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# Plasma Flow in an Electromagnetic Shock Tube and in a Compression Shock Tube

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Plasma Flow in an Electromagnetic Shock Tube  
and in a Compression Shock Tube

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J. L. Wilson, D. Schofield and J. D. Regan

SUMMARY

A comparison has been made of two facilities at N.P.L. designed to produce short-duration, high-enthalpy flows. These facilities are both shock tubes, the first driven electrically, the second gasdynamically using an adiabatic piston compressor. Instantaneous and streak photographs of the flow show that, although the electromagnetic shock tube is capable of producing higher enthalpies, the resulting flow is not of the ideal one-dimensional blast-wave form. The piston-compression shock tube produces a length of shock-heated gas of almost constant velocity, which would be more useful for most aerodynamic studies.

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1./

## 1. Introduction

In the production of high-temperature gas flows, the conventional shock tube is limited by the speed of sound in the driver gas at room temperature. To obtain very high enthalpies, extra energy must be supplied to the driver gas. Two shock tube facilities based on this principle, which are in Aerodynamics Division, N.P.L., are described here.

The first of these is an electromagnetic shock tube with a coaxial discharge configuration<sup>1</sup>. In this type of tube the flow enthalpy is determined by the power input. As the power is added in a time which is short compared with the duration of the flow, ideally this flow is of blast-wave form rather than of constant velocity along the shock tube.

The second facility is a 'compression shock tube' in which the driver gas is heated by a preliminary adiabatic compression<sup>2</sup>. This is an improvement of the combustion-driven shock tube, since the driver is a pure gas of low molecular weight. For this apparatus the upper limit for the shock Mach number in argon is 25 to 30.

The low enthalpy range of the electromagnetic shock tube overlaps the high enthalpy range of the compression shock tube, and the flows produced in this common range are studied in this report by means of instantaneous and streak photography.

## 2. The Electromagnetic Shock Tube

The electromagnetically driven shock tube is a 2 in. i.d. Pyrex tube with a coaxial driver located at one end. This driver consists of a stainless-steel ring electrode separated from the central electrode by a silica insulator, as shown in Fig. 1. The ring electrode is connected coaxially to a parallel-plate transmission line which leads from the driver, via a switch, to a 40  $\mu\text{F}$ , 10 kV fast-discharge capacitor bank.

The switch consists of two copper strips, separated by a sheet of Mylar 0.006 in. thick. This sandwich is pierced to complete the circuit either by a mechanical plunger or, if synchronism with the streak camera is required, by a fast-acting explosive detonator. The inductance of the capacitor bank and switch, excluding the shock driver, is about 6 nanohenries.

When the circuit is closed, current starts to flow through the gas along the path of minimum inductance, i.e., close to the insulator. As the current in this discharge increases, the magnetic force drives the plasma radially inwards. The plasma is then ejected along the axis of the tube.

An alternative outer conductor was made having a series of helical slots around its circumference. These constrained the current flow so that it produced an axial component of magnetic field in the discharge region. This was done to investigate whether the efficiency of the energy transfer to the plasma, and the stability of the flow, were improved.

In all the experiments reported here, a voltage of 4.5 kV was used on the capacitor bank.

### 3. The Compression Shock Tube

In this facility the driver gas is heated by being compressed adiabatically in front of a heavy piston. This piston, 3 in. in diameter and 5 lb in weight, is propelled down the compression tube by high-pressure nitrogen which is released from a reservoir by bursting a double diaphragm.

The driver gas is compressed into a 1 in. diameter tube which is the driver section of the shock tube. The diaphragm between this and the 1 in. diameter driven section is chosen so that it bursts at the peak driver pressure, when the piston is momentarily at rest. The test section of the shock tube is a 1 in. i.d. thick-walled Pyrex tube, 5 ft long.

The reflected expansion wave associated with the diaphragm opening overtakes the contact surface relatively slowly for very strong shock waves, so that a 4 in. long driver section was sufficient for this series of experiments. The maximum compression ratio which could be achieved with this length of driver was 100 to 1. The facility is designed to operate with driver pressures of up to 1000 ats. For the results given here a driver pressure of 200 ats of hydrogen was used, at a compression ratio of 50 to 1.

### 4. Photography of the Flow

Instantaneous photographs were taken of the luminous gas, using a ~~Kerr-cell~~ shutter with exposure times of 0.1 and 0.2  $\mu$  sec. During this time the shock waves moved 0.5 - 1 mm. The photographs were taken using a 35 mm camera with a 95 mm lens. The camera, which was 2 ft from the shock tube, was placed so that the expected position of the shock front was in the centre of the field of view, minimising parallax. Ilford HP3 and HPS films were used, developed in Ilford ID3.

In the experiments with the electromagnetic shock tube, shock velocities were measured using three photomultipliers placed at intervals along the tube. The outputs from these photomultipliers, together with the instant at which the discharge took place, were recorded on an oscilloscope. For the compression shock tube, only two photomultipliers were necessary because of the comparative constancy of the shock velocity along the tube.

Streak photographs were also taken of the flows in the two facilities. For the electromagnetic shock tube, a Barr and Stroud type C6 streak camera was used, and the shock wave was synchronised with the camera by means of the explosive switch. A continuously active camera was needed for the compression shock tube since this could not be synchronised. A streak camera was constructed with a four-sided mirror and two 90° film tracks, separated by the object lens, which gave nearly continuous recording.

### 5. Results

The experiments were done in that region where the two facilities could produce shock waves of approximately the same strength. Starting pressures from 0.3 to 5 torr of argon were used. The electromagnetic shock tube could extend this region to lower pressures, and the compression shock tube to higher pressures.

## 5.1 Electromagnetic shock tube

Only one Kerr-cell picture could be taken during each experiment. By using the same initial conditions, and moving the camera progressively down the tube, the behaviour of the luminous front could be determined. The repeatability of the shock trajectory was confirmed from the photomultiplier records.

The first two sets of pictures (Figs. 4-7, 8-11) were taken using the return conductor which was without slots. They show the progress of the plasma down the first 9 in. of the tube, at initial pressures of 0.3 and 1.0 torr of argon, respectively. Corresponding streak pictures are shown in Figs. 16 and 17. The initial Mach number as the plasma leaves the shock driver was 26.3 at a pressure of 0.3 torr and 17.1 at 1 torr, falling to 14.7 and 9.8 respectively at a distance of 14.5 in. down the tube. It is seen that initially a quantity of plasma is ejected from the driver into the centre of the tube. As more plasma emerges, it forms a structure which appears to be a vortex ring, e.g., Figs. 5, 6 and 9. This structure, which is at the front of the luminous plasma, is followed by a region which is both cooler and of smaller diameter. Behind this region the plasma again fills the tube. Later, when the plasma is further from the discharge, this initial structure disappears and the whole flow becomes irregular, e.g., Figs. 7 and 11. The plasma front is never plane as it would be for a one-dimensional blast wave. The results for the two initial pressures show no essential difference apart from the higher shock velocities at the lower pressure.

A further series of experiments was performed, in which the helically slotted outer conductor was used to give an axial magnetic field in the discharge region. Figs. 12-15 show the results for an initial pressure of 0.3 torr of argon. The initially ejected plasma is more prominent, and there appears to be more structure behind the shock front. The photomultiplier records showed an increase in shock velocity of 20% over the velocity when the unslotted return conductor was used, indicating an increase in the efficiency of the energy transfer to the gas. However, there was no increase in the uniformity of the flow.

It was not clear whether, as the luminous front progressed further down the tube, the freshly heated gas was continually mixed with the irregular luminous region, or whether a less luminous shock wave was formed ahead of this region<sup>3</sup>. Such a shock wave could not be seen in either the Kerr-cell or streak photographs, but these pictures could not be taken very far from the discharge because of the rapid decay of brightness. Therefore a small flat plate was placed normal to the flow, 19 in. from the discharge. Shock heated gas in front of the luminous plasma would be brought to rest by the plate, and the consequent increase in enthalpy would make it visible ahead of the plasma. When the already luminous plasma reaches the plate, intense emission occurs from the stagnation region. This can be seen in the streak photographs, Figs. 16 and 17. No earlier radiation can be seen from this region, and therefore it is concluded that no shock wave exists ahead of the luminous plasma. The region behind the visible, irregular shock front engulfs the gas as it is added to the plasma, and continual mixing occurs. The absence of a plane shock wave preceding the flow has been noted also by Koopman<sup>4</sup> in a similar type of apparatus.

An attempt was made to take instantaneous photographs of the plate immediately before the arrival of the plasma. Unfortunately the Kerr cell did not have a large enough open/closed transmission ratio, and the pictures were masked by the intense radiation caused by the stagnation of the luminous plasma in front of the plate.

## 5.2 Compression shock tube

A series of Kerr-cell photographs was taken in the compression shock tube at initial pressures in the range 0.3 to 5.0 torr of argon. These pictures, Figs. 18-21, were taken a distance of 4 ft downstream of the diaphragm, using constant driver conditions of 200 ats of hydrogen at a compression ratio of 50 to 1. They show that the length of the luminous region is, as expected, clearly dependent on the initial pressure. The ratio of this length to that calculated from one-dimensional theory decreases from 0.4, at an initial pressure of 5 torr, to 0.25 at an initial pressure of 0.3 torr. This shows the increasing importance of boundary-layer effects<sup>5</sup>, which limit the operation of the tube at lower pressures.

The individual pictures show the plane shock wave, which appears slightly curved because of parallax, and the fairly sharp but irregular contact surface. The slight luminosity on either side of the hot gas is due to the imperfect extinction of the Kerr-cell. A certain amount of cooling is visible behind the shock wave. A preliminary estimate of this cooling has been made, based on the assumption of thermodynamic equilibrium of the gas. A monochromator was set to accept the entire 4198 Å and 4200 Å argon spectrum lines, and the integrated emission from these lines was recorded as a function of time using a photomultiplier. For the case of a Mach 16.3 shock into 5 torr of argon, this emission fell by a factor of 1.51 during the 10 μsec (laboratory time) after the shock wave. This corresponds to a cooling of approximately 13%, from 12 900°K to 11 200°K, assuming that the gas is optically thin. It is intended to make more accurate measurements of the temperature behind the shock wave, using a two-line emission method.

The attenuation of the shock wave is small, as can be seen on the streak photograph (Fig. 22).

## 6. Conclusions

In an electromagnetic shock tube of the type used here it is shown that the flow is not of ideal blast wave form, preceded by a plane shock wave, but that it contains considerable structure. When the plasma first emerges from the discharge region, it has a well defined form which is tentatively identified as a vortex ring. At later times this comparatively regular structure disappears, and an irregular front continues down the tube.

All the photographs given here show the flow within 18 in. of the discharge, by which point the luminosity had fallen below the limit of the photographic equipment.

For a Tee tube, at similar pressures to those used here, Cloupeau<sup>3</sup> has shown that the plasma is heated principally by the discharge rather than by the shock wave. Vortex rings are not expected in a Tee tube because of the lack of axial symmetry. Koopman has studied an electromagnetic shock tube with a coaxial driver of a different type from that used here<sup>4</sup>. He found that the plasma had a turbulent structure. There was an irregular luminous front with no distinction between shock-heated and discharge-heated gas. Koopman has used this tube to measure the intensities of various spectral lines of neon<sup>6</sup>. The present work is consistent with both these investigations.

The compression shock tube is shown to produce a relatively uniform flow behind a constant velocity shock wave. The available enthalpy is limited by the

compression/

compression ratio used, and by the heat loss from the driver gas. The present facility has operated up to a shock Mach number of 25 in. argon, and shocks of up to Mach 30 should be possible.

We conclude that, within its region of operation, the compression shock tube is potentially more useful for aerodynamic purposes. At very high enthalpies, some form of electromagnetic shock tube is required. Such shock tubes have been used for several years as sources of high-temperature plasma for spectroscopic studies. We have shown that the type of tube described here is more suitable for such spectroscopic experiments than for flow studies.

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References/

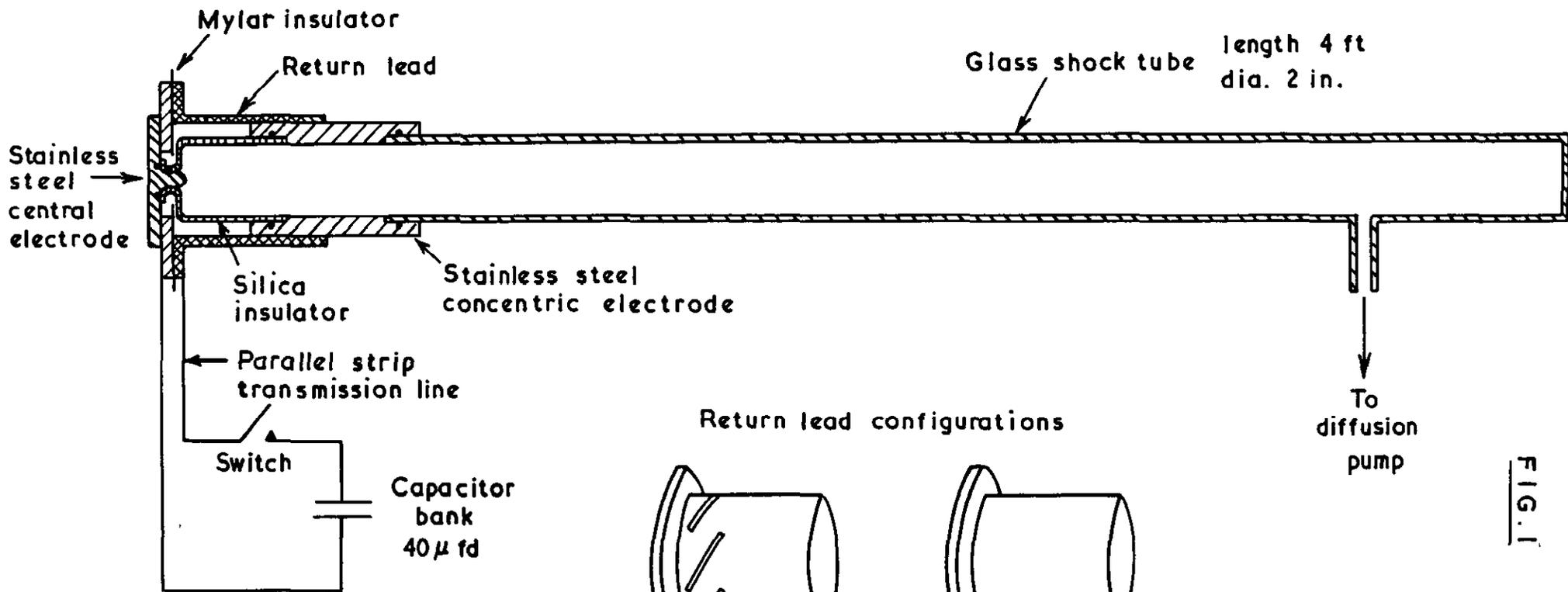
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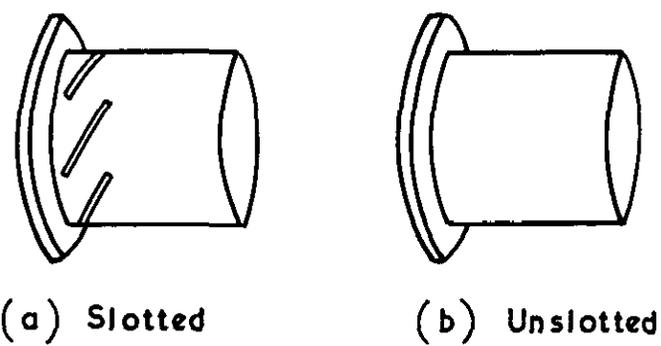
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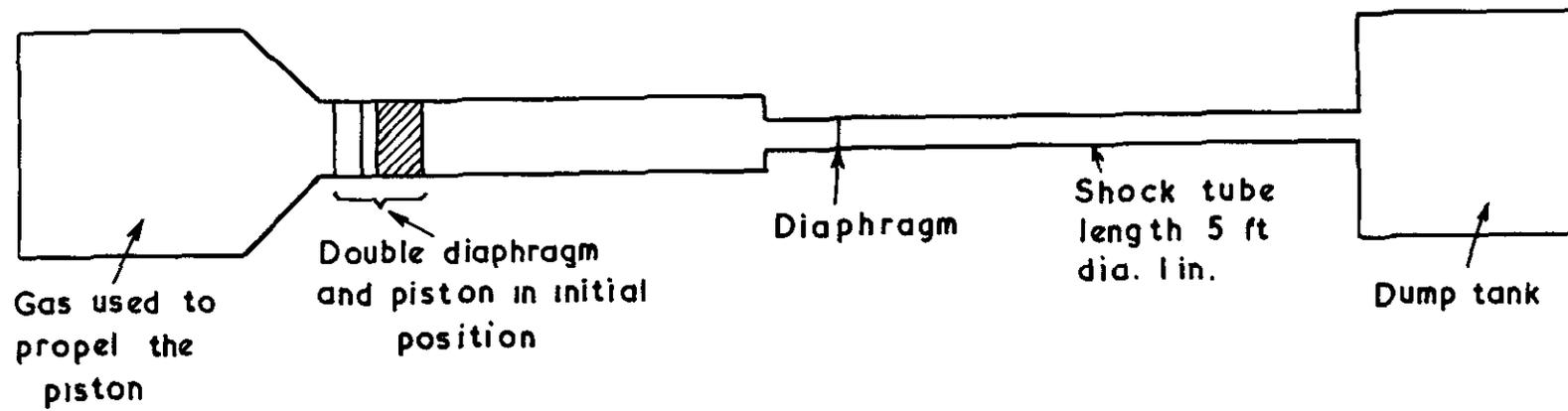


Return lead configurations



Electromagnetic shock tube

FIG. 1



The compression shock tube

FIG. 2

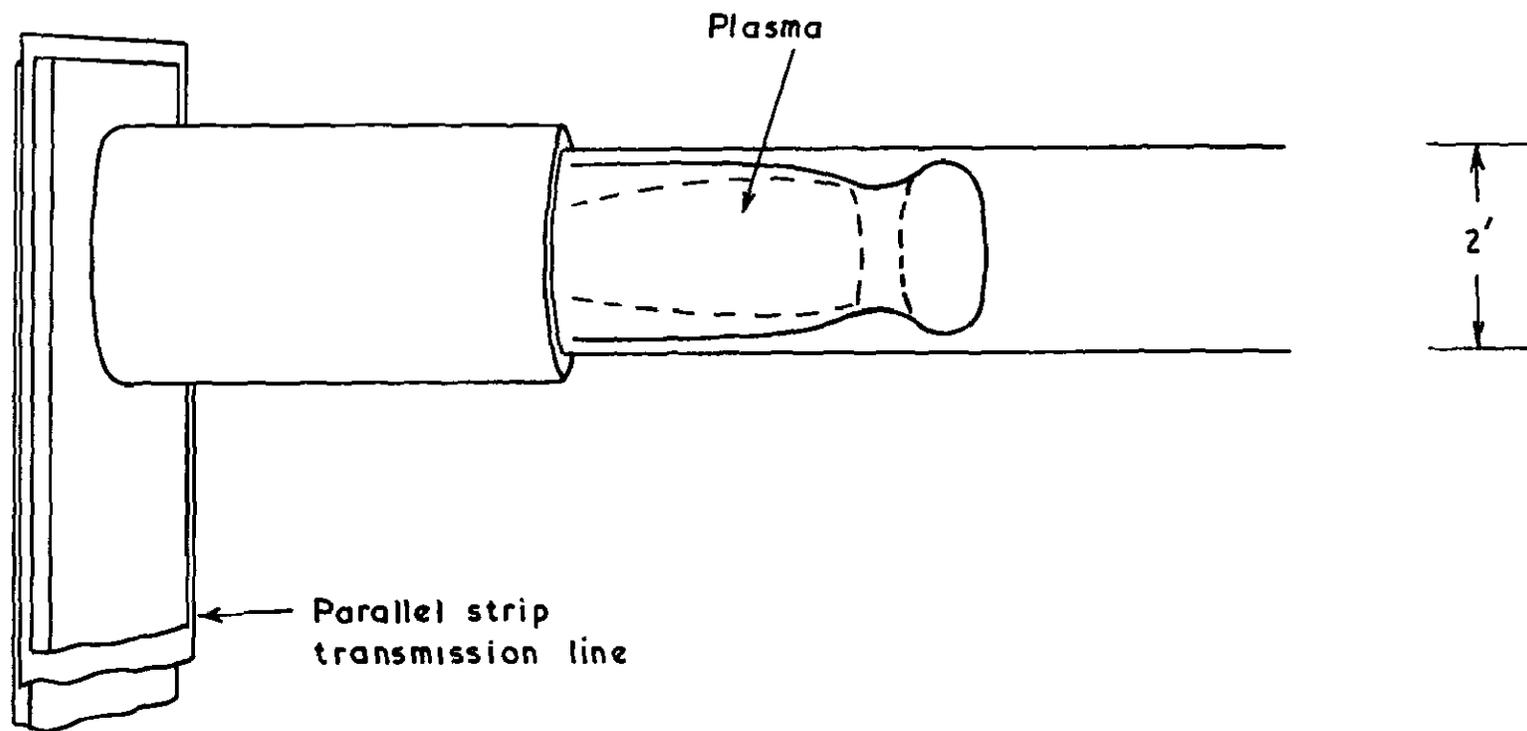


FIG. 3

Electromagnetic shock tube. Sketch showing perspective of Figs 4-15



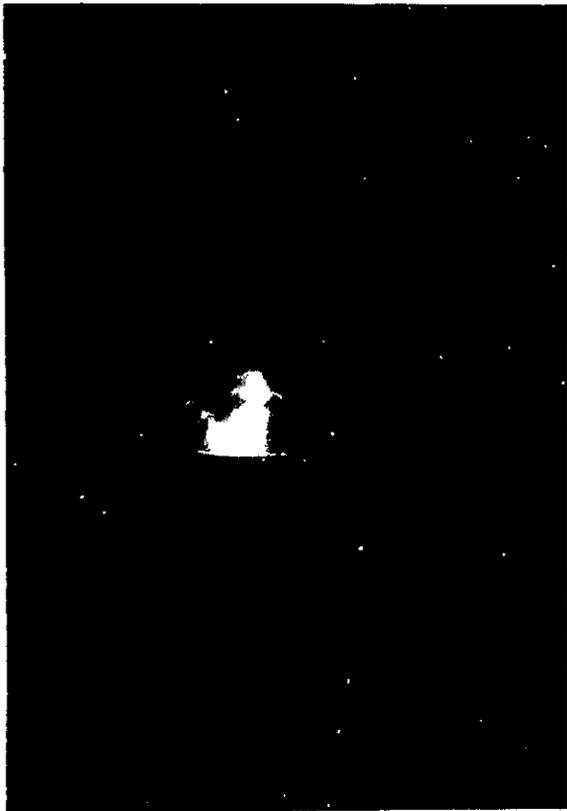


FIG. 4  $t = 5 \mu\text{sec}$

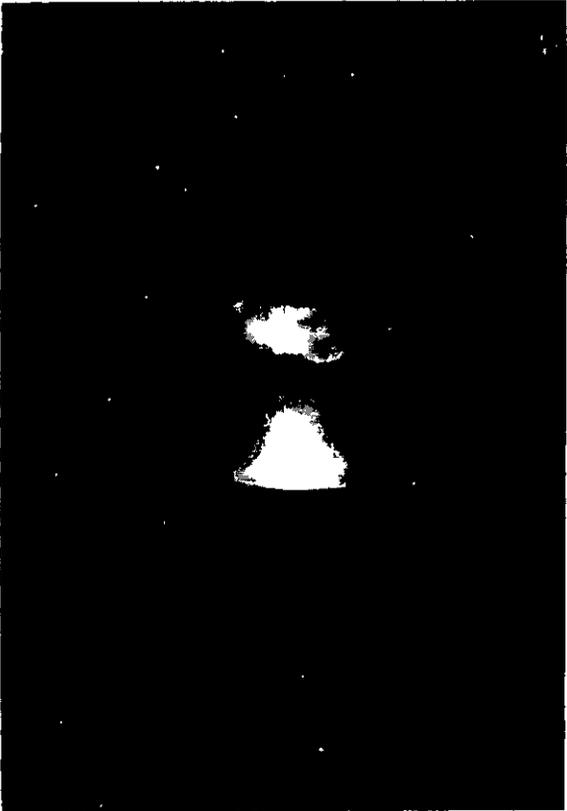


FIG. 5  $t = 8 \mu\text{sec}$

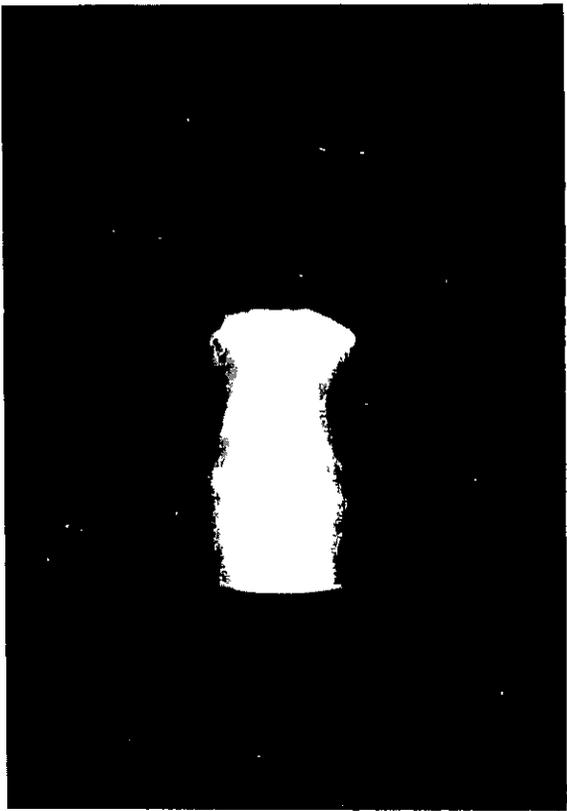


FIG 6.  $t = 13 \mu\text{sec}$

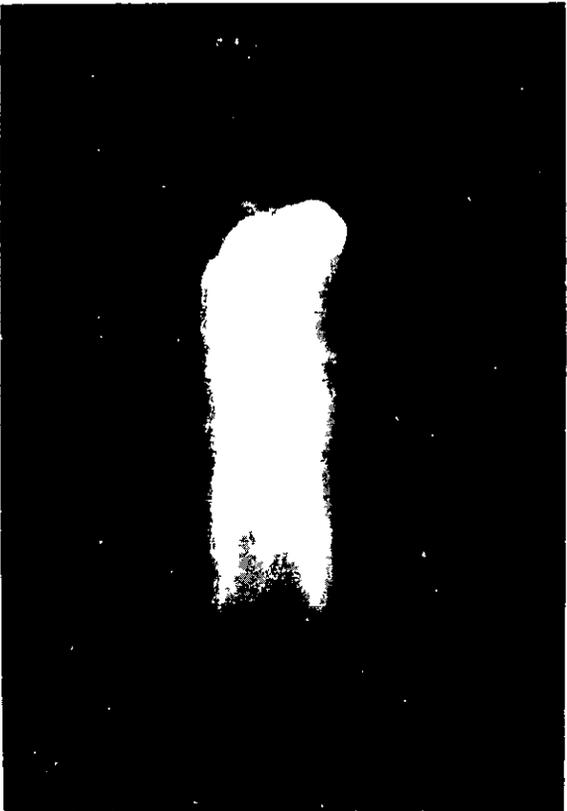


FIG. 7  $t = 20 \mu\text{sec}$

Electromagnetic shock tube.  $P_1 = 0.3$  torr. Kerr cell photographs at stated times after the discharge

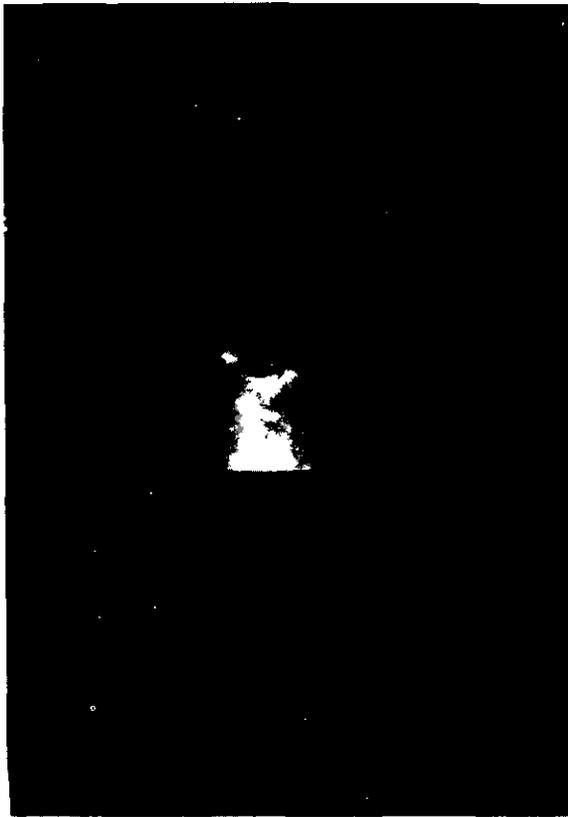


FIG. 8  $t = 10 \mu\text{sec}$

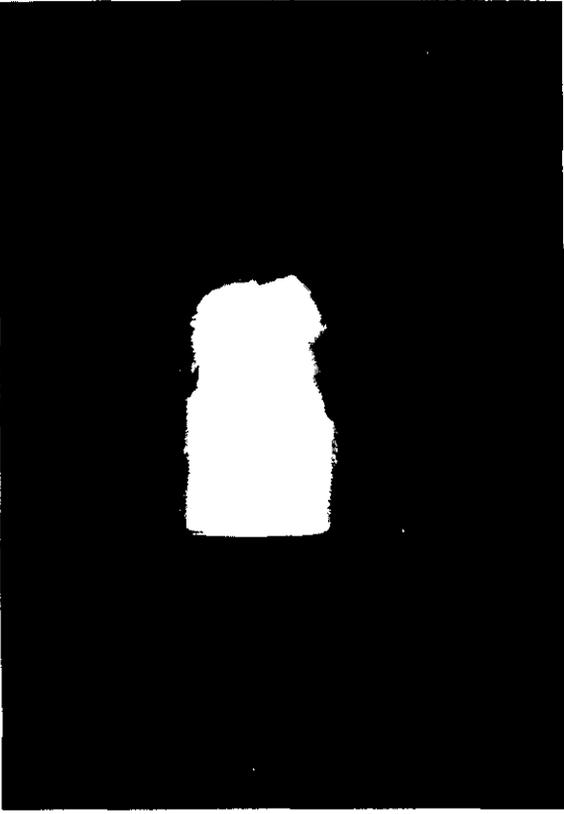


FIG. 9  $t = 20 \mu\text{sec}$

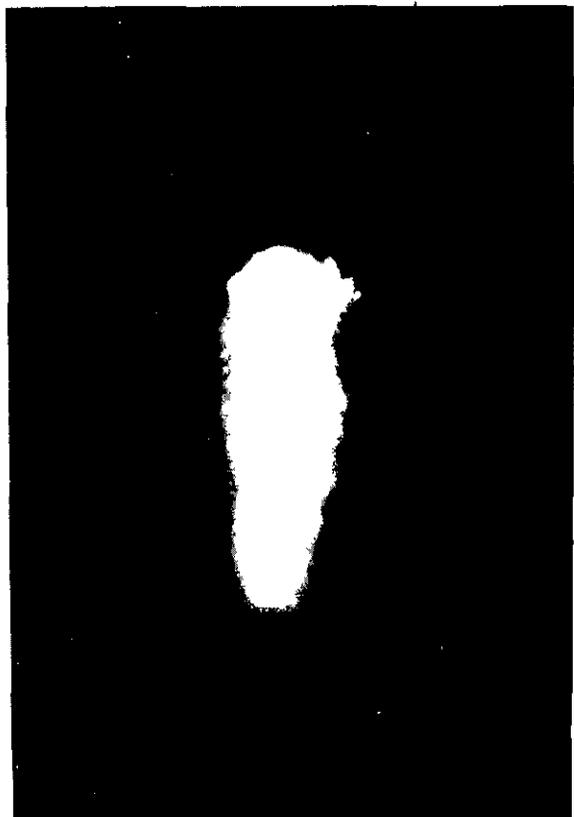


FIG. 10  $t = 30 \mu\text{sec}$

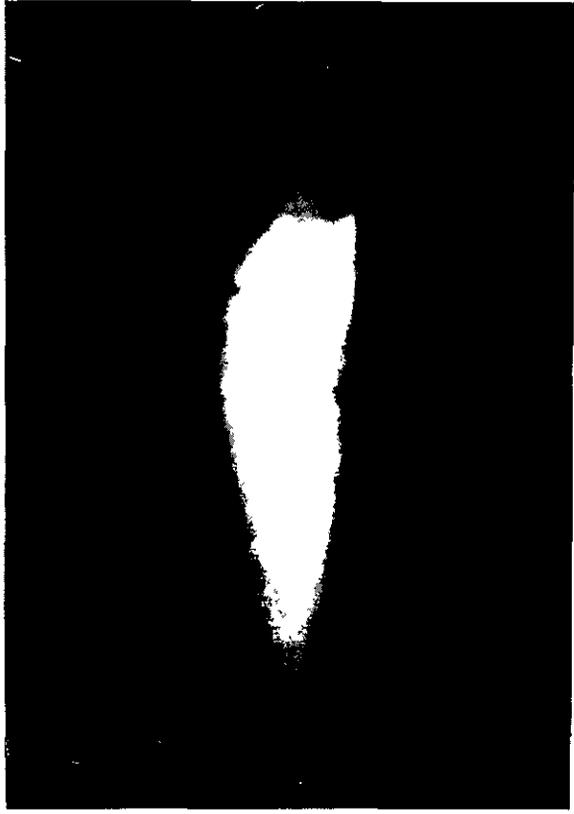


FIG. 11  $t = 50 \mu\text{sec}$

Electromagnetic shock tube.  $p_1 = 1.0 \text{ torr}$ . Kerr cell photographs at stated times after the discharge

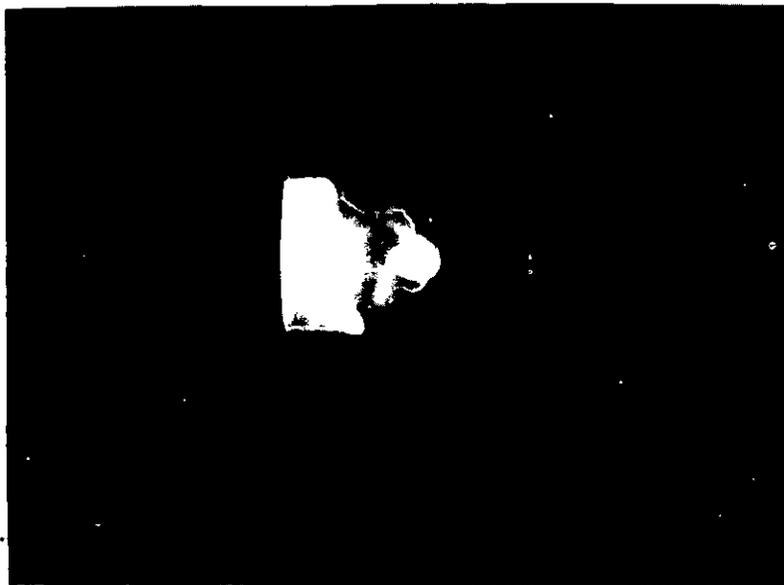


FIG. 12  $t = 10 \mu sec$

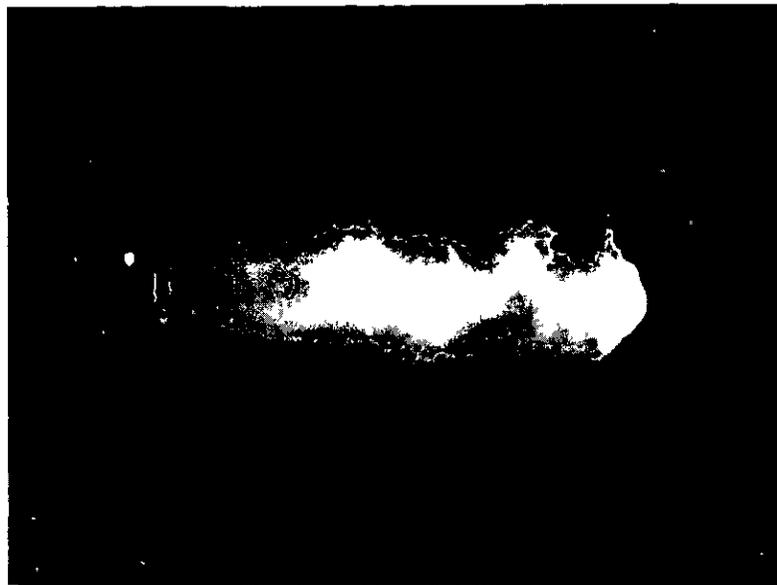


FIG. 13  $t = 22 \mu sec$



FIG. 14  $t = 36 \mu sec$

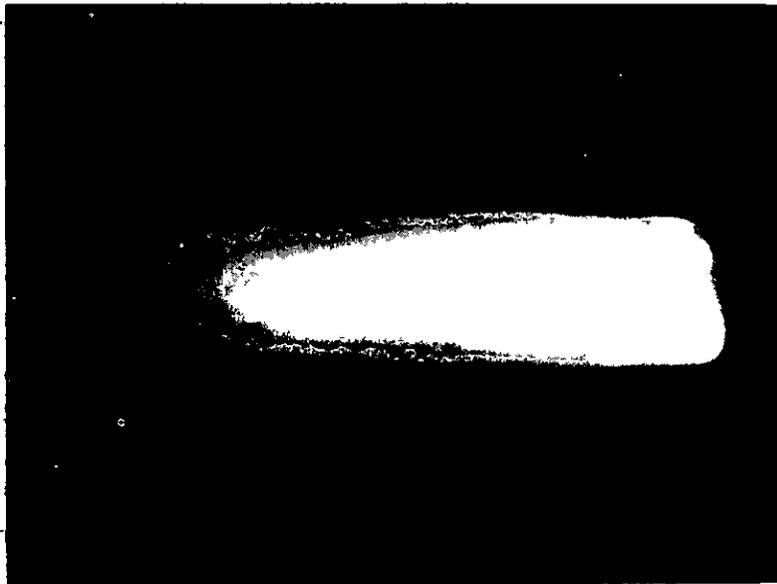


FIG. 15  $t = 48 \mu sec$

Electromagnetic shock tube with axial magnetic field.  $p_1 = 0.3$  torr. Kerr cell photographs at stated times  
after the discharge

FIGS. 12 - 15

FIGS. 16 & 17

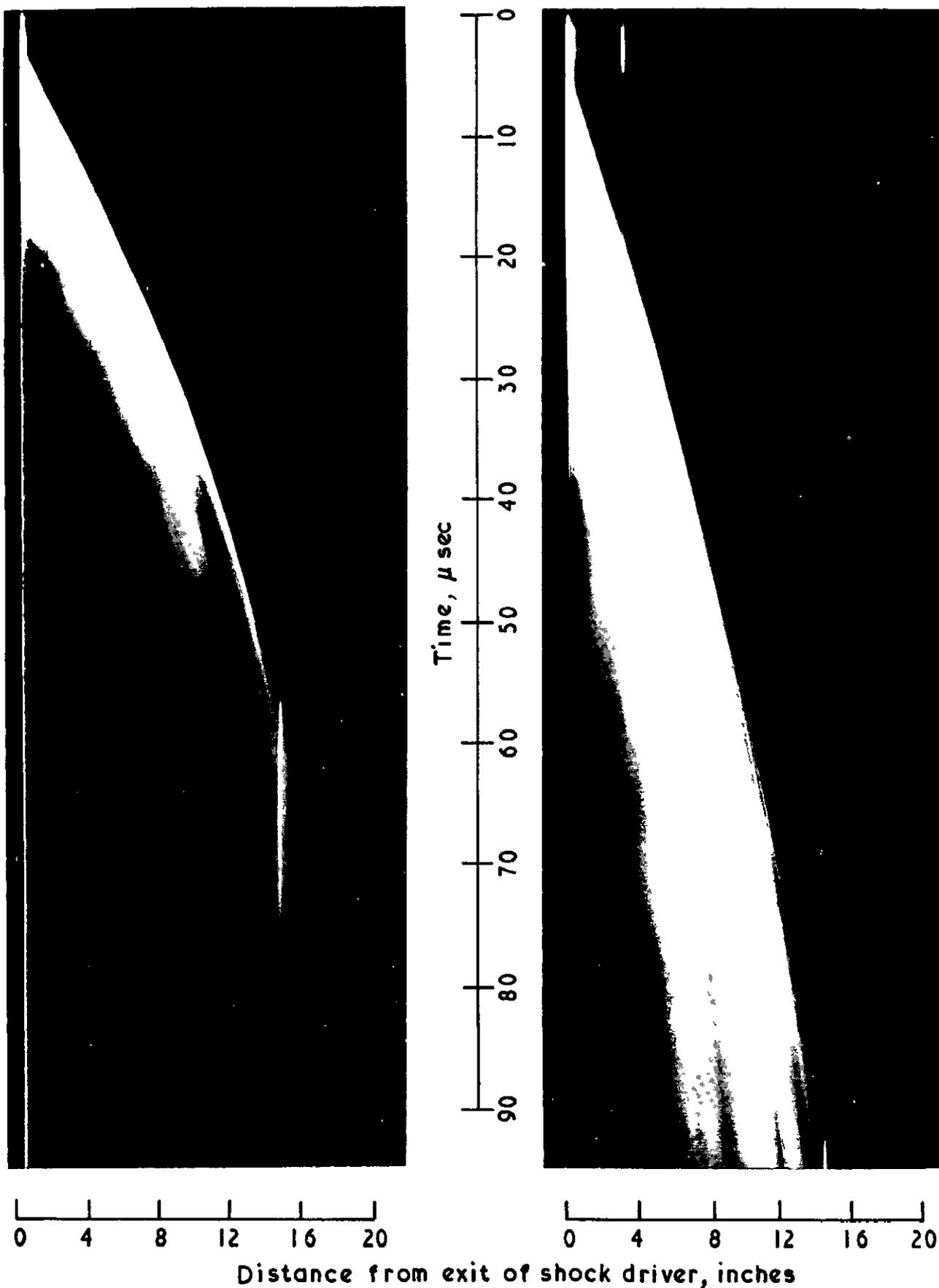


FIG. 16  $p_1 = 0.3$  torr

FIG. 17  $p_1 = 1.0$  torr

Streak photographs of flow in electromagnetic shock tube

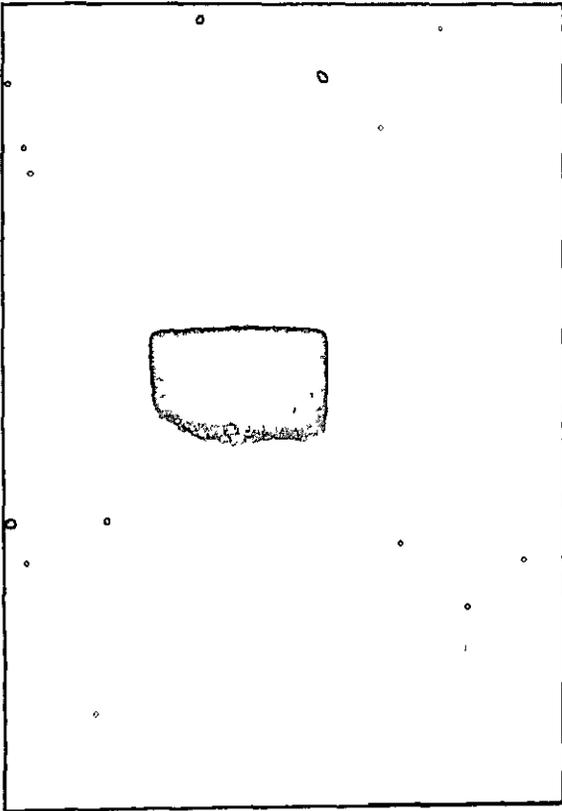


FIG. 18  $p_i = 0.3$  torr  $M_s = 24.0$

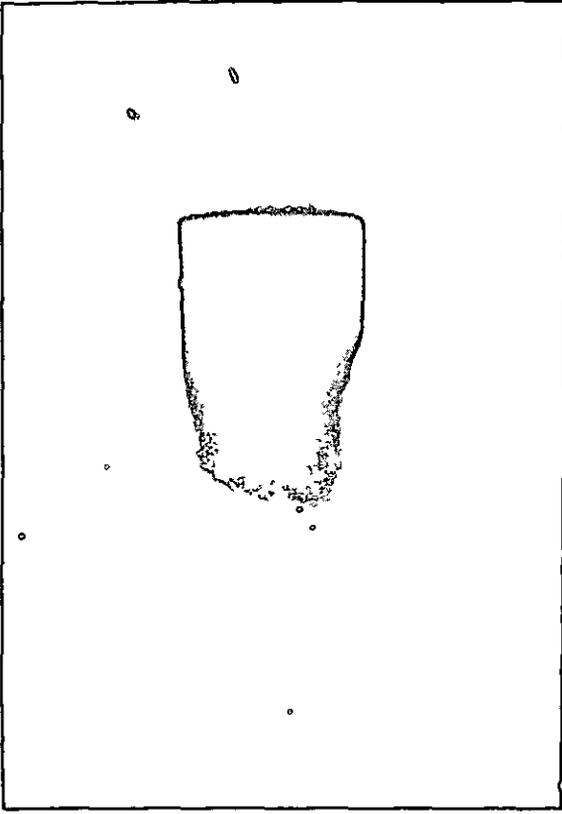


FIG. 19  $p_i = 1.0$  torr.  $M_s = 20.6$

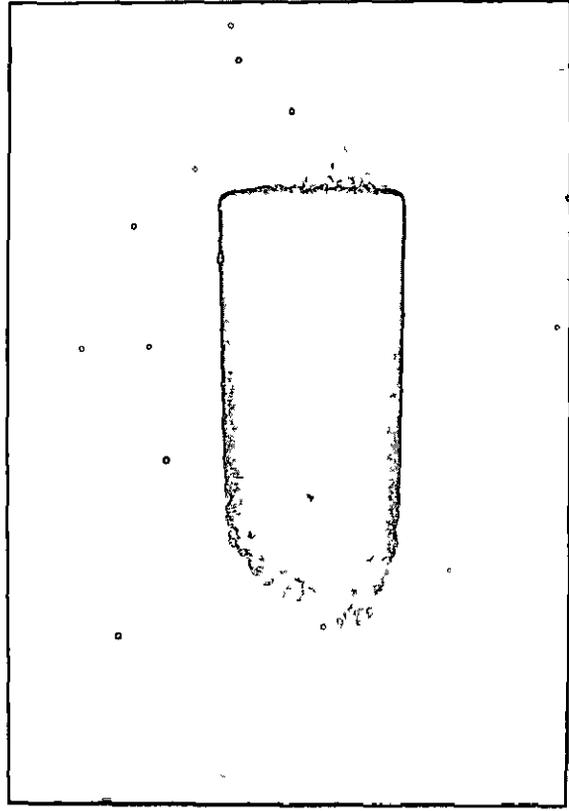


FIG. 20  $p_i = 2.0$  torr.  $M_s = 17.3$

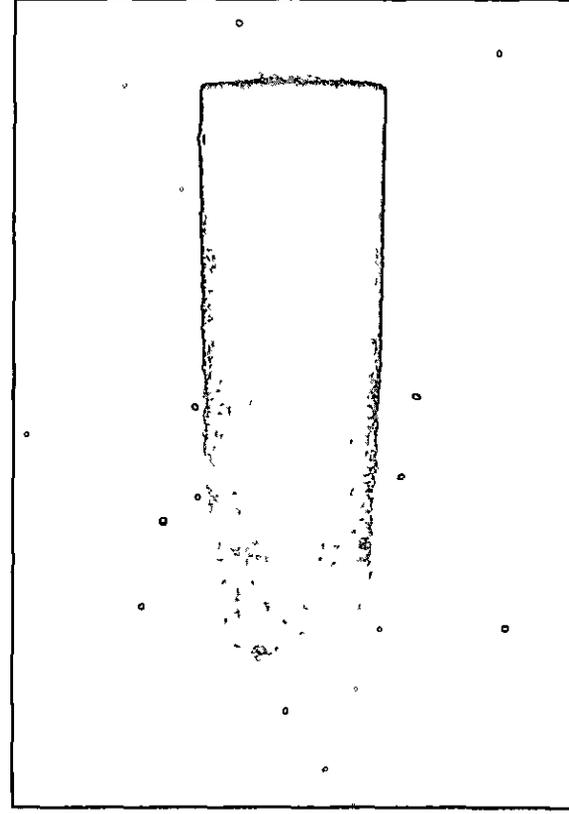
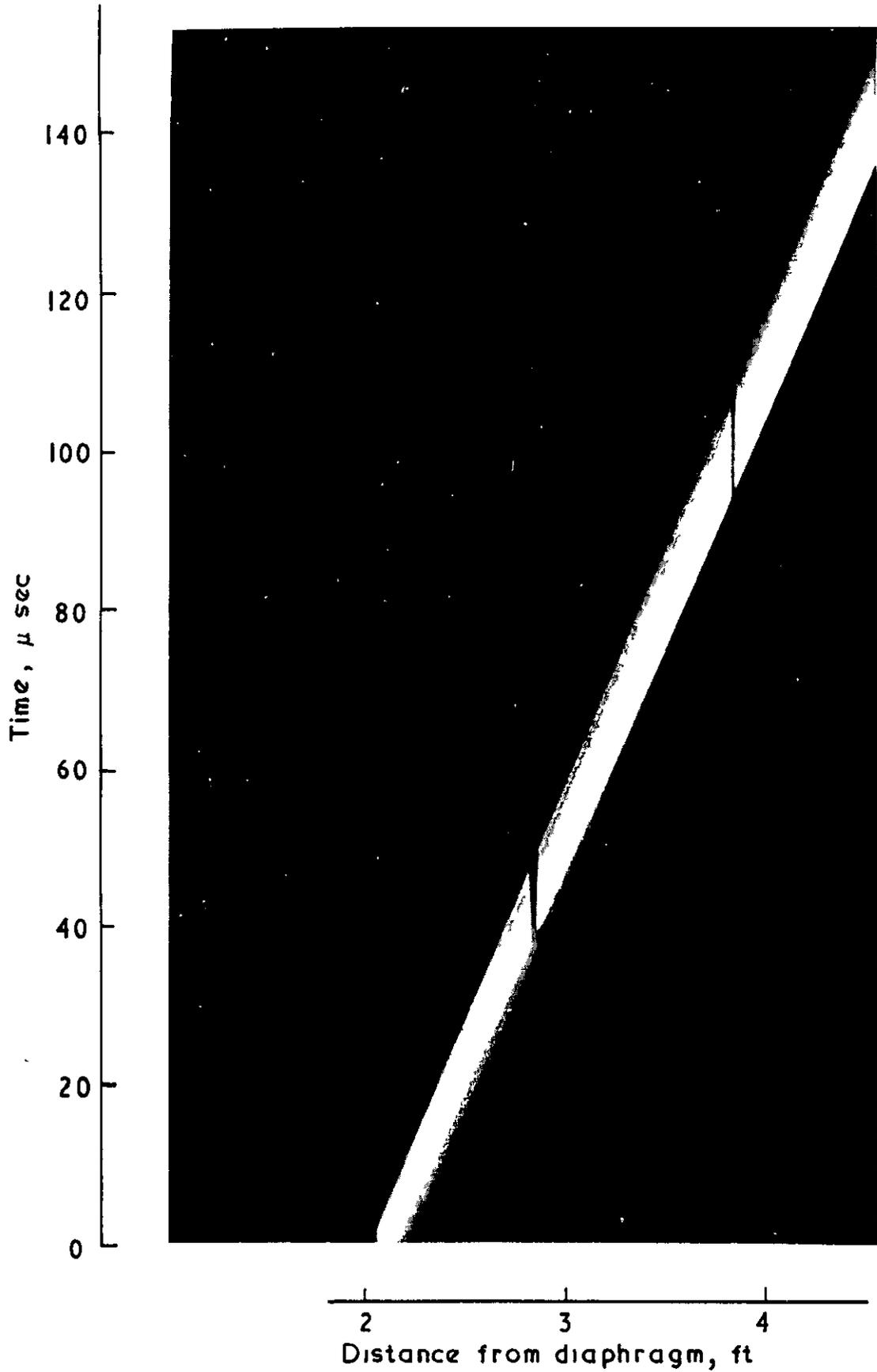


FIG. 21  $p_i = 5.0$  torr.  $M_s = 16.3$

Compression shock tube. Kerr cell photographs 48" from diaphragm

FIG. 22



Streak photograph of flow in compression shock tube

$p_1 = 5.0$  torr.     $M_s = 17$

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Wilson, J. L., Schofield, D., and Regan, J. D.

PLASMA FLOW IN AN ELECTROMAGNETIC SHOCK TUBE AND IN A COMPRESSION SHOCK TUBE

A comparison has been made of two facilities at N.P.L. designed to produce short-duration, high-enthalpy flows. These facilities are both shock tubes, the first driven electrically, the second gasdynamically using an adiabatic piston compressor. Instantaneous and streak photographs of the flow show that, although the electromagnetic shock tube is capable of producing higher enthalpies, the resulting flow is not of the ideal one-dimensional blast-wave form. The piston-compression shock tube produces a length of shock-heated gas of almost constant velocity, which would be more useful for most aerodynamic studies.

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