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The Pressure Calibration of the R.A.E. 6 inch Diameter Shock Tube with a View to its use as the Driver of a Cold High-Density Hypersonic Tunnel

by

S. G. Cox, R. J. Pallant and J. M. Shaw

LONDON: HER MAJESTY'S STATIONERY OFFICE

1963

FIVE SHILLINGS NET

U.D.C. No. 533.6.073.4/.5 : 533.6.071.2.011.55

C.P. No.698

April, 1963

THE PRESSURE CALIBRATION OF THE R.A.E. 6 INCH DIAMETER SHOCK TUBE WITH A VIEW TO ITS USE AS THE DRIVER OF A COLD HIGH-DENSITY HYPERSONIC TUNNEL

by

S. G. Cox,
R. J. Pallant
and
J. M. Shaw

SUMMARY

This Note describes a systematic investigation of the pressure fields produced within the R.A.E. 6 inch shock tube at low shock speeds. This work was undertaken to investigate the tube's suitability as the driver of a cold high-density hypersonic tunnel. It is concluded that the tube is suitable and should produce expanded flows at Mach numbers up to 15. The duration of steady flow, approximately 3·5 m sec, is short and further investigation is proposed to realise the potential advantages of tailored operation.

Replaces R.A.E. Tech. Note No. Aero 2894 - A.R.C. 24,722.

LIST OF CONTENTS

		Page
1	INTRODUCTION	3
2	INSTRUMENTATION	3
	2.1 Driver pressure	3
	2.2 Initial channel pressure	3
	2.3 Shock speed	4
	2.4 Wall pressure	4
	2.5 Pressure after shock reflection	4
	2.6 Pitot pressure measurement	4
3	EXPERIMENTAL RESULTS	4
	3.1 The increase of initial channel pressure above atmospheric	5
	3.2 Measurement of wall and pitot pressures along the channel	5
	3.3 Measurement of pressures behind the reflected shock at various channel lengths	6
	3.4 Measurement of pressure behind the reflected shock with a 60 ft channel at various shock speeds	7
4	DISCUSSION OF RESULTS	8
	4.1 Position of the hydrogen-nitrogen interface	8
	4.2 Suitability of the tube as a driver for a cold high density hypersonic tunnel	9
	4.3 Further developments	10
5	CONCLUSIONS	10
LIST OF REFERENCES		11
ILLUSTRATIONS - Figs.1-8		-
DETACHABLE ABSTRACT CARDS		-

LIST OF ILLUSTRATIONS

	Fig.
Pressure measuring rigs	1
Pressure behind reflected shock at 124'-2" from diaphragm at various shock speeds	2
Wall and pitot pressure measured at various stations along channel	3
Experimental distance-time diagram of shock tube flow	4
Pressure behind reflected shock at various channel lengths	5
Pressure behind reflected shock at various shock speeds	6
Reflection of slow shock wave at channel end and interaction with interface	7
Expansion of nitrogen to hypersonic Mach numbers	8

1 INTRODUCTION

The R.A.E. 6 inch diameter shock tube was originally constructed as a wind tunnel driver with the object of supplementing the R.A.E. Hypersonic Tunnel. The latter is a cold (working section conditions near to liquefaction) high density hypersonic tunnel operating in the Mach number range 5-9 with a stagnation pressure of 50 atmospheres. The original intention was that the shock tube driven tunnel should have a Mach number near to 7 but with enthalpies equivalent to flight speeds above 10.

The tube was constructed from 6 inch internal diameter tubes throughout. The driver section was 30 ft long and had a designed working pressure of 1000 atmospheres. The channel was 120 ft long. Hydrogen was the driver gas.

The original intention was to operate the tunnel on the straight through principle and a nozzle, bye-pass system, working section and dump tank were built. These were subsequently converted for reflected operation.

Firing with a cold hydrogen driver at just below 200 atmospheres pressure revealed, what is now well known, that at shock speeds in the interesting range above $M_s = 7$ the duration of hot flow was too short for successful expansion in the nozzle by the straight through method.

Attention was therefore turned to alternative modes of operation and uses for the shock tube. This Note is concerned with the exploration, at low shock speeds, of the pressure fields in the channel when initially filled with nitrogen, with a view to the possible use of the tube as the driver of a cold high density hypersonic tunnel. To be useful such a tunnel would have to offer substantial advantages over the existing long duration R.A.E. Hypersonic Tunnel. These would most probably be an increase in stagnation pressure and an increase in Mach number.

2 INSTRUMENTATION

Throughout these experiments the following quantities were measured:- Driver pressure at the time of diaphragm burst; initial channel pressure; shock speed at various stations along the channel; wall pressure after passage of the shock at various positions along the tube; the pressure after shock reflection with different channel lengths and the pitot pressure on the centre line of the channel at various positions along the channel.

2.1 Driver pressure

The driver pressure was measured with a Bourden tube operated transducer coupled to a remote dynamometer instrument. Pressures could be read to within ±1%.

2.2 Initial channel pressure

The channel was evacuated to a pressure of about 3 m.m. Hg absolute and then filled with nitrogen to the required pressure. The pressure was measured with a mercury manometer.

2.3 Shock speed

The shock speed was measured using thin film wall thermometer gauges installed two feet apart at each measuring station. The measuring stations were at 20 feet intervals. The pulses from the thin film gauges were passed through an amplifier and pulse shaper and used to start and stop microsecond counter-chronometers. Thus the time interval over 2 feet was measured and the shock speed determined. The basic accuracy of timing was ± one microsecond giving an accuracy in speed of better than 1%. However difficulty was experienced at low shock speeds and further errors were introduced due to the weak signals produced in the gauges. At a shock speed of $M_s = 3{\cdot}5$ the error may be as big as $0{\cdot}5$ in M_s.

2.4 Wall pressures

The wall pressures were measured with piezo-electric transducers. These were the S.L.M. PZ6 type. Pressures were recorded on a Tektronix oscilloscope Type 535 through a piezo-head amplifier. Records were obtained using a Polaroid camera. The transducers were calibrated statically with a dead weight calibrator. The overall accuracy of calibration and recording was about ±5%, however in operation additional errors may be introduced due to vibration and thermal effects.

2.5 Pressure after shock reflection

These were measured and recorded using the same equipment as for the wall pressures with the transducer adjacent to the reflecting face. The reflecting face was either that just upstream of the nozzle throat or a steel plate mounted between pipe flanges. Fig.1.

2.6 Pitot pressure measurements

A ring with a thin web across the diameter was used to measure pitot pressure. Fig.1. This was inserted between pipe flanges where required. A PZ6 transducer was fitted into the centre of the web. The calibration and recording was as for the other pressures.

3 EXPERIMENTAL RESULTS

Throughout all the work reported here the driver gas was hydrogen and the test gas nitrogen. No special precautions were taken regarding gas purity. The driver pressures varied, due to changes in diaphragm strength, between 140 and 200 atmospheres. During each test series the variation was smaller and a nominal value is given on the figure appropriate to each test series. The actual values were within ±15 atmospheres of the nominal.

On the figures giving the test results are the exact distances from the diaphragm at which the measurements were made. However in the following text for convenience these distances are referred to in round numbers. e.g. 62 ft - 9 in. from the diaphragm is referred to as 60 ft.

3.1 The increase of initial channel pressure above atmospheric

The first tests were exploratory, performed for largely mechanical reasons, and yielded results of pressure behind the reflected shock at 120 ft over a range of initial channel pressures. Fig.2.

These tunnel stagnation pressure records, purposely taken at a slow recording speed of 2 m sec/square in order to obtain a broad picture of events, show that as the shock speed falls the pressure during say the first 10 m sec becomes more steady and of course the general pressure level increases.

These results were encouraging but difficulty was experienced in measuring shock speeds below $M_s = 3$ so the very bottom end of the speed range has yet to be explored.

The decision was taken to concentrate on exploring the tube performance at one value of initial channel pressure, 2·2 atmospheres.

3.2 Measurement of wall and pitot pressures along the channel

The second series of tests involved repetitive firings with an initial channel pressure of 2·2 atmospheres and the measurement of wall and pitot pressures. Due to a lack of instrumentation all the wall pressures could not be recorded on one run. In addition the pitot pressure mount interfered with the flow so no wall pressures were taken behind it, nor in front when a long time base was being used, because reflections from the down stream end were then recorded. The results are shown in Fig.3.

Consider first the results with the slowest time base, 10 m sec/square. If the shocks in each record are plotted on a distance time diagram, as in Fig.4, it becomes quite easy to connect up the points. However each record indicates elapsed time from the arrival of the shock at the particular station in the tube so it was first necessary to draw in the incident shock wave. This was done by plotting a shock speed-distance curve and then performing a graphical integration to derive the shock time-distance curve.

It will be seen that the reflected shock can be traced back to the diaphragm station where it is partially reflected, that part which is transmitted subsequently reflecting from the end face of the high pressure chamber. That a partial reflection should occur at the diaphragm is not unreasonable as it is found that on removal the diaphragm petals are bent upstream with reflected type operation.

Consider next the records taken at 2 m sec/square. Here small inconsistencies from run to run become apparent. However it is clear that the first peak in pressure after the initial shock represents the head of the reflected rarefaction and this has been plotted in Fig.4. The record taken at 100 ft shows the incident shock, the reflected head of the rarefaction and the reflected shock in that order. However at 120 ft the order is changed, the incident shock is followed by the reflected shock and then by the reflected head of the rarefaction. There is also an indication from these records that the pressure behind the incident shock increases with time at short tube lengths, but at great tube lengths it decreases. The decrease is clearly seen in the record taken at 120 ft.

The records taken at 500 μ sec/square confirm this trend although at both speeds the record at 60 ft is inconsistent having an initial decrease followed by an increase. The two records at 60 ft were taken on separate runs. The fastest records clearly show that close to the diaphragm there is considerable unsteadiness behind the shock and although this is not obviously apparent farther from the diaphragm it may account for some of the detail behaviour.

Finally, in an attempt to locate the hydrogen-nitrogen interface, pitot pressure records were taken. This was a technique which at higher shock speeds had been very successful. At low speeds it is not so effective and interpretation cannot be positive. However we know from later tests that the gauge used can be affected by heat and then momentarily give a low reading. It could be that this accounts for the rising pitot pressure indicated behind the initial shock, the gauge during this period recovering from the initial heat flash. If we then assume that the peak of the pressure record corresponds to the arrival of some hydrogen it will be seen that at 40 ft from the diaphragm it takes 2 m sec before a steady pressure is reached. At this time we may assume only hydrogen is passing the gauge and that the interface region takes 2 m sec to pass at the centre of the tube. At 60 ft the time is longer, whilst at 80 ft a steady pressure record is never achieved due to the arrival of the head of the reflected rarefaction.

3.3 Measurement of pressures behind the reflected shock at various channel lengths

The third series of tests involved repetitive firings again with an initial channel pressure of 2·2 atmospheres but this time with a reflection plate containing a dummy nozzle throat inserted at different positions along the channel. The pressure behind the reflected shock was measured with a transducer mounted in the wall of the pipe just adjacent to the face of the plate. A second transducer was mounted in the reflecting plate to record the pressure on the reflecting face. These two gauges produced identical records and only those obtained at the wall are shown in Fig.5.

Looking first at the records taken at 500 μ sec/square, that at 20 ft from the diaphragm shows a steady pressure behind the reflected shock lasting for about 1 m sec. This is followed by a fall in pressure for the next 1·5 m sec. This is certainly the rarefaction fan produced where the reflected shock meets the interface. The pressure then remains steady for the remainder of the record. The remaining records taken at this speed show how the duration of steady pressure increases with channel length. However with increased channel length the pressure immediately behind the reflected shock is less, due to the slower incident shock and a tendency for the pressure to increase slowly with time is evident. This is in contrast to the wall pressure behind an incident shock which tends to fall with increasing time at large channel lengths (para 3.2).

The records, Fig.5, at 2 m sec/square show how events are effected by the reflected rarefaction. The record obtained at 20 ft shows the short plateau of pressure behind the reflected shock, the fall in pressure produced by the interaction of the reflected shock and interface and then a small rise in pressure. This rise probably results from the second reflection at the interface i.e. the expansion reflects at the end wall and returns from the interface as pressure waves. Subsequent reflections are too small to be significant. However at 13 m sec after the incident shock the head of the reflected rarefaction arrives and the pressure falls rapidly. The records obtained at 40 ft and 60 ft are similar except that the initial plateaux are longer and the head of the reflected rarefaction appears earlier and earlier until at 80 ft the reflected head merges with the expansion coming from the intersection of the interface and reflected shock. The record at 100 ft is similar to that at 80 ft but at this position there is a very substantial increase in pressure after 2 m sec probably due to viscous effects. Finally at 120 ft this increase is swallowed up by the reflected rarefaction.

These results indicated that at a low shock Mach number little would be lost in the duration of steady pressure behind the reflected shock if the channel were shortened to 60 ft and that there would be a gain in stagnation pressure if the initial conditions were unaltered. In fact the temperature produced is really the controlling factor and hence due to shock attenuation a given stagnation temperature can be produced at 60 ft with a higher initial channel pressure than at 120 ft (assuming the driver unaltered). Thus a double gain in stagnation pressure can be achieved by shortening the channel. This is further discussed in para 4.2.

3.4 Measurement of pressures behind the reflected shock with a 60 ft channel at various shock speeds

For the final series of tests reported here, the reflection plate was located at 60 ft from the diaphragm and the effect of changing the shock speed explored. Again pressures were measured on the wall and on the face of the plate with identical results. Only the wall pressures are shown in Fig.6. The shock speed varied from $M_s = 3{\cdot}60$ to $M_s = 6{\cdot}62$.

Consider first the records taken at 2 m sec/square. That at $M_s = 3{\cdot}60$ is identical to that described in para 3.3. There is a good plateau of steady pressure behind the reflected shock, this is followed by a fall due to the rarefaction arising from the shock wave interface interaction, then by a small rise and lastly by a large fall when the head of the reflected rarefaction arrives.

As the shock speed is progressively increased, the time between the arrival of the shock wave and the head of the reflected rarefaction becomes longer. This is to be expected because the motion of the rarefaction head is unaffected by the shock speed until the former is back into the channel after traversing the driver length twice.

At $M_s = 4{\cdot}2$ the record is very similar to that at $M_s = 3{\cdot}6$ except that the fall in pressure after the initial plateau is smaller, as is the subsequent rise before the head of the reflected rarefaction. Again this is to be expected. However at $M_s = 4{\cdot}7$ the initial plateau becomes disturbed, a fall and rise of pressure being recorded, followed consecutively by the fall and rise seen at lower shock speeds and the head of the reflected rarefaction. As the shock speed is still further increased the disturbance of the expected plateau becomes more and more marked. In addition the pressure after about 4 m sec rises considerably until at M_s = 6·62 it reaches a value of 1·6 times that behind the reflected shock before the head of the reflected rarefaction arrives.

The reason for the disturbance of the expected plateau behind the reflected shock at M_s > 4·2 is not known. A similar result has been reported by Henshall[1] and there is a possibility that it is a spurious signal produced by heat affecting the pressure gauge. The latter is to be investigated further.

Of far greater interest is the absence of any recorded shock wave, other than the initial one, at the higher shock speeds. Simple theory indicates that at M_s > 6 the interaction of the reflected shock with the interface will produce a shock wave. However, although shocks are normally the most easily recorded phenomena, they are not seen. This indicates that in this tube the simple one dimensional theory may be inadequate to even qualitatively explain the reflection process at higher shock speeds.

Finally it is worth noting two things from the records taken at 500 μ sec/square. Firstly the great penalty in stagnation pressure incurred by increasing the shock speed and secondly how deceptive records taken at high speed can be. These records are in fact identical to those shown beside them which are from the same gauge and amplifier. At first sight they might be thought to be satisfactory for tunnel driving. Closer inspection will reveal that the indicated stagnation pressure at M_s = 6·25 varies by ±19% during the first m sec and by ±12% between 2 to 4 m sec after shock arrival.

4 DISCUSSION OF RESULTS

4.1 Position of hydrogen-nitrogen interface

From the experimenter's point of view one of the disappointing features of this work is the lack of direct information obtained regarding the position of the hydrogen-nitrogen interface on the tube centre line. The attempt to determine its position by measuring pitot pressures yielded very inconclusive results as described in para 3.2. However further information can be obtained from Fig.5.

Fig.7 shows diagrammatically the events occurring at the end wall of the channel where the incident wave is reflected. Different regions are numbered for easy reference. With a driver pressure of approximately 180 atmospheres and an initial channel pressure of 2·2 atmospheres the shock speed varies from M_s = 3·89 to 3·25 between the 20 ft and 120 ft stations. Within this range of shock speeds the interaction of the reflected shock with the interface should produce an expansion fan as shown and it is this which produces the drop of pressure after the initial plateau recorded at 20 ft, 40 ft, and 60 ft and displayed in Fig.5. As explained in para 3.3 and illustrated in Fig.4 the records at 80 ft and above (Fig.5) do not clearly indicate the time of arrival of this expansion fan because it becomes coincident with the head of the reflected rarefaction.

Consider the conditions as shown in Fig.5 at 20 ft. We know conditions in region (1) and have measured the shock speed just upstream of the reflecting wall. We can therefore calculate conditions in region (2) provided we neglect attenuation effects. Similarly we can calculate the speed of the reflected shock and conditions in region (5). The calculations were done assuming ideal nitrogen with an initial temperature in region (1) of 288°K.

If t_1 and t_2 are the times and d the distance defined in Fig.7 then we have

$$d = t_1 u_{rs} = t_2 a_5 \qquad (1)$$

where u_{rs} is the velocity of the reflected shock and a_5 is the velocity of sound in region (5). In addition we can measure from Fig.5 the time $(t_1 + t_2)$. Hence t_1, t_2 and d can be derived.

This was done for the results at 20 ft, 40 ft and 60 ft, Fig.5, and the position of the interface plotted in Fig.4. The curve thus obtained was extended to the far end of the channel.

It should be noted that the interface intersects with the head of the reflected rarefaction at about 100 ft and that the latter, at this point, suffers an appreciable reduction in speed. This is to be expected because the reflected head travels at a speed in the hydrogen of $(u_3 + a_3)$ and in the nitrogen $(u_2 + a_2)$ where $u_3 \approx u_2$ but $a_3 > a_2$. [The approximate values of $(u_3 + a_3)$ and $(u_2 + a_2)$ are 6500 ft/sec and 5000 ft/sec respectively.]

The above analysis indicates that the interface lags behind the shock by 2, 3 and 4 m sec at 40 ft, 60 ft and 80 ft. If these values are compared with the pitot records in Fig.3 it will be seen that they indicate that the front of the interface comes after the peak pitot pressure was recorded and where the recorded pitot pressure starts to fall quickly. There is still an appreciable interval thereafter before a steady pitot pressure is recorded possibly indicating a thick interface as discussed in para 3.2.

4.2 Suitability of the tube as a driver for a cold high density hypersonic tunnel

As discussed in para 3.3 there would be a considerable gain in stagnation pressure if the channel were shortened to 60 ft from its present length of 120 ft. This will shortly be done and the following is concerned only with the performance with the shortened channel.

Fig.6 shows the stagnation pressure records obtained at 60 ft at various shock Mach numbers. It will be seen that at low shock speeds there is a good steady plateau of pressure existing between the arrival of the incident shock and the time of arrival of the expansion produced at the reflected shock interface intersection. At higher shock speeds the plateau appears to be disturbed and the best operating time is after approximately 1·5 m sec. The lowest shock speed investigated, $M_s = 3{\cdot}6$, gives the steadiest pressure, the variation being less than ±2% over a period of 3·5 m sec.

At higher shock speeds the performance is spoilt by the dip in the pressure record immediately after the reflected shock. As discussed in para 3.4 the reason for this is not understood. If this is a true pressure change it is particularly unfortunate that it should be present at $M_s = 5{\cdot}86$ because near this shock speed tailoring[2] should occur with a cold hydrogen driver. The successful use of the tailored form of operation would appear to be the only way of obtaining longer running times with this tube and this must be explored further.

A shock Mach number of 3·6 should produce a stagnation temperature after reflection of 1704°K[3]. Inspection of Fig.8 reveals that this is a suitable temperature for a cold high density hypersonic tunnel with a working section Mach number of about 15. The stagnation pressure recorded in Fig.6 at $M_s = 3{\cdot}6$ is about 163 atmospheres. This will give a working section static pressure of just above 2×10^{-4} atmospheres which is only just above the low limit of pressure for Schlieren operation and ideally should be increased by up to one order of magnitude for really good results. When shortening the channel to 60 ft we will replace the existing diaphragm section with one suitable for operation at 400 atmospheres thereby permitting an increase in pressure by a factor of 2·4. This will then produce a tunnel stagnation pressure approaching 400 atmospheres. Further increases can be obtained by running at lower shock speeds.

4.3 Further developments

The flow produced in the working section after expansion to high Mach numbers should be investigated. At the time of writing this has almost been completed with a channel length of 120 ft and will be reported soon.

The shock reflection process should be studied theoretically[4] and experimentally and further checks made upon the present instrumentation with a view to resolving the discrepancies between measured and predicted pressures near to tailoring shock speeds.

5 CONCLUSIONS

The R.A.E. 6 inch diameter shock tube is suitable for use as the driver of a cold high-density hypersonic tunnel. However it will be greatly improved if the channel length is reduced to 60 ft and the driver pressure increased to about 400 atmospheres. It should then be possible to operate the tunnel with a stagnation pressure of about 400 atmospheres and a stagnation temperature near 1700°K. Under these conditions the stagnation pressure should remain constant within ±2% over a period of 3·5 m sec.

Further investigation should be made of the tube behaviour in an effort to realise the theoretical increase in running time at tailored shock speeds.

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No.	Author(s)	Title, etc
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2	Hertzberg, A.	The shock tunnel and its applications to hypersonic flight. A.G.A.R.D. Report 144. July 1957.
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Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough. W.T.59.

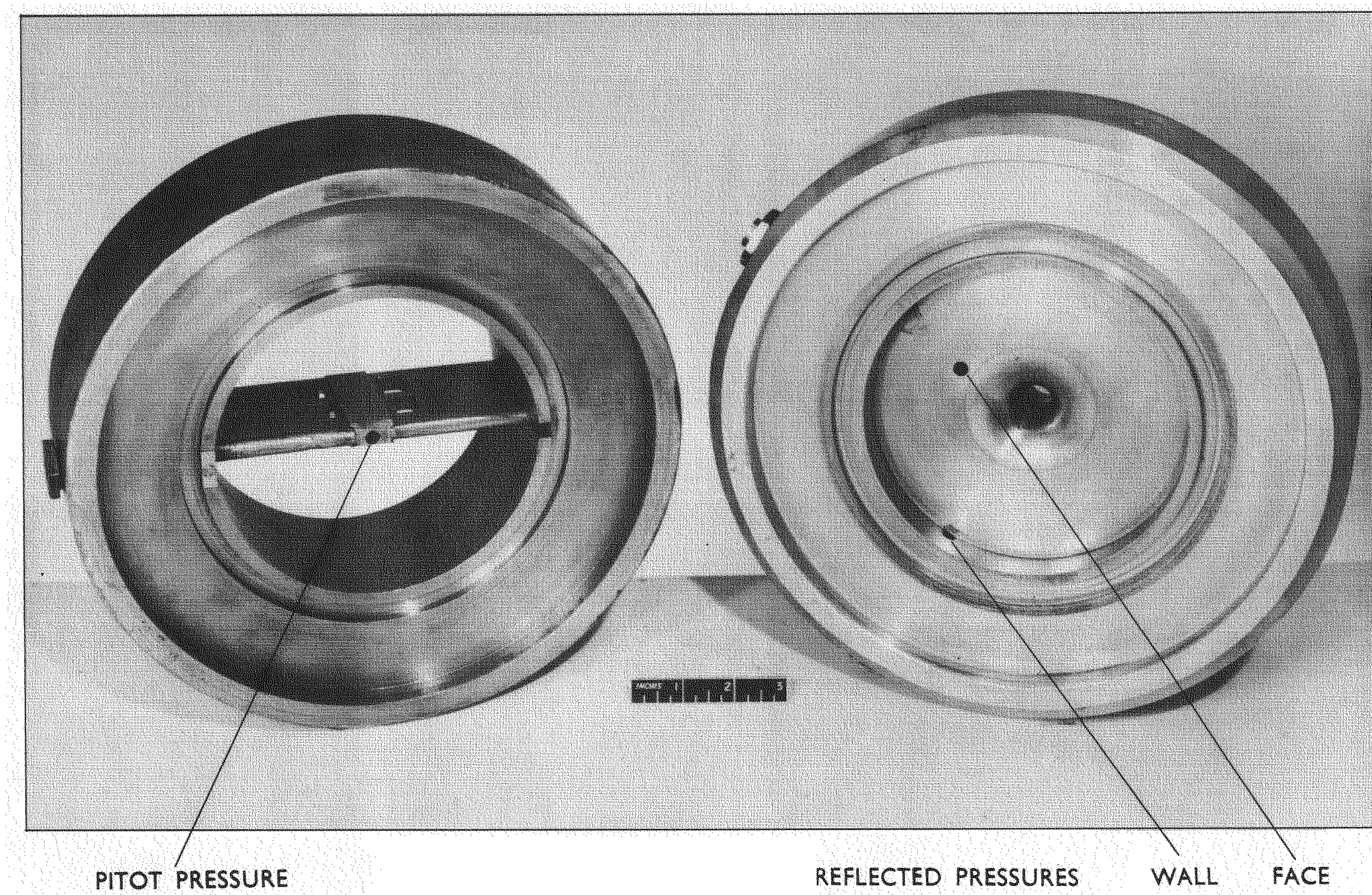


FIG.1. PRESSURE MEASURING RIGS

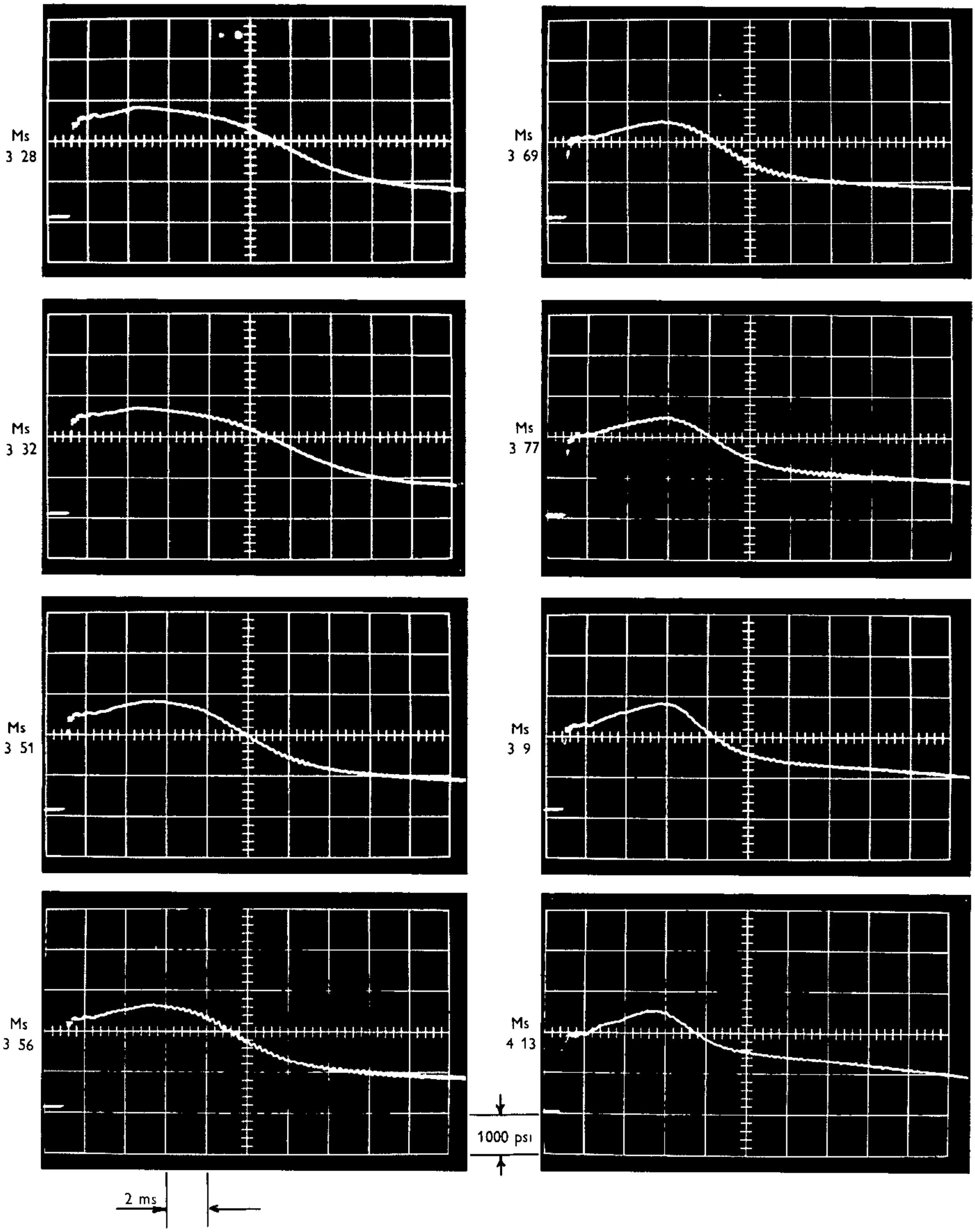


FIG 2 PRESSURE BEHIND REFLECTED SHOCK AT 124 - 2″ FROM DIAPHRAGM AT VARIOUS SHOCK SPEEDS

NOMINAL DRIVER PRESSURE 190 ATS

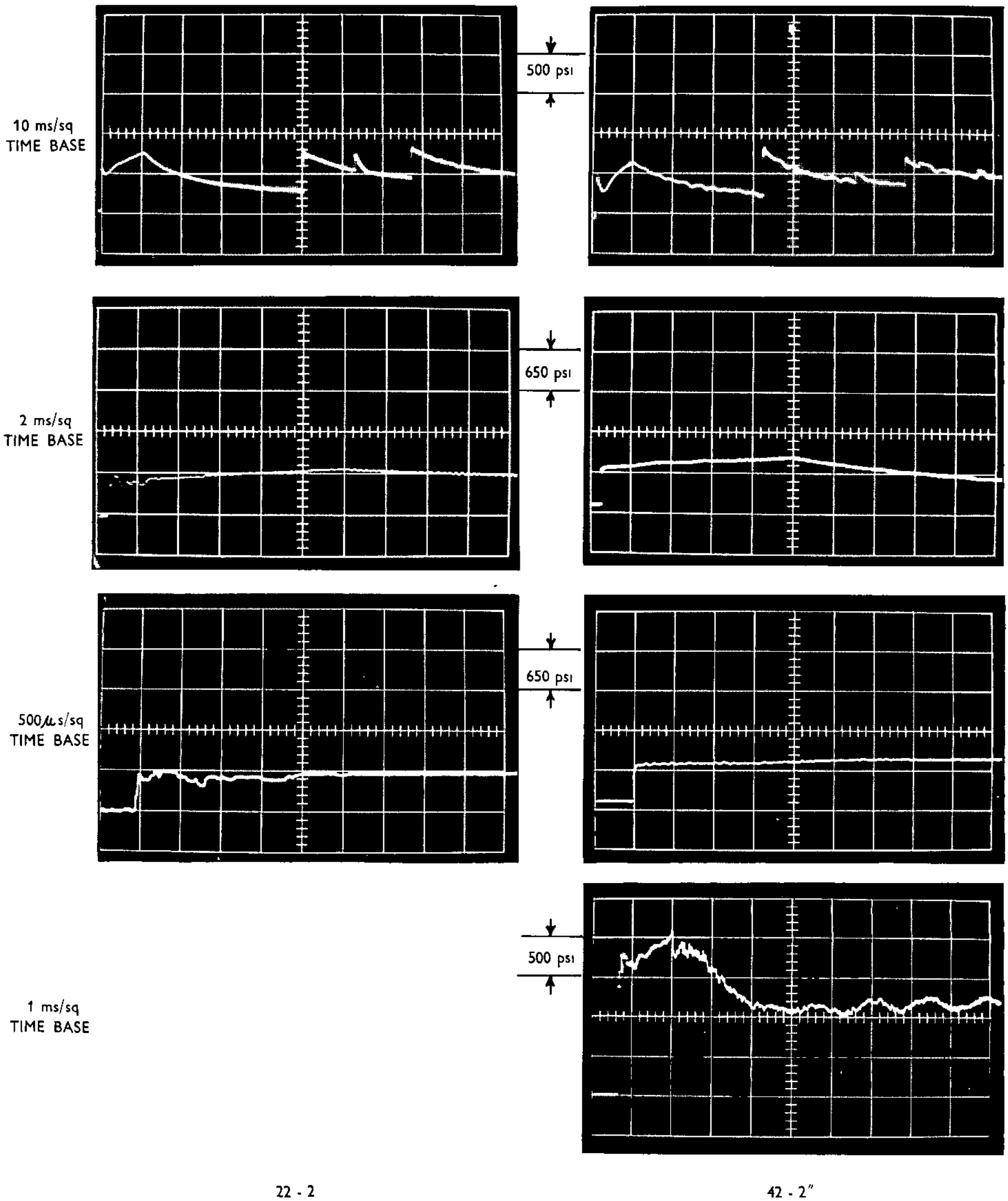
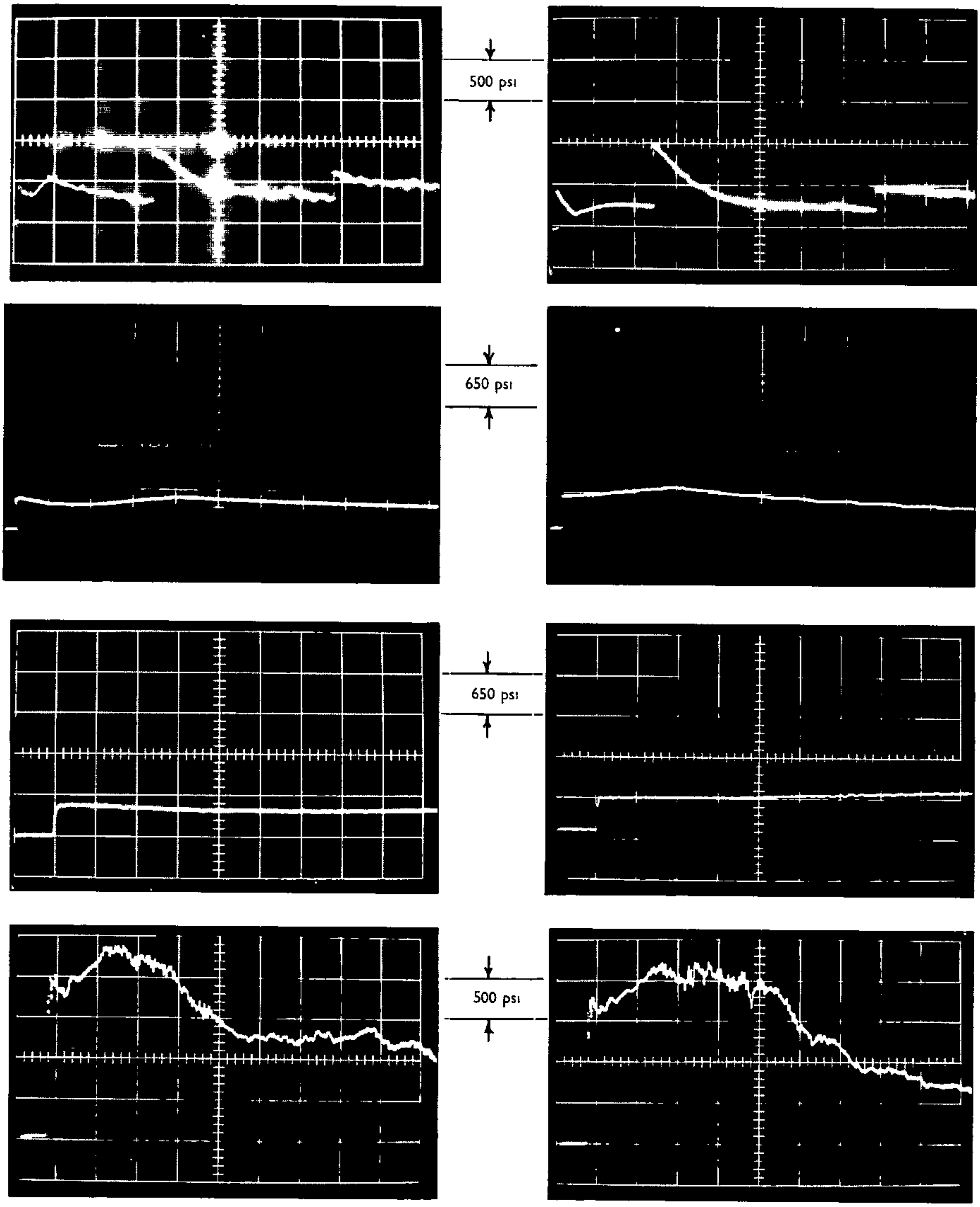


FIG 3 WALL AND PITOT PRESSURE MEASURED AT VARIOUS STATIONS ALONG CHANNEL

NOMINAL DRIVER PRESSURE 190 ATS
INITIAL CHANNEL PRESSURE 2 2 ATS



62′- 2″ 82′- 2″

FIG 3 contd WALL AND PITOT PRESSURE MEASURED AT VARIOUS STATIONS ALONG CHANNEL

NOMINAL DRIVER PRESSURE 190 ATS
INITIAL CHANNEL PRESSURE 2 2 ATS

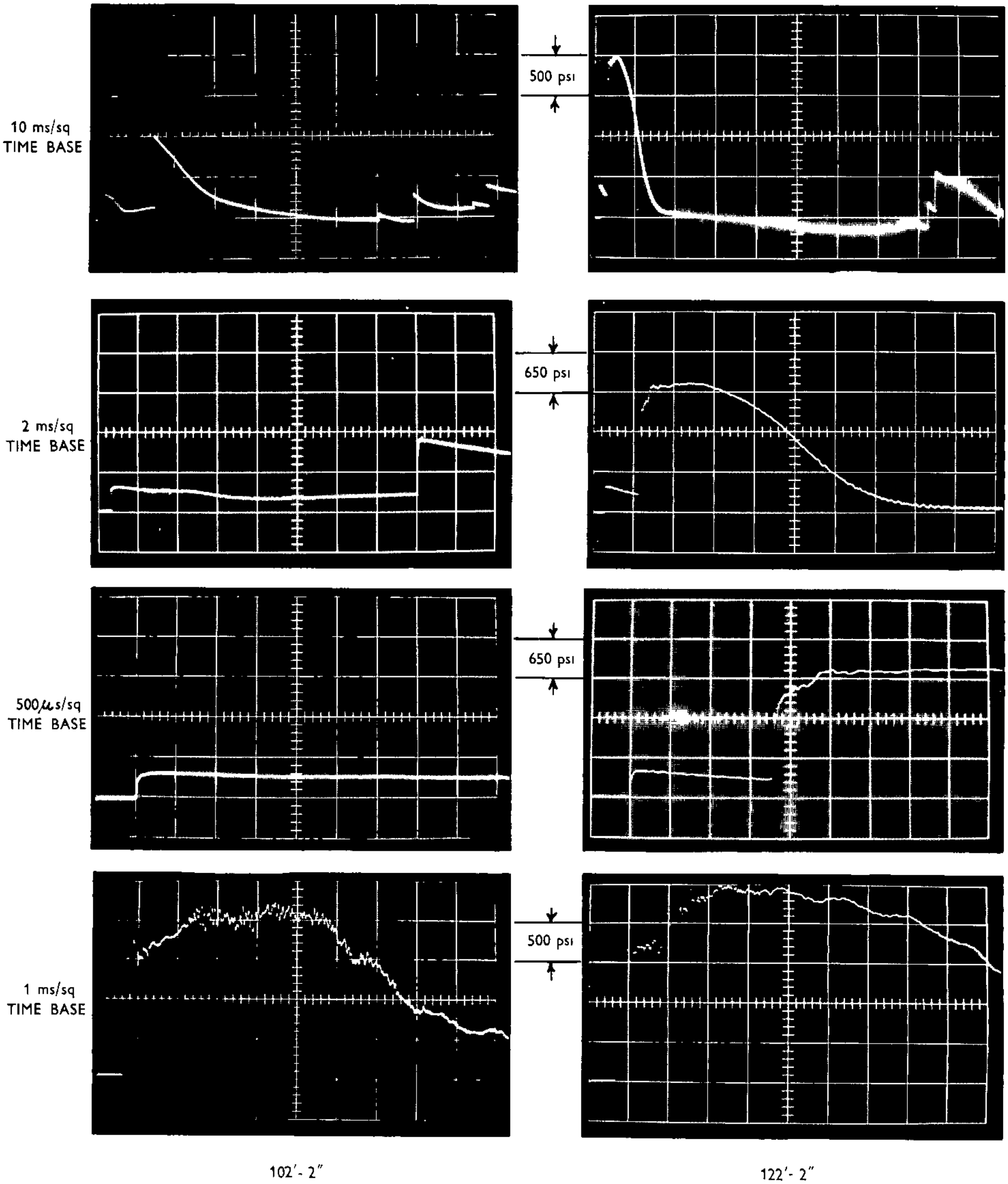


FIG 3 contd WALL AND PITOT PRESSURE MEASURED AT VARIOUS STATIONS ALONG CHANNEL

NOMINAL DRIVER PRESSURE 190 ATS
INITIAL CHANNEL PRESSURE 2 2 ATS

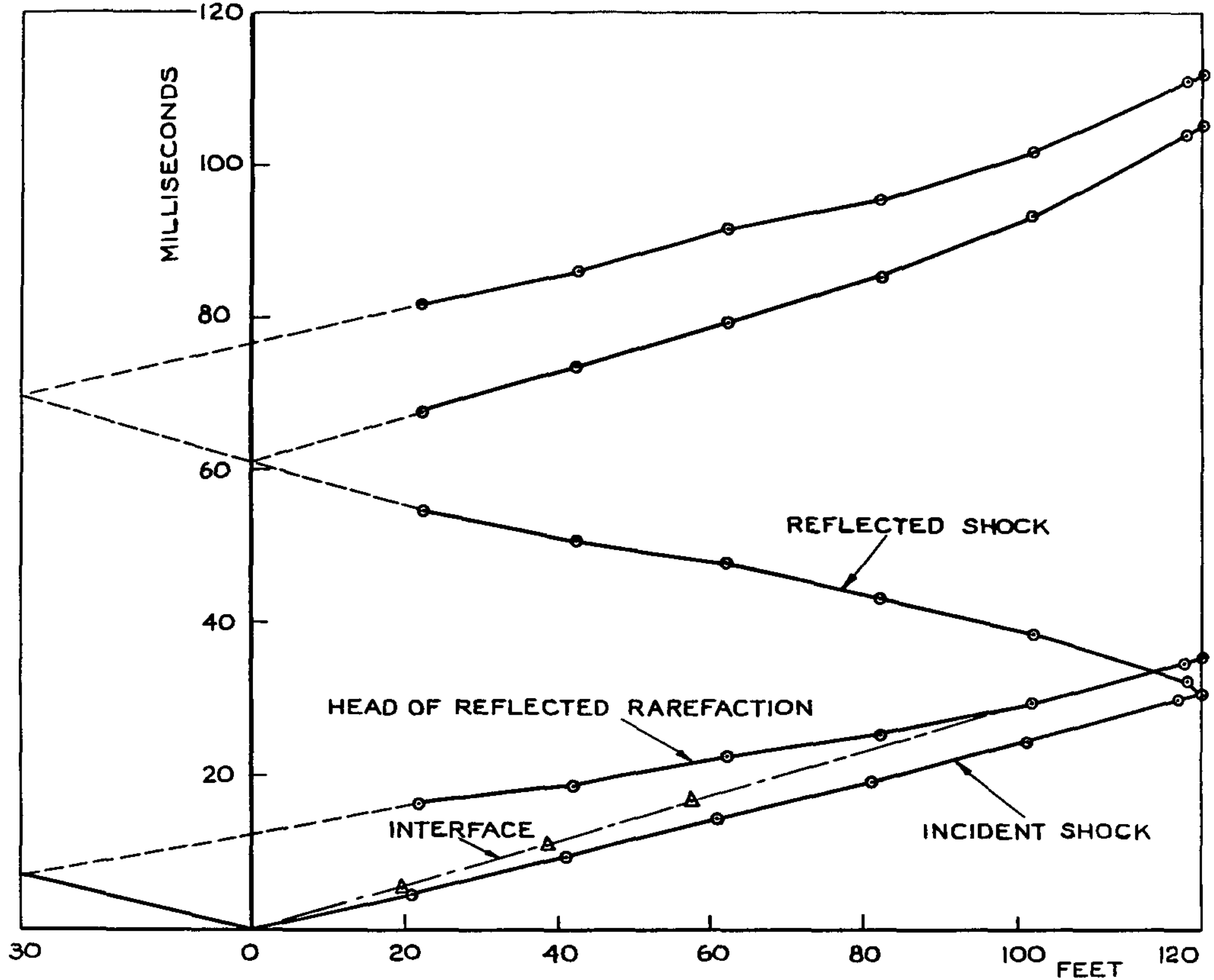


FIG. 4. EXPERIMENTAL DISTANCE-TIME DIAGRAM OF SHOCK TUBE FLOW.
NOMINAL DRIVER PRESSURE 190 ATS.
INITIAL CHANNEL PRESSURE 2·2 ATS.

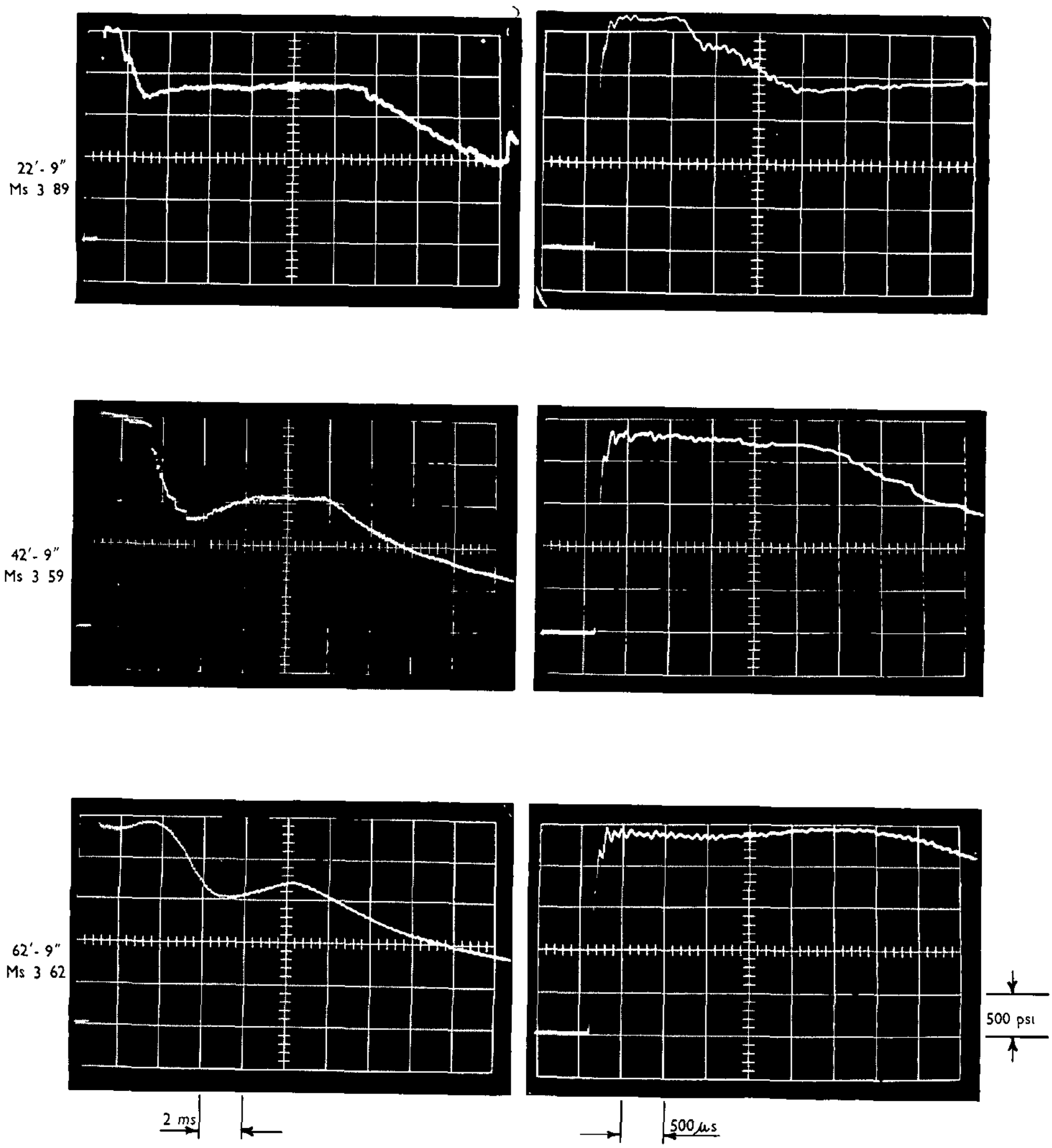


FIG 5 PRESSURE BEHIND REFLECTED SHOCK AT VARIOUS CHANNEL LENGHTS

NOMINAL DRIVER PRESSURE 165 ATS
INITIAL CHANNEL PRESSURE 2 2 ATS

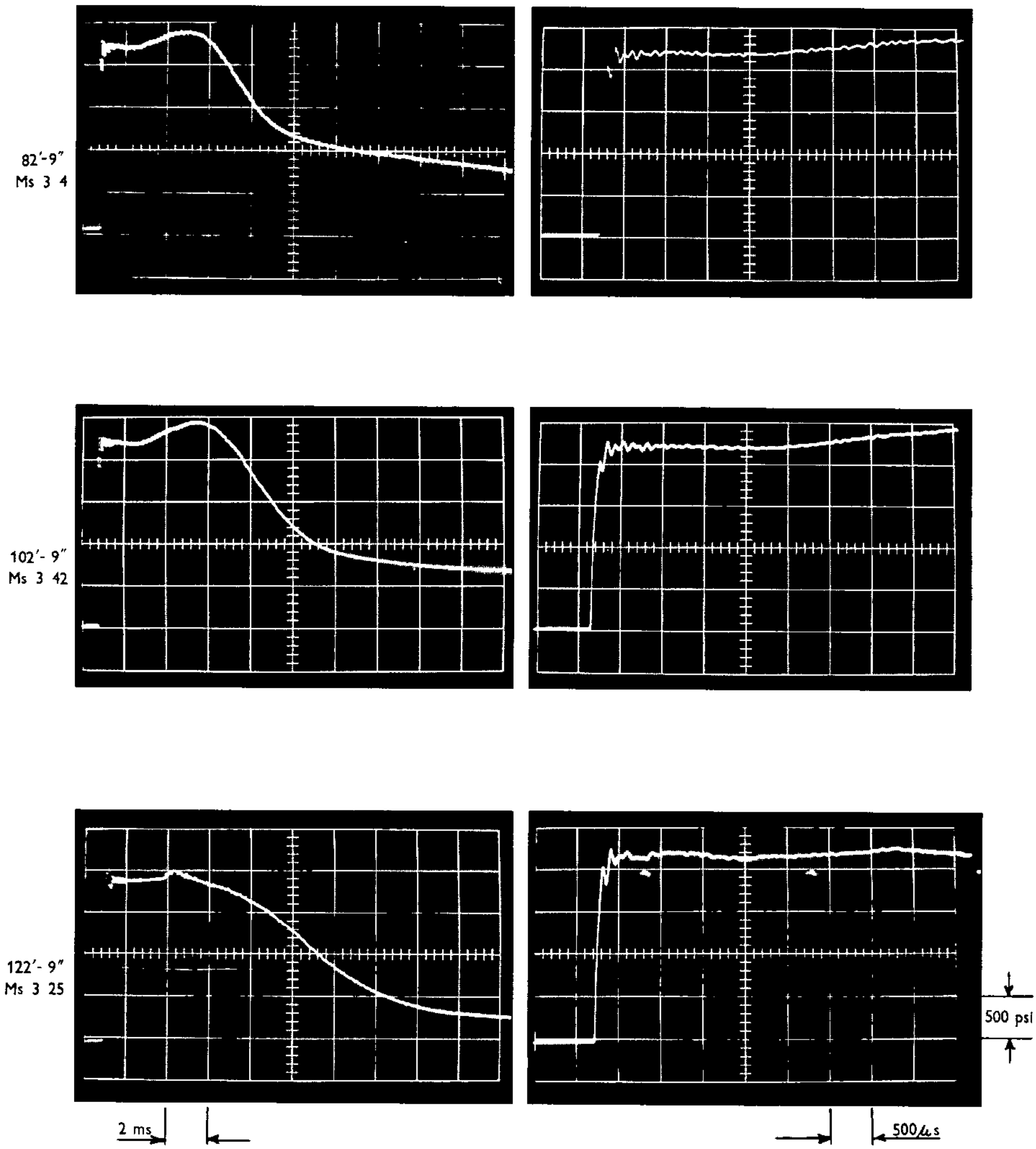


FIG 5 contd, PRESSURE BEHIND REFLECTED SHOCK AT VARIOUS CHANNEL LENGHTS

NOMINAL DRIVER PRESSURE 165 ATS
INITIAL CHANNEL PRESSURE 2 2 ATS

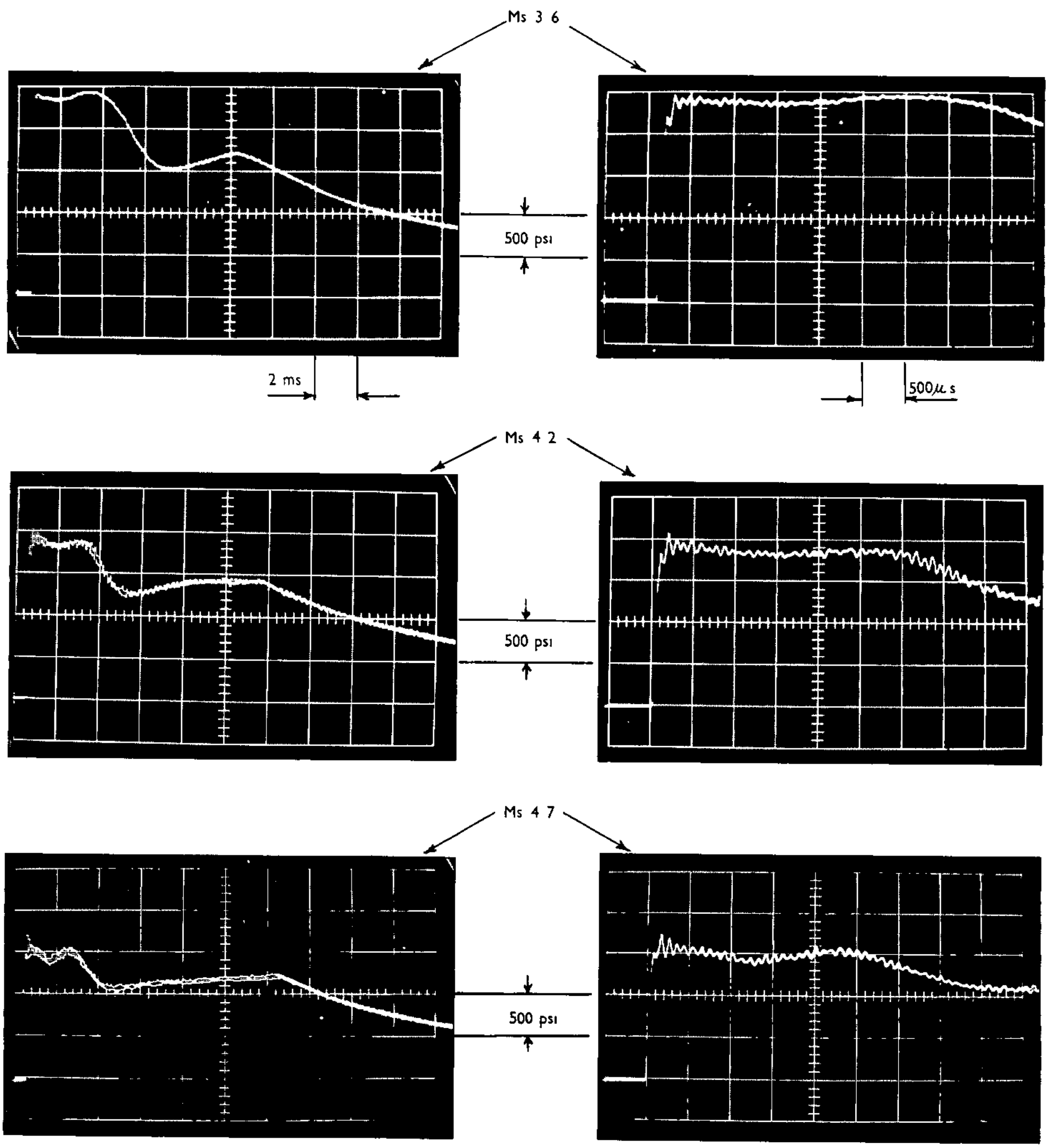


FIG 6 PRESSURE BEHIND REFLECTED SHOCK AT VARIOUS SHOCK SPEEDS

NOMINAL DRIVER PRESSURE 160 ATS

CHANNEL LENGTH 62′-9″

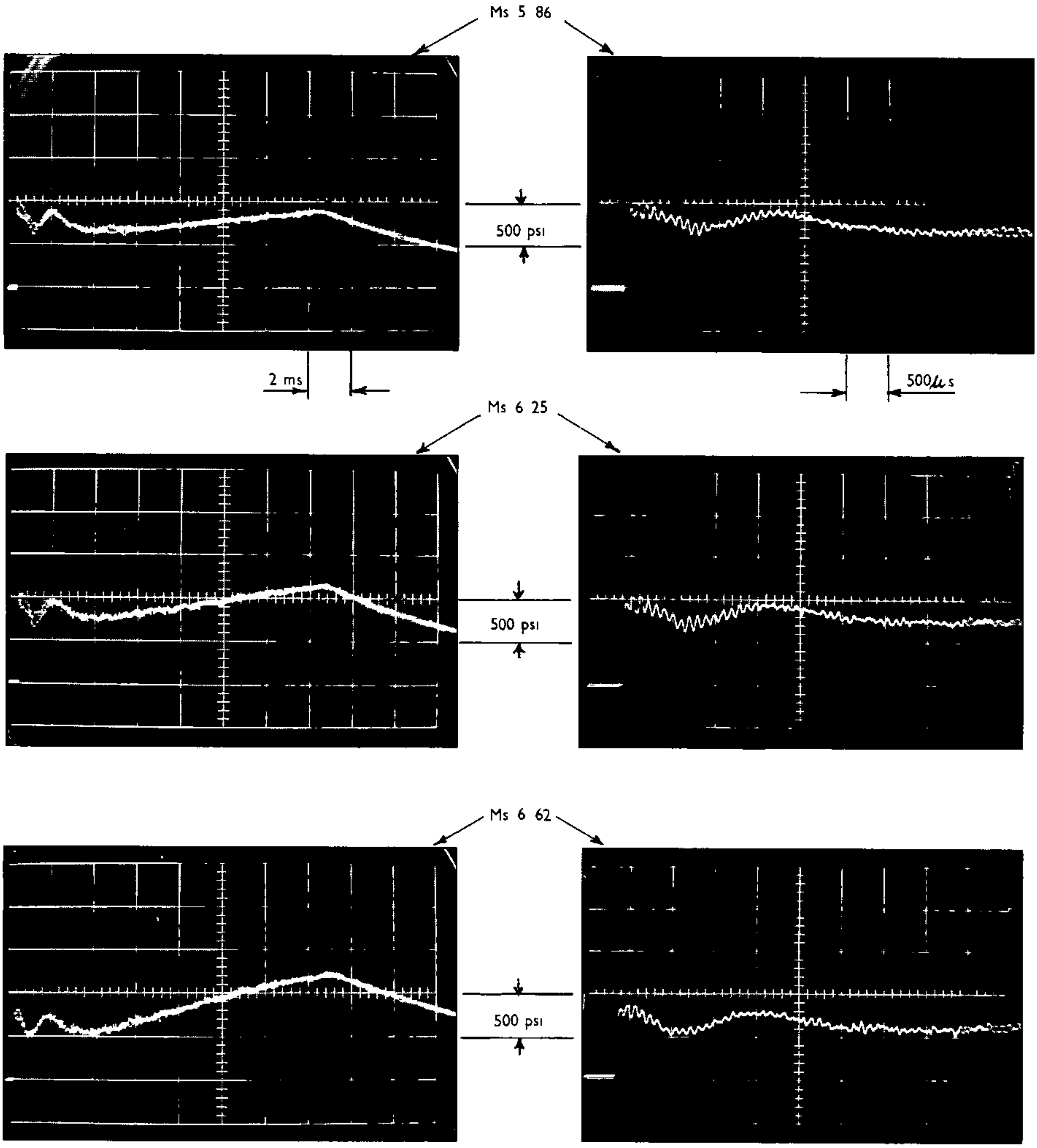


FIG 6 contd PRESSURE BEHIND REFLECTED SHOCK AT VARIOUS SHOCK SPEEDS

NOMINAL DRIVER PRESSURE 160 ATS

CHANNEL LENGTH 62′-9″

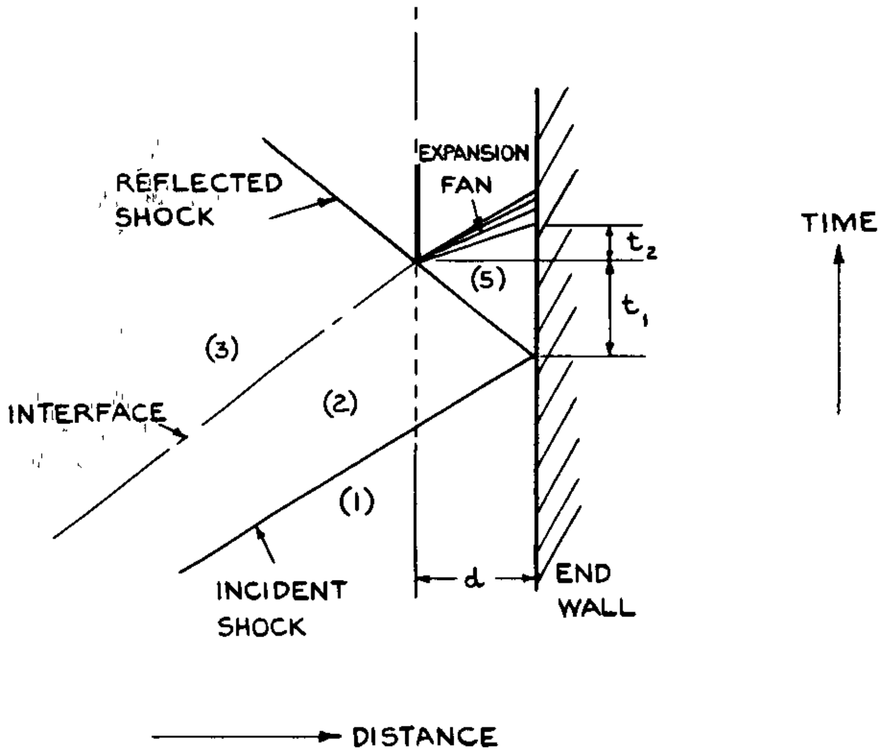


FIG.7. REFLECTION OF SLOW SHOCK WAVE AT CHANNEL END AND INTERACTION WITH INTERFACE.

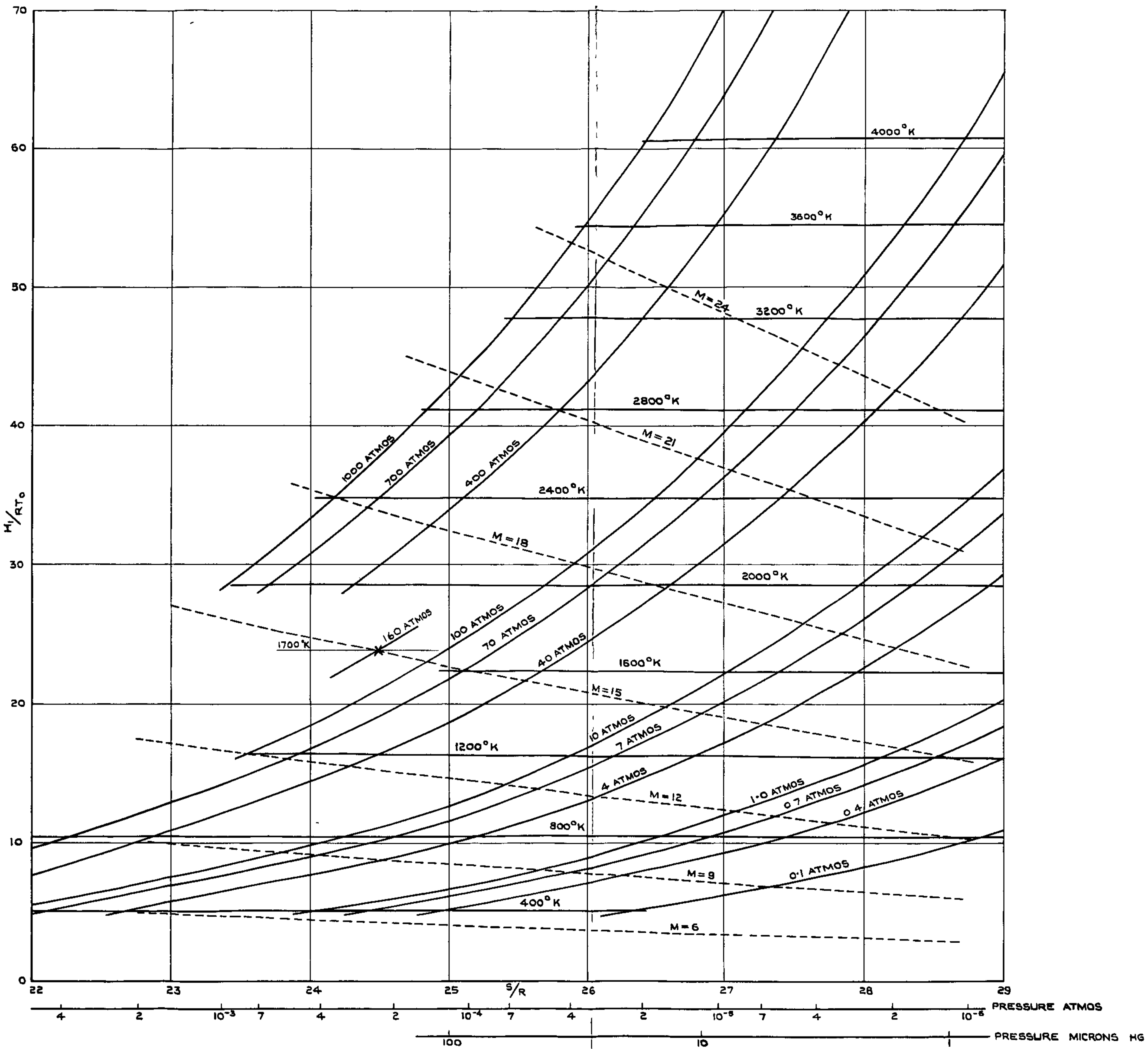


FIG. 8. EXPANSION OF NITROGEN TO HYPERSONIC MACH NUMBERS.

WORKING SECTION PRESSURE VARIABLE, TEMPERATURE AT CORRESPONDING LIQUEFACTION VALUE

A.R.C. C.P. No.698

533.6.073.4/.5 :
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