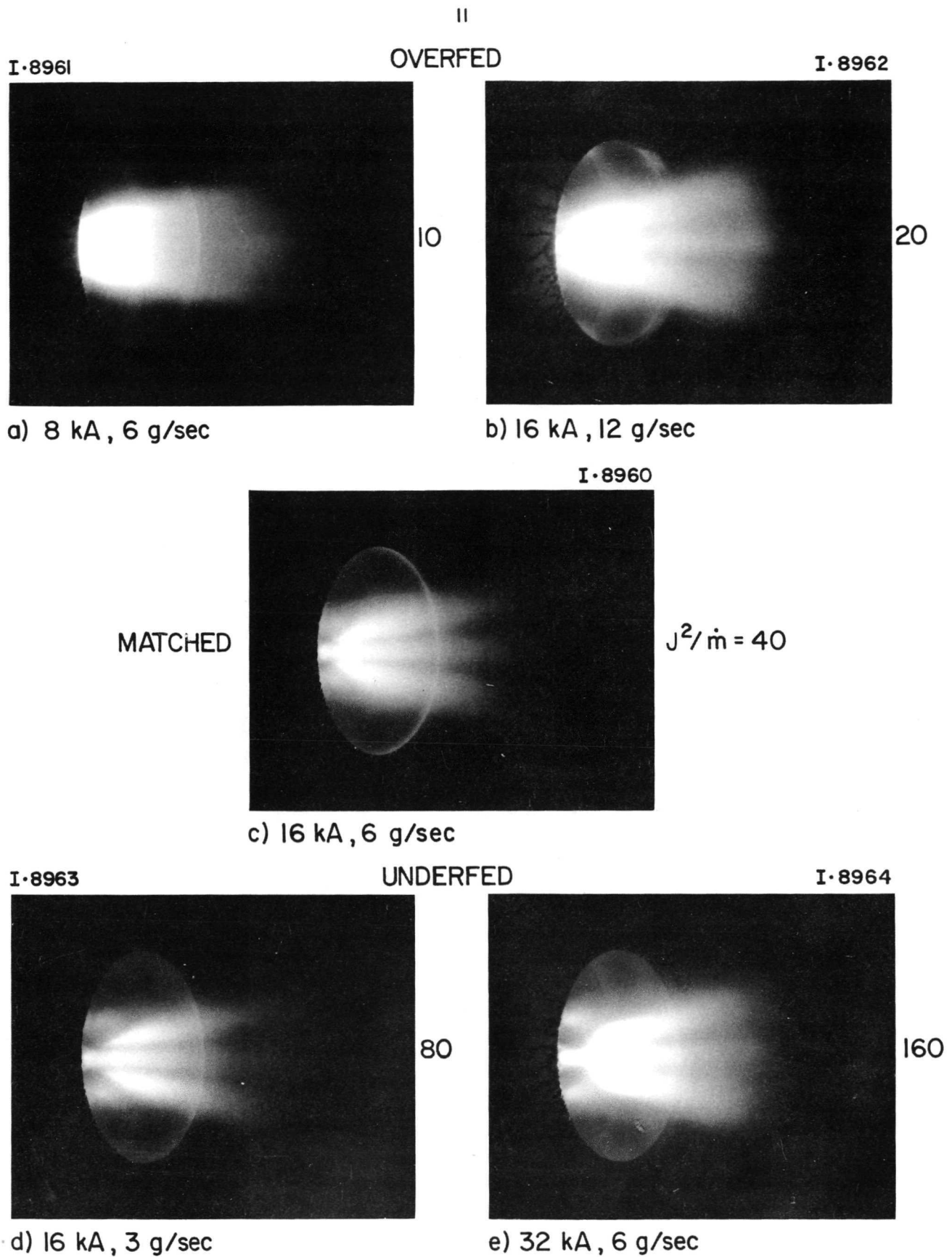
d)

FIGURE 4  
AP25-P 431

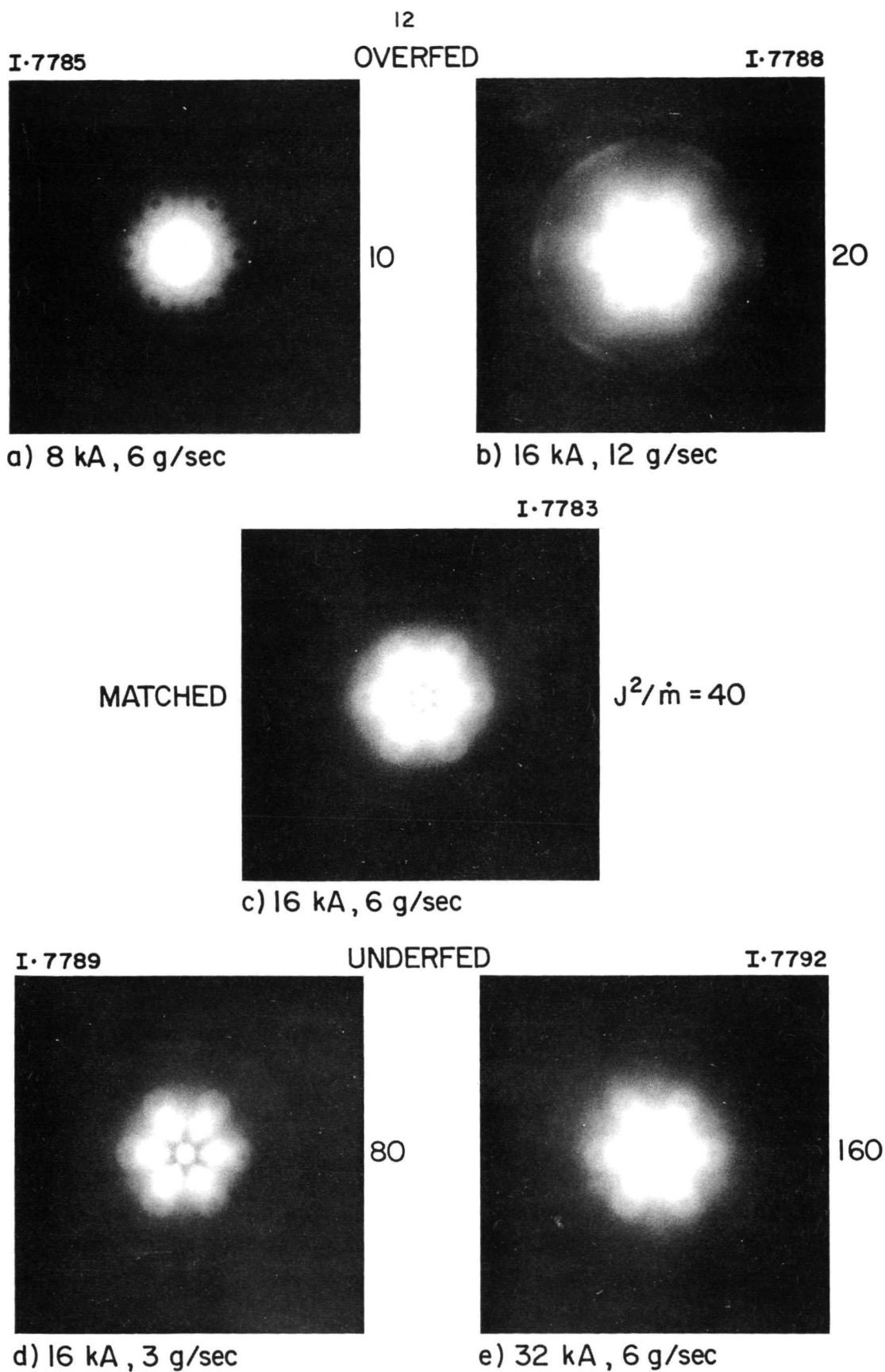
the luminosity, thus indicating that the luminous argon "jets" actually define the flow direction. Figure 4b also taken at  $4880 \text{ \AA}$  shows the probe located on the axis. No bow shock is visible attesting to the lack of argon in the core of the flow. In contrast, Figs. 4c and 4d, taken with the  $5910 \text{ \AA}$  filter show the flow of CII over the spherical body. No shock is visible when the probe is in the argon jet, indicating the absence of CII. On the other hand, a very strong bow shock is visible when the body is on the axis, emphatically demonstrating the presence of CII in the core of the exhaust.

#### Operation at Other Conditions

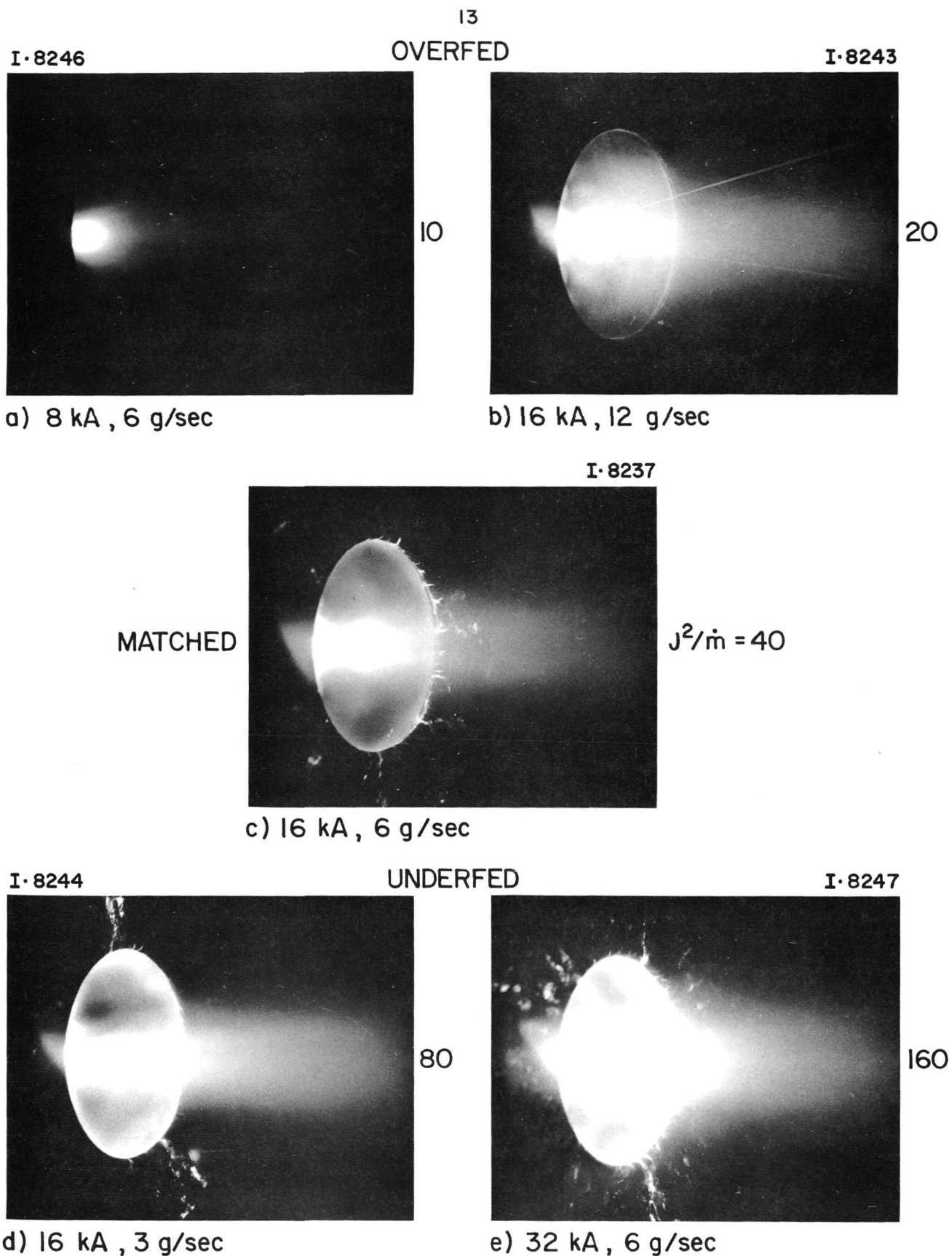
It is well known that a number of important features of arc behavior can be characterized by the parameter  $J^2/\dot{m}$ , where  $J$  is the total arc current and  $\dot{m}$  the injected mass flow, rather than by  $J$  and  $\dot{m}$  separately.<sup>87,113,125,A-1</sup> The question immediately arises as to what effect a variation of  $J^2/\dot{m}$  has on the structure of the exhaust plume of the arc. In an effort to provide an answer, experiments at values of  $J^2/\dot{m}$  corresponding to both the starved ( $J^2/\dot{m} \gtrsim 40 \text{ kA}^2\text{-sec-g}^{-1}$ ) and overfed ( $J^2/\dot{m} \lesssim 40$ ) regimes were undertaken. The discharge was photographed at  $4880 \text{ \AA}$  and  $5910 \text{ \AA}$  to reveal the distribution of argon and carbon respectively in both the chamber and the exhaust. The results are presented in Figs. 5 through 8 in the form of perspective and end views, at five different operating conditions ( $J^2/\dot{m} = 10, 20, 40, 80, 160$ ). The matched condition,  $J^2/\dot{m} = 40$ , is included for reference. It can be seen from Figs. 5a,b and 6a,b that as the arc is overfed the discrete argon jets diffuse azimuthally and towards the axis, leading to a more uniform distribution of the argon. When the arc is starved (Figs. 5d,e and 6d,e) the argon jets become even more sharply delineated than at the matched condition, and exhibit hints of an additional substructure. The carbon photographs show



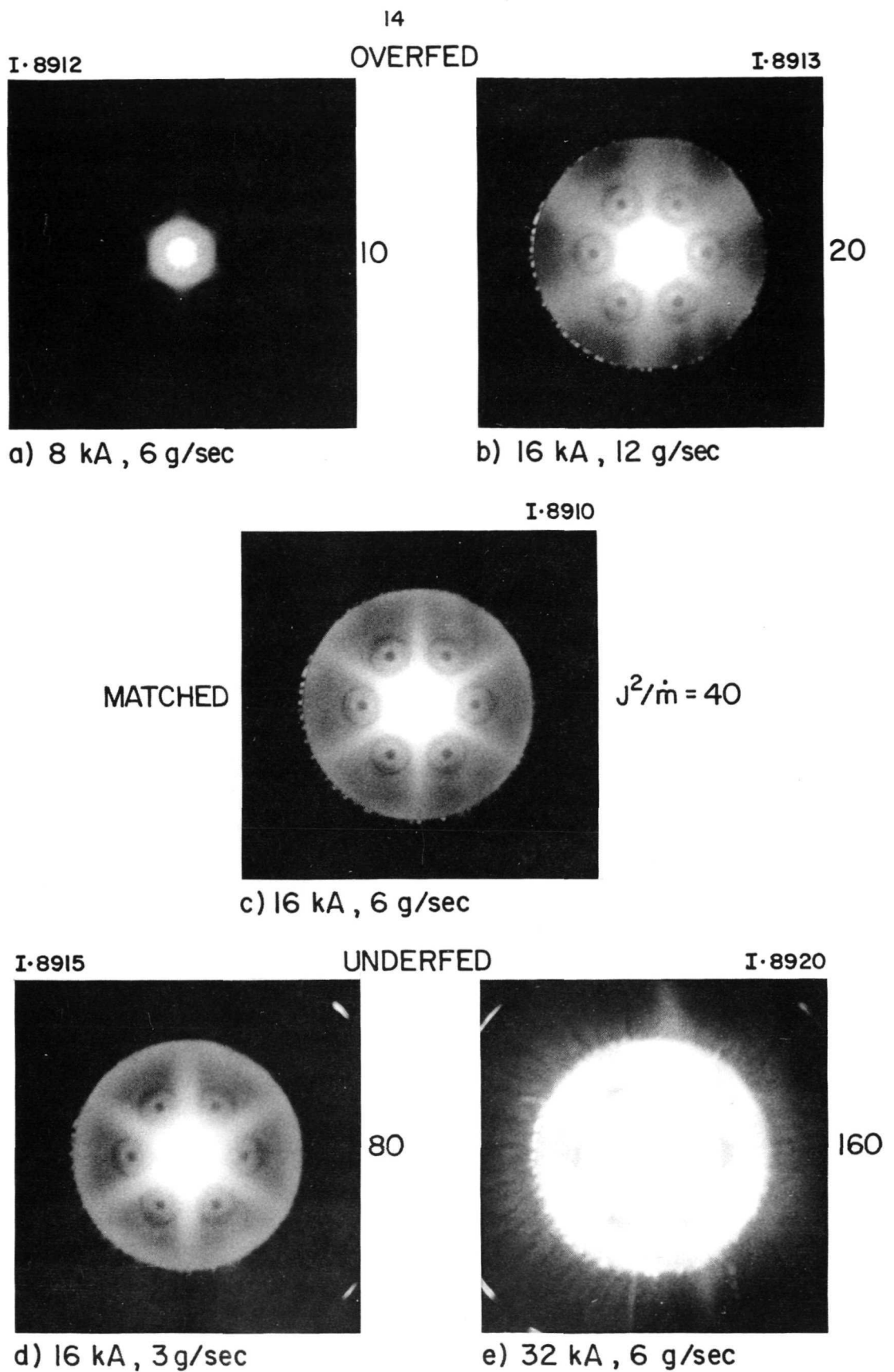
DISTRIBUTION OF AII AT VARIOUS OPERATING CONDITIONS.  
PERSPECTIVE VIEW, 4880Å FILTER



DISTRIBUTION OF AII AT VARIOUS OPERATING CONDITIONS.  
END VIEW, 4880 Å FILTER



DISTRIBUTION OF CII AT VARIOUS OPERATING CONDITIONS.  
PERSPECTIVE VIEW, 5910 Å FILTER



DISTRIBUTION OF  $Cl$  &  $C_2$  AT VARIOUS OPERATING CONDITIONS.  
END VIEW, 5910 Å FILTER

FIGURE 8  
AP 25-P 435

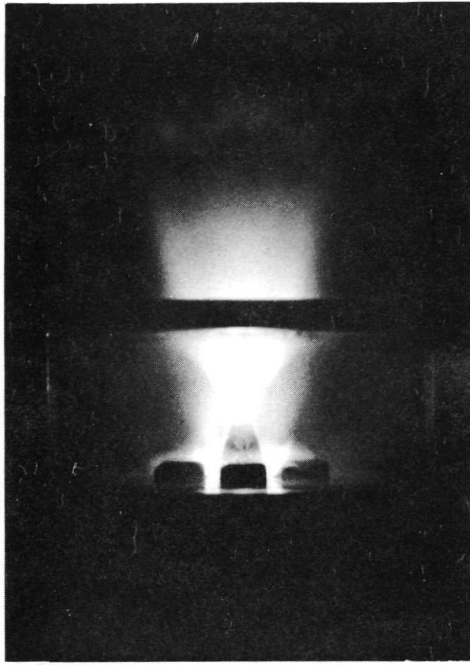


complementary changes. At overfed conditions (Figs. 7a,b and 8a,b) ablation is considerably diminished and little carbon is found in abundance in the chamber and exhaust. At any condition ablation appears most severe in the annular region between the cathode and the injectors.

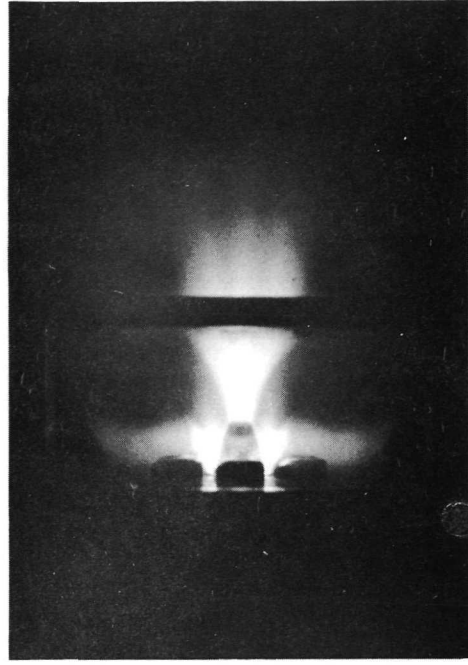
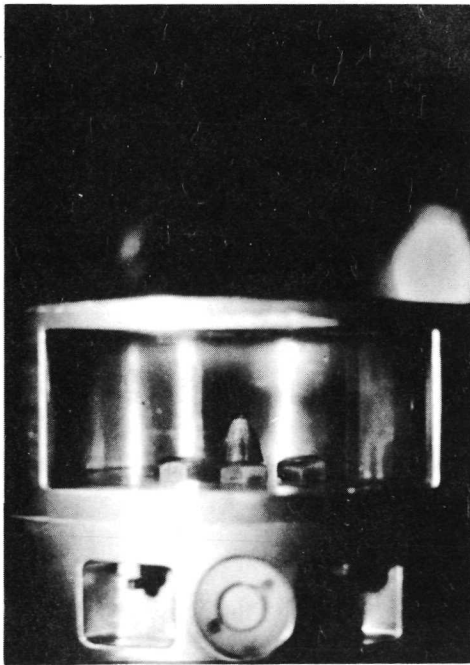
#### Ablation Model

A careful study of time-resolved Kerr-cell photographs of the arc chamber interior, taken during the first 160  $\mu\text{sec}$  of the discharge,<sup>131</sup> has provided compelling evidence that the onset of ablation is a relatively slow process requiring about 150  $\mu\text{sec}$  for stabilization (as compared to  $\approx 30 \mu\text{sec}$  for current pattern stabilization). This process appears to be partly dependent on the initial amount of argon in the chamber prior to breakdown. After breakdown and current stabilization the self-field Lorentz body force depletes argon from the inter-injector regions at the Plexiglas base-plate forcing the current pattern near the surface to ablate the insulator material in order to satisfy its local mass flow requirements. Near the Plexiglas insulator the current density is essentially radial and thus is most intense near the cathode. Consequently, the initial argon fill is most quickly depleted in this region and ablation first begins at the cathode base. The radius of argon depletion increases with time, eventually reaching the side walls of the arc chamber. At this time, about 150  $\mu\text{sec}$  into the discharge, the total ablation rate reaches a steady state. This behavior can be seen in Fig. 9 as an increase in the radial and axial dimensions of the luminous region of ablated products at the insulator during the first 150  $\mu\text{sec}$ . At the injectors, on the other hand, there is always sufficient argon and ablation is less severe. Because the argon enters the chamber 6 mm downstream of the Plexiglas insulator very little of it reaches the latter between the injectors and consequently the discharge remains starved there.

30-70

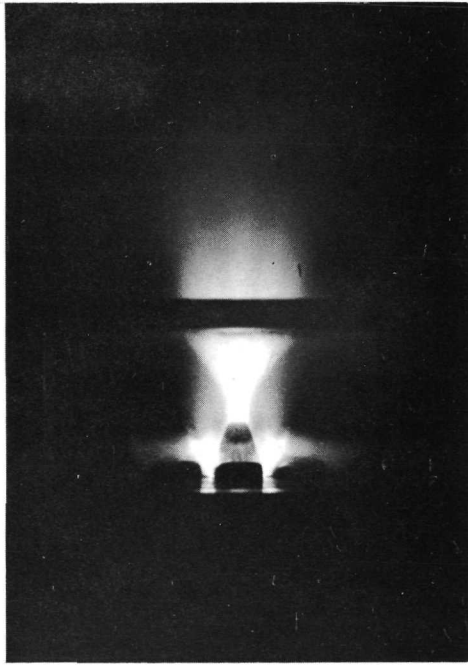
b) DISCHARGE AT  $t = 40 \mu\text{sec}$ 

30-75

d) DISCHARGE AT  $t = 150 \mu\text{sec}$   
STRUCTURE STABILIZED

a) ARC CHAMBER THRU SIDEWALL WINDOW

30-73

c) DISCHARGE AT  $t = 100 \mu\text{sec}$ 

DEVELOPMENT OF DISCHARGE STRUCTURE

FIGURE 9  
AP25-P436



This model is supported by arc voltage records (Fig. 10) which show, for all but the highly overfed case, a monotonic rise in voltage during the first 150  $\mu$ sec of the discharge, after the drop from bank voltage. This rise is believed to correspond to the energy the discharge must expend in pyrolyzing, dissociating, and ionizing the Plexiglas it ablates to satisfy local mass flow requirements. Calculations done for the 16 kA, 6 g/sec case indicate that the voltage is consistent with an ablation rate of about 1 g/sec, which agrees with previous measurements.<sup>111</sup>

An important consequence of this model is that the exhaust plume structure of six argon jets surrounding a core of ablated material will not be fully developed until about 150  $\mu$ sec into the discharge. Again, Kerr-cell photographs support this contention (Fig. 9). At 40  $\mu$ sec no structure is visible in the plume downstream of the anode or in the trumpet shaped luminous region between cathode and anode. By 100  $\mu$ sec, however, a structure is clearly visible and at 150  $\mu$ sec this structure has reached its final steady configuration.

Presently, work is under way to develop a mass injection geometry which will minimize insulator ablation. It appears that the mass flow of argon must be matched locally to the current density everywhere on the surface of the Plexiglas base plate. A possible solution may be to inject argon radially from each injector head, thus providing a film of argon along the entire surface of the Plexiglas insulator.

It is not yet clear whether substitution of a refractory material for Plexiglas, without a change in mass injection geometry, will alleviate the ablation problem. On the other hand, the thermal diffusivity and ablation temperature of refractories such as boron nitride and quartz are much higher than of Plexiglas, which means that for a given heat

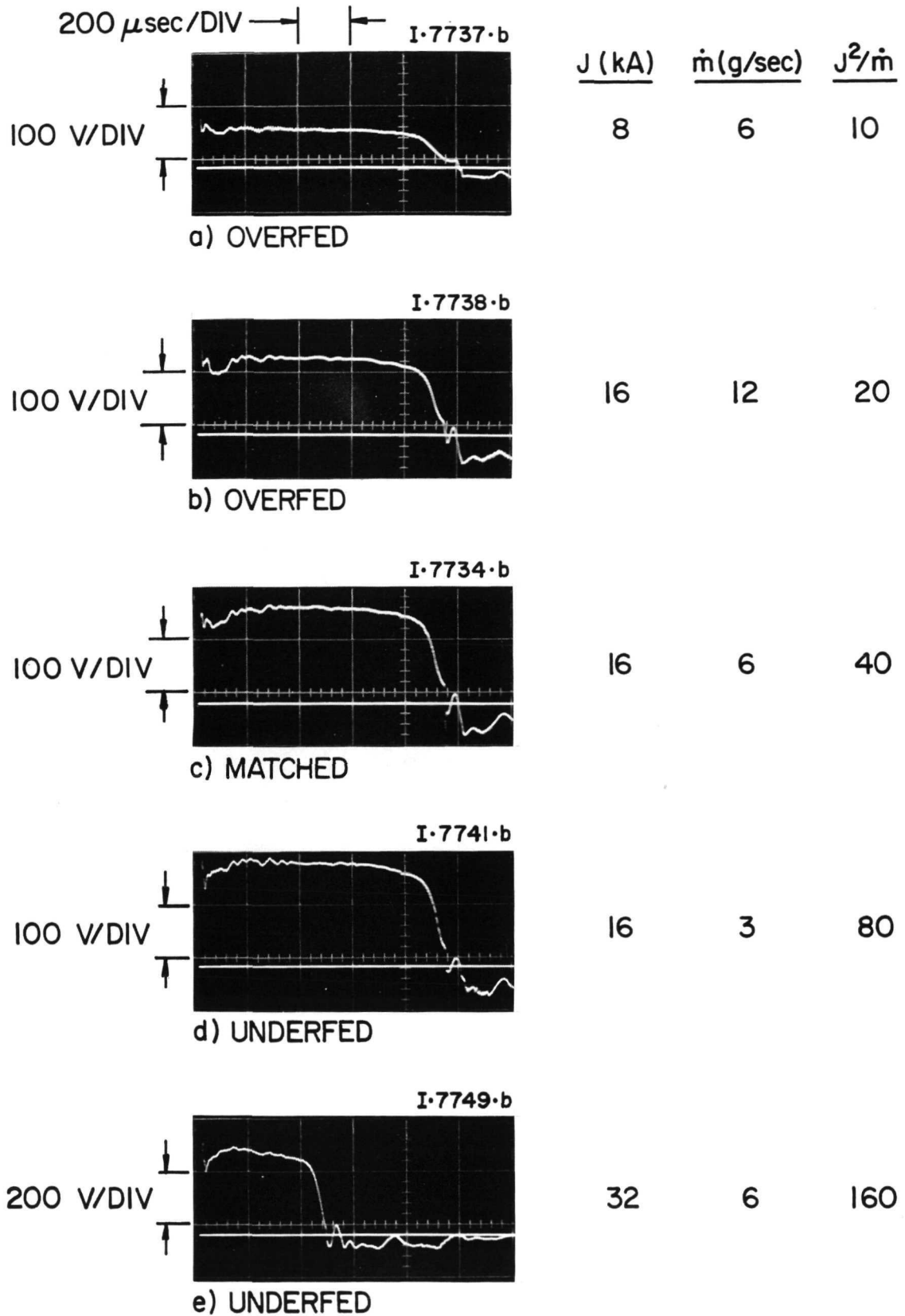
flux it will take the surface of a refractory longer to reach the ablation temperature. On the other hand, the total energy required to vaporize and ionize a refractory does not differ greatly from that for Plexiglas. Thus, if the ablation temperature is reached during the arc current pulse the refractory will also suffer erosion in the regions of argon starvation between the injectors and around the base of the cathode. If the time to reach ablation temperature exceeds the current pulse length the refractory will not erode. However, it is not known how the current density along the insulator, and thus the rate of energy deposition to its surface, would change if it cannot be readily vaporized.

#### II-C. Velocity and Temperature Measurements

In view of the six-jet distribution of the argon in the exhaust plume a somewhat different approach to Doppler velocity and temperature measurements was taken than if the plume had been cylindrically symmetric. This lack of cylindrical symmetry precludes the reduction of spectrometric data to purely local values.<sup>123,131</sup> Nevertheless, the rather sharp collimation of the argon jets does allow deduction of reliable values of mass averaged velocity and temperature as a function of axial distance within the individual argon jets.

#### Experimental Apparatus

The high spectral resolution necessary to detect velocities of the order of  $10^4$  m/sec and temperatures of the order of 1 eV is easily achieved with a Fabry-Perot interferometer.<sup>A-2,A-3</sup> The instrument used in the present experiments is capable of scanning operation, affording time resolution better than 100  $\mu$ sec in sweeping a spectral line.<sup>131</sup> The interferometer and its supporting optics are shown schematically in Fig. 11. The output of the pulsed argon ion laser can be superimposed on the optical train to provide a convenient reference wavelength for Doppler shift measurements. The



ARC VOLTAGE RECORDS AT VARIOUS  
OPERATING CONDITIONS

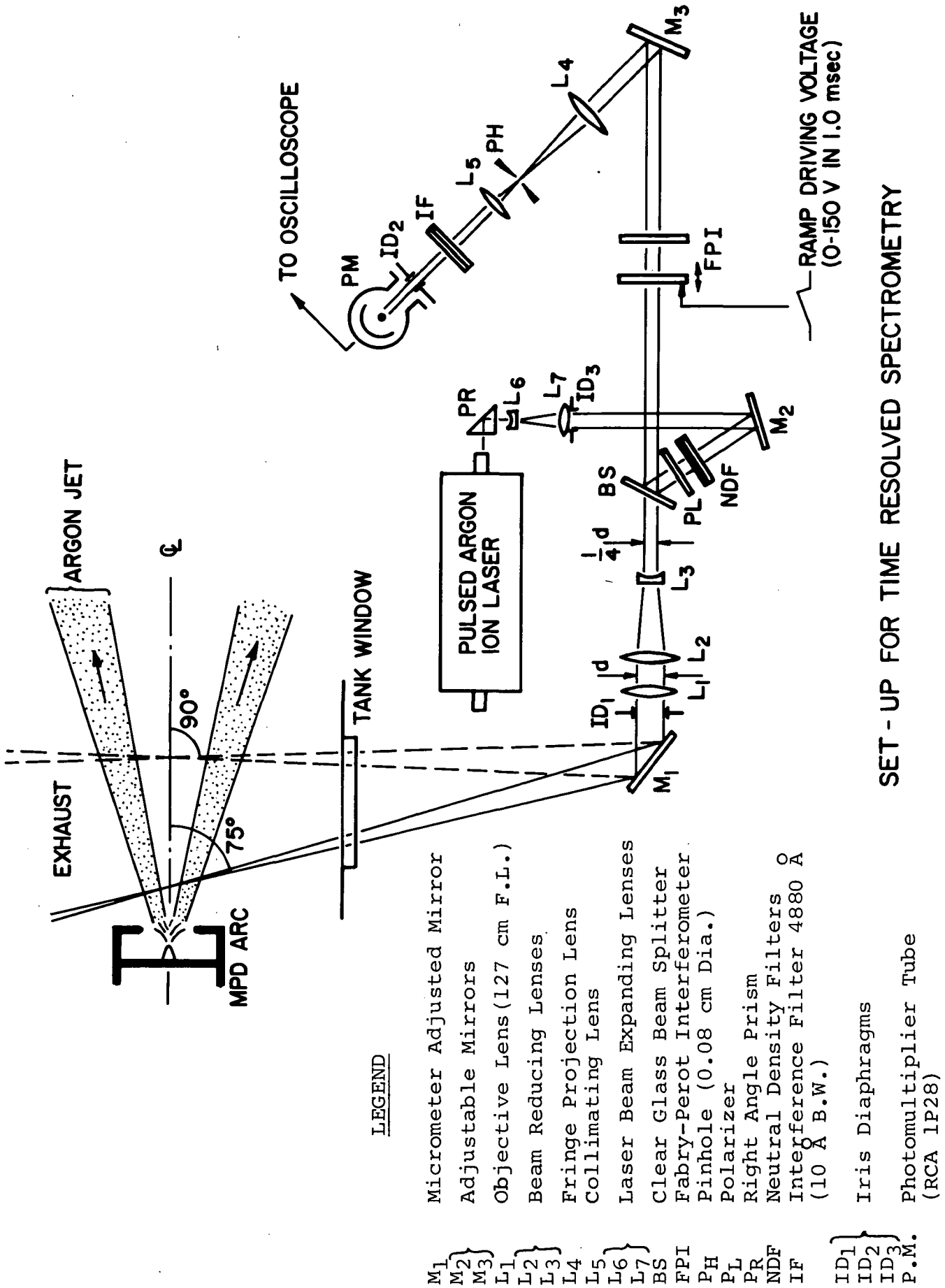
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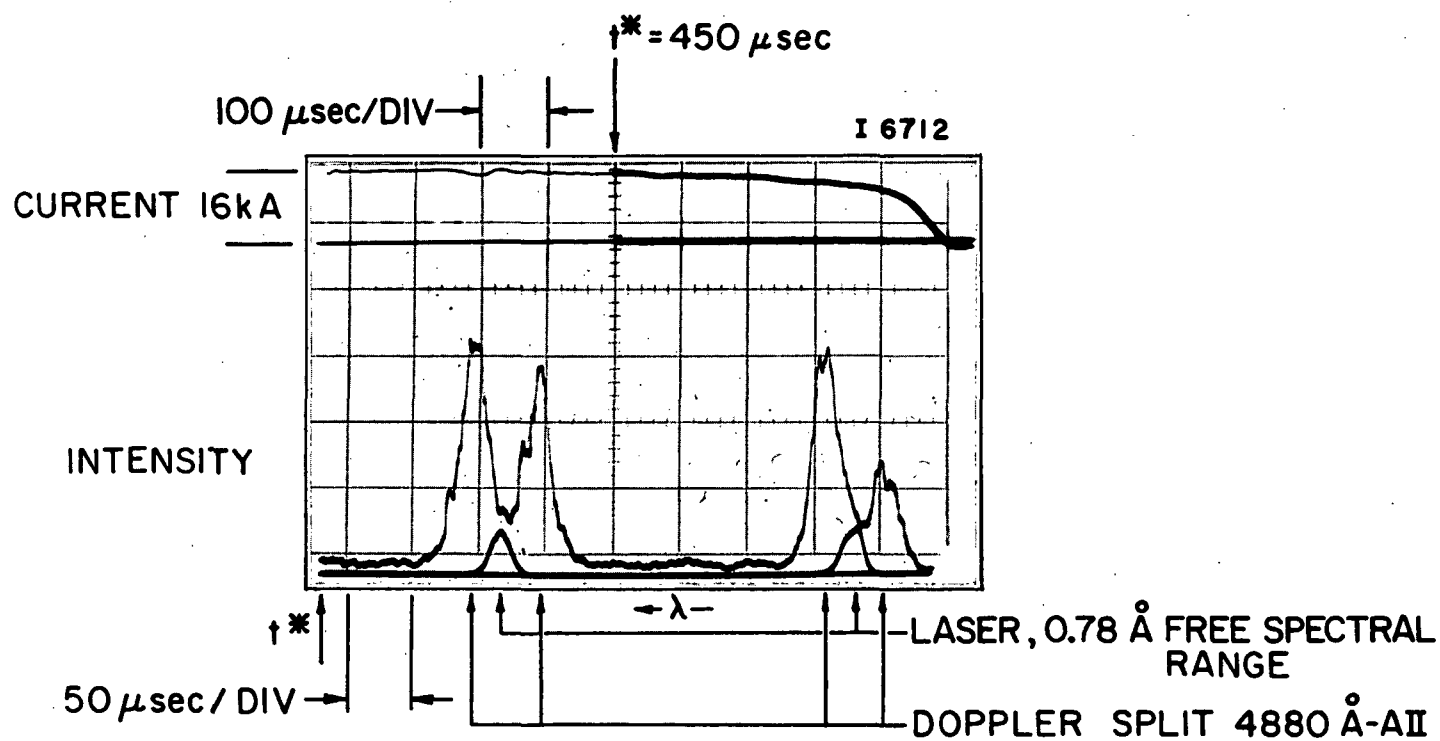


pinhole behind lens  $L_4$  selects the center of the scanning fringe pattern produced by the interferometer and acts as a spatial filter, defining, in conjunction with the lenses and stops ahead of it, the narrow conical volume of plasma which will contribute light to the photomultiplier detector. The desired line of sight through the exhaust plume is chosen by means of a micrometer adjusted mirror,  $M_1$ . The entire system is enclosed in a sound absorbing metal box and mounted on a heavy metal table which is vibration isolated from the floor of the laboratory.

#### Surveys at $90^\circ$ Lines of Sight

Extensive radial surveys have been carried out at four axial positions (4.6, 10.9, 15.9, and 30.6 cm from the anode exit plane) with the line of sight perpendicular to the discharge axis. A typical result obtained level with the axis 10.9 cm from the anode is shown in Fig. 12. The upper trace is the discharge current, and the lower trace is the scan of the  $4880 \text{ \AA}$  spectral line of AII by the Fabry-Perot interferometer. (Somewhat more than one free spectral range of scan is displayed.) The spectral line exhibits the characteristic Doppler split resulting from the radial velocity components of two diametrically opposed argon jets. The radial velocity components of the jets are shown plotted against axial distance in Fig. 13. The bulk of the acceleration appears to occur within roughly one anode orifice diameter of the exit plane (10 cm).

Figure 14 shows the variation of  $4880 \text{ \AA}$  line intensity with vertical distance above and below the axis at the four axial positions investigated. The off-center peaks correspond to the upper and lower argon jets visible in Fig. 1a. A plot of the loci of these off-center maxima, suitably corrected for the azimuthal inclinations of the upper and lower jets, is shown in Fig. 15. In effect, these loci, which turn out to be straight lines inclined at  $\approx 15^\circ$  to the axis, are



THE 4880  $\text{\AA}$  AII LINE AT 10.9 cm FROM ANODE

FIGURE 12  
AP 25-P 395

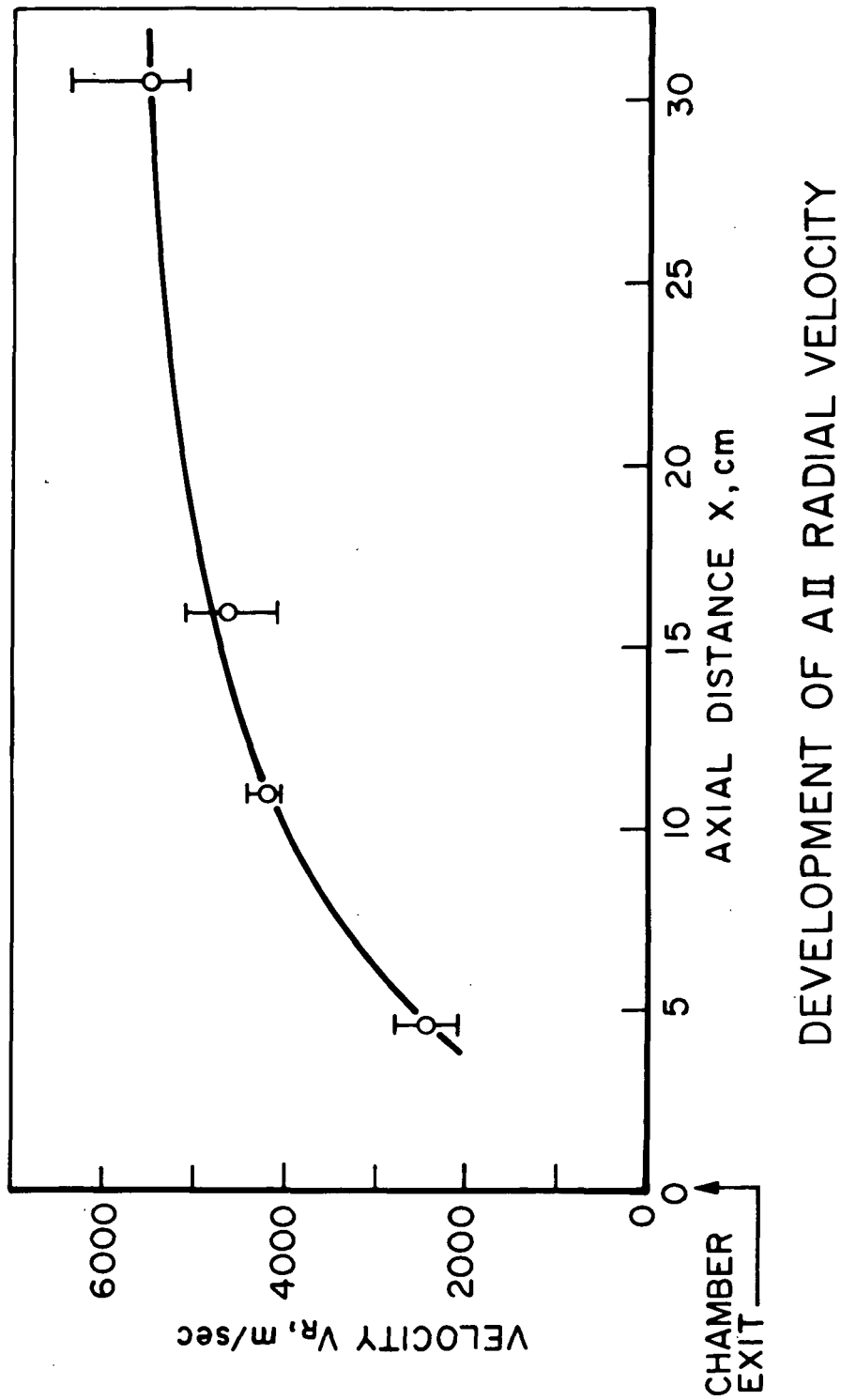


FIGURE 13  
AP25-4806



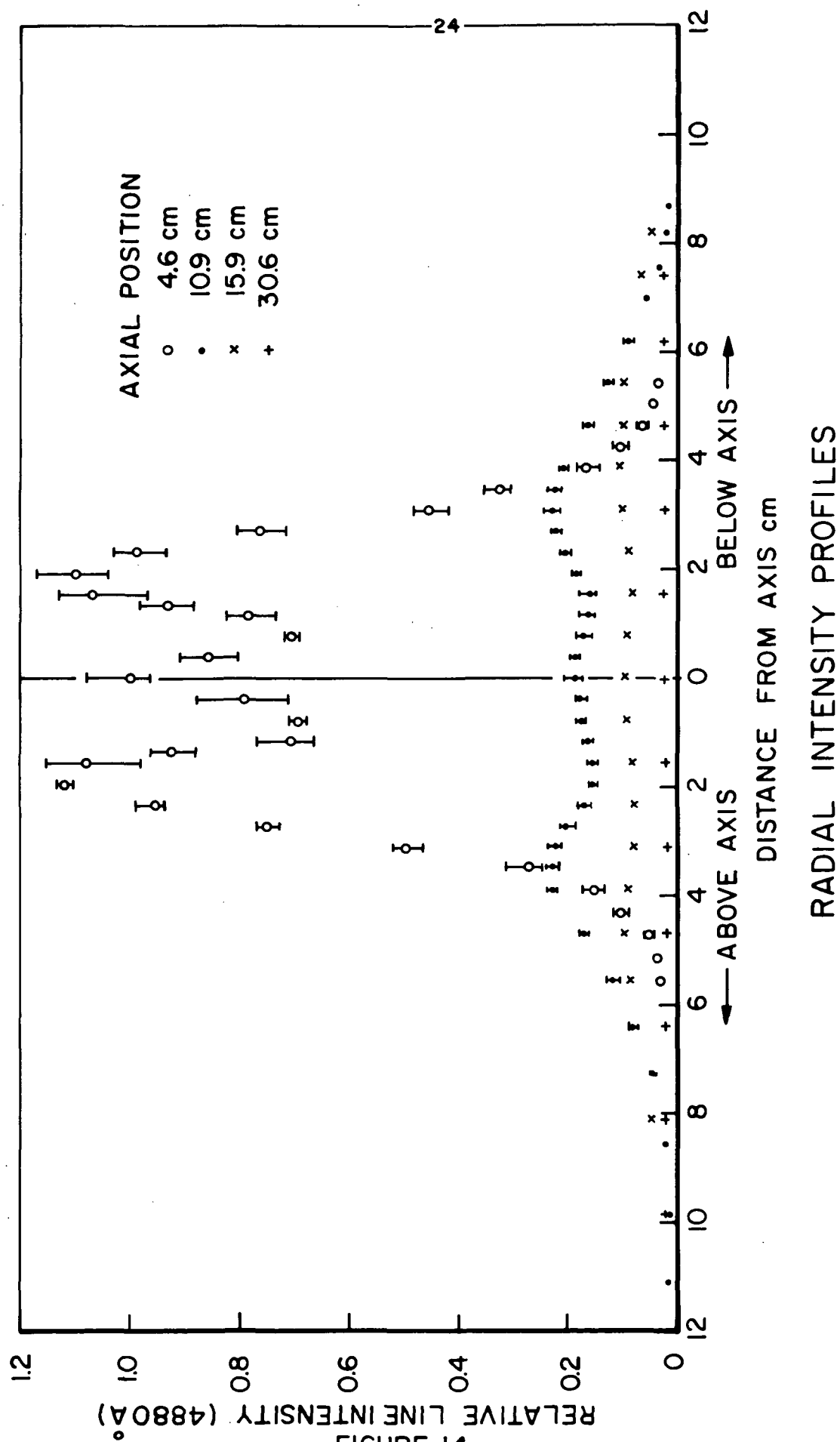
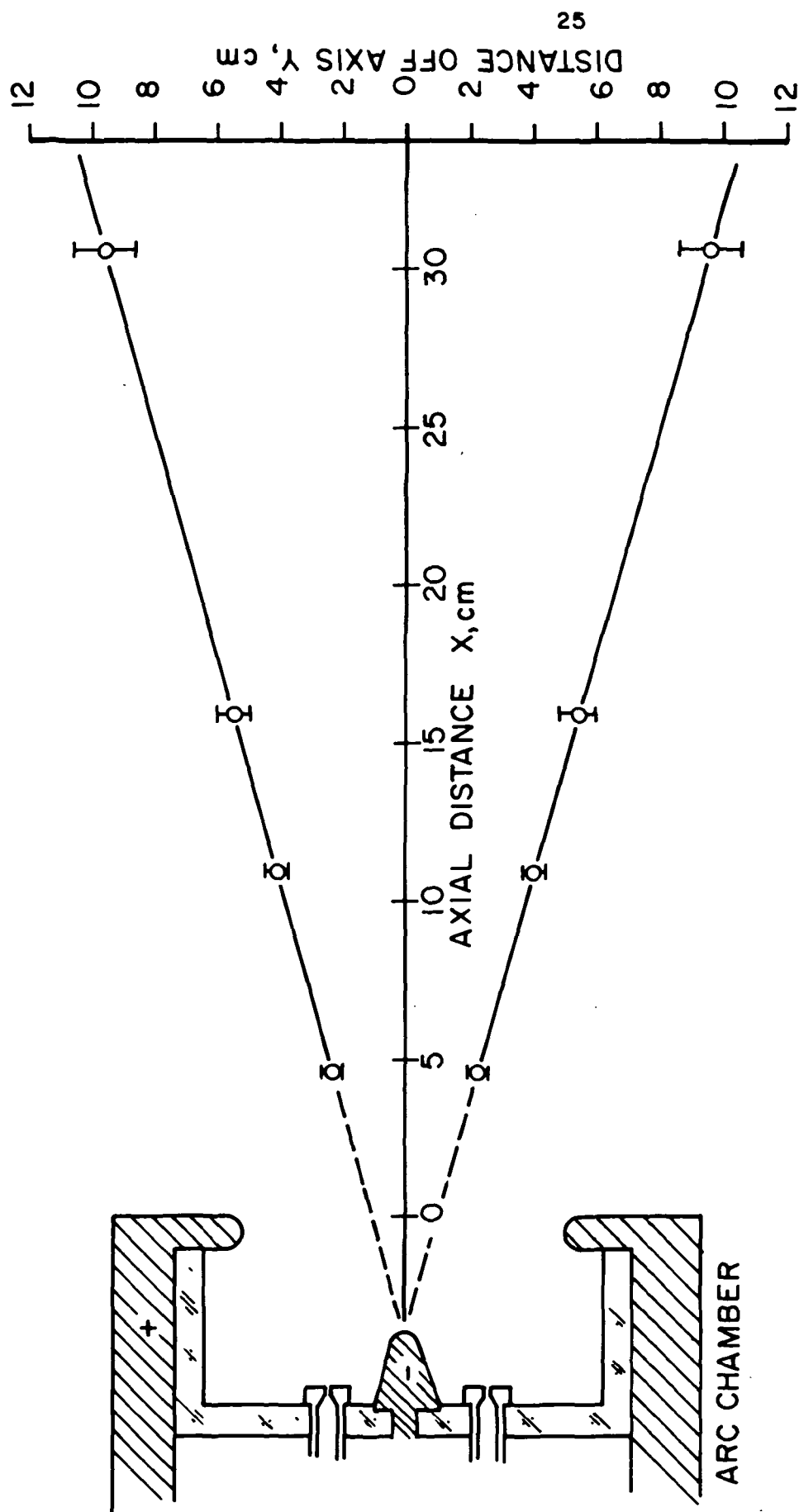


FIGURE 14  
AP25-4807



LOCI OF MAXIMUM 4880 Å LINE INTENSITY IN ARC JET

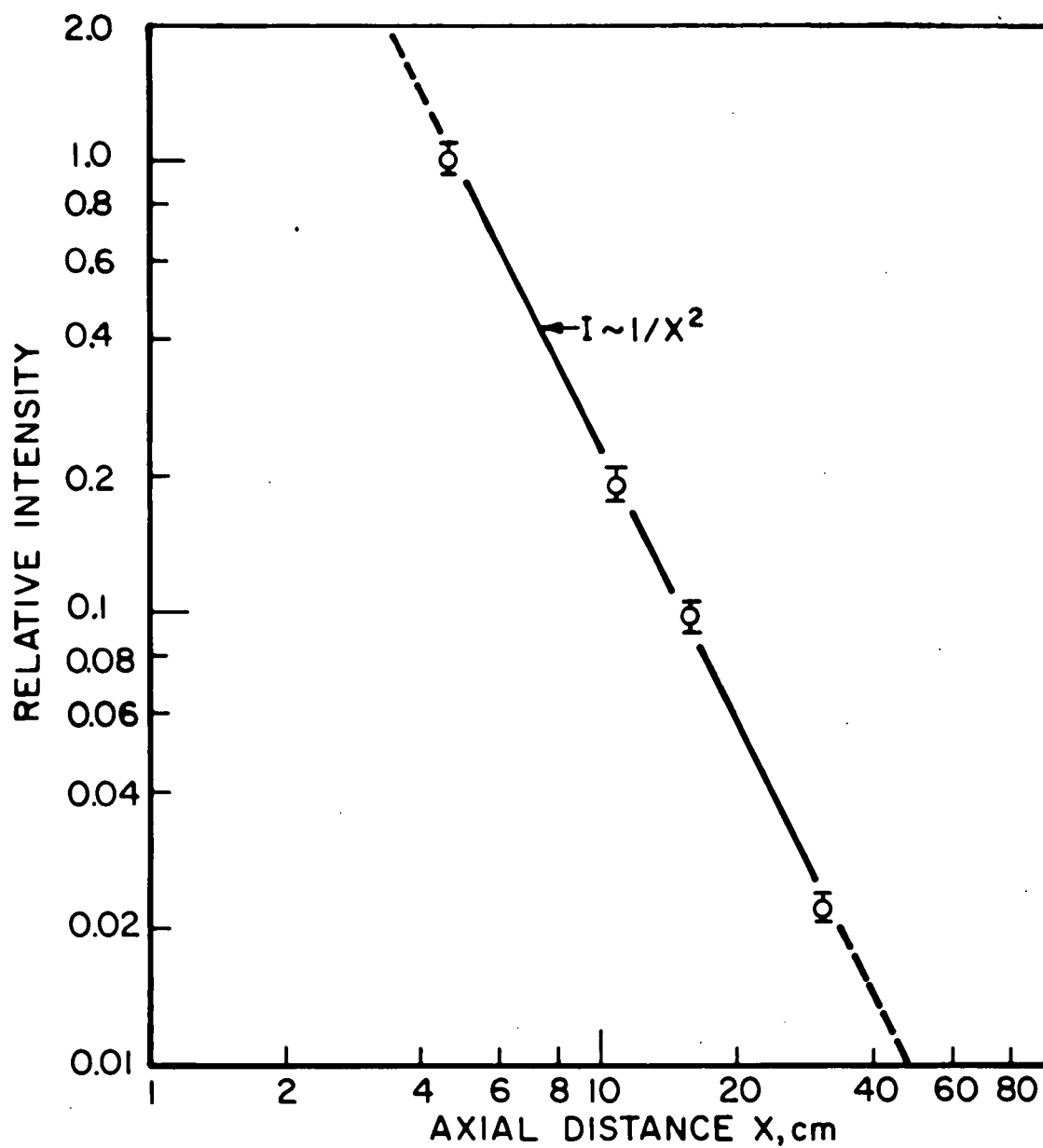
FIGURE 15  
AP25-4808

a good approximation to the average flow direction in each argon jet. The axial variation of the  $4880\text{ \AA}$  line intensity in an individual jet, displayed in Fig. 16, appears to follow an inverse square law. This does not, however, necessarily imply an inverse square dependence of radiating particle density on distance, as is the case in free expansion flows.<sup>131</sup>

#### Survey at $75^\circ$ Line of Sight

A series of Doppler shift velocity measurements was done at five axial positions with the line of sight at an angle of  $75^\circ$  to the discharge axis, passing through the two jets in the horizontal plane (Fig. 17). This line of sight is perpendicular to one of the jets and makes a  $60^\circ$  angle with the other. The observed line profile should thus have a shifted and an unshifted component. This is evident in Fig. 18, taken at a line of sight crossing the axis 27.8 cm from the anode face. The upper traces in each oscillogram correspond to the discharge current history, while lower traces exhibit line profiles scanned by the Fabry-Perot. Figure 18a shows the relative Doppler shift between the near and far jets. The "unshifted" peak on the left corresponds to the far jet, crossed at  $90^\circ$  while the blue shifted peak on the right corresponds to the near jet, crossed at  $60^\circ$ . Figure 18b displays the absolute Doppler shift between the laser reference and the near jet. In reality it turns out that there is a slight red shift associated with the far jet, indicating that the mass averaged velocity vector in the jets makes an angle somewhat greater than  $15^\circ$  with the axis.

Once the velocity components at  $75^\circ$  and at  $90^\circ$  to the axis are known at various axial positions along the argon jets, it is relatively straightforward to deduce both the magnitude and direction of the mass averaged velocity vector in the jets at any axial distance. This is done by means of vector diagrams such as the example shown in Fig. 19. Here,  $V_R$  is the average radial component of velocity,  $V_\theta$  the



DEVELOPMENT OF 4880 Å LINE INTENSITY IN Ar II JET

FIGURE 16  
AP25-4809

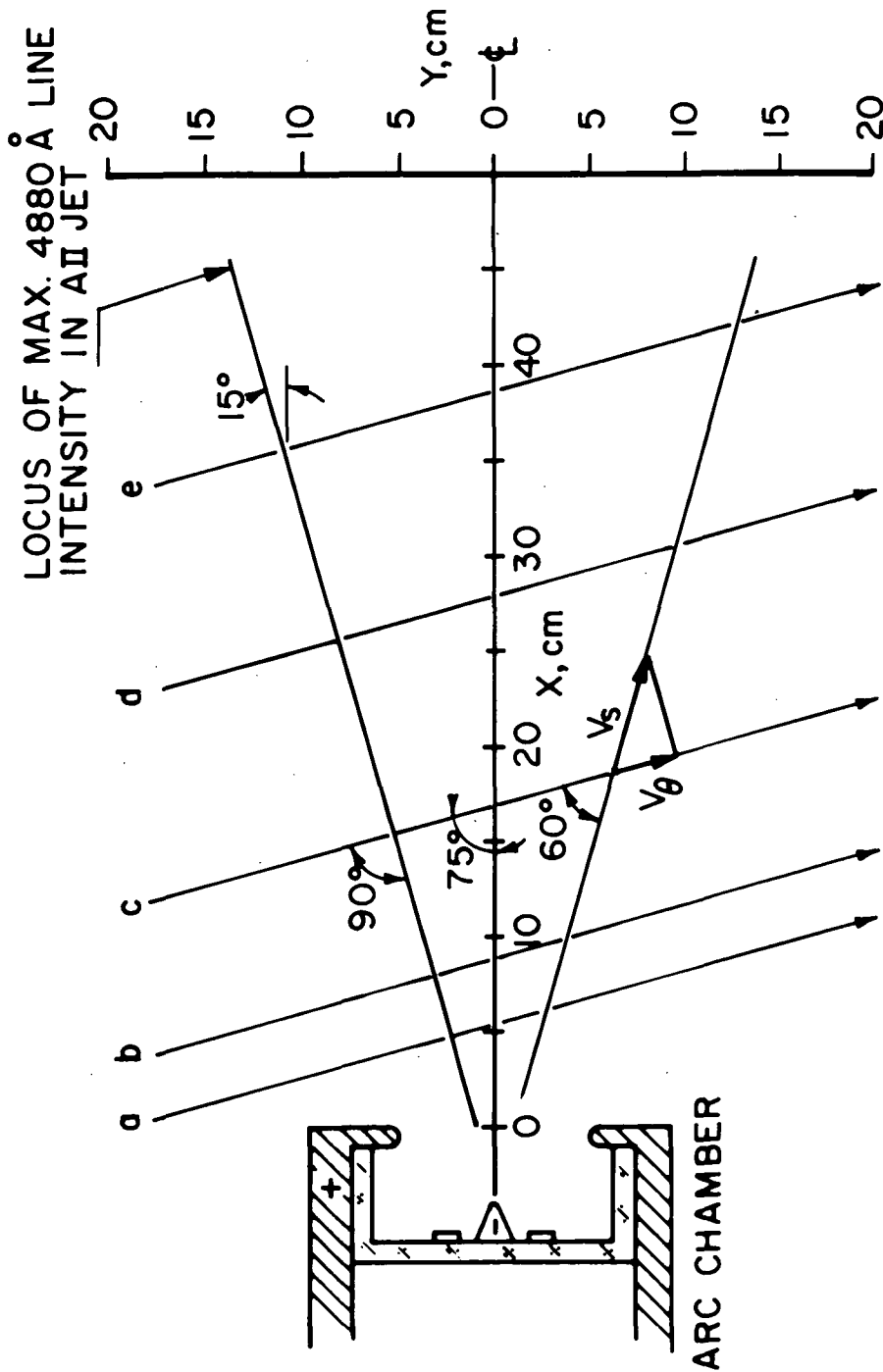
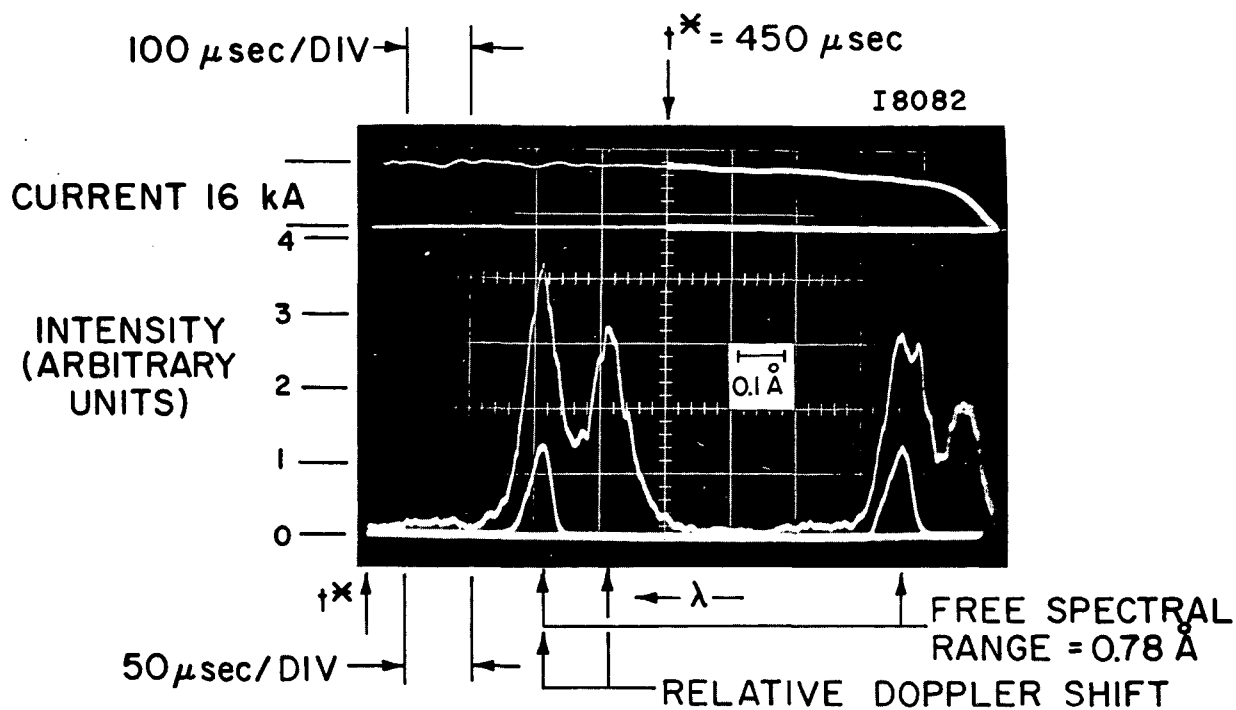
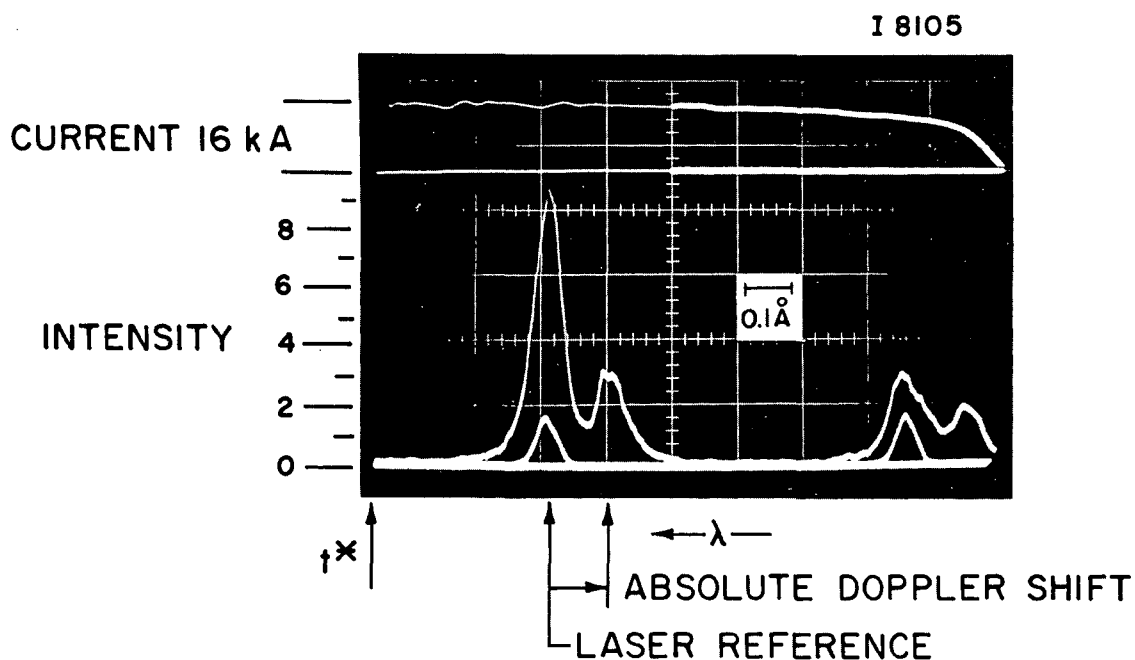


FIGURE 17  
AP 25-4810

## LINES OF SIGHT USED IN VELOCITY MEASUREMENTS



a) LIGHT FROM ARGON JETS ONLY



b) LASER REFERENCE SUPERIMPOSED

PROFILES AND DOPPLER SHIFTS OF 4880 Å  
 AII LINE ON LINE OF SIGHT CROSSING AXIS  
 AT X=16.8 cm

FIGURE 18

AP25-P438

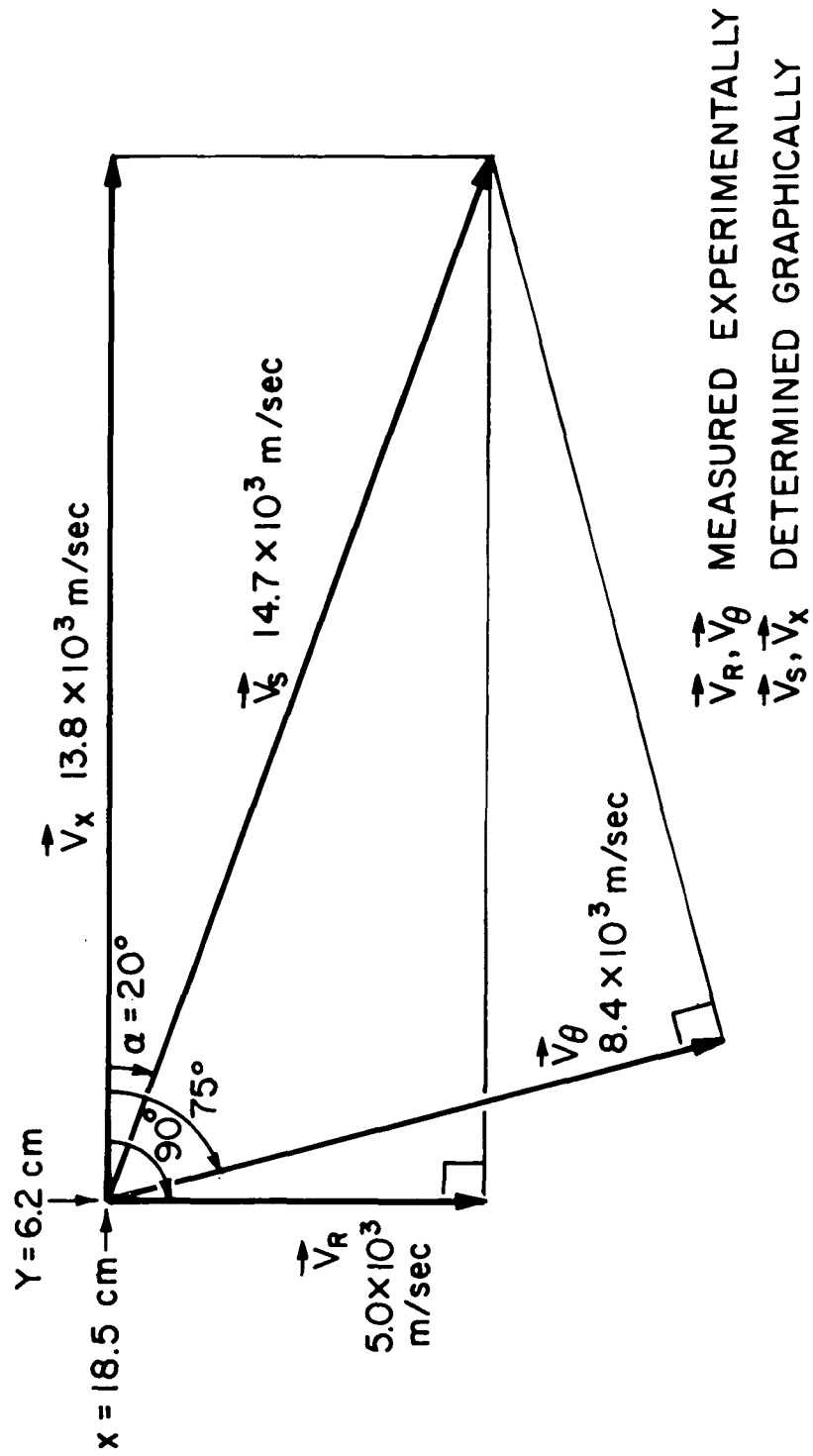


FIGURE 19  
AP25-4811

GRAPHICAL DETERMINATION OF AII JET VELOCITY

component along the  $75^\circ$  line of sight,  $V_S$  is the resultant velocity along the jet,  $V_X$  its axial component, and  $\alpha$  is the resulting average flow angle, all at a position 18.5 cm downstream of the chamber exit plane.

The axial variation of velocity  $V_S$  along each argon jet is shown in Fig. 20. The velocity increases from  $\approx 8500$  m/sec 5 cm from the chamber exit to  $\approx 16,500$  m/sec 40 cm downstream. At the same time the average jet flow angle increases from  $17^\circ$  at 5 cm to  $20^\circ$  at 18 cm and remains constant at  $20^\circ$  from there on. It is interesting to note that the observed final velocity is considerably higher than the so-called Alfvén critical velocity for argon (8700 m/sec).<sup>118</sup> Since it can be shown that electromagnetic acceleration is negligible at distances greater than about 2.5 cm from the exit,<sup>131</sup> the high exhaust velocity may be a result of significant conversion of thermal energy into directed kinetic energy.

#### Temperature Measurements

Argon ion temperatures in the jets have been deduced from measurements of widths of the line profiles obtained in the  $90^\circ$  line of sight surveys. Suitable corrections have been made for instrumental broadening and the broadening due to radial velocity dispersion in the jets.<sup>131</sup> Figure 21 shows the development of average argon ion temperature in the jets. The error bars represent the range of values obtained at each axial distance and the circled points the average of each range. The temperature appears to follow an inverse power law,  $T_i \propto x^{-3/4}$ , decreasing from  $\approx 1.7$  eV at  $x = 5$  cm to  $\approx 0.5$  eV at  $x = 25$  cm. This change is not in itself sufficient to account for the observed acceleration in the argon jets, and consequently the profiles of electron temperature along the jets must be examined for additional clues. Twin Langmuir probe measurements in the chamber<sup>111</sup> and recent double probe measurements at  $x = 25$  cm in the argon jets (Section III-C) indicate that



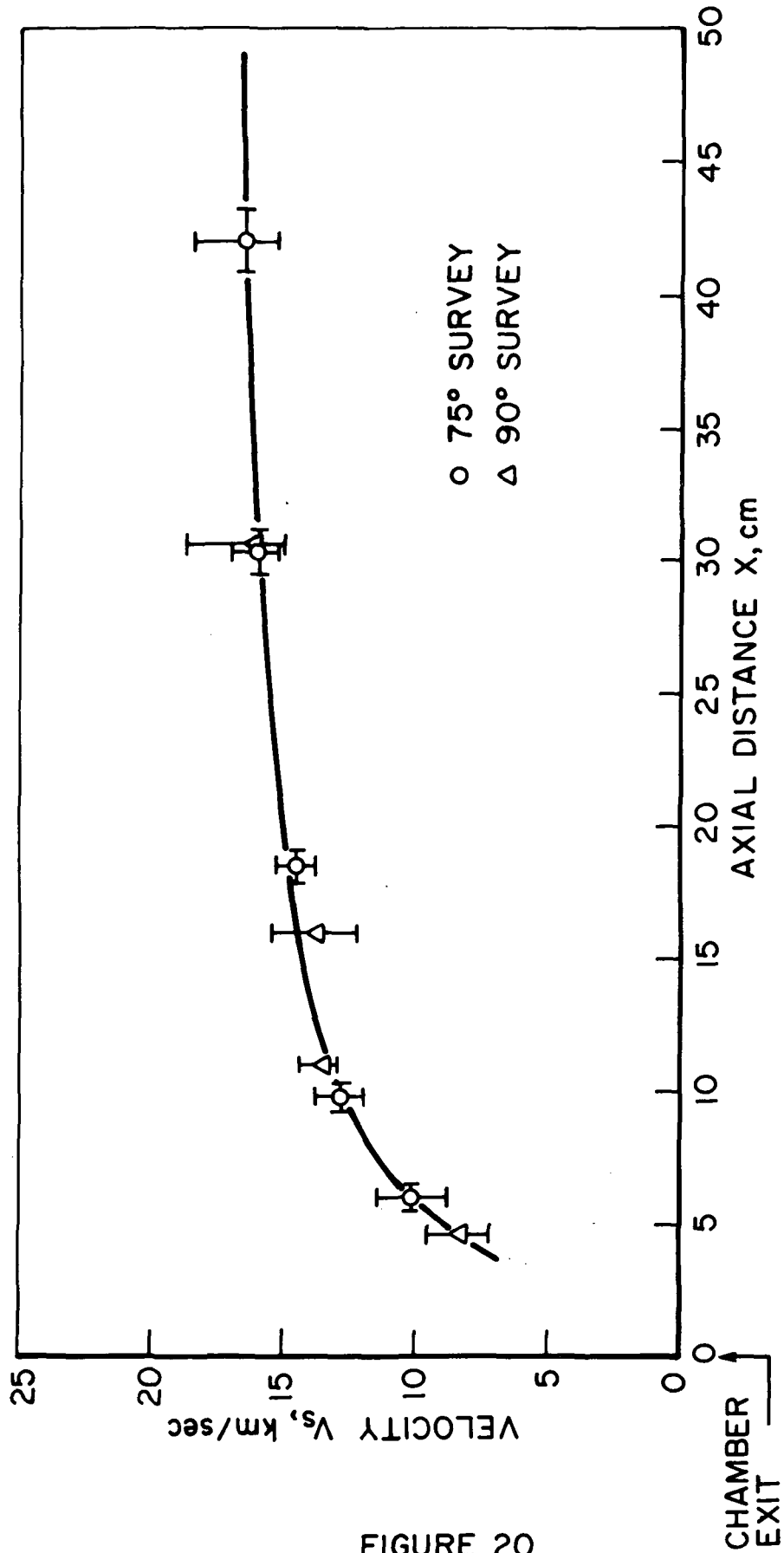
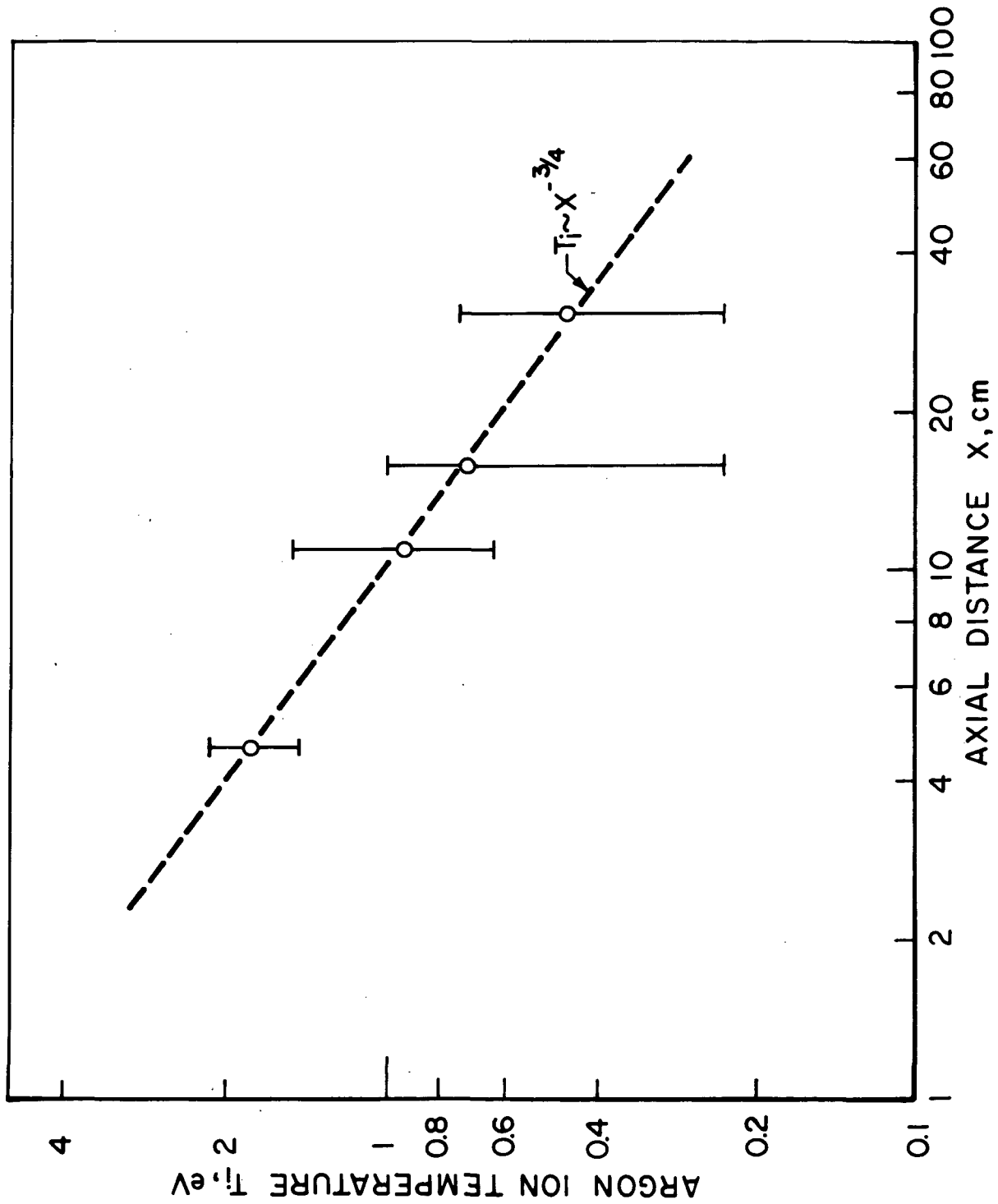


FIGURE 20  
AP25-4812



DEVELOPMENT OF ION TEMPERATURE IN ARGON JETS

FIGURE 21  
AP25-4813

the electron temperature decreases from about 1.5 - 2.0 eV in the chamber to  $\approx 0.8$  eV at  $x = 25$ . If it is assumed that the level of ionization is in equilibrium with the electron temperature everywhere, it can be shown that the acceleration downstream of  $x = 5$  cm is a result of the recovery of a large fraction of the ionization energy. However, spectroscopic evidence does not entirely support such a model<sup>131</sup> and the true nature of the acceleration mechanism outside the chamber remains incompletely understood at present.

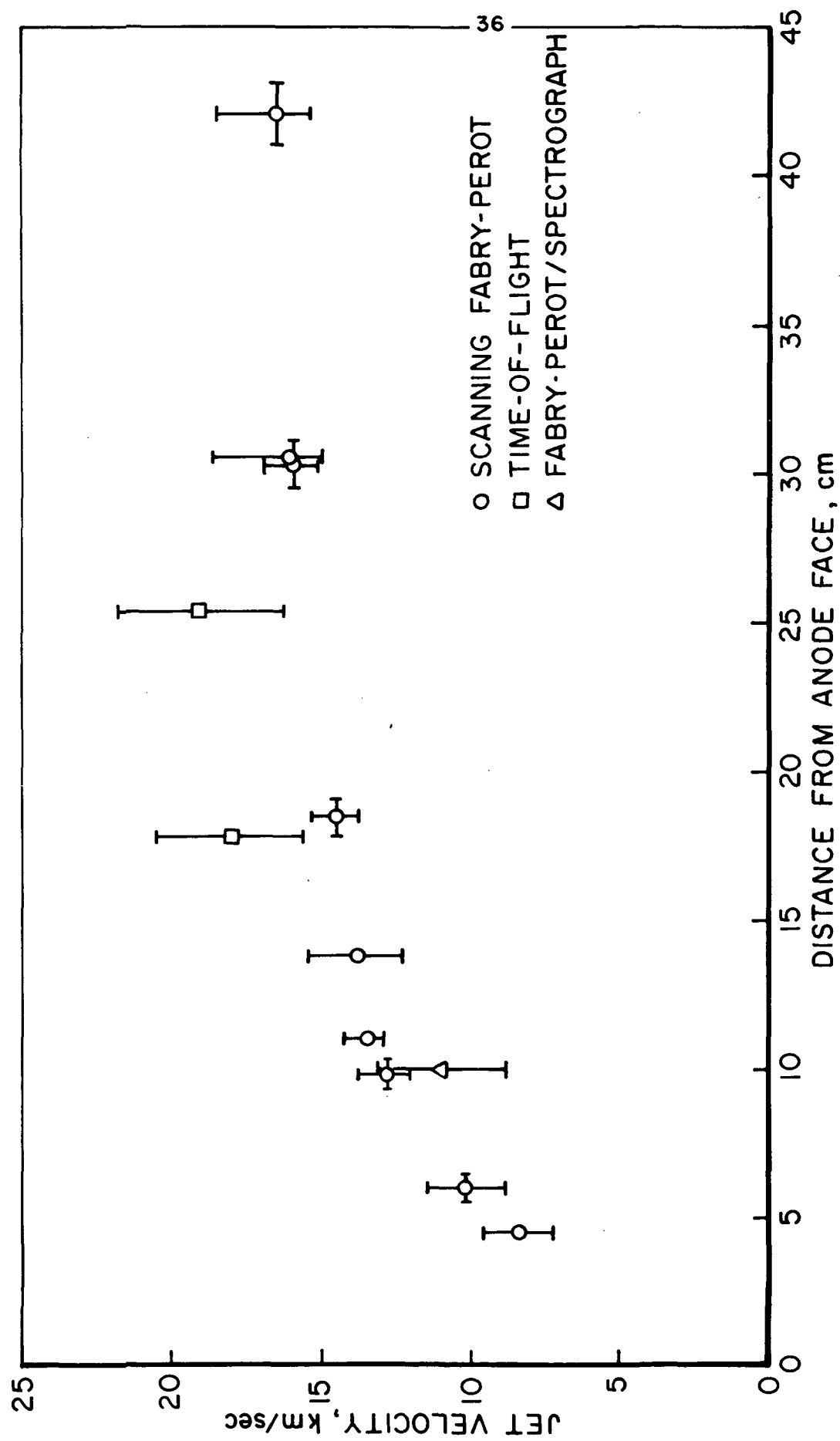
### III. QUASI-STEADY DISCHARGE PROPERTIES

#### III-A. Summary of Velocity Data (Clark)

As described in the previous section, photographic study of the discharge through selected spectral filters clearly shows a species structure related to the mass injection locations. This identification of regions in the exhaust plume of high argon or impurity concentration has been of primary importance in the determination of the exhaust velocity profiles, such that we now have three independent measurements of argon velocity which agree within experimental error.

The accumulated velocity data are shown in Fig. 22. The circle data points, shown earlier in Fig. 20, are the final results of the argon jet velocity survey by Bruckner using the scanning Fabry-Perot interferometer. The Fabry-Perot interferometer has also been used in combination with a Steinheil glass spectrograph for detailed spectral observations along an optical path perpendicular to the accelerator centerline at an axial position 10 cm from the anode face. This technique, described in ref. 123, revealed an argon line structure which could only be caused by radial spreading of two diametrically opposed argon jets. When combined with the known jet angle, this radial velocity yields a jet velocity shown by the triangle data point in the figure. Time-of-flight velocity measurements, which have been used extensively in the past for preliminary indications of jet profiles,<sup>118</sup> have been obtained in the argon jet and are shown as the square data points in the figure. The time-of-flight measurement is based on similar fluctuations in the ion saturation current recorded by two axially displaced pairs of biased double probes.

The velocity data from these three techniques are in agreement within the experimental accuracy shown by the error brackets. For this geometry, argon leaves the chamber with a velocity of



SUMMARY OF VELOCITY DATA

FIGURE 22  
AP 25-4814

several kilometers/sec and is monotonically accelerated to a velocity of approximately 16 km/sec at the 30-cm axial location, nearly twice the Alfvén critical speed for argon.

The consistently high time-of-flight data in Fig. 22 may occur if the probe, instead of recording the velocity of a disturbance convected along with the flow, indicates the summation of a local wave speed and the convective velocity. Until this question of the nature of fluctuations in ion saturation current is resolved, time-of-flight data cannot provide absolute velocity levels. They can however provide a rapid, reasonably accurate indication of the axial and radial velocity profiles in the exhaust. Interpretation of biased double probe signals in the exhaust plasma is presently a subject of active investigation (Section III-C) and may eventually yield not only absolute velocity levels, but number densities and electron temperatures as well.

### III-B. Axial Electric-Field Survey (Villani)

Recent experiments on MPD arcjets under conditions of high current,  $J$ , and low mass flow,  $\dot{m}$ , have suggested the existence of an undesirable operating mode resulting in low efficiency and high ablation.<sup>A-1,97,113</sup> Data indicate that for a given thruster geometry and propellant specie, the onset of this mode occurs at a characteristic value of  $J^2/\dot{m}$  throughout the power range under consideration ( $\sim 1-10$  MW).<sup>A-1, 97</sup>

Little is known about the physical processes causing this mode shift, even to the extent of whether it is gradual or abrupt, or whether it is the manifestation of a single controlling phenomenon or of several occurring in overlapping ranges of operating conditions. Nevertheless, the identification of this phenomena is necessary in order to determine the extent to which it imposes a fundamental limit on arc performance.

A study of the MPD discharge in the regime of this mode transition is now in progress, with initial tests directed toward finding the most sensitive transition indicator. While at some laboratories the mode shift was sharply and unambiguously<sup>A-1</sup> manifested in large terminal voltage fluctuations, MPD arc voltages in this laboratory were found to depend only weakly on mass flow, for constant current. Oberth's earlier survey of the floating potential distribution in the discharge revealed a significant increase in the magnitude of the axial electric field near the anode for operation under "starved" conditions, i.e. where  $J^2/\dot{m}$  exceeded the characteristic value. Continuing these experiments, the axial electric field in the vicinity of the anode has recently been measured with a floating double electric probe over a considerably larger range of currents and mass flows.

The floating potential double probe was first used and described in this laboratory by A. Eckbreth.<sup>70</sup> It consists of two 1-mm-dia spherical electrodes separated by 1.6 cm and extending from a mounting on the tip of a glass tube. In the experiments the probe was used to record the difference in floating potential  $\Delta\phi$  between two points in the horizontal plane through the centerline of the apparatus, 7.6 cm out radially and 1.3 cm from the anode. The axial component of the electric field was recorded at only one radial and azimuthal station since the electric field had been found<sup>113</sup> to be uniform and parallel to the axis over most of the volume adjacent to and downstream of the anode surface. The fore and aft probe tips were connected, respectively, to the + and - inputs of a Tektronix Type 1A7A differential amplifier through P6006 10:1 attenuators, and displayed on the upper beam of a Tektronix Type 555 dual-beam oscilloscope. The terminal voltage (V) was monitored

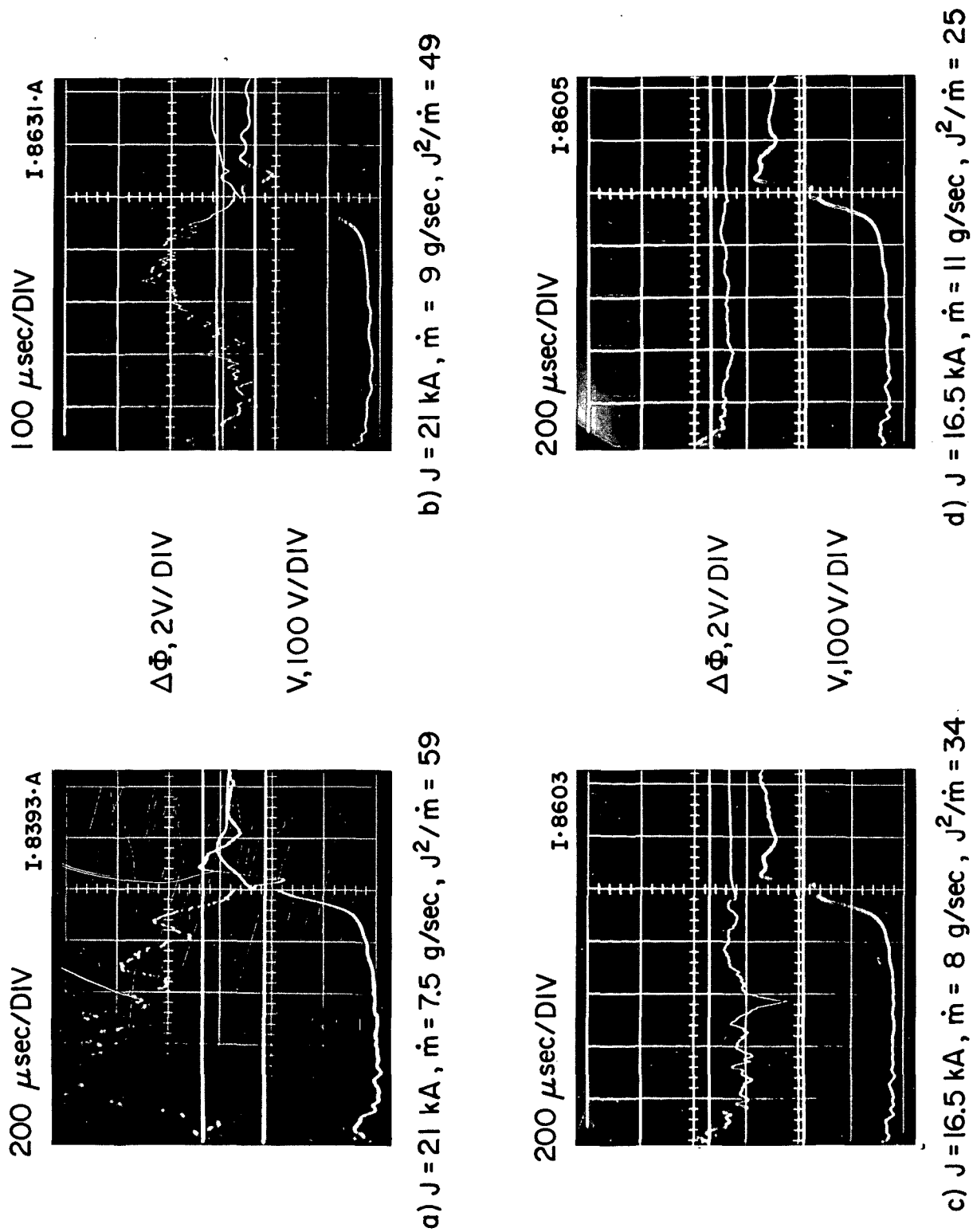
on the lower beam through a P6013A 1000:1 attenuator and a Type L preamplifier. A second oscilloscope monitored the discharge current through the usual Rogowsky coil/integrator combination.

Typical floating potential and terminal voltage records are shown in Fig. 23 for various combinations of  $J$  and  $\dot{m}$ . For high values of  $J^2/\dot{m}$ , it can be seen in Figs. 23a and 23b that the output of the  $\Delta\phi$ -probe becomes very noisy. In an attempt to achieve some repeatability in the average value of  $\Delta\phi$ , the high-frequency cutoff of the 1A7A amplifier was set at 100 kHz. This reduced most of the fluctuations, but it was still necessary to take an average of the trace from 20% to 80% of pulse duration to achieve sufficient reproducibility to make the trends visible. The mass flow of the injected propellant was varied from 2 to 15 g/sec by adjusting the pressure in the supply line of the injection valve. Nominal levels of the arc current of 8.0, 12.7, 16.5, 21 and 32 kA were selected by adjusting the capacitor bank charging voltages to 2, 3, 4 and 5 kV depending on the configuration of the pulse forming network.

The results are exhibited in Fig. 24 as a plot of floating potential difference versus mass flow for the mentioned discharge current levels. There is a sharp break in the values of the potential difference, or the corresponding electric field, at a characteristic value of mass flow for each level of current.

When the potential difference is plotted against the parameter  $J^2/\dot{m}$  in Fig. 25 it can be seen that the break, for all currents, falls at a value of  $J^2/\dot{m}$  of approximately  $37 \text{ kA}^2\text{-g}^{-1}\text{-sec}$ . This value, when scaled by the geometric coefficient in the MPD thrust equation, falls within 20% of the "critical"  $J^2/\dot{m}$  measured by Malliaris<sup>A-1</sup> from terminal voltage signatures and Doppler shift velocity measurements.





FLOATING POTENTIAL DIFFERENCE  $\Delta\Phi$  AND TERMINAL VOLTAGE V

FIGURE 23  
AP25-P439

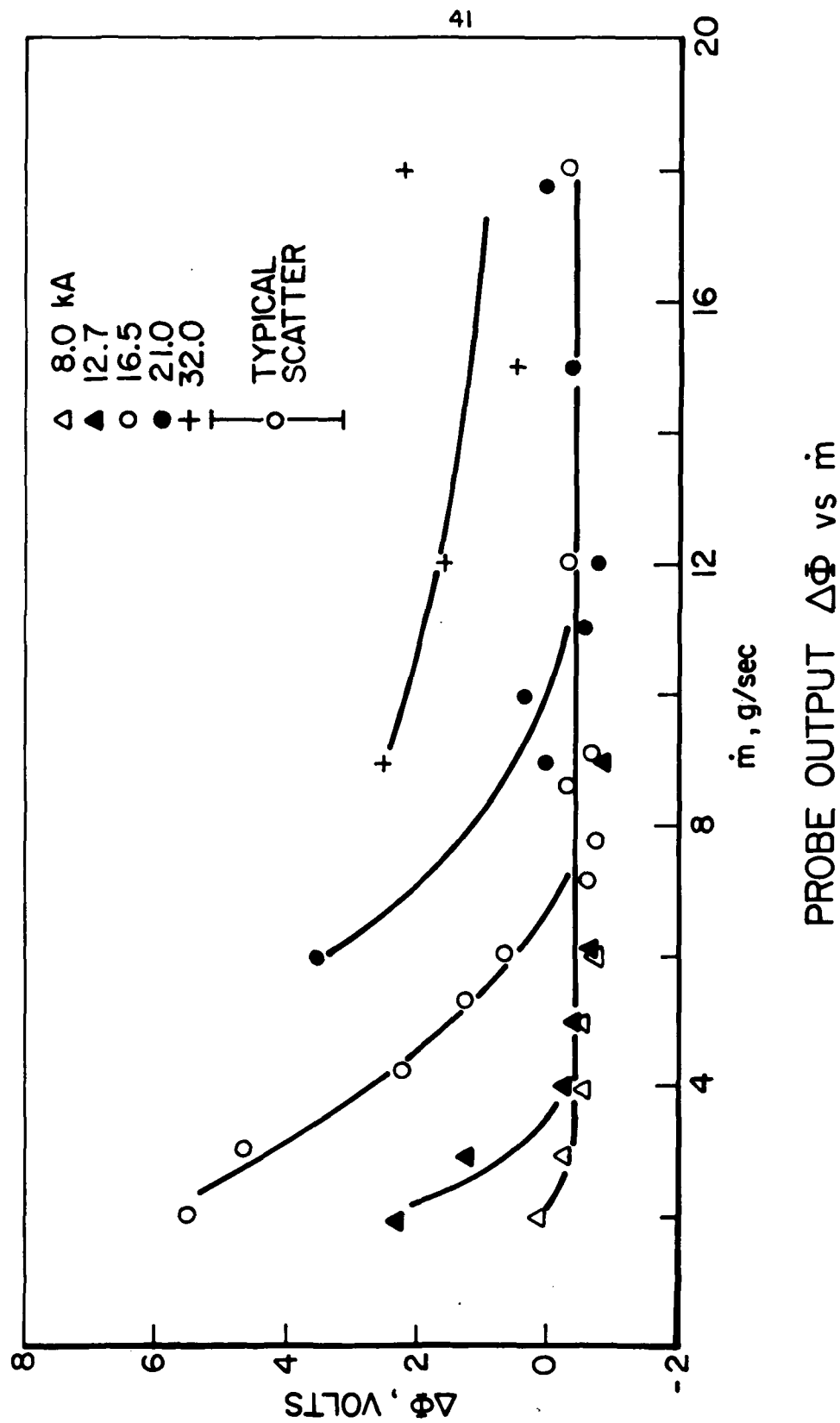
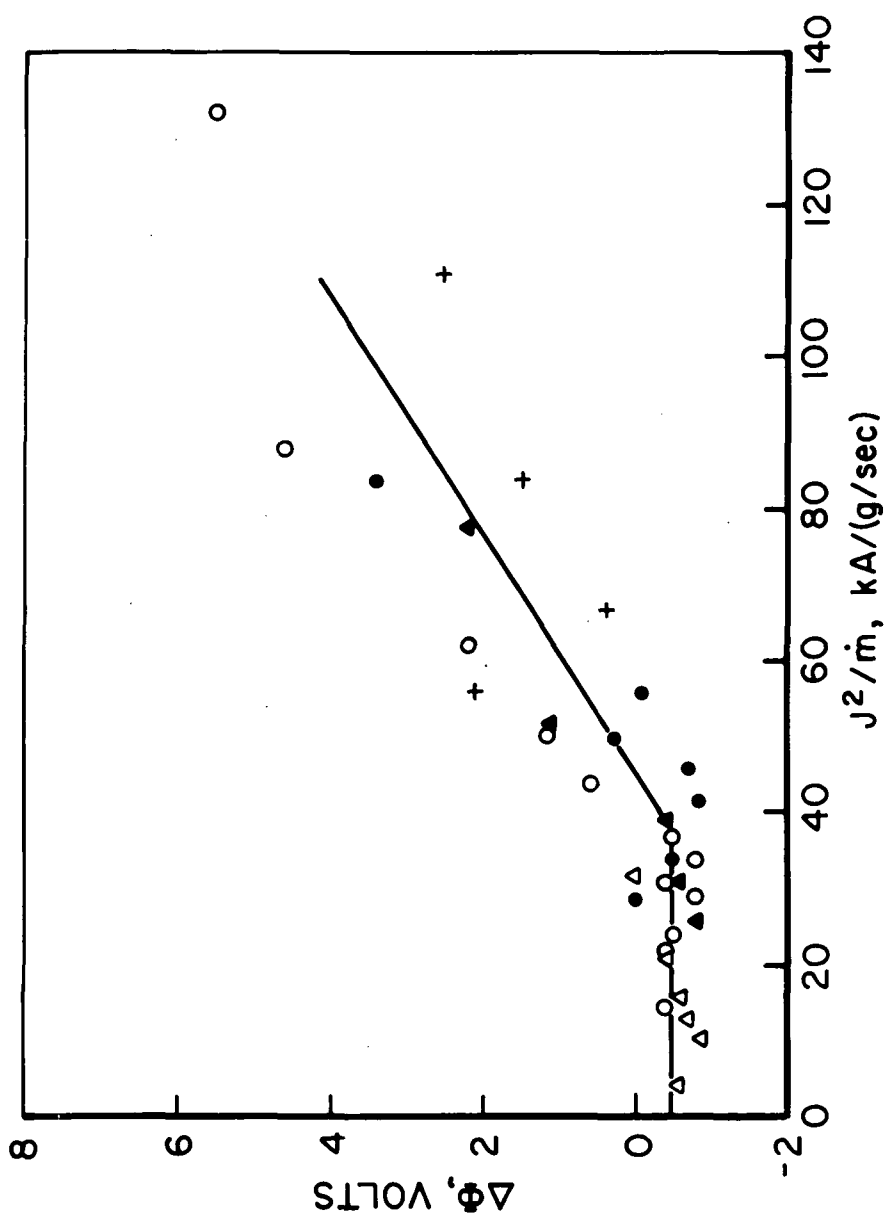


FIGURE 24  
AP25-4815



PROBE OUTPUT  $\Delta\Phi$  AS A FUNCTION OF  $J^2/\dot{m}$

FIGURE 25  
AP 25-4816

These data show that the sudden growth of the axial electric field in the region around the anode is a sensitive means of detecting the "starved" discharge condition. However, its effectiveness with the present injection geometry may be limited since part of the arc can be overfed while some other part is starved due to the discrete locations of the mass injection ports. Further use of this probe will be continued after the development of azimuthally uniform injection configuration, as described in Section IV-D, has been completed.

### III-C. Double Probe Studies in the Exhaust Plume (Boyle)

The program investigating the use of the double probe as a diagnostic device in a streaming plasma has broadened in scope. Deduction of the plasma velocity vector from experimental current-voltage probe characteristics and its comparison with the velocity measured from the time-of-flight of local fluctuations in the ion saturation current remains the major objective of this program. A second goal is the identification of the source and nature of the ion current fluctuations which provide the time-of-flight data. Preliminary results associated with the first objective were reported earlier.<sup>123</sup> More recent results of that work and an introduction to the program initiated to achieve the second objective are discussed here.

As reported in Sec. II, a detailed exhaust plume structure was detected optically by Bruckner in the quasi-steady MPD accelerator operating at a current level of 16 kA and an injected mass flow rate of 6 g/sec. Interferometric data indicated an argon velocity of 15.5 km/sec  $\pm$  1.5 km/sec in a jet structure angled 20° to the centerline at an axial position 25.4 cm downstream of the anode orifice and a radius of 8 cm. Because this measurement provides an independently

determined velocity with which probe results can be compared, the same axial and radial coordinates are used for all double probe measurements reported herein.

Double probes can be used to give plasma velocity by two different methods. Time-of-flight velocities, derived by correlating fluctuations between displaced pairs of biased double probes, may be due in part to a plasma wave component superimposed upon the convective plasma stream. Although straightforward experimentally, the validity of this technique hinges on the determination of the ratio of streaming velocity to wave velocity. The alternative method of calculating the velocity from the average current-voltage characteristic of a double probe has the advantage that it is only a function of the convective velocity, and thereby allows the convective and plasma wave effects to be separated when compared with time-of-flight data.

Looking first at the latter calculated velocity, the ion saturation currents to a probe aligned with the flow ( $I_{||}$ ) and perpendicular to the flow ( $I_{\perp}$ ) for the case of a single species plasma where the ion thermal speed is much less than the streaming velocity which, in turn, is much less than the electron thermal velocity, are given by

$$I_{||} = K e A_{||} n_i \left( \frac{k T_e}{m_i} \right)^{1/2} \quad (\text{III-1})$$

$$I_{\perp} = e n_i A_{\perp} U_p \quad (\text{III-2})$$

where  $K$  is a non-dimensional ion current correction factor and  $U_p$  is the plasma streaming velocity. Eliminating the ion number density, the plasma velocity is given by

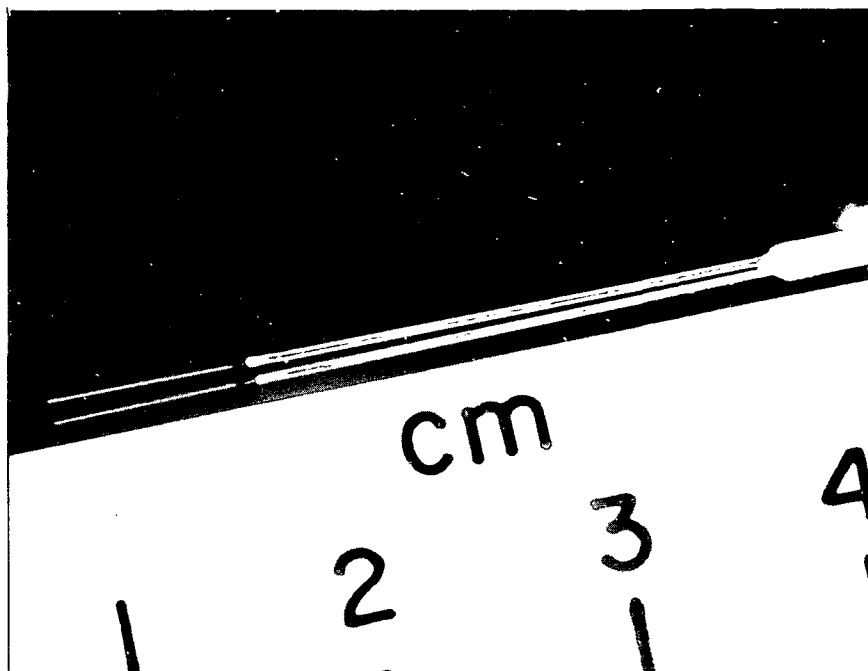
$$U_p = \frac{A_{||}}{A_{\perp}} \frac{I_{\perp}}{I_{||}} K \left( \frac{k T_e}{m_i} \right)^{1/2} \quad (\text{III-3})$$

Thus, if the electron temperature is known, the ion saturation currents parallel with and perpendicular to the flow must be measured and combined with the known probe geometry to give the streaming velocity.

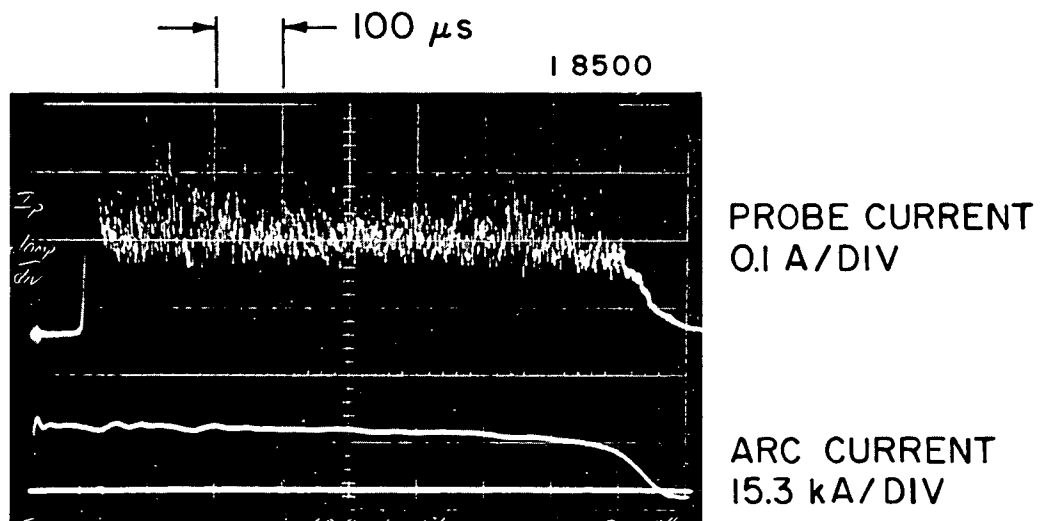
To trace current-voltage characteristics parallel and perpendicular to the flow, and to measure time-of-flight velocities, the local flow direction must be known. The flow direction is experimentally determined by measuring the net probe current as a function of probe angle with respect to the accelerator centerline. For ratios of probe radius to Debye length much greater than one, a minimum in probe current as a function of probe orientation is theoretically predicted when the local flow vector and the cylindrical probe axis are aligned. This dependence of net probe current on relative flow angle has been verified on the accelerator centerline 25.4 cm downstream of the anode orifice.

The double probes used for these measurements are a modified version of earlier probes. The modification consists of placing small glass capillary tubes over the tungsten electrodes to prevent any probe material in the neighborhood of the electrodes from influencing the local plasma species concentration. The electrode dimensions remain 0.076 mm in diameter and 8 mm in length. Figure 26a is a photograph of a typical probe employed in these studies. The net probe current is monitored by a Tektronix P6042 Current Probe which, with its DC to 60 MHz frequency response, permits double probe measurements throughout the entire duration of the millisecond current pulse. Figure 26b depicts a typical history of probe current on the same time scale as the arc current.

A survey of probe current as a function of probe angle taken within one of the six argon jets ( $Z = 25.4$  cm,  $r = 8$  cm) yields a flow direction of  $15^\circ - 20^\circ$  as shown in Fig. 27. The probe current plotted in this and later figures corresponds to the visually determined average of the fluctuations in



a) DOUBLE PROBE



b) TYPICAL DOUBLE PROBE SIGNAL

DOUBLE PROBE

FIGURE 26  
AP25-P440

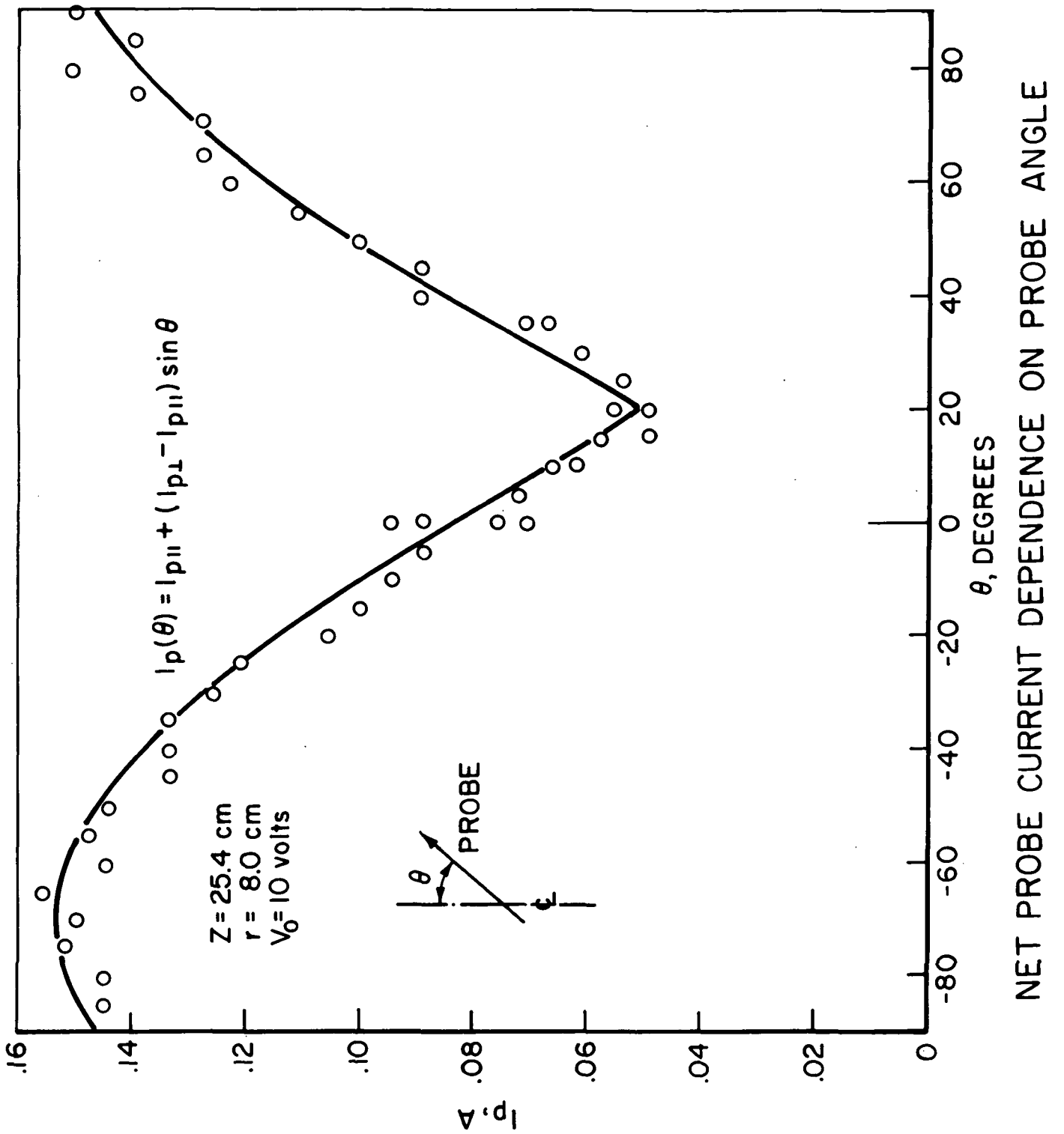


FIGURE 27  
AP25-4817



probe signal (see Fig. 26b). The flow angle in Fig. 27 agrees well with the  $20^\circ$  angle determined from optical data. On both the centerline and within the argon jets, the angular dependence of the net probe current is sinusoidal.

With the local flow direction established, the complete probe characteristics both parallel and perpendicular to the flow were measured. From the parallel characteristic, shown in Fig. 28, it is seen that ion saturation is clearly attained.

For a double probe, the graph of  $\ln(I_p + i_{1+})/(i_{2+} - I_p)$  vs  $V_o$  (where  $I_p$  is the net probe current,  $i_{1,2+}$  the ion current to electrode 1,2, and  $V_o$  the applied bias potential) is a straight line for Maxwellian distributed electrons. Figure 29, which examines this dependence from experimental data, thus implies that for these operating conditions electron temperature calculations based on a Maxwellian electron distribution are justified. The smallness of the slope of the saturation regions in Fig. 28 compared with the slope about  $V_o = 0$  assures that the sheath area's dependence upon  $V_o$  can be neglected in calculating the electron temperature. The equivalent resistance method is therefore used to estimate  $T_e$ . Because the electron thermal velocity is much greater than the indicated streaming velocity, electron temperature determination is unaffected by the orientation of the probe.

Using the above technique, an electron temperature of 0.78 eV is indicated. Combining this with an ion temperature of approximately 0.5 eV (see Section II) and the experimentally measured parallel and perpendicular ion saturation currents, the plasma streaming velocity calculated using equation III-3 is 10.5 km/sec. For comparison, the time-of-flight velocity, obtained from two axially displaced double

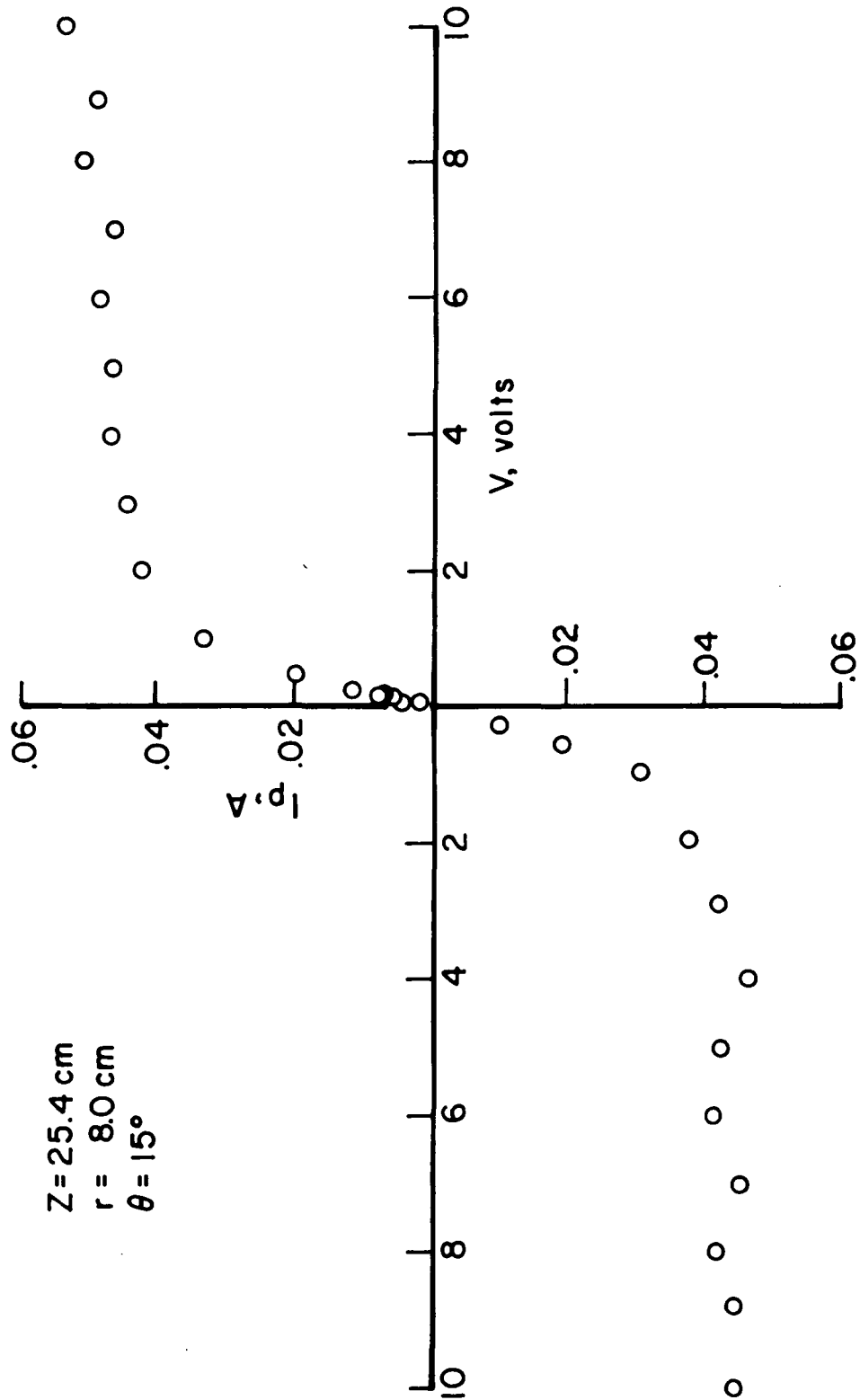
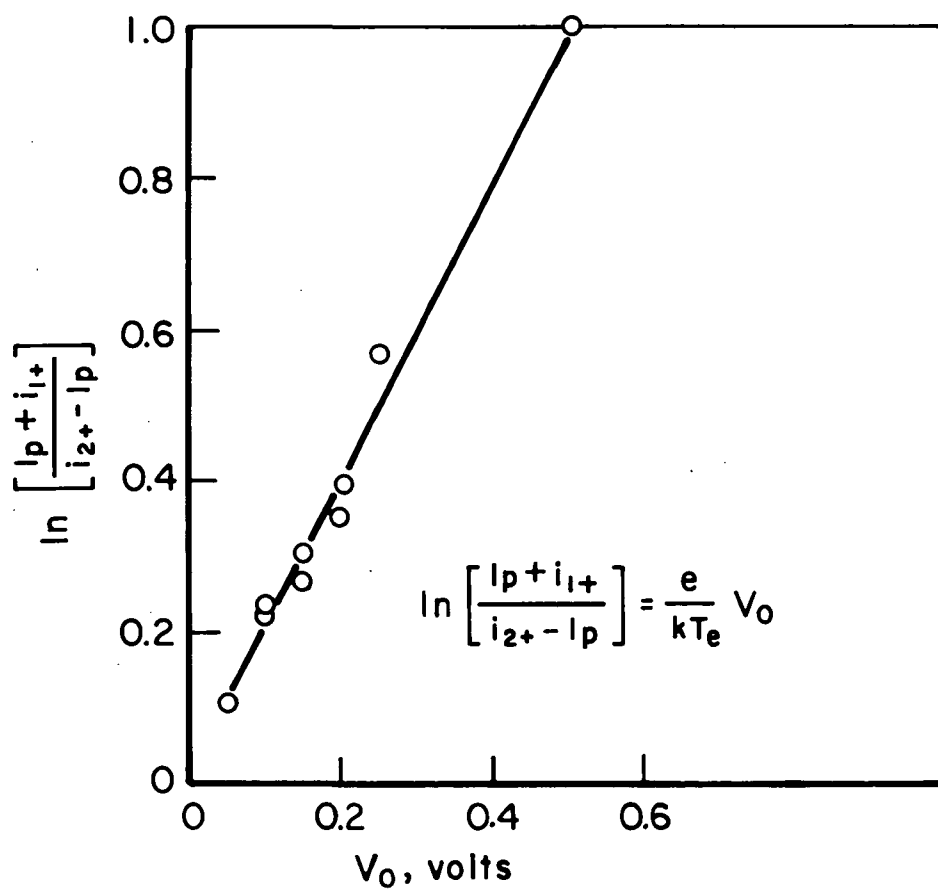


FIGURE 28  
AP 25-4818

DOUBLE PROBE CHARACTERISTIC IN ARGON JET (PARALLEL)



ELECTRON TEMPERATURE FROM  
DOUBLE PROBE CURRENTS

FIGURE 29  
AP25-4819

probes at approximately the same location in the argon jet, is found to be 19 km/sec with a root mean square deviation of 2.6 km/sec. Although this latter value agrees with the optical data within the limits of the error bars, its acceptance remains open until the nature of the fluctuations from which it is derived is established.

The difference between the time-of-flight or optically measured velocity and the velocity calculated from the probe characteristics indicates that a major factor has not been considered. Photography of the discharge through optical filters indicates a possible source for this discrepancy. Ablation products, primarily the constituents of Plexiglas, are found to be distributed in varying proportions throughout the discharge exhaust. The presence of small amounts of hydrogen ions influences the calculation of  $n_i$  from the parallel ion saturation current significantly due to the large argon to hydrogen mass ratio. Since local number density ratios of impurity elements to argon can only be grossly estimated, deduction of a plasma velocity from Eqn. III-3 must wait until the proper data reduction scheme for a multi-component plasma is achieved. Additional evidence for the crucial role which impurities play in this data reduction scheme is found in a plot of  $I(\theta)/I_{||}$  vs  $\sin \theta$  for a constant bias voltage of 10V. As mentioned earlier, the dependence of the saturation current on probe orientation  $\theta$  is sinusoidal. Thus the slope of such a graph should be related to the streaming velocity, and is also a function of the ion mass. Assuming an argon plasma as before, the velocity calculated is approximately 9.4 km/sec. Once again the difference is most likely credited to the presence of impurity ions. For this reason, experiments are underway to create a pure argon environment so that a mono-species probe theory may be used for data reduction.

Work is also underway to identify the source and nature of fluctuations in the ion saturation signal from the double probe. Correlation between probe current fluctuations and fluctuations in spectral line intensities should provide insight into their common cause. Experiments designed to determine the axial and/or radial wavelengths of characteristic fluctuations in the exhaust are also planned.

### III-D. Power Deposition to the Anode

#### Earlier Work

In his dissertation on "Anode Phenomena in High Current Discharges" R. Oberth of this laboratory has studied the rate of energy deposition at the anode of a quasi-steady MPD arc.<sup>113</sup> If it is assumed that the electron temperature  $T_e$  of the plasma adjacent to the anode is constant and that the work function of the anode  $\phi_A$  does not vary, and if radiative and convective heat transfer can be neglected, then the anode power deposition can be written as<sup>A-4</sup>

$$P_A = J \left( \frac{5}{2} \frac{kT_e}{e} + \phi_A \right) + \int_{\text{Anode Surface}} j_A V_A dA \quad (\text{III-4})$$

where

$P_A$  = power deposited to the anode, W

$j_A$  = current density at the anode, A/cm<sup>2</sup>

$J$  = total current, A

$k$  = Boltzmann's constant

$e$  = electronic charge

$V_A$  = anode voltage drop defined in text

$dA$  = surface element of anode

The heat transfer mechanism at the anode therefore appears predominantly due to the flux of current carrying electrons which deposit both their thermal energy and their kinetic energy to the anode after passage through the adjacent anode voltage drop. Oberth determined the deposited power fraction indirectly from measurements of the current density at the anode surface and the corresponding local voltage drop between the anode and a point 0.1 cm adjacent to it.<sup>113</sup> This voltage drop is not to be confused with the conventional definition of the "anode fall" which occurs over dimensions of the order of the electron mean free-path of approximately 0.01 cm at the upstream portions of the anode, and of the Debye length of approximately 0.001 cm over the front or downstream locations of the anode. The measurement of the potential at a distance of 0.1 cm from the anode surface provides only an upper estimate of the true anode fall voltage since the contribution from a layer of cooled plasma ( $\mathcal{E}$ -layer) adjacent to the anode may be included in the probe response. For operation at currents from 9 to 42 kA and matched mass flows from 1.2 to 36 g/sec, the power density at the anode was determined to be approximately constant and given by

$$P_A = j_A V_A \approx 2 \text{ kW/cm}^2 \quad (\text{III-5})$$

These indirect measurements indicated that the anode power fraction of the total arc power went down as the power was increased. A detailed study of the power deposition by direct measurement of the anode temperature rise over a range of quasi-steady operating conditions has therefore been initiated and some preliminary results are reported here.

### One-Dimensional Model

To verify this technique, initial experiments were conducted with an anode which was insulated except for a 0.5 cm strip at the lip of the orifice. The energy flow in this anode is modelled by the one-dimensional flow in a semi-infinite solid. The anode is initially at zero temperature. At time  $t=0$  a constant heat flux of  $F_0$  watts/cm<sup>2</sup> is supplied at the uninsulated part of the anode at  $x=0$  shown in Fig. 30a and 30b where the current has access to the electrode. The heat flux pulse persists for a time  $T$  equal to the duration of the constant magnitude current pulse. When the current pulse shuts off at  $t=T=1$  msec the supply of heat ceases and the exposed lip of the solid is then assumed to be an adiabatic boundary.

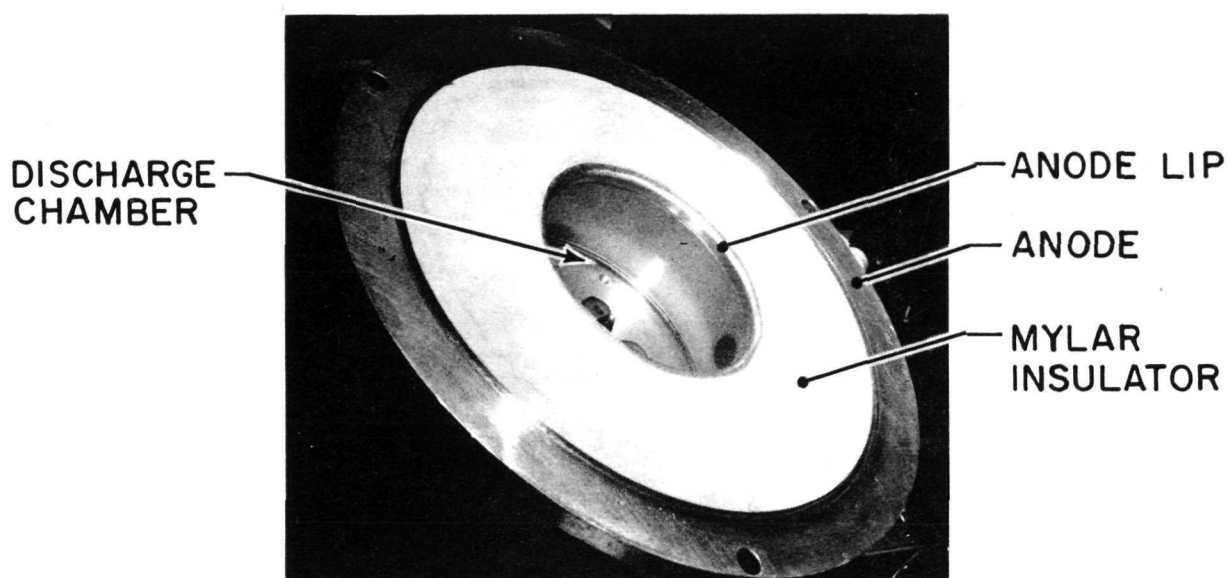
For times  $t > T$  the temperature  $\theta(^{\circ}\text{C})$  at a location  $x$  is given by:<sup>A-5</sup>

$$\theta(t) = \frac{F_0}{2.09k} (\mathcal{K}\tau)^{1/2} \text{erfc} \left[ \frac{x}{2} (\mathcal{K}\tau)^{-1/2} \right] \bigg|_{\tau=t-T}^{\tau=t} \quad (\text{III-6})$$

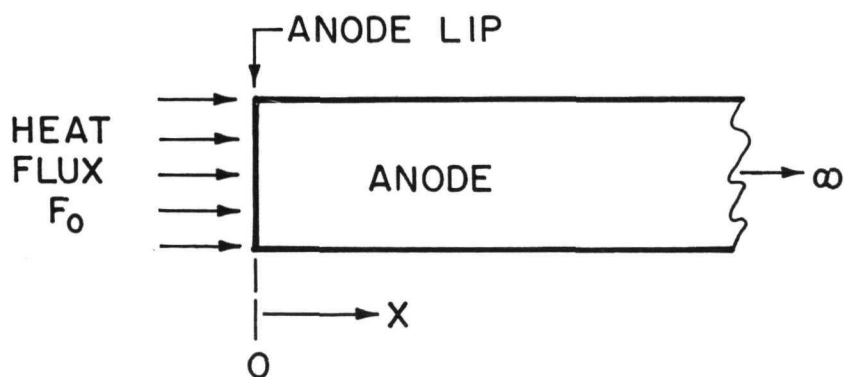
For Aluminum:  $\mathcal{K} = 0.822 \text{ cm}^2/\text{sec}$ , thermal diffusivity

$k = 0.48 \text{ cal/cm-sec-}^{\circ}\text{C}$ , thermal conductivity

The equation was solved numerically on the IBM 360/91 for the temperature at various locations  $x$  in the solid, using an available library sub-program for the complementary error-functions. The results are plotted in terms of  $\theta/F_0$  in Fig. 31 for times  $t$  up to 10 sec. For small  $x$  the temperature goes through a maximum which in the present case of  $x=0.8$  cm occurs at a time of approximately 0.5 seconds, long after cessation of the  $T=1$  msec current pulse. With increasing time the temperature traces for different locations soon converge into a narrow band. In the one-dimensional semi-infinite solid model this band of temperature



a) ANODE OF MPD APPARATUS



b) ONE DIMENSIONAL, SEMI-INFINITE SOLID MODEL

# ANODE CONFIGURATION

FIGURE 30

AP25-P441



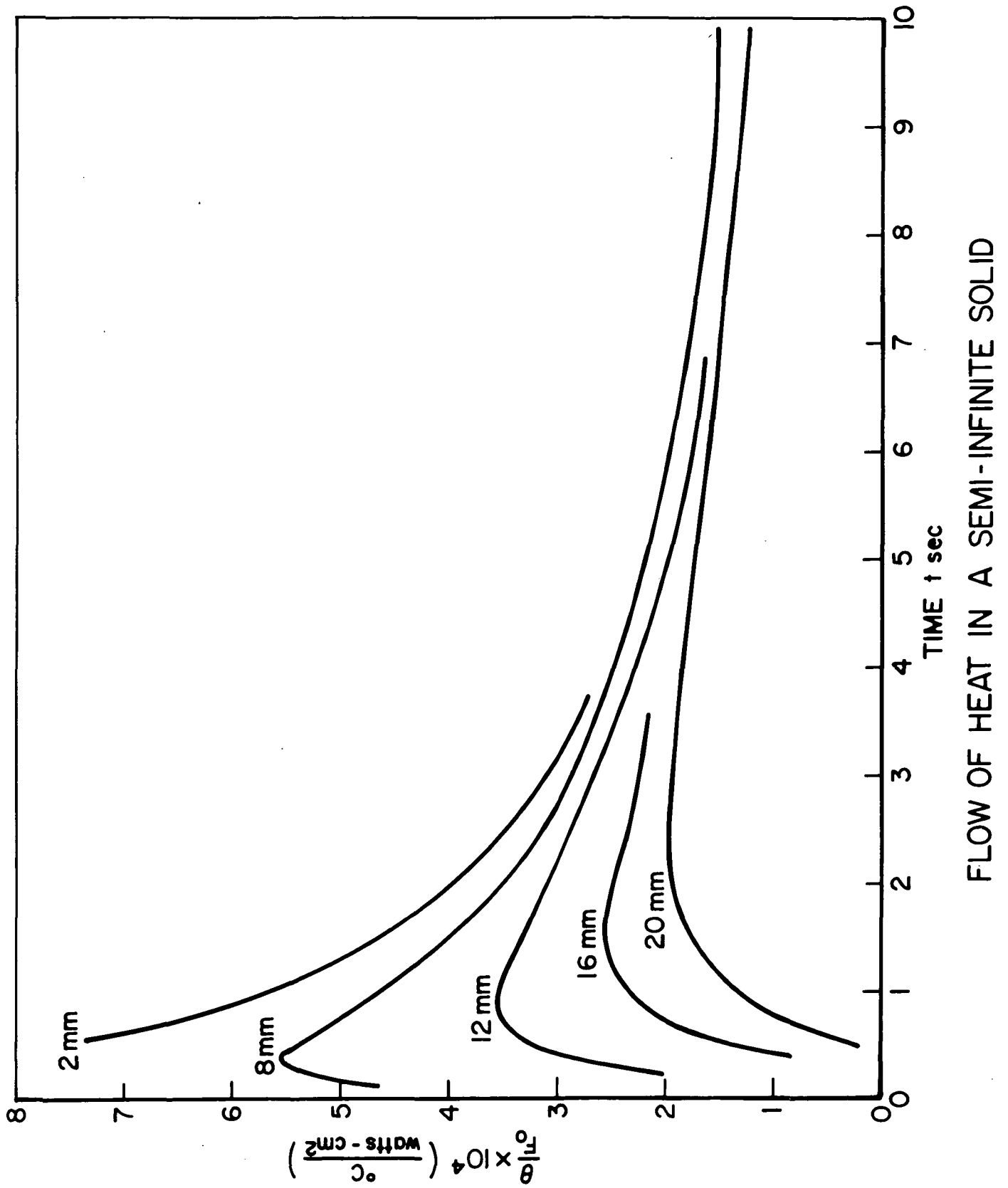


FIGURE 31  
AP25-4820

profiles  $\theta/F_0$  tends to zero for long times, while it would achieve a constant value for a finite size solid.

### Experimental Studies

For the experimental energy deposition investigation a quasi-steady MPD apparatus was employed which differed from the conventional design by its partially insulated 28 cm diameter anode and the relatively small 24 cm diameter by 43 cm long Pyrex belljar into which the propellant plasma flow was exhausted. A schematic of the apparatus is shown in Fig. 32. Constant current pulses of 11 to 25 kA were supplied for 1 msec from a pulse forming network and were connected through a gas switch to the electrodes of the discharge chamber. Argon propellant at mass flow rates from 2.8 to 15.4 g/sec was admitted to the discharge through a fast acting solenoid valve. The temperature rise in the anode at a distance of 0.8 cm from the lip of the orifice was detected with a #30 gauge copper-constantan thermocouple (Thermal Products Inc.) with a sensitivity of  $39.6 \mu\text{V}/^\circ\text{C} \cdot \text{A}^{-6}$ . The thermocouple was electrically insulated with an epoxy coating shown in Fig. 33a as well as shielded in copper braid tubing which in turn was insulated by heat shrinkable plastic tubing. The assembly was then inserted into a 0.3 cm diameter well drilled radially into the anode from its outer rim. An operational amplifier with a low pass filter cutoff at 4 kHz and an experimentally determined amplification-factor of 930 was used in the circuit shown in Fig. 33b for preamplification of the expected low level thermocouple signals ( $\approx 5 \mu\text{V}$ ) before recording the response on the oscilloscope.

Typical amplified thermocouple responses at current levels from 13 to 25 kA and mass flow rates from 5.3 to 15.4 g/sec are shown in Fig. 34. These experimental thermocouple signatures are to be compared with the computed

0.3 cm DIA. WELL

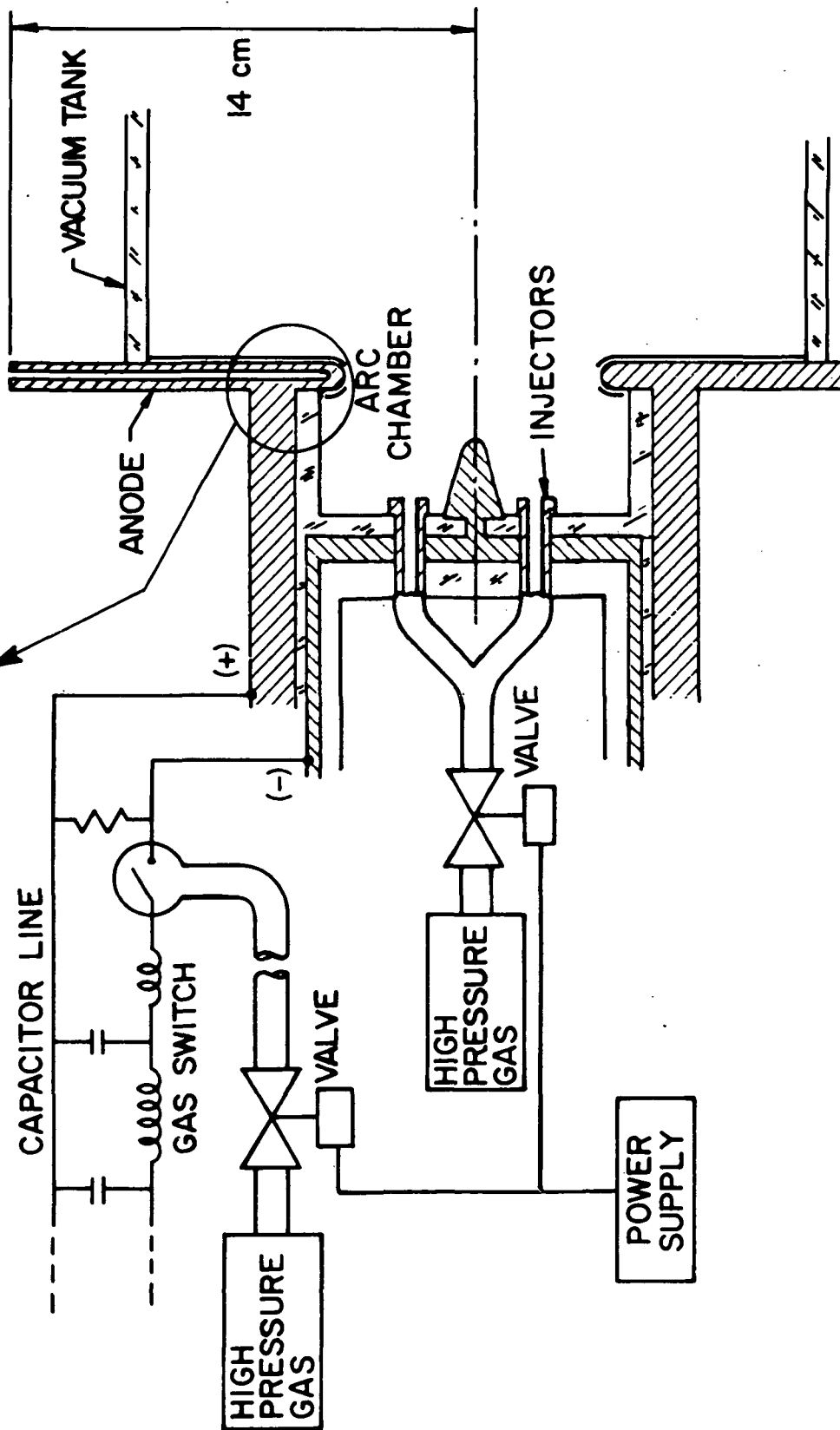
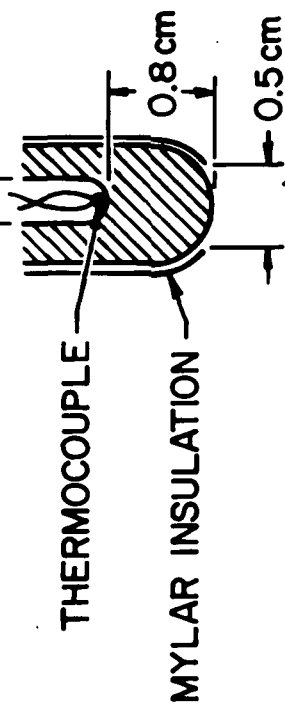
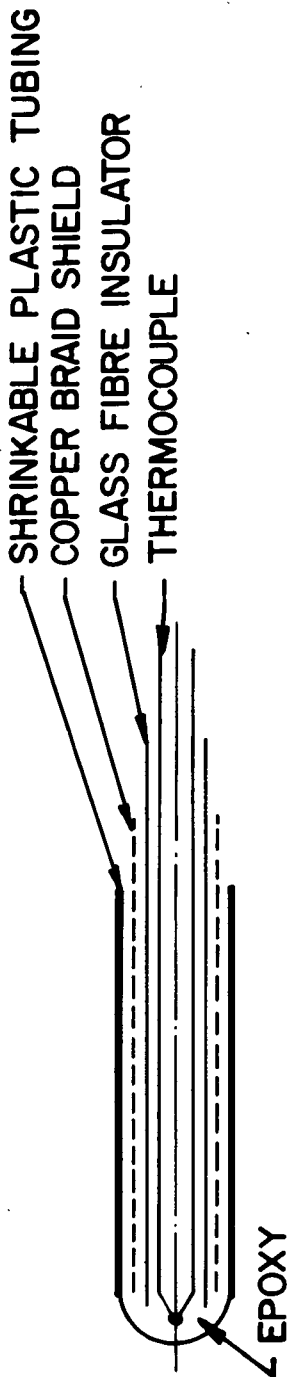
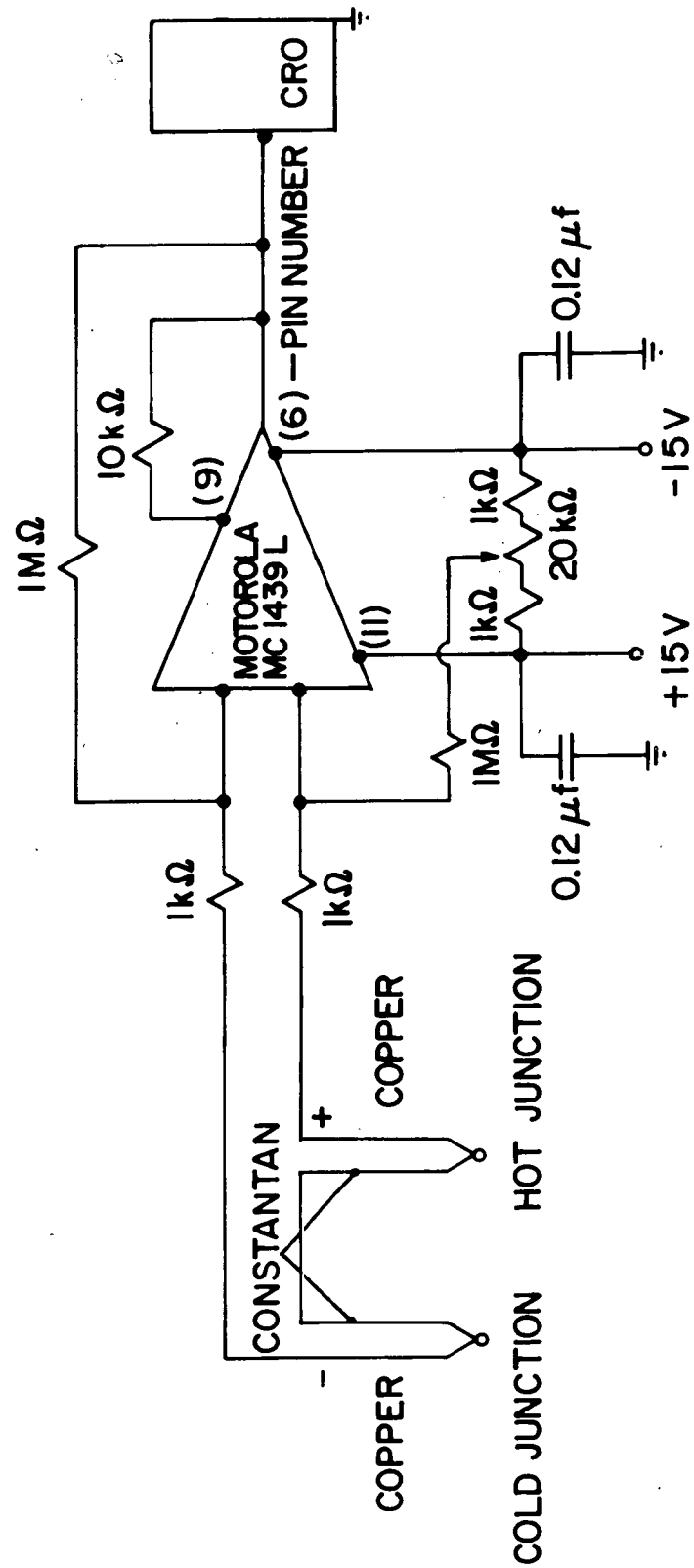


FIGURE 32  
AP25-4821



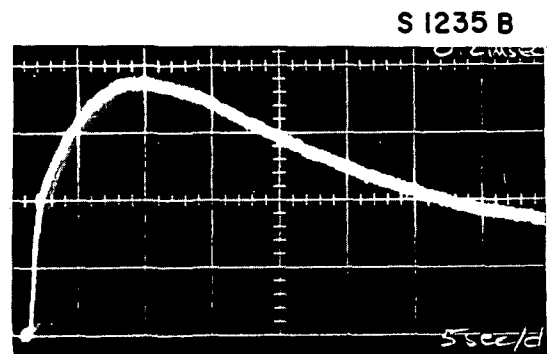
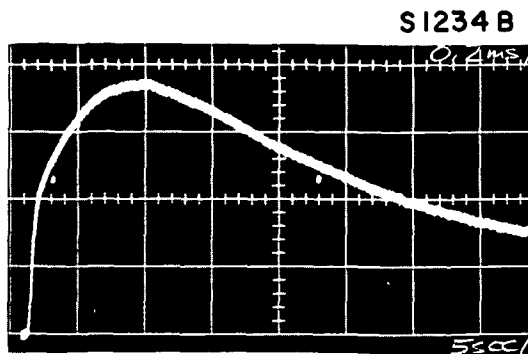
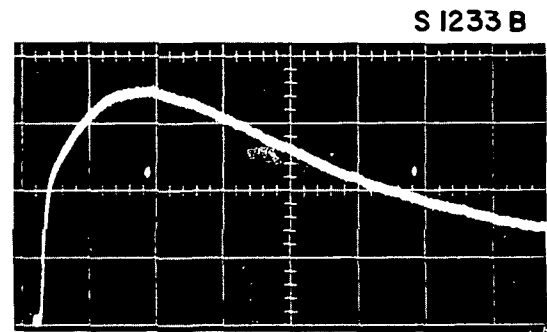
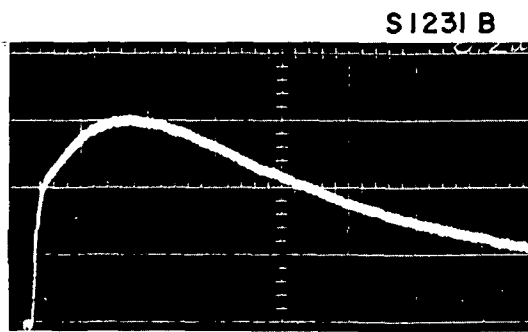
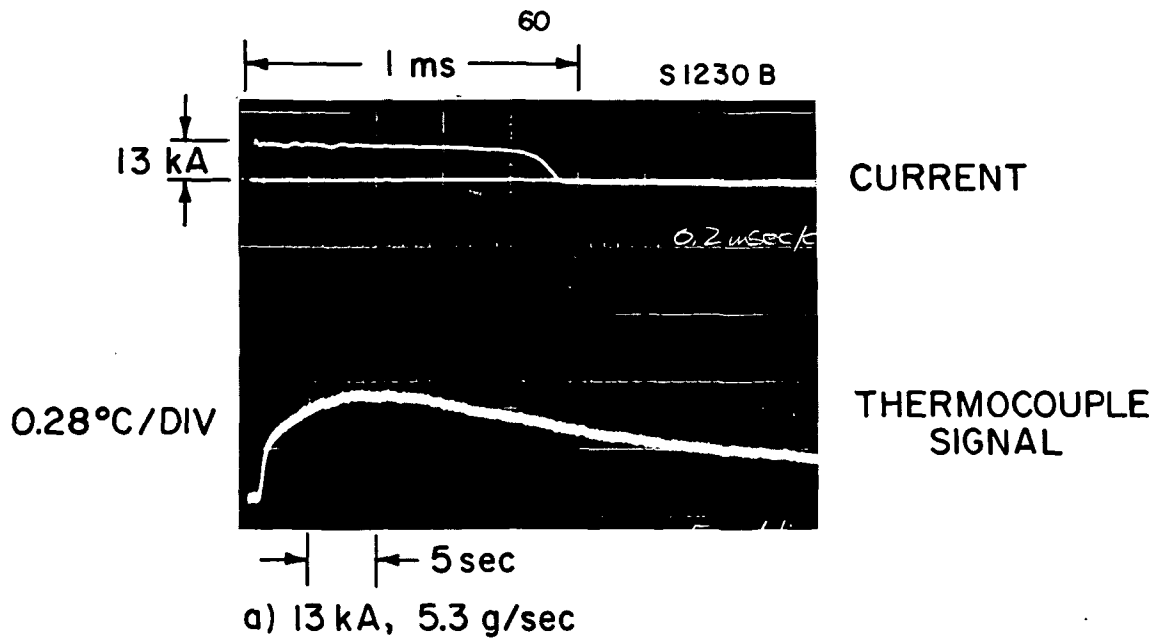
a) THERMOCOUPLE



b) DETECTION CIRCUIT

## THERMOCOUPLE DETECTION SYSTEM

FIGURE 33  
AP25-4822



## THERMOCOUPLE RESPONSES

FIGURE 34  
AP25-P442

temperature profile in Fig. 31 for the  $x = 0.8$  cm location of the thermocouple. The comparison shows that the thermocouple signal starts rising 0.1 sec after the beginning of the current pulse which lasts 1 msec. The maximum is reached at approximately 7.5 sec showing a delay of 7 sec relative to the computed position at approximately 0.5 sec. This delay may be caused by the retardation of the heat wave through the epoxy insulation on the tip of the thermocouple. This same epoxy coating undoubtedly degraded the thermocouple signal such that calculation of absolute power deposition in the anode is not meaningful. However, an indication of the fractional power deposition at the anode can be obtained from the oscillograms of the temperature signals at a time  $t = 25$  sec. This time was chosen as a compromise between the time at which the computed temperature starts to level off at approximately 5 sec in Fig. 31 and the later time corresponding to the delay of the signal by approximately one-order of magnitude due to the epoxy insulation mentioned above. For example, for the discharge at 17.5 kA and 200 volts at a mass flow of 7.8 g/sec, the temperature rise of  $0.5^{\circ}\text{C}$  at 25 sec in Fig. 34b is divided by  $\theta/F_0 = 1.25 \times 10^{-4}^{\circ}\text{C/Watt-cm}^2$ ) which is computed from equation III-6 for the  $x = 0.8$  cm location and the same time  $t = 25$  sec. Multiplication by the cross-sectional area of  $37\text{ cm}^2$  at  $x = 0.8$  cm then yields the point plotted at 3.5 MW in Fig. 35. The computed heat flux amounts to 150 kW and would indicate a power fraction of 5% of deposited power; however, arbitrary units have been used for the presentation in Fig. 35 for the reasons cited above. The other points in Fig. 35 were obtained from the thermocouple responses in Fig. 34a,c,d, and e for discharges at 13, 20.5, 23 and 25 kA. The decrease by almost a factor of two in fractional deposited power over the observed range of power from 3 MW to 7.5 MW differs from the factor of approximately

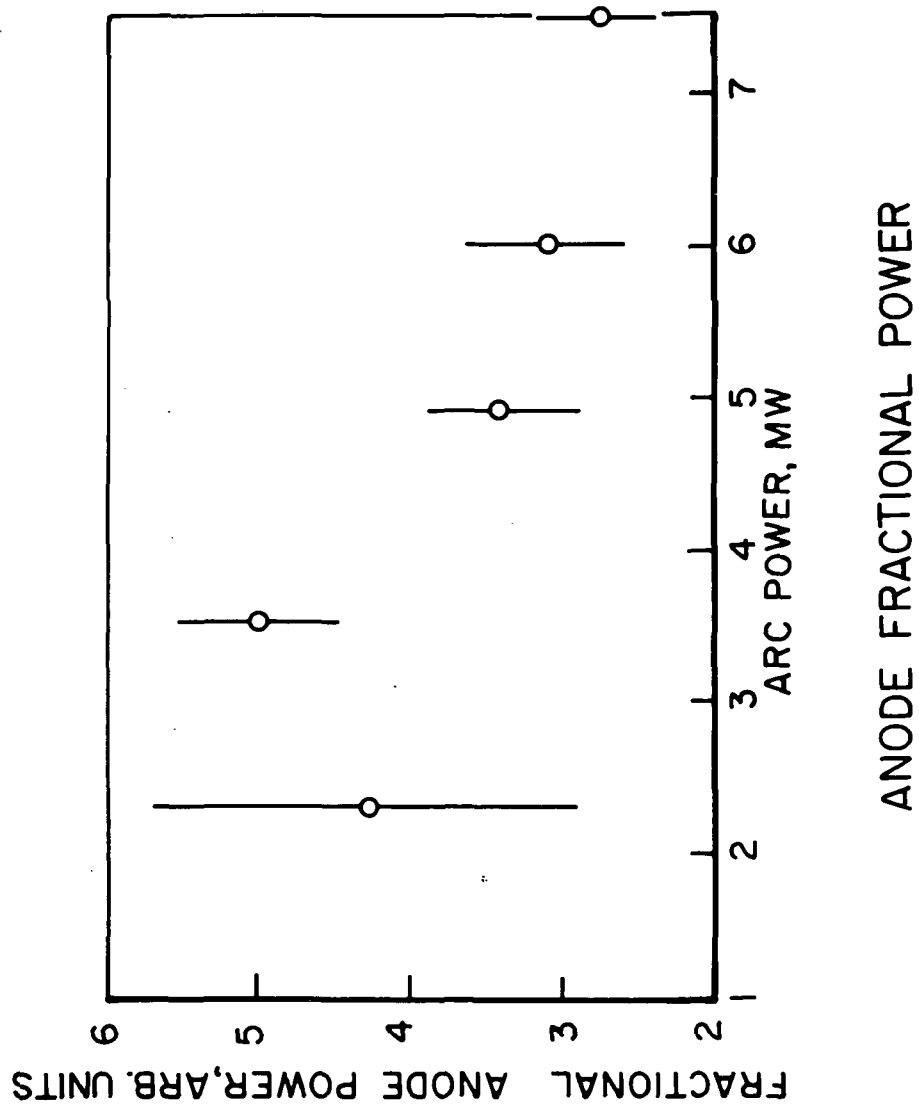


FIGURE 35  
AP25-4823

three which was determined by Oberth for the same power range.

#### Continuing Studies

An aluminum anode of the same shape and dimensions as those in the reported work but with a wall thickness of only 0.1 cm has been designed and manufactured. This configuration can be expected to represent very closely a one-dimensional finite solid model perpendicular to the anode surface since the temperature gradients should be small over anode dimensions which are much larger than the 1 mm wall thickness. This hollow anode has been assembled into a new MPD discharge facility which offers the substantially increased volume of a new Pyrex bell jar of 45 cm diameter x 76 cm length to the exhaust flow. Initial calibration experiments are now in process on this new facility.



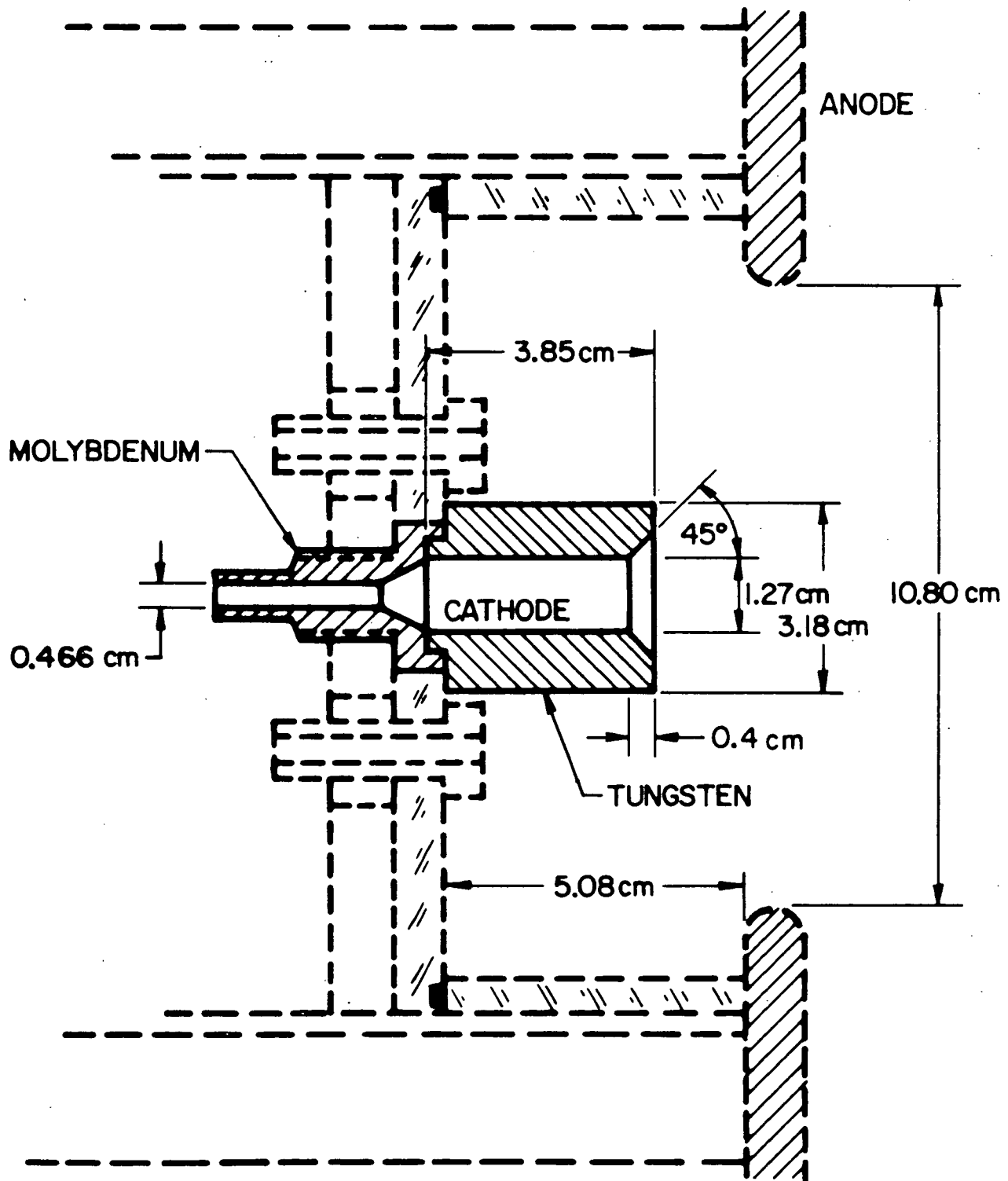
## IV. SELECTION OF OTHER PROGRAMS IN PROGRESS

IV-A. Hollow Cathode, Quasi-Steady MPD Arc (Parmentier)

The advantages of hollow cathode operation in low power arc discharges have been well documented.<sup>130</sup> When the operating conditions and geometry are proper, a stable discharge emanates from the cathode cavity resulting in a lower cathode fall voltage, lower radiation losses, and less erosion. The realization of similar performance improvements at high arc power has been the motivation for an exploratory series of experiments in a pulsed MPD configuration.

The first experiments in this program involved stainless steel hollow cathodes, both with and without nylon insulation over the outer surface. Arc operation with these cathodes produced changes in the current-voltage characteristics from solid cathode operation depending upon the particular cathode geometry and division of the flow between cathode and chamber injectors.<sup>123</sup> However, since these data were accompanied by severe erosion of cathode or insulation for most operating conditions, it was difficult to isolate the effect of hollow cathode.

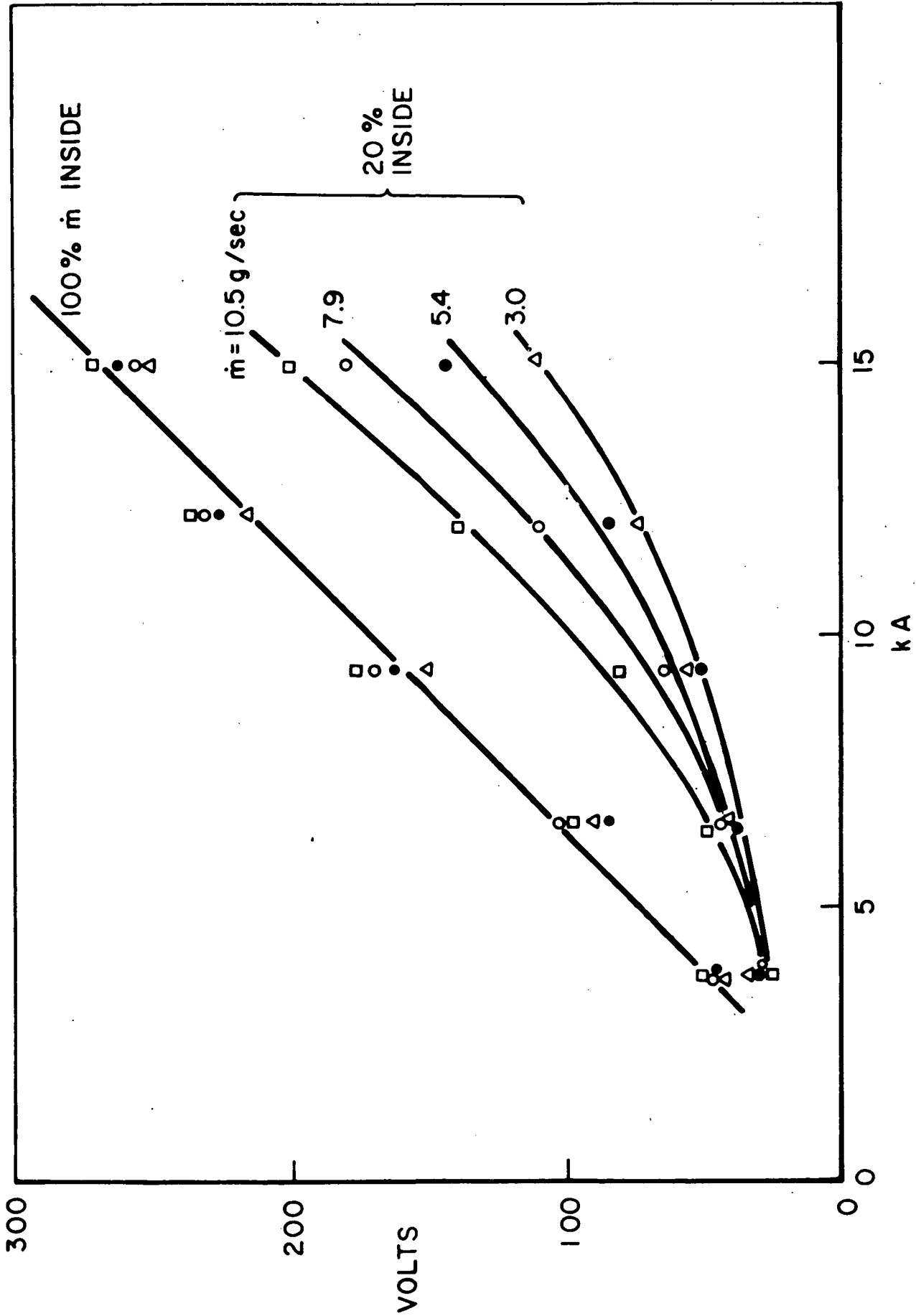
A new cathode has been manufactured from 2% thoriated tungsten and installed in the arc chamber. This cathode, shown in Fig. 36, has a 3.18-cm O.D. and a 1.27-cm I.D., which should be amenable to detailed probing of its interior. The 45° bevel on the downstream face closely coincides with erosion patterns of previous stainless steel hollow cathodes, and resembles the shape found empirically in ref. A-7 to produce a stable steady state discharge over a wide range of mass flows.



TUNGSTEN HOLLOW CATHODE  
AND DISCHARGE CHAMBER GEOMETRY

The voltage-current characteristics for the tungsten hollow cathode differ considerably from those of the solid conical tungsten cathode. Typical tungsten hollow cathode discharge characteristics for different total mass flows and combinations of mass flow through the cathode cavity and outer injectors are shown in Fig. 37. Particularly interesting is the sensitivity of the characteristic to total mass flow for the 20% inside case, and the apparent insensitivity to mass flow for 100% of the flow through the cathode. For comparison, the characteristics of the solid conical tungsten cathode discharge are shown in Fig. 38 for the same regime of operation. Note that for the tungsten hollow cathode the voltage increases with increasing mass flow, whereas for the tungsten solid conical cathode the voltage decreases for increasing total mass flow. This difference was observed even when all of the flow in the hollow cathode case was injected through the outer orifices, which means that the very existence of a cavity in the cathode causes a drastic change in operation.

Since we have a combination of mass flow outside and inside, there are the possibilities that only the gas flow outside, or inside, or both together determine the discharge impedance characteristics. Figure 39 shows the results of tests to determine whether just the inside or just the outside flow is dominant. The dashed line is the characteristic for a total mass flow of 5.4 g/sec of which 45% is inside, i.e., 2.45 g/sec inside, and 2.95 g/sec outside. If the mass flow inside does not participate in the discharge, the characteristic of 5.4 g/sec total (2.95 g/sec outside) should agree with the 3 g/sec outside, zero flow inside case. That it does not implies that the hollow cathode mass flow has an effect on the discharge. A similar comparison between the 5.4 g/sec characteristic and the 3 g/sec inside, zero



TUNGSTEN H.C. CHARACTERISTICS

FIGURE 37  
AP 25-4772

## TUNGSTEN SOLID CONICAL CATHODE CHARACTERISTICS

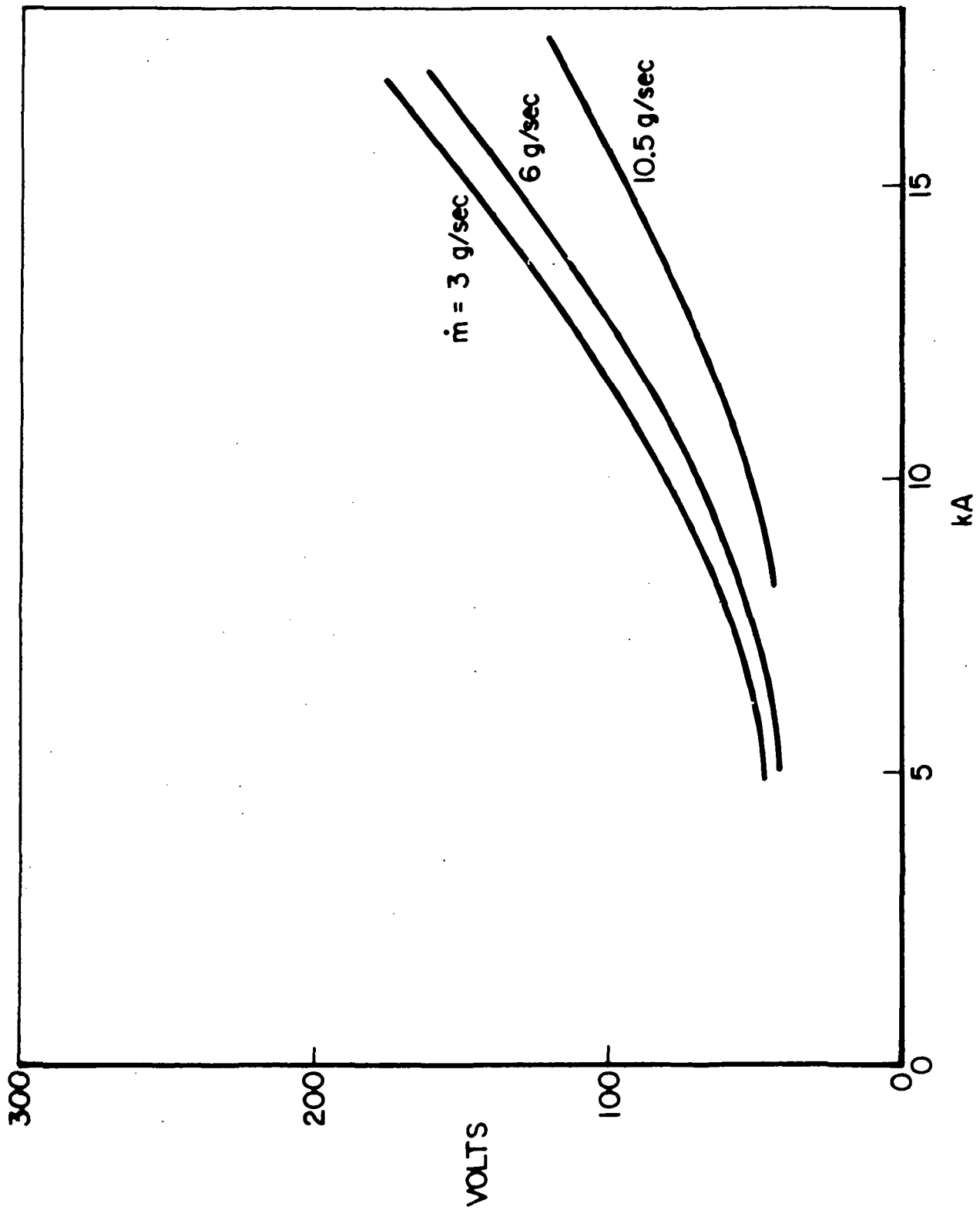


FIGURE 38  
AP25-4771

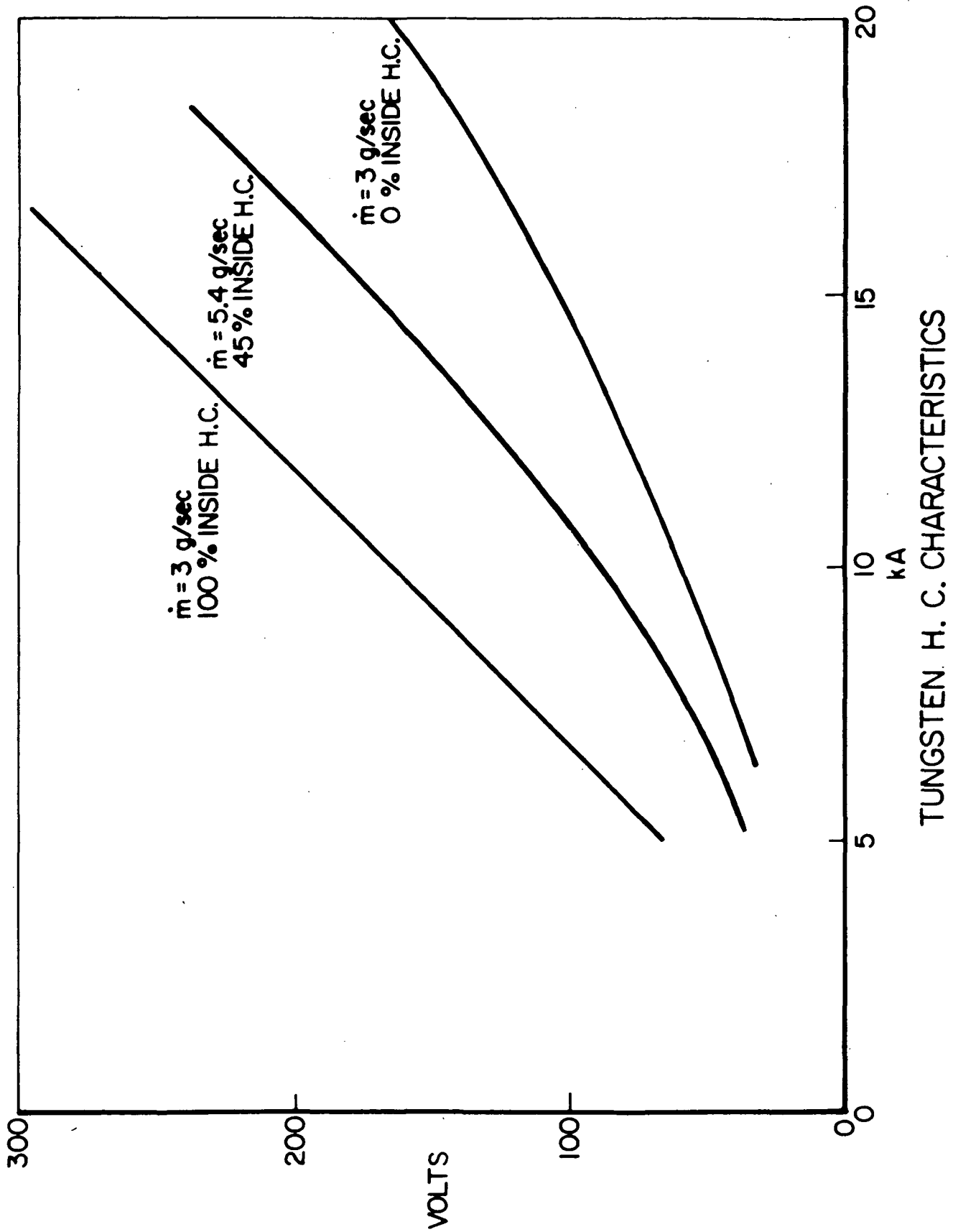
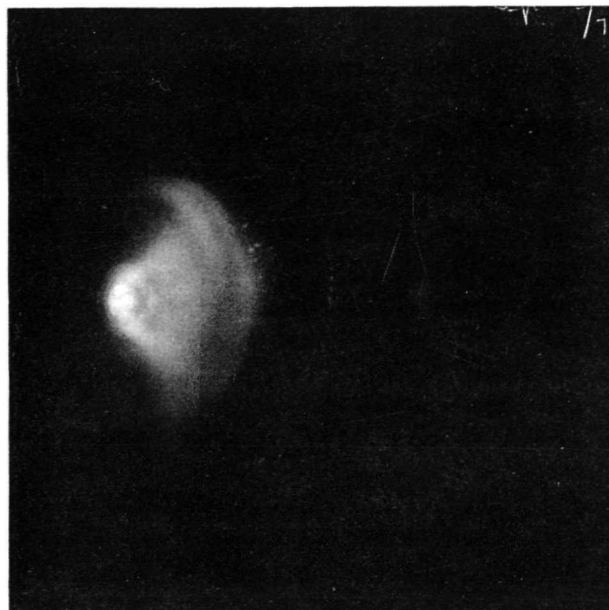


FIGURE 39  
AP25-4774

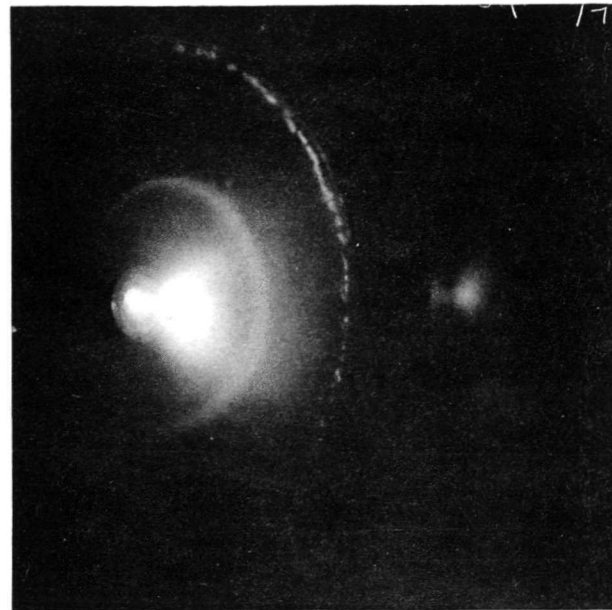
flow outside case reveals that the hollow cathode does not completely dominate the characteristic. Thus, we can conclude that both mass flows outside and inside influence the operation of the hollow cathode discharge.

One factor which may influence whether the discharge attaches inside the cathode cavity is the balance between magnetic pressure which tends to drive the discharge upstream into the cavity, and gasdynamic pressure which tends to blow it out. There is experimental evidence which indicates that under certain operating conditions, the imbalance of these pressures in either direction can dominate the discharge behavior. Figure 40 shows a typical sequence of 5  $\mu$ sec Kerr-cell photographs of the start of the discharge with the tungsten hollow cathode for a total mass flow of 7.9 g/sec of which 82% is inside. The discharge appears to start inside the cavity, where a luminous plasma is observed in Fig. 40a. This initiation of the discharge may be related to a higher neutral density inside the cavity providing the required product of pressure and gap spacing for breakdown. After several microseconds, a luminous plasma is seen to be expelled from the hollow cathode, Fig. 40b and 40c. One possible explanation for this phenomena is that the gasdynamic pressure inside the cavity is increased by ohmic heating and subsequently overwhelms the rather small magnetic pressure at this early phase of the discharge. At later times, Fig. 40d, the luminosity moves to the front surface of the cathode, where it remains during the quasi-steady part of the pulse.

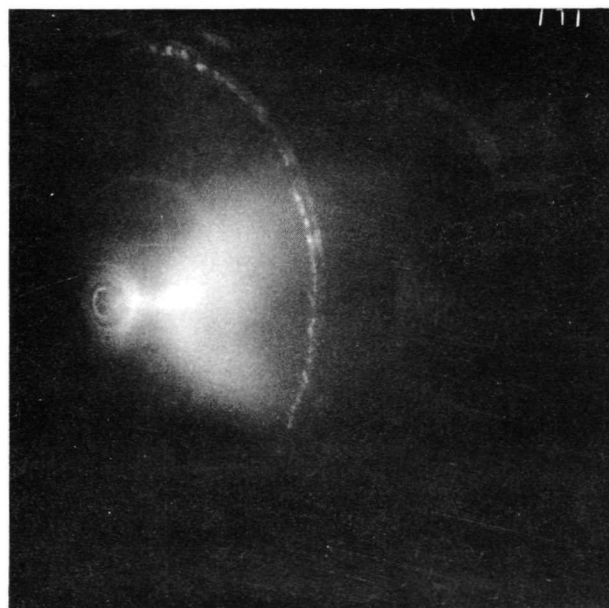
Evidence that the magnetic pressure can dominate the gasdynamic pressure is shown in Fig. 41. The stainless steel hollow cathode shown sectioned in the photograph initially had a constant diameter cavity and a nylon covering over both the outer surface and the downstream face. After approximately



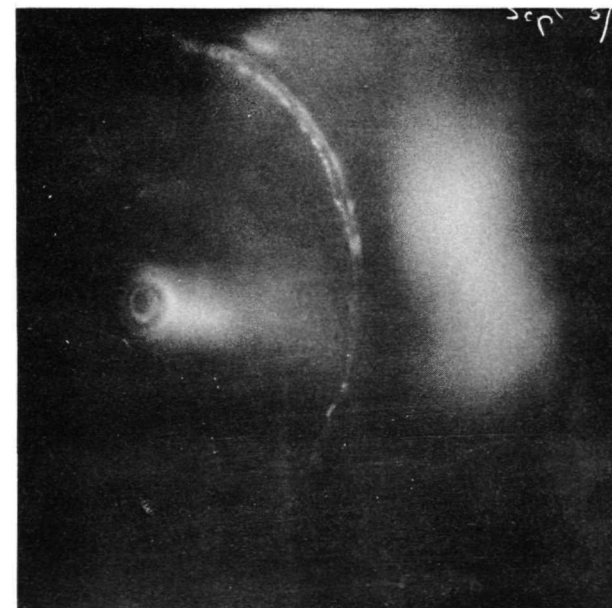
a) 1.8 kA , 143 V  
1.5  $\mu$ sec



b) 11 kA , 195 V  
8.7  $\mu$ sec



c) 14.7 kA , 240 V  
16.5  $\mu$ sec

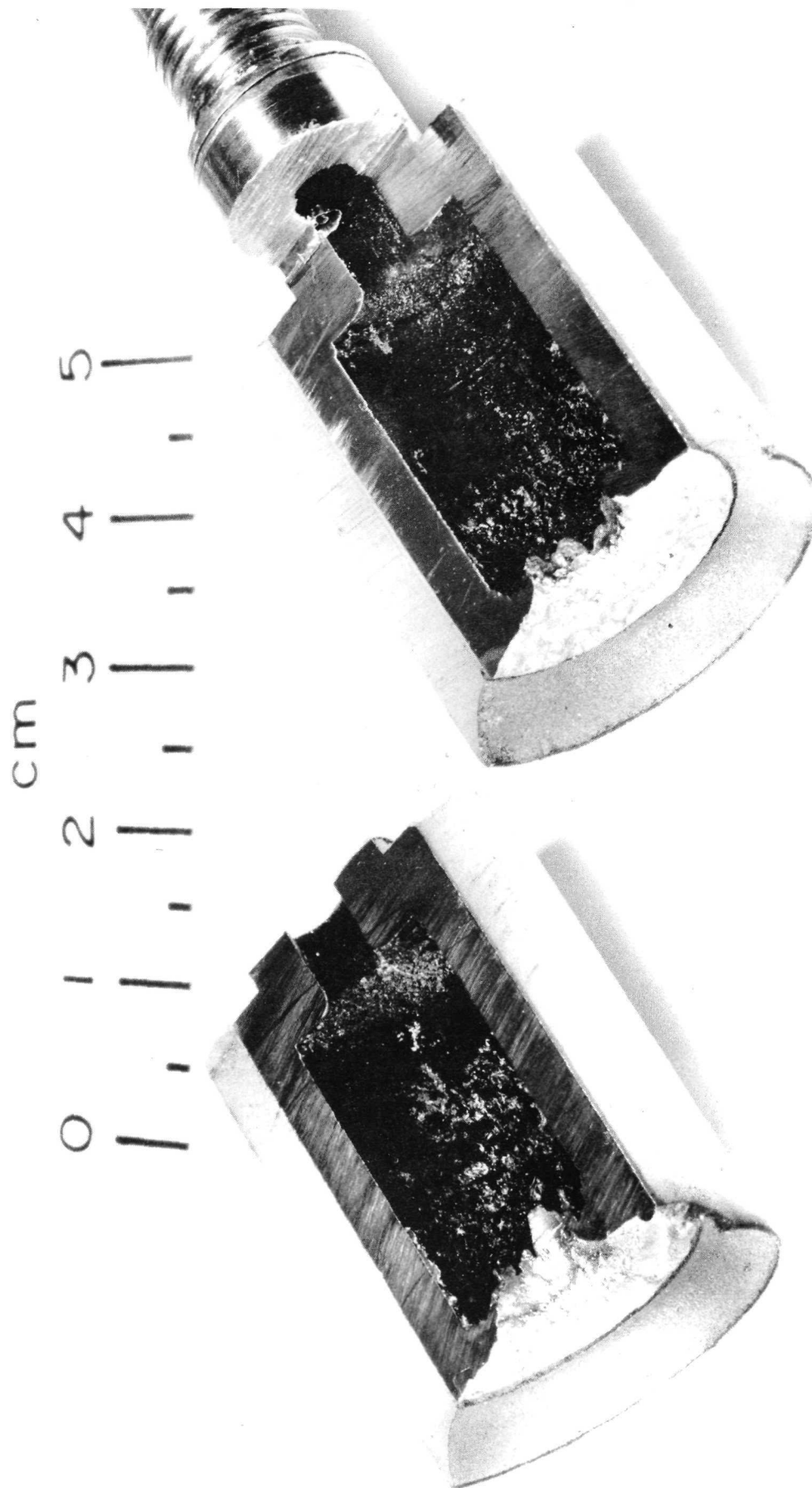


d) 15 kA , 290 V  
30  $\mu$ sec

STARTING SEQUENCE WITH TUNGSTEN HOLLOW CATHODE  
 $\dot{m} = 7.9$  g/sec , 82 % INSIDE







SECTIONED HOLLOW CATHODE

FIGURE 41  
AP25-P 451



100 shots, striking changes are observed. The cathode face has been severely eroded, most probably because the nylon has forced all of the current to attach within the cavity. It is seen that this eroded material has been forced upstream by the magnetic pressure and deposited uniformly on the inner walls of the cavity. Molten material from the cathode face has also flowed inwards, decreasing the cavity exit diameter from 1.2 cm to 0.6 cm. The conclusion to be drawn from Figs. 40 and 41 is that the pressure balance is an important parameter which must be controlled in future experiments.

The preceding work concludes the preliminary phase of the hollow cathode experimental program. More complete details and analysis of these data are available in the MSE Thesis of Mr. Noël Parmentier, who has subsequently returned to Belgium.

Although valuable experience has been gained regarding the operation of a hollow cathode in a high power quasi-steady MPD discharge, many fundamental questions remain to be answered. In order to study this problem in more detail, a new facility is under construction which will be used solely for hollow cathode work. This facility will have a current capability of 1 to 20 kA and will be constructed to allow the necessary detailed diagnostics for determining the current and potential distribution around the cathode as well as species distribution within the cavity. First experiments should be conducted in approximately four weeks.

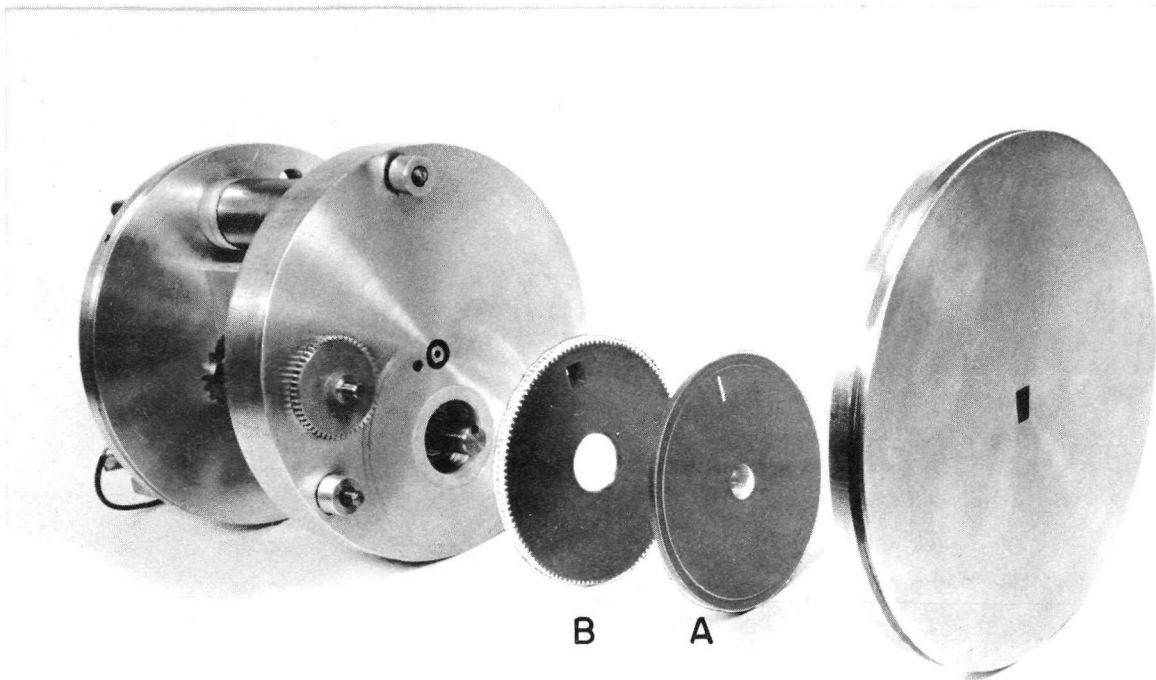
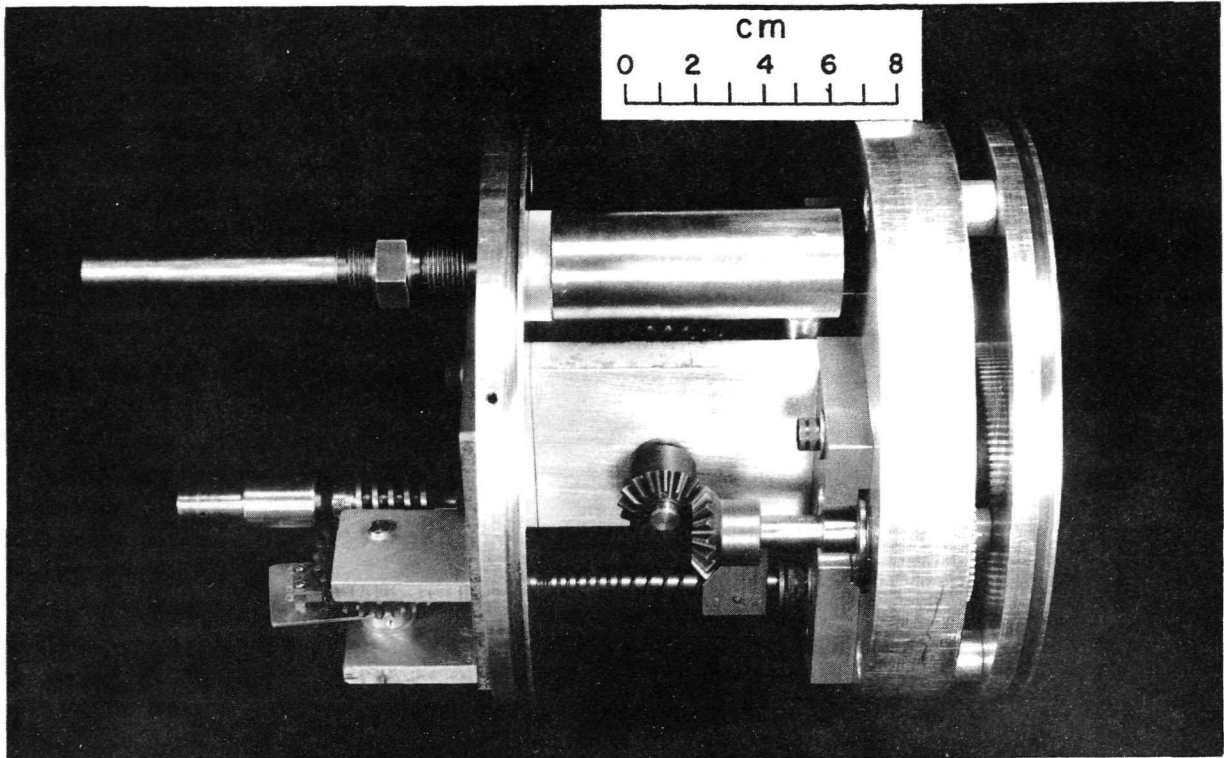
#### IV-B. Repetitive Pulse Propellant Injection (White)

The generation of discrete mass pulses with stringent requirements on pulse risetime and shape and minimum leakage between pulses has been identified as one of the major problems to be solved in a complete quasi-steady thruster

system. In an effort to initiate interest in this problem, we have undertaken an experimental program to examine the range of pulse shapes which can be produced by a propellant injection scheme with no reciprocating parts.

A prototype of this valve, which is called the turbo-pulse gas injector, is shown in Fig. 42. The heart of the valve is the pair of Teflon-coated discs (A and B), each with a single slot and rotating at a different angular velocity. The discs are housed in an evacuated manifold to one side of which is attached an argon reservoir and feed line. Gas flows through the manifold and disc combination when both slots are coincident with the inlet and outlet ports of the manifold, the pulse shape and frequency thus determined by the slot and disc dimensions, angular rotation rates, and the number of slots. For the configuration shown in Fig. 42 the mass pulse should ideally have rise and fall times one-tenth the constant flow time, with a duty cycle  $\delta$  (on-time divided by the sum of on-time plus off-time) of  $10^{-3}$ . Gas leakage is prevented by applying slight pressure to the closely machined, Teflon-coated discs, thus forming a seal which should absorb less energy, and hence wear less, than the seals in reciprocating valves.

Early data with this valve<sup>123</sup> showed a pulse shape in reasonable agreement with calculated profiles, but with a total risetime considerably longer than anticipated. The problem was traced to the difficulty in precisely aligning both slots with the fixed outlet port in the valve housing during the assembly process. Recently, a linkage was added to the gear train which allowed continuous adjustment of the slot coincidence location with respect to the outlet port during valve operation.



MULTIPLE PULSE PROPELLANT VALVE

FIGURE 42  
AP25-P394

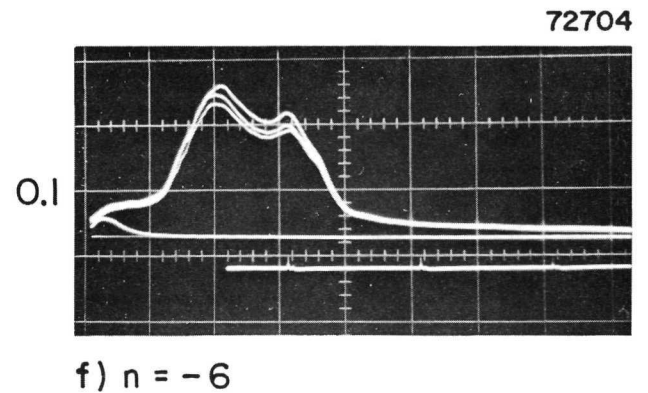
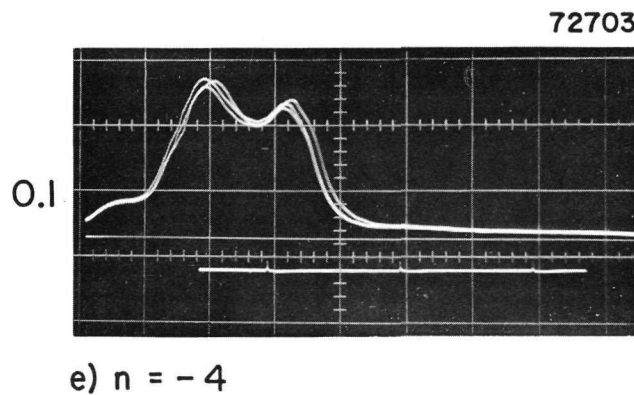
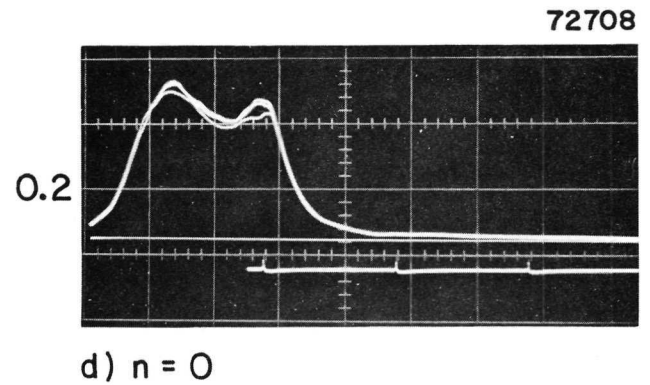
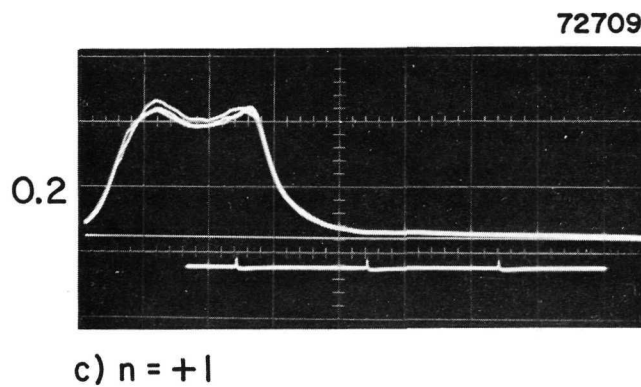
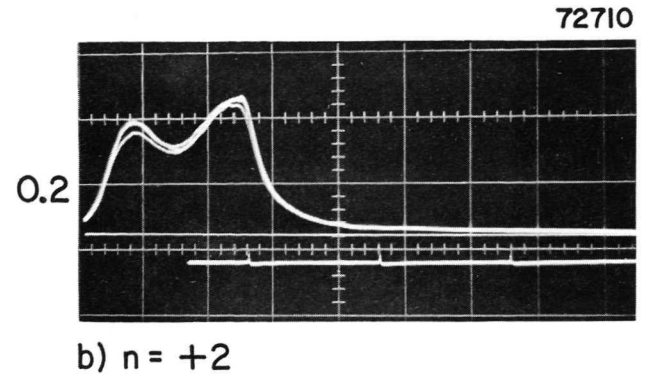
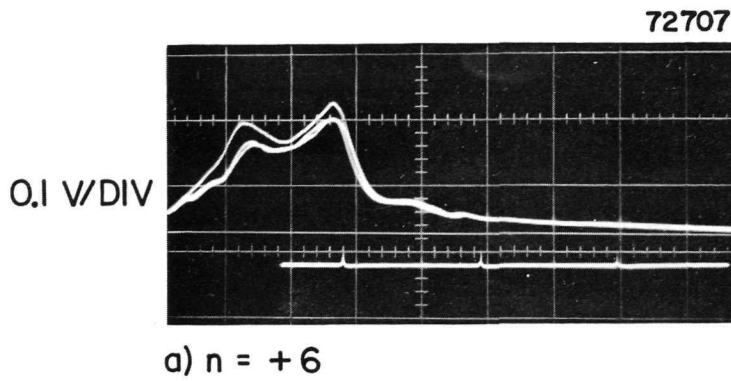


Figure 43 shows the mass pulse profile on two different time scales, as recorded by a Millitorr fast ionization gauge, for various settings of the coincidence adjustment nut (shown as an integral number of turns  $n$  from an arbitrary zero reference position). The lower trace, on a 0.5 sec/division time scale, shows the pulse repetition rate, which was held constant at 1 pulse per second (pps) for these data. The null signal between pulses indicates that leakage through the valve is negligible. Details of the pulse shape are displayed on the upper trace of each oscillogram, which is a triple overlay on a 0.5 msec/division sweep rate. The mass pulse profile is seen to be both reproducible and sensitive to the setting of the adjustment nut. Comparison of these profiles and their corresponding deflection scale factors reveals that not only is the best pulse shape produced at the  $n=+1$  setting, but the maximum flow rate also occurs at this position. Consequently, the  $n=+1$  setting was retained for all subsequent pulse conditions discussed.

A portion of the range of pulse lengths and pulse repetition rates that the present valve can produce is shown in Fig. 44. The operating range for other combinations of slots and duty cycles are shown in reference 123. Movement along the line shown in Fig. 44 is accomplished by varying the speed of the motor driving the high speed disc. For reference purposes, the 1 msec pulse, 1 pps condition corresponds to a motor speed of 1500 rpm. Mass pulse shapes have been recorded for the four conditions circled in this figure. These profiles, shown in Fig. 45, display the similarity that the rise and fall times are approximately the same fraction of the total pulse length in all cases.







### MASS PULSE PROFILE VARIATION WITH SLOT COINCIDENCE

UPPER TRACE : 0.5 msec/DIV

LOWER TRACE : 0.5 msec/DIV

$P_0 = 1.67 \text{ atm}$

FIGURE 43

AP 25-P443



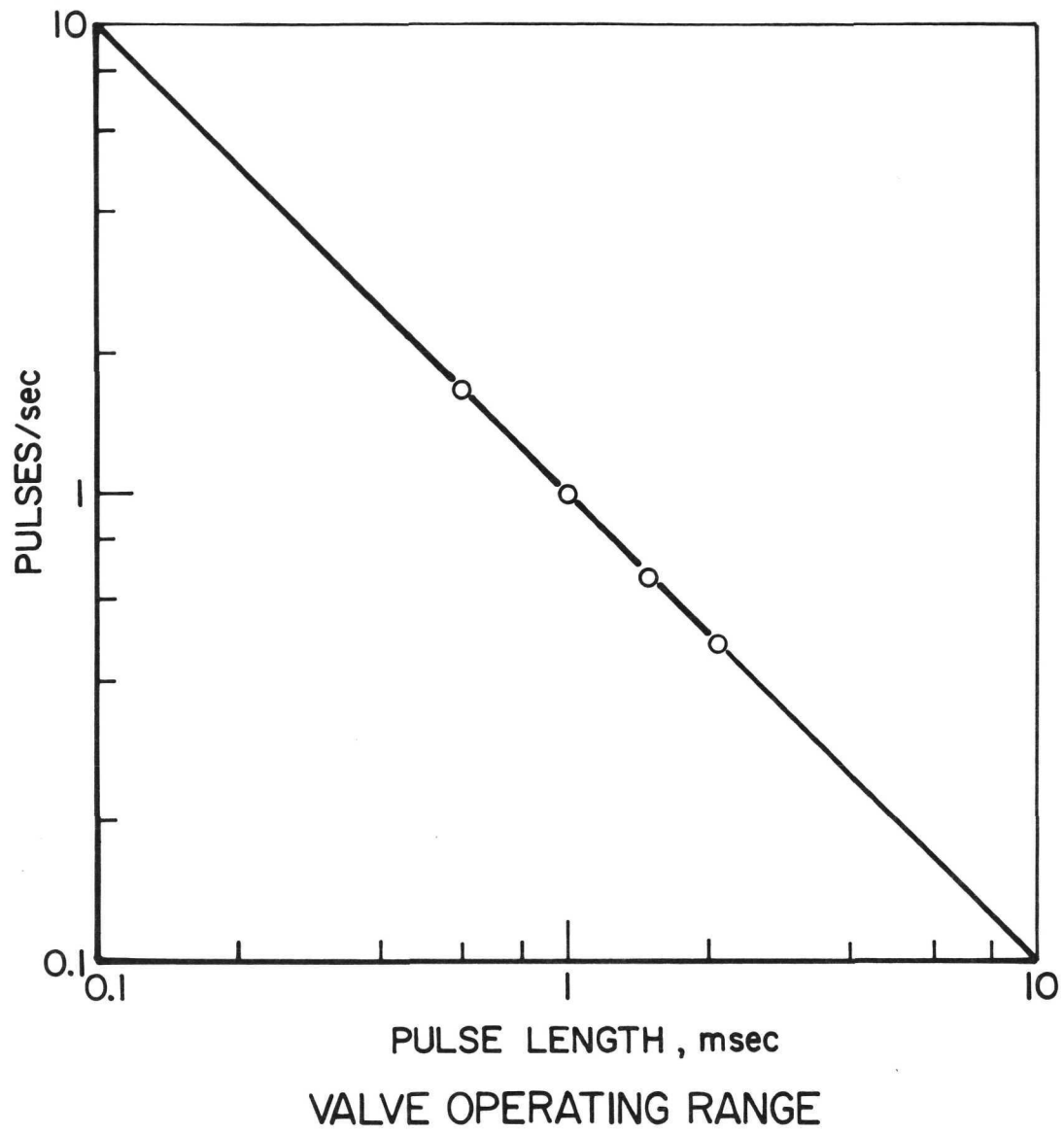
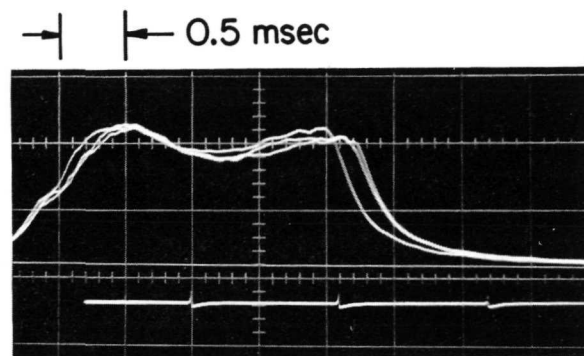
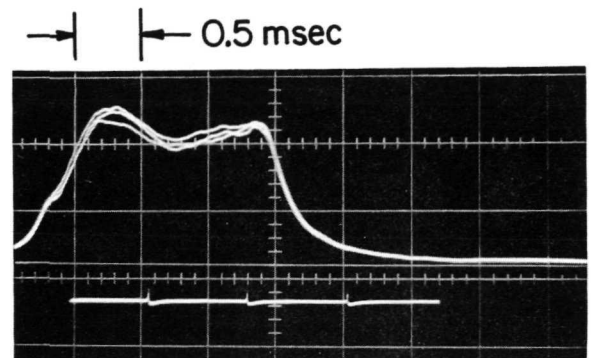


FIGURE 44  
AP25-4824

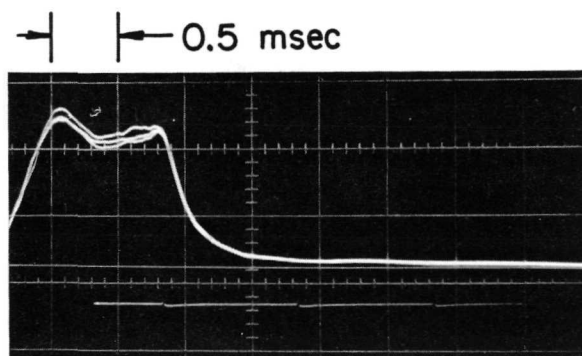




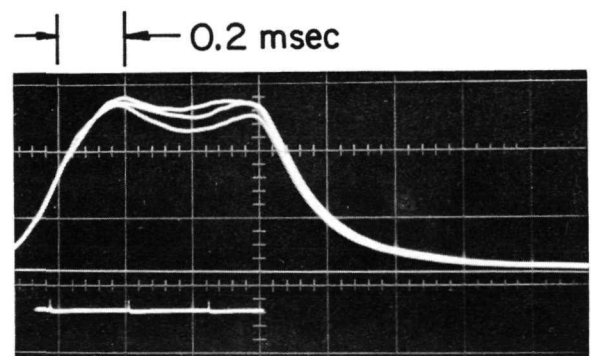
a) 0.46 pulses/sec



b) 0.67 pulses/sec



c) 1.0 pulse/sec



d) 1.7 pulses/sec

PULSE SHAPE VARIATION WITH  
PULSE FREQUENCY  
 $P_0 = 1.67 \text{ atm}$

FIGURE 45  
AP25-P 444

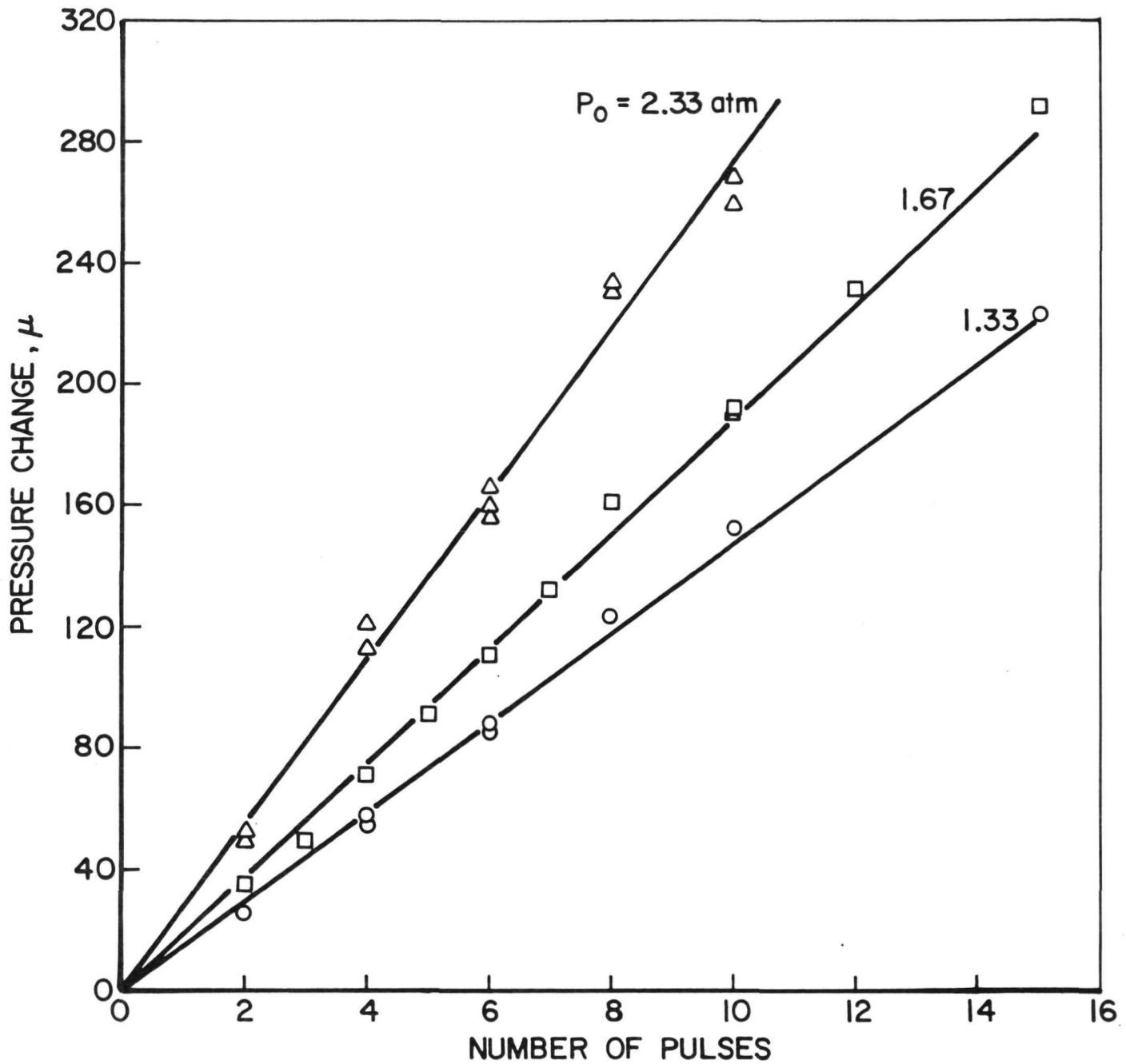


The characteristic double-humped shape of each mass pulse was at first thought to be caused by gasdynamic transients in this particular geometry. However, the data of Fig. 45 refute this premise since no single characteristic time can be identified for the various length pulses. Saturation of the ionization gauge, which could cause the apparent dip in the recorded signal, has been eliminated as a source of the problem since the profiles are virtually identical at both high and low argon reservoir pressures (and thus high and low ambient density levels at the valve exit where the pulse shape is monitored). One possible explanation is that the actual cross sectional area through the discs and manifold combination may have a time dependence similar to that of the observed pulse. This geometrical effect is presently under investigation.

The reproducible pulse shapes allow a calculation of the total mass flow through the valve and of the mass flow rate during the flat portion. The total mass injected per pulse was determined by injecting a given number of pulses into a closed vacuum tank of known volume. Figure 46 presents net pressure rise data in the vacuum tank for various numbers of pulses at three argon reservoir pressures,  $P_0$ . The slopes of these lines give the net pressure increase per injected pulse which, for the known volume, implies injected mass per pulse at a particular reservoir pressure.

Determination of the instantaneous mass flow rate requires an integration of the pulse shape in time and comparison of the integral with the total injected mass calculated above. This process yields a value for the arbitrary scale factor on the ordinate of the typical mass flow profile shown in Fig. 47. For this particular condition, the scale factor is calculated to be 0.163 g/sec per division. Thus,





PRESSURE RISE FOR MULTIPLE VALVE PULSES

FIGURE 46  
AP25-4831

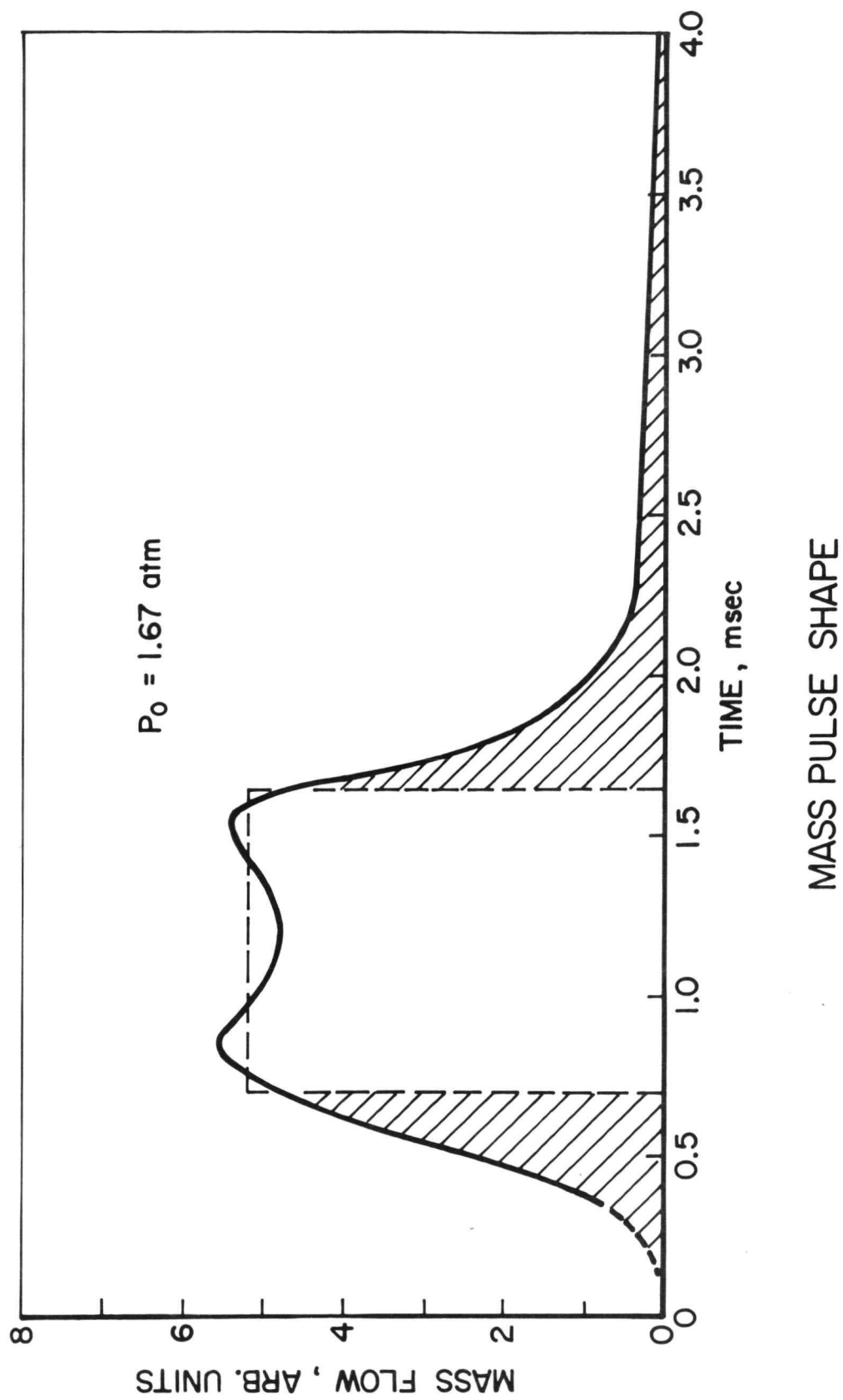


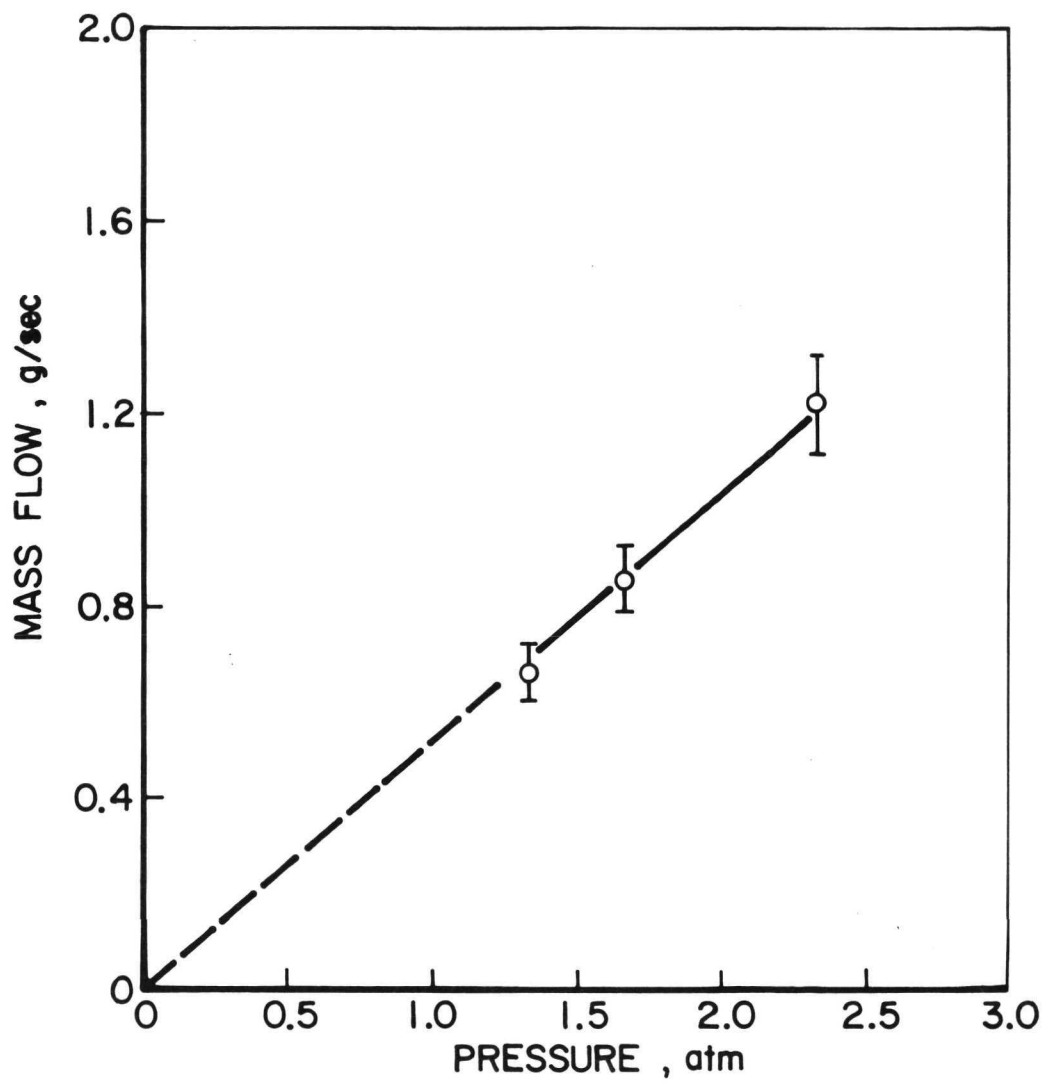
FIGURE 47  
AP25-4825

the mass flow as shown by the dashed line is  $0.85 \text{ g/sec} \pm 8\%$  during the 0.95 msec plateau of this pulse.

Following a similar procedure for the other two reservoir pressures results in the mass flow calibration curve shown in Fig. 48. It is seen that a line drawn from the origin passes through the data points, which is consistent with the assumption of supersonic flow through the choked orifice in the high speed disc.

The dashed area shown in Fig. 47 at the beginning and end of the pulse represents mass which would not be accelerated by a 1-msec discharge and would thus decrease the effective specific impulse. In an analogy to ion engine technology, a mass utilization efficiency can be defined as mass accelerated by the discharge divided by total mass injected. For the pulse shown in Fig. 47, this mass utilization is approximately 68%, a reasonable value considering the early stage of valve development.

It is clear from the mass flow calibration that in order for such a valve to be considered further for a space thruster, both mass flow rate and the mass utilization must be greater. The mass flow can be increased by either increasing the reservoir pressure or increasing the slot area in the high speed disc. Because a greater reservoir pressure will require closer contact between the discs to prevent leakage and will thus result in increased wear, the former appears least desirable. The slot area can best be increased by scaling up all radial dimensions. Then, for the same angular rotation rate both the mass flow rate and mass utilization should be improved. In addition, further testing is required to determine the valve's long term wear characteristics and compatibility with the discharge.



MASS FLOW CALIBRATION

FIGURE 48  
AP25-4826

#### IV-C. Probe for Impact Pressure Measurement (Dutt)

Piezoelectric pressure measurements in the exhaust plume and discharge chamber have been previously obtained by J. Cory using the standard MPD arc geometry and shock tube injection of mass flow.<sup>123,125</sup> This mode of mass injection made it extremely difficult to determine experimentally the mass flow rate during the arc discharge due to the time-dependent post-discharge flow. Consequently, mass flow rates were calculated based on measured stagnation pressure in the driven section and an assumed stagnation temperature. This uncertainty necessarily qualified some of Cory's results concerning the mass flux and its distribution downstream of the anode orifice, as determined by measured impact pressure and velocity profiles. With the new valve injection system, the mass flow rate can be accurately determined experimentally. Repeating the impact pressure and velocity measurements in this exhaust should thus provide a more accurate assessment of the distribution of mass, momentum and energy in the plasma flow.

Prior to these measurements, the piezoelectric probe was modified to improve the signal-to-noise ratio. The calibration of this probe, by a technique not previously described in these semi-annual reports, was undertaken by Mr. Gautam S. Dutt, a new graduate student in our laboratory who received his earlier training at the University of London. His report of these preparatory steps follows.

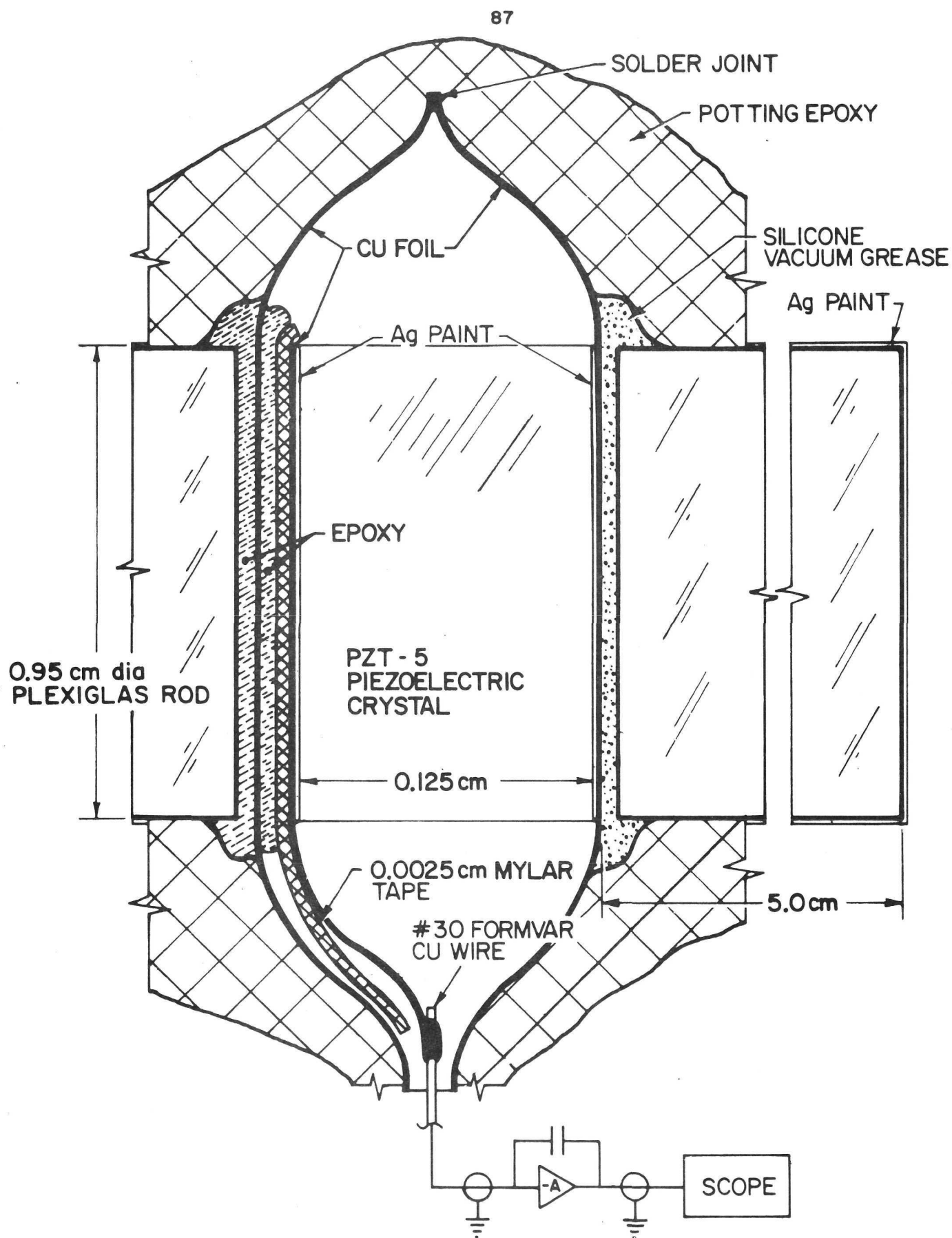
The pressure sensor is a 0.95-cm-dia, 0.125-cm-thick lead zirconate titanate crystal (PZT-5) mounted coaxially between two 0.95-cm-dia Plexiglas rods whose lengths are 5 and 90 cm. The tip of the shorter rod faces the pressure to be measured and serves to protect the crystal from direct plasma impingement. The longer backing rod prevents the reflected acoustic wave from interfering with the crystal

response during the 1 msec time of interest. The crystal is mounted between the two rods as shown in Fig. 49 to prevent extraneous acoustic, thermal, and electrical disturbances. Coaxial leads connect the crystal to a charge amplifier and oscilloscope.

The purpose of the calibration experiments are three fold: 1) to verify that the charge developed by the crystal is proportional to the normal force applied at the probe tip and to determine this proportionality constant; 2) to ensure that the probe response time is sufficiently short to measure the plasma pressure history during the 1 msec pulse; 3) to confirm that the reflections of propagated stress waves from the end of the Plexiglas rod do not interfere with the force on the crystal during the time interval of interest.

The voltage-force characteristic of the crystal and charge amplifier system was determined by the "yanked weight" method. The probe was placed on foam rubber isolators with its axis vertical and the probe tip on top. Various known weights are placed concentrically on the probe tip and rapidly yanked off with a string. The resulting sudden drop in voltage was recorded on the oscilloscope, an example of which is shown in Fig. 50a. The sensitivity of the crystal as determined by this technique is  $3.5 \times 10^{-2} \text{ pC}/(\text{N}/\text{m}^2)$  with an error of 3%.

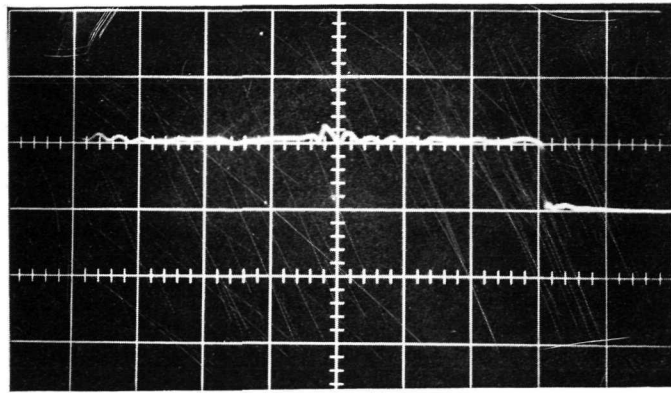
To determine the response time, the probe was suspended horizontally with its sensing surface inserted 0.5 cm into a 5-cm-dia, 1-m-long copper tube open at both ends. A shock wave was generated in the opposite end of the tube via a small detonation from a starter's pistol. The probe response (Fig. 50b) shows a risetime of approximately 14  $\mu\text{sec}$ , which provides adequate resolution for the 1 msec exhaust flow to be probed.



SCHEMATIC OF PRESSURE TRANSDUCER

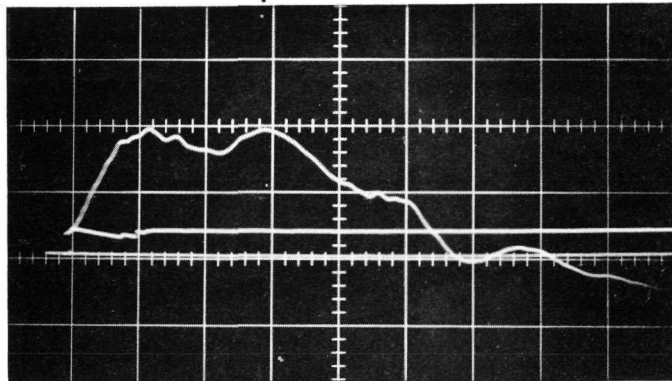
FIGURE 49  
AP25 · 4713

0.1 sec/DIV



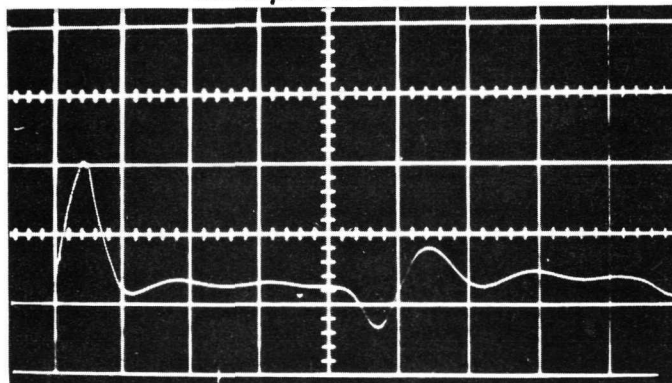
0.5 V/DIV

a) CALIBRATION WITH 50g WEIGHT

20  $\mu$ sec/DIV

0.2 V/DIV

b) RESPONSE TO SHOCK WAVE

200  $\mu$ sec/DIV

c) REFLECTION TIME IN DELAY ROD

## RESPONSE OF PIEZOELECTRIC PROBE



The reflection time in the acoustic delay rod was measured with the probe in this same horizontal position. The 0.3-cm-dia bob of a simple pendulum was made to strike the probe tip. The result, shown in Fig. 50c, indicates that the time interval between the passage of the initial wave and its reflection is 0.86 msec with the intermediate time undistorted.

These tests show that the piezoelectric probe responds with a known output, provides undistorted pressure records for 0.86 msec, and possesses adequate risetime to determine the impact pressure history in the plasma exhaust. Initial measurements of the impact pressure profile are now in progress.

#### IV-D. Propellant Injection (Villani)

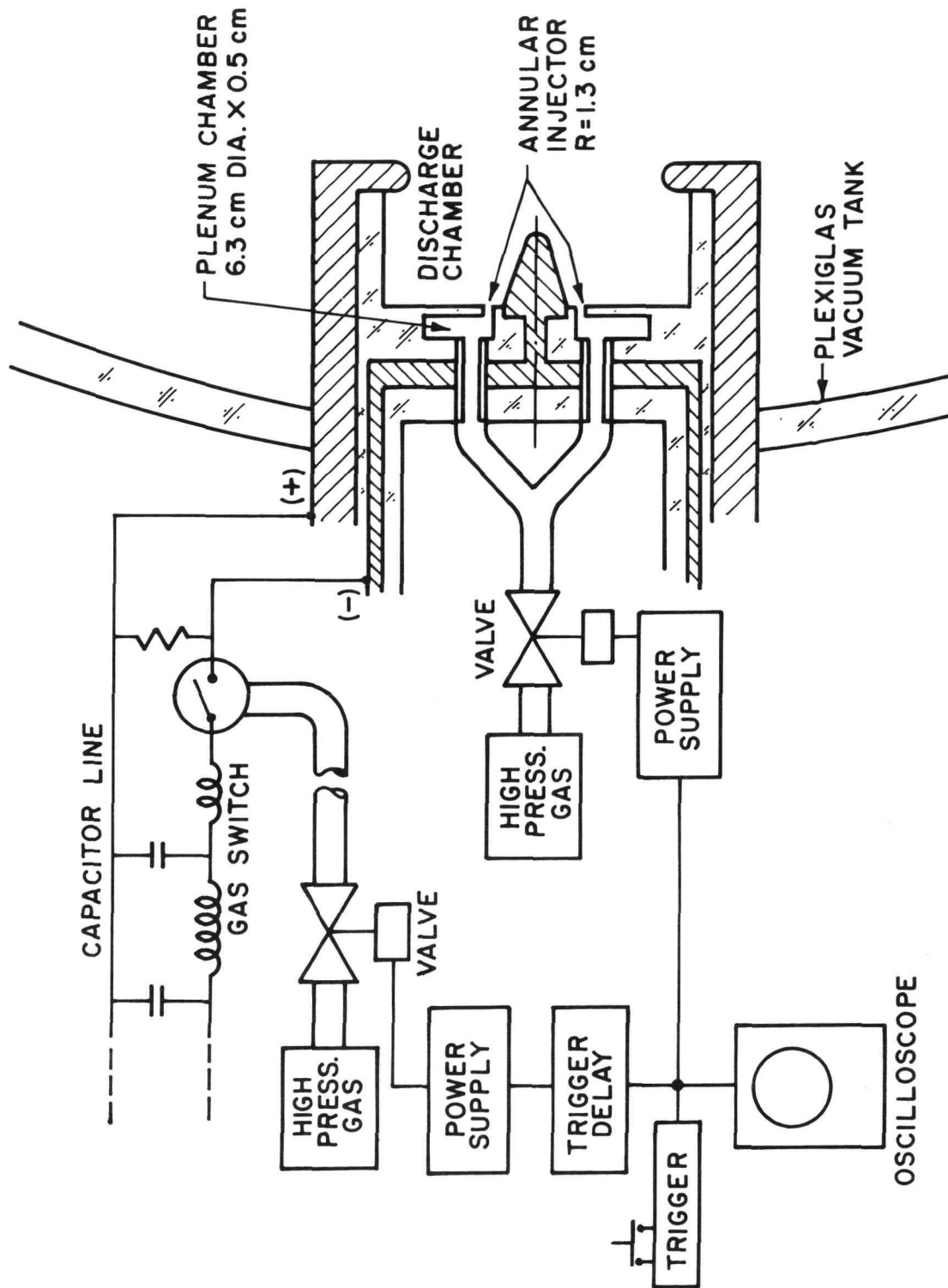
Recent photographs taken through spectral filters have revealed the existence of a previously unsuspected azimuthal structure in the discharge region and in the exhaust flow of the MPD accelerator used at this laboratory. The argon propellant, instead of being uniformly distributed, remains in six well-collimated jets separated by regions with material ablated from the back-plate insulator (Fig. 1c and 2c). The central fastest-moving portion of the exhaust plume contains almost no argon except under conditions of gross oversupply of propellant. In an attempt to provide a more uniform distribution of propellant to the MPD arc, a redesign of the mass injection ports is underway. The first modification, consisting of an annular injector concentric with the cathode has been fabricated and preliminary tests have been conducted, the results of which are presented in this section.

In this modified injector design a circular disk shaped plenum chamber of 6.3-cm-diameter and 0.5-cm-depth, directly behind the rear wall of the discharge chamber, supplies the

propellant to the injector as shown in Fig. 51. The annular injector of 0.16-cm-width and 1.3-cm-inner radius provides the same cross-sectional area to the flow as the six injector ports used previously. The plenum chamber, in turn, receives the argon propellant from six supply lines uniformly spaced in the azimuthal direction.

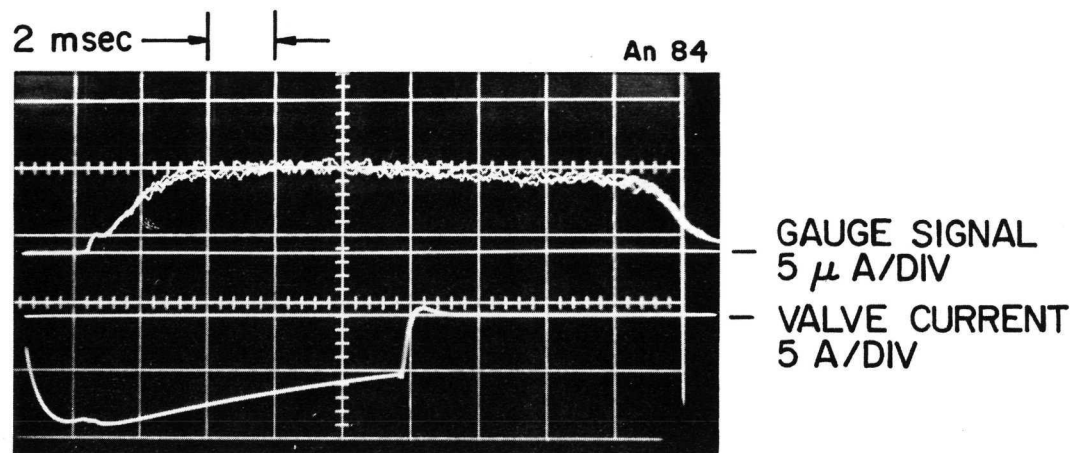
The neutral density pattern of injected propellant was monitored with a Varian Millitorr (TM) fast ionization gauge during cold flow tests, using a technique described in a previous report.<sup>119</sup> The response of the gauge is proportional to neutral density up to a saturation value of approximately 20  $\mu\text{A}$  at approximately  $7 \times 10^{22} \text{ m}^{-3}$ . A typical record of the response of the gauge, located on the center-line in the plane of the anode is shown in Fig. 52 together with the current to the solenoid of the propellant supply valve. The triple overlay of the signal indicates the high degree of reproducibility of the density pattern, while the 2 msec risetime and the decay of the propellant density pulse is seen to be short compared with the duration of the quasi-steady phase of propellant flow. After the propellant flow and the density have reached the steady-state value, the discharge current pulse is initiated by the gas-triggered switch which, in turn, is activated by a pulse of gas from another solenoid valve. Since the additional dead volume and gasdynamic path length of the modified annular injector would require a considerable lengthening of the gas-delay line to the switch, an alternate solution was chosen with an adjustable electronic delay with separate power supply for the switch solenoid valve, Fig. 51.

Figure 53 presents a photographic comparison of the annular injector discharge (Fig. 53a) with that of the hexagonal propellant supply mode (Fig. 53b reproduced here for convenience from Fig. 1c) for the 16.5 kA, 6 g/sec operating condition. The photographs were taken end-on



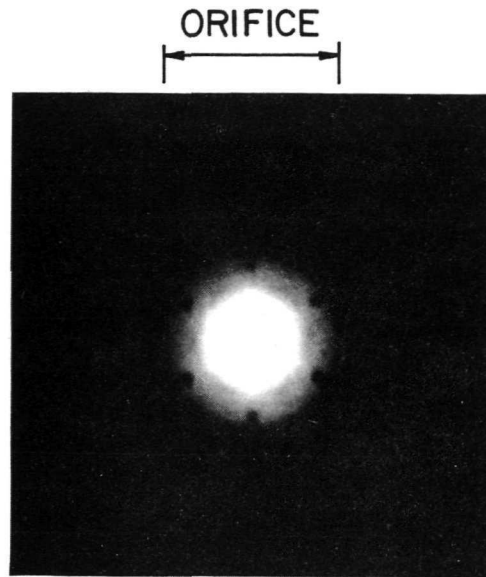
PROPELLANT SUPPLY SCHEMATIC

FIGURE 51  
AP25-4828

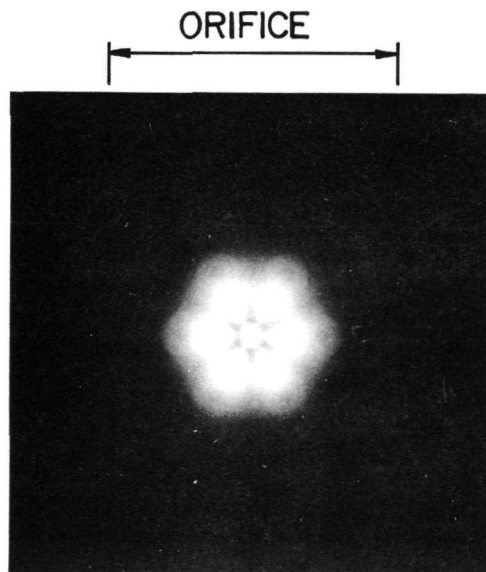


MILLITORR GAUGE RESPONSE WITH ANNULAR INJECTOR

FIGURE 52  
AP25-P 446



a) ANNULAR INJECTOR



b) HEX INJECTORS

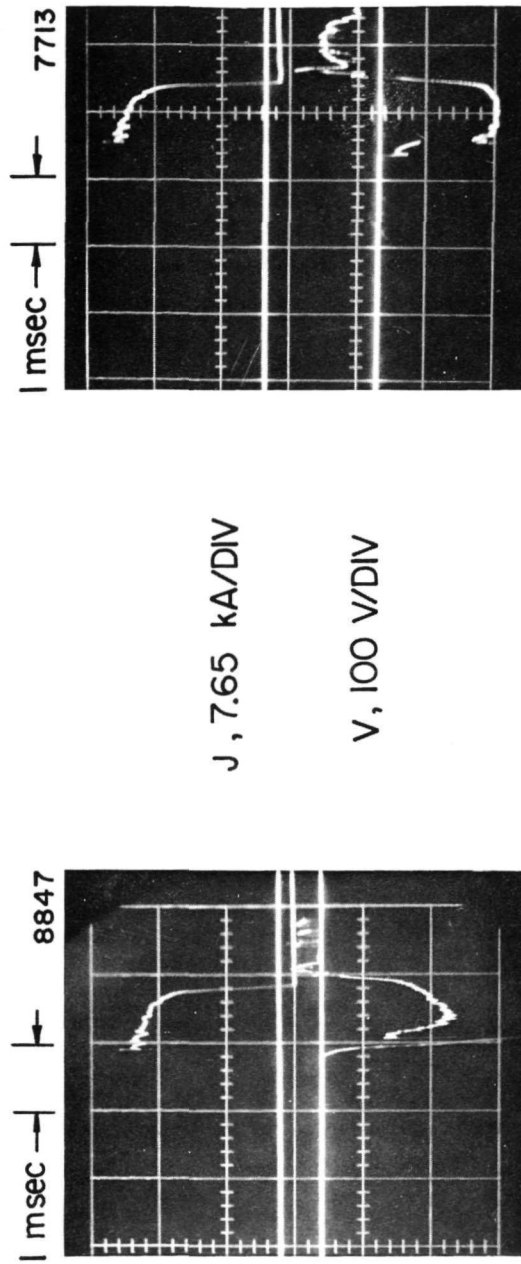
STRUCTURE OF DISCHARGE  
16.5 kA ; 6 g/sec ; FILTER 4880 Å

through the 4880 Å narrow band filter which isolates AII. Although the magnification in Fig. 53b is 1.5 times that of Fig. 53a, the previously observed azimuthal structure of the discharge and exhaust flow cannot be recognized and may have disappeared altogether.

The terminal voltage  $V$  record of the MPD arc with the annular injector, Fig. 54a, is seen to differ considerably from that with the six hexagonally arranged injectors in Fig. 54b. The annular mode is characterized by a noisy and peaked voltage record while the hexagonal mode exhibits a relatively flat record. Note that the current trace is identical in both injection modes due to the high impedance of the pulse forming network.

The dependence of the terminal voltage on the propellant mass flow with the annular injector was also explored and is shown in Fig. 55. For comparison the voltage-mass flow characteristic for the six hexagonally arranged injectors has also been included in the figure for the same current of 16.5 kA. The slope of the characteristic for the annular injector is significantly increased for mass flows below a characteristic value. For mass flow rates above this value the terminal voltage record is found to be constant, or flat, as before. The lower value of the voltage in this region might suggest a higher efficiency for the annular injector; however, examination of the value of  $J^2/\dot{m}$  at these higher mass flow rates shows that this regime is probably one of very low specific impulse and therefore of correspondingly reduced interest as an operating region.

Other preliminary investigations of propellant injection indicate that the propellant density near the anode surface may be a sensitive parameter for efficient operation. Accordingly, an experimental study of mass injection through annuli of various radii and of the direction of propellant injection is in progress.



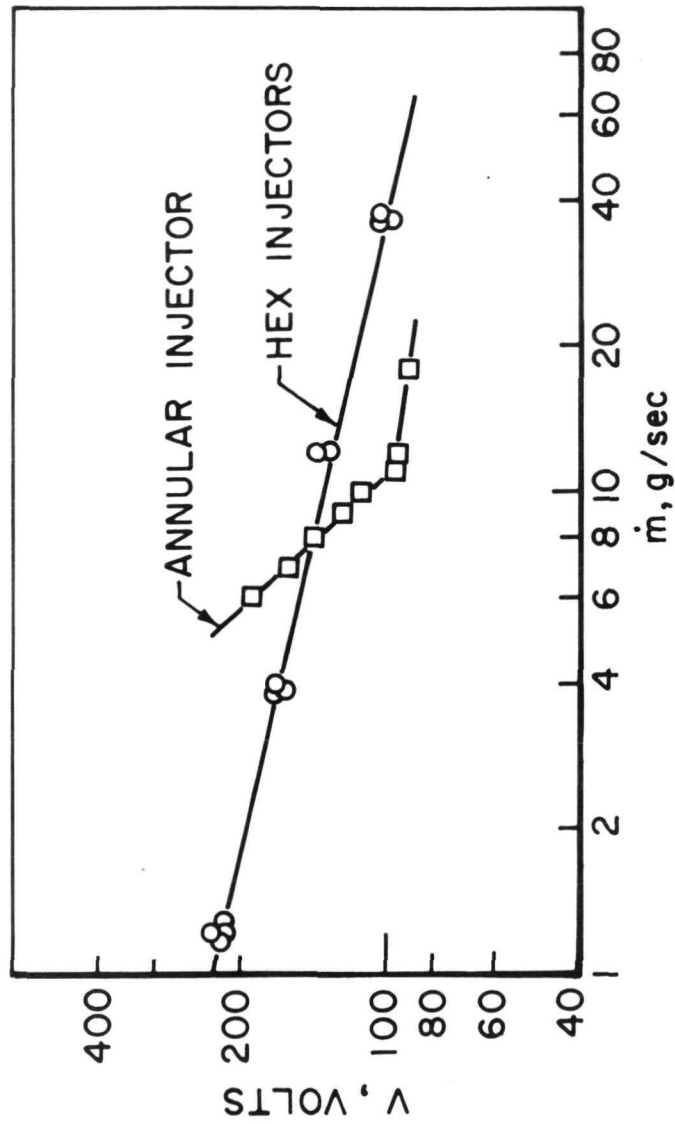
a) ANNULAR INJECTOR

b) HEX INJECTORS

## CURRENT J AND TERMINAL VOLTAGE V SIGNATURES

$$J = 16.5 \text{ kA} ; \dot{m} = 6 \text{ g/sec}$$

FIGURE 54  
AP25-P 448



TERMINAL VOLTAGE AT  $J=16.5$  kA

FIGURE 55  
AP25-4829



#### IV-E. Synchronization of Mass and Current Pulses (Saber)

Precise delay of the current pulse with respect to the injected mass pulse is necessary in order to achieve proper quasi-steady operation. If the delay is too long, the large amount of injected pre-discharge mass increases the back-pressure in the vacuum tank and compromises the simulation of a space environment in the vicinity of the accelerator exhaust. If the delay is too short, the discharge is initiated before the mass flow is steady resulting in a time-varying acceleration process.

In the past, the relative delay between mass and current pulses has been set gasdynamically as shown in Fig. 56. Both fast acting solenoid valves are triggered simultaneously. The delay is provided by increasing the length of the gas path in the switch line which increases the time before the initially evacuated switch reaches the Paschen breakdown pressure. Figure 57 shows sample voltage profiles on a compressed time scale for three different length switch tubes ( $l$ ). Also shown on the same time scale is the injected mass flow profile as measured by a Millitorr fast ionization gauge, Fig. 57e. (Although the ionization gauge actually senses local number density of neutrals, the observed profile is proportional to mass flow when a constant ambient temperature is assumed.) All traces in this figure begin 0.5 msec after the firing command to the solenoid valves. When the delay is sufficiently long, Fig. 57a, the voltage profile, as well as other internal diagnostic measurements not shown here, attains a well defined quasi-steady operating value. As the delay time is decreased, Fig. 57b, the voltage is again seen to be approximately constant, although at a somewhat greater value. This increase is explained by recalling the established increase in quasi-steady voltage as mass flow is decreased for a fixed current, and by noting in Fig. 57e that the discharge begins at a time before

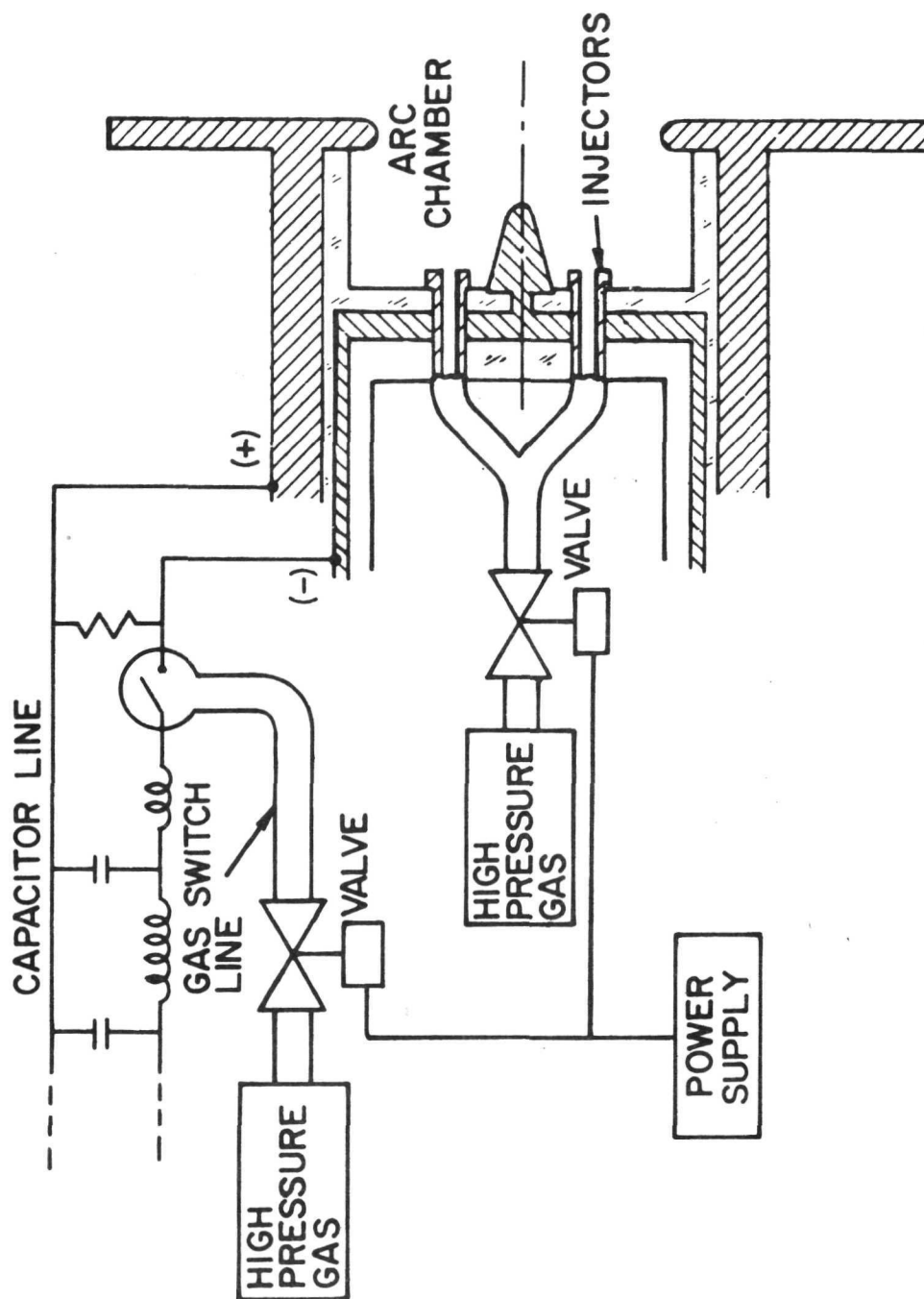
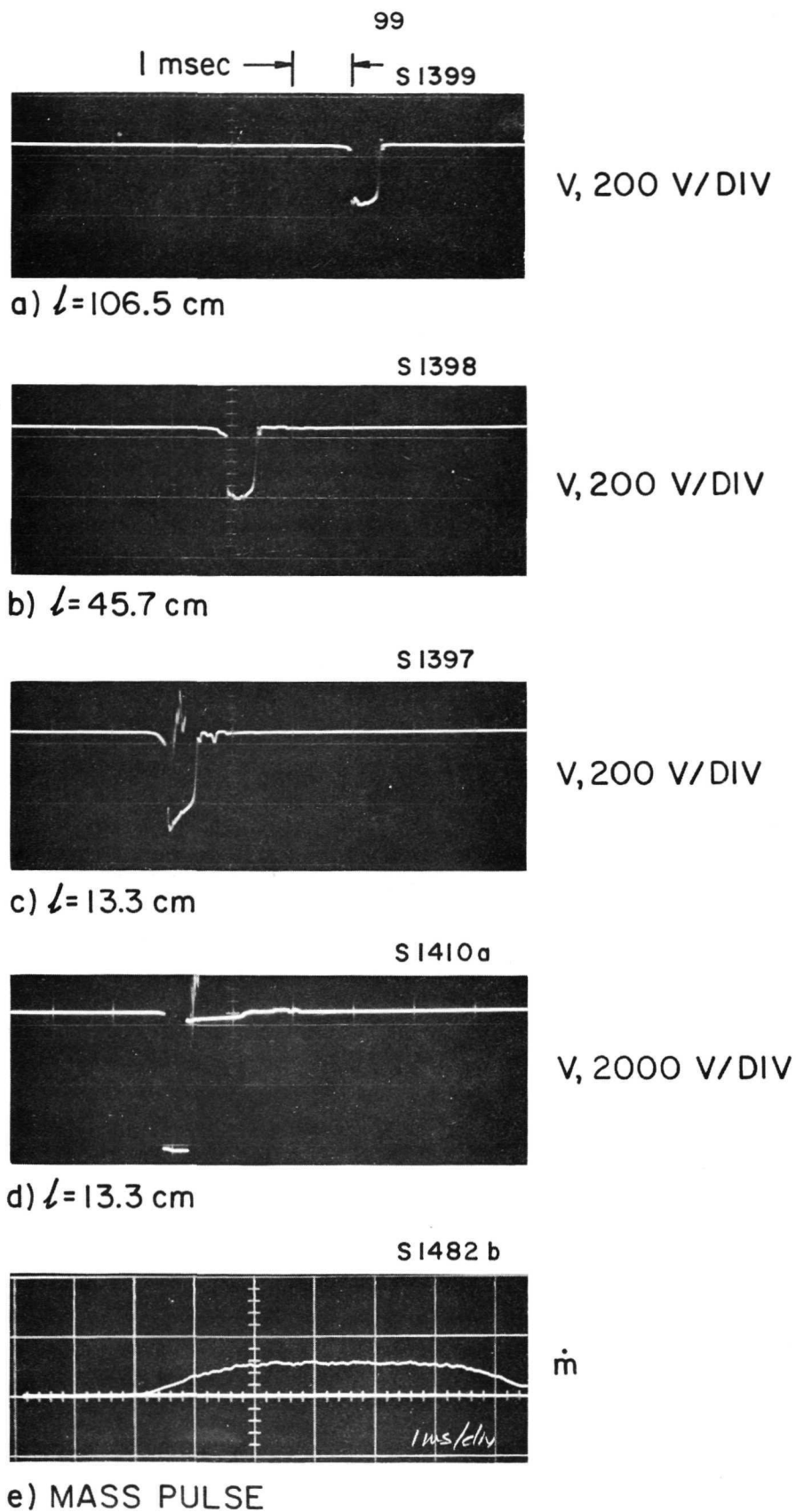


FIGURE 56  
AP25-4681

SYNCHRONIZATION OF PROPELLANT SUPPLY

AP 25, R, 4681 71

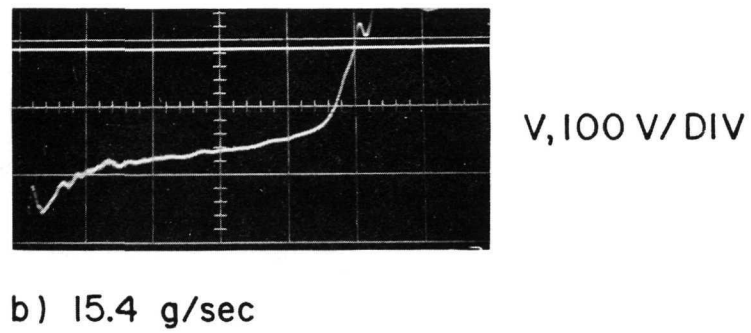
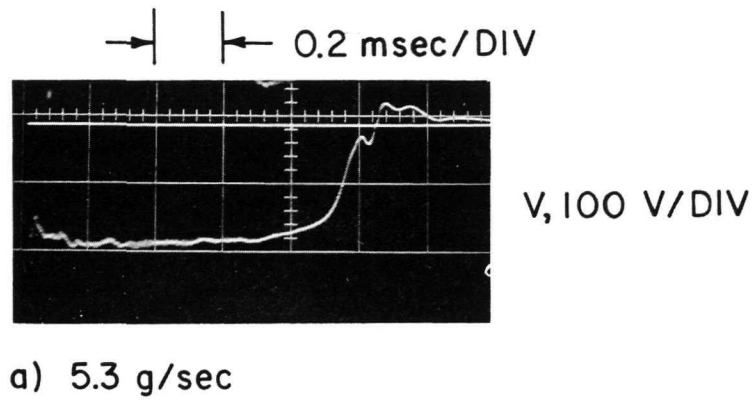


EFFECT OF DELAY TIME ON DISCHARGE VOLTAGE

FIGURE 57  
AP25·P 449

the injected mass flow has reached its plateau value. A further decrease in delay time, Fig. 57c, produces a monotonically decaying voltage during the entire pulse consistent with the large change in mass flow over the same period. Delays shorter than this frequently result in a voltage history such as seen in Fig. 57d. Noting the change in scale sensitivity, the discharge chamber voltage first jumps to the initial charging voltage of the capacitor bank, over 4 kV, indicating that the switch breaks down transferring the high voltage to the main chamber before enough gas is in the chamber to allow a discharge to occur. For the particular shot shown, the voltage hangs up for approximately 0.4 msec before a discharge begins, the voltage during the latter resembling Fig. 57c when properly amplified.

Recent tests have shown that caution must be exercised at high mass flows, even with a switch line of proper length, as established in Fig. 57. The reason is a protective feature in the solenoid valve design in which the upstream or reservoir pressure is used to assist in keeping the valve closed. Cold flow tests show that as the pressure is increased, the time for the valve to rise off the seat increases linearly from 1.7 msec at 35 psia to 3.0 msec at 225 psia, although the risetime of the pulse remains approximately constant at 1.5 to 2.0 msec. Thus, the necessary delay from valve energizing time until arc discharge must be increased as the reservoir pressure is increased. This effect is shown in Fig. 58. The upper trace shows a quasi-steady voltage history for the 14.6 kA, 5.3 g/sec operating condition, appropriately delayed with respect to the mass pulse. In the lower trace, only the mass flow has been changed by raising the reservoir pressure behind the solenoid valve. Proper quasi-steady operation at this increased mass flow would yield a flat voltage whose magnitude is less than that of Fig. 58a.



VOLTAGES FOR FIXED DELAY TIME  
 $J = 14.6 \text{ kA}$

FIGURE 58  
AP25-P 450

It is seen that by not increasing the delay time, the observed voltage trace at 15.4 g/sec decays monotonically reflecting the increasing mass flow over the pulse time, as observed in Fig. 57c.

These data have shown that the delay time between mass and current pulses must be carefully adjusted as the mass flow rate is varied. This has been accomplished in the past by changing the length of tubing between switch valve and switch. In order to simplify this process and to make the delay time continuously variable, an electronic delay circuit will be added which will delay the switch valve firing until some predetermined interval after the main chamber valve. (see Fig. 51).

#### IV-F. Mass Sampling of the Exhaust Plume (Hough)

A new technique has been developed for extracting a sample from the exhaust of a pulsed plasma accelerator. Initial experiments have shown that a sample of the quasi-steady exhaust flow can be captured reproducibly and subjected to diagnostic tests such as a mass spectrometric analysis. Thus, in a completed form, this technique could be used to determine impurity levels as well as species distribution in the exhaust for various accelerator operating conditions.

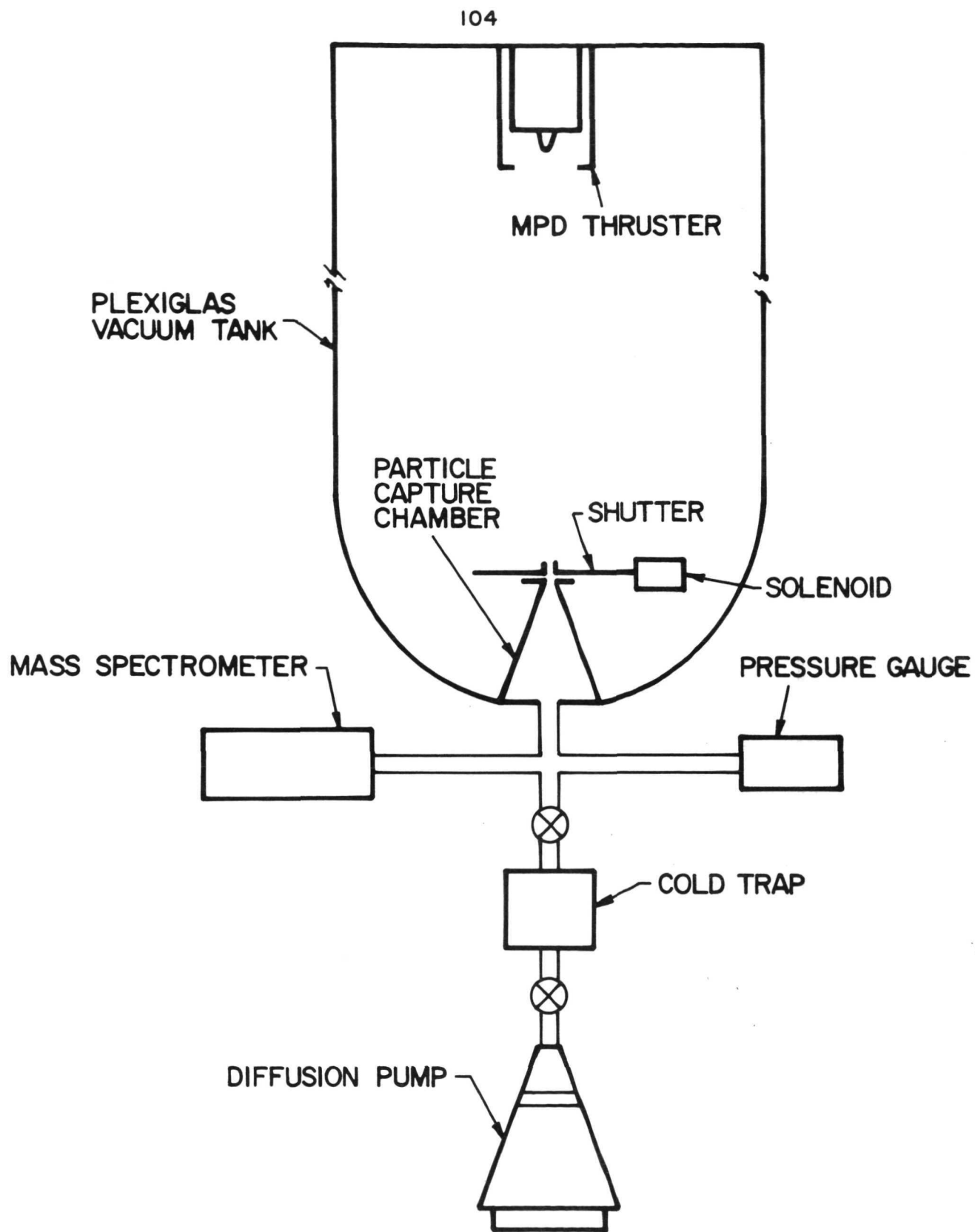
Early experiments have been conducted with a 12.5-cm-base dia, 25-cm-long conical brass capture chamber whose 0.5-cm-dia orifice is aligned toward the plasma flow. At a predetermined time during the arc discharge, the orifice is closed with an aluminum shutter drawn by a fast-action solenoid. When closed, the shutter is pressed against an O-ring, prohibiting leakage of the trapped sample and contamination of the sample from the post discharge mass flow. Tests showed that this closing and sealing operation is completed 1 msec after the shutter begins to move.

The capture volume and its shutter are mounted at the far end of the Plexiglas vacuum tank as shown in Fig. 59. The rear of this chamber leads directly outside the vacuum tank into a diagnostic manifold backed by a separate diffusion pump and cold trap combination capable of evacuating the cone and manifold to a pressure of less than  $5 \times 10^{-3} \mu$  Hg. Typical samples captured during the arc discharge produce a pressure of approximately  $1 \mu$ , which is compatible with the upper pressure limit of mass spectrometers.

Since the samples are trapped with the cone isolated from the auxiliary diffusion pump, there is some chance that outgassing from the inner walls of the cone may distort the true species distribution of the sample. Tests showed that when isolated with no sample, the pressure rise due to outgassing reaches  $5 \times 10^{-2} \mu$  in four minutes. Thus, mass spectrometric analysis to measure the outgassed components is necessary for an accurate determination of the species distribution of the sample.

The shutter solenoid is primarily the inductive element in an LC circuit which provides the necessary current to close the shutter. Triggering this circuit must be carefully synchronized with the arc discharge in order to capture the maximum plasma from the exhaust while excluding the trailing un-ionized argon. The synchronization is provided by a variable delay trigger unit inserted between the firing signal to the mass injection valves and the shutter closing circuit.

Using this chamber and associated circuitry, plasma samples have been routinely and reproducibly extracted from the quasi-steady accelerator exhaust. Mass spectrometric analysis of the captured samples, although displaying an abundance of argon, is incomplete since the only available mass spectrometer is not a sensitive indicator of hydrogen and oxygen, two species which are produced if the Plexiglas



MASS SAMPLING APPARATUS



insulators are ablated during the discharge. Incorporation of a mass spectrometer sensitive to a wider range of mass numbers should more fully utilize the potential of this exhaust sampling technique.

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## Appendix A: Semi-annual Statement of Expenditures

PULSED ELECTROMAGNETIC GAS ACCELERATION  
NASA NGL 31-001-005

1 July 1971 - 31 December 1971

Direct Costs

|                                                 |              |
|-------------------------------------------------|--------------|
| I. Salaries and Wages                           |              |
| A. Professional                                 | \$16,937     |
| B. Students                                     | 5,122        |
| C. Technicians                                  | 10,566       |
| D. Supporting Staff                             | 7,206        |
|                                                 | <hr/>        |
|                                                 | \$39,831     |
| II. Employee Benefits<br>(19% of IA, IC and ID) | 6,595        |
| III. Equipment                                  | 734          |
| IV. Expendable Materials and Services           | 6,834        |
| V. Travel                                       | 723          |
| VI. Tuition                                     | <u>1,100</u> |
| Total Direct Costs                              | \$55,817     |

Indirect Costs

|               |               |
|---------------|---------------|
| VII. Overhead | <u>27,085</u> |
| TOTAL         | \$82,902      |