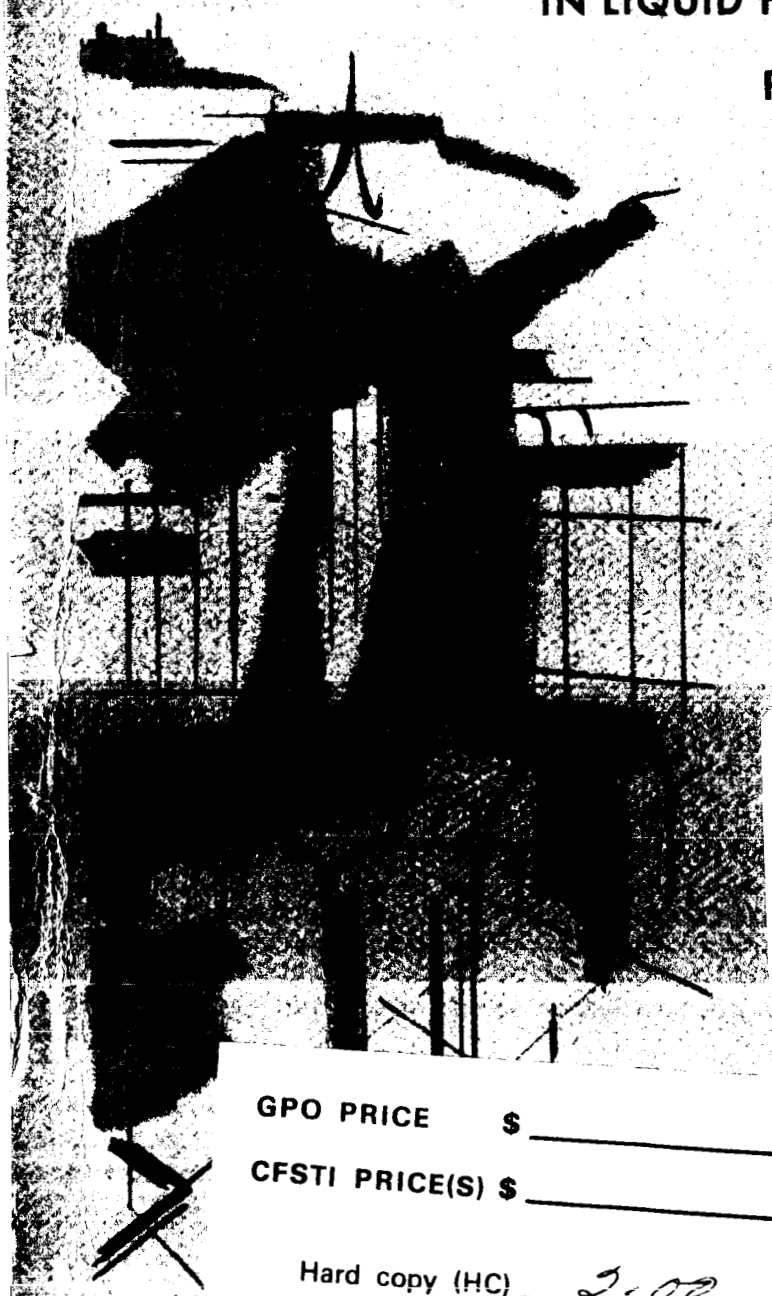
DEVELOPMENT OF DETONATION IN LIQUID FUEL SPRAY WITH GASEOUS OXIDIZER

PRELIMINARY EXPERIMENTS



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Technical Note No. 3
NASA Grant NsG—702
Report No. AS-66-15

October 1966

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ABSTRACT

Experimental apparatus for the study of accelerating flames in a two-phase mixture consisting of a liquid fuel spray in a gaseous oxidizer is described. Observations of the development of detonation in liquid kerosene-oxygen mixtures made by means of streak self-light photographs in a 1-1/2 inch square plexiglas tube, initially at atmospheric pressure and room temperature, are reported.

Due to the slow reaction kinetics of a two-phase system, as compared to a homogencous gascous mixture, acceleration of the combustion front was found to be controlled primarily by the flow field ahead of the flame and this was attributed to the effect it had on the power density of energy deposition in the reaction zone. Results of experimental observations represented on the induction time-distance plane demonstrate a distinct dependence of the plot on the manner in which combustion was initiated, the time to distance ratios being larger when it occurred at a point than in the cases when it started in the form of a bulk explosion.

Results of numerical thermodynamic-equilibrium analysis of pressure, density, temperature, velocity and Mach number for Chapman-Jouget detonations are given as a function of stoichiometric ratio. Velocities of detonation computed for the same initial conditions of a purely gaseous system have been shown to be identical to those of spray combustion, but the corresponding pressure increase in the gas was lower.

Author

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EXPERIMENTAL APPARATUS

Reaction Tube

The reaction tube, shown in Fig. 1, was constructed from 1/2 inch thick plexiglas forming a square 1 1/2 x 1 1/2 inch cross section over a length of 75 inches. The sides were glued together and then the tube was held in compression over its full length by 1 inch steel angles at each corner fastened by seven clamps. At 15 inch intervals the tube was fitted with ignition ports made of brass bushings that screwed into the plexiglas and were tapped to accommodate 18mm spark plugs.

Spray Head

The fuel was introduced into the tube through the spray head shown in Fig. 2. The flow was divided into separate streams by a set of stainless steel hypodermic tubes 1/4 inch long held in a brass plate by epoxy cement. Three such plates were constructed; the first had 36 No. 24 tubes (0.0115 inches I.D.), the second - 18 No. 21 tubes (0.0195 inches I.D.), and the third - 9 No. 18 tubes (0.0330 inches I.D.).

The top of the spray head had a thin metal membrane to introduce acoustic vibrations into the stagnation reservoir of the fuel. The purpose of the vibrations was to cause the jets issuing from the tubes to break up into uniform streams of drops. The fundamental theory of this phenomenon has been developed by Raleigh,[12] Weber,[13] and Chandrasekhar[14]. Characteristic features of the acoustic technique for the generation of spray will be described in a separate report.

The spray head had provision for the introduction of oxygen or nitrogen to the tube. Pure oxygen was used for burning and nitrogen for purging. Both gases entered through separate ports parallel to the fuel tubes in an attempt to reduce turbulence at the inlet section.

Fuel System

The fuel was stored in a military surplus breathing oxygen bottle with a volume of approximately 500 cubic inches and then supplied to the spray head by regulated nitrogen pressure.

The unburned fuel was trapped in a wedge-bottomed box and continuously pumped through a filter to a second fuel bottle which replaced the supply when it was empty. The flow and control system is described schematically in Fig. 3.

Ignition

The ignitor, shown in Fig. 4, was made from a Champion 18mm spark plug. The center electrode was extended 3/8 inch and the ground electrode was straightened. Then a strip of one mil aluminum foil 3/16 inch wide was stretched across the gap and wrapped around each electrode. The foil burned rapidly due to ohmic heating when 120 volts A.C. was applied across the electrodes. The width of the foil was limited to approximately 3/16 inch in order to insure that it would carry a maximum current of about 9 amps before burning.

Records

All records were taken by means of streak self-light photography. Thus a portion of one side of the tube was left as an unmasked slit along the tube axis which was focused by means of a single objective lens on the film plane of a rotating drum camera. A slit width of 2mm was found to pass sufficient light to expose Kodak Tri-X film with an image size of 0.07mm.

The camera used for the experiments was a Southern Instruments Rotating Drum Camera, Model M1020. The 16 inch diameter drum was operated at a peripheral speed of 300 inches per second. The objective lens was a 7-inch focal length f/2.5 aperature, Kodak Aero-Ektar aerial camera lens. The experimental set-up is shown in Fig. 6.

It was necessary to perform the experiments in complete darkness since the early stages of burning were dim relative to normal background lighting.

Besides this, an automatic shutter was needed to prevent double exposure due to slow burning at the top and bottom of the tube. The shutter mechanism is shown in Fig. 5. Ignition timing was accomplished by the microswitch which was closed by the shutter as it opened to the position of minimum acceptable exposure. The mechanism was actuated by a selonoid and closed by a spring. The spring tension was adjusted so that the shutter remained open for approximately one revolution of the drum camera and the microswitch trip-mechanism was set, after several trials, to close at the acceptable exposure.

Drop Measurement

A shuttle mechanism that was made to sample drop sizes is shown in Fig. 7 along with a typical record obtained with its use. Drops were caught on the small plate coated with a smooth thin layer of silicone grease to prevent wetting. The plate went through the stream twice as it went out and back. The results were found to depend strongly upon the operator's skill and it was observed that the acceleration at the end of the stroke was large enough to cause coalesence of some drops.

The most reliable method for recording drop size was found to be direct photography of the spray with a five-fold magnification using Polaroid 4 x 5 Land Film Packets and a short duration Xenon light source. A typical example of the records obtained in this way showing drop formation near the generator is represented by Fig. 8.

RESULTS

A set of typical records are given by Plates 1 to 13. Self-light streak photographs clearly show the paths of the flame fronts and the particles in the combustion zone. In particular, one can observe the effect of rarefactions and of shock waves by changes in luminosity as well as sharp deflections in particle paths. The parallel lines crossing all of the records are the images of the clamps spaced at 10 inch intervals along the tube length.

All records shown were made with an initial oxygen flow velocity of 1.7 m/sec corresponding to a Reynolds Number of 2800 based on the hydraulic diameter of the tube. With the use of oxygen the burning process was reproducible and the transition to detonation normally occurred within the 75 inches of the tube length. Without the oxygen flow the burning process tended to die out or travel at a relatively low velocity of 6 to 11 m/sec with almost no observable acceleration along its path. The introduction of the oxygen at high flow rates disrupted the initially uniform drop streams after approximately 8 cm of flow. However, the effect on the distribution of drops in the lower portion of the tube was unnoticeable since the drops were generally scattered by wakes behind the drops by the time they had traveled 30 cm. With smaller drop sizes this effect was more pronounced.

Two distinct types of records were obtained, depending on the type of ignition that occurred. Characteristic of the first type are Plates 1 through 5. In these records the burning appears to have originated from a point source. Examination of the ignitor after such runs showed the foil to be intact except for a hairline burn across its width.

Examples of the second type of record are shown in Plates 6 through 9. Here the ignition appears to have occurred in bulk over a finite width and examination of the ignitor after these runs showed that almost the entire piece of foil had burned,introducing a brilliant flash at the moment of ignition.

The reason for separating the two types of runs is shown in Fig. 9, where time to detonation is plotted versus distance to detonation. It may be seen that in the case of bulk ignition the transition occurred appreciably earlier than in the case of point ignition. Figure 9 demonstrates also that the type of ignition becomes less important as the induction distance is shortened. The main causes of the two types of ignition were probably minute tears in the foil made during preparation and the effect of the kerosene seeping between the electrodes and the aluminum foil. The range of induction distances for all runs was found to be about 0.3 to 1.5 meters.

The inlet stoichiometric ratio for the lowest flow rates (fuel/oxygen) varied from 0.4 for the No. 24 tubes to 3.6 for the No. 18 tubes, but no

correlation was made with flow rates. The detonation velocity was found to vary from 1550 m/sec to 2200 m/sec; however it showed no consistent variation with either plate size or flow rate as shown by inspection of Fig. 10.

DISCUSSION

One of the most significant features of the streak records is the asymmetry of the flame world lines. The downstream flame always accelerated more rapidly. This can be explained as a consequence of the long burning time of drops (which is an order of magnitude larger than that of a flame in a homogeneous gaseous mixture [15]) combined with the relative velocities between the flame fronts and the drops. These two effects cause the downstream combustion zone to be thinner and thus increase the power density of energy release.

A specific example of the effects mentioned above is graphically illustrated by Fig. 11. The conditions correspond to the record of Plate 3, at 13 m/sec. after ignition, giving upstream and downstream flame velocities of 2.5 and 5.0 m/sec respectively. A 75 micron diameter drop traveling 3.0 m/sec would, in accordance with Godsave, [2] have a lifetime of 5.62 msec. It would thus release all of its energy within 1.1 cm of the downstream flame front, but it would be 3.1 cm away from the upstream flame by the time it is burned and release only 51% of its energy within the 1.1 cm distance from the upstream flame front. A similar example with a 200 micron drop shows that 38% would burn within 1.1 cm distance from the front of the downstream flame while only 8% would be consumed under similar conditions for the upstream propagating flame.

As the downstream flame accelerates, its higher velocity tends to increase the combustion zone width and thereby decrease the power density. However, the pressure waves generated by the accelerating front pre-compress the medium and cause the drops to burn more rapidly and thus allow the flame to continue its acceleration. This is in agreement with the results of Hall and Diederichsen [16] who demonstrated experimentally the enhancement of the rate of combustion associated with an increase in chamber pressure.

It may be seen that in all cases the rarefaction following the downstream flame slowed and then reversed the flow behind it as the flame accelerated. This reverse flow, as measured from Plate 1, reached a velocity of 105 m/sec at 15 cm below the upstream flame when the flame had a velocity of only 150 m/sec. The effect of this was again a decrease in the combustion zone or an increase in the power density which allowed the upstream flame to accelerate. Plates 2 and 12 show that the processes were identical irrespective of where ignition occurred.

Although the upstream flame was accelerating, it is of interest to note that the flame was normally transformed into a detonation by interaction with the retonation from the downstream detonation. Examples showing that the upstream flame could transform into a detonation by a continuous acceleration are given in Plates 12 and 13. Plate 12 is a case where the ignitor was near the bottom of the tube and the downstream flame passed out of the end before it detonated but the rarefaction from it was sufficiently strong to initiate the upstream flame's acceleration. In Plate 13 the upstream flame accelerated to detonation before it was intercepted by the downstream detonation wave.

The drop-gas system was not homogeneous as are gaseous systems; but the records revealed remarkably smooth combustion processes. Expansions of the length scales for Plates 3 and 4 are given in Figs. 12 and 13 respectively along with a plot of the downstream flame velocity and acceleration from Plate 3 in Fig. 14. These figures demonstrate that the observable smooth flame world lines are associated with smooth variations in both the velocity and acceleration. Similarly Plate 11 (an enlarged section of Plate 10) indicates that, in at least some cases, detonation was achieved as the culmination of a continuously accelerating flame as contrasted to purely gaseous systems which often show a large discontinuity in velocity. The detonation wave velocity itself exhibited these smooth characteristics notwithstanding the change in conditions along the tube. This invariance of the detonation wave velocity is shown most strikingly in Plate 6.

A plot of the flame world lines for Plate 5 is shown in Fig. 15. In contrast to Figs. 12 and 13 the velocity was almost constant from 9 to 17 m/sec after ignition. However, inspection of Plate 5 shows that this coincides with the time that the flame passed through a region of much lower fuel concentration as demonstrated by the dark streak on the record there.

Perhaps one of the most significant features of Plate 5 is shown by the path of the upstream flame which had zero absolute velocity during the time the downstream flame passed through the region discussed above. This suggests that the mechanism of feedback, due to the rarefaction behind the downstream flame, influences the upper flame at a much earlier stage than previously indicated.

The effect of drops which have hit the walls is shown by the particle paths of Plates 5 and 9. While the rest of the drops were accelerated, the drops at the walls remained motionless until they were disturbed by the large reverse flow resulting from the rarefaction following the downstream flame.

A source program developed at the Propulsion Dynamics Laboratory [17] was used to calculate the Chapman-Jouget conditions as a function of stoichiometric ratio. Computations were made for liquid fuel in pure oxygen (spray) and also for gaseous hydrocarbon and oxygen. Analysis of the kerosene fuel showed that it was largely composed of pariffins so the physical data of dimethyl pentane was chosen as a model to match the molecular weight and the heat of combustion. All other thermal data used in the program was taken from the JANAF Tables.

Results of the computations are presented in Figs. 16 and 17. The detonation velocity was found to have the same value irrespective of whether the fuel was assumed to be initially in liquid or gaseous phase. The computed detonation velocities (1700-2600 m/sec.) compared favorably with the measured values (1550-2200 m/sec.). The pressure ratio across the detonation was found to be higher for the spray than for the gas. This was attributed to the large expansion of the fuel as it changed from liquid to gaseous phase.

SUMMARY AND CONCLUSIONS

Apparatus for the optical observation of two-phase combustion was described. It consists of: (a) a plexiglas tube of 1 1/2 x 1 1/2 inch cross-section x 75 inches long, (b) the associated fuel and oxidizer supply systems, and (c) the optical system consisting of a rotating drum camera fitted with an automatic shutter. The system yielded streak self-light photographs of accelerating flames in liquid kerosene-oxygen mixtures including the transition to detonation.

Essential features of the development of the process were not affected by the position of the ignitor. Detonations were observed to develop in a distance as short as 25 cm and as long as 150 cm from the point of ignition.

There has been a marked difference observed between the upstream and downstream propagating flames. The latter always accelerated first. This was explained on the basis of the extent of the reaction zone and consequently the power density of energy release within the flame fronts. The downstream flame always had a thinner reaction zone, dur to smaller relative velocity with the stream, and thus a higher power density.

The transition to detonation of the upstream flame was normally caused by the rarefaction behind the accelerating downstream flame which reversed the flow and promoted the increase in power density of energy release by the upstream flame.

The measured detonation velocities ranged from 1550 to 2200 m/sec. This variation comes within the values predicted by theory.

ACKNOWLEDGMENT

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REACTION TUBE

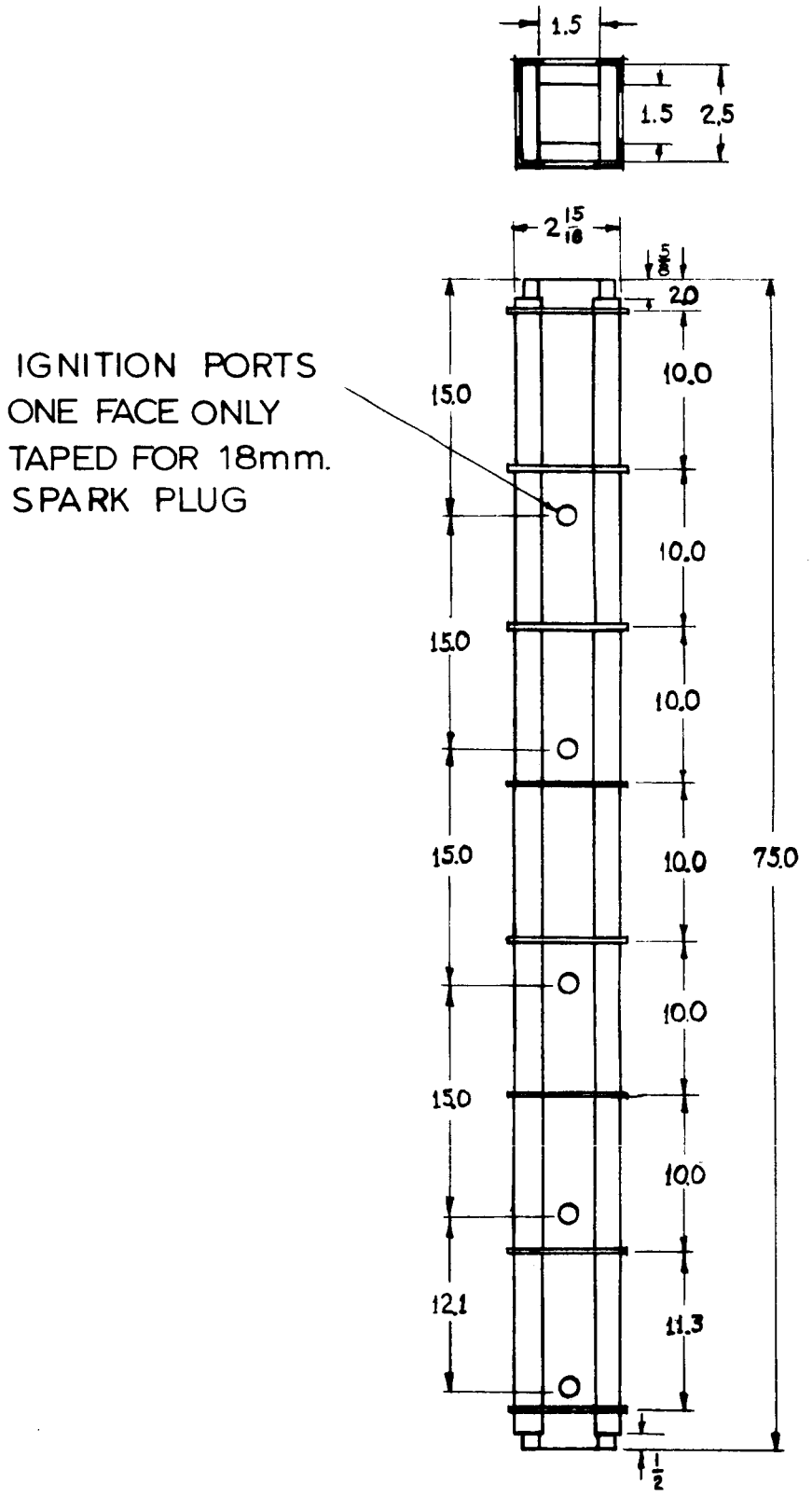
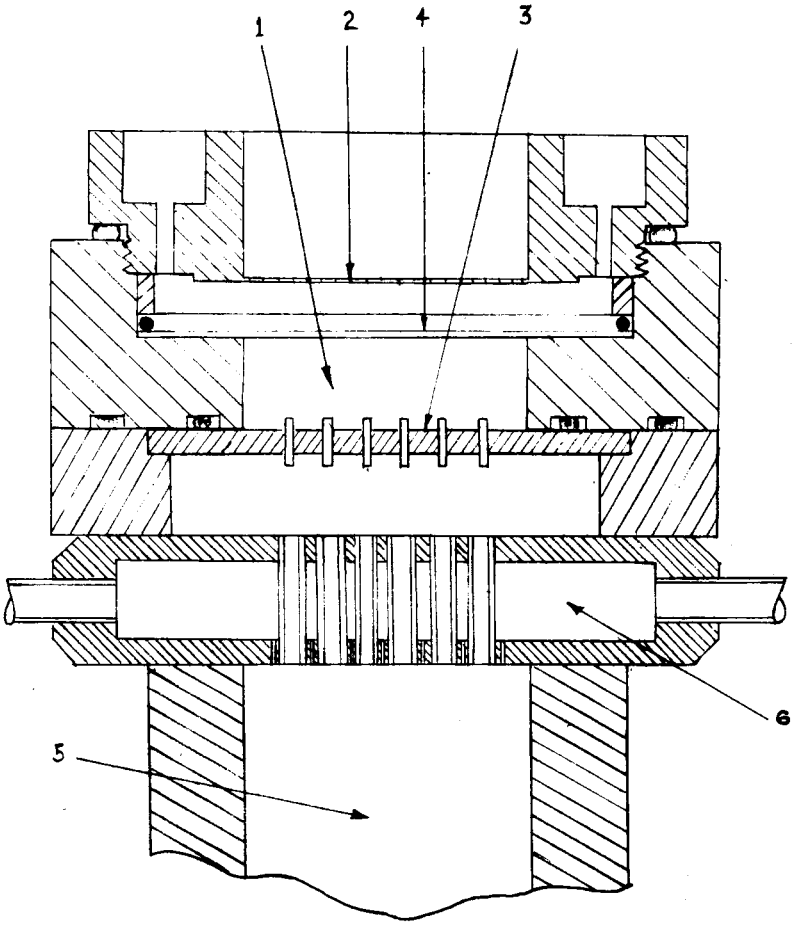


FIG. 1

SPRAY HEAD



1. FUEL CHAMBER
2. DIAPHRAGM
3. PLATE
4. FILTER
5. REACTION TUBE
6. O_2 AND N_2 CHAMBER

FIG. 2

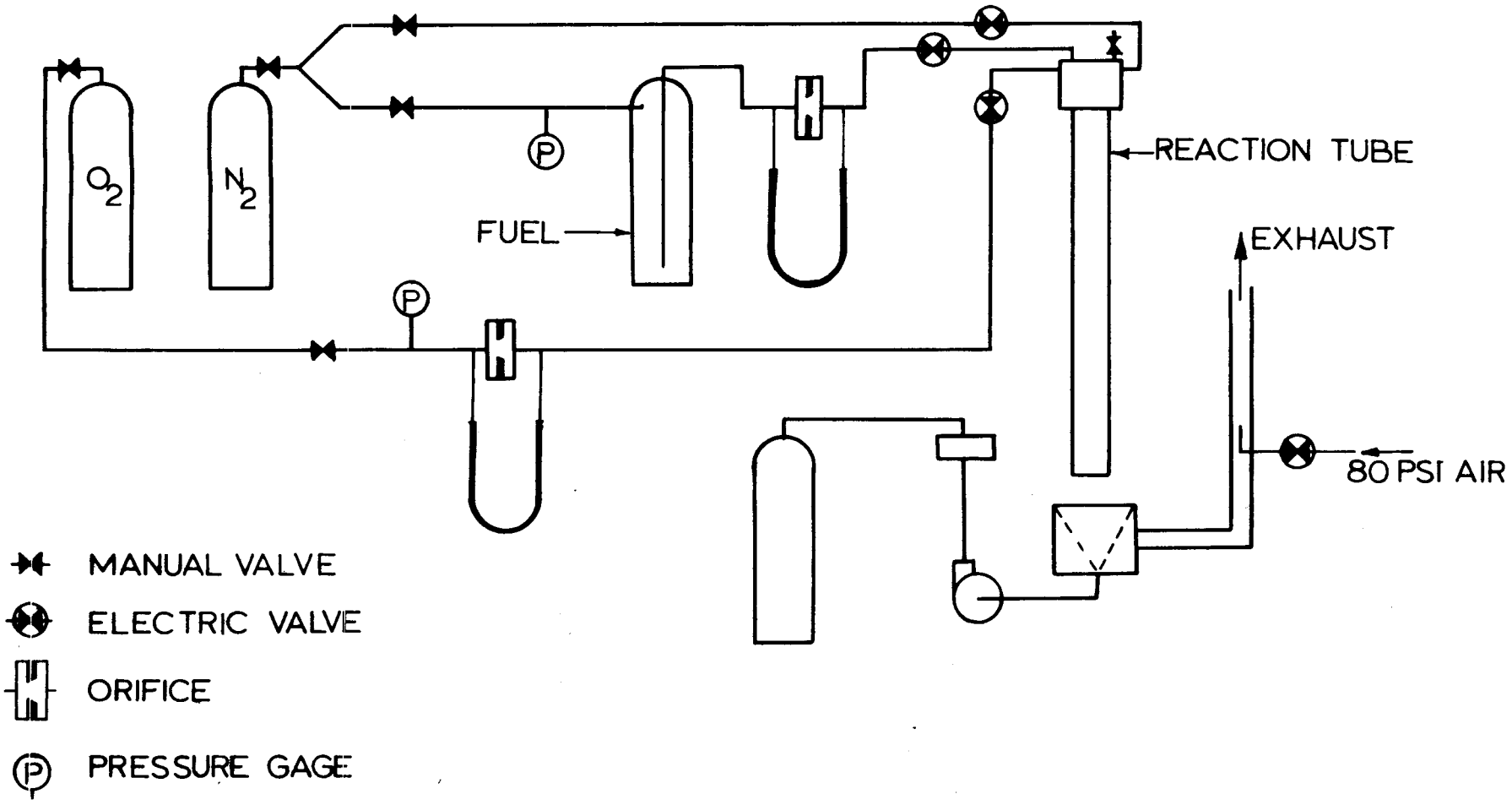
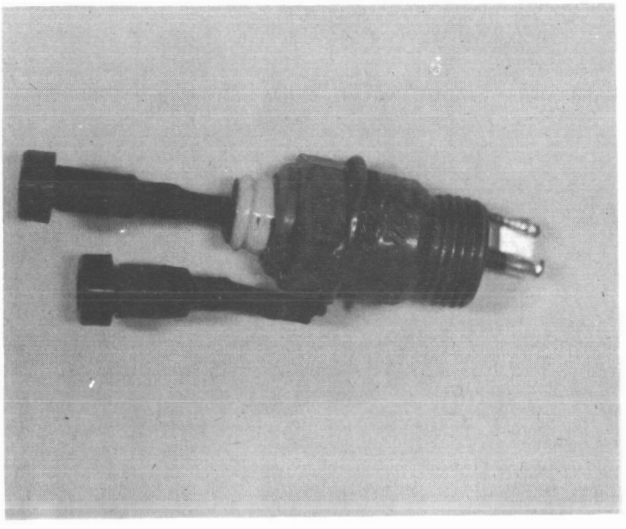
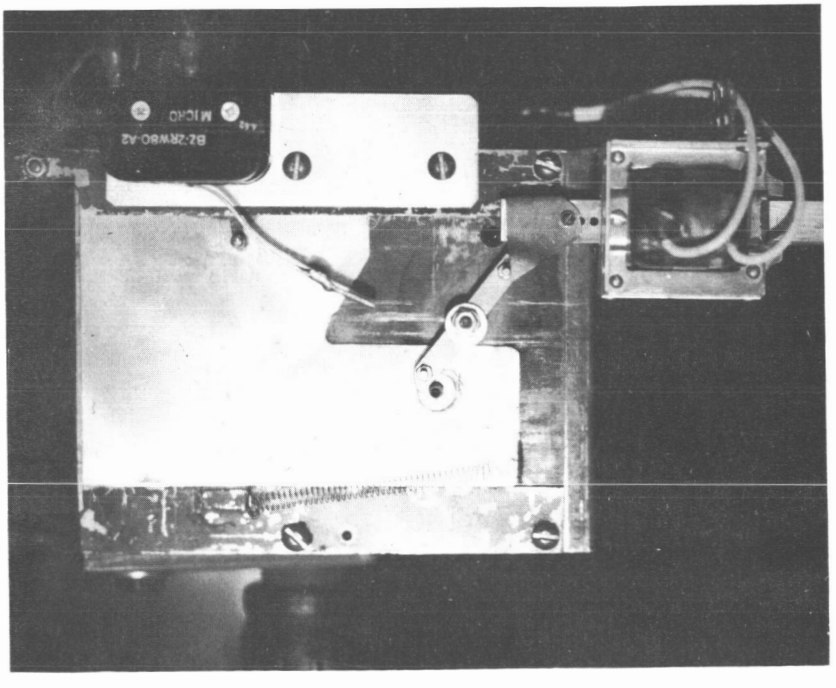


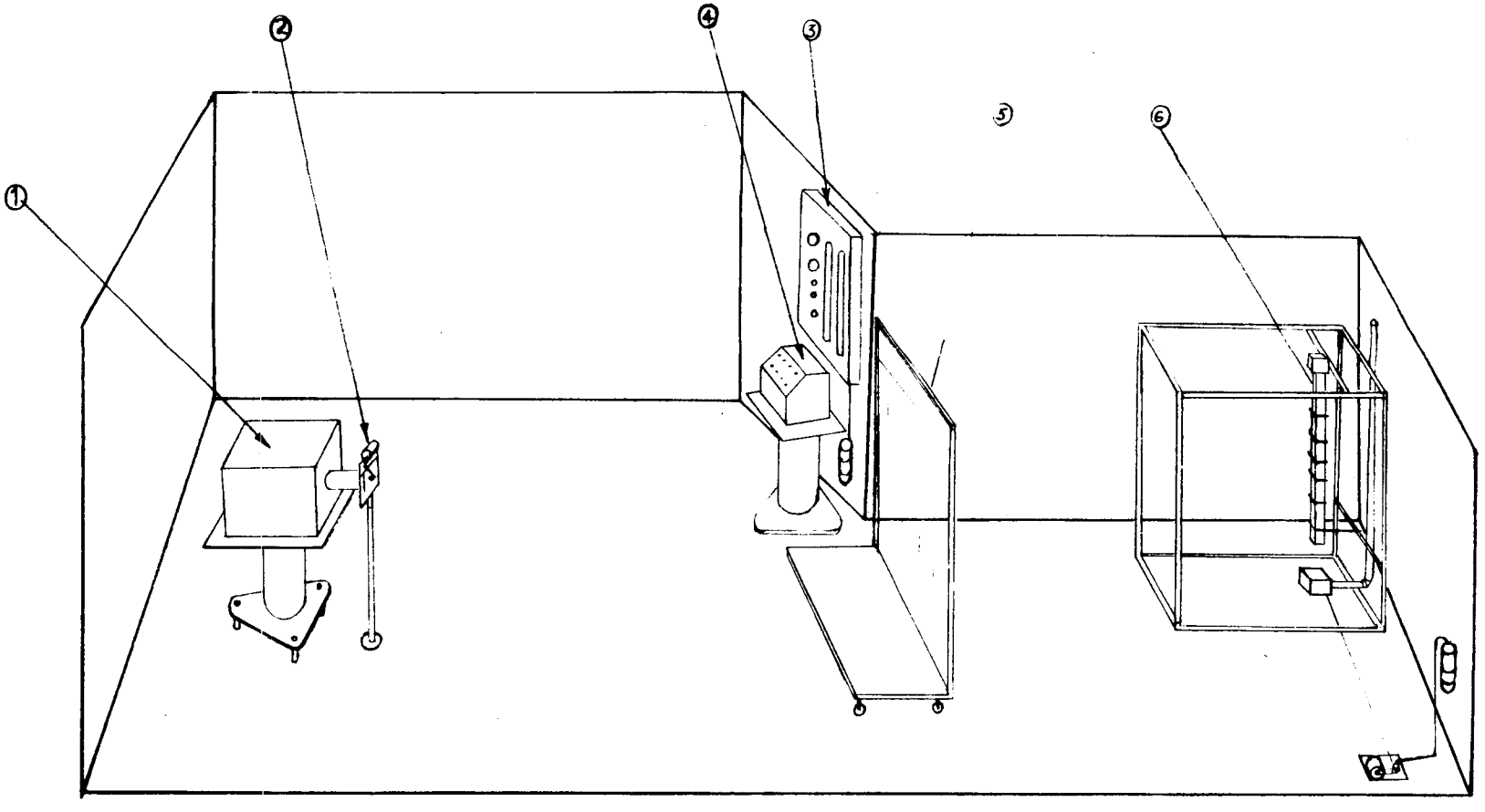
FIG 3 SCHEMATIC OF FLOW SYSTEM



IGNITOR
FIG. 4

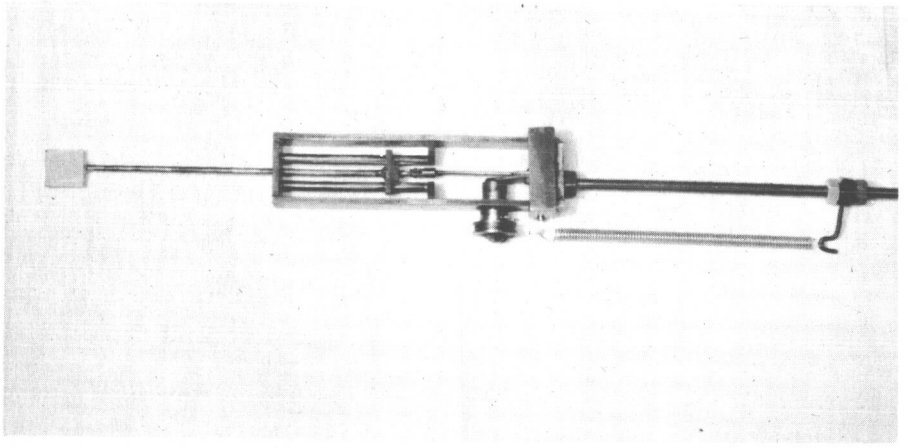


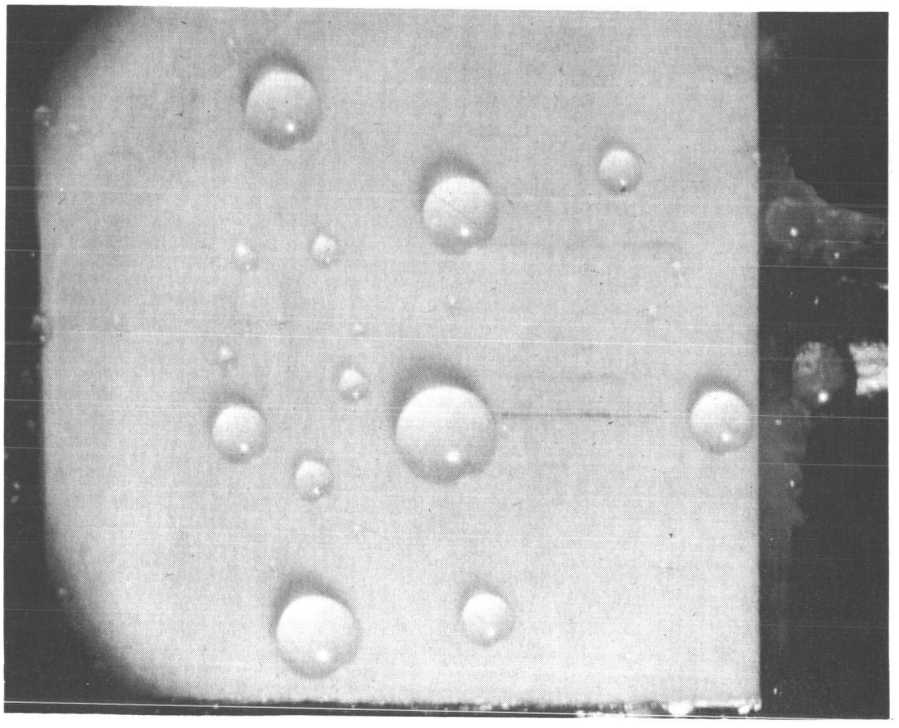
SHUTTER
FIG. 5



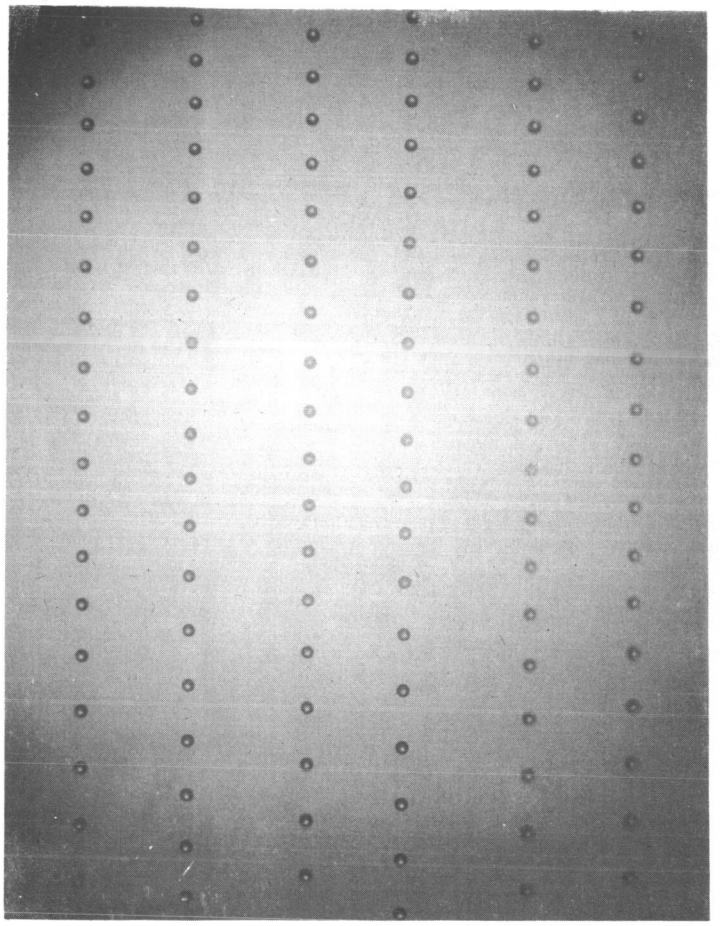
1. CAMERA
2. SHUTTER
3. CONTROL BOARD
4. CONTROL PANEL
5. SHIELD
6. TUBE

FIG. 6 EXPERIMENTAL APPARATUS





DROP SAMPLER AND RECORD
FIG. 7



DROP STREAMS

FIG. 8

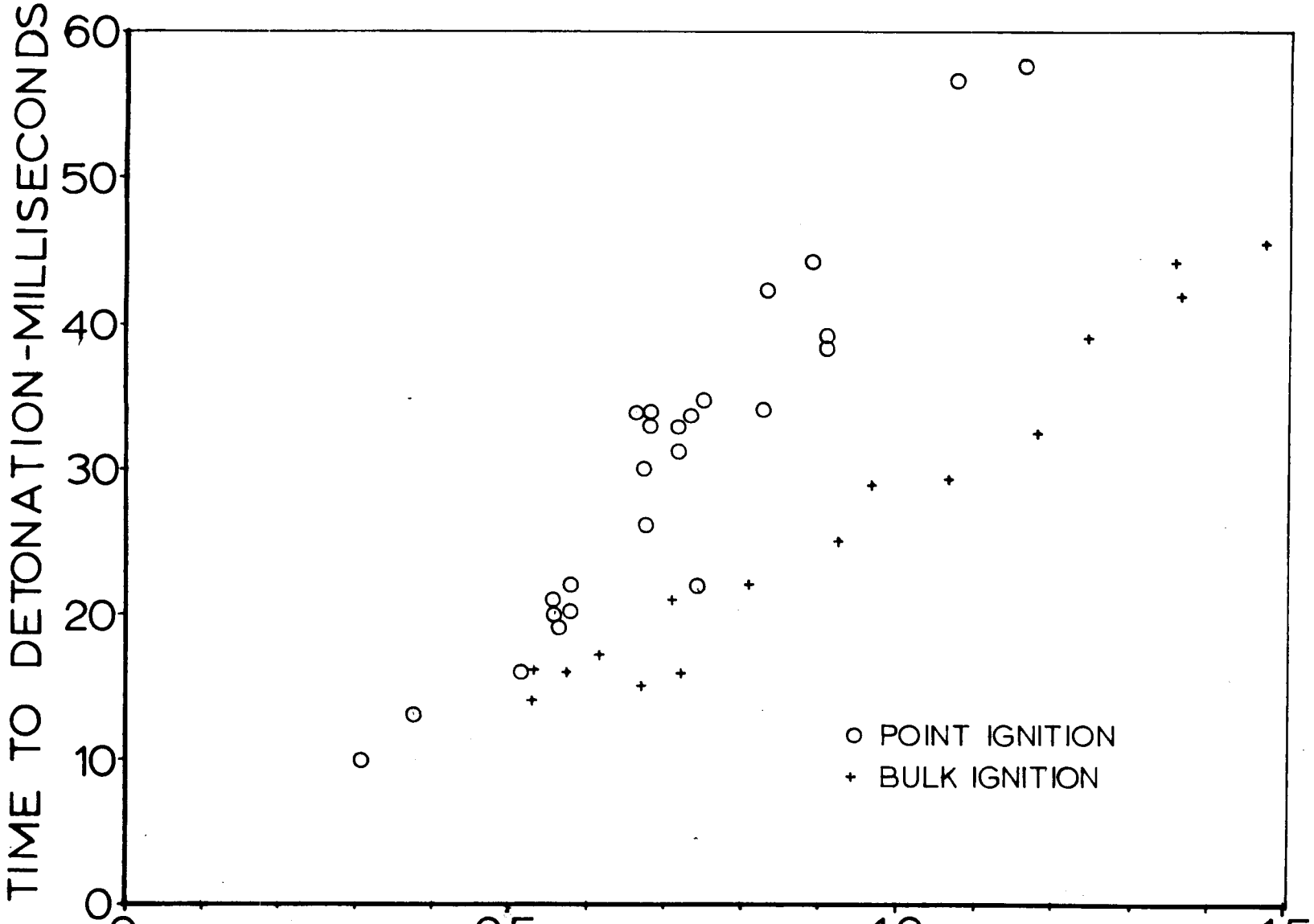

TIME TO DETONATION-MILLISECONDS
60
50
40
30
20
10
0
0
0.5
1.0
1.5
DISTANCE TO DETONATION-METERS
POINT IGNITION
BULK IGNITION

FIG. 9

Experiment Run No.	Plate No.	Spray Plate No.	Fuel Flow Rate gm/min	Induction Distance (meters)	Induction Time (milliseconds)	Detonation Velocity m/sec.	Ignition
32	6	1	562	0.31	10.2	2070	Point
33		1	680	0.38	13.2	1830	"
9		1	240	0.53	16.7	1770	"
10		1	240	0.56	21.0	1600	"
49		2	680	0.56	18.8	1940	"
35	2	1	240	0.56	20.0	-	"
20		1	240	0.58	22.0	1940	"
31	1	1	470	0.59	20.7	1600	"
24		1	240	0.66	34.0	1580	"
46		2	430	0.69	26.2	1730	"
29	4	1	350	0.69	30.0	1680	"
8		1	240	0.69	33.0	-	"
47		2	510	0.69	33.6	1860	"
28	3	1	300	0.74	31.3	1770	"
14		1	240	0.74	33.6	1810	"
36		1	240	0.74	34.0	1730	"
48		2	600	0.76	35.2	1950	"
74	5	3	350	0.76	20.8	1880	"
75		3	430	0.83	42.6	1830	"
26		1	240	0.84	34.0	1640	"

FIG. 10

Experiment Run No.	Plate No.	Spray Plate No.	Fuel Flow Rate gm/min	Induction Distance (meters)	Induction Time (milliseconds)	Detonation Velocity m/sec.	Ignition
67		2	240	0.89	44.6	-	"
16		1	240	0.91	38.4	-	"
27		1	240	0.91	39.0	1600	"
57		3	680	1.07	57.6	1580	"
50		2	220	1.17	59.0	1760	"
37	12	1	240	-	-	-	"
62	10	1	240	0.51	15.8	1980	Bulk
30		1	390	0.54	14.1	1730	"
34		1	240	0.58	16.2	2110	"
13		1	240	0.64	17.1	-	"
15		1	240	0.69	15.3	1940	"
65	8	1	240	0.71	20.7	2150	"
11	13	1	240	0.74	16.7	1730	"
64		1	240	0.81	22.1	2150	"
63	7	1	240	0.94	25.7	2110	"
61		1	225	0.97	27.0	2080	"
69		2	240	1.07	29.5	1870	"
70	9	3	240	1.19	31.6	2110	"
72		3	240	1.24	39.0	-	"
73		3	240	1.36	44.1	-	"
68		2	240	1.37	42.2	2020	"
71		3	240	1.47	46.6	-	"

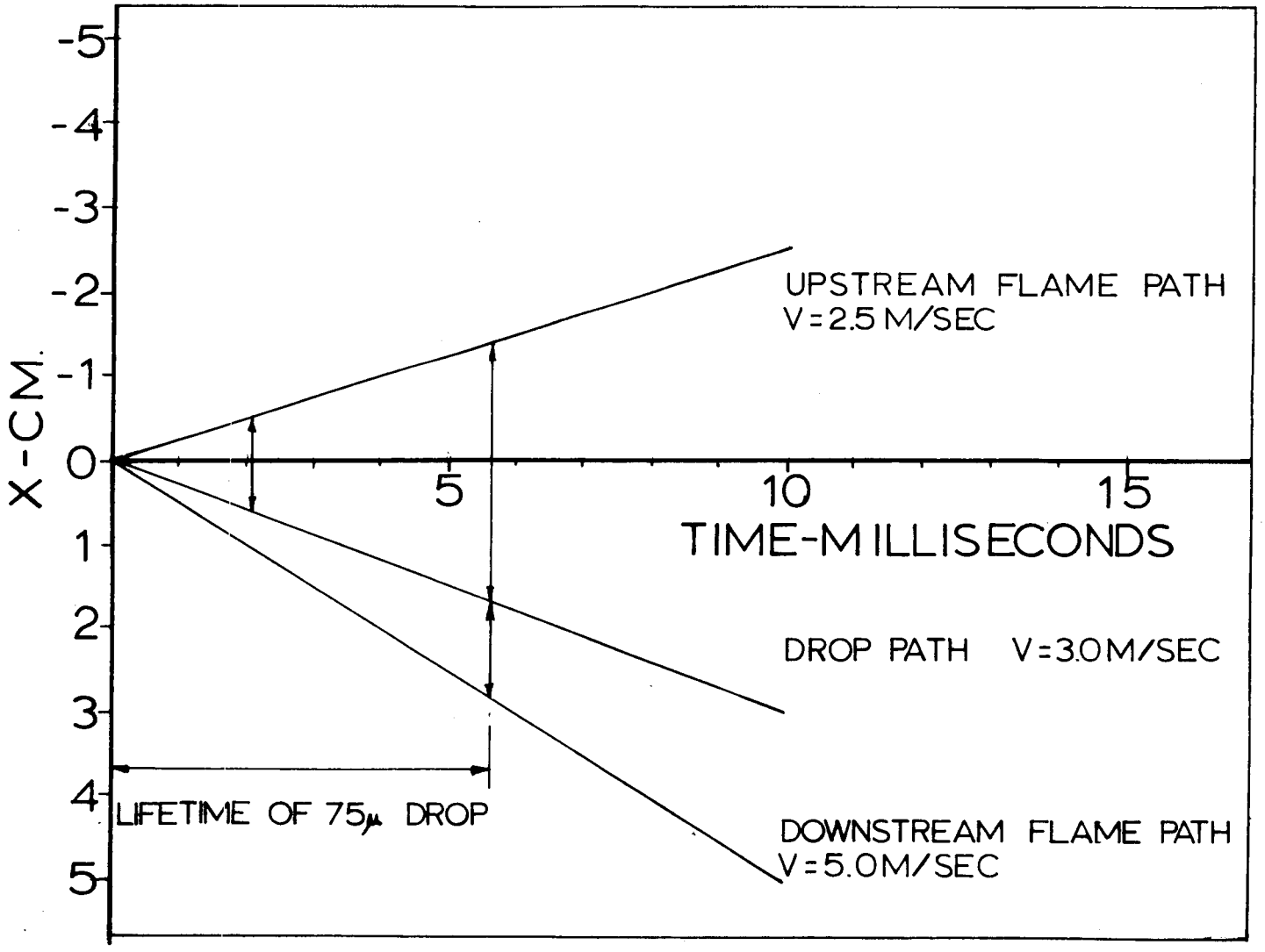

-5
-4
-3
-2
-1
0
1
2
3
4
5
X-CM.
5
10
15
TIME-MILLISECONDS
UPSTREAM FLAME PATH
V=2.5 M/SEC
DROP PATH V=3.0M/SEC
LIFETIME OF 75μ DROP
DOWNSTREAM FLAME PATH
V=5.0M/SEC

FIG. 11

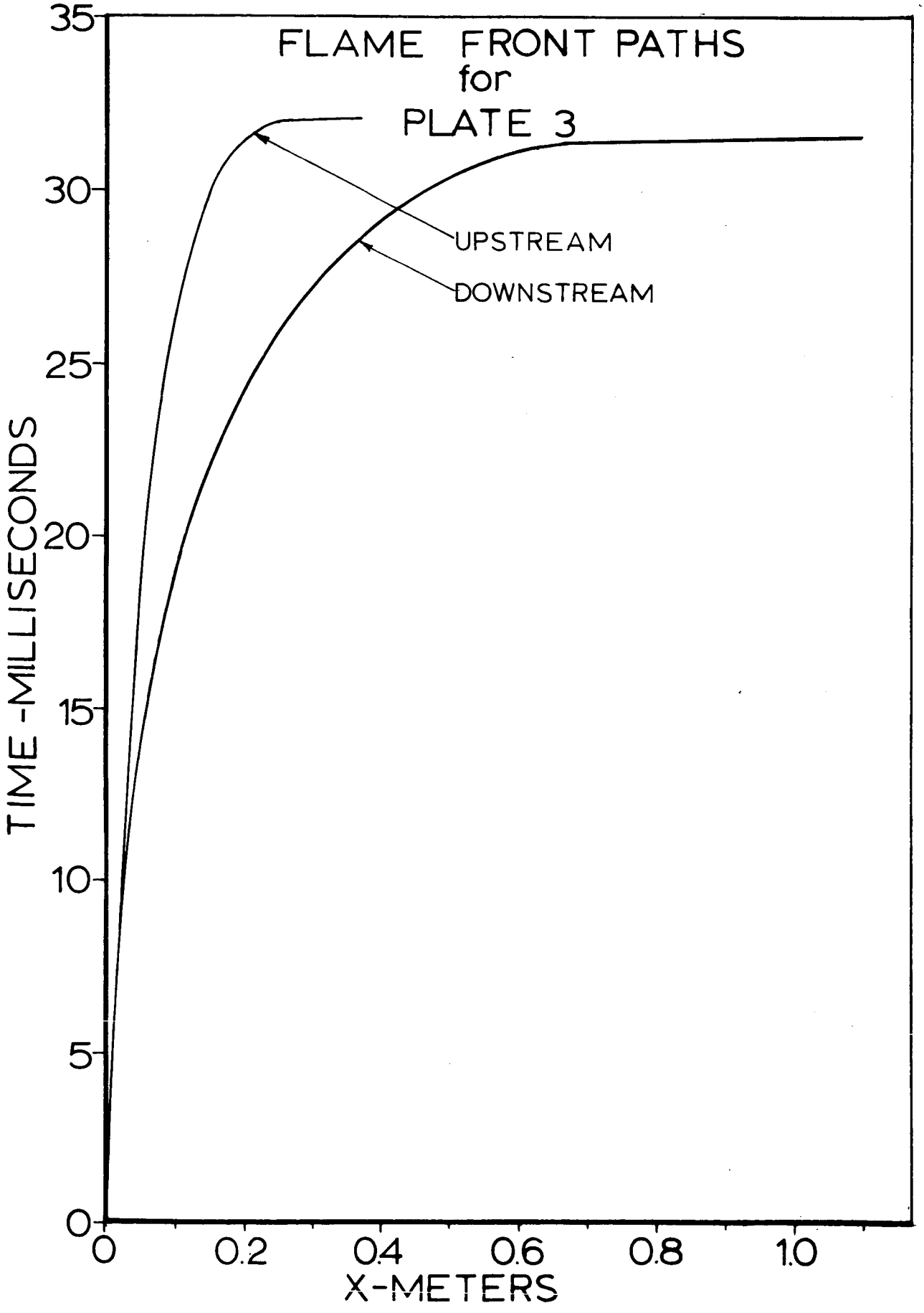

FLAME FRONT PATHS
for
PLATE 3
UPSTREAM
DOWNSTREAM
TIME -MILLISECONDS
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1.0
X-METERS

FIG. 12

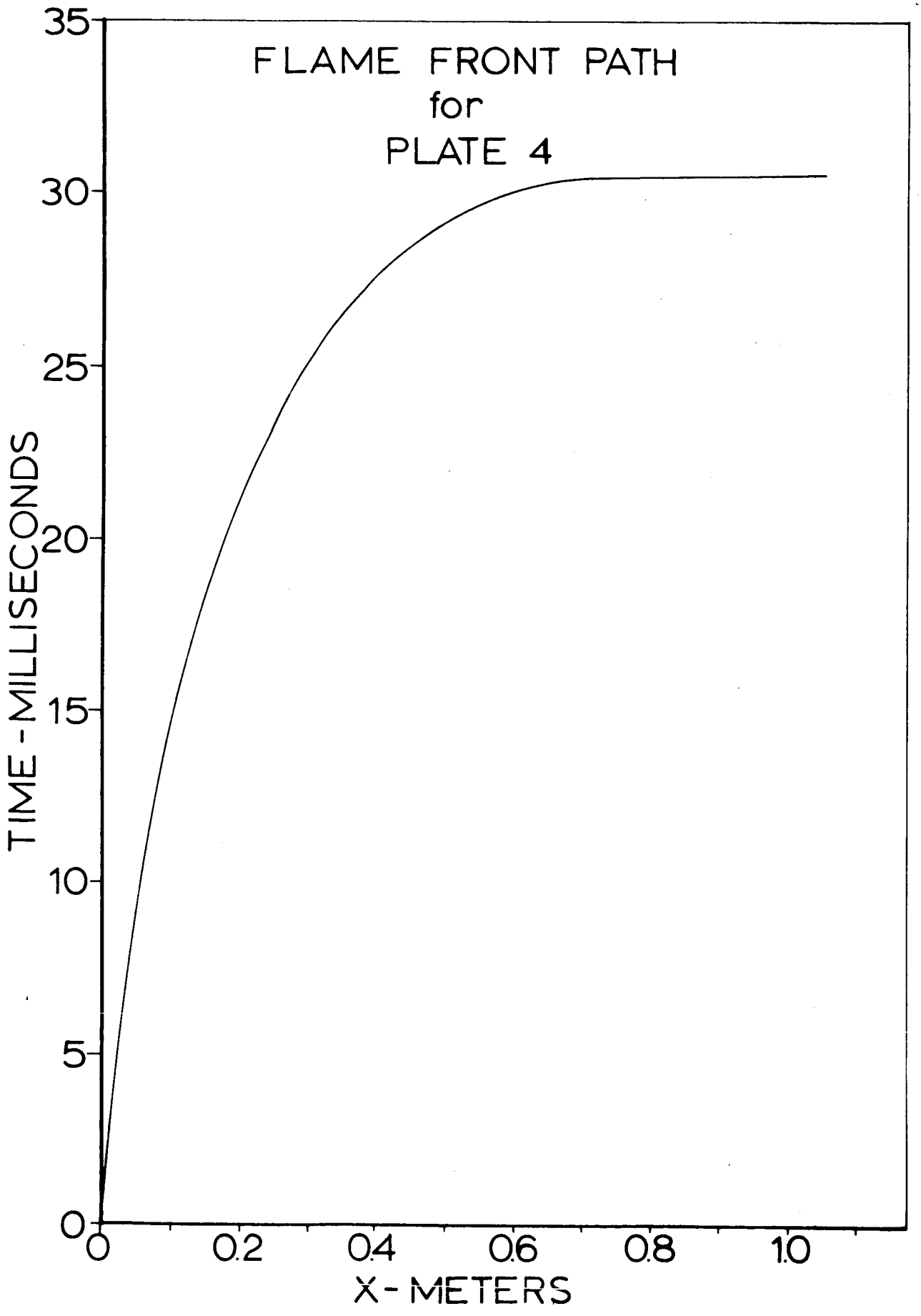

FLAME FRONT PATH
for
PLATE 4
TIME - MILLISECONDS
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1.0
X - METERS

FIG. 13

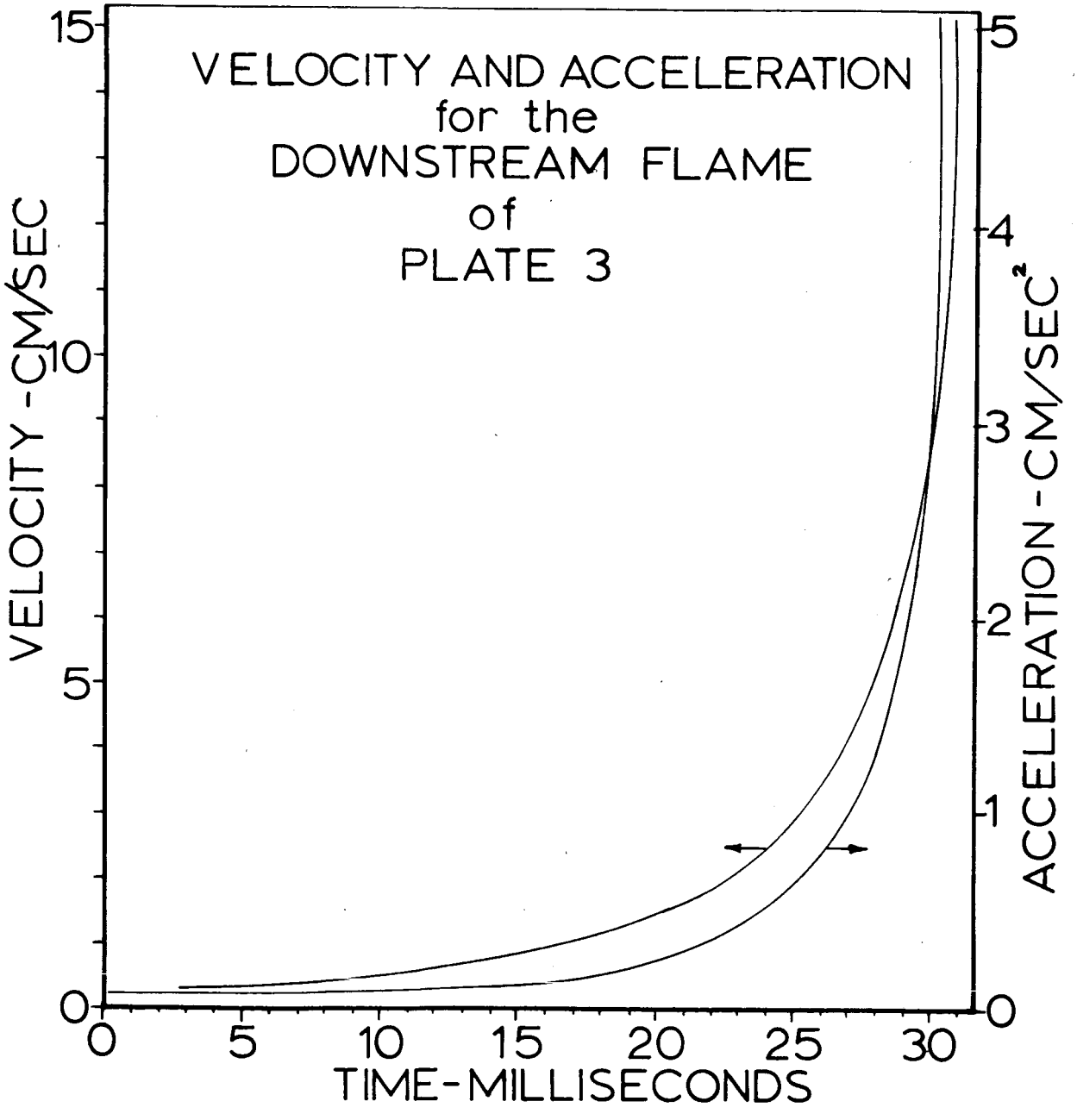

VELOCITY AND ACCELERATION
for the
DOWNSTREAM FLAME
of
PLATE 3
VELOCITY - CM/SEC
ACCELERATION - CM/SEC²
TIME - MILLISECONDS
0
5
10
15
20
25
30
0
1
2
3
4
5

FIG. 14

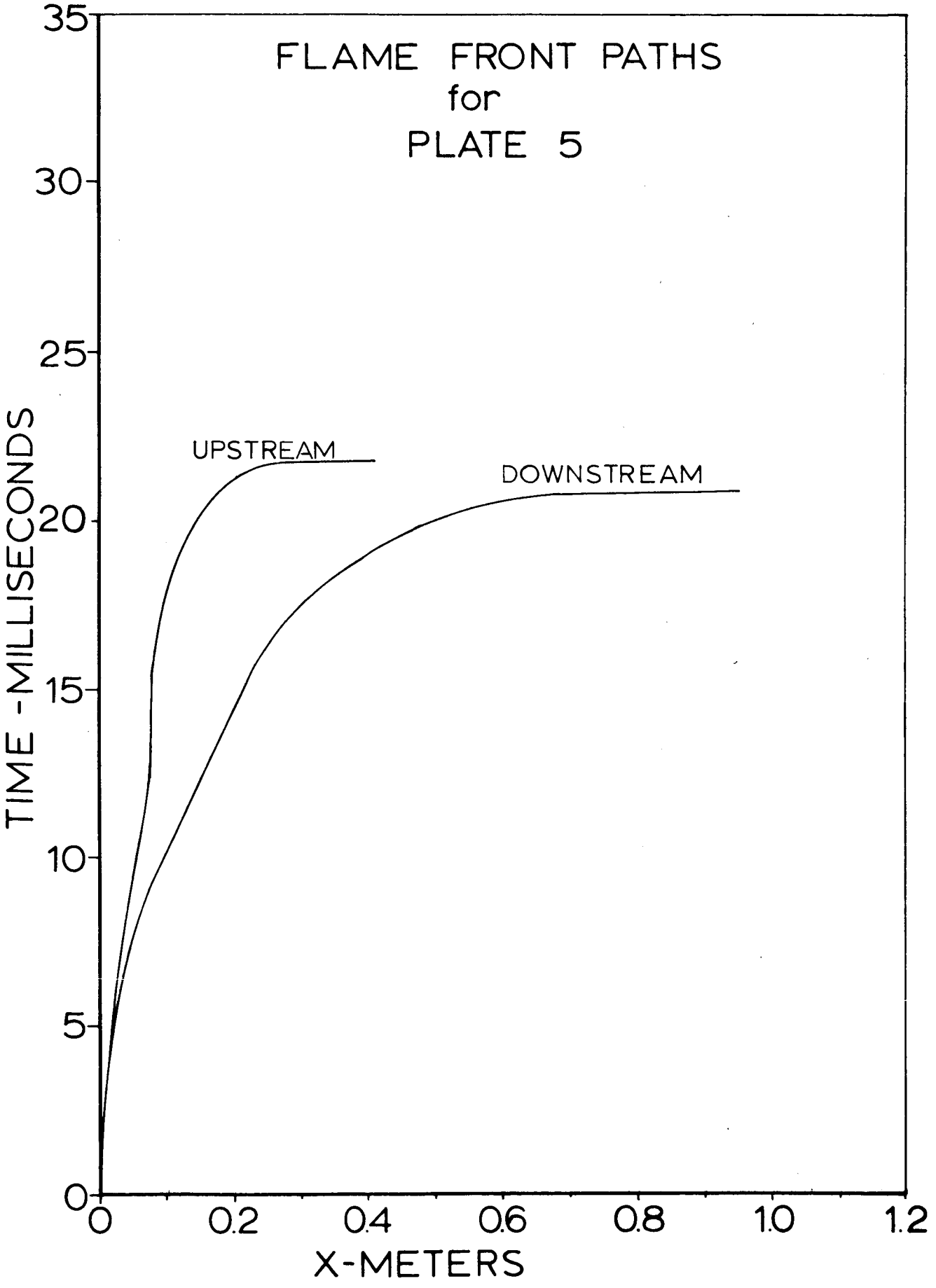

FLAME FRONT PATHS
for
PLATE 5
UPSTREAM
DOWNSTREAM
TIME - MILLISECONDS
X-METERS
0
5
10
15
20
25
30
35
0
0.2
0.4
0.6
0.8
1.0
1.2

FIG. 15

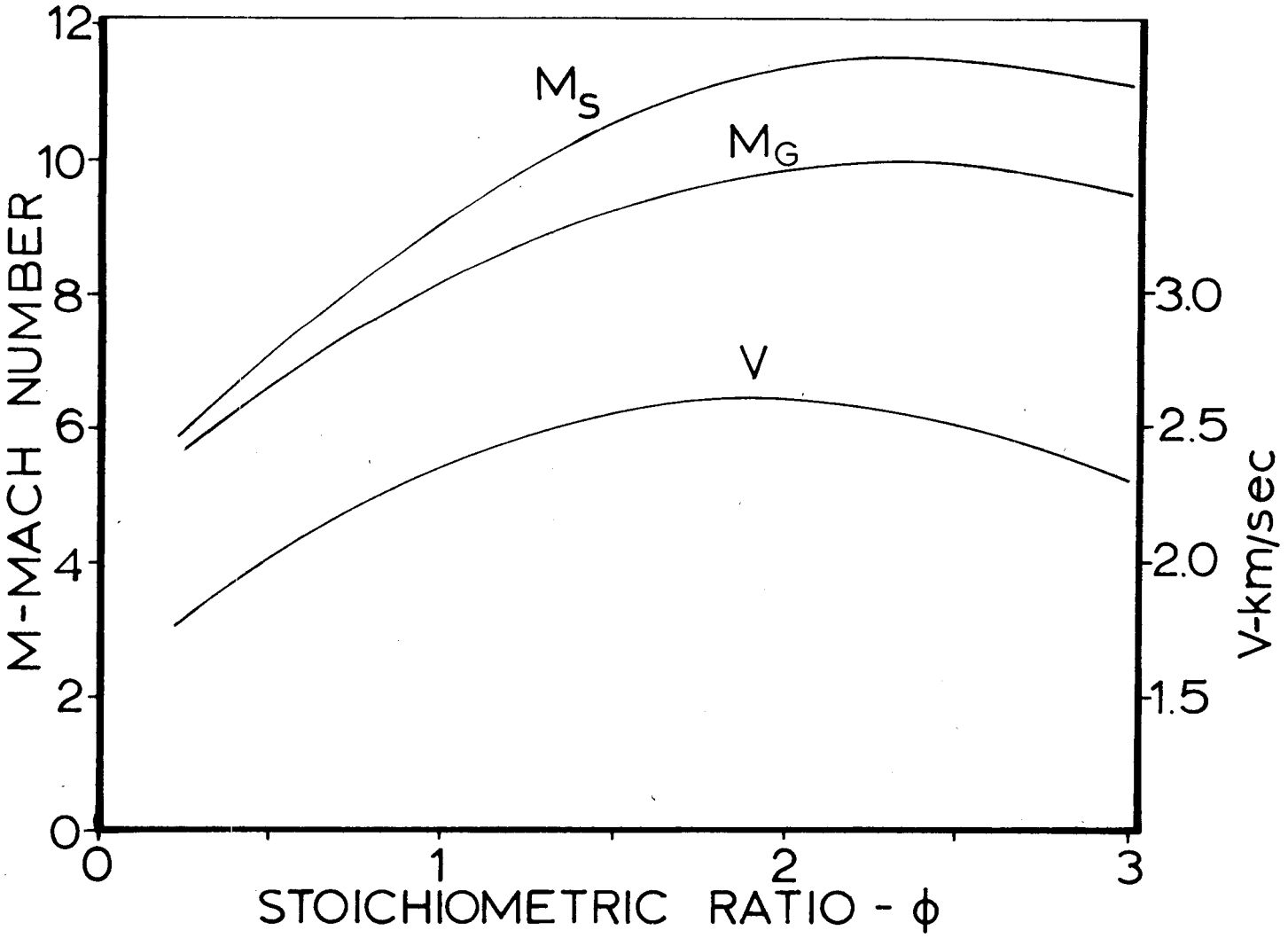

12
10
8
6
4
2
0
M-MACH NUMBER
M_S
M_G
V
3.0
2.5
2.0
1.5
V-km/sec
0
1
2
3
STOICHIOMETRIC RATIO - ϕ

FIG. 16

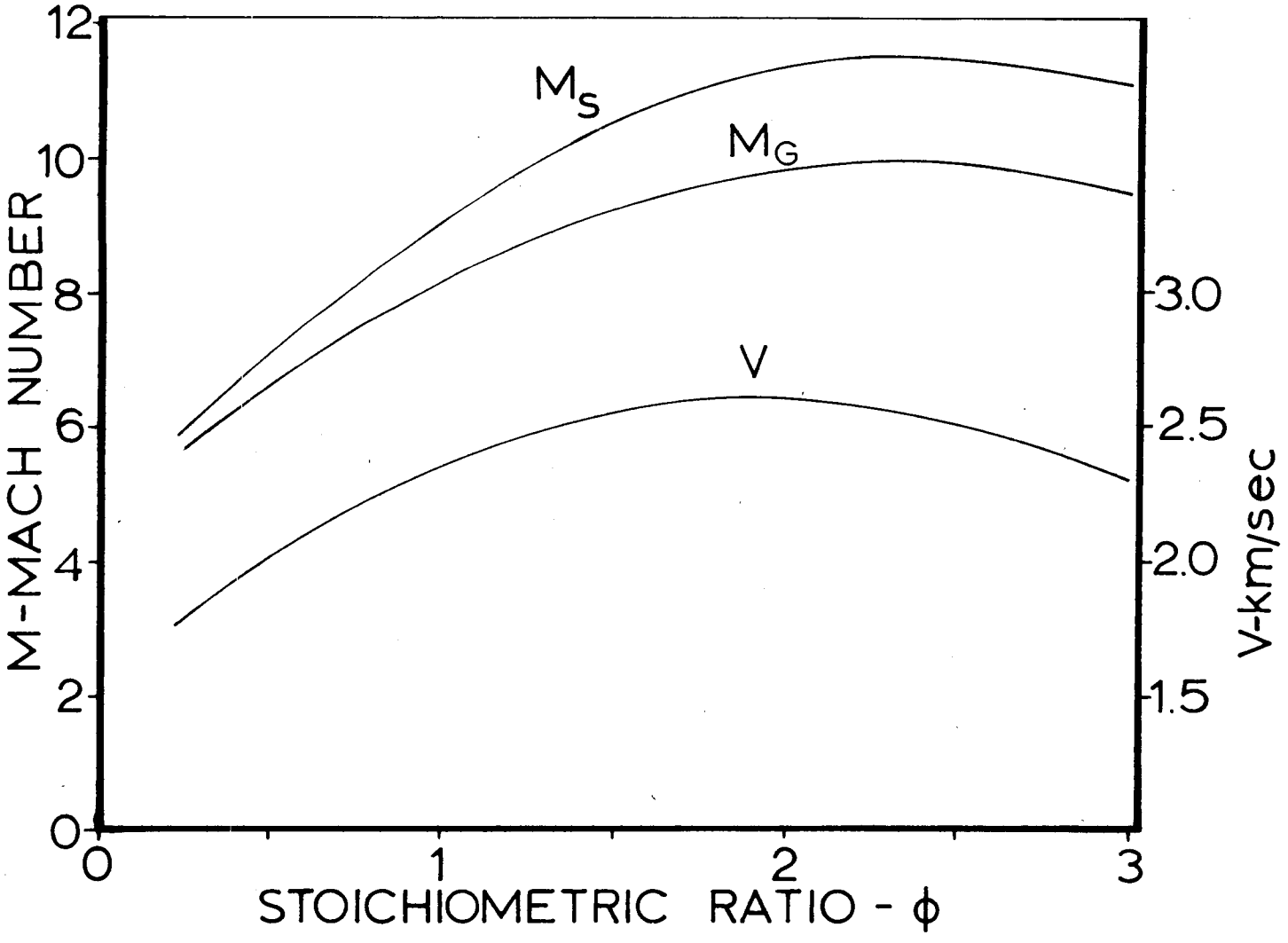
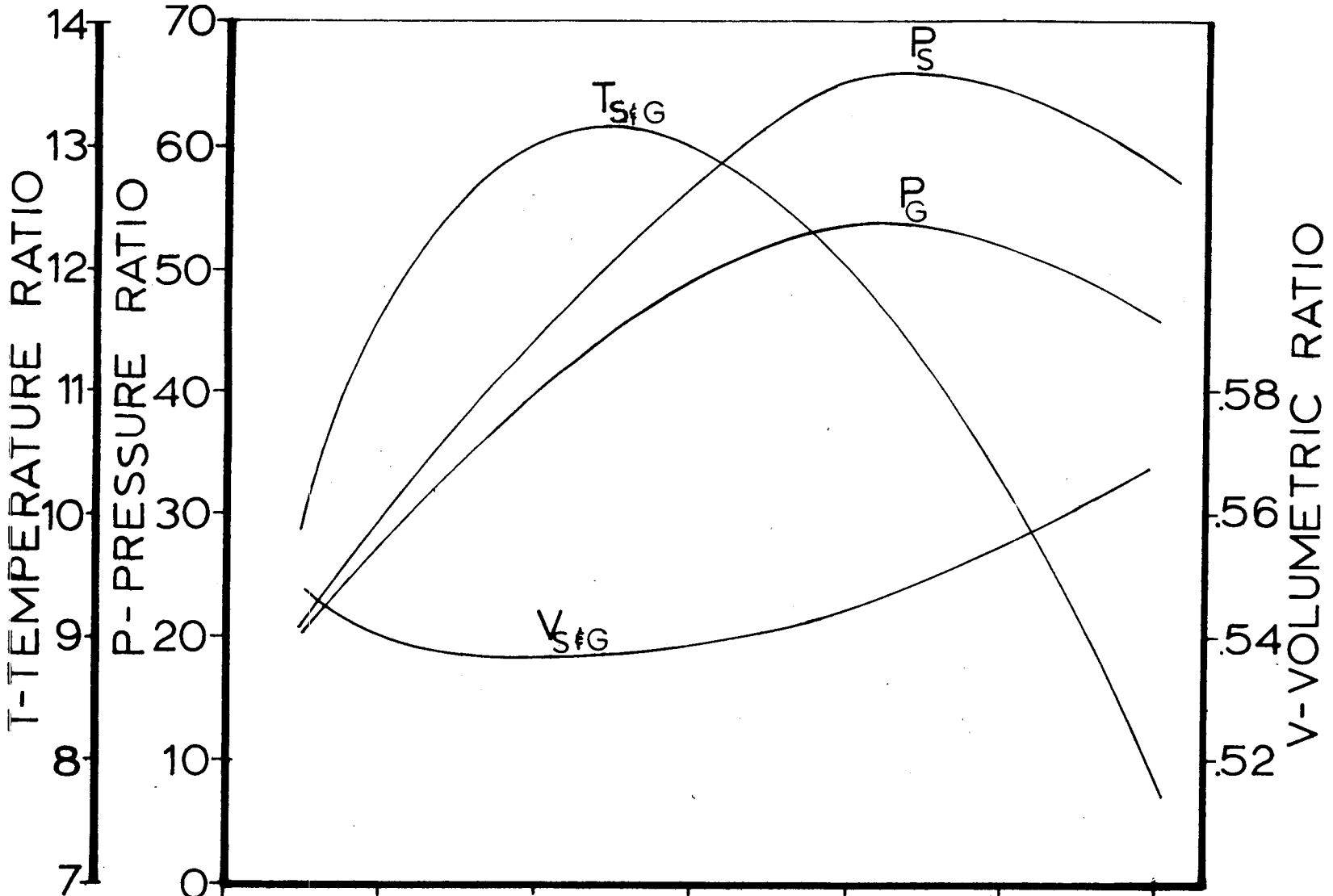
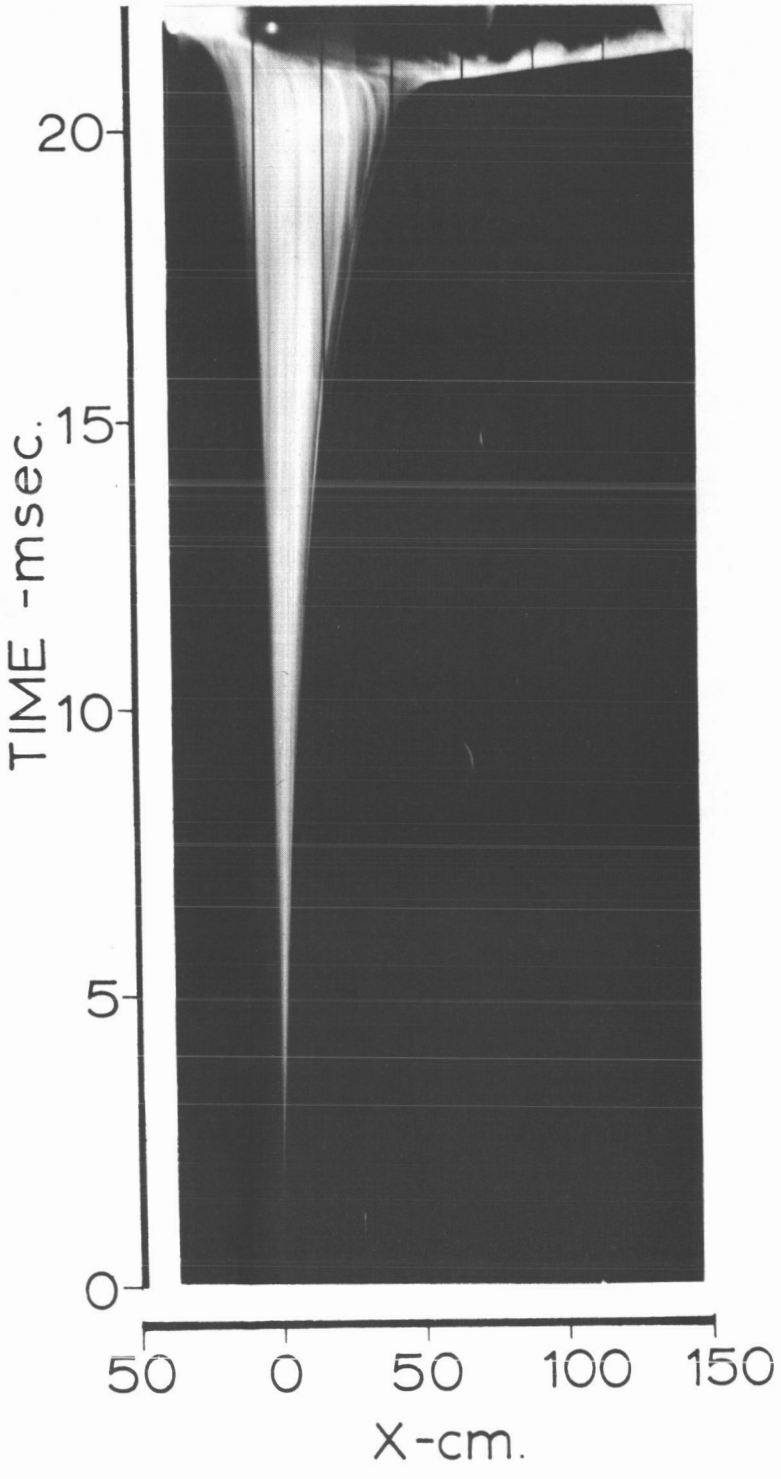
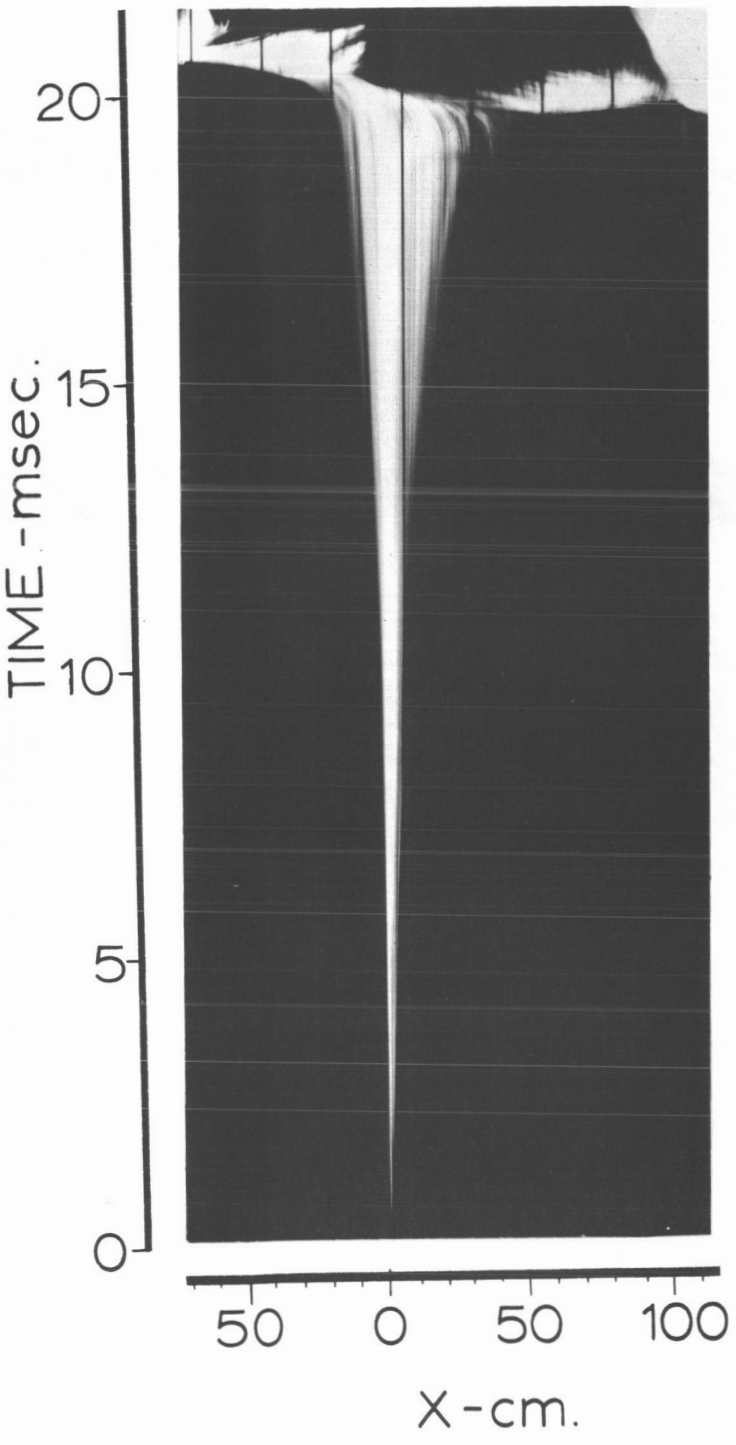
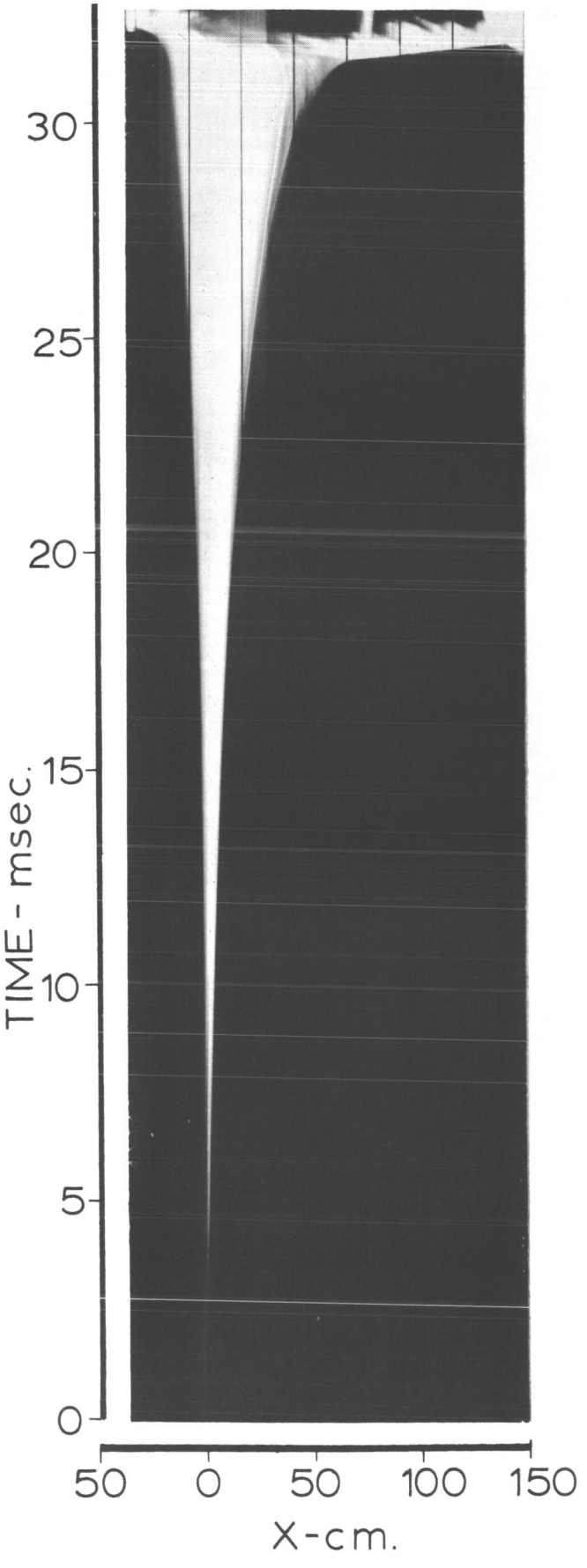

12
10
8
6
4
2
0
M-MACH NUMBER
M_S
M_G
V
3.0
2.5
2.0
1.5
V-km/sec
0
1
2
3
STOICHIOMETRIC RATIO - ϕ

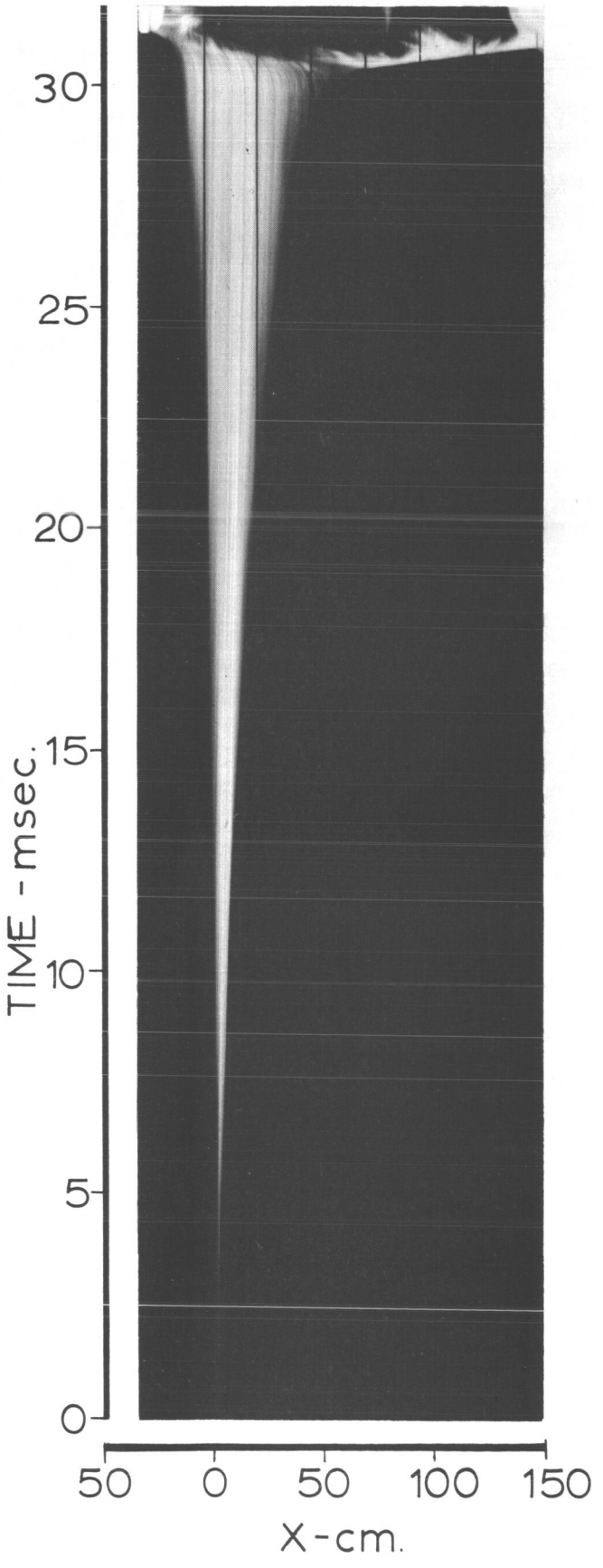
FIG. 16

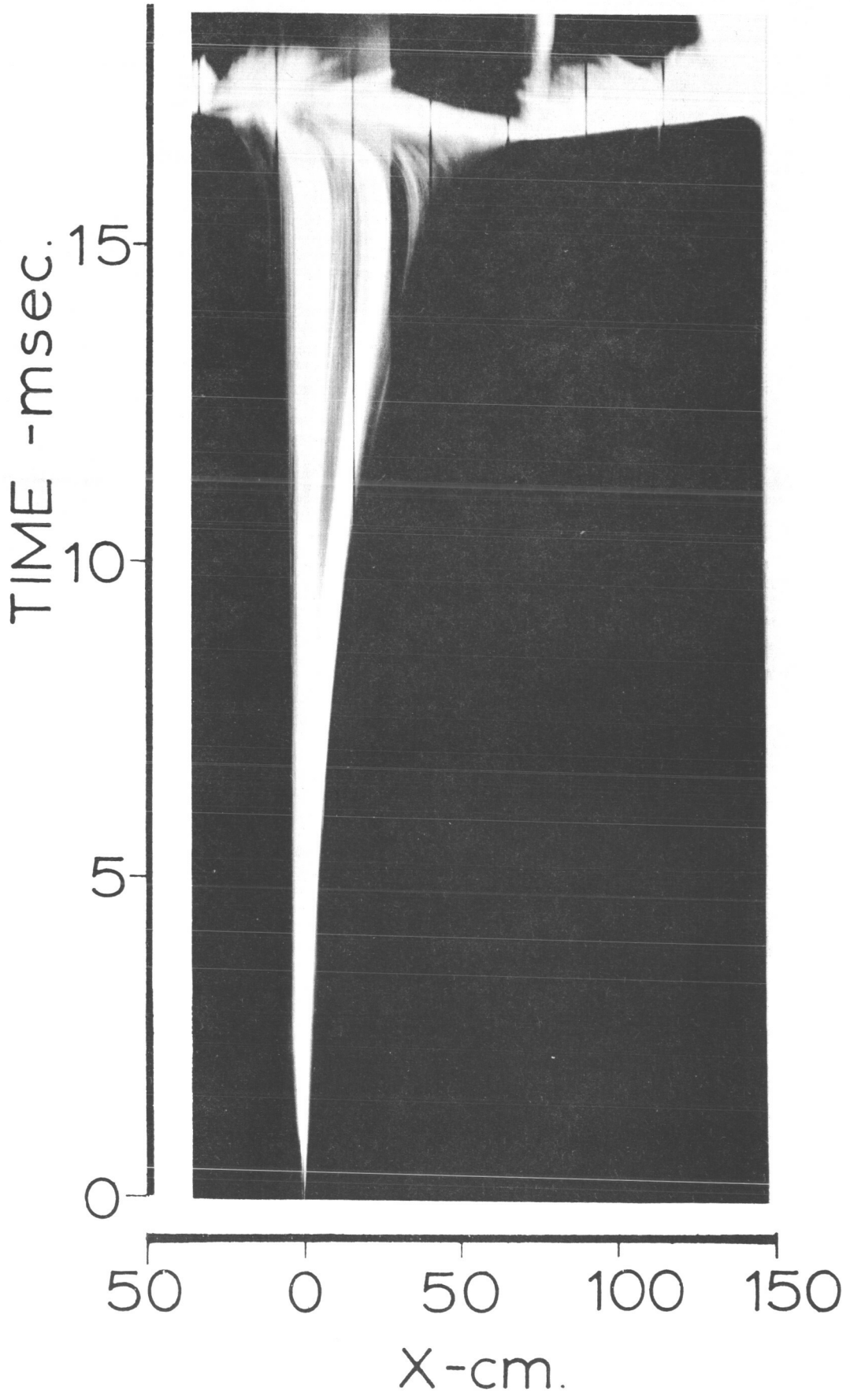

T-TEMPERATURE RATIO
P-PRESSURE RATIO
V-VOLUMETRIC RATIO
STOICHIOMETRIC RATIO - Φ
$T_{S\&G}$
P_S
P_G
$V_{S\&G}$
14
13
12
11
10
9
8
7
70
60
50
40
30
20
10
0
.58
.56
.54
.52
0
1
2
3
FIG. 17

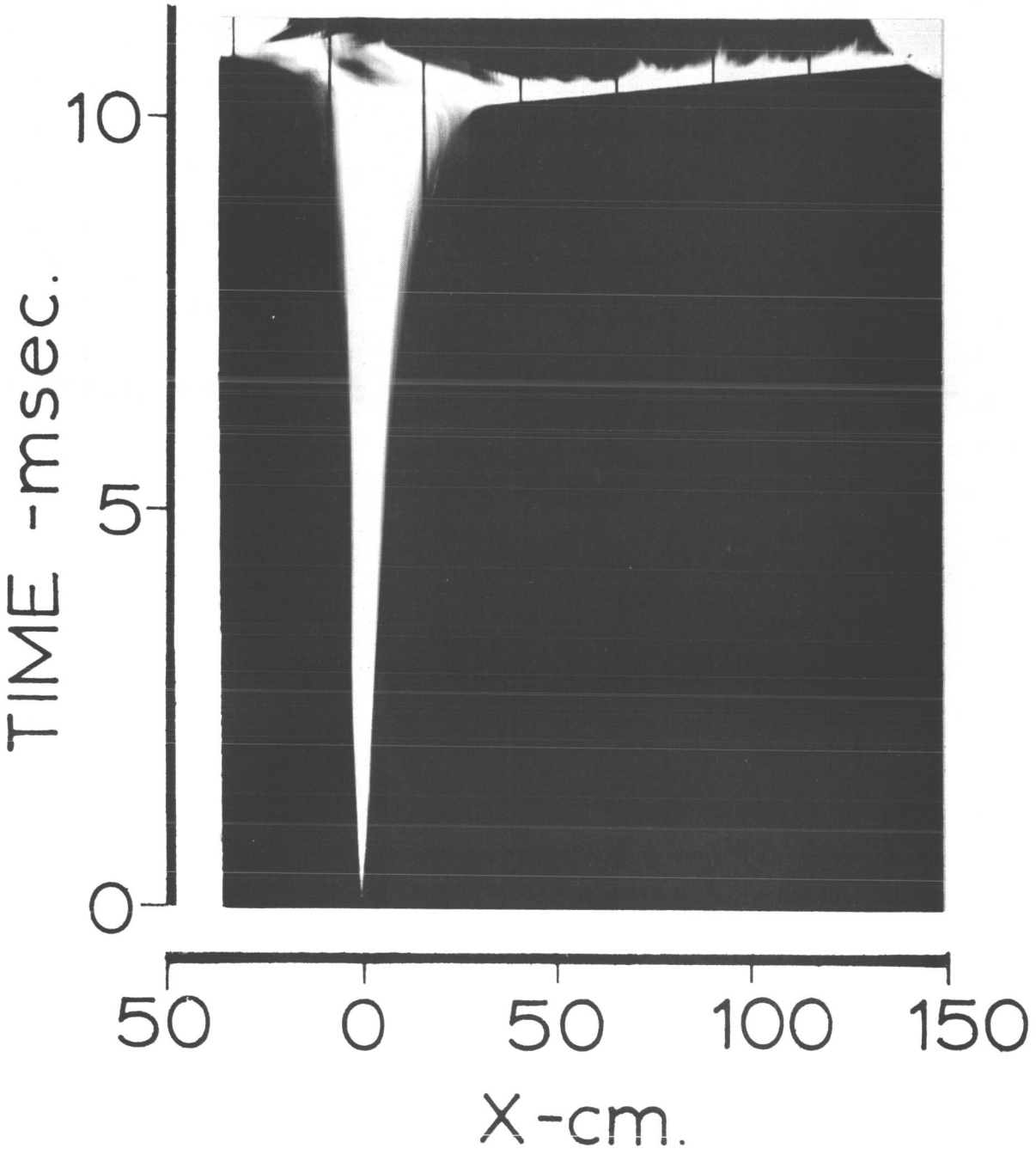

20
15
10
5
0
TIME -msec.
50
0
50
100
150
X-cm.

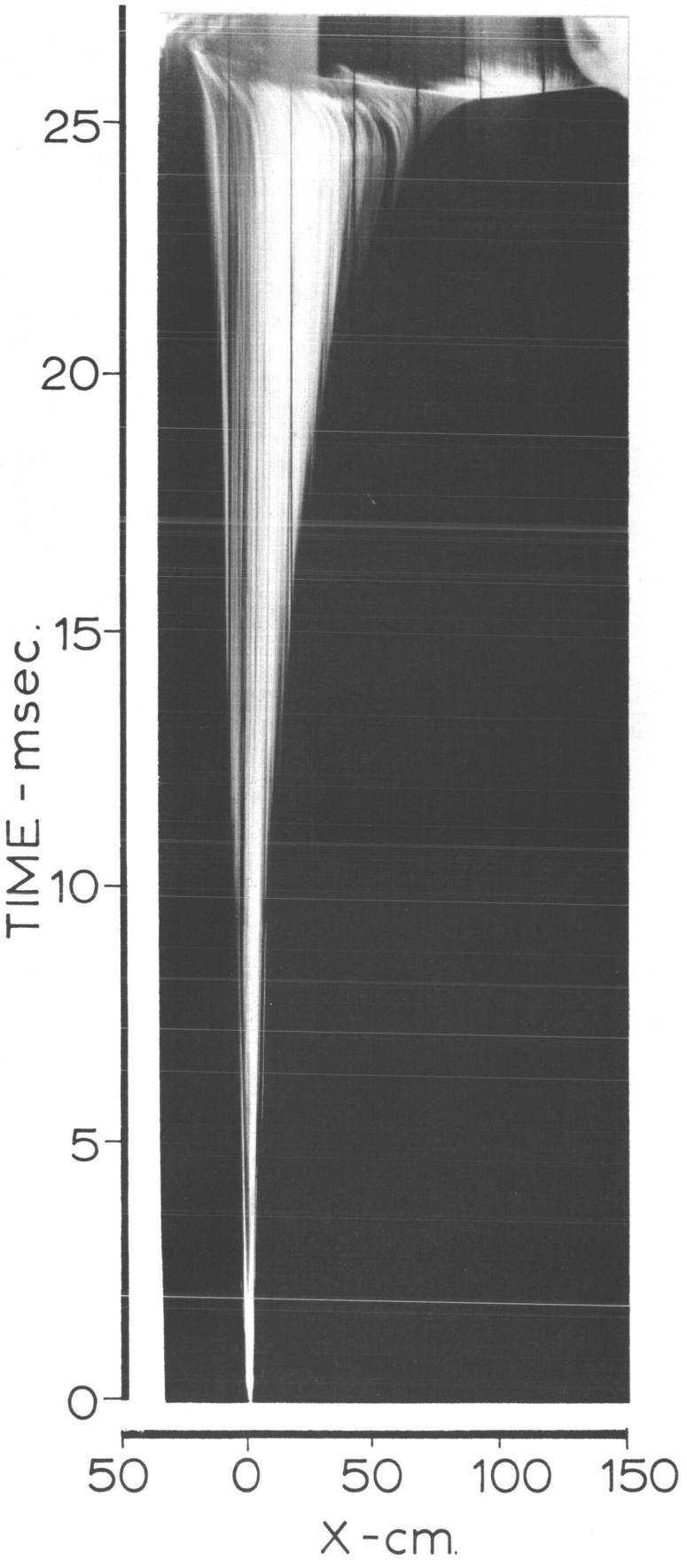

20
15
10
5
0
TIME - msec.
50
0
50
100
X - cm.

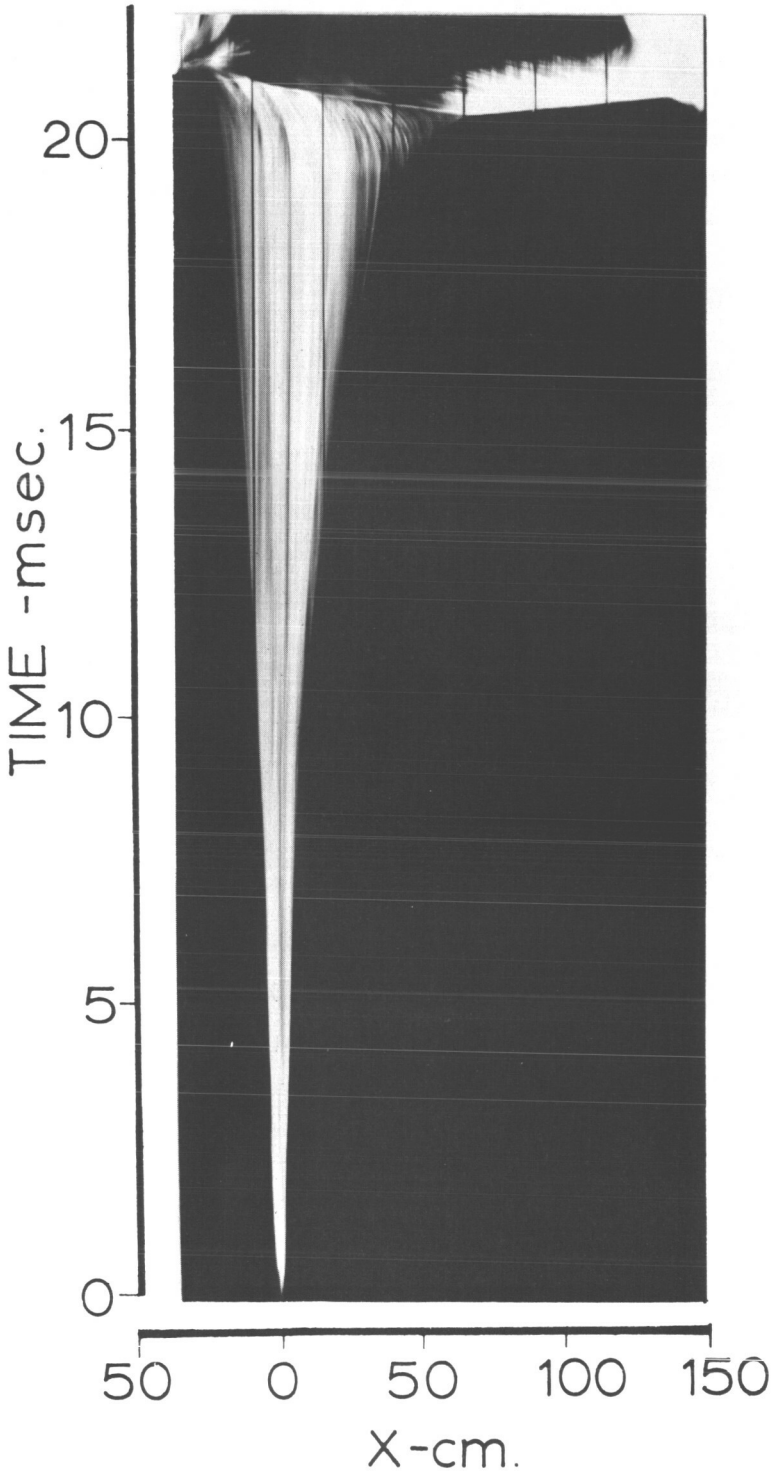

30
25
20
15
10
5
0
TIME - msec.
50
0
50
100
150
X - cm.

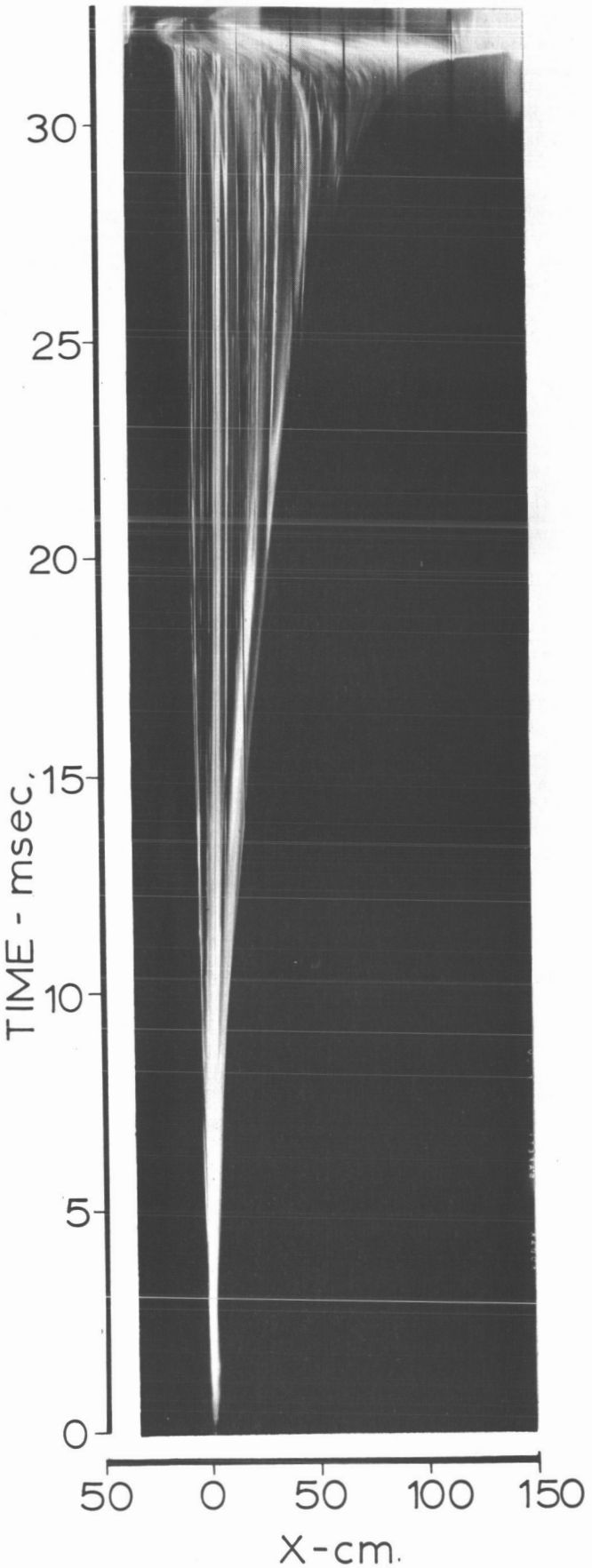

30
25
20
15
10
5
0
TIME - msec.
50
0
50
100
150
X - cm.

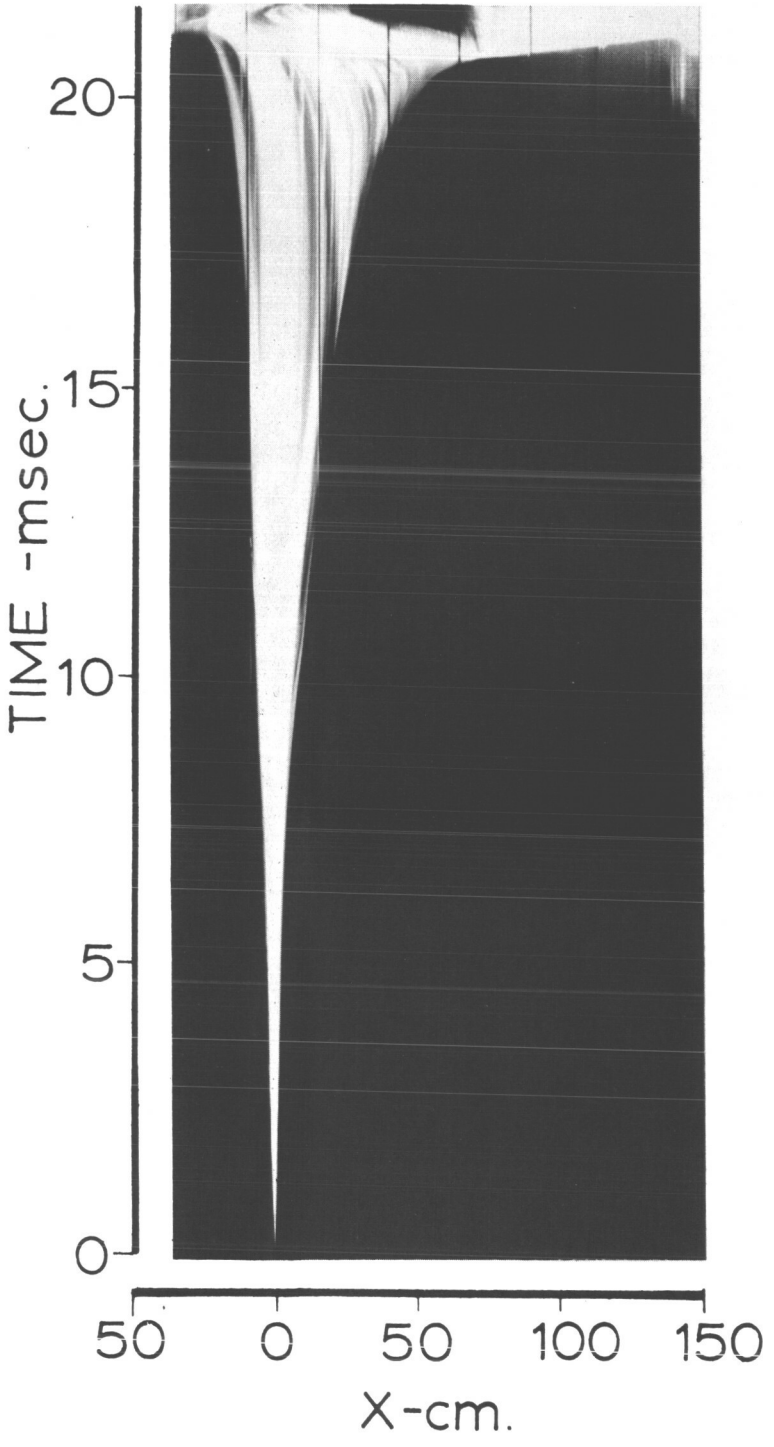

TIME -msec.
15
10
5
0
50
0
50
100
150
X-cm.


10
5
0
TIME -msec.
50
0
50
100
150
X-cm.


25
20
15
10
5
0
TIME - msec.
50
0
50
100
150
X - cm.


20
15
10
5
0
TIME -msec.
50
0
50
100
150
X-cm.


30
25
20
15
10
5
0
TIME - msec.
50
0
50
100
150
X - cm.


20
15
10
5
0
TIME -msec.
50
0
50
100
150
X-cm.

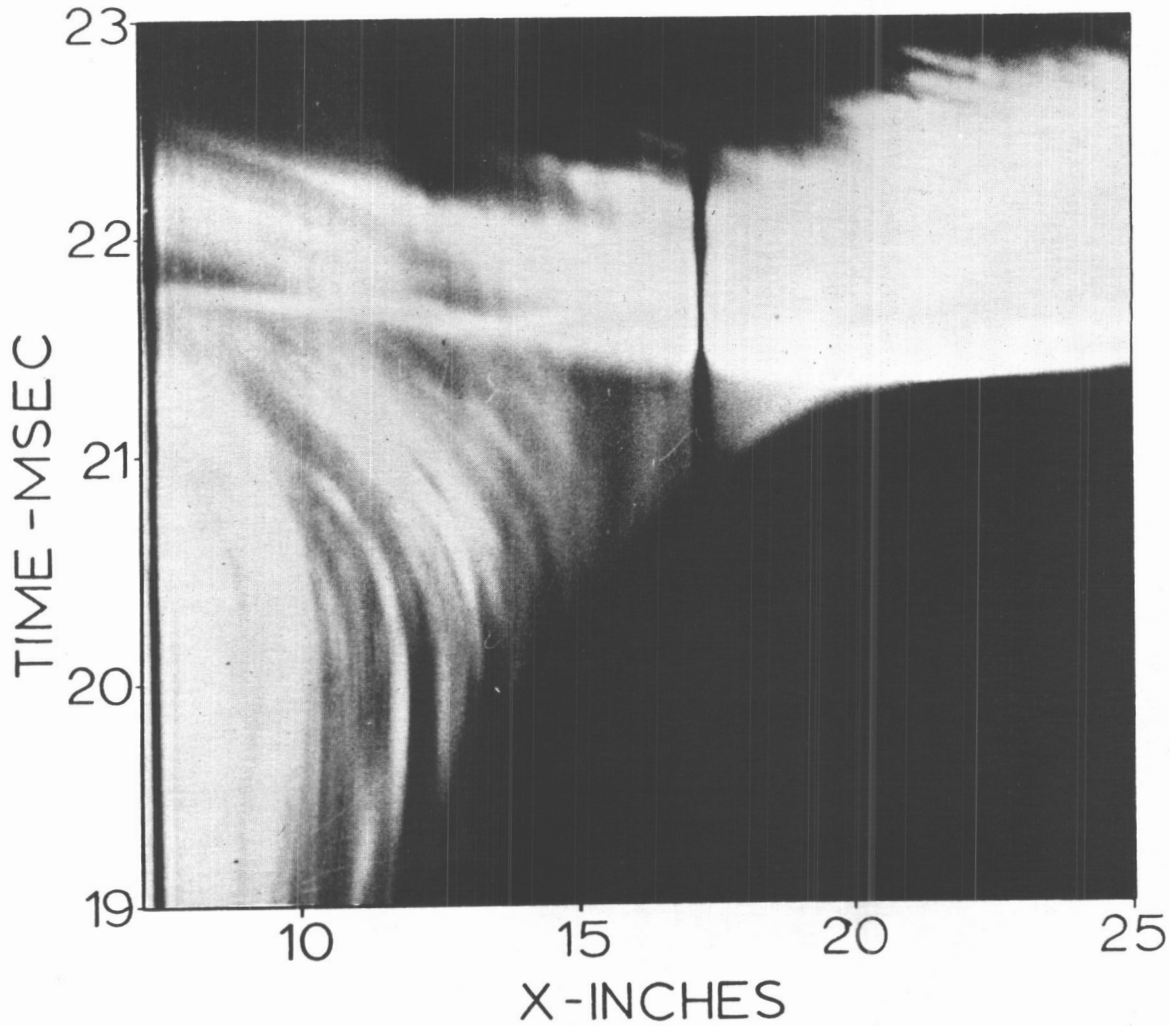
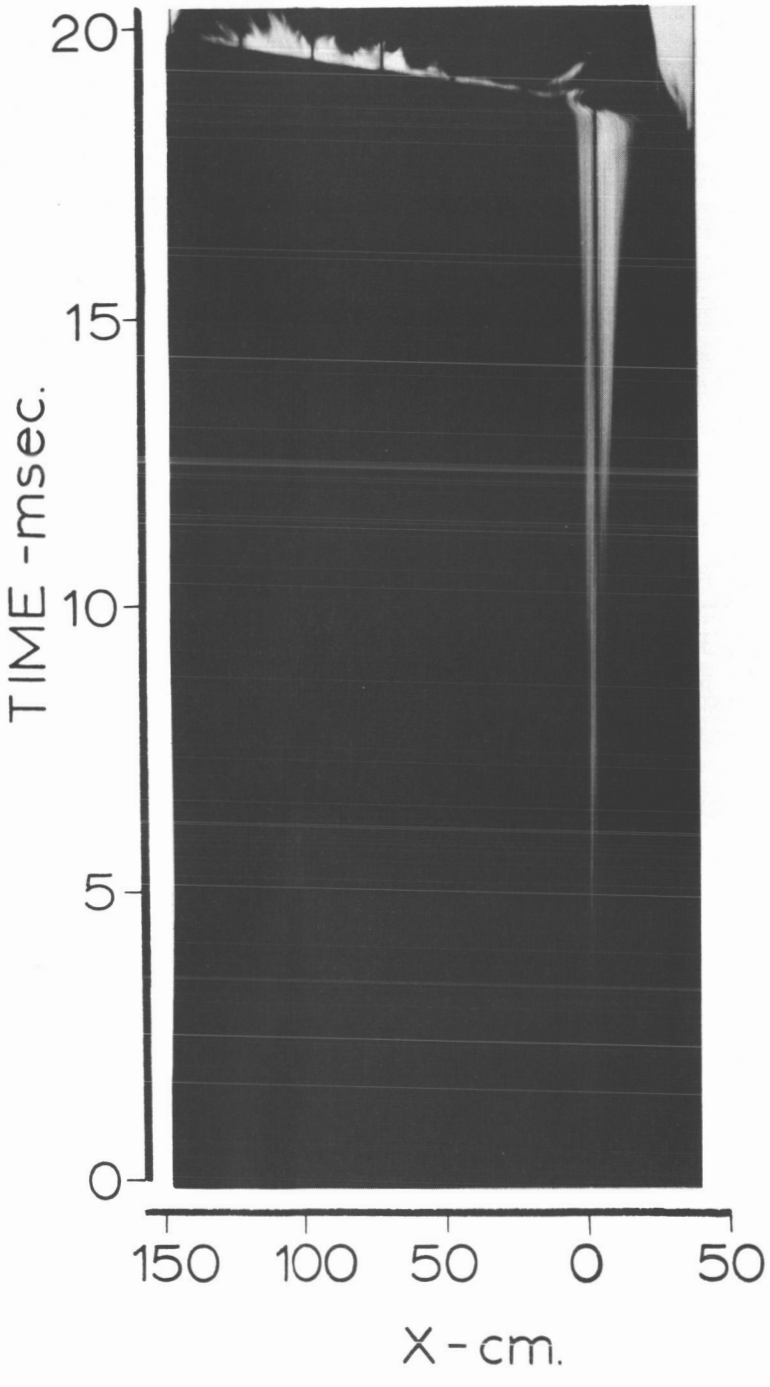
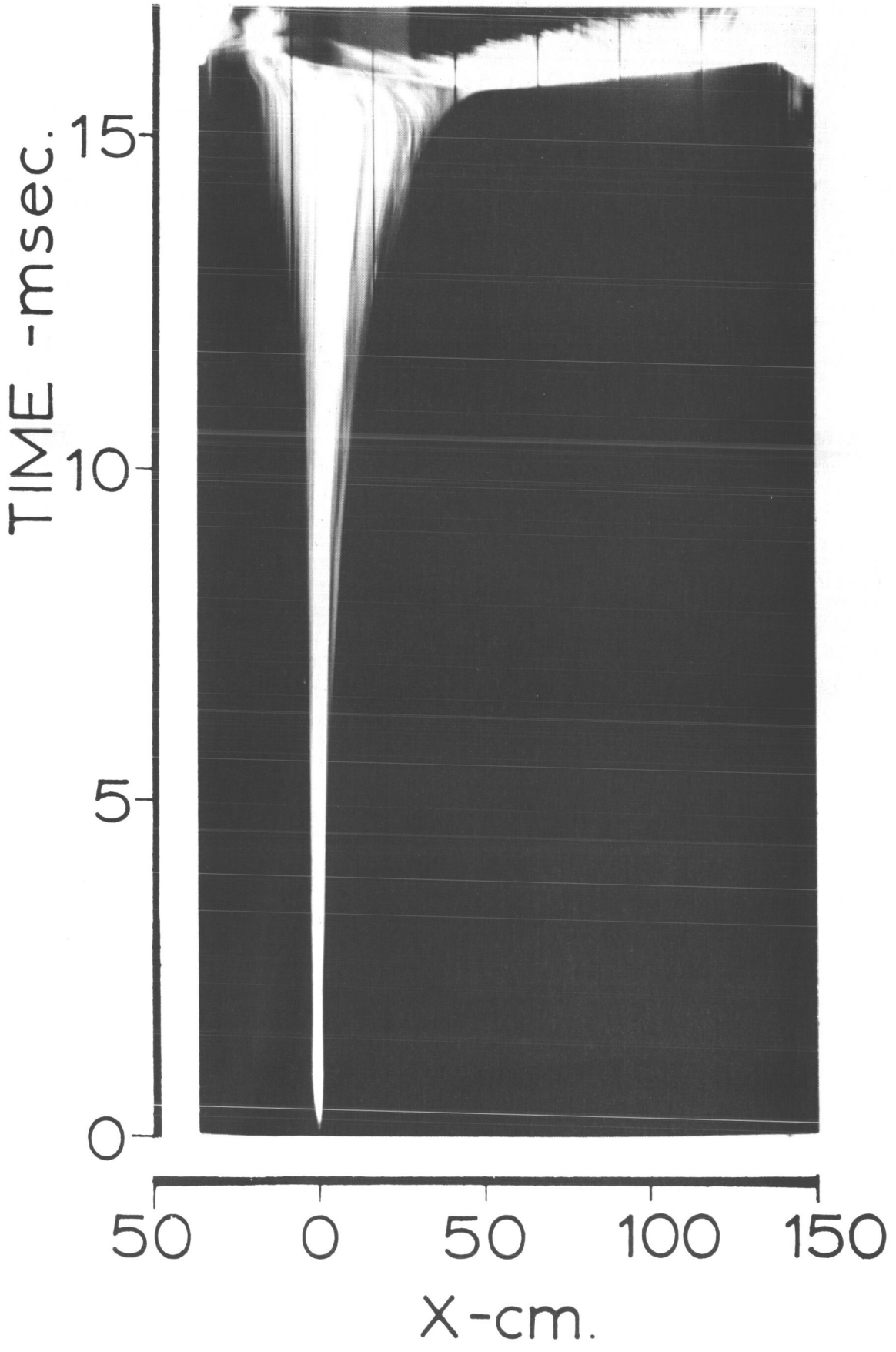


PLATE 11


20
15
10
5
0
TIME - msec.
150
100
50
0
50
X - cm.


TIME -msec.
15
10
5
0
50
0
50
100
150
X-cm.