UNIVERSITY OF

CAPE TOWN

DEPARTMENT OF

MECHANICAL ENGINEERING

SHOCK WAVE INTERACTION IN A TEE JUNCTION

Thesis submitted in part fulfilment for consideration for the Master of Science Degree in Engineering by

ABSTRACT

The problem was to determine the unsteady shock wave interaction at a tee junction, and to measure the transmitted shock strength.

Two tee-junctions of different cross-sectional shape were constructed, and instrumented with three piezoelectric pressure transducers and two hot wire anemometers. Tests were run in air for a Mach number range of 1.5 to 3.0, the different pressure ratios being obtained by varying the degree of vacuum in the driven section of the shock tube.

A shock diffraction pattern for the tee is proposed and the transmitted shock strength is compared with the existing theories on shock diffraction around large corners.

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CONTENTS

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NOMENCLATURE

a	speed of sound
d	hot wire diameter
f	body forces
g	circuit transconductance for hot wire
g	shock tube performance factor
i	small change in hot wire heating current
j	complex unit $\sqrt{-1}$
l	hot wire length
m	angle to the wall at which the diffracted shock curvature begins
n	number of discs in a piezo transducer
p	pressure
q	heat transfer per unit mass and time
r	radius
t	time
u	velocity
v	velocity
x	co-ordinate
y	co-ordinate
A	area
C	constants of integration subscripted for the specific heats
D	diameter
E	energy
I	hot wire heating current
K	piezoelectric modulus constant
M	Mach number
M	time constant
O	overheating ratio
R	rarefaction
S	entropy
U	velocity
V	velocity

α curves describing successive shock positions

β rays; curves orthogonal to x

γ ratio of specific heats

δ small increment

change in flow direction at an oblique shock

$\left.\begin{matrix}\xi \\ \eta\end{matrix}\right\}$ transforms onto the pseudostationary plane

ζ oblique shock wave angle

θ angle

Subscripts

1 conditions ahead of the incident shock

2 conditions behind the incident shock

4 conditions in the driver before firing

e end

f calculated at the film temperature

g gas

r reflected

w wall

$\frac{\partial x}{\partial \alpha}$ partial derivative

Upper case letters A,B,C,D,E,F,G,H,S,T, are also used to the tapping positions in the tee.

INTRODUCTION

INTRODUCTION - GENERAL

The shock tube is essentially a device for generating shock and rarefaction waves, and for generating the resulting high speed gas flows of very short duration. With modern development its use has been extended to a multitude of applications ranging from simple one-dimensional gas dynamics to the production of extremely high temperatures for hypersonic flows. Shock tube theory has also been extensively developed and as a result has become a rather standard tool of compressible flow research.

In its simplest form the shock tube usually consists of a long tube separated into two sections by a diaphragm across which a pressure differential can be created. The high pressure side is called the driver chamber, and the low pressure side the driven chamber. When the desired pressure ratio is attained, the diaphragm is ruptured, generating a pressure wave propagating down the driven chamber. Within a short distance from the diaphragm the pressure wave steepens into a sharp pressure discontinuity forming a shock wave. The shock wave accelerates the gas it moves into up to some speed less than that of the shock wave itself, but in the same direction.

A rarefaction, or expansion wave, travels backward into the driver chamber and also accelerates the gas it moves into, however in opposite direction to itself, or in the same sense as the shock accelerated gas. The gas particles that before rupture have been at the two sides of the diaphragm have different entropy values. After rupture this entropy discontinuity travels down the tube with the shock accelerated gas velocity forming a cold front known as the contact surface. (see fig. 1-1)

After the shock front has formed, its strength can be characterized in a number of ways. Two of the most convenient ways are by specifying the pressure ratio across the shock, or by specifying the shock Mach number.

Successful use of the shock tube as a research or test facility is, of course, entirely dependent on suitable instrumentation for flow measurement. Because of the highly transient nature of the flows involved, an essential requirement of the measuring instrument, is very fast response. This requirement, in addition to other demands of adequate sensitivity, range, and accuracy, greatly compounds the technical difficulties of shock tube instrumentation.

INTRODUCTION - SPECIFIC

The shock tube is used specifically for the generation of medium strength shock waves in this project. Both the driver and driven gas are air and the Mach number range explored was from Mach 1.5 to Mach 3.0. Two metallic diaphragms were used to separate the driver and driven sections, there being an area reduction from driver to driven section at the diaphragms. The tube was circular in section.

The interaction of the unsteady shock wave, generated by the shock tube, as it enters and leaves a tee-junction is the problem to be studied.

The nearest applicable theory, besides the one dimensional gas dynamics theory used for the shock tube itself, was the approximate theory of Witham for the diffraction of unsteady shock waves about large corners. The diffracting shock model of Jones, ~~Moira~~, Martin and Thornhill is also considered.

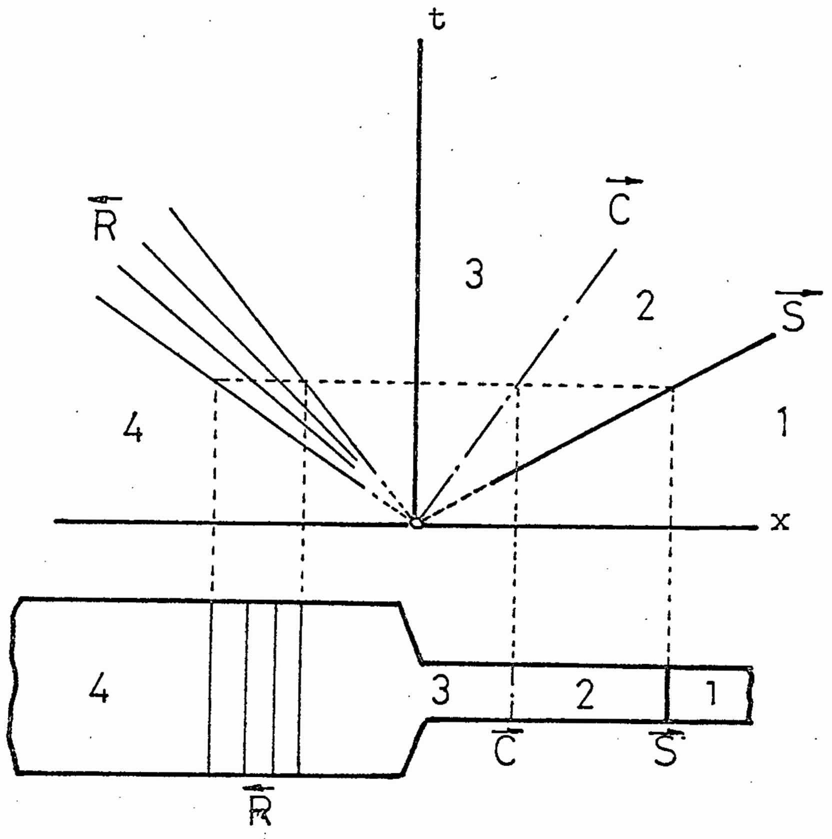


Fig. 1-1 Typical x-t diagram for a shock tube

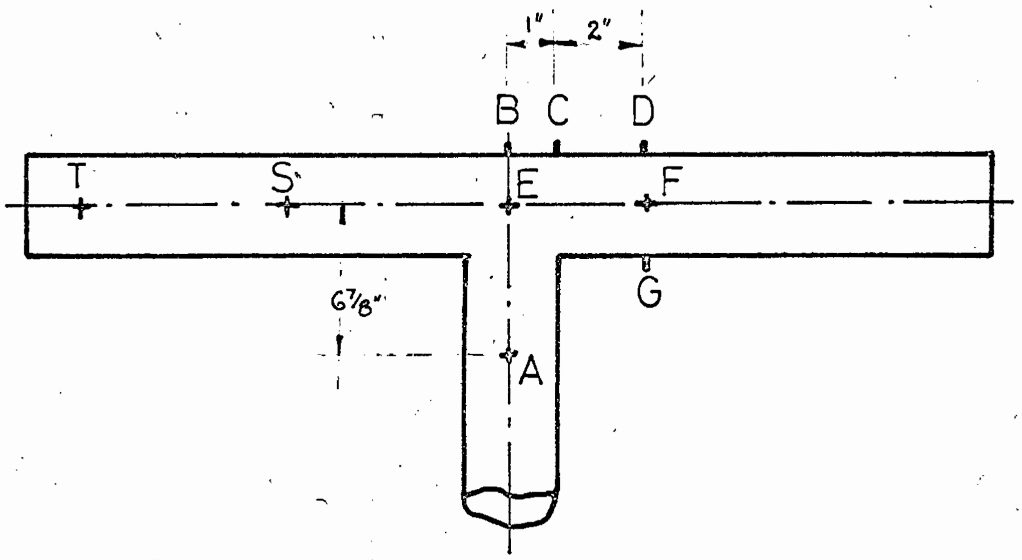


Fig. 1-2 Tapping positions in tee

APPARATUS

SECTION 2 APPARATUS

All the apparatus used belongs to the Department of Mechanical Engineering, U.C.T. A brief description of the 2 inch diameter shock tube is given below and then a more detailed description of the apparatus specifically made for this project follows.

2-1 The Shock Tube

See Fig. 2-1-1

1. The Driver

This is a 3 inch internal diameter steel tube of 4 ft. length, made up of two sections which are flanged and bolted together. It was designed for an operating pressure of 2000 lb/in^2. The charging line enters at the back end and also serves as a pressure tapping.

2. The Driven Tube

This is made of several interchangable lengths of 2 inch I.D. 10 gauge brass tubing which are joined together by a sleeve type coupling. Sealing is effected by O-rings on the outside of the tubing. Tube lengths vary from 2 to 4 ft andthe maximum obtainable length is 17 ft. The couplings are used for the pressure tappings.

3. The Intermediate Chamber

In between the driver and the driven tube is a 2½ inch I.D. by 2 inches long removable section. When in the 'loaded' position there are diaphragms clamped in between the driver and this section and between the section and the tube. There is a supply-bleed line fitted with a solenoid valve

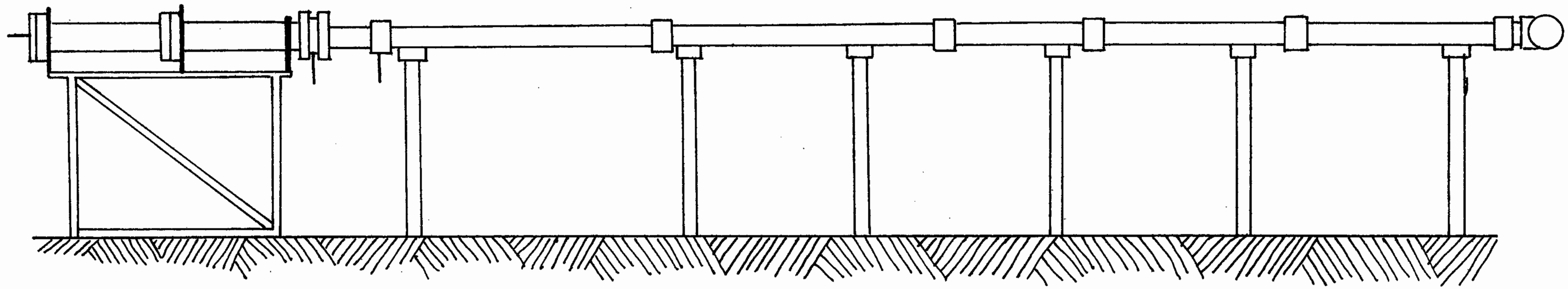


FIG 1-2-1-1 Schematic diagram of the shock tube for rapid exhausting. This arrangement facilitates the two-disc method of firing the tube. Sealing is again effected by O-rings.

The Control Panel

The shock tube was pressurised and fired from the control panel, which was the mounting place for most of the operating valves and gauges. See photograph 2-1-1. The gauges monitored the driver section pressure, the driven section pressure, the intermediate chamber pressure and the air bottle pressure, where each gauge could be individually isolated. For the low pressures in the driven tube there was one gauge which had a range of 0 to -26 inches of mercury, relative to atmospheric, and another gauge with a range of 10 to 100 millimeters absolute. As a precautionary measure, a solenoid valve was fitted into the line leading to the vacuum gauges, such that the tube could not be fired without this valve being closed.

Gauge reading accuracy and range:

Driver pressure		Range 60 to 3000 p.s.i. Reading accuracy 10 p.s.i.
Driven section	gauge 1	Range 0 to -26 in. Hg. Reading accuracy 0.1 inches
	gauge 2	Range 10 to 100 mm Hg. abs. Reading accuracy 0.2 mm

The Vacuum Pump.

The driven section was evacuated with a Speedivac E.S.250 pump made by Edwards High Vacuum Limited. Its performance was good and it was capable of getting the driven section pressure below 10 mm. Hg. absolute in less than 30 seconds. It was also possible to isolate the vacuum pump from the shock tube, so that the pump was not pressurized on firing the tube,

2-2 TEE SECTIONS

The terms shown in figure 2-2-1 will be used to indicate what portions of the tee are being discussed.

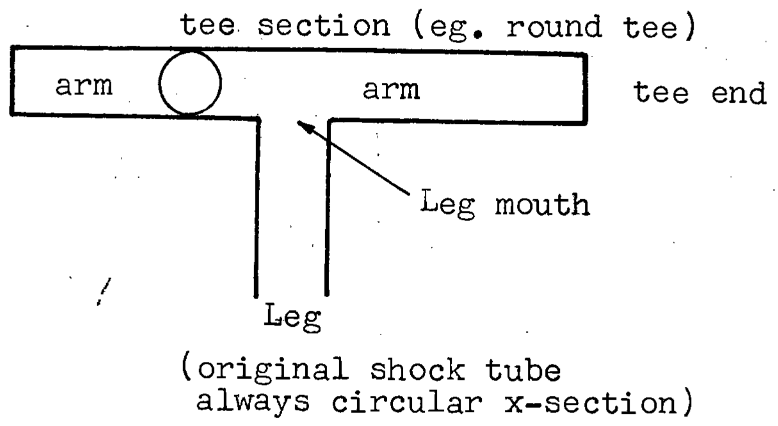


Figure 2-2-1 Terms used in describing a tee

The Rectangular Tee

The rectangular tee was fabricated from ½ inch thick alluminium strip. Constructional details are shown in Figure 2-2-2.

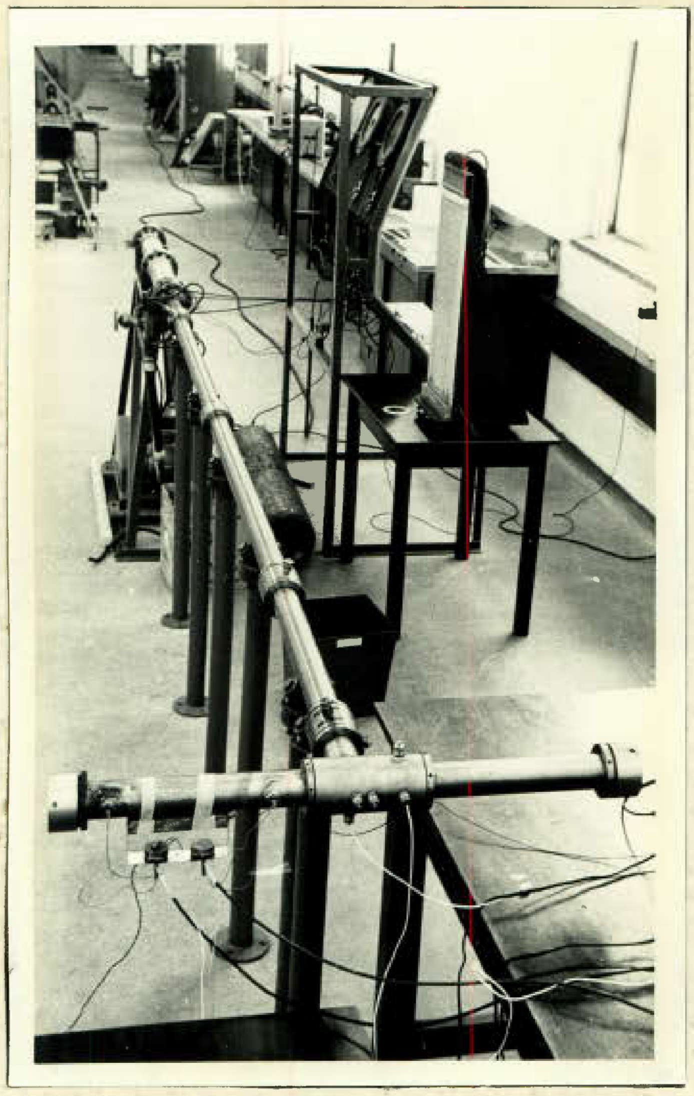
The cross-sectional area of arm was made to equal that of the leg and for the leg to match into the arm, the one dimension of the rectangle was made equal to the leg diameter.

$$A = \pi r^2 = w \times h$$

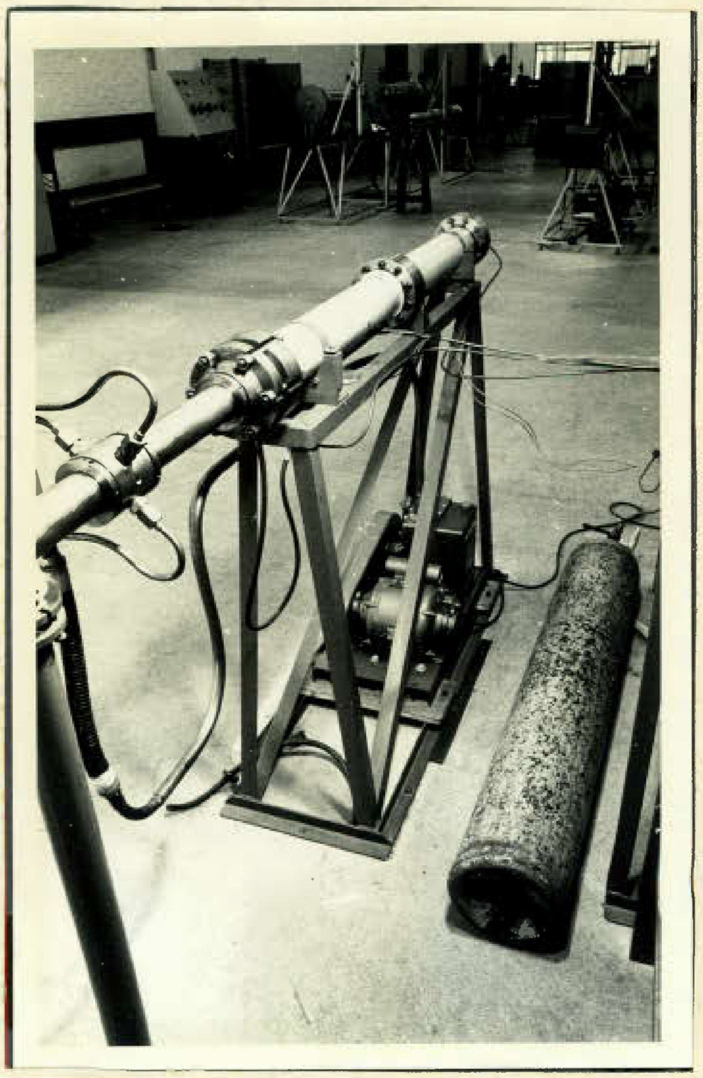
$$w = \frac{\pi}{2} = 1.57 \text{ inches}$$

Trouble was experienced in getting the arms and arm ends to seal under both vacuum and pressure. The final arm sealing arrangement was achieved with use of a neoprene seal along the length of the arm, and 10 G-clamps to give the correct sealing load, ~~as shown in figure 2-2-3~~.

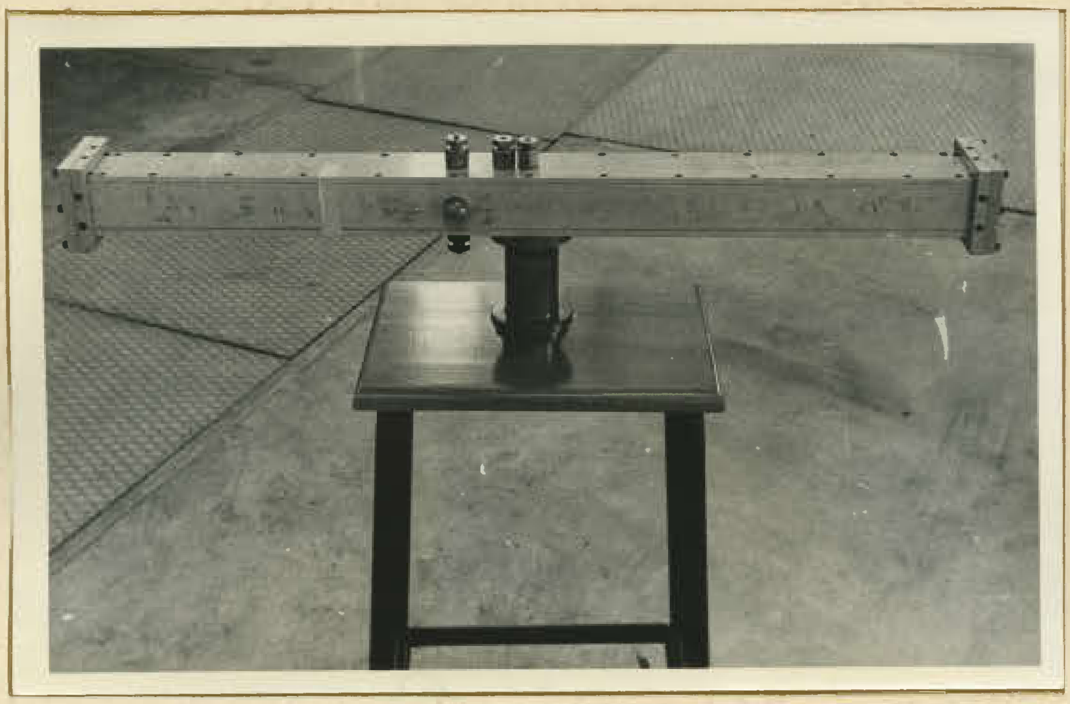
The arm ends were milled to take an O-ring seal, which pressed up against thin plates araldited to the arm.



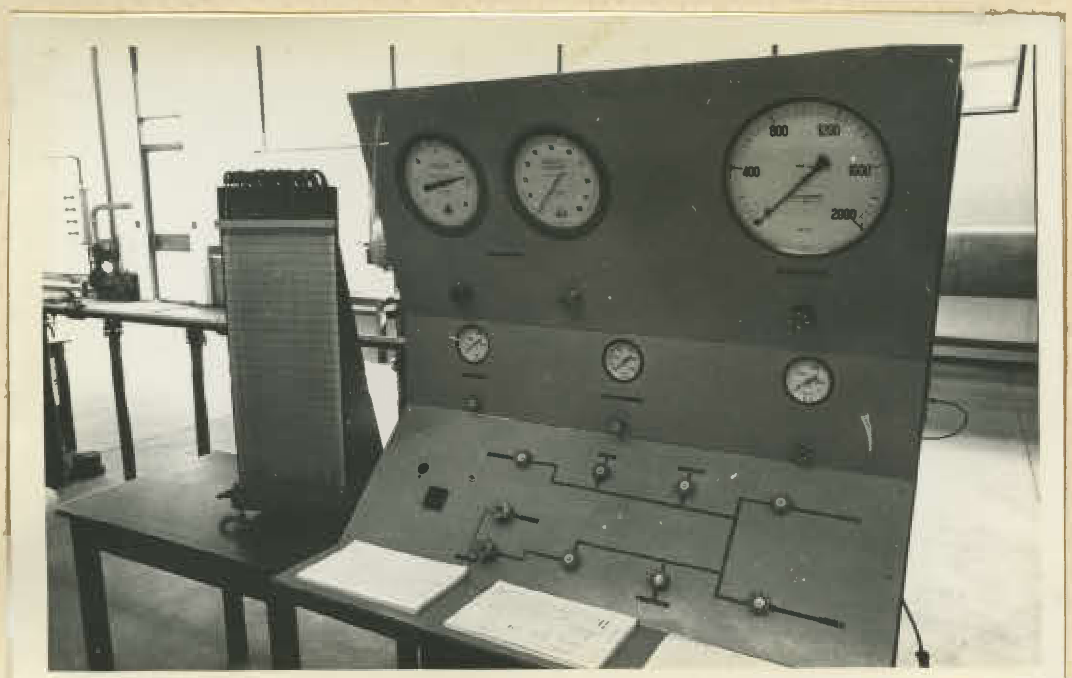
Photograph 2-1-2
Overall view of the shock tube



Photograph 2-1-3
Driver section plus vacuum pump



Photograph 2-2-1 Rectangular tee



Photograph 2-1-1 Operating panel

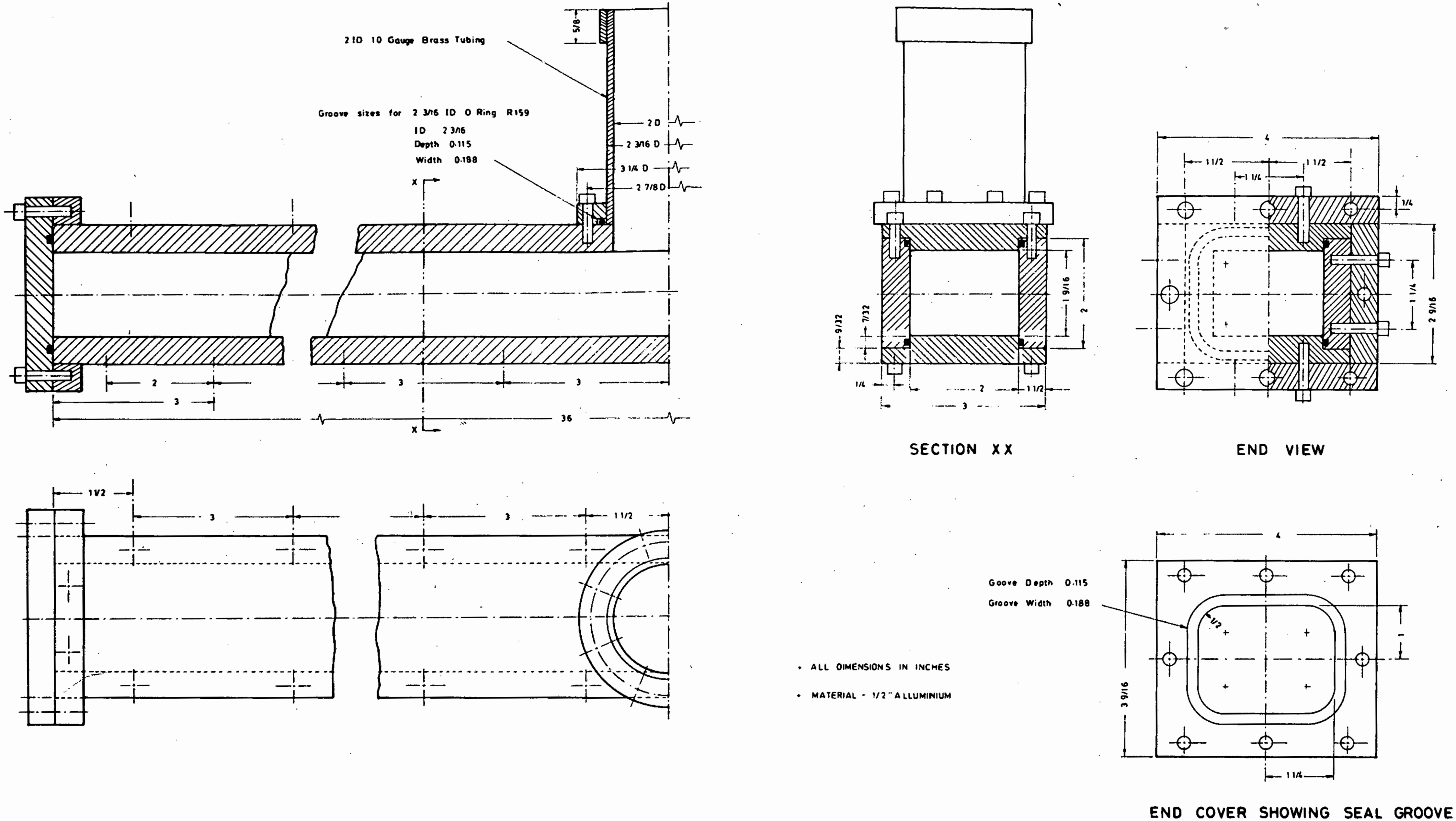


FIG. 2-2-2 RECTANGULAR TEE

The pressure transducer mountings, shown in figure 2-2-4, were turned up out of brass and screwed directly into the arm wall. The P.T.F.E. (nylon) tape was used for sealing. Care was taken to ensure that the clearance between the end of the transducer, and the bottom of the location in the mounting, was between 0.001 and 0.002 of an inch. This was done in order that the frequency response should not be impaired. The hole diameter finally used in the mounting was 1/16 inch, thus giving a length over diameter ratio of 2.

The hot wire probe shown in figure 2-2-5 was made up in three steps. Firstly the body was turned out of brass. Secondly, a piece of 5-hole ceramic and the two needles were glued into position using Araldite. Thirdly, the needle ends were prepared and the 5 micron tungsten wire was spot welded to the needle ends, using the Disa 55A11/12 Micro-manipulator and welding Power Generator. The most successful welding settings were with an energy of 175 millijoules and time 200 microseconds. Care had to be taken to get the correct pressure with the electrode for welding, as the tendency is to make the pressure too great. The most successful method of removing the excess wire was found to be the burning off of the wire, just outside of the needles, by using the welding power generator.

The direct screwing of the hot wire probe into the arm wall was not all thatsuccessful, because of the need for the wire to lie normal to the flow, and yet to have the mounting screwed in tightly enough in order to seal the tube. Again P.T.F.E. tape was used.

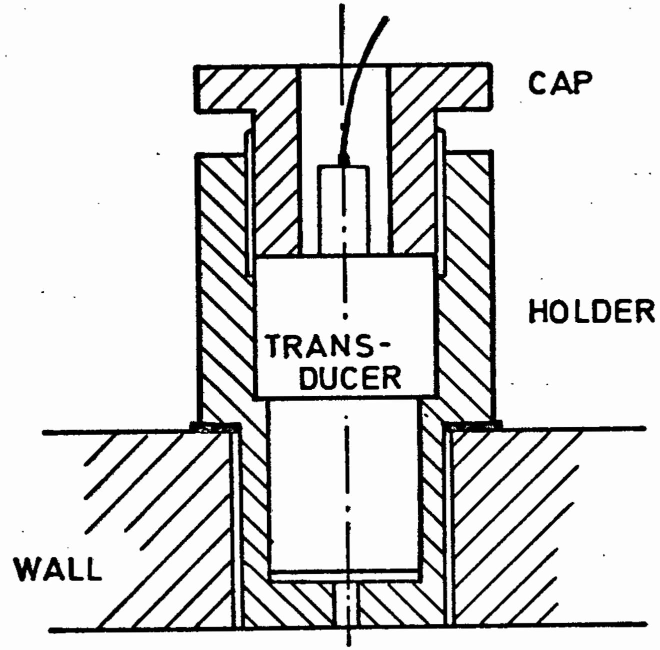


FIG. 2-2-4 TRANSDUCER MOUNTING

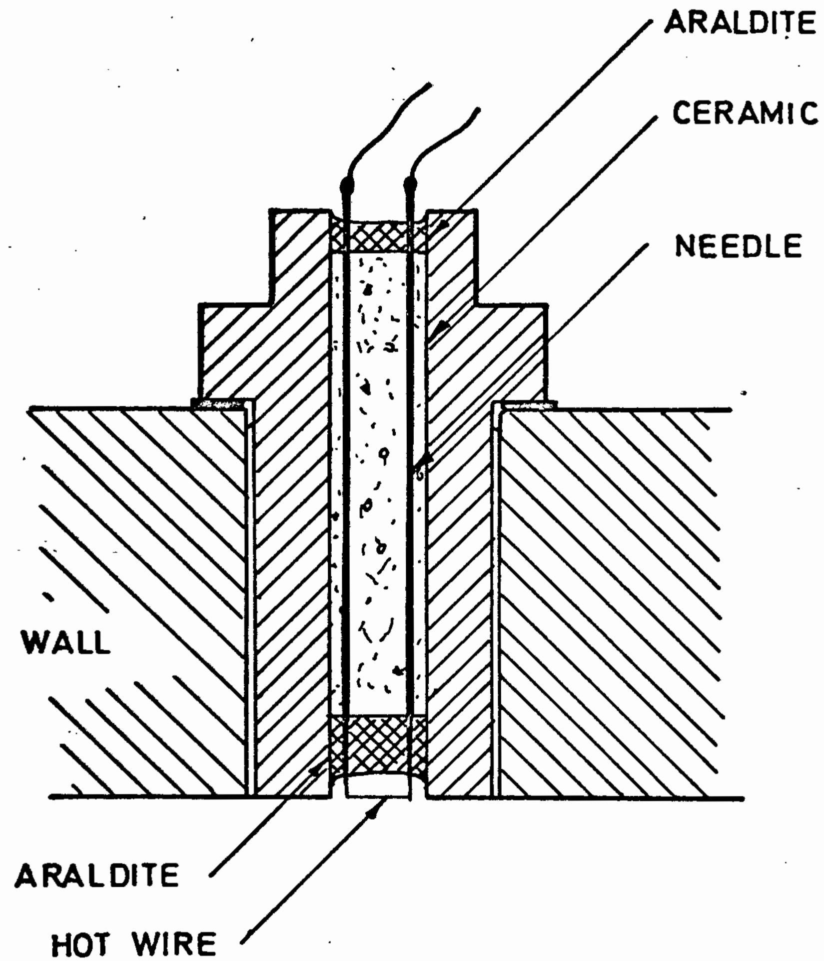


FIG. 2-2-5 HOT WIRE

The Round Tee

The round tee was constructed entirely in brass, as shown in figure 2-2-6. Sealing was much simpler in this case, the same technique being used as was used on the original shock tube.

Except for ~~r~~ minor modifications to suit the curved wall, the transducer and hot wire mountings were the same as for the rectangular tee.

Six transducer and two hot wire locations were made in each tee.

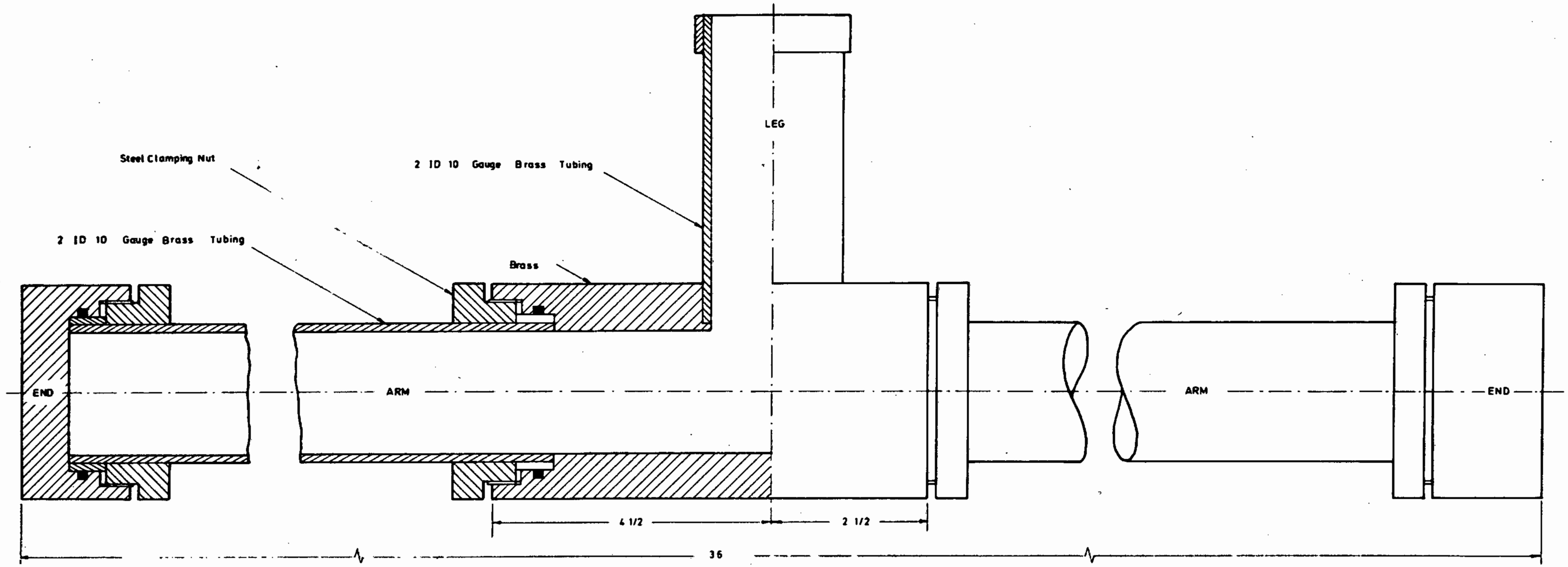


FIG. 2-2-6 ROUND TEE

2-3 DIAPHRAGMS

The diaphragm materials in common use are usually selected for their characteristics over the pressure difference range to be used. For low pressure differences, in the range of 1 to 200 p.s.i., the non-metallic discs, such as cellophane or cellulose acetate, are very much used. The pressure differences employed in this present project were all near the upper limit of the suitable non-metallic disc pressure range and it was therefore decided to continue using the metallic diaphragms previously used.

It is not only important that the diaphragm should burst, but that it should burst properly. Ideally, it is desired that the metal diaphragm burst by petalling cleanly, without fragmentation, and that the petals fold back against the tube walls so as not to obstruct the flow. If there was fragmentation the loose diaphragm pieces would be accelerated down the tube, and could cause damage to both the tube and the shock measuring devices.

In order to produce good petalling characteristics, the practice here was to use a controlled scribing technique on the diaphragm. Scribing was done on two perpendicular diameters by a scriber arrangement described later. Control of the scribing load allowed the selection of the diaphragm bursting pressure required. The tube was made with a large radius on the downstream side of each diaphragm, so that the petals could fold around the radius and not be cut off.

The two-diaphragm technique of firing the tube was used here. The driver, intermediate chamber, and driven section were each charged individually (the driven section going to a pressure below atmospheric) such that the pressure drop across each diaphragm was less than the diaphragms bursting pressure, but the pressure difference between the driver pressure and atmospheric pressure was well above the bursting pressure. Then to fire the tube the pressure in the intermediate chamber was rapidly dropped to atmospheric pressure (small capacity and a fast opening solenoid valve) thus initiating the bursting of the first diaphragm and subsequently the second.

It was initially decided to continue usingthe 20 and 22 gauge, 2S hard Alluminium for the diaphragm material. Preparation of the discs was a long and tedious process, as the aluminium squares had to be first hand snipped until they were nearly round, and then trimmed in a lathe. Scribing was originally done with a rolling cutter as shown in figure 2-2-7.

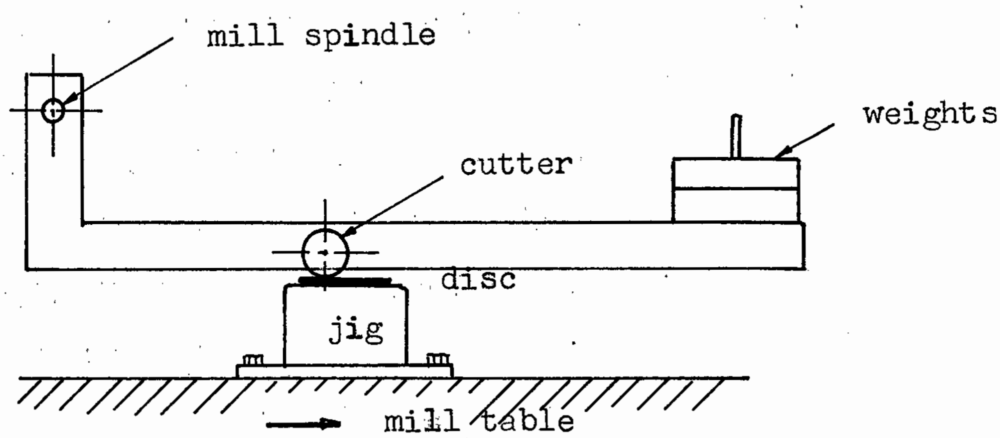
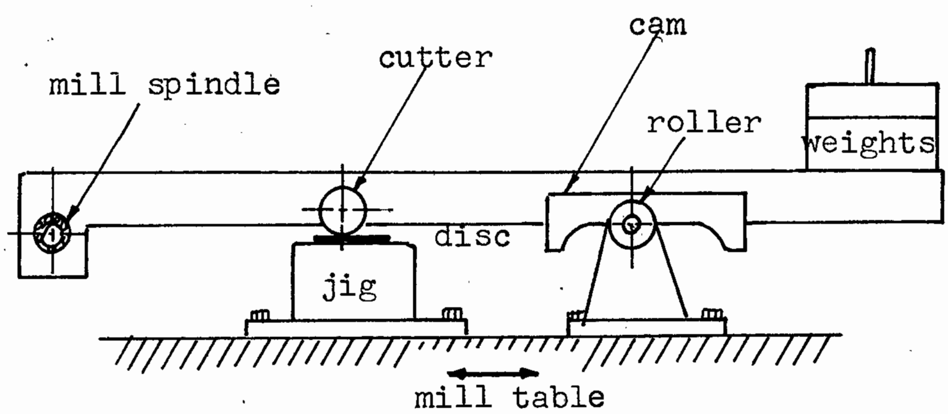


Fig. 2-2-7 Showing original scribing system

Very little success was achieved with the aluminium discs, as they would only half rupture instead of petalling completely. In an attempt to track down the cause, the scribing mechanism was redesigned and thinner steel diaphragms were tried. The final conclusion as to the cause of the poor bursting response was that it was due to bad procedure in the clamping of the discs in place. Both uneven and insufficient tightening ofthe clamping bolts allow too much 'drawing in' of the disc on pressurizing. However, by this time the steel discs had shown themselves to be more easily prepared and hence all the later tests were done using these steel diaphragms. A punch was made in the Departments Workshop for stamping out the $4\frac{1}{8}$ inch diameter discs from sheet steel discards supplied by a local tine manufacturer. The discs had a thickness of 0.009 inches.

The redesigned scriber shown in figure 2-2-8 had certain advantages over the original arrangement.



1. The line of action of the friction force at the cutting edge was made to pass through the centre of the pivot (mill spindle). This made the scribing action independent of the sribing direction, because of the elimination of the lifting or dragging friction moment about the pivot.

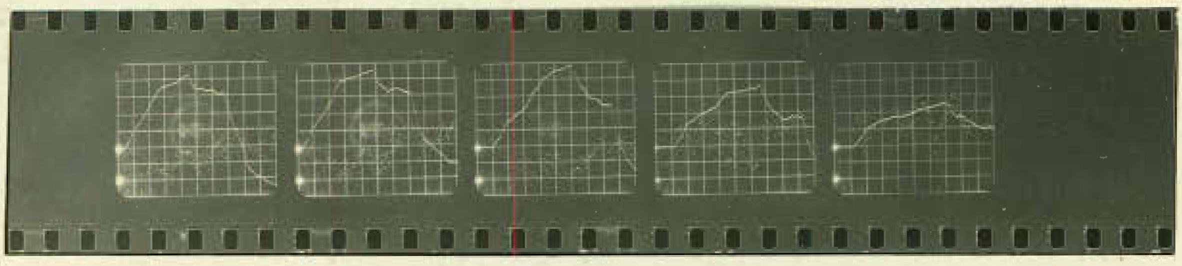
2. Whereas the old scribing system required manual lifting of the weights while the disc was being positioned, the cam-roller action on the redesigned model facilitated the automatic lifting of the cutter. This also improved the consistent reproducibility of the system.

3. The ball bearing mounted on the mill spindle afforded better lateral guidance of the cutter.

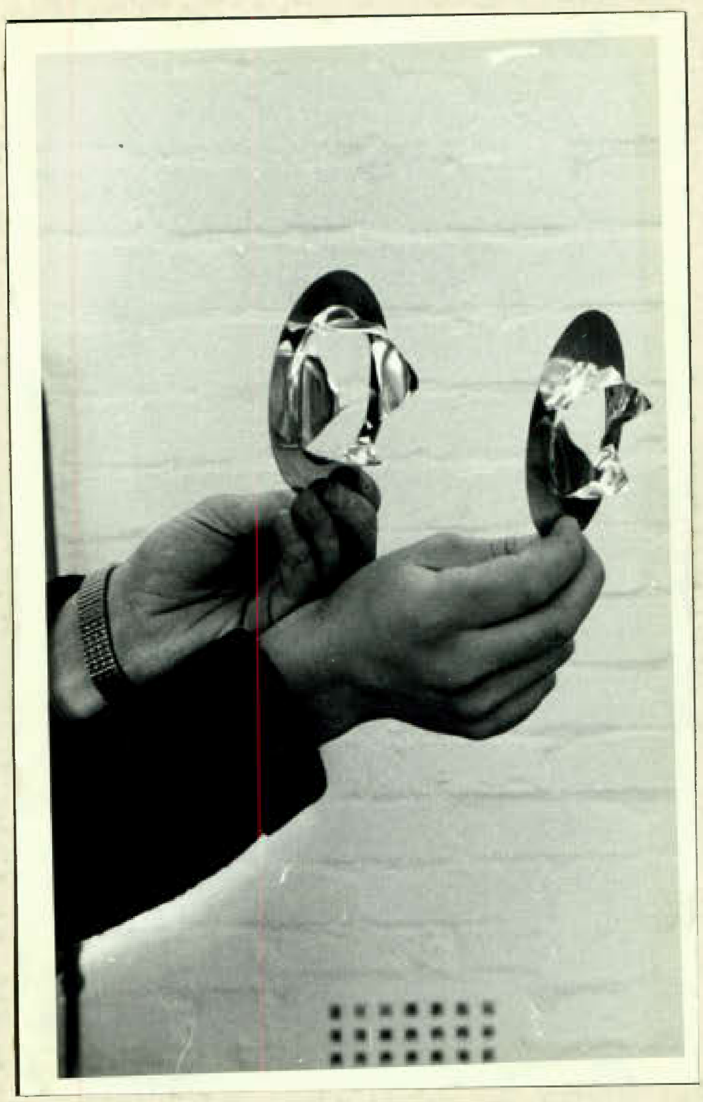
A calibration curve of the bursting pressure against scribing weight is given in graph F-11. These calibration figures were obtained by clamping only one diaphragm in the tube at a time and recording its natural burst pressure.

Diaphragms were usually prepared in lots of about 40. This was done to strike a balance between the minimum number of times the scriber had to be set-up and the minimum number of diaphragms that would have to be discarded if there was a change in working pressures.

The system proved reliable, approximately 1,600 discs being burst with only an estimated 10% disc failure.



Photograph 3-3-7 Hot wire signals



Photograph 2-4-1 Burst diaphragms

2.4 PROCEDURE

Once the apparatus was all set up and working the following procedure was adhered to in doing test runs.

1. Clamp two correctly prepared diaphragms into position, making sure that all six clamping bolts were evenly andwell tightened.

2. Check the positions of the pressure transducers and change if necessary.

3. Check that the settings on the oscilloscope were as wanted. If the gain control had to be adjusted then the triggering level was checked.

4. Evacuate the driven section with the speedivac pump and then release the vacuum gauges to get a reading. By bleeding in air through a control valve, get the vacuum in the range required. Shut off valves to the vacuum gauges and the valve to the vacuum pump.

5. Charge the driver section and the intermediate chamber simultaneously, so that the pressure in the intermediate chamber is approximately half ofthat in the driver section. For most runs charging was first done from a 150 psi receiver (Air dried by passing over silica-gel when compressing) and then the topping was done from a 2000 psi dry air bottle.

6. Set the oscilloscopes ready for a single sweep action and activate the storage screen. If photographs of the trace were to be taken, the camera shutter was opened on a time exposure, but the screen was not activated. A check was made on the hot wire current.

7. Open valve to suitable vacuum gauge to get a reading of the final driven section pressure. Close the vacuum gauge valve and flick the safety solenoid valve switch, to make sure the gauges are isolated.

8. Fire the tube by pressing the push button exhausting valve (solenoid).

9. Release the resulting system pressure by a bleed valve.

10. Release the camera shutter if a photograph was taken. Take down all relevant settings and sketch out traces. Clear oscilloscope screens and record the room temperature.

Photogpaphic results were poor. The film used for most of the photographs was the Kodak Tri x. The Kodak Recording film was also tried, but with little success. This was largely due to the poor oscillatory signals and the short exposure times.

INSTRUMENTATION

SECTION 3 INSTRUMENTATION

The usefulness of a shock tube is often determined by the extent of the instrumention. The conditions encountered are often extreme and there are often several variables that are changing simultaneously. As a result several techniques have been developed for special applications. There are basically two types of measurement; one where the sensing elements are situated at the wall and the other which allows probing into the flow. Only wall type elements were used here and this very much limited analysis and flow visualization.

3-1 GENERAL REQUIREMENTS

The flows involved in shock tube work are largely of a high speed transient nature and thus require quick response instrumentation. In addition to this the need for adequate sensitivity, range and accuracy only make instrumentation more difficult.

The general requirements for flow history measuring elements may be listed as follows:

1) Good Frequency Response

This is probably the most essential aspect as it is necessary for the element to be sensitive to extremely high frequencies and yet at the same time be able to monitor relatively low flow change frequencies. For shock front measurement it is often desirable to have a response time of only a few microseconds.

In addition the element should have a natural frequency well above any of the frequencies to be measured and also sufficient damping to avoid "ringing" of the element. This includes disturbances that may be transmitted to the element by the shock tube wall.

2) Sensitivity and Range

The need for a high sensitivity is obvious but often has to be compromised with other factors such as frequency, stability and reproducibility. A wide range coupled with the correct sensitivity is very desirable because of the large variation in signal size to be measured.

3) Accuracy

The dynamic accuracy of the measuring element is often a question of the elements response to interference effects. These interference effects may be electrical noise, temperature response, acceleration response, or pressure response, depending on what the element is meant to sense.

The accuracy of the recording should preferably be as good if not better than the element accuracy.

4) Size and Shape

The element size should be as small as sensitivity permits in order to obtain the best spatial resolution possible and to allow the frequency response (inertial effects). In terms of shape it should create the least disturbance possible in the flow and yet be able to seal the shock tube under pressure or vacuum.

5) Linearity

Although not essential it is usually desirable to have the output proportional to the input to facilitate calibration and record interpretation.

Sensitivity and accuracy are also more difficult to determine for a non-linear element response.

6) Calibration

Calibration of most elements is necessary and should if possible be fairly quick and accurate. Dynamic calibration is ideal, but is very seldom realised, except where the conditions are known or can be imdependently measured.

7) Stability and Reproducibility

For consistent results the element and associated circuitry should be thermally, mechanically and electrically stable. In addition, the calibration values should preferably not change with time.

8) Mechanical Strength

The element should be able to withstand the loads without failure.

Very seldom are all these requirements fulfilled by one type of element. Where elements are used only as shock dtectors and not for flow measurement most of these requirements fall away. However, a good frequency response is always needed.

3-2 ANALYSIS OF THE TYPES OF SYSTEMS USED

The only two methods employed for this project for shock measurement were by pressure transducers and by hot wire anemometers. For that reason they will both be dealt with here. The hot wires as used were only detecting elements but as this mode of instrumentation has good possibilities it will receive the same amount of attention as the pressure transducer.

PRESSURE TRANSDUCERS

Of particular interest is the piezoelectric transducer which utilizes the piezoelectric effect whereby a change in the stress (pressure) applied to a piezoactive crystal generates a proportionate electrical charge over certain crystal faces (2). The magnitude and character of the effect depends on the orientation of applied stress with respect to the crystallographic axes. Often the crystal transducer makes use of a number of adjacent discs to form a pile.

A pressure change of P would generate a charge Q such that

$$Q = nKAP$$

Where n = number of discs

K = piezoelectric modulus (constant)

A = area of one side of one disc

For most practical purposes the equivalent electrical circuit may be represented by a generator of emf $E = (nKAP/C_c)$ in series with total crystal element capacitance C_c and shunt leakage resistance. Rc. (2) This is all shown in Fig. 3-2-1 where the external load has shunt capacitance C_L and shunt resistance R_L.

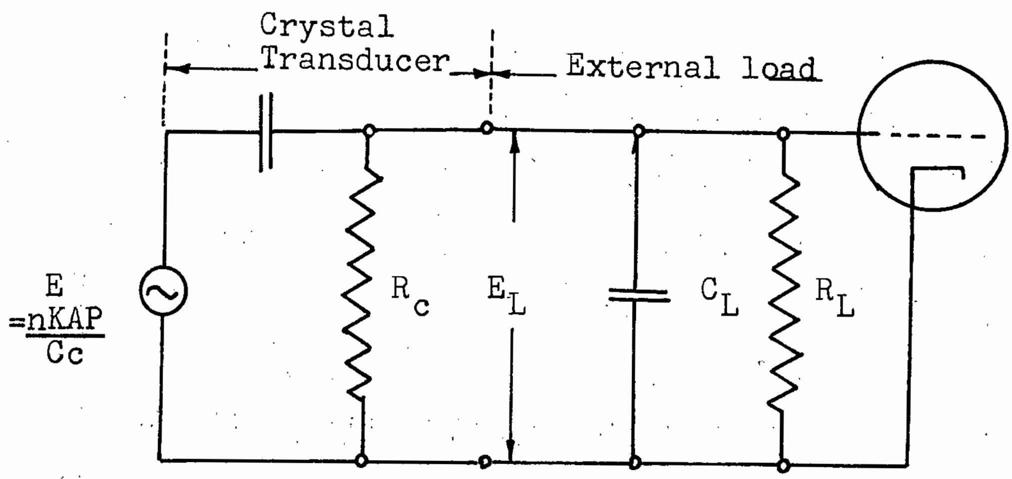


Fig. 3-2-1 Equivalent circuit of piezoelectric transducer (2)

If p is a sinusoidal pressure signal of amplitude P and frequency f then

$$E_L = \frac{jf\tau}{1+jf\tau} \cdot \frac{nKAP}{C_c+C_L}$$

where

$$\tau = R(C_c + C_L)$$

$$R = \frac{Rc\ RL}{Rc+RL}$$

$$j^2 = -1$$

Now for the very high frequency response i.e. $f\tau >> 1$

$$E_L \simeq \frac{nKAP}{C_c + C_L}$$

From this it is clear that at high frequencies requirement 5 is fulfilled (linearity) and the output signal is independent of frequency f.

The output is however effected by the load shunt capacitance C_L.

For the case where f is not unduly large, consider the output for a step change of P at time t = o

$$E_L = \frac{nKAP}{C_c+C_L} \qquad e^{-\frac{t}{\tau}}$$

This shows ~~the~~ that E_L drops off exponentially with time at a rate determined by τ . This then is one of the bad points of the piezolectric transducer in that it has a bad low frequency response. In order to minimize this effect, τ should be made as large as possible. The only way to make τ large is by making R large, as Co is naturally small and C_L is limited by the required sensitivity. This explains the need for a charge amplifier in conjunction with a piezo transducer.

The transducers either have natural crystals such as quartz or tourmaline or they have a barium titanate ceramic which is made piezoelectric by electric polarization. Although the ceramics have a considerably higher piezoelectric modulus they do also have a narrow stable temperature range. Quartz crystals were used for this project.

The moduli for quartz and tourmaline are relatively insensitive to temperature. The tourmaline and barium titanate produce a net charge when all crystal faces experience the same pressure change i.e., they are said to be hydrostatically sensitive, whereas the quartz is not. This means that for the quartz certain faces have to be screened from the pressure. It also means however that the quartz is not as senstitive to the pyroelectric effect i.e., charge generation due to thermally induced stresses.

The piezo transducer therefore fulfills several of the requirements satisfacorily; high frequency response, linearity is good over a large range, sensitive, stable and has good mechanicl strength. It does, however, have the poor low frequency response (which can be compensated for); it could also do to be smaller in size, and also the high output impedance can make it susceptible to electrical interference (2). The accuracy is generally good except it is hampered by ringing at its natural frequency and is to ~~be~~ a certain extent sensitive to the shock tube wall acceleration.

HOT WIRE ANEMOMETER

The hot wire has been extensively used to study unsteady flow phenomena. It ~~is~~ essentially consists of a very small, electrically heated wire and the electronic equipment that goes with it. The wire temperature (and hence the wire resistance) is a function of the heat transfer from the wire, which in turn depends on the fluid temperature, the cooling effect of the flow and on the heating current.

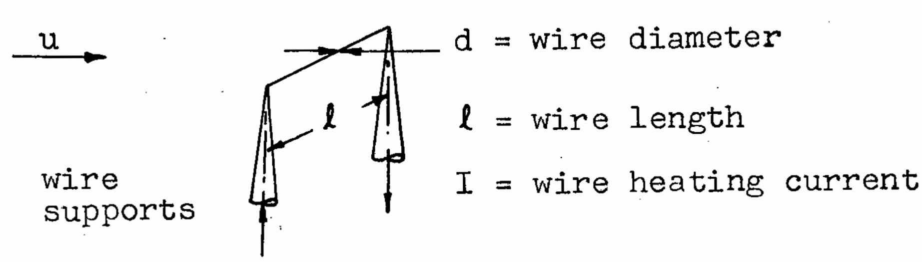


Fig. 3-2-2- Hot wire.

Basically there are two modes of operation. The constant-current mode keeps the heating current constant while the wire temperature (and resistance) and hence wire voltage - drop, fluctuate. The constant-temperature mode maintains the wire temperature (and resistance) at a constant value by varying the heating current according to the cooling effect on the wire. This is done by a very fast-acting, small offset feedback control system.

The constant-current operation is thus much simpler with regard to associated circuitry, however the thermal lag of the wire, due to finite heat capacity of the wire, results in a poorer frequency response when compared with the constant-temperature operation. This fact is clear if we take a look at the relationship betwen the time constants for the two operations; equation B-1-7.

$$M_T = \frac{Mc}{1+2gRw(Rw-RG)/R_G}$$

where M_T and Mc are the time constants for constant-temperature and constant-current operation respectively, and R_W, R_G refer to the wire resistance at wire and gas temperatures. The term g refers to the trans-conductance of the circuitry. From this it is obvious that $M_T < Mc$. The transconductance $g = \div \frac{i}{Ir}$ is however limited in size by the need for stability in the feedback system (feedback gain).

The time constant Mc can be improved by suitable electronic compensation for the thermal inertia term (8)

Constant-current operation was used for this project because of the simple circuitry. No compensation was made.

Consider the expression for the time constant from equation B-1-4

$$Mc = \frac{C_W (R_W - R_G)}{\delta I^2 Ro R_G}$$

Terms δ and Ro are fixed by the properties of the wire; I^2 is limited by wire burn-out temperature and by the variable to be monitored (see later); the heating ratio $\frac{Rw}{R_G}$ or the overheating ratio

$O_W = \frac{(Rw-R_G)}{R_G}$ are limited by the maximum allowable wire temperature. Thus for Mc to be as small as possible the total wire heat capacity Cw must be as small as possible. This implies that ld^2 must be small for wire length l and diameter d. Since l needs to be as long as possible to obtain a high sensitivity, d must be correspondingly very small. Typical diameters are of a couple of microns and lengths of 2 to 3 mm or $\frac{1}{8}$ inch.

The discussion from here on is primarily for constant-current operation.

The change in wire resistance is related to two effects. One is the change in recovery temperature and the other is the change in mass flow (velocity and density). The ratio of the two sensitivities is dependent principally on the operating temperature of the wire. Again consider the overheating ratio. When the temperature is low, Ow is small, the wire becomes a resistance thermometer. This is known as small current operation. When the wire is well heated, Ow large (>0.5) the sensitivity to mass flow fluctuation is predominant although the temperature sensitivity remains. Because for an increase in mass flow there is a drop in wire voltage this large current operation creates a negative signal with respect to the small current operation.

In shock tube both temperature changes and mass flow changes occur simultaneously. Consider as a shock wave passes over the wire with a contact surface not far behind. The shock wave causes two opposing effects on the wire because the temperature increases across the shock but the mass flow also increases. With small current operation, Ow small, the first effect predominates and the hot-wire essentially measures the recovery temperature. With large current operation, Ow above 0.5, the second effect is larger and the hot-wire is essentially a mass flow rate recorder. This then gives a method for determining both the mass flow rate and the recovery temperature variation by doing two identical runs on the shock tube with different settings of the overheating ratio in each. The recovery temperature is equal to the flow stagnation temperature to within a few per cent (2).
The contact surface produces two effects of the same sign being a cold front and an increase in mass flow.

Reference (14) shows how Ow can be suitably adjusted for the particular application.

The frequency response of the simple form of constant-current set-up is not as good as that of the piezo transducer but this can be improved with a compensating circuit (14). The big problems associated with the hot-wire anemometer are mainly due to its non-linearity. It is difficult to calibrate dynamically under its working conditions. A particular disadvantage for shock-tube studies is the extreme fragility of the wire, which makes it a vulnerable target for particles in the flow. Being small it can be mounted near the tube wall without causing much flow disturbance, however, it is largely affected by the growth of the boundary layer. For pressure measurement by piezotransducers the boundary layer has a small effect on the true pressure measurement as the static pressure is assumed to remain constant through the boundary layer. In the case of the hot wire it is sensitive to velocity and temperature, both of which vary through the boundary layer. For shock wave measurement itself this effect is not important as the boundary layer only develops after the passage of the shock. For long time histories though, it can be important. The hot-wires are not as sensitive to the shock tube wall acceleration as the piezo transducer.

3-3 DESCRIPTION OF THE SYSTEMS USED

Piezoelectric Transducers

Three Kistler type 701A piezo transducers were used in conjunction with three Kistler Model 568 Universal Electrostatic Charge Amplifiers. The transducers have a pressure range of 3500 psi and a resolution of 0.05 psi. The sensitivity was 5.5 pC/lb $/in^2$ and the natural frequency 6.5 Kc. Actual recording of traces was done on two Type 564 Tektronix Storage Oscilloscopes.

The frequency response for the higher frequencies was found to be excellent, the transducer having a very good rise time. However, this also made the unit prone to detecting its own 'ringing' frequency and other short period oscillations. Examples of this are shown in photograph 3-3-1. There seems to be a beat frequency response between the 'ringing' or natural frequency of the transducer (6.5 Kc.) and another frequency close to it. The other frequency is thought to have occured either from vibrations in the shock tube wall or by the natural frequency of the system formed by the cavity in the wall.

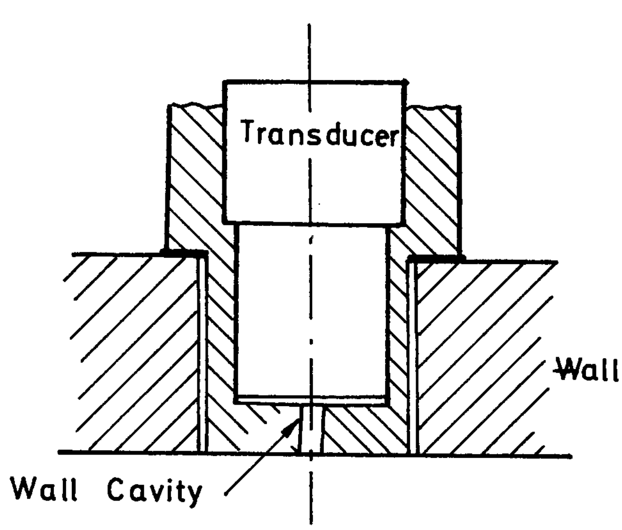
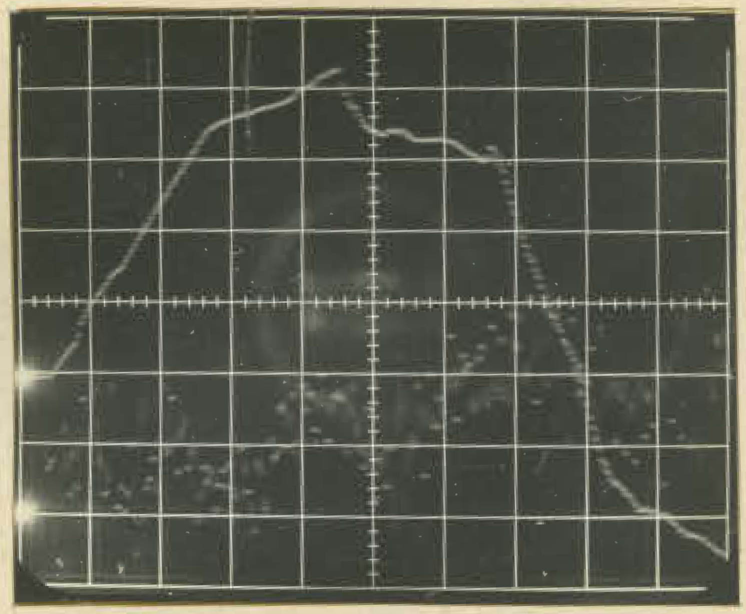
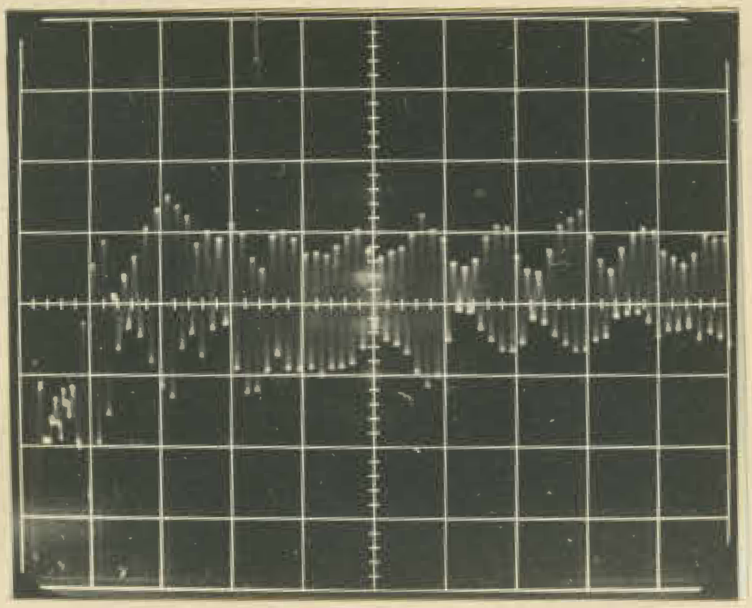


Figure 3-3-1 Showing Wall Cavity



Photograph 3-3-3 Hot wire signal with a time base of 0.1 mS per division and gain of 0.5 mV per division



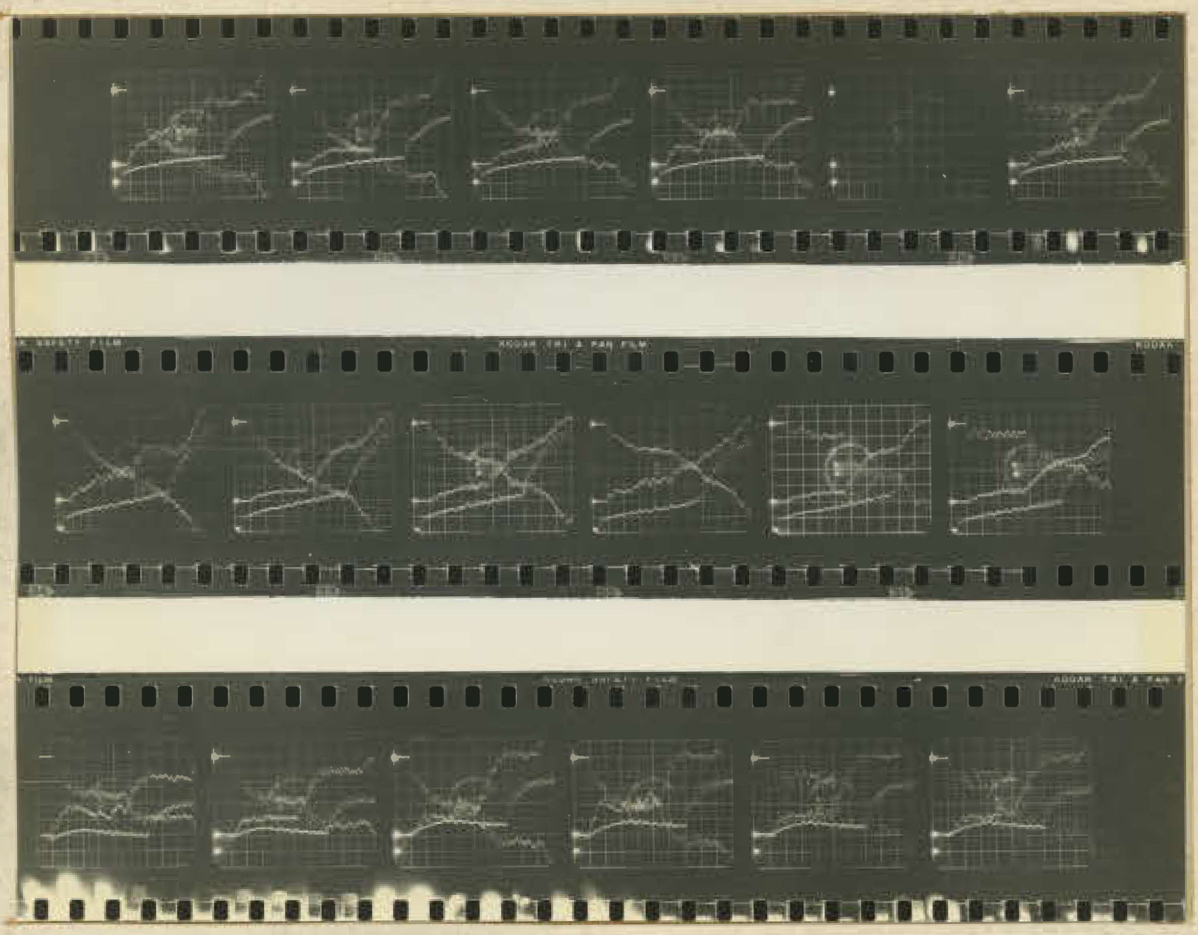
Photograph 3-3-1 Noise on piezo transducer signal; time base 0.1 mS per division gain 2 psi per division

Attempts to improve matters by changing the length over diameter ratio for the hole passing through the wall were not particularly successful. By increasing the ratio a damping effect is introduced. It was found that for a ratio large enough to maintain the small oscillations within a tolerable limit, the frequency response to the primary signal was unacceptable. See trace A in photograph 3-3-2.

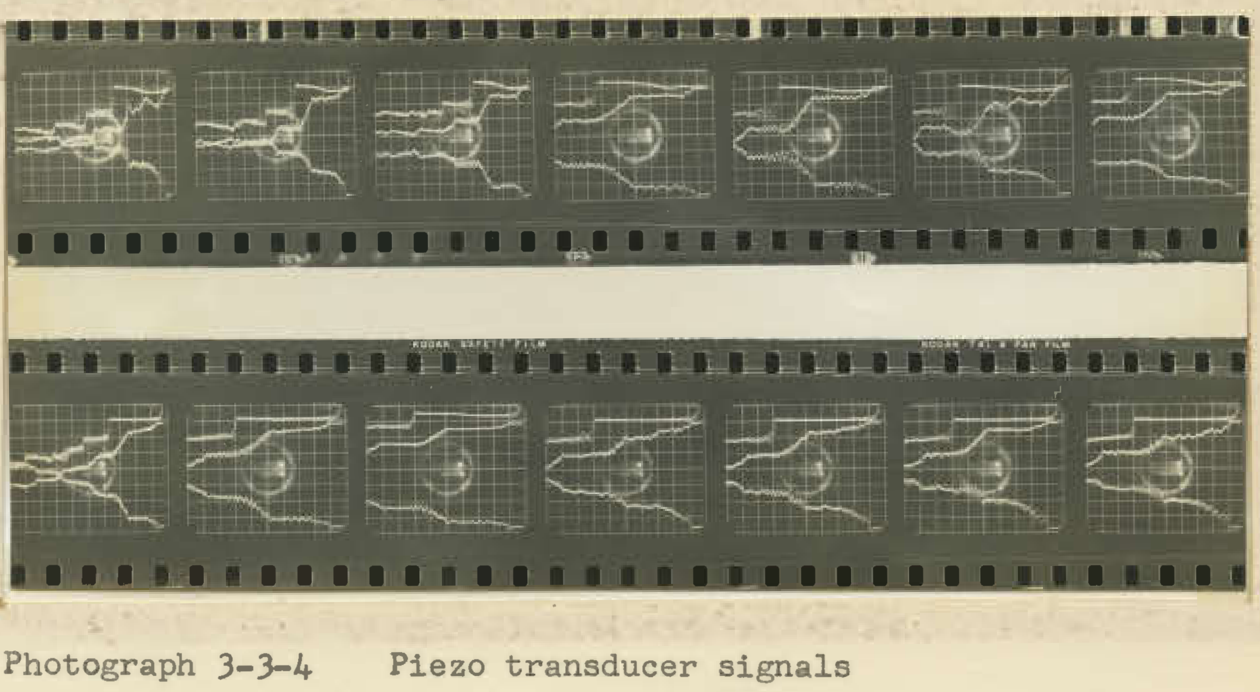
It is thought that a damping system incorporated in the mounting itself might improve the signal. However, it is also true that only the lower end of the transducers pressure range has been utilized for this project. A much improved 'signal to noise' ratio could be expected if the transducer was used nearer the centre of its pressure range. From this it was concluded that the tests should be done with much higher driver gas pressures, so as to increase the signal size, and hence put the transducers in a fair operating range.

Hot Wire Anemometer

The two hot-wires were used, in this project, only as shock detectors. Constant-current operation was used. The circuit diagram is given in figure 3-3-2. The power was supplied by a 12 volt storage battery, with a large variable resistance in series with each hot wire so as to create a large current-source impedance and keep the current constant at 12 mA. per hot wire.



Photograph 3-3-2 Piezo transducer signals damped by wall hole
time base 0.5 mS per division
gain 10 psi per division



Photograph 3-3-4 Piezo transducer signals

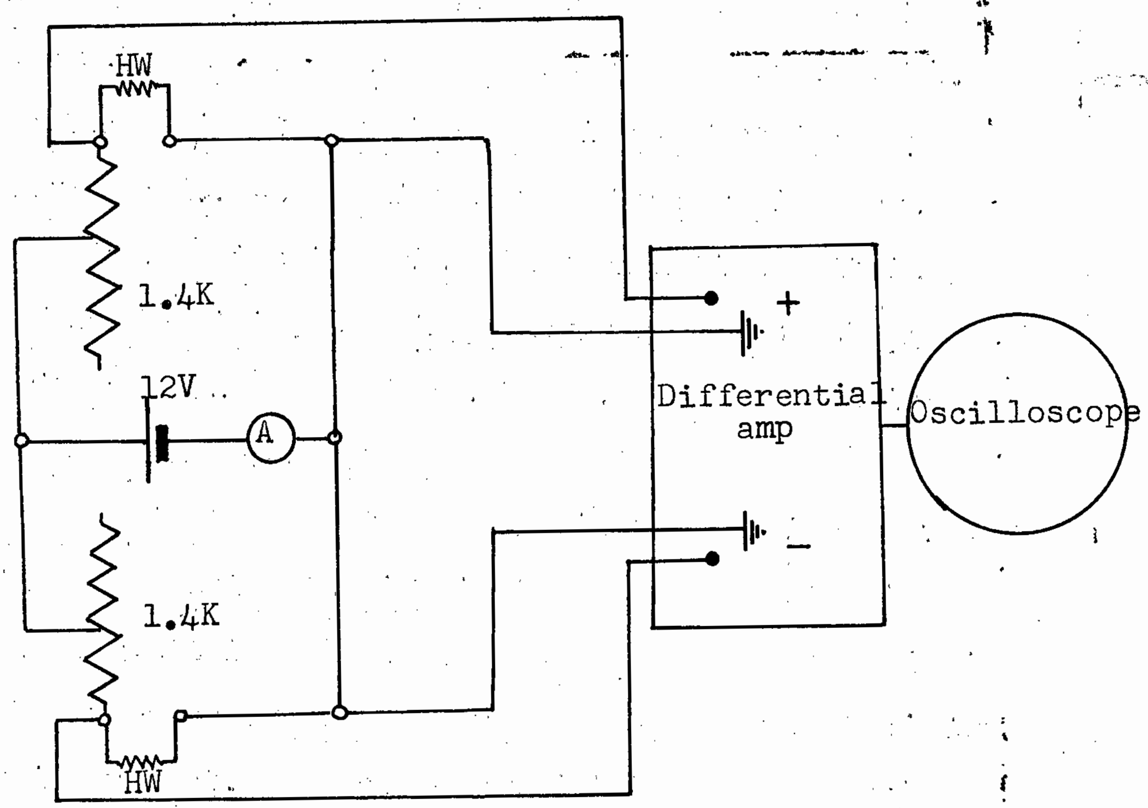
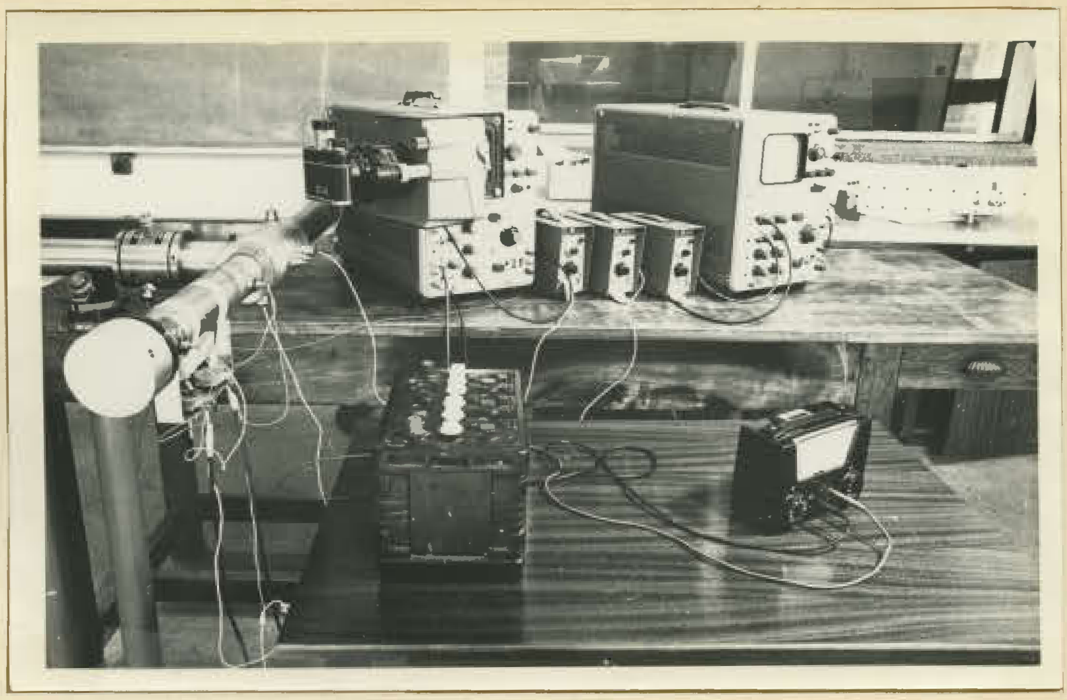


Fig. 3-3-2 Circuit diagram for constant-current operation of the hot wires

Signals from the hot wires were fed into a Tektronix type 3A3 differential amplifier and then displayed on the storage Oscilloscope. Examples of the hot wire traces are given in photograph 3-3-3.

The time constant for these particular settings and wires was estimated from equation B-1-4 to be of the order of 0.3 mS. This seems to be somewhere near the actual rise time recorded. The signals were much stronger and sharper for the higher pressure ratios.

Because of the low overheating ratio very little trouble with wire 'burn out' was encountered. It was found, however, that at 40 mA heating current the wire was very susceptible to this trouble.



Photograph 3-3-5   Electronic equipment used

Photograph 3-3-6   Micromanipulator and welder

SHOCK DIFFRACTION ANALYSIS

WHITHAM'S SHOCK DIFFRACTION ANALYSIS

The theory and terminology described below was presented by G.B. Whitham in two papers in the Journal of Fluid Mechanics (3)(4)

In the approximate theory of Whitham the shock positions are described by curves of constant α, and the orthogonal trajectories to these shock positions are described by curves of constant β. Curves of constant β are termed "rays". These two families of curves then define an orthogonal set of co-ordinates (α, β) such that $\alpha = a_1 t$, where a_1 is the speed of sound in the uniform gas ahead of the shock.

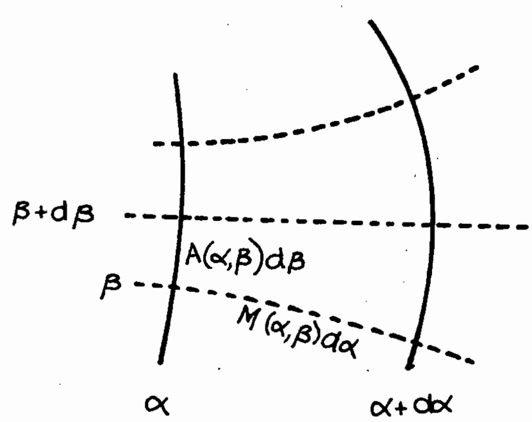


Fig. 4-1 Two successive positions of a shock front with the rays shown dotted.

Hence the distance along a ray between shock positions α and $\alpha + d\alpha$ is $M(\alpha, \beta)\, d\alpha$ where M is the Mach number of the shock front at (α, β). Also if the distance along a shock front between rays β and $\beta + d\beta$ is $A(\alpha, \beta)\, d\beta$ then

$$\frac{\partial}{\partial \alpha}\left(\frac{1}{M} \cdot \frac{\partial A}{\partial \alpha}\right) + \frac{\partial}{\partial \beta}\left(\frac{1}{A} \cdot \frac{\partial M}{\partial \beta}\right) = 0$$

The second relation between A and M should then be obtained by solution of the flow behind the shock, subject to the Rankine-Hugonoit shock equations and boundary conditions. However, as a simple approximation Whitham suggested that any two successive rays could be treated as solid walls and shock propagation considered in the 'channel' formed. This is exactly true just behind the shock where the particle path is the same as a ray, however the particle paths and rays will in general diverge. For any one such channel the shock Mach number is a function of the area only and then

$$A = A(M)$$

is the second functional relation between A and M. The actual relation is given in the form suggested by Chester and was found by considering a small change in channel area dA. He obtained

$$\frac{dA}{A} = -\frac{2MdM}{(M^2-1)K(M)}$$

Where K(M) is a slowly varying function, decreasing from 0.5 at M=1 to 0.3941 as $M \to \infty$ for $\gamma = 1.4$ - The function is

$$\left.\begin{aligned} K(M) &= 2\left[\left(1+\frac{2}{\gamma+1}\,\frac{1-\mu^2}{\mu}\right)\left(2\mu+1+M^{-2}\right)\right]^{-1} \\ \text{where } \mu^2 &= \frac{(\gamma-1)M^2+2}{2\gamma M^2-(\gamma-1)} \end{aligned}\right\} \quad 4-1$$

R.F. Chisnell (9) suggested the integrated form for the area as:

$$A = kf(M) \qquad f(M) = \exp\left\{ - \int \frac{2M\, dM}{(M^2-1)K(M)} \right\} \qquad 4\text{-}2$$

where k is an arbitrary constant which is different for each channel.

From this it is shown (3) that there is a close analogy between the waves travelling on the shock and the wave structure described in one-dimensional gas-dynamics (1). An increase in M increases the propagation speed (rate of change of β with respect to α) and hence waves carrying an increase in M will steepen as a compression wave in gas dynamics to form a shock-shock, which has all the same properties as a shock but is termed differently to avoid confusion; similarly waves travelling on a shock and carrying a decrease in M will spead out like expansion waves in gas dynamics

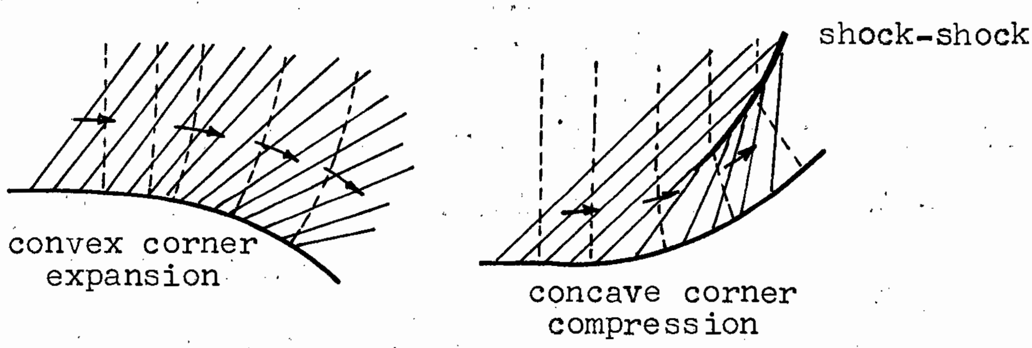


Fig. 4-2 Motion of a shock front (broken lines) along the corners indicated. The full lines are characteristics

As pointed out by Witham this method is developed by avoiding a detailed analysis on the flow behind the shock and it is on this approximation that the applicability of the method depends.

Consider the case of a plane shock moving along a wall of given shape and let the shape be given in terms of the inclination and the distance s along the wall. If the initial shock has a Mach number M_1 and the wall is straight up to a certain point then the wall will be a ray, $\beta = c$ because the shock is always normal to the wall. For convenience take the wall as the ray $\beta = 0$

For the special case of a convex corner θ jumps from zero to minus θ_w and the solution is a centred simple wave, with the characteristics forming a fan in the (α, β) plane behind the shock. (see equation C-1-8)

Here θ is given in terms of s but can be put in terms of α by:

$$\alpha = \int \frac{ds}{Mw}$$

The wall shock Mach number Mw can be determined from θ_w in the case of the simple wave by

$$\theta_w = \int_{M_1}^{Mw} \frac{dM}{Ac} \qquad 4-3$$

(see equation C-1-6)

The equation of each of the characteristics is given by $\beta = \alpha c$ where c is a function of M. Hence the characteristics (along which M is constant) can be drawn as in Fig. 4-3

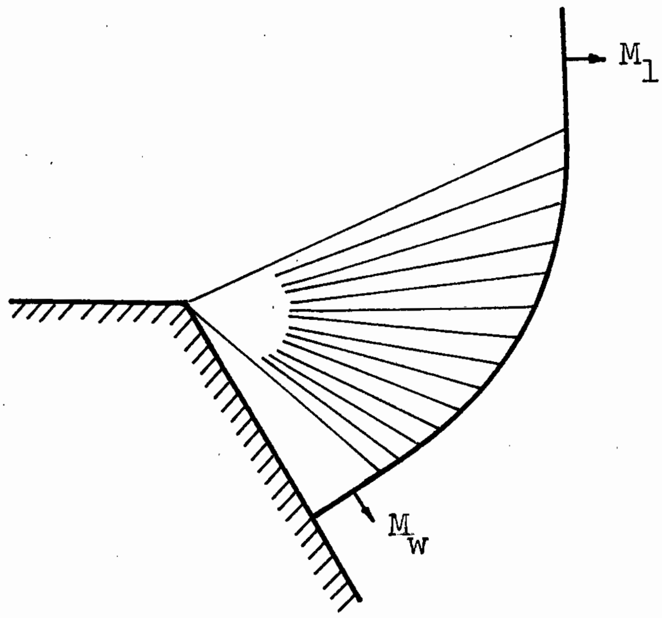


Fig. 4-3 Diffraction of a shock around a convex corner

Take β as the value of the distance y from the wall in the initial undisturbed field so that Ao = 1

For the case of strong shocks Witham solved the equations to get (see equation C-1-8)

$$K(M) \simeq 0.3941 \qquad Ac \simeq n^{-\frac{1}{2}}M$$

$$\frac{A}{Ao} \simeq \left(\frac{Mo}{M}\right)^{n} \qquad c \simeq \frac{n^{-\frac{1}{2}}M^{n+1}}{Ao\ Mo^{n}}$$

$$\int_{M_1}^{M} \frac{dM}{Ac} \simeq n^{\frac{1}{2}} \mathrm{Log}\ \frac{M}{Mo}$$

for $M \to \infty$ 4-4

Where $n = \left(\frac{2}{K_\infty}\right) \doteq 5.0743$

By integration of equation 4-3 using the strong shock approximation

$$Mw = M_1 \quad \exp\left(\theta_w / \sqrt{n}\right) \qquad 4\text{-}5$$

This equation was solved for a range of values of M_1 and $a\theta_w$ of minus 90 degrees, but the results for Mach numbers below 4 were poor and not applicable.

In order to get the shock shape the strong shock again is considered (3). The x and y co-ordinates are given by

$$\frac{x}{M_1\alpha} = \frac{(n+1)^{\frac{1}{2}}}{n^{\frac{1}{2}}} \; e^{\theta/\sqrt{n}} \; \sin(\lambda - \theta)$$

$$\frac{y}{M_1\alpha} = \frac{(n+1)^{\frac{1}{2}}}{n^{\frac{1}{2}}} \; e^{\theta/\sqrt{n}} \; \operatorname{Cos}(\lambda - \theta)$$

where $\tan\lambda = \sqrt{n}$

This has also been numerically solved in programme G-1 and the results plotted in Fig. 4-4

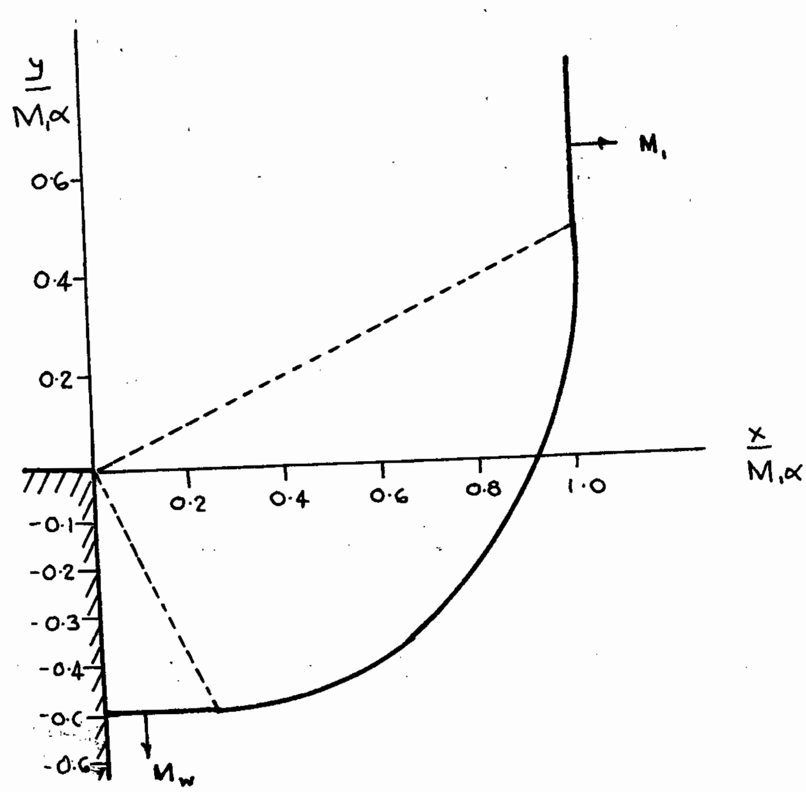


Fig. 4-4 Strong shock diffraction about a 90 degree corner

The plot shown is in the dimensionless form and implies that the shape shown expands uniformly with time and that a change in M_1 means only a change of scale. This pseudo-stationary behaviour has been confirmed by Skewes (5) and analysed by Jones, ~~Moira~~, Martin and Thornhill (11)

In reference (11) Jones, ~~Moira~~, Martin and Thornhill consider the problem of unsteady compressible flow which is pseudo-stationary in nature and show that this flow can be mapped from the (x,y) plane to an (ξ,η) plane where the flow can be considered as steady compressible flow with a non-conservative field of external forces and a field of sinks.

A brief summary of ref. (11) is given here with the mathematical detail in section C.

Figures 4 -5 (a) and (b) show qualitatively the steady flow conditions corresponding to transformed equations C-2-7 for a convex corner. The only difference between the two is that 4-5 (a) is for subsonic flow behind the shock GB in the (x,y) plane $(Ms<2.068)$ and 4-5 (b) is for supersonic flow behind shock GB in the (x,y) plane $(Ms>2.068)$

The original shock front is undisturbed down to a point B and then has a diffracted portion BA. To the right of AG the flow in the (ξ,η) plane is supersonic throughout and has a velocity at any point which is directed towards the corner O. This then forms part of a sink centre O. To the left of CBG or ODBG there is a flow region which is unaware of the existence of the corner at O. This flow in the (ξ,η) plane has a velocity at any point (ξ,η) which is directed towards the point (P $(U_1, 0)$.

P corresponds to the centre for the reflected Mach wave CB or DB. This forms the second sink centre P.

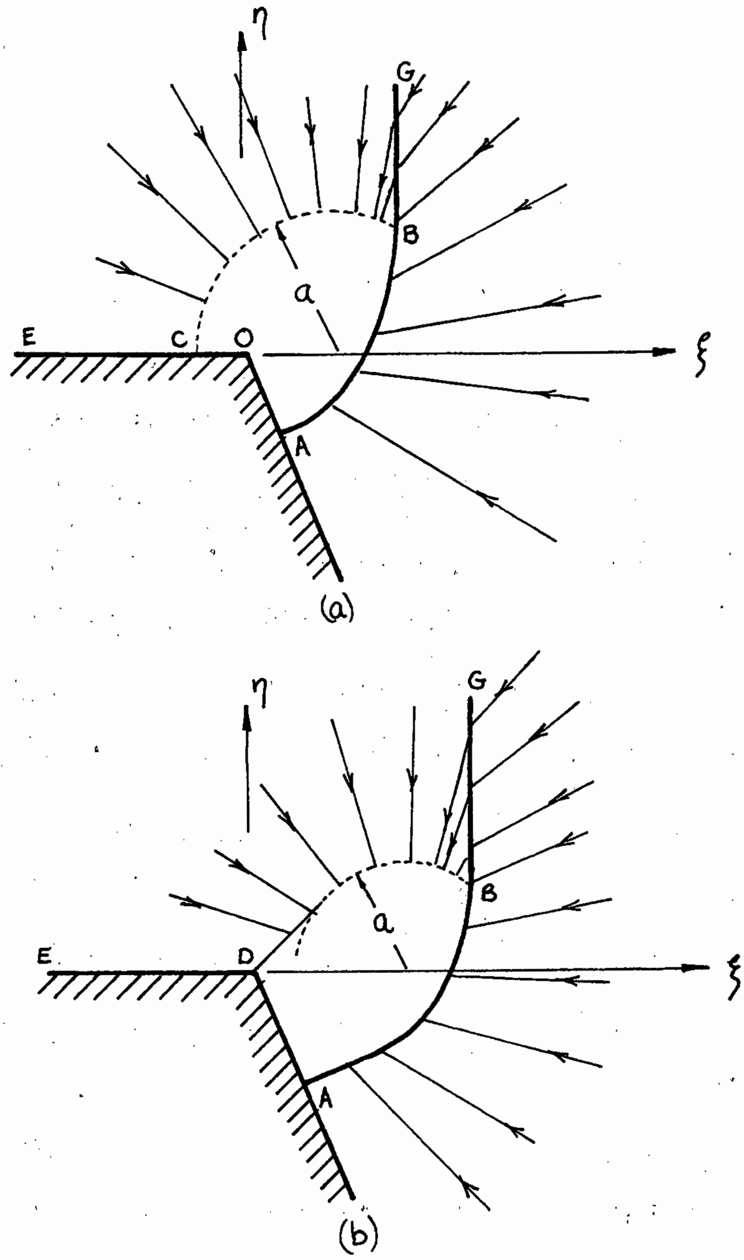


Fig. 4-5 Diagrams of the shock diffraction at a convex corner plotted in the (ξ, η) plane (11)
(a) Ms<2.068 (b) Ms>2.068

The region within boundary ODBA is then the only region left unsolved. For the supersonic case Jones, Moira, Martin and Thornhill suggest that for part of this flow region there is a solution which satisfies the equations C-2-7, the boundary condition along the characteristic OD, and the boundary condition appropriate to the wall OA. This solution takes the form of a Prandtl-Meyer type flow around the comer

EOA with a velocity vector XO superimposed at every point x in the pseudo-stationary plane (ξ,η). In the physical (x,y) plane this corresponds to a Prandtl-Meyer fan which starts at OD and ends on another radial line OM if the corner angle is large enough.

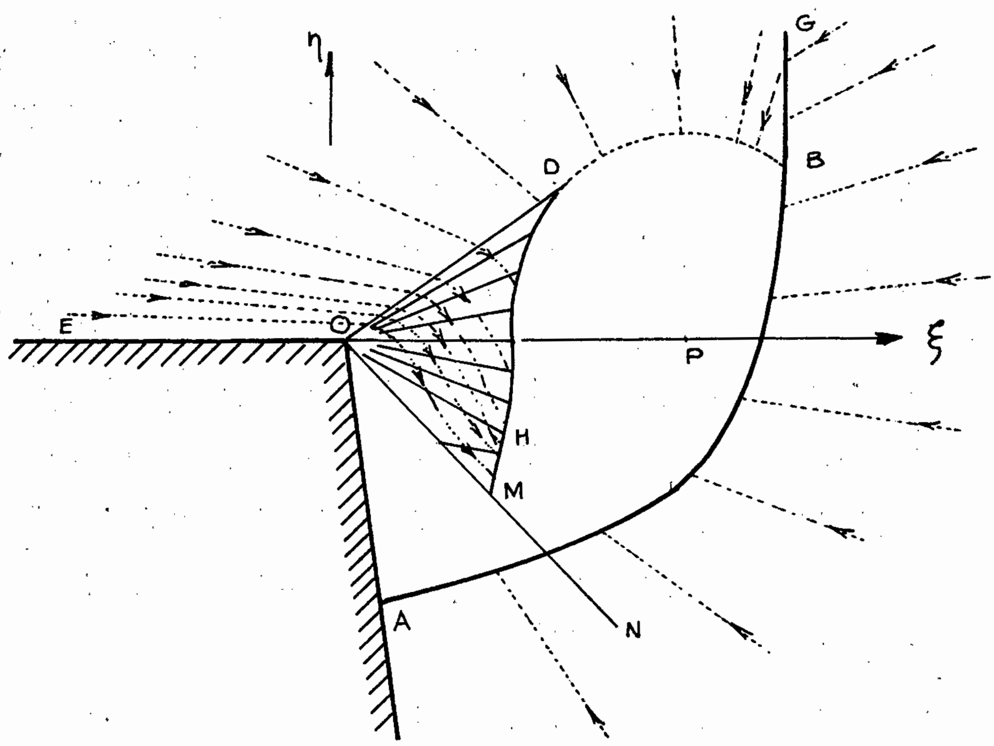


Fig. 4·6 The extent of the Prandtl-Meyer fan (11)

The limit to the extent of this region in which the flow is determined is got by considering the characteristics in the pseudo-stationary plane (ξ,η) (11) The suggestion is that the flow in the region OHm is parallel to some streamline OM and that some other flow exists between OM and the wall OF such that there is no pressure jump at the slipstream.

RESULTS AND CONCLUSIONS

5-1 PREDICTED RESULTS

The actual Tee-junctions as used are described in detail in section 2. Because of the complexity of the three-dimensional problem involved, the predictions here are going to be restricted to the two-dimensional case and a note on the expected qualitative effect of the third-dimension given at the end. Even on the assumption of a two-dimensional field the resulting shock and rarefaction interaction at the junction itself are extremely involved and complex and a very limited analysis can be done. No optical or flow visualization techniques were used so that confirmation or disagreement are only achieved by indirect measurement.

The discussion will be mainly for a tee with the leg and arms of equal diameter and then extended at the end to estimate the effect of the smaller width in the rectangular case.

The theories developed in section 4 for the diffraction of an unsteady shock through an angle of 90 degrees should be directly applicable to the Tee-junction except where the two diffractions so formed interact.

Whitham's approximate theory completely ignores the effect of the perturbed region behind the shock front. The first point of disagreement (15) between Whitham's prediction and experiment is to do with the starting point of initial shock curvature. This can be fairly easily analysed (15). Consider Figure 5-1-1 As shown it is for the case where the flow behind the initial shock is subsonic, but the same reasoning applies to the supersonic case. If the initial shock has a velocity of U_s, and the particle velocity behind the initial shock is U_2, then the centre of the reflected sound wave would have moved a distance of U_2t, whereas the shock front would have moved a distance U_st, in time t as shown

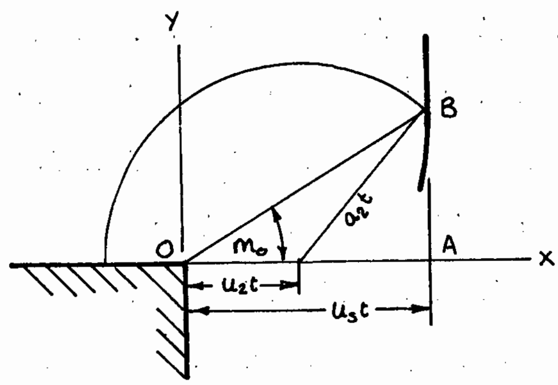


Fig. 5-1-1 The starting point of initial shock curvature.

The reflected wave front itself would have moved a distance a_2t from the centre of the wave, where a_2 is the speed of sound in the gas immediately behind the initial shock.

From Figure 5-1-1

$$\tan m_o = \frac{AB}{OA} = \frac{\left(a_2^{\,2} - (U_s - U_2)^2\right)^{\frac{1}{2}}}{U_s}$$

$$= \frac{a_2}{U_s}\left[1 - \frac{(U_s - U_2)^2}{(a_2)^2}\right]^{\frac{1}{2}}$$

Substituting for $Ms = \frac{Us}{a_1}$ and $M_2 = \frac{U_2}{a_2}$ and using the normal shock relations (equations A-3-5) gives:

$$\tan^2 m_o = \frac{(\gamma - 1)(M_s^{\,2} - 1)\left[M_s^{\,2} + 2/(\gamma - 1)\right]}{(\gamma + 1)\, M_s^{\,4}}$$

This variation of m_o with M_s was plotted by Skewes and found to be in good agreement with experimental data. Whitham's predictions were quite substantially different from the experimental data at lower Mach numbers but improved above Mach 3.0.

Skewes (10) considered the problem of the perturbed region behind the initial shock. The features of the diffraction pattern which he obtained are given in figure 5-1-2. The definitions of the different terms and some of conclusions drawn in reference (10) are given here

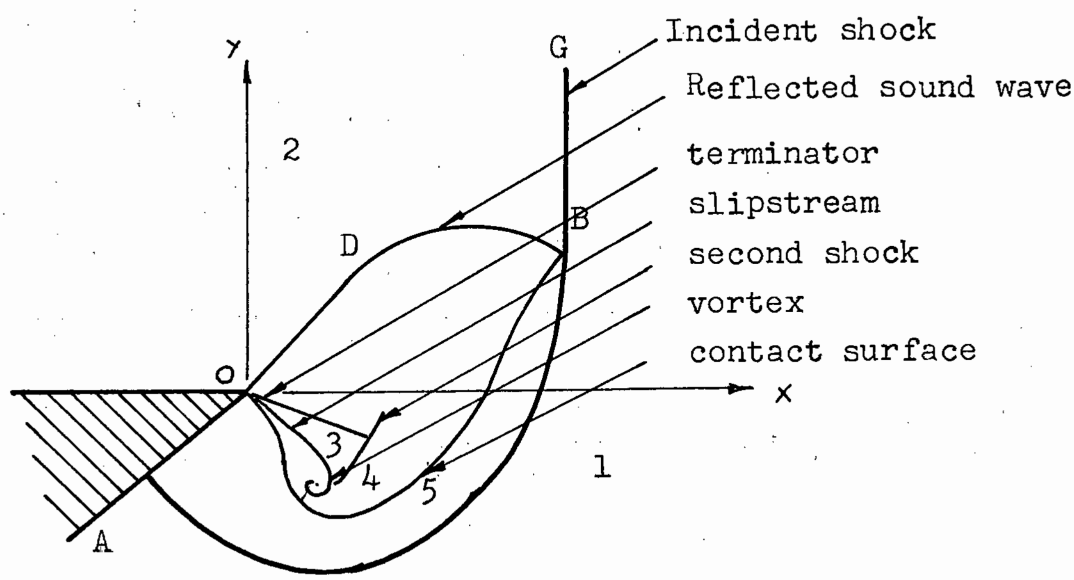


Figure 5-1-2 Features of the diffraction pattern.

The region concerned lies within the ~~two~~ curved part of the initial shock and the reflected sound wave i.e., ODBA. The pattern was found to be pseudo-stationary.

<u>The Slipstream</u> The slipstream exists because of the inability of the flow to negotiate the corner, giving rise to flow separation at the corner.

The slipstream corresponds to the slipstream OM given by reference (11) in figure 4-6
The slipstream is essentially straight on a radial line through the corner O except where it interacts with the vortex. For large corner angle (75 degrees and over) it has been found that the angle at which the slipstream occurs is independent of the corner angles and appears to reach some limiting position. In the model suggested by reference (11) (Section 4) there is an expansion of the flow through a Prandtl-Meyer fan, centred at the corner, from the pressure just behind the incident shock to the pressure just in front of the shock ie., from p_2 to p_1. The pressure along the slipstream is then p_1. Above the slipstream, region 3, there is uniform flow, parallel to the slipstream. This theory also implies that the pressure between the slipstream and the wall is constant and equal to p_1, which was found not to be the case, by reference (10).

The Terminator The terminator OH corresponds to the last characteristic of the Prandtl-Meyer expansion fan. The terminator angle may be directly calculated from the simple wave theory. However, after separation has occured, the slipstream forms and the flow is parallel to the slipstream. Thus the calculation of the terminator angle should be based on the experimentally found slipstream angle and not on the corner angle. Skewe did this and got good agreement.

The terminator can only exist if the gas flow is supersonic. This then at first appears to rule out the cases where the initial shock Mach number is below

2.068. Skewes established that this was not the case and recorded a terminator at an initial shock Mach number of 1.45. This observation is explained by the fact that the expansion process will travel back up the tube for $M_1 < 2.068$ and this expansion will accelerate the gas towards the corner. Skewes showed that by extrapolating his experimental curve for the terminator to give an angle of 90° (ie, sonic conditions) leads to an incident shock Mach number of approximately 1.45. From shock tables $M_1 = 1.45$ corresponds to a particle Mach number behind the shock of 0.56. From the equations for isentropic flow this implies that the pressure is expanded to $0.65p_2$ at the corner. Because all the readings for this project were done with an incident shock Mach number greater than 1.5, the above is directly applicable.

<u>The Second Shock</u> The second shock starts at the vortex and corresponds in position to the limit of the Prantl-Meyer expansion fan. The theory applicable to the second shock does not agree very well with the experimental values for large corner angles. The same condition about supersonic flow is found here as for the terminator.

As the second shock faces upstream ie. into the flow, the pressure on the downstream side is higher. Since the pressure along the slipstream was found to be p_1, the pressure on the downstream side of the second shock must be above p_1.

Skewes found that the formation of the second shock, for large corner angles, was very similar to the formation of a normal shock wave from a number of wavelets which converge. The second shock was also found to grow in a pseudo-stationary manner for a given M_1.

The Contact Surface This contact surface is formed between the gas flowing behind the incident shock and the gas accelerated by the diffracted shock. It, therefore, originates at the point of intersection of the reflected sound wave and the incident shock. The contact surface represents a sudden change in entropy, temperature and density. Theory predicts that the contact surface should terminate at the wall such that it is perpendicular to the wall. Skewes found that for large corner angles this was not so and that the contact surface curved round the vortex and then back towards the corner O. (Figure 5-1-2)

Because the contact surface moves at the velocity of the gas just behind the incident shock, it is a good indication of the actual gas movement through the corner. The process between the wall shock and the corner is thus originally one of compression (across the shock) followed by one of expansion, such that the gas immediately below the corner, between the slipstream and the wall, is stationary.

The tee-junction can be thought of essentially being made up of two adjacent right angle corners, with a third boundary perpendicular to the incident flow. The predictions for a right angle corner can therefore be extended to this case, up until such time as the incident shock meets the third boundary. The expected shock wave shapes are given in figures 5-1-3 and 5-1-4 for the two different cases i.e., subsonic flow behind the incident shock $M_1 = 1.5$;

and supersonic flow behind the incident shock

$M_1 = 3.0$;

<u>Subsonic Flow behind the Incident Shock</u> (figure 5-1-3)

Because the flow is subsonic the reflected sound waves will propagate back up the leg of the tube. The shock front will be curved from the point of interaction with the reflected sound wave right up to the wall. As explained before, the expansion in the leg will then accelerate the flow, such that it is supersonic at the entrance to the tee. This will cause a terminator and second shock to develop, as shown in the fourth diagram.

<u>Supersonic Flow behind the Incident Shock</u> (Fig.5-1-4)

The pattern is not much different. The reflected sound wave is effectively swept away from the corner. The terminator and second-shock will exist as before.

Both of these figures were drawn for values of the slipstream and terminator angles got from the results of Skews. The contact surface should be curved around the vortex centre, as described earlier.

After reflection of the incident shock from the third boundary there is an extremely complicated interaction of shocks, rarefaction waves, contact surfaces and slipstreams. However, the following is expected to occur.

The reflected shock will <u>initially</u> have a shape which is very much the mirror image of the incident shock just before reflection. The two ends of the reflected shock will be at the points where the incident shock is interacting with the third boundary. It will be expanding outwards very much like the incident shock did on reaching the tee.

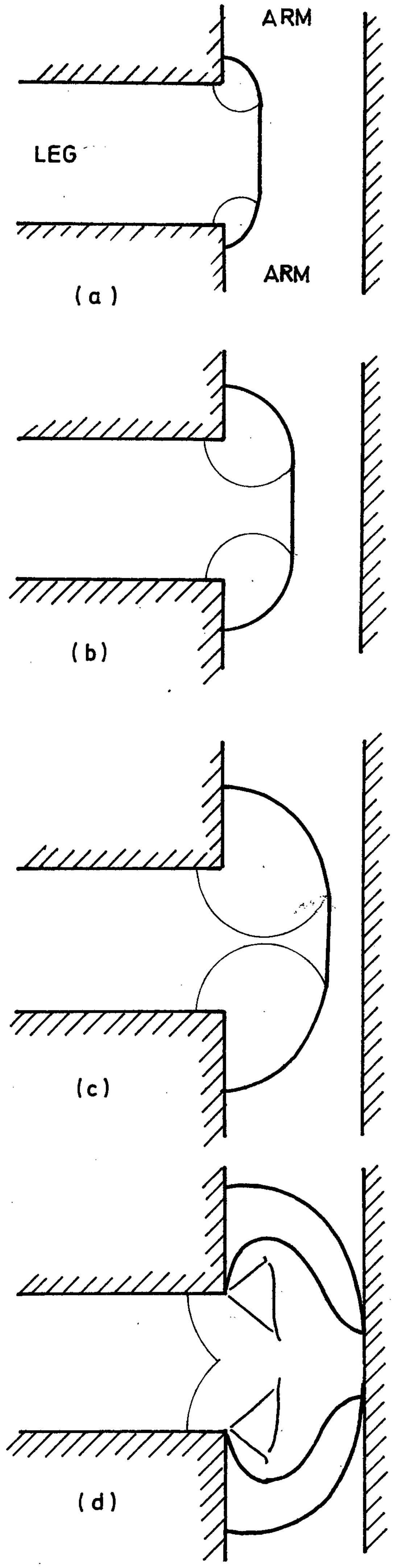


FIG. 5-1-3 Diffraction patterns for $M_1 = 1.5$

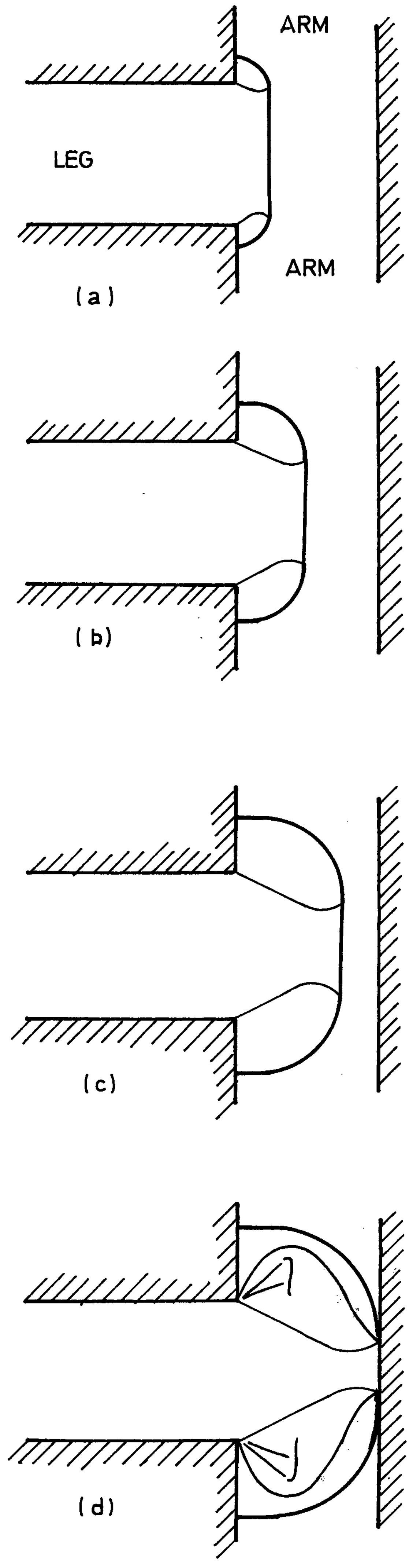


FIG. 5-1-4 Diffraction patterns for $M_1 = 3{\cdot}0$

Very soon after reflection, part of the reflected shock will collide with the oncoming contact surface. It then depends on the relative strength of the shock and contact surface as to what develops on collision. Whatever the case, there will always be a shock transmitted in the direction of the approaching shock. See figure 5-1-5

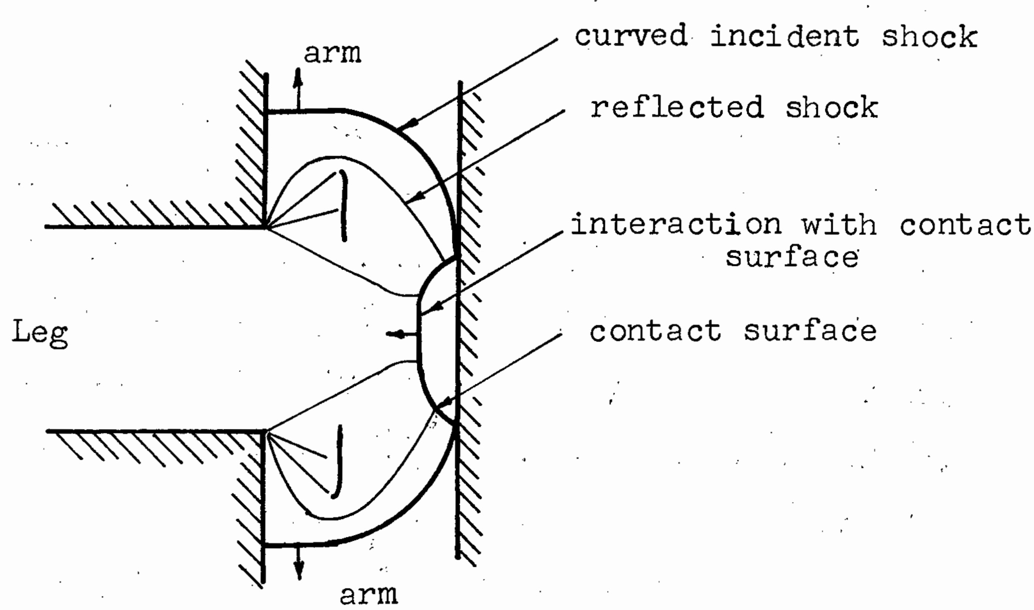


Fig. 5-1-5 Interaction of the reflected shock with the contact surface

The centre portion of the reflected shock heads back for the leg of the tee, while the two outer portions head outwards towards the arms of the tee.

It is expected that after a certain time, the reflected shock will reach the position of the second shocks. Because the reflected and second shocks are essentially facing in the same direction ie. both have the higher pressure on the downstream side, they will reinforce. The centre portion of the reflected shock will bridge the gap between the second shocks. For convenience of description, this combination of the reflected shock and the two second shocks, will be termed the third shock. See Figure 5-1-6. No mathematical estimates of the third shock strength are attempted though, as it has now already involved a reflection, a collision with a contact surface, movement through a pressure gradiant, and interaction with the second shocks.

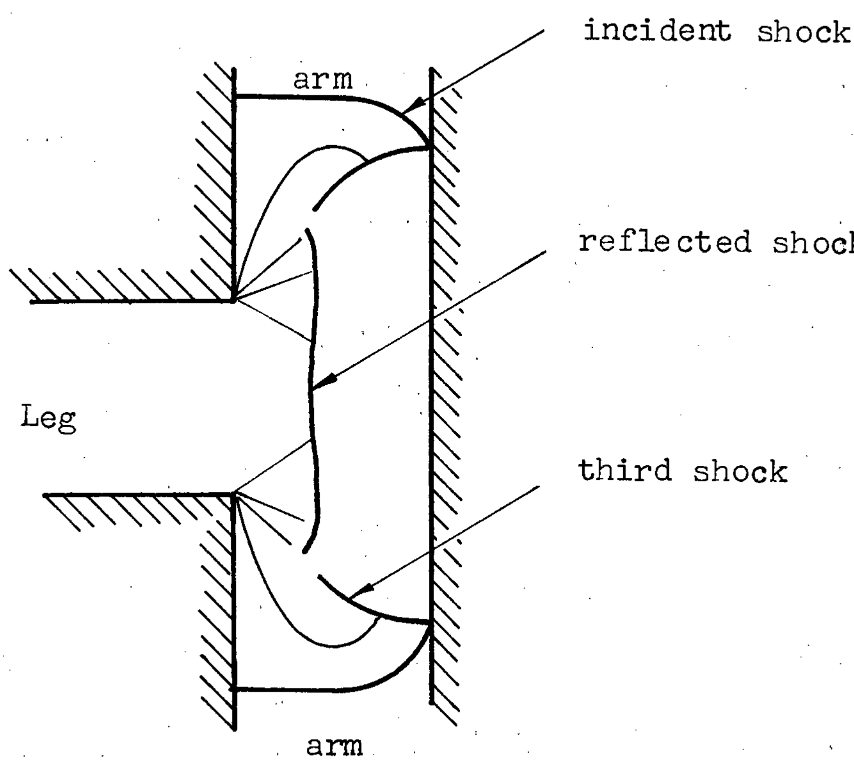


Fig. 5-1-6 Formation of the third shock

The strength of the third shock is then just enough to maintain it in its formation position, (or may be just move it closer to the mouth of the leg).

The two outside portions of the reflected shock have, in the meatime, been propagated out further, toward the arms, the reflected shock still originating at the tip of the incident shock wave, at the wall. This reflected shock must then be travelling at a greater speed than the incident shock in order to exist. This follows naturally from the shock equations and the condition that the shock speed must be supersonic relative to the approaching flow velocity. From this it can be seen that the reflected shock will eventually catch up on the incident shock and reinforce it. See figure 5-1-7.

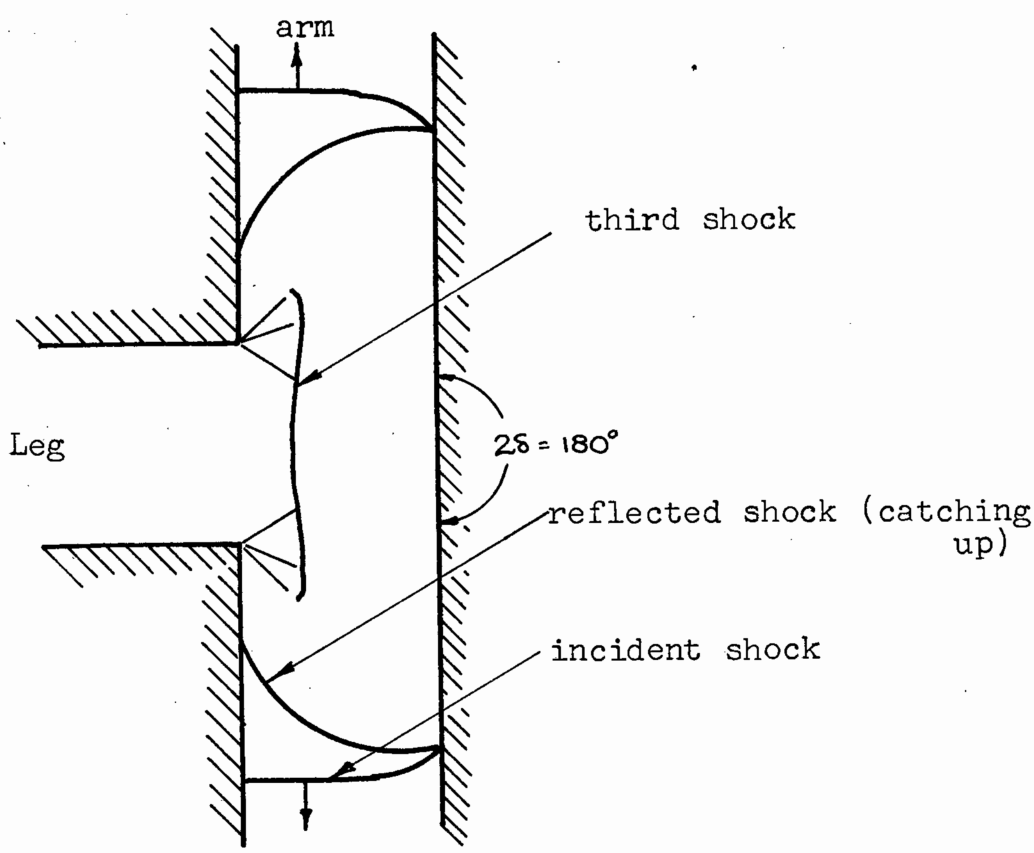
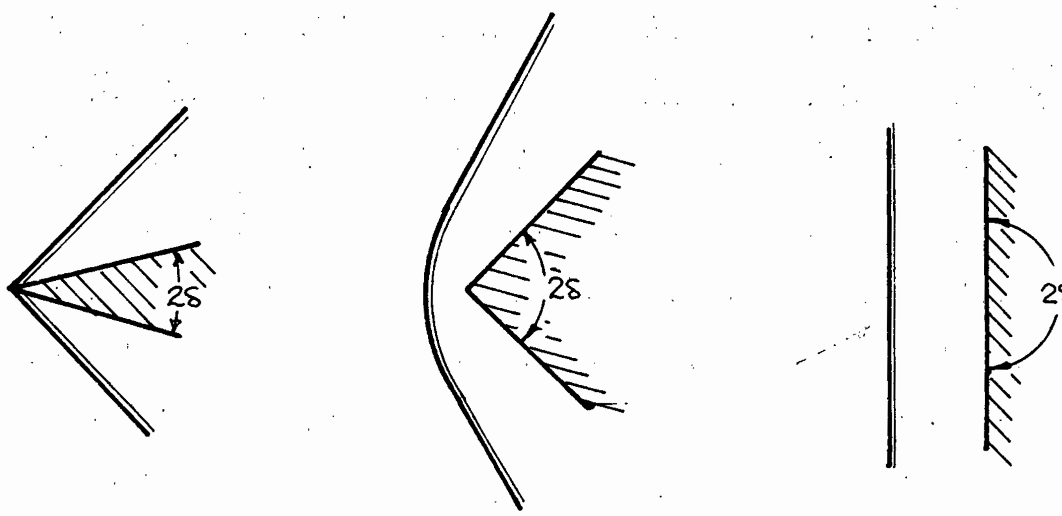


Fig. 5-1-7 The reflected shock catching up with the incident shock

The third shock spanned across the mouth of the leg is what we expect in the final steady flow problem, when we consider the oblique shock theory. (Equations A-3-9 to A-3-12)

Consider supersonic flow over a wedge of included angle 2δ.



$\delta < \delta_{max}$ attached shock (a)

$\delta > \delta_{max}$ detached shock (b)

$\delta > \delta_{max}$ detached shock (c)

Figure 5-1-8 The attached and detached oblique shock

δ is the change in flow direction

δ_{max} is the maximum flow direction change, for a given flow Mach number, that can occur such that the shock is still attached.

From this it can be seen that the case here of $2\delta = 180^{\circ}$ corresponds to a detached shock case, for all the shock Mach numbers encountered in this project.

The same type of reasoning applies to the reflection of an oblique shock. In the case of a reflection, where the angle between the boundary and the incident shock is larger than some particular value, a Mach reflection exists. This type of reflection cannot be studied analytically.

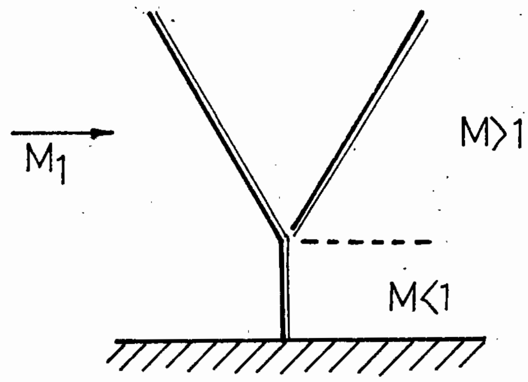


Figure 5-1-9 Mach reflection

This then might easily happen in the tee where the incident shock is reflecting off the third boundary.

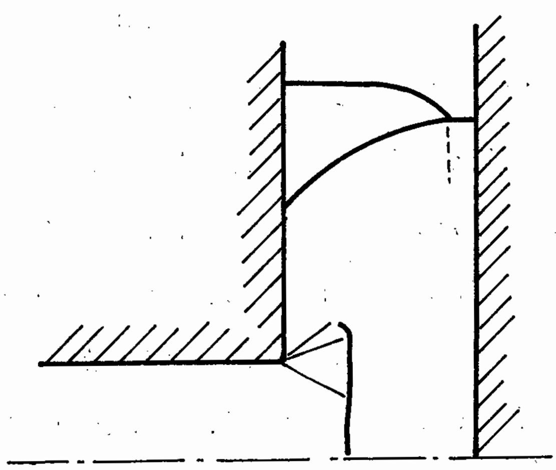


Figure 5-1-10 Mach reflection in tee

The effect of a narrower arm than leg, is expected to be an increase in the reflected shock strength due to an earlier reflection.

The three dimensional effect is going to be significant. It is expected to effect the arm with a rectangular cross-dection more than the arm with the circular cross-section, for the same circular section leg.

For the circular section arm, any x-y plane section will give the same leg to arm diameter ratio, whereas it will not for the rectangular section arm.

5-2 COMPARISON WITH FINAL RESULTS

The actual readings are given in section D.

The terms 'round tee' and 'rectangular tee' will be used to describe the configurations of a round leg plus round arms and a round leg plus rectangular arms respectively.

The Diffracted Shock Strength in the Arms Remote from the Tee

The shock strength was measured by timing the time taken for the shock front to cover a fixed distance. For the rectangular tee this distance was 12 inches, whereas for the round tee it was 10 inches. The detecting devices used were the hot-wires described earlier. Time measurement was done on one trace of the Type 564 Tetronix storage oscilloscope. The graphs of shock strength are individually plotted for the round and rectangular tee in graphs F-1 and F-2 respectively. The 'best fit' straight lines from these graphs are then transferred to graph F-3, for comparison. In addition, the prediction of the wall shock strength by Whitham's theory is given, to obtain an idea of the relative strengthening effect of the reflected shock.

The relation between the incident shock strength and the transmitted shock strengths appears, within the experimental accuracy, to be a linear one, over the range in which the experiments were done. In addition, if these 'best fit' lines are extrapolated down to lower Mach numbers, both lines seem to very nearly go through, the point (1,1). This is significant as it implies that the transmitted shock does not become vanishingly weak while there is an incident shock of some value. Notice how Whitham's theory does predict that the wall shock, and hence the transmitted shock does vanish ~~the~~ at some incident shock mach number above 1 (M_1 = 1-3) Skews however also showed that the wall shock does not become vanishingly small up until M_1 = 1. Both cases also show quite a considerable amount more absolute strengthening at the higher M_1 than at the lower M_1 (comparing with Whitham's line).

In both cases the strengthening of the transmitted shock seems to confirm the original prediction of a reflected shock, which will 'catch up' the diffracted shock, and reinforce it. Both cases also confirm the known fact that the losses associated with supersonic flow are a minimum at Mach one.

In comparing the two different tee configuration it is seen that the slopes of the two lines are significantly different. The higher Mach numbers for the rectangular tee are believed to be due to two effects.

1) Because the rectangular tee has a narrower arm (however same cross-sectional area) width than leg diameter, the reflected shock will be stronger than for the round tee, as suggested in section 5-1. The stronger reflected shock will then reinforce the diffracted shock to a larger extent.

2) It is expected that the losses associated with rectangular tee would be less than that for the round tee, due to the more involved third dimension interaction, in the round tee.

These two effects as given would then act with one another to give the increased slope for the rectangular tee.

Reason 2) is open to some doubt as it is purely based on intuition. However, if it were the opposite way round ie., the losses for the rectangular tee due to the third dimension effect were larger, then the effect of the narrower arm producing a stronger reflected shock would have to be enormous to compensate.

The scatter of the points in plotting graphs F-1 and F-2, seems to be contained within a scatter band of $\pm$ 4.5% based on the transmitted shock strength. This would seem to be in accordance with the experimental accuracy expected. As a check that these time measurements were not affected by their position, readings were taken in both positions shown (figure 5-2-1) for the round tee.

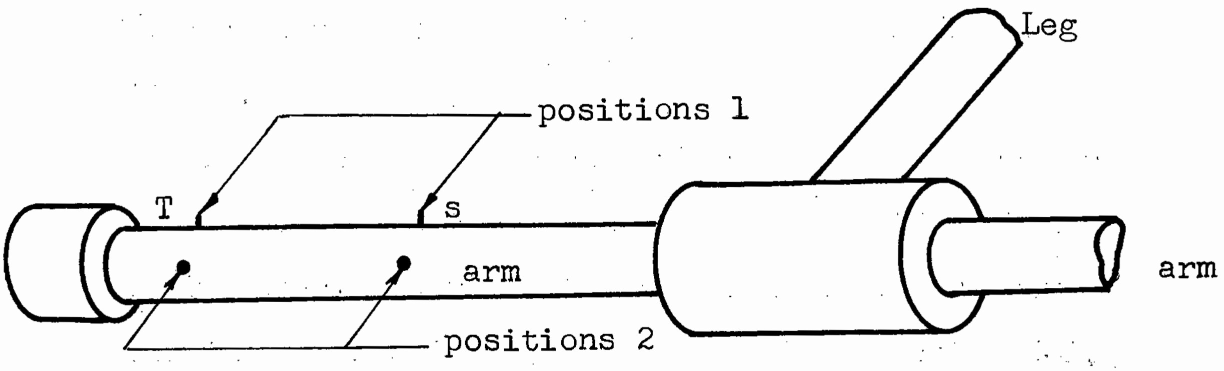


Figure 5-2-1 Hot-wire positions

The values obtained agreed very well with one another as can be seen from graph F-1.

A possible source of error may have been the positioning of the hot wire at s, being too close to the disturbed area of the tee itself.

The Shock Strength as Measured by a Transducer at Position D

The shock strength was calculated from the pressure rise reading of a piezoelectric transducer situated at position D, using the one dimensional, normal, unsteady shock wave theory. The results are plotted on graphs F-4 and F-5 for the round and rectangular tees respectively. Again the curve for Witham's wall shock is included. The values of Witham's prediction were calculated using equation

$$\theta w = \int_{M_1}^{Mw} \frac{dM}{Ac} = \int_{M_1}^{Mw} \left[\frac{2}{(M^2 1)K(M)}\right]^{\frac{1}{2}} dM$$

Where $$K(M) = 2\left[(1 + \frac{2}{\gamma+1} \frac{1-\mu^2}{\mu})(2\mu+1+M^{-2})\right]^{-1}$$

and $$\mu^2 = \frac{(\gamma-1)M^2+2}{2\gamma M^2-(\gamma-1)}$$

for θ_w = 90 degrees. The procedure was to numerically integrate the expression over very small intervals $M_1 \rightarrow M_1 - \delta M$; $M-\delta M \rightarrow M-2\delta M$; etc. until the sum over all these ranges just exceeded the θ_w value of 90 degrees. The wall shock Mach number was taken as $M-n\delta M$. The numerical integration was of the Simpsons approximation type. Computation was done on I.C.T. 1300 computer of the University of Cape Town. A listing of the appropriate programme, written in the M.A.C. code language is given, G-1. With the δM

interval at 0.005 the computation time, for all twenty values, was twenty-five minutes.

For the round tee, the experimental values obtained are in near exact agreement with experimental results obtained by Skewes of measurement of the wall shock for a 90 degree bend. The results also show fair agreement with Whitham's predictions, except at low Mach numbers. Skewes attributes the difference in experimental values and Whitham's predictions to the fact that the theory cannot avoid concentrating the shock curvature over a relatively small portion of the shock. The experimental values obtained here are questionable however, as there is no guarantee that the shock was normal as supposed. Also it is not quite clear as to the reason why a tapping at position D should measure the wall shock.

Again on extrapolation of the 'best fit' line we see that the diffracted shock should not become vanishingly small until the incident shock number approaches one.

For the rectangular tee the results are definitely not in as good agreement as for the round tee. In addition to showing slightly higher values at the higher incident shock Mach numbers, there is a distinct jump in value at $M_1 = 2.07$ ie., at an incident shock Mach number corresponding to the speed at which the flow just becomes supersonic behind the shock. This may be explained by the reflected shock and contact surface collision described earlier. The collision can result in any of the three different final conditions, depending on the relative strengths of the shock and contact surface, and their relation to one another. See figure 5-2-2

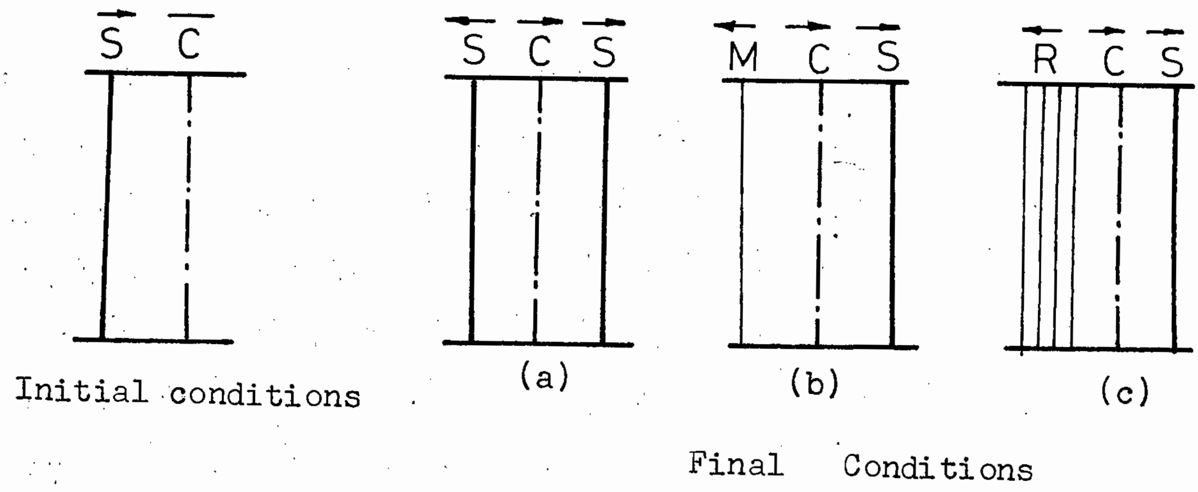


Figure 5-2-2 Normal refraction of a shock wave at a contact surface.

The jump in values may then be attributed to a switch from case (a) at low incident shock Mach numbers where the pressure is high, to case (c) where the corresponding pressure is lower, on the side remote from the approaching shock. i.e., at the third boundary.

However, whatever causes the jump, it is fairly localised, as it does not cause a corresponding jump in the transmitted shock. Graph F-2. If the lower portion of a 'best fit' straight line is extrapolated back to $M_1 = 1$ in this instance, then it implies the impossible condition of a diffracted shock with no incident shock. This then further questions the validity of the assumption of a normal shock at that point.

Interpretation of the readings taken at transducer D is difficult because of all the uncertainty of the diffracting shock pattern. The values obtained cannot be shown to confirm or contradict the proposed model.

The scatter is generally much larger than that found with the hot-wire measurement. This may be due in part to the increased difficulty of signal reading because of the noise, as described under instrumentation. However, even this would not seem to cover the scatter, and the conclusion drawn is that the flow conditions are turbulent and unsteady at this point.

A point of interest is the fact that pressures measured at a transducer at position G agree entirely with those values from position D.

The 'best fit' lines from graphs F-1; F-2; F4 and F5 are transferred onto graph F6 for comparison.

Reflected Rarefaction Wave

When the incident shock Mach number is below 2.068, then the particle velocity just behind the shock is subsonic. This will result in the sound waves being reflected back up the leg of the tee. The succession of sound waves will form a normal rarefaction or expansion wave. ~~See photograph 5-2-1~~. The wave strength p_{rare}/p_2 is plotted against M_1 in graph F-7. The plot shows that the rarefaction gets very much stronger with a lower M_1. These measurements were taken at position A, approximately 6 inches from the tee, so it seems quite possible for the pressure to fall to $0.65p_2$ at the corner, for an incident shock Mach number of 1.45, as predicted by Skews. On the other end of the plot the curve can be extrapolated to show that p_{rare}/p_2 approaches zero as M_1 approaches 2.068.

The time taken for the incident shock to travel from position A to the mouth of the corner, plus the time taken for the reflected sound wave to travel from the corner to position A, is given as t_{rare} in a plot against M_1, on graph F-8. In addition, a number of theoretical times have been caluclated and included for comparison. The agreement is very good. Again the curve can be extended to show that the time becomes infinite as M_1 approaches 2.068.

Pressure histories taken by a piezo transducer at position E show the existence of the reflected shock. This is quite clear in some of the photographs in section 3. In some cases there are also signs of an expansion prior to the reflection, as is expected at lower Mach numbers. ~~See photograph 5-2-2.~~ The pressure readings obtained from a piezo transducer placed at the position B, further confirm that there is a shock reflection and that the second signal recorded at E was that reflection.

Timed readings of the shock were also taken in the leg of the tee, in order to check the Mach numbers calculated from the pressure-rise signal recorded with a piezo transducer at position A. The shock detectors used were piezo transducers at a distance of 24.75 inches apart. The results are plotted in graph F-9 and show very good agreement.

A plot of the diaphragm pressure p_4/p_1 against recorded shock pressure p_2/p_1 is given in graph F-10 in order to compare the actual shock tube performance and the predicted performance.

5-3 CONCLUSIONS

The problem is one of extreme complexity and as such could not be analysed completely. A model was proposed on a purely qualitative basis where intuition was the main deciding factor. Because of this, the proposed model is very much a simplified version of what may occur, and is questionable on many counts. However, certain results obtained do indicate an agreement of the proposed and actual models. It is also significant that no definite contradictions were observed.

The transmitted shock strength was found, within the limits of experimental accuracy, to be a linear function of the incident shock strength, where the transmitted shock did not become vanishingly weak above $M_1 = 1$. The transmitted shock was also found to be considerably stronger than a predicted wall shock, lending support to the idea of a reflected shock "overtaking" and so reinforcing, the transmitted shock.

The elementary use of the hot-wire anemometer as a shock detector in this project has definitely been a success and this indicates that this type of instrumentation may be a useful tool in shock tube work.

Extensive research still needs to be done in order to fully understand, or be able to predict with any certainty, both the disturbed portion of the flow in the tee junction and the transmitted shock strength. In this respect the need for far more extensive instrumentation is indicated, coupled with a more detailed investigation of certain aspects and portions of the flow.

Optical methods by which the flow pattern can be 'seen' seem to be called for, in order to permit actual flow visualization. Examples of suitable optical methods would be interferometry and Schlieren photography, however this would require a truly two-dimensional model.

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THEORY OF ONE DIMENSIONAL GAS DYNAMICS

A ONE DIMENSIONAL THEORY OF GAS DYNAMICS

A-1 FUNDAMENTAL EQUATIONS

The derivation of the fundamental equations governing a one dimensional flow field are covered in most texts on gas dynamics (1), (6), (7), (8) and therefore only the results are quoted here (2)

1. Continuity Equation

Conservation of mass

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho u A)}{\partial x} = 0 \qquad \text{A-1-1}$$

2. Momentum Equation

Conservation of momentum, which expresses Newton's Second Law that the resultant force on a particle equals the time rate of change of the momentum of that particle:

$$\frac{Du}{Dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + f \qquad \text{A-1-2}$$

All body and viscous forces are here represented by the single body force f

3. Energy Equation

If we neglect the gravitational forces then the total energy, E, per unit mass is given by $E = C\,T + \frac{1}{2}U^2$ ie., the sum of the internal and kinetic energy per unit mass (assuming an ideal gas with constant specific heats). Let the rate of heat transfer per unit mass per unit time be given by q, then :

$$\frac{\partial}{\partial t}\left[\rho A E\, dx\right] = -\frac{\partial}{\partial x}\left[\rho u AE + p Au\right] dx + q.\rho.A\, dx$$

or

$$q\rho A\, dx = \frac{\partial}{\partial t}\left[\rho A\, dx\, (CvT + \tfrac{1}{2}u^2)\right] + \frac{\partial}{\partial x}$$

$$\left[\rho uA(CvT + \frac{p}{\rho} + \tfrac{1}{2}u^2)\right] dx \qquad \text{A-1-3}$$

Substituting into equation A-3 from equations A-1 and A-2 gives

$$q - u.f = \frac{D}{Dt}(CvT) + \frac{p}{\rho A}\frac{\partial}{\partial x}(Au) \qquad \text{A-1-4}$$

or

Heat transferred by external sources plus the heat transferred by the product of the body forces and the velocity equals the total time rate of change of the internal energy along a particle path plus the power generated by the pressure forces.

4 Equation of State

For perfect gases the thermal equation of state may be stated in the following form

$$\frac{p}{\rho} = \frac{\mathcal{R}.T}{m} = RT \qquad \text{A-1-5}$$

If in addition the gas is calorically perfect, i.e., C_v and C_p are constants, independent of both volume and temperature then:

$$Cp - Cv = \frac{\mathcal{R}}{m} = R \qquad \text{A-1-6}$$

5. Velocity of Sound

$$a = \sqrt{\gamma RT} = \sqrt{\frac{p\gamma}{\rho}} \qquad \text{A-1-7}$$

Also for a thermally perfect gas, the entropy change of a fluid element may be expressed from thermodyhamic considerations as

$$ds = Cp \frac{dT}{T} - R \frac{dp}{p} \qquad \text{A-1-8}$$

A-2 PRANDTL-MEYER FLOW

Consider supersonic flow turned through an elementally small angle $d\theta$

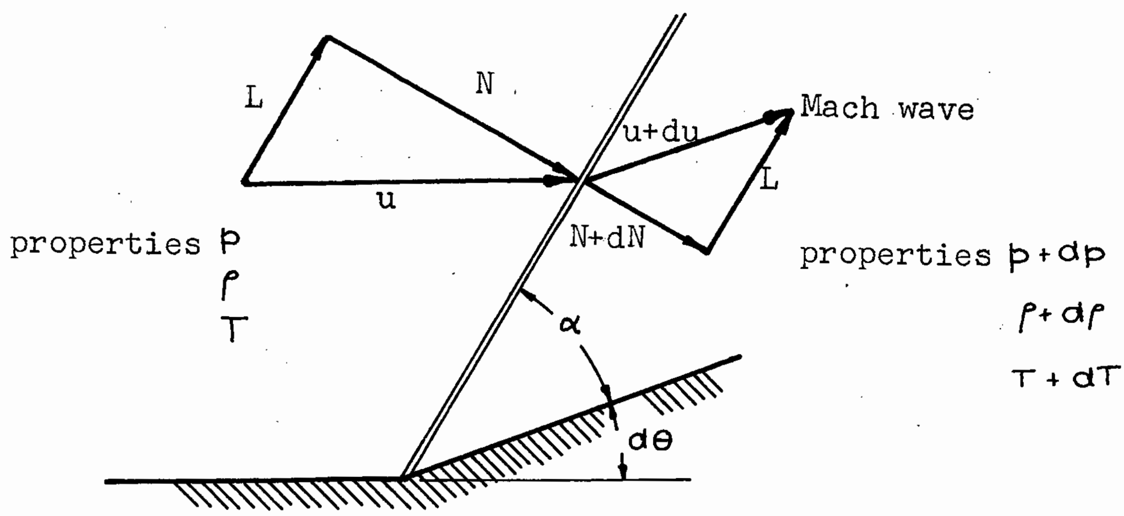

Fig. A-2-1 The wave front caused by a very small change in wall inclination $d\theta$

Consider steady flow through unit area of the wave front:

Continuity Equation

For steady flow $\dfrac{\partial(\rho A)}{\partial t} = 0$

and the equation A-1-1 can be integrated to give

$$\rho . N = (\rho + d\rho)(N + dN)$$

because no mass is carried through the unit area considered by the L-component .
Neglecting second and higher order terms

$$\rho \, dN + N d\rho = 0 \qquad \text{(a)}$$

Momentum Equation

For steady flow and no body forces A-1-2 reduces to

$$U \frac{du}{dx} = - \frac{1}{\rho} \frac{dp}{dx}$$

As this requires a knowledge of the variation of ρ with p it is easier to write down the momentum change directly:

Nett force = mass flow rate x change in velocity

$$p-(p+dp) = \rho N(N + dN - N)$$

$$\text{or} \quad -dp = \rho N dN \qquad \text{(b)}$$

Substituting for dN from equation b into equation a and comparing with equation A-1-7 gives

$$\frac{dp}{d\rho} = N^2 = a^2$$

or N = the speed of sound a

From the geometry of the flow, Fig. A-2-1

$$(u+du) \cos (\alpha - d\theta) = U \cos\alpha$$

$$\text{or} \quad \frac{du}{u} = -\tan\alpha \, d\theta$$

$$\text{from} \quad \sin \alpha = \frac{u}{a} = \frac{1}{M}$$

$$\text{we get} \quad \frac{du}{u} = \frac{-d\theta}{\sqrt{M^2 - 1}} \qquad \text{(c)}$$

Energy equation

For steady adiabatic flow, equation A-1-3 reduces to

$$\rho u \left(CvT + \frac{p}{\rho} + \frac{u^2}{2} \right) = \text{Const.}$$

and from equations A-1-5 and A-1-6

$$Cv = \frac{R}{\gamma - 1} \quad \text{and} \quad RT = \frac{p}{\rho}$$

hence $$\frac{2\gamma}{\gamma-1} \cdot \frac{p}{\rho} + u^2 = \frac{2\gamma(p+dp)}{(\gamma-1)(\rho + d\rho)} + (u+du)^2$$

Simplifying this and using equations A-1-7 and (c) gives

$$\frac{dp}{p} = \frac{\gamma M^2}{\sqrt{M^2-1}} \, d\theta$$

and $$\frac{d\rho}{\rho} = \frac{M^2}{\sqrt{M^2-1}} \, d\theta$$

From the integration of equation A-1-8 the change in entropy s is given by

$$\frac{\Delta s}{R} = \frac{1}{\gamma-1} \cdot \text{Log}_e \left[1 + \frac{dp}{p} \right] - \frac{\gamma}{\gamma-1} \text{Log}_e \left[1 + \frac{d\rho}{\rho} \right]$$

Then using the Taylor type expansion of Log(1+x) and retaining only the first term yields

$$\frac{\Delta s}{R} = \frac{1}{\gamma-1} \frac{dp}{p} - \frac{\gamma}{\gamma-1} \cdot \frac{d\rho}{\rho}$$

$$= \frac{1}{\gamma-1} \frac{\gamma M^2}{\sqrt{M^2-1}} d\theta - \frac{1}{\gamma-1} \frac{\gamma M^2}{\sqrt{M^2-1}} d\theta$$

$$= 0$$

Thus we conclude that the first order disturbance introduced by a differentially small change in flow direction is isentropic.

A corner can be thought of as being made up of a series of differentially small changes in flow direction giving rise to the Mach line or characteristic wave pattern as shown in Fig. A-2-2.

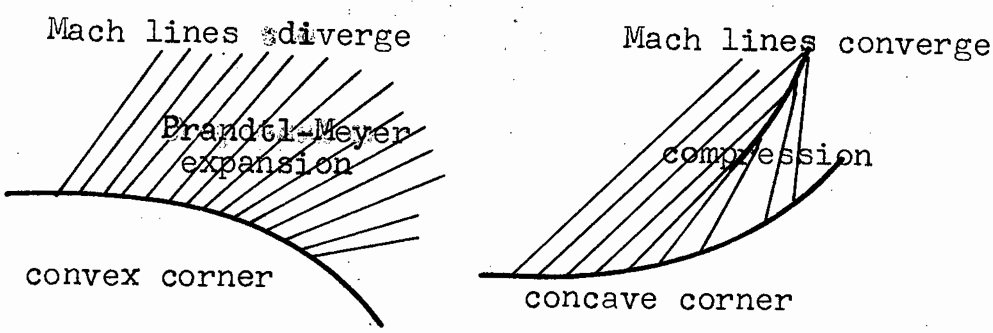

Fig. A-2-2 Characteristics for two types of corners in supersonic flow

For positive angular changes the Mach waves converge and form an oblique shock wave which is no longer isentropic~~e~~. For negative angular changes the Mach lines diverge and do not interact with one another and hence the whole flow is isentropic. This then is termed Prandtl-Meyer flow.

In order to determine the changes across a Prandtl Meyer fan we integrate equation (d)

$$\int -d\theta = \int \frac{\sqrt{M^2 - 1}}{u} \, du + C$$

Where C is a constant of integration.

With some manipulation and the use of equation A-1-3 this becomes

$$\int -d\theta \doteq \int \sqrt{\frac{(\ +1)u^2 - 2a_o^2}{2a_o^2 - (\gamma-1)u^2}} \; \frac{du}{u} \quad + C^1$$

Where a_o is the speed of sound at stagnation conditions.

The terms in this equation can now be integrated. For determination of the constant we shall take the definition of θ such that

$\theta = 0$ when $M = 1$ and hence $u = a = a*$

Integration then gives

$$\theta = -\tfrac{1}{2}\sqrt{\frac{\gamma+1}{\gamma-1}}\left\{ \sin^{-1}\left[\left(\frac{1-\gamma^2}{2}\right)\frac{u^2}{a_o^2} + \gamma\right] - \sin^{-1}\left[\left(\frac{1-\gamma^2}{2}\right)\frac{a^{*2}}{a_o^2} + \gamma\right]\right\}$$

$$-\tfrac{1}{2}\left\{\sin^{-1}\left(\gamma - \frac{2a_o^2}{u^2}\right) - \sin^{-1}\left(\gamma - \frac{2a_o^2}{a^{*2}}\right)\right\}$$

or in terms of the Mach number

$$\theta = -\tfrac{1}{2}\sqrt{\frac{\gamma+1}{\gamma-1}}\left\{\sin^{-1}\left[\left(\frac{1-\gamma^2}{2}\right)\left(\frac{M^2}{1+\frac{\gamma-1}{2}M^2}\right) + \gamma\right] - \frac{\pi}{2}\right\}$$

$$-\tfrac{1}{2}\left\{\sin^{-1}\left[\gamma - 2\left(\frac{1+\frac{\gamma-1}{2}M^2}{M^2}\right)\right] + \frac{\pi}{2}\right\} \qquad \text{A-2-1}$$

For the unsteady expansion wave the analysis is similar only there is no angle $d\theta$.

In ref. (12) these equations have been numerically solved and tables drawn up.

A-3 SHOCK WAVES

In its simplest form the shock front in a perfect gas is regarded as a discontinuity across which changes in the dynamic and thermodynamic flow quantities occur. In fact the shock is a very thin front in which a rapid but continuous transition in velocity, pressure, density and temperature takes place.

Consider the equations derived by assuming the shock a discontinuity, for a normal shock with a reference frame on the shock itself.

Continuity equation:

$$\rho_1 u_1 = \rho_2 U_2$$

or dividing by a_1 and rearranging

$$\frac{\rho_2}{\rho_1} = \frac{M_1}{M_2} \frac{a_1}{a_2} \tag{a}$$

Momentum Equation:

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$

substituting $p = \frac{a^2 \rho}{\gamma}$ into this equatioh and dividing by $\frac{a^2}{\gamma}$ gives

$$\rho_1 + \gamma \rho_1 M_1^2 = \left(\frac{a_2}{a_1}\right)^2 (\rho_2 + \gamma \rho_2 M_2^2)$$

or
$$\frac{\rho_2}{\rho_1} = \left(\frac{1 + \gamma M_1^2}{1 + \gamma M_2^2}\right)\left(\frac{a_1}{a_2}\right)^2 \tag{b}$$

Steady Flow adiabatic energy equation

$$u_1^2 + \frac{2}{\gamma-1} a_1^2 = u_2^2 + \frac{2}{\gamma-1} a_2^2$$

Dividing by $\frac{2}{\gamma-1} a_1^2$ and rearranging gives

$$\left(\frac{a_2}{a_1}\right)^2 = \frac{2 + (\gamma - 1)M_1^2}{2 + (\gamma - 1)M_2^2} \qquad (c)$$

solving between (a), (b) and (c) we get

$$M_2^2 = \frac{M_1^2 + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1}M_1^2 - 1} \qquad \text{A-3-1}$$

$$\left(\frac{a_2}{a_1}\right)^2 = \frac{T_2}{T_1} = \frac{\left[2 + (\gamma-1)M_1^2\right]\left[2\gamma M_1^2 - (\gamma-1)\right]}{(\gamma+1)^2 M_1^2} \qquad \text{A-3-2}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1) M_1^2}{2 + (\gamma-1)M_1^2} \qquad \text{A-3-3}$$

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma-1)}{\gamma + 1} \qquad \text{A-3-4}$$

As was stated earlier these values are given with reference to the shock itself. We are more interested in the moving or unsteady shock case where the reference frame is fixed in space and the shock moves relative to the frame. This can be done by a simple co-ordinate transformation.

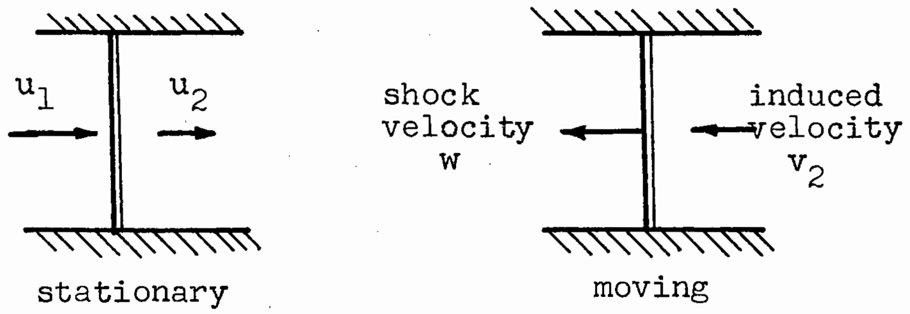

Fig. A-3-1 The stationary and moving shock terminology.

We assume that the velocities are obvious and work only with velocity magnitudes.

$$|u_1| = |w| \quad ; \quad |u_2| = |W| - |V_2|$$

then $M_1 = \dfrac{u_1}{a_1} = \dfrac{w}{a_1}$ = shock mach. number Ms.

$$M_2 = \frac{u_2^2}{a_2} = \frac{w}{a_2} - \frac{v_2}{a_2} = Ms.\frac{a_1}{a_2} - M_2'$$

Substituting these into equations A-3-1, -2, -3 and -4 give

$$M^{1}_{2} = \frac{2(M_s^{2}-1)}{\left[2\gamma Ms^2 - (\gamma-1)\right]^{0.5}\left[2 + (\gamma-1)Ms^2\right]^{0.5}} \qquad \text{A-3-5}$$

$$\left(\frac{a_2}{a_1}\right)^2 = \frac{T_2}{T_1} = \frac{\left[2+(\gamma-1)Ms^2\right]\left[2\gamma Ms^2 - (\gamma-1)\right]}{(\gamma+1)^2 M_1^2} \qquad \text{A-3-6}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\, Ms^2}{2 + (\gamma-1)Ms^2} \qquad \text{A-3-7}$$

$$\frac{p_2}{p_1} = \frac{2\, Ms^2 - (\gamma-1)}{\gamma + 1} \qquad \text{A-3-8}$$

In ref. (12) these ratios have been calculated for air, $\gamma = 1.4$, for a range of shock Mach numbers.

Flow through oblique shock waves can be considered as being made up of two components, i.e., one normal and the other parallel to the shock

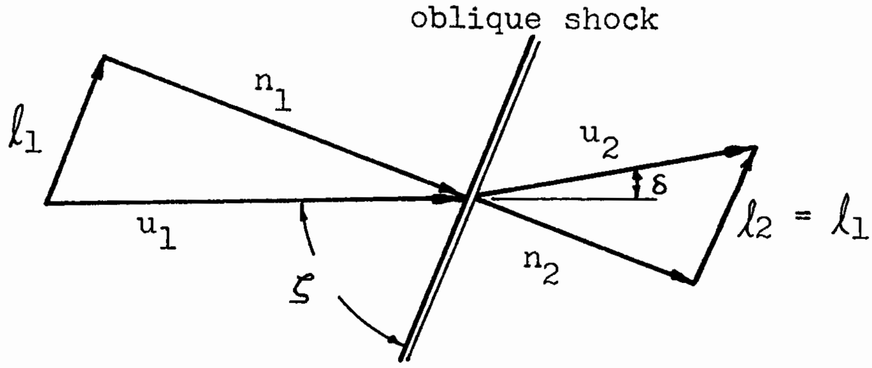

Fig. A-3-2 Terminology for oblique shock.

As shown before the parallel component remains unchanged and the normal component can be treated as flow through a normal shock.

ζ is the shock wave angle

δ is the change in flow direction

From Fig. A-3-2

$$n_1 = u_1 \text{ Sin } \zeta$$

$$n_2 = u_2 \text{ Sin } (\zeta - \delta)$$

Hence replacing u_1 by $u_1 \text{Sin}\zeta$ and u_2 by $u_2 \text{Sin } (\zeta - \delta)$ in equations A-3-1, -2, -3 and -4 gives the ratios for an oblique shock

$$M_2^2 \text{ Sin}^2 (\zeta - \delta) = \frac{M_1^2 \text{ Sin}^2 \zeta + \frac{2}{\gamma - 1}}{\frac{2\gamma}{\gamma - 1} M_1^2 \text{ Sin}^2 \zeta - 1} \qquad \text{A-3-9}$$

$$\left(\frac{a_2}{a_1}\right)^2 = \frac{T_2}{T_1} = \frac{\left[2 + (\gamma - 1) M_1^2 \text{Sin} \zeta\right]\left[2\gamma M_1^2 \text{Sin}^2 \zeta - (\gamma - 1)\right]}{(\gamma + 1)^2 M_1^2 \text{Sin}^2 \zeta} \qquad \text{A-3-10}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1) M_1^2 \text{ Sin}^2 \zeta}{2 + (\gamma - 1) M_1^2 \text{Sin}^2 \zeta} \qquad \text{A-3-11}$$

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 \text{Sin}^2 \zeta - (\gamma - 1)}{\gamma + 1} \qquad \text{A-3-12}$$

In addition it is necessary to know a relationship between ζ, δ, and M_1.

From Fig. A-3-2

$$\tan \zeta = \frac{n_1}{\ell_1} \quad ; \quad \tan (\zeta - \delta) = \frac{n_2}{\ell_2}$$

therefore $\dfrac{\tan(\zeta - \delta)}{\tan \zeta} = \dfrac{n_2}{n_1} = \dfrac{\rho_2}{\rho_1}$ by continuity

Then using equation A-3-11 and the property that

$$\tan(\zeta - \delta) = \frac{\tan\zeta - \tan\delta}{1 + \tan\zeta \tan\delta}$$

and rearranging finally gives

$$\tan\delta = \frac{2\ \mathrm{Cot}\delta\ (M_1^2 \mathrm{Sin}^2\zeta - 1)}{2 + M_1^2\ (\gamma + \mathrm{Cos}2\zeta)} \qquad \text{A-3-13}$$

Plots of δ and ζ for different mach numbers can be found in ref. (13)

A-4 SHOCK TUBE PERFORMANCE

In order to determine the shock tube performance it is necessary to know the relationship between the diaphragm pressure ratio $p4/p1$ and the strength of shock produced $p2/p1$, where regions 1, 2, 3 and 4 are as shown in Fig. 1-2

Across the contact surface in between the shock and the rarefaction wave produced only the velocity and the pressure are continuous.

$$U_2 = U_3 \tag{a}$$

$$p_3 = p_2 \tag{b}$$

Also the quantity $\frac{U2}{a_1}$ can be derived from the shock relations (2) to give

$$\frac{u_2}{a_1} = \left(\frac{p_2}{p_1} - 1\right)\left(\frac{2}{\gamma_1\left[(\gamma_1+1)\frac{p_2}{p_1} + (\gamma_1-1)\right]}\right)^{\frac{1}{2}} \tag{c}$$

Across the rarefaction wave

$$\frac{u_3}{a_4} = \frac{2}{\gamma_4 - 1}\left[1 - \left(\frac{p_3}{p_4}\right)^{\frac{\gamma_4-1}{2\gamma_4}}\right] \tag{d}$$

With some manipulation (2), the combination of the above four equations give

$$\frac{p_1}{p_4} = \frac{p_1}{p_2}\left[1 - \left(\frac{p_2}{p_1} - 1\right)\sqrt{\frac{\beta_4 \, \varepsilon_{14}}{\alpha_1\frac{p_2}{p_1} + 1}}\;\right]^{1/\beta_4} \qquad \text{A-4-1}$$

for a constant area shock tube where,

$$\beta_4 = \frac{\gamma_4 - 1}{2\gamma_4} \quad ; \quad \alpha_1 = \frac{\gamma_1 + 1}{\gamma_1 - 1}$$

$$E_{14} = \frac{e_1}{e_4} = \frac{(CvT)_1}{(CvT)_2}$$

The use of an area reduction from driver to driven sections provides a stronger shock for a given diaphragm pressure ratio. This effect of area change is taken into account in the equations by introducing a parameter g. This parameter is such that for a given area reduction the shock produced has strength equivalent to the shock produced in a constant area tube with diaphragm pressure ratio of $g \frac{p_4}{p_1}$.

and a sound speed ratio of

$$\frac{a_4}{a_1} (g)^{\beta_4}$$

From the perfect gas law from A-1-6

$$C_p - C_v = R \quad ; \quad Cp/Cv = \gamma$$

therefore $Cv = \frac{R}{\gamma - 1}$

For a constant area tube

$$E_{14} = \frac{(CvT)_1}{(CvT)_4} = \left(\frac{a_1}{a_4}\right)^2 \frac{(\gamma_4 - 1)}{(\gamma_1 - 1)} \frac{R_4}{R_1}$$

and for the case we are concerned with $R_4 = R_1$; $\gamma_4 = \gamma_1$; $a_1 = a_4$; $E_{14} = 1$

For the area reduction case

$$E_{14} = \left(\frac{a_1}{a_4\, g^{\beta_4}} \right)^2 \frac{\gamma_4 - 1}{\gamma_1 - 1} \frac{R_4}{R_1}$$

$$= g^{-2\beta_4}$$

HOT WIRE

ANEMOMETER

B-1 THE HOT-WIRE ANEMOMETER

The temperature dependence of the electric resistance of a wire may be expressed as follows

$$R_w = R_o \left[1 + \sigma (\theta_w - \theta_o) + \sigma_1 (\theta_w - \theta_o)^2 + \cdots \right]$$

where R_o is the resistance at some reference temperature θo_1; σ, σ_1 are the temperature coefficients of electric resistivity of the wire,

R_w is the resistance at θ_w

Ignoring the quadratic term above and introducing the electric resistance R_g of the wire at the gas temperature and rearranging gives

$$\theta_w - \theta_g = \frac{Rw - Rg}{\sigma R_o} \qquad \text{B-1-1}$$

The thermal equilibrium of the wire can be stated in an equation of the form (8)

$$I^2 Rw = J (\theta w - \theta g) \left[0.42 (Pr)_f^{0.20} + 0.57 (Pr)_f^{0.33} (Re)_f^{0.50} \right] \qquad \text{B-1-2}$$

Where the combination of Prandtl and Reynold's numbers here come from the emperical relationship for the Nusselt number evolved by Kramers.

Combining equations B-1-1 and B-1-2 it then becomes more convenient to express the equation in the form

$$\frac{I^2 Rw}{Rw - Rg} = A + B \sqrt{U}$$

The factors A and B can be expressed in terms of the wire and fluid properties; however it is usually safer in hot wire anemometry to determine these constants experimentally.

However equation B-1-2 is not quite complete as it neglects the thermal inertia of the wire. In order to do this we introduce a term $Cw \frac{d\Theta_w}{dt}$ where Cw is the heat capacity of the entire wire.

$$I^2Rw = (Rw - Rg)(A + B\sqrt{U}) + Cw \frac{d\Theta_w}{dt} \qquad \text{B-1-3}$$

For actually carrying out velocity measurement there are basically two different methods which may be used

a) Constant-current method

b) Constant-temperature method

CONSTANT-CURRENT METHOD

As the name implies the current through the wire is maintained at a constant value, (usually done by placing a large resistance in series with the wire) and the wire resistance and voltage drop change. The voltage change is then recorded. In order to obtain the time constant for the wire in this constant-current set-up, consider a small change in velocity U and a resultant small change in Rw and Θw such that

$$U_2 = U + u \quad ; \quad Rw_2 = Rw + r \quad ; \quad \Theta w_2 = \Theta w + \Delta\Theta$$

Substituting these values into B-1-3 and dropping quadratic terms from the expansion

$$(U+u)^{\frac{1}{2}} = U^{\frac{1}{2}} \left(1+\frac{u}{U}\right)^{\frac{1}{2}} = U^{\frac{1}{2}} \left(1+\frac{u}{2U} + \cdots\right)$$

gives

$$I^2Rw + I^2r = (Rw - Rg)(A + B\sqrt{U}) + (A + B\sqrt{U})r$$
$$+ (Rw - Rg)B \frac{u}{2\sqrt{U}} + Cw \frac{d\Delta\Theta}{dt}$$

which reduces to

$$I^2r = (A + B\sqrt{U})r + (Rw - Rg)B\frac{u}{2\sqrt{U}} + Cw\frac{d\Delta\theta}{dt}$$

Expressing $\Delta\theta$ in terms of r by means of the temperature dependence of r on $\Delta\theta$ as follows

$$r = Ro\,\delta\,\Delta\theta$$

leads to the expression

$$I^2r = (A + B\sqrt{U})r + (Rw - Rg)B\frac{u}{2\sqrt{U}} + \frac{Cw}{\delta Ro}\frac{dr}{dt}$$

rearranging this in the integegrating factor form

$$\frac{dr}{dt} + \frac{1}{Mc}.r = f(t)$$

gives the time constant M such that

$$Mc = \frac{Cw}{Ro(-I^2 + (A + B\sqrt{U}))}$$

or since $A + B\sqrt{U} - I^2 = \frac{Rg}{Rw-Rg} I^2$

$$M_c = \frac{Cw\ (Rw-Rg)}{\delta.I^2.Ro.Rg} \qquad \text{B-1-4}$$

CONSTANT TEMPERATURE METHOD

In this method the electric resistance of the wire and accordingly its temperature are kept constant as far as possible. This is done by means of an electronic feedback system whereby compensation in the current is made for a slight variation in resistance. Again the voltage change is recorded.

Let r be the slight variation (very small) in the electric resistance Rw. Then for a transconductance of the electronic circuit of g the compensating current i is given by

$$i = -gIr \qquad \text{B-1-5}$$

In order to find the time constant for this method again consider small changes in U, I and Rw such that

$$I_2 = I + i \quad ; \quad U_2 = U + u \quad ; \quad Rw_2 = Rw + r$$

Substituting these in equation B-1-3, calculating and neglecting quadratic terms in the small fluctuations i, r and u yields

$$I^2 r + 2IRwi = (A+B\sqrt{U})r + (Rw-Rg)\,\frac{B\,u}{2\sqrt{U}} + Cw\,\frac{d\Delta\theta_w}{dt}$$

Again using $r = Ro\,\sigma.\Delta\theta_w$ and the equation B-1-5, this expands to a form

$$\frac{di}{dt} + \frac{1}{M_T} \cdot i = h(t)$$

Where $M_T = \dfrac{Cw}{\sigma\, Ro(A+B\sqrt{U} - I^2 + 2I^2 Rwg)}$

or since $A + B\sqrt{U} - I^2 = \dfrac{Rg}{Rw - Rg} \cdot I^2$

$$M_T = \frac{Cw\ (Rw-Rg)}{\sigma Ro(RgI^2)(1 + 2gRw\ (Rw-R_G)/Rg\ )} \qquad \text{B-1-6}$$

Comparison of equation B-1-6 with equation B-1-4 shows that

$$M = \frac{Mc}{1 + 2gRw\ (Rw-R_G)/R_G} \qquad \text{B-1-7}$$

Hence the time constant at constant-temperature operation is much smaller than that at constant-current operation.

The transconductance g is an amplification factor of the error signal to the compensating signal. If this gain or amplification is too high, the system is likely to become unstable. This explains the need for a negative feedback on this mode of operation.

SHOCK DIFFRACTION

THEORY

C-1 WITHAM'S TWO-DIMENSIONAL THEORY OF THE WAVE MOTION ON A SHOCK (3)

Only the mathematics of Whitham's approximate theory (3) is given here, for the definition of the different terms see section 4.

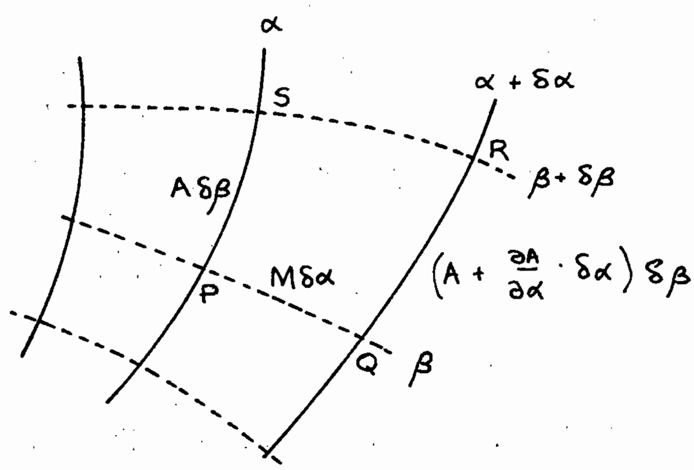

Fig. C-1-1 Curvilinear quadrilateral PQ RS formed by neighbouring α and β curves

Consider the curvilinear quadilateral PQRS with vertices (α, β), $(\alpha+\delta\alpha, \beta)$, $(\alpha+\delta\alpha, \beta+\delta\beta)$ and $(\alpha, \beta+\delta\beta)$ respectively. Let $\theta(\alpha, \beta)$ be the angle made by the ray with a fixed direction.

The change in ray inclination from P to S is then

$$\delta\theta = \frac{QR - PS}{PQ}$$

or substituting in the values of QR, PS and PQ from Fig. C-1-1

$$\delta\theta = \frac{\left(A + \frac{\partial A}{\partial \alpha} \cdot \delta\alpha\right)\delta\beta - A\delta\beta}{M\delta\alpha}$$

$$= \frac{1}{M}\frac{\partial A}{\partial \alpha} \cdot \delta\beta$$

or rearranging

$$\frac{\partial\theta}{\partial\beta} = \frac{I}{M}\,\frac{\partial A}{\partial\alpha} \qquad \text{C-1-1}$$

Since the rays are orthogonal to the α - curves it is also directly apparent that

$$\frac{\partial\theta}{\partial\alpha} = -\frac{I}{A}\cdot\frac{\partial M}{\partial\beta} \qquad \text{C-1-2}$$

Now using the assumption that A is a function of M only i.e. $A = A(M)$ and that it is a decreasing function of M so that the first derivative $A^1(M) < 0$ in equations C-1-1 and C-1-2 :

$$\frac{\partial\theta}{\partial\beta} - \frac{A^1(M)}{M}\cdot\frac{\partial M}{\partial\alpha} = 0 \qquad \text{C-1-3}$$

and

$$\frac{\partial\theta}{\partial\alpha} - \frac{I}{A(M)}\,\frac{\partial M}{\partial\beta} = 0 \qquad \text{C-1-4}$$

There are thus two equations in the functions $M(\alpha,\beta)$ and $\theta(\alpha,\beta)$. Once these functions have been found they can be transformed to the (x,y) plane by the following transformations

$$y = \int M\sin\theta\, d\alpha$$

$$x = \int M\cos\theta\, d\alpha$$

obtained by integrating along a ray.

It is then convenient to express equations C-1-3 and C-1-4 in the form

$$\left(\frac{\partial}{\partial\alpha} \pm C\frac{\partial}{\partial\beta}\right)\left(\theta \pm \int\frac{dM}{Ac}\right) = 0 \qquad \text{C-1-5}$$

Where C is a function of M given by

$$C = \sqrt{\frac{-M}{AA^1}}$$

Equation C-1-4 shows that

$$\theta - \int\frac{dM}{Ac} = \text{constant on } \frac{d\beta}{d\alpha} = C \text{ (increasing } \beta\text{)}$$

$$\theta + \int \frac{dM}{Ac} = \text{constant on } \frac{d\beta}{d\alpha} = -C \quad (\text{decreasing } \beta)$$

The expressions $\theta \pm \int \frac{dM}{Ac}$ correspond to the Riemann invariants of gas dynamics (1), (2) usually given as $\frac{2}{\gamma-1} a \pm u$

For the case of the simple wave moving in the direction of increasing β the Riemann invariant is constant everywhere. Thus θ and M must be individually constant on each characteristic $\frac{d\beta}{d\alpha}$, making each characteristic a straight line. For the case where θ is given at the wall ($\theta_w(\alpha)$) where $\beta = 0$ and the shock Mach number is initially M_1 at $\theta_w = 0$ then

$$\theta_w = \int_{M_1}^{M_w} \frac{dM}{Ac} \qquad \text{C-1-6}$$

Using the relation between A and M as proposed by Chester

$$A^1 = \frac{-2MA}{(M^2-1)K(M)} \qquad \text{C-1-7}$$

Where K(M) is the decreasing function of M

$$K(M) = 2\left[(1 + \frac{2}{\gamma+1} \frac{1-\mu^2)}{} (2\mu + 1 + M^{-2})\right]^{-1}$$

where $$\mu^2 = \frac{(\gamma-1)M^2 + 2}{2\gamma M^2 - (\gamma-1)}$$

From these

$$\frac{1}{Ac} = \frac{1}{A}\left(\frac{AA^1}{-M}\right)^{\frac{1}{2}}$$

$$= \left(\frac{A^1}{-AM}\right)^{\frac{1}{2}}$$

$$= \left(\frac{-2AM}{-AM} \frac{1}{(M^2-1)K(M)}\right)^{\frac{1}{2}}$$

Hence

$$\theta_w = \int_{M_1}^{Mw} \frac{dM}{Ac} = \int_{M_1}^{Mw} \left(\frac{2}{(M^2-1)K(M)}\right)^{\frac{1}{2}} dM \qquad \text{C-1-8}$$

Whitham's paper (3) also describes the mechanics of a shock-shock moving on a shock wave but as we have no direct need for it here it will not be included.

In reference (4) the above derivation has been generalised to three dimensional flow.

C-2 MATHEMATICS FOR PSEUDO-STATIONARY FLOW BEHIND A STRONG SHOCK

This is taken from reference (11)

Consider the case of unsteady compressible flow in the (x, y) plane:

Continuity equation

From equation A-1-1

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0$$

or using the notation $\frac{\partial X}{\partial i} = X_i$

$$\rho_t + (\rho u)_x + (\rho v)_y = 0 \qquad \text{C-2-1}$$

Momentum equation

From equation A-1-2

$$u_t + uu_x + vu_y = -P_x/\rho \qquad \text{C-2-2}$$

$$v_t + uv_x + vv_y = -P_y/\rho \qquad \text{C-2-3}$$

Energy equation

If heat transfer between fluid elements by friction, conduction and radiation is neglected, the energy equation can be expressed in terms of the entropy (11) such that

$$S_t + uS_x + vS_y = 0 \qquad \text{C-2-4}$$

where the entropy S is defined by

$$P/\rho^{\gamma} = (\gamma-1) \exp\left[(S-S_o)/C_v\right] P_o/\rho_o^{\gamma}$$

u and v here denote the components of the fluid velocity in the x and y directions and t denotes time.

The idea here is to transform from the (x,y) plane to the (ξ, η) plane where

$$\xi = x/t \quad ; \qquad \eta = y/t \qquad \text{C-2-5}$$

If the resulting equations, after substitution, are independent of t then the flow is pseudo -

stationary by definition.

In this case the equations become

$$
\left.
\begin{aligned}
(u - \xi)\rho_\xi &+ (v - \eta)\rho_\eta + \rho(u_\xi + v_\eta) = 0 \\
(u - \xi)u_\xi &+ (v - \eta)u_\eta = - p_\xi/\rho \\
(u - \xi)v_\xi &+ (v - \eta)v_\eta = - p_\eta/\rho \\
(u - \xi)S_\xi &+ (v - \eta)S_\eta = 0
\end{aligned}
\right| \quad \text{C-2-6}
$$

Now substituting $U = u - \xi$; $V = v - \eta$ and noting that

$$\frac{\partial u}{\partial \xi} = \frac{\partial^2 x}{\partial t \partial \xi} = \frac{\partial^2 t\xi}{\partial t \partial \xi}$$

$$= \frac{\partial t}{\partial t}$$

$$= 1$$

similarly $\dfrac{\partial v}{\partial \eta} = 1$

then the equations C-2-6 reduce to

$$
\left.
\begin{aligned}
(\rho U)_\xi &+ (\rho V)_\eta + 2\rho = 0 \\
UU_\xi &+ VU_\eta + U = - p_\xi/\rho \\
UV_\xi &+ VV_\eta + V = - p_\eta/\rho \\
& \quad US_\xi + VS_\eta = 0
\end{aligned}
\right| \quad \text{C-2-7}
$$

From equations C-2-7 it can be seen that they are identical to the equations that would have been written down for a compressible steady flow problem with a non-conservative field of forces, and a distribution of sinks of strength proportional to the local density ρ . The substitution made implies that the steady flow plot is got from the unsteady state by superimposing a velocity $(-x/t, -y/t)$ at every point in the flow.

READINGS

The readings given here are a sample set taken from an estimated 850 runs. The set here has been chosen so as to give the same scatter band as was found with all the readings plotted out.

The readings are given on the same sheets as were originally used to record data from each run. When running the tests these sheets were used in conjunction with either photographic or sketch records of the oscilloscope traces.

SHOCK TUBE

Run no. L 1

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·587	A+E time : 0·5 mS/div
T_1 = 59 °F	p_{rare}/p_2 = 0·25	press: 10 psi /div
p_A = 26 psi	t_r = 3·5 mS	time : /div
p_{rA} = 34 psi	P_2/P_1 = 2·77	press: /div
p_{rare} = 10 psi	t_{rare} = 1·5 mS	M_{part} = 0·68
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 13·5 psi	t =	t =	P_{D2}/P_r = 1·92
p_E = 26 psi	t_E = 0·5 mS	t =	M_t = 1·40
p_{Erare} = 17 psi	t_{Erare} = 0·9 mS	t =	M_p = 1·34
p =	t =	t =	M_{part} = 0·66
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·06 mS	t_{ST} = 0·64 mS	M_{rp} =
p =	t_T = 0·70 mS	t =	
	t_{rS} = 1·92 mS	t_{rSrT} = 0·92 mS	
	t_{rT} = 1·0 mS		
	t =	Scale :	D + HW time: 0·2 mS/div
			press: 5 psi/div

p_4 =	145 psig	P_4/P_1 =	10·9
P_{atmos} =	29·9 " Hg.	Station	
T_{atmos} =	59 °F	a_1 =	1116 fps.
T_{tee} =	59 °F	a_t =	1116 fps.

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SHOCK TUBE

Run no. L 2

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·695	A+E time: 0·5 mS/div
T_1 = 60°F	p_{rare}/p_2 = 0·11	press: 10 psi /div
p_A = 32 psi	t_r = 3·4 mS	time: /div
p_{rA} = 44 psi	p_2/p_1 = 3·18	press: /div
p_{rare} = 5 psi	t_{rare} = 1·75 mS	M_{part} = 0·76
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20 psi	t =	t =	p_{D2}/p_1 = 2·36
p_E = 32 psi	t =	t =	Mt = 1·60
p =	t =	t =	Mp = 1·47
p =	t =	t =	M_{part} = 0·68
p =	t =	t =	
p =	t =	t =	p_i/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04 mS	t_{ST} = 0·56 mS	M_{rp} =
p =	t_T = 0·60 mS	t =	
	t_{rS} = 1·88 mS	t_{rST} = 0·94 mS	
	t_{rT} = 0·94 mS		
	t =	Scale :	D + HW time: 0·2 mS/div
			press: 5 psi/div

p_4 =	250 psig	p_4/p_1 =	18·0
Patmos =	29·9 "Hg.	Station	
Tatmos =	60°F	a_1 =	1117 fps.
Ttee =	60°F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L 3

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·678	A+E time : 0·5 mS /div
T_1 = 60 °F	P_{rare}/p_2 = 0·07	press: 10 psi /div
P_A = 31 psi	t_r = 3·4 mS	time : /div
P_{rA} = 39 psi	P_2/P_1 = 3·11	press: /div
P_{rare} = 3 psi	t_{rare} = 1·7 mS	M_{part} = 0·75
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20 psi	t =	t =	P_{D2}/p_1 = 2·36
p =	t =	t =	Mt = 1·54
p =	t =	t =	Mp = 1·47
p =	t =	t =	M_{part} = 0·58
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04 mS	t_{ST} = 0·58 mS	M_{rp} =
p =	t_T = 0·62 mS	t =	
	t_{rS} = 1·84 mS	t_{rsrT} = 0·94 mS	
	t_{rT} = 0·90 mS		
	t =	Scale : D+HW time: 0·2mS/div	
		press: 5 psi/div	

P_4 =	215 psig	P_4/P_1 =	15·6
P_{atmos} =	29·9" Hg	Station	
T_{atmos} =	60 °F	a_1 =	1117 fps
T_{tee} =	60° F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L 4

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·606	time : 0·5 mS /div (A)
T_1 = 59 °F	p_{rare}/p_2 = 0·22	press: 10 psi /div
p_A = 27 psi	t_r = 3·4 mS	time : /div
p_{rA} = 38 psi	p_2/p_1 = 2·84	press: /div
p_{rare} = 9 psi	t_{rare} = 1·6 mS	M_{part} = 0·69
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20 psi	t =	t =	p_{D2}/p_1 = 2·36
p =	t =	t =	M_t = 1·40
p =	t =	t =	M_p = 1·47
p =	t =	t =	M_{part} = 0·58
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04 mS	t_{sT} = 0·64 ms	M_{rp} =
p =	t_T = 0·68 mS	t =	
	t_{rT} = 1·88 mS	t_{rsrT} = 0·94 mS	
	t_{rT} = 0·94 mS		
	t =	Scale :	time: 0·2 mS/div (D+HW)
			press: 2 psi/div

p_4 =	200 psig	p_4/p_1 =	14·7
P_{atmos} =	29·9 " Hg	Station	
T_{atmos} =	59 °F	a_1 =	1116 fps
T_{tee} =	59 °F	a_t =	1116 fps.

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SHOCK TUBE

Run no. L 5

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·606	time$_A$: 0·5 ms/div
T_1 = 59 °F	P_{rare}/P_2 = 0·19	press: 10 psi /div
P_A = 27 psi	t_r = 3·4 mS	time : /div
P_{rA} = 36 psi	P_2/P_1 = 2·84	press: /div
P_{rare} = 8 psi	t_{rare} = 1·6 mS	M_{part} = 0·69
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 15 psi	t =	t =	P_{D2}/P_1 = 2·02
p =	t =	t =	Mt = 1·40
p =	t =	t =	Mp = 1·37
p =	t =	t =	M_{part} = 0·51
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04mS	t_{ST} = 0·64 mS	M_{rp} =
p =	t_T = 0·68 mS	t =	
	t_{rs} = 1·88 mS	t_{rsrT} = 0·94 mS	
	t_{rT} = 0·94mS		
	t =	Scale :	time$_{D+HW}$: 0·2mS/div
			press: 2 psi/div

P_4 =	185 psig	P_4/P_1 =	13·6
Patmos =	29·9 " Hg	Station	
Tatmos =	59 °F	a_1 =	1116 fps
T tee =	59°F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 6

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 7·22 psi	M_{1p} = 1·992	time : 0·5 ms/div (A+E)
T_1 = 60°F		press: 10 psi /div
p_A = 24 psi	t_r = 3·6 mS	time : /div
p_{rA} = 34 psi	P_2/P_1 = 4·46	press: /div
P_{rare} =	t_{rare} =	M_{part} = 0·96
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 10 psi	t =	t =	P_{D2}/P_1 = 2·38
p =	t =	t =	Mt = 1·66
p =	t =	t =	Mp = 1·48
p =	t =	t =	M part = 0·74
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·14 mS	t_{ST} = 0·54 mS	Mrp =
p =	t_T = 0·68 mS	t =	
	t_{rS} = 1·80 mS	t_{rsrT} = 0·88 mS	
	t_{rT} = 0·92 mS		
	t =	Scale : time: 0·2 mS/div (D+HW)	
		press: 5 psi /div	

P4 =	195 psig	P_4/P_1 =	28·0
Patmos =	29·9 " Hg	Station	
Tatmos =	60°F	a_1 =	1117 fps
T tee =	60°F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 7

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 4·3 psi	M_{1p} = 2·143	time (A) : 0·5 mS /div
T_1 = 60°F		press: 10 psi /div
p_A = 18 psi	t_r = 4·51 mS	time (E) : 0·5 mS /div
p_{rA} =	P_2/P_1 = 5·19	press: 20 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·04
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 5 psi	t =	t =	P_{D2}/P_1 = 2·16
p =	t =	t =	Mt = 1·73
p =	t =	t =	Mp = 1·41
p =	t =	t =	M part = 0·79
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 mS	t_{ST} = 0·52	M_{rp} =
p =	t_T = 0·64 mS	t =	
	t_{rS} = 1·76 mS	t_{rSrT} = 0·88	
	t_{rT} = 0·88 mS		
	t =	Scale :	time (D + HW): 0·2 mS/div
			press: 5 psi /div

p_4 =	200 psig	P_4/P_1 =	47·4
Patmos =	29·9" Hg	Station	
Tatmos =	60°F	a_1 =	1117 fps
T tee =	60°F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 8

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·045 psi	M_{1p} = 2·432	time$_A$: 0·5 ms/div
T_1 = 60°F		press: 2 psi /div
p_A = 6 psi	t_r =	time$_E$: 0·5 ms/div
p_{rA} =	P_2/P_1 = 6·74	press: 10 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·17
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2 psi	t =	t =	P_{D2}/p_1 = 2·92
p =	t =	t =	M_t = 2·04
p =	t =	t =	M_p = 1·63
p =	t =	t =	M_{part} = 0·71
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0	t_{ST} = 0·44 ms	M_{rp} =
p =	t_T = 0·44 ms	t =	
	t_{TT} = 0·68 ms	t =	
	t =		
	t =	Scale :	time$_{D+HW}$: 0·2 ms/div
			press: 2 psi /div

p_4 =	200 psig	P_4/P_1 =	192
P_{atmos} =	29·9 " Hg	Station	
T_{atmos} =	60°F	a_1 =	1117 fps
T_{tee} =	60°F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 9

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14.7 psi	M_{1p} = 1.587	time : 0.2ms/div (A+H)
T_1 = 60°F		press: 10 psi /div
p_A = 26 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 2.77	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0.64
TEE	M_{1t} = 1.545	$t_H - t_A$ = 1.2ms

Readings		Derived results	
p_D = 15 psi	t =	t =	p_{D2}/p_1 = 2.02
p =	t =	t =	M_t = 1.38
p =	t =	t =	M_p = 1.37
p =	t =	t =	M_{part} = 0.49
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.03 ms	t_{ST} = 0.65 ms	M_{rp} =
p =	t_T = 0.68 ms	t =	
	t =	t =	
	t =		
	t =	Scale : time: 0.1ms/div (D+HW)	
		press: 2 psi /div	

P_4 =	200 psig	P_4/P_1 =	14.6
P_{atmos} =	29.9" Hg	Station	
T_{atmos} =	60°F	a_1 =	1117 fps
T_{tee} =	60°F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L 10

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·548	A+H time : 0·2 mS/div
T_1 = 58°F		press: 5 psi /div
P_A = 24 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 2·63	press: /div
P_{rare} =	t_{rare} =	M_{part} = 0·63
TEE	M_{1t} = 1·528	$t_H - t_A$ = 1·22 mS

Readings		Derived results	
p_D = 14 psi	t =	t =	P_{D2}/P_1 = 1·95
p =	t =	t =	Mt = 1·35
p =	t =	t =	Mp = 1·38
p =	t =	t =	M_{part} = 0·46
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·04mS	t =	Mrp =
p =	t_T = 0·69mS	t =	
	t =	t =	
	t =		
	t =	Scale :	D+HW time: 0·1mS/div
			press: 2 psi /div

P_4 =	200 psi	P_4/P_1 =	14·6
Patmos =	29·9" Hg	Station	
Tatmos =	58 °F	a_1 =	1116 fps
Ttee =	58 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 11

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 7·17 psi	M_{ip} = 1·67	A + H time : 0·5 mS/div
T_1 = 58 °F		press: 5 psi /div
p_A = 15 psi	t_r = 3·35 mS	time : /div
p_{rA} =	P_2/p_1 = 3·09	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·75
TEE	M_{it} = 1·68	$t_H - t_A$ = 1·1 mS

Readings		Derived results	
p_D = 8 psi	t =	t =	P_{D2}/p_1 = 2·11
p =	t =	t =	Mt =
p =	t =	t =	Mp = 1·40
p =	t =	t =	M part =
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·03 ms	t =	Mrp =
p =	t =	t =	
	t_{rT} = 0·88 mS	t =	
	t =		
	t =	Scale : D + HW time: 0·1 ms/div	
		press: 2 psi /div	

p_4 =	200 psi	P_4/P_1 =	28·9
Patmos =	29·9 " Hg	Station	
Tatmos =	58 °F	a_1 =	1116 fps
T tee =	58 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 12

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 3·54 psi	M_{1p} = 2·15	time (A+H) : 0·5 ms/div
T_1 = 58°F		press: 2 psi /div
p_A = 15 psi.	t_r =	time : /div
p_{rA} =	P_2/p_1 = 5·24	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·82
TEE	M_{1t} = 1·78	$t_H - t_A$ = 1·05 mS

Readings		Derived results	
p_D = 4·4 psi	t =	t =	p_{D2}/p_1 = 2·23
p =	t =	t =	Mt = 1·72
p =	t =	t =	Mp = 1·46
p =	t =	t =	M part = 0·78
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·02 mS	t_{s1} = 0·52 mS	M_{rp} =
p =	t_T = 0·54 mS	t =	
	t_{rT} = 0·68 mS	t =	
	t =		
	t =	Scale :	time (D+HW): 0·1 ms/div
			press: 2 psi/div

p_4 =	200 psi	P_4/P_1 =	57·3
Patmos =	29·9" Hg	Station	
Tatmos =	58°F	a_1 =	1116 fps
T tee =	58°F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 13

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 11·35 psi	M_{1p} = 1·86	A+H time : 0·5 mS/div
T_1 = 58·5 °F		press: 5psi /div
p_A = 32 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·84	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 1·85	$t_H - t_A$ = 1·0 mS

Readings		Derived results	
p_D = 16 psi	t =	t =	p_{D2}/p_1 = 2·41
p =	t =	t =	Mt = 1·51
p =	t =	t =	Mp = 1·49
p =	t =	t =	M part = 0·61
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·03 mS	t_{ST} = 0·57	Mrp =
p =	t_T = 0·60 mS	t =	
	t_{rT} = 0·87 mS	t =	
	t =		
	t =	Scale : time: 0·1mS/div	
		press: 2 psi/div	

p_4 =	200 psig	p_4/p_1 =	18·6
Patmos =	29·88 " Hg	Station	
Tatmos =	58·5°F	a_1 =	1116 fps
T tee =	58·5°F	a_t =	1116 fps.

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SHOCK TUBE

Run no. L 14

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 9·42 psi	M_{1p} = 1·63	A + H time : 0·5 ms/div
T_1 = 58·5 °F	p_{rare}/p_2 = 0·18	press: 5 psi/div
p_A = 18 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 2·91	press: /div
P_{rare} = 5 psi	t_{rare} = 1·6 ms	M_{part} =
TEE	M_{1t} = 1·61	$t_H - t_A$ = 1·15 ms

Readings		Derived results	
p_D = 11 psi	t =	t =	P_{D2}/P_1 = 2·17
p =	t =	t =	Mt = 1·42
p =	t =	t =	Mp = 1·42
p =	t =	t =	M_{part} = 0·53
p =	t =	t =	
p =	t =	t =	P_1/p=
p =	t_s = 0·04 ms	t_{ST} = 0·63 ms	Mrt =
p =	t_T = 0·67 ms	t =	Mrp =
p =	t_{rs} = 0·96 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	D + HW time: 0·1 ms/div
			press: 2 psi/div

P_4 =	140 psig	P_4/P_1 =	15·9
Patmos =	29·88 " Hg	Station	
Tatmos =	58·5 °F	a_1 =	1116 fps
T tee =	58·5 °F	a_t =	1116 fps

SHOCK TUBE

Run no. L 15

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 8·88 psi	M_{1p} = 1·89	A + H time : 0·5mS/div
T_1 = 58·5 °F		press: 5 psi /div
P_A = 26·5 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 3·98	press: /div
P_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 1·85	$t_H - t_A$ = 1·00mS

Readings		Derived results	
p_D = 12 psi	t =	t =	P_{D2}/P_1 = 2·36
p =	t =	t =	Mt =
p =	t =	t =	Mp = 1·47
p =	t =	t =	M part =
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·02mS	t =	Mrp =
p =	t = —	t =	
	t_{rr} = 0·83mS	t =	
	t =		
	t =	Scale : D + HW time: 0·1mS/div	
		press: 2 psi/div	

P4 =	200 psig	P_4/P_1 =	23·6
Patmos =	29·88 " Hg	Station	
Tatmos =	58·5 °F	a_1 =	1116 fps
T tee =	58·5 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 16

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 6·17 psi	M_{1p} = 1·89	time: 0·2ms/div (A + H)
T_1 = 58·5 °F		press: 5psi /div
p_A = 18·5 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 4·00	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2·05	$t_H - t_A$ = 0·90ms

Readings		Derived results	
p_D = 9·4 psi	t =	t =	p_{D2}/p_1 = 2·52
p =	t =	t =	Mt = 1·66
p =	t =	t =	Mp = 1·52
p =	t =	t =	M part = 0·74
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·02mS	t_{ST} = 0·54 mS	M_{rp} =
p =	t_T = 0·56mS	t =	
	t_{rT} = 0·83mS	t =	
	t =		
	t =	Scale : time: 0·1mS/div	
		press: 2psi /div	

P4 =	—	P_4/P_1 =	
P_{atmos} =	29·88 " Hg	Station	
T_{atmos} =	58·5 °F	a_1 =	1116 fps
T tee =	58·5°F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 17

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 5.18 psi	M_{1p} = 1.32	A+H time: 0.5 mS/div
T_1 = 58.5°F	P_{rare}/p_2 = 0.31	press: 5 psi /div
P_A = 4.5 psi	t_r =	time: /div
P_{rA} =	P_2/P_1 = 1.87	press: /div
P_{rare} = 3 psi	t_{rare} = 1.1 mS	M_{part} =
TEE	M_{1t} = 1.32	$t_H - t_A$ = 1.4 mS

Readings		Derived results	
P_D = 3.6 psi	t =	t =	P_{D2}/P_1 = 1.68
p =	t =	t =	Mt = 1.26
p =	t =	t =	Mp = 1.26
p =	t =	t =	M_{part} = 0.36
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{1t} =
p =	t_s = 0.02 mS	t_{ST} = 0.71 mS	M_{1p} =
p =	t_T = 0.73 mS	t =	
	t =	t =	
	t =		
	t =	Scale:	D+HW time: 0.1 ms/div
			press: 2 psi/div

P4 =	140 psig	P_4/P_1 =	28.0
Patmos =	29.88 "Hg	Station	
Tatmos =	58.5 °F	a_1 =	1116 fps
T tee =	58.5 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 18

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 5·1 psi	M_{1p} = 1·96	A+H time : 0·2mS/div
T_1 = 58·5 °F		press: 5 psi /div
P_A = 17·0 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 4·32	press: /div
P_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 1·85	$t_H - t_A$ = 1·00 mS

Readings		Derived results	
P_D = 9·2 psi	t =	t =	P_{D2}/P_1 = 2·80
p =	t =	t =	Mt =
p =	t =	t =	Mp = 1·60
p =	t =	t =	M part =
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t =	t =	M_{rp} =
p =	t =	t =	
	t =	t =	
	t =		
	t =	Scale :	D+HW time: 0·1mS/div
			press: 2psi/div

P_4 =	200 psig	P_4/P_1 =	40·2
Patmos =	29·88" Hg	Station	
Tatmos =	58·5 °F	a_1 =	1116 fps
Ttee =	58·5 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 19

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 3.53 psi	M_{1p} = 2.15	A + H time : 0.2 mS/div
T_1 = 58.5 °F		press: 5 psi /div
P_A = 15 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 5.24	press: /div
P_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2.10	$t_H - t_A$ = 0.88 mS

Readings		Derived results	
p_D = 4.6 psi	t =	t =	P_{D2}/P_1 = 2.31
p =	t =	t =	Mt = 1.79
p =	t =	t =	Mp = 1.46
p =	t =	t =	M part = 0.83
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0.01	t_{ST} = 0.50	Mrp =
p =	t_T = 0.51	t =	
	t_{rT} = 0.77	t =	
	t =		
	t =	Scale :	D + HW time: 0.1mS/div
			press: 2psi/div

P_4 = 200 psig		P_4/P_1 =	57.5
Patmos = 29.88 " Hg		Station	
Tatmos = 59° F		a_1 =	1116 fps
T tee = 59° F		a_t =	1116 fps.

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SHOCK TUBE

Run no. L 20

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 3·68 psi	M_{1p} = 2·20	A+H time : 0·2ms/div
T_1 = 59 °F		press: 5 psi /div
p_A = 16·5 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 5·46	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2·15	$t_H - t_A$ = 0·86 ms

Readings		Derived results	
p_D = 4·8 psi	t =	t =	p_{D2}/p_1 = 2·36
p =	t =	t =	Mt = 1·76
p =	t =	t =	Mp = 1·47
p =	t =	t =	M part = 0·81
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0	t_{ST} = 0·51 ms	Mrp =
p =	t_T = 0·51mS	t. =	
	t_{rT} = 0·77 mS	t =	
	t =		
	t =	Scale :	D+HW time: 0·1ms/div
			press: 2psi/div

P_4 =	200 psig	P_4/P_1 =	55·2
Patmos =	29·88 " Hg	Station	
Tatmos =	59 °F	a_1 =	1116 fps
T tee =	59 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 21

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 2·2 psi	M_{1p} = 2·42	time : 0·2 mS/div (A+H)
T_1 = 59 °F		press: 5 psi /div
p_A = 12·5	t_r =	time : /div
p_{rA} =	p_2/p_1 = 6·68	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2·43	$t_H - t_A$ = 0·76 mS

Readings		Derived results	
p_D = 3·8 psi	t =	t =	p_{D2}/p_1 = 2·73
p =	t =	t =	Mt = 2·04
p =	t =	t =	Mp = 1·58
p =	t =	t =	M_{part} = 1·98
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·01 mS	t_{ST} = 0·44 mS	M_{rp} =
p =	t_T = 0·45 mS	t =	
	t_{rT} = 0·68 mS	t =	
	t =		
	t =	Scale : time: 0·1 mS/div (D + HW)	
		press: 2 psi/div	

p_4 = 200 psi		p_4/p_1 =	91·7
Patmos =	29·88" Hg	Station	
Tatmos =	59 °F	a_1 =	1116 fps
T tee =	59 °F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 22

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·74 psi	M_{1p} = 2·43	A + H time : 0·1ms/div
T_1 = 60°F		press: 2 psi /div
p_A = 10 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 6·75	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2·40	$t_H - t_A$ = 0·77ms

Readings		Derived results	
p_D = 2·5 psi	t =	t =	p_{D2}/p_1 = 2·44
p =	t =	t =	Mt = 1·99
p =	t =	t =	Mp = 1·50
p =	t =	t =	M part = 0·96
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0	t_{ST} = 0·45 ms	M_{rp} =
p =	t_T = 0·45mS	t =	
	t_{rT} = 0·67mS	t =	
	t =		
	t =	Scale :	D + HW time: 0·1ms/div
			press: 1psi /div

p_4 =	200 psig	p_4/p_1 =	115·6
P_{atmos} =	29·60″ Hg	Station	
T_{atmos} =	60°F	a_1 =	1117 fps
T_{tee} =	60°F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 23

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 1·275 psi	M_{1p} = 2·60	A + H time: 0·1ms/div
T_1 = 60°F		press: 2 psi /div
P_A = 9·6 psi	tr =	time: /div
P_{rA} =	P_2/P_1 = 7·75	press: /div
P_{rare} =	t_{rare} =	M_{part} = 1·23
TEE	M_{1t} = 2·60	$t_H - t_A$ = 0·71ms

Readings		Derived results	
p_D = 2 psi	t =	t =	P_{D2}/P_1 = 2·67
p =	t =	t =	Mt = 2·18
p =	t =	t =	Mp = 1·56
p =	t =	t =	M_{part} = 1·06
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0	t_{ST} = 0·41 ms	M_{rp} =
p =	t_T = 0·41ms	t =	
	t_{rT} = 0·64mS	t =	
	t =		
	t =	Scale :	D + HW time: 0·1ms/div
			press: 1psi /div

P_4 =	200 psig	P_4/P_1 =	157
P_{atmos} =	29·60" Hg	Station	
T_{atmos} =	60°F	a_1 =	1116 fps
T_{tee} =	60°F	a_t =	1116 fps

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SHOCK TUBE

Run no. L 25

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 0.685 psi	M_{1p} = 2.83	A + H time: 0.1ms/div
T_1 = 60°F		press: 2 psi /div
p_A = 5.6 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 9.17	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2.64	$t_H - t_A$ = 0.70ms

Readings		Derived results	
p_D = 1.4psi	t =	t =	p_{D2}/p_1 = 3.05
p =	t =	t =	Mt = 2.36
p =	t =	t =	Mp = 1.660
p =	t =	t =	M_{part} = 1.14
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0	t_{ST} = 0.38ms	M_{rp} =
p =	t_T = 0.38ms	t =	
	t_{rT} = 0.51ms	t =	
	t =		
	t =	Scale : time: 0.1ms/div	
		press: 1psi/div	

p_4 =	200 psig	p_4/p_1 =	294
P_{atmos} =	29.60" Hg	Station	
T_{atmos} =	60°F	a_1 =	1117 fps
T_{tee} =	60°F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 26

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 0·433 psi	M_{1p} = 3·17	A+H time : 0·1mS/div
T_1 = 60°F		press: 2 psi /div
p_A = 4·6 psi	tr =	time : /div
p_{rA} =	P_2/P_1 = 11·6	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 3·07	$t_H - t_A$ = 0·60 mS

Readings		Derived results	
p_D = 1·3 psi	t =	t =	P_{D2}/P_1 = 4·0
p =	t =	t =	Mt = 2·56
p =	t =	t =	Mp = 1·89
p =	t =	t =	M part = 1·22
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0	t_{ST} = 0·35 mS	M_{rp} =
p =	t_T = 0·35mS	t =	
	t_{rT} = 0·57mS	t =	
	t =		
	t =	Scale :	D+HW time: 0·1mS/div
			press: 1 psi /div

P4 =	200 psig	P_4/P_1 =	461
Patmos =	29·60" Hg	Station	
Tatmos =	60°F	a_1 =	1117 fps
Ttee =	60°F	a_t =	1117 fps

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Ttee = 60°F at = 1116 fps

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SHOCK TUBE

Run no. L 28

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·51 psi	M_{1p} = 2·54	A + E time : 0·2ms/div
T_1 = 61°F		press: 2 psi /div
p_A = 9·6 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 7·35	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·21
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 3 psi	t =	t =	p_{D2}/p_1 = 2·98
p_E = 6·6 psi	t =	t =	Mt = 1·98
p_{eE} = 7 psi	t =	t =	Mp = 1·64
p =	t =	t =	M_{part} = 0·95
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.05 ms	t_{ST} = 0·45 ms	M_{rp} =
p =	t_T = 0·50 ms	t =	
	t_{rT} = 0·74 mS	t =	
	t =		
	t =	Scale : D + HW time: 0·1ms/div	
		press: 2 psi/div	

P4 =	200 psig	P_4/P_1 =	133
Patmos =	29·81" Hg	Station	
Tatmos =	61°F	a_1 =	1118 fps
T tee =	61°F	a_t =	1118 fps

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SHOCK TUBE

Run no. L 29

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·52 psi	M_{1p} = 2·58	time^A: 0·2ms/div
T_1 = 61°F		press: 2psi/div
p_A = 10 psi	t_r =	time^B: 0·2ms/div
p_{rA} =	p_2/p_1 = 7·58	press: 10psi/div
p_{rare} =	t_{rare} =	M_{part} = 1·23
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_B = 30 psi	t =	t =	P/p =
p =	t =	t =	Mt = 1·94
p_C = 15 psi	t =	t =	Mp =
p =	t =	t =	M_{part} = 0·93
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·1ms	t_{ST} = 0·46mS	M_{rp} =
p =	t_T = 0·56mS	t =	
	t_{rT} = 0·70mS	t =	
	t =		
	t =	Scale :	time^{C+HW}: 0·1ms/div
			press: 5psi/div

p_4 =	200 psig	P_4/P_1 =	132
Patmos =	29·81" Hg	Station	
Tatmos =	61°F	a_1 =	1118 fps
Ttee =	61°F	a_t =	1118 fps

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SHOCK TUBE

Run no. L 30

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 5·65 psi	M_{1p} = 1·95	time A : 0·2ms/div
T_1 = 61°F		press: 5 psi /div
p_A = 18·5 psi	t_r =	time E : 0·2ms/div
p_{rA} =	p_2/p_1 = 4·27	press: 10 psi/div
p_{rare} =	t_{rare} =	M_{part} = 0·93
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 10 psi	t =	t =	p_{D2}/p_1 = 2·77
p_E = 18 psi	t =	t =	Mt = 1·66
p =	t =	t =	Mp = 1·59
p =	t =	t =	M_{part} = 0·74
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·12mS	t_{ST} = 0·54mS	M_{rp} =
p =	t_T = 0·66mS	t =	
	t_{rT} = 0·94mS	t =	
	t =		
	t =	Scale :	time D + HW : 0·1ms/div
			press: 2psi/div

p_4 =	200 psig	p_4/p_1 =	36·4
Patmos =	29·88" Hg	Station	
Tatmos =	61°F	a_1 =	1118 fps
Ttee =	61°F	a_t =	1118 fps

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SHOCK TUBE

Run no. L 31

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 5·65 psi	M_{1p} = 2·01	time^A: 0·5 ms/div
T_1 = 61°F		press: 5 psi/div
p_A = 20 psi	t_r =	time^E: 0·5 ms/div
p_{rA} =	p_2/p_1 = 4·54	press: 10 psi/div
p_{rare} =	t_{rare} =	M_{part} = 0·97
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 9 psi	t =	t =	p_{D2}/p_1 = 2·59
p_E = 23 psi	t =	t =	M_t = 1·66
p =	t =	t =	M_p = 1·54
p =	t =	t =	M_{part} = 0·74
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·1 ms	t_{ST} = 0·54 ms	M_{rp} =
p =	t_r = 0·64 ms	t =	
	t_{rT} = 0·9 ms	t =	
	t =		
	t =	Scale :	time^{D+HW}: 0·1 ms/div
			press: 5 psi/div

p_4 =	200 psig	p_4/p_1 =	36·4
P_{atmos} =	29·88 " Hg	Station	
T_{atmos} =	61°F	a_1 =	1118 fps
T_{tee} =	61°F	a_t =	1118 fps

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SHOCK TUBE

Run no. L 32

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 5·64 psi	M_{ip} = 2·01	A+E time : 0·2mS/div
T_1 = 63°F		press: 5psi /div
p_A = 20 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 4·54	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·96
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_G = 12psi	t =	t =	p_{G2}/p_1 = 3·13
p =	t =	t =	Mt = 1·66
p =	t =	t =	Mp = 1·68
p =	t =	t =	M_{part} = 0·74
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04mS	t_{ST} = 0·54mS	M_{rp} =
p =	t_T = 0·58 mS	t =	
	t_{rT} = 0·78mS	t =	
	t =		
	t =	Scale :	G time: 0·1mS/div
			press: 5psi/div

p_4 =	200 psig	p_4/p_1 =	36·4
Patmos =	29·9" Hg	Station	
Tatmos =	63°F	a_1 =	1119 fps
Ttee =	63°F	a_t =	1119 fps

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SHOCK TUBE

Run no. L 33

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·725	A+E time: 0·5 ms/div
T_1 = 63°F	p_{rare}/p_2 = 0·10	press: 10 psi /div
p_A = 34 psi	t_r = 3·3 ms	time: /div
p_{rA} = 47 psi	p_2/p_1 = 3·32	press: /div
p_{rare} = 5 psi	t_{rare} = 2·0 ms	M_{part} = 0·78
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20 psi	t =	t =	p_{D2}/p_1 = 2·36
p =	t =	t =	M_t = 1·42
p =	t =	t =	M_p = 1·47
p =	t =	t =	M_{part} = 0·53
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 ms	t_{ST} = 0·63 ms	M_{rp} =
p =	t_T = 0·75 ms	t =	
	t_{rT} = 0·98 ms	t =	
	t =		
	t =	Scale : time: 0·1 ms/div	
		press: 5 psi/div	

p_4 =	200 psi	p_4/p_1 =	14·6
P_{atmos} =	29·9" Hg	Station	
T_{atmos} =	63°F	a_1 =	1119 fps.
T_{tee} =	63°F	a_t =	1119 fps

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SHOCK TUBE

Run no. L 34

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{Ip} = 1·66	A+E time : 0·5 ms/div
T_1 = 63°F	p_{rare}/p_2 = 0·13	press: 10 psi/div
p_A = 30 psi	t_r = 3·5 ms	time : /div
p_{rA} = 41 psi	p_2/p_1 = 3·04	press: /div
p_{rare} = 6 psi	t_{rare} = 1·5 ms	M_{part} = 0·74
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20·5 psi	t =	t =	p_{02}/p_1 = 2·39
p =	t =	t =	Mt = 1·45
p =	t =	t =	Mp = 1·48
p =	t =	t =	M part = 0·56
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 ms	t_{ST} = 0·62 ms	M_{rp} =
p =	t_r = 0·74 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	D+HW time: 0·1 ms/div
			press: 5 psi/div

P_4 =	145 psig	P_4/P_1 =	10·9
P_{atmos} =	29·9" Hg	Station	
T_{atmos} =	63°F	a_1 =	1118 fps
T_{tee} =	63°F	a_t =	1118 fps

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SHOCK TUBE

Run no. L 35

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·75	time (A+E): 0·5ms/div
T_1 = 63°F	p_{rare}/p_1 = 0·08	press: 10psi/div
p_A = 35 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 3·39	press: /div
p_{rare} = 4 psi	t_{rare} = 2·0 mS	M_{part} = 0·80
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20psi	t =	t =	p_{D2}/p_1 = 2·36
p =	t =	t =	M_t = 1·45
p =	t =	t =	M_p = 1·47
p =	t =	t =	M_{part} = 0·56
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·12mS	t_{ST} = 0·62mS	M_{rp} =
p =	t_T = 0·74mS	t =	
	t_{rT} = 0·96mS	t =	
	t =		
	t =	Scale :	time (D+HW): 0·1mS/div
			press: 5psi/div

p_4 =	200 psig	p_4/p_1 =	10·9
Patmos =	29·9" Hg	Station	
Tatmos =	63°F	a_1 =	1119 fps
Ttee =	63°F	a_t =	1119 fps.

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SHOCK TUBE

Run no. L 36

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·75	time^A: 0·5ms/div
T_1 = 63°F	P_{rare}/p_2 = 0·06	press: 10 psi/div
p_A = 35 psi	t_r =	time^E: 0·5ms/div
p_{rA} =	P_2/P_1 = 3·39	press: 20 psi/div
p_{rare} = 3 psi	t_{rare} = 2 ms	M_{part} = 0·80
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 20 psi	t =	t =	P_{D2}/p_1 = 2·36
p =	t =	t =	Mt = 1·45
p =	t =	t =	Mp = 1·47
p =	t =	t =	M part = 0·56
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·11 ms	t_{ST} = 0·62 ms	M_{rp} =
p =	t_T = 0·73 ms	t =	
	t_{rT} = 1·04 ms	t =	
	t =		
	t =	Scale : time^{D+HW}: 0·2ms/div	
		press: 5 psi/div	

P_4 = 200 psi		P_4/P_1 = 10·9	
Patmos = 29·9″ Hg		Station	
Tatmos = 63°F		a_1 = 1119 fps	
T tee = 63°F		a_t = 1119 fps	

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SHOCK TUBE

Run no. L 37

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{IP} = 1·64	time A : 0·5 mS/div
T_1 = 63 °F	p_{rare}/p_2 = 0·15	press: 5 psi /div
p_A = 29 psi	t_r = 3·35 mS	time : /div
p_{rA} =	p_2/p_1 = 2·98	press: /div
p_{rare} = 6·5 psi	t_{rare} = 1·25 mS	M_{part} = 0·72
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 15 psi	t =	t =	p_{D2}/p_1 = 2·02
p =	t =	t =	M_t = 1·40
p =	t =	t =	M_p = 1·37
p =	t =	t =	M_{part} = 0·51
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 mS	t_{ST} = 0·64 mS	M_{rp} =
p =	t_T = 0·76 mS	t =	
	t_{rT} = 0·86 mS	t =	
	t =		
	t =	Scale : time D+HW : 0·2 mS/div	
		press: 5 psi/div	

P4 =	130 psi	P_4/P_1 =	8·85
Patmos =	29·9 " Hg	Station	
Tatmos =	63 °F	a_1 =	1119 fps
T tee =	63 °F	a_t =	1119 fps

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SHOCK TUBE

Run no. L 38

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·57	time : 0·5 ms /div
T_1 = 63°F	p_{rare}/p_2 = 0·19	press: 5 psi /div
p_A = 25 psi	t_r = 6·6 ms	time : /div
p_{rA} =	p_2/p_1 = 2·70	press: /div
p_{rare} = 7·5 psi	t_{rare} = 1·5 ms	M_{part} = 0·66
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 16·5 psi	t =	t =	p_{D2}/p_1 = 2·12
p =	t =	t =	Mt = 1·32
p =	t =	t =	Mp = 1·40
p =	t =	t =	M_{part} = 0·43
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 ms	t_{ST} = 0·68 ms	M_{rp} =
p =	t_T = 0·80 ms	t =	
	t_{rT} = 1·08 ms	t =	
	t =		
	t =	Scale : time: 0·2 ms/div	
		press: 5 psi /div	

p_4 =	120 psig	p_4/p_1 =	8·16
p_{atmos} =	29·9 " Hg	Station	
T_{atmos} =	63°F	a_1 =	1119 fps
T_{tee} =	63°F	a_t =	1119 fps

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SHOCK TUBE

Run no. L 39

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·44	time: 0·5 ms/div (A + E)
T_1 = 63°F	p_{rare}/p_2 = 0·30	press: 5 psi/div
p_A = 18·5 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 2·26	press: /div
p_{rare} = 10 psi	t_{rare} = 1·25 mS	M_{part} = 0·55
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 12·5 psi	t =	t =	p_{D2}/p_1 = 1·85
p =	t =	t =	M_t = 1·15
p =	t =	t =	M_p = 1·31
p =	t =	t =	M_{part} = 0·22
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 mS	t_{ST} = 0·78 mS	M_{rp} =
p =	t_T = 0·90 mS	t =	
	t_{rT} = 1·16 mS	t =	
	t =		
	t =	Scale :	time: 0·2 ms/div (D + HW)
			press: 5 psi/div

P_4 =	90 psi	P_4/P_1 =	6·12
P_{atmos} =	29·9″ Hg	Station	
T_{atmos} =	63°F	a_1 =	1119 fps
T_{tee} =	63°F	a_t =	1119 fps

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SHOCK TUBE

Run no. L 40

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·45 psi	M_{1p} = 1·65	time (A+H): 0·2mS /div
T_1 = 65·5 °F		press: 10 psi /div
p_A = 29 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·0	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·73
TEE	M_{1t} = 1·69	$t_H - t_A$ = 1·08 mS

Readings		Derived results	
p_D = 15 psi	t =	t =	p_{D2}/p_1 = 2·04
p =	t =	t =	Mt = 1·41
p =	t =	t =	Mp = 1·38
p =	t =	t =	M_{part} = 0·52
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_3 = 0·12mS	t_{3T} = 0·63 mS	M_{rp} =
p =	t_T = 0·75 mS	t =	
	t =	t =	
	t =		
	t =	Scale : time (D+HW): 0·1mS/div	
		press: 5 psi/div	

p_4 = 200 psig		p_4/p_1 = 13·8	
P_{atmos} = 29·67 " Hg		Station	
T_{atmos} = 65·5 °F		a_1 = 1124 fps	
T_{tee} = 65·5 °F		a_t = 1124 fps.	

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SHOCK TUBE   Run no. L 41

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 11·55 psi	M_{1p} = 1·82	time (A+H): 0·2ms /div
T_1 = 65·5 °F		press: 10 psi /div
p_A = 31 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·69	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·85

TEE

		M_{1t} = 1·80	$t_H - t_A$ = 1·02 mS

Readings		Derived results	
p_D = 15 psi	t =	t =	p_{D2}/p_1 = 2·30
p =	t =	t =	Mt = 1·48
p =	t =	t =	Mp = 1·45
p =	t =	t =	M_{part} = 0·59
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12mS	t_{ST} = 0·60 mS	M_{rp} =
p =	t_T = 0·72mS	t =	
	t =	t =	
	t =		
	t =	Scale : time (D+HW): 0·1mS/div	
		press: 5psi /div	

p_4 =	200 psig	p_4/p_1 =	18·3
P_{atmos} =	29·73 " Hg	Station	
T_{atmos} =	65·5 °F	a_1 =	1124 fps
T_{tee} =	65·5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 42

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 10·48 psi	M_{1p} = 1·86	time^{A+H} : 0·2mS/div
T_1 = 65·5°F		press: 10 psi /div
p_A = 30 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·86	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·88
TEE	M_{1t} = 1·84	$t_H - t_A$ = 1·00 mS

Readings		Derived results	
p_D = 12·5 psi	t =	t =	p_{D2}/p_1 = 2·19
p =	t =	t =	Mt = 1·53
p =	t =	t =	Mp = 1·43
p =	t =	t =	M_{part} = 0·63
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t =	t =	M_{rp} =
p =	t_s = 0·12 mS	t_{ST} = 0·58 mS	
	t_T = 0·70 mS	t =	
	t =		
	t =	Scale : time^{D+HW}: 0·1mS/div	
		press: 5 psi/div	

p_4 =	200 psig	p_4/p_1 =	20
P_{atmos} =	29·73" Hg	Station	
T_{atmos} =	65·5 °F	a_1 =	1124 fps
T_{tee} =	65·5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 43

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 10·55 psi	M_{1p} = 1·85	A + H time : 0·2 ms/div
T_1 = 65·5 °F		press: 10 psi /div
p_A = 30 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·84	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·87
TEE	M_{1t} = 1·84	$t_H - t_A$ = 1·00 ms

Readings		Derived results	
p_D = 14 psi	t =	t =	p_{D2}/p_1 = 2·32
p =	t =	t =	Mt = 1·53
p =	t =	t =	Mp = 1·46
p =	t =	t =	M_{part} = 0·63
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 mS	t_{ST} = 0·58 mS	M_{rp} =
p =	t_T = 0·70 mS	t =	
	t =	t =	
	t =		
	t =	Scale : D + HW time: 0·1 ms/div	
		press: 5 psi/div	

p_4 =	200 psig	p_4/p_1 =	20
P_{atmos} =	29·73" Hg	Station	
T_{atmos} =	65·5°F	a_1 =	1122 fps
T_{tee} =	65·5 °F	a_t =	1122 fps

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SHOCK TUBE

Run no. L 44

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 9.45 psi	M_{1p} = 1.89	time: 0.2 mS/div
T_1 = 65.5 °F		press: 5 psi /div
P_A = 28.5 psi	t_r =	time: /div
P_{rA} =	P_2/P_1 = 4.02	press: /div
P_{rare} =	t_{rare} =	M_{part} = 0.90
TEE	M_{1t} = 1.89	$t_H - t_A$ = 0.97 mS

Readings		Derived results	
p_D = 13 psi	t =	t =	P_{D2}/p_1 = 2.38
p =	t =	t =	Mt = 1.59
p =	t =	t =	Mp = 1.48
p =	t =	t =	M part = 0.68
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.12 mS	t_{ST} = 0.56 mS	M_{rp} =
p =	t_T = 0.68 mS	t =	
	t_{rT} = 0.94 mS	t =	
	t =		
	t =	Scale :	D + HW time: 0.1mS/div
			press: 5psi/div

P_4 =	200 psig	P_4/P_1 =	22.1
P_{atmos} =	29.73" Hg	Station	
T_{atmos} =	65.5 °F	a_1 =	1124 fps
T_{tee} =	65.5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 45

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 7·6 psi	M_{1p} = 1·93	time^{A+H} : 0·2 mS/div
T_1 = 65·5 °F		press: 5 psi /div
p_A = 24 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 4·16	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·93
TEE	M_{1t} = 1·95	$t_H - t_A$ = 0·94 mS

Readings		Derived results	
p_D = 11 psi	t =	t =	P_{D2}/P_1 = 2·45
p =	t =	t =	Mt = 1·62
p =	t =	t =	Mp = 1·50
p =	t =	t =	M_{part} = 0·71
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 mS	t_{ST} = 0·55 mS	M_{rp} =
p =	t_T = 0·67 mS	t =	
	t =	t =	
	t =		
	t =	Scale :	time^{D+RW}: 0·1 mS/div
			press: 5 psi/div

p_4 =	200 psig	P_4/P_1 =	27·2
P_{atmos} =	29·73 " Hg	Station	
T_{atmos} =	65·5 °F	a_1 =	1124 fps
T_{tee} =		a_t =	1124 fps

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SHOCK TUBE

Run no. II 46

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 6·1 psi	M_{1p} = 1·95	time (A+E) : 0·1ms /div
T_1 = 65·5 °F		press: 5 psi /div
p_A = 20 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 4·28	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·94
TEE	M_{1t} = 1·96	$t_H - t_A$ = 0·93 ms

Readings		Derived results	
p_D = 9 psi	t =	t =	p_{D2}/p_1 = 2·47
p =	t =	t =	M_t = 1·71
p =	t =	t =	M_p = 1·51
p =	t =	t =	M_{part} = 0·77
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·12 ms	t_{ST} = 0·52 ms	M_{rp} =
p =	t_T = 0·64 ms	t =	
	t_{rT} = 0·90 ms	t =	
	t =		
	t =	Scale : time (D+HW): 0·1mS/div	
		press: 5psi/div	

p_4 =	200 psig	p_4/p_1 =	33·8
P_{atmos} =	29·73 " Hg	Station	
T_{atmos} =	65·5 °F	a_1 =	1124 fps
T_{tee} =	65·5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 49

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 2·52 psi	M_{1p} = 2·21	time (A) : 0·1ms /div
T_1 = 65·5 °F		press: 5 psi /div
p_A = 11·5 psi	tr =	time : /div
p_{rA} =	P_2/P_1 = 5·55	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} = 2·26	$t_H - t_A$ = 0·81 mS

Readings		Derived results	
p_D = 4 psi	t =	t =	P_{D2}/p_1 = 2·59
p =	t =	t =	Mt = 1·85
p =	t =	t =	Mp = 1·54
p =	t =	t =	M_{part} = 0·87
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·10mS	t_{sr} = 0·48 mS	M_{rp} =
p =	t_T = 0·58 mS	t =	
	t =	t =	
	t =		
	t =	Scale :	(D+HW) time: 0·1mS/div
			press: 2 psi /div

P4 =	200 psig	P_4/P_1 =	80·4
P_{atmos} =	29·73" Hg	Station	
T_{atmos} =	65·5 °F	a_1 =	1124 fps
T_{tee} =	65·5 °F	a_t =	1124 fps.

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SHOCK TUBE

Run no. L 50

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 1.68 psi	M_{1p} = 2.47	time: 0.1mS /div
T_1 = 65.5 °F		press: 2psi /div
p_A = 10 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 6.94	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1.18
TEE	M_{1t} = 2.44	$t_H - t_A$ = 0.75 mS

Readings		Derived results	
p_D = 3 psi	t =	t =	p_{D2}/p_1 = 2.79
p =	t =	t =	M_t = 2.02
p =	t =	t =	M_p = 1.59
p =	t =	t =	M_{part} = 0.97
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.10 mS	t_{sT} = 0.44 mS	M_{rp} =
p =	t_T = 0.54 mS	t =	
	t_{rT} = 0.76 mS	t =	
	t =		
	t =	Scale : time: 0.1mS/div	
		press: 2 psi/div	

P_4 =	200 psig	P_4/P_1 =	120
P_{atmos} =	29.73" Hg	Station	
T_{atmos} =	65.5 °F	a_1 =	1124 fps
T_{tee} =	65.5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 51

DRIVEN TUBE :

Readings		Derived results		Scale
p_1 =	1.2 psi	M_{Ip} =	1.89	A+H time : 0.1 ms/div
T_1 =	65.5°F			press: 2 psi /div
p_A =	3.6 psi	t_r =		time : /div
p_{rA} =		p_2/p_1 =	4.0	press: /div
p_{rare} =		t_{rare} =		M_{part} = 0.89
TEE		M_{It} =	1.85	$t_H - t_A$ = 0.99 ms

Readings		Derived results	
p_D = 2 psi	t =	t =	p_{D2}/p_1 = 2.67
p =	t =	t =	Mt = 1.53
p =	t =	t =	Mp = 1.56
p =	t =	t =	M_{part} = 0.63
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{It} =
p =	t_S = 0	t_{ST} = 0.58 ms	M_{Ip} =
p =	t_T = 0.58 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	D+HW time: 0.1 ms/div
			press: 2 psi /div

p_4 =	140 psig	p_4/p_1 =	118
P_{atmos} =	29.67 " Hg	Station	
T_{atmos} =	65.5°F	a_1 =	1124 fps
T_{tee} =	65.5°F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 52

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 1·17 psi	M_{IP} = 2·62	time (A+H) : 0·1mS /div
T_1 = 65·5 °F		press: 5 psi /div
P_A = 8·0 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 7·85	press: /div
P_{rare} =	t_{rare} =	M_{part} = 1·23
TEE	M_{It} = 2·58	$t_H - t_A$ =

Readings		Derived results	
P_D = 2·8 psi	t =	t =	P_{D2}/P_1 = 3·39
p =	t =	t =	Mt = 2·07
p =	t =	t =	Mp = 1·75
p =	t =	t =	M part = 1·00
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_S = 0·03mS	t_{ST} = 0·43 mS	Mrp =
p =	t_T = 0·46mS	t =	
	t =	t =	
	t =		
	t =	Scale :	time (D+HW): 0·1mS/div
			press: 2psi /div

P4 =	200 psig	P_4/P_1 =	171
Patmos =	29·67" Hg	Station	
Tatmos =	65·5 °F	a_1 =	1124 fps
T tee =	65·5 °F	a_t =	1124 fps

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SHOCK TUBE

Run no. L 53

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 0.712 psi	M_{1p} = 2.86	A+E time : 0.1ms/div
T_1 = 65.5 °F		press: 2 psi /div
p_A = 6 psi.	t_r =	time : /div
p_{rA} =	P_2/P_1 = 9.4	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1.32
TEE	M_{1t} = 2.86	$t_H - t_A$ = 0.64 mS

Readings		Derived results	
p_D = 2 psi	t =	t =	P_{D2}/P_1 = 3.81
p =	t =	t =	Mt = 2.33
p =	t =	t =	Mp = 1.85
p =	t =	t =	M part = 1.13
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0	t_{ST} = 0.38 mS	Mrp =
p =	t_T = 0.38 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	D+HW time: 0.1ms/div
			press: 2 psi/div

P_4 =	200 psig	P_4/P_1 =	281
Patmos =	29.67 " Hg	Station	
Tatmos =	65.5 °F	a_1 =	1124 fps
T tee =	65.5 °F	a_t =	1124 fps.

R.R. JOHNSON 1969

SHOCK TUBE

Run no. L 54

DRIVEN TUBE:

Readings	Derived results	Scale
P_1 = 0.609 psi	M_{Ip} = 2.89	time A: 0.1ms /div
T_1 = 62.5°F		press: 2psi /div
P_A = 5.2 psi	t_r =	time: /div
P_{rA} =	P_2/P_1 = 9.56	press: /div
P_{rare} =	t_{rare} =	M_{part} = 1.33
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
P_D = 2 psi	t =	t =	P_{D2}/P_1 = 4.29
p =	t =	t =	Mt = 2.21
p =	t =	t =	Mp = 1.96
p =	t =	t =	M part = 1.07
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0.05 mS	t_{ST} = 0.40 mS	Mrp =
p =	t_T = 0.45 mS	t =	
	t =	t =	
	t =		
	t =	Scale D+HW: time: 0.1ms/div	
		press: 2 psi /div	

P_4 =	200 psig	P_4/P_1 =	328
Patmos =	29.70" Hg	Station	
Tatmos =	62.5 °F	a_1 =	1120 fps
Ttee =	62.5 °F	a_t =	1120 fps

R.R. JOHNSON 1969

SHOCK TUBE

Run no. L 55

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 0·795 psi	M_{1p} = 3·00	time$_A$: 0·1 ms/div
T_1 = 62·5 °F		press: 2 psi /div
P_A = 7·4 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 10·3	press: /div
P_{rare} =	t_{rare} =	M_{part} = 1·36
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
P_D = 2 psi	t =	t =	P_{D2}/P_1 = 3·52
p =	t =	t =	Mt = 2·16
p =	t =	t =	Mp = 1·78
p =	t =	t =	M_{part} = 1·05
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·04 ms	t_{ST} = 0·41 ms	M_{rp} =
p =	t_7 = 0·45 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	D + HW time: 0·1 ms/div
			press: 2 psi /div

P_4 =	200 psig	P_4/P_1 =	253
P_{atmos} =	29·70 " Hg	Station	
T_{atmos} =	62·5 °F	a_1 =	1120 fps
T_{tee} =	62·5 °F	a_t =	1120 fps

R. R. JOHNSON 1969

SHOCK TUBE

Run no. L 56

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 0.915 psi	M_{1p} = 2.78	time : 0.1mS /div (A)
T_1 = 62.5 °F		press: 2 psi /div
P_A = 7.2 psi	tr =	time : /div
P_{rA} =	P_2/P_1 = 8.86	press: /div
P_{rare} =	t_{rare} =	M_{part} = 1.29
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2.2 psi	t =	t =	P_{D2}/P_1 = 3.39
p =	t =	t =	Mt = 2.11
p =	t =	t =	Mp = 1.75
p =	t =	t =	M part = 1.02
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.04ms	t =	M_{rp} =
p =	t_T = 0.46ms	t =	
	t_{rT} = 0.69ms	t =	
	t =		
	t =	Scale :	time: 0.1ms/div (D + HW)
			press: 2 psi /div

P4 =	200 psig	P_4/P_1 =	220
Patmos =	29.70 " Hg	Station	
Tatmos =	62.5 °F	a_1 =	1120 fps
T tee =	62.5 °F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 57

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 0·795 psi	M_{1p} = 3·00	A time : 0·1ms /div
T_1 = 62·5 °F		press: 2 psi /div
p_A = 7·4 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 10·3	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·36
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2psi	t =	t =	P_{D2}/p_1 = 3·52
p =	t =	t =	Mt = 2·21
p =	t =	t =	Mp = 1·78
p =	t =	t =	M part = 1·07
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·04mS	t_{ST} = 0·40	Mrp =
p =	t_T = 0·44mS	t =	
	t_{rT} = 0·67mS	t =	
	t =		
	t =	Scale :	D+HW time: 0·1mS/div
			press: 2 psi/div

P4 =	200 psig	P_4/P_1 =	253
Patmos =	29·70" Hg	Station	
Tatmos =	62·5 °F	a_1 =	1120 fps
Ttee =	62·5°F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 58

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·635 psi	M_{1p} = 2·50	time^A : 0·1 mS/div
T_1 = 62·5°F		press: 2 psi /div
p_A = 10 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 7·13	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·20
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·4 psi	t =	t =	p_{D2}/p_1 = 2·47
p =	t =	t =	Mt = 1·97
p =	t =	t =	Mp = 1·51
p =	t =	t =	M part = 0·94
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·03 mS	t_{ST} = 0·45 mS	M_{rp} =
p =	t_T = 0·48 mS	t =	
	t_{rT} = 0·72 mS	t =	
	t =		
	t =	Scale :	time^{D+HW}: 0·1mS/div
			press: 2 psi/div

P_4 =	200 psig	P_4/P_1 =	123
Patmos =	29·70" Hg	Station	
Tatmos =	62·5°F	a_1 =	1120 fps
T tee =	62·5°F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 59

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 4.62 psi	M_{1p} = 2.17	$time_A$: 0.1 ms /div
T_1 = 62.5°F		press: 5 psi /div
p_A = 20 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 5.34	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1.05
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 5 psi	t =	t =	p_{D2}/p_1 = 2.08
p =	t =	t =	Mt = 1.77
p =	t =	t =	Mp = 1.39
p =	t =	t =	M_{part} = 0.82
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{1rt} =
p =	t_s = 0.10 mS	t_{ST} = 0.50 mS	M_{1rp} =
p =	t_T = 0.60 mS	t =	
	t_{rT} = 0.84 mS	t =	
	t =		
	t =	Scale :	$time_{D+HW}$: 0.1 mS/div
			press: 5 psi/div

p_4 =	220 psig	P_4/P_1 =	48.4
P_{atmos} =	29.70" Hg	Station	
T_{atmos} =	62.5°F	a_1 =	1120 fps
T_{tee} =	62.5°F	a_t =	1120 fps.

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SHOCK TUBE

Run no. L 60

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 9·4 psi	M_{IP} = 1·91	time: A 0·2mS/div
T_1 = 62·5°F		press: 5 psi /div
p_A = 29 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 4·08	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·91 n
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 12·5 psi	t =	t =	p_{02}/p_1 = 2·33
p =	t =	t =	Mt = 1·61
p =	t =	t =	Mp = 1·46
p =	t =	t =	M part = 0·70
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·12 mS	t_{ST} = 0·55	Mrp =
p =	t_T = 0·67 mS	t =	
	t_{rT} = 0·92 mS	t =	
	t =		
	t =	Scale :	~~D+HW~~ time: 0·1mS/div
			press: 5 psi/div

p_4 =	230 psig	P_4/P_1 =	25·4
Patmos =	29·70 " Hg	Station	
Tatmos =	62·5 °F	a_1 =	1120 fps
T tee =	62·5 °F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 61

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 14.54 psi	M_{1p} = 1.78	time (A): 0.5 ms/div
T_1 = 62.5°F	p_{rare}/p_2 = 0.06	press: 10 psi /div
p_A = 37 psi	t_r = 3.4 ms	time: /div
p_{rA} =	p_2/p_1 = 3.55	press: /div
p_{rare} = 3 psi	t_{rare} = 2.5 ms	M_{part} = 0.82
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 17 psi	t =	t =	p_{D2}/p_1 = 2.17
p =	t =	t =	M_t = 1.41
p =	t =	t =	M_p = 1.42
p =	t =	t =	M_{part} = 0.52
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.12 ms	t_{ST} = 0.63 ms	M_{rp} =
p =	t_T = 0.75 ms	t =	
	t_{rT} = 1.0 ms	t =	
	t =		
	t =	Scale:	time (D+HW): 0.1 ms/div
			press: 5 psi/div

p_4 =	200 psig	p_4/p_1 =	14.8
P_{atmos} =	29.76" Hg	Station	
T_{atmos} =	62.5°F	a_1 =	1120 fps
T_{tee} =	62.5°F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 62

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 9.13 psi	M_{1p} = 1.81	time^A : 0.2ms/div
T_1 = 62.5 °F		press: 10 psi /div
P_A = 24 psi	t_r =	time : /div
P_{rA} =	P_2/P_1 = 3.63	press: /div
P_{rare} =	t_{rare} =	M_{part} = 0.84
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_c = 40 psi	t =	t =	P /p =
p =	t =	t =	Mt = 1.58
p =	t =	t =	Mp =
p =	t =	t =	M_{part} = 0.67
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.10ms	t_{ST} = 0.56ms	M_{rp} =
p =	t_T = 0.66ms	t =	
	t =	t =	
	t =		
	t =	Scale : time^{HW}: 0.1ms/div	
		press: 10 psi/div	

P_4 =	200 psig	P_4/P_1 =	22.9
P_{atmos} =	29.76" Hg	Station	
T_{atmos} =	62.5°F	a_1 =	1120 fps
T_{tee} =	62.5°F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 63

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·55 psi	M_{Ip} = 2·40	time (A+E): 0·1ms /div
T_1 = 62·5 °F		press: 2 psi /div
p_A = 8·6 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 6·55	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·16
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_c = 16·5 psi	t =	t =	P /p =
p =	t =	t =	Mt = 1·93
p =	t =	t =	Mp =
p =	t =	t =	M part = 0·92
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·07ms	t_{ST} = 0·46ms	Mrp =
p =	t_T = 0·53ms	t =	
	t_{rT} = 0·75 ms	t =	
	t =		
	t =	Scale :	time (C+HW): 0·1ms/div
			press: 5 psi/div

P4 =	200 psig	P_4/P_1 =	130
Patmos =	29·76" Hg	Station	
Tatmos =	62·5 °F	a_1 =	1120 fps
T tee =	62·5° F	a_t =	1120 fps

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SHOCK TUBE

Run no. L 64

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·53 psi	M_{Ip} = 2·39	time (A+C): 0·1ms /div
T_1 = 62·5 °F		press: 2 psi /div
p_A = 8·4 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 6·49	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·15
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_E = 8·2 psi	t =	t =	P /p =
p =	t =	t =	Mt = 2·01
p =	t =	t =	Mp =
p =	t =	t =	M part = 0·97
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{Irt} =
p =	t_s = 0·12 ms	t_{ST} = 0·44ms	M_{Irp} =
p =	t_T = 0·56mS	t =	
	t_{rT} = 0·80mS	t =	
	t =		
	t =	Scale : time (E+HW): 0·1mS/div	
		press: 2psi /div	

P4 =	200 psig	P_4/P_1 =	132
Patmos =	29·76 " Hg	Station	
Tatmos =	62·5 °F	a_1 =	1120 fps
T tee =		a_t =	1120 fps

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SHOCK TUBE

Run no. L 65

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 15 psi	M_{1p} = 1.70	time : 0.5 ms/div
T_1 = 59°F	p_{rare}/p_2 = 0.06	press: 10 psi /div
p_A = 33 psi	t_r = 3.4 ms	time : /div
p_{rA} =	p_2/p_1 = 3.20	press: /div
p_{rare} = 3 psi	t_{rare} = 2.5 ms	M_{part} = 0.77
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 19 psi	t =	t =	p_{D2}/p_1 = 2.27
p =	t =	t =	M_t = 1.34
p =	t =	t =	M_p = 1.45
p =	t =	t =	M_{part} = 0.45
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.10 ms	t_{ST} = 0.66 ms	M_{rp} =
p =	t_T = 0.76 ms	t =	
	t_{rs} = 0.96 ms	t =	
	t =		
	t =	Scale : D+HW time: 0.1 ms/div	
		press: 5 psi /div	

p_4 =	200 psig	p_4/p_1 =	14.3
P_{atmos} =	30.58 " Hg	Station	
T_{atmos} =	59 °F	a_1 =	1117 fps
T_{tee} =	59 °F	a_t =	1117 fps

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SHOCK TUBE

Run no. L 66

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 9.0 psi	M_{1p} = 1.90	time: 0.1mS/div (A)
T_1 = 59 °F		press: 5 psi /div
p_A = 27.5 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 4.06	press: /div
p_{rare} =	t_{rare} =	M_{part} =
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 14 psi	t =	t =	p_{D2}/p_1 = 2.55
p =	t =	t =	Mt = 1.64
p =	t =	t =	Mp = 1.53
p =	t =	t =	M part = 0.72
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.11mS	t_{ST} = 0.54	M_{rp} =
p =	t_T = 0.65mS	t =	
	t =	t =	
	t =		
	t =	Scale :	time: 0.1mS/div (D+HW)
			press: 2 psi /div

P_4 =	200 psig	P_4/P_1 =	23.2
Patmos =	30.58 " Hg	Station	
Tatmos =	59°F	a_1 =	1117 fps
T tee =	59 °F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L 67

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·16 psi	M_{1p} = 2·40	time^A : 0·1 ms/div
T_1 = 59°F		press: 2 psi /div
p_A = 7·4 psi	t_r =	time : /div
p_{rA} =	P_2/P_1 = 6·53	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·16
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_c = 14·4 psi	t =	t =	P /p =
p =	t =	t =	Mt = 1·93
p =	t =	t =	Mp =
p =	t =	t =	M_{part} = 0·92
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·06 mS	t_{ST} = 0·46 mS	M_{rp} =
p =	t_T = 0·52 mS	t =	
	t_{rT} = 0·73 mS	t =	
	t =		
	t =	Scale :	time^{C+HW}: 0·1ms/div
			press: 2psi /div

p_4 =	200 psig	P_4/P_1 =	173
Patmos =	30·58 " Hg	Station	
Tatmos =	59 °F	a_1 =	1117 fps
T tee =	59 °F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L 68

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 15 psi	M_{Ip} = 1·70	time^A : 0·1ms /div
T_1 = 59°F		press: 10 psi /div
p_A = 33 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 3·2	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·77
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 16 psi	t =	t =	p_{D2}/p_1 = 2·07
p =	t =	t =	M_t = 1·48
p =	t =	t =	M_p = 1·39
p =	t =	t =	M_{part} = 0·59
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·05 ms	t_{ST} = 0·60 ms	M_{rp} =
p =	t_T = 0·65 ms	t =	
	t =	t =	
	t =		
	t =	Scale : time^{D+HW}: 0·1ms/div	
		press: 10 psi/div	

P_4 =	200 psig	P_4/P_1 =	14·3
P_{atmos} =	30·58 " Hg	Station	
T_{atmos} =	59°F	a_1 =	1117 fps
T_{tee} =	59°F	a_t =	1117 fps.

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SHOCK TUBE

Run no. L69

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 1·41 psi	M_{IP} = 2·52	time : 0·1 ms /div
T_1 = 59 °F		press: 2 psi /div
p_A = 8·8 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 7·22	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·20
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·4 psi	t =	t =	p_2/p_1 = 2·70
p =	t =	t =	Mt = 2·01
p =	t =	t =	Mp = 1·57
p =	t =	t =	M part = 0·97
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·02 ms	t_{ST} = 0·44 ms	M_{rp} =
p =	t_T = 0·46 mS	t =	
	t =	t =	
	t =		
	t =	Scale : time: 0·1 ms /div	
		press: 2 psi /div	

p_4 =	200 psig	p_4/p_1 =	143
Patmos =	30·58 "Hg	Station	
Tatmos =	59° F	a_1 =	1117 · fps
T tee =	59° F	a_t =	1117 fps.

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SHOCK TUBE

Run no. R 1

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·9 psi	M_{1p} = 1·69	time$_A$: 0·1ms/div
T_1 = 61°F		press: 10 psi /div
p_A = 32 psi	t_r =	time$_D$: 0·1ms/div
p_{rA} =	P_2/P_1 = 3·15	press: 5 psi /div
p_{rare} =	t_{rare} =	M_{part} = 0·76
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 12 psi	t =	t =	p_{D2}/p_1 = 1·81
p_E = 20 psi	t =	t =	Mt = 1·38
p_{eE} = 14 psi	t_{eE} = 0·22 ms	t =	Mp = 1·30
p =	t =	t =	M_{part} = 0·49
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·21 ms	t_{sT} = 0·54 ms	M_{rp} =
p =	t_T = 0·75 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	time$_{E+HW}$: 0·1ms/div
			press: 5 psi /div

p_4 = –	P_4/P_1 = –
P_{atmos} = 30·15" Hg	Station
T_{atmos} = 61°F	a_1 = 1117 fps
T_{tee} = 61°F	a_t = 1117 fps

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SHOCK TUBE

Run no. R 2

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 0·773 psi	M_{1p} = 2·96	A + D time : 0·1ms/div
T_1 = 61°F		press: 2 psi /div
p_A = 7 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 10·06	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·35
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 1·6 psi	t =	t =	p_{D2}/p_1 = 3·07
p_E = 9 psi	t =	t =	M_t = 2·09
p_{EE} = 6 psi	t_{EE} = 0·2mS	t =	M_p = 1·67
p =	t =	t =	M_{part} = 1·01
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·13 mS	t_{ST} = 0·34 mS	M_{rp} =
p =	t_T = 0·47 mS	t =	
	t_{rT} = 0·77 mS	t =	
	t =		
	t =	Scale :	E time: 0·1mS/div
			press: 2 psi/div

p_4 =	/	p_4/p_1 =	
P_{atmos} =	30·15″ Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 3

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 0·908 psi	M_{1p} = 2·70	time^A : 0·1ms/div
T_1 = 61°F		press: 2 psi /div
p_A = 7·2 psi	t_r =	time^D : 0·1ms/div
p_{rA} =	P_2/P_1 = 8·35	press: 1psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·27
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 1·6 psi	t =	t =	P_{D2}/p_1 = 2·76
p_E = 7·2 psi	t =	t =	Mt = 2·01
p_{eE} = 4 psi	t_{eE} = 0·2 ms	t =	Mp = 1·59
p =	t =	t =	M part = 0·97
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t =	t =	M_{rp} =
p =	t_s = 0·13ms	t_{ST} = 0·37	
	t_T = 0·50mS	t =	
	t =		
	t =	Scale : time^{E+HW}: 0·1mS/div	
		press: 2 psi/div	

P4 = 200 psig		P_4/P_1 = 221	
Patmos = 30·15" Hg		Station	
Tatmos = 61°F		a_1 =	1117 fps
Ttee = 61°F		a_t =	1117 fps

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SHOCK TUBE

Run no. R 4

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 0.936 psi	M_{1p} = 2.79	time^A : 0.1mS/div
T_1 = 61°F		press: 2 psi /div
P_A = 7.4 psi	t_r =	time^D : 0.1mS/div
P_{rA} =	P_2/P_1 = 8.88	press: 1 psi /div
P_{rare} =	t_{rare} =	M_{part} = 1.30
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 1.8 psi	t =	t =	P_{D2}/p_1 = 2.92
p =	t =	t =	M_t = 2.07
p =	t =	t =	M_p = 1.63
p =	t =	t =	M_{part} = 1.00
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.18mS	t_{ST} = 0.36mS	M_{rp} =
p =	t_T = 0.54mS	t =	
	t =	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0.1mS/div
			press: 5 psi/div

P_4 =	200 psig	P_4/P_1 =	214
P_{atmos} =	30.15" Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 5

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 1.173 psi	M_{ip} = 2.62	time^A: 0.1 ms/div
T_1 = 61°F		press: 2 psi /div
p_A = 8 psi	t_r =	time^D: 0.1 ms/div
p_{rA} =	p_2/p_1 = 7.81	press: 1 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1.24
TEE	M_{it} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2.2 psi	t =	t =	p_{D2}/p_1 = 2.82
p =	t =	t =	M_t = 1.96
p =	t =	t =	M_p = 1.60
p =	t =	t =	M_{part} = 0.94
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.12 ms	t_{ST} = 0.38	M_{rp} =
p =	t_T = 0.50 ms	t =	
	t =	t =	
	t =		
	t =	Scale : time$^{E}_{D+HW}$: 0.1 ms/div	
		press: 5 psi/div	

P4 =	200 psig	P_4/P_1 =	187
Patmos =	30.15″ Hg	Station	
Tatmos =	61°F	a_1 =	1117. fps
T tee =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 6

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 1·25 psi	M_{1p} = 2·62	time (A): 0·1ms /div
T_1 = 61°F		press: 2 psi /div
p_A = 8·6 psi	t_r =	time (D): 0·1ms /div
p_{rA} =	P_2/P_1 = 7·88	press: 1 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·24
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·5 psi	t =	t =	P_{D2}/p_1 = 3·00
p =	t =	t =	Mt = 1·96
p =	t =	t =	Mp = 1·60
p =	t =	t =	M_{part} = 0·94
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{1t} =
p =	t_S = 0·12 ms	t_{ST} = 0·38 ms	M_{1p} =
p =	t_T = 0·50ms	t =	
	t =	t =	
	t =		
	t =	Scale : time (E): 0·1ms/div	
		press: 5 psi/div	

P_4 = 200 psig		P_4/P_1 =	161
P_{atmos} = 30·15″ Hg		Station	
T_{atmos} = 61°F		a_1 =	1117 fps
T_{tee} = 61°F		a_t =	1117 fps

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SHOCK TUBE

Run no. R 7

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·46 psi	M_{Ip} = 2·55	time^A: 0·1ms/div
T_1 = 61°F		press: 2 psi /div
p_A = 9·4 psi	t_r =	time^D : 0·1ms/div
p_{rA} =	P_2/p_1 = 7·43	press: 1 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·22
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·6 psi	t =	t =	P_{D2}/p_1 = 2·78
p =	t =	t =	Mt = 1·91
p =	t =	t =	Mp = 1·59
p =	t =	t =	M_{part} = 0·91
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·11ms	t_{ST} = 0·39mS	Mrp =
p =	t_T = 0·50mS	t =	
	t =	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0·1mS/div
			press: 5 psi /div

P_4 =	200 psig	P_4/P_1 =	138
P_{atmos} =	30·15" Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps.

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SHOCK TUBE

Run no. R 8

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1.52 psi	M_{1p} = 2.57	time A : 0.1 ms /div
T_1 = 61°F		press: 5 psi /div
p_A = 10 psi	t_r =	time D : 0.1 ms /div
p_{rA} =	p_2/p_1 = 7.56	press: 1 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1.22
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2.6 psi	t =	t =	p_{D2}/p_1 = 2.71
p =	t =	t =	Mt = 1.91
p =	t =	t =	Mp = 1.57
p =	t =	t =	M part = 0.91
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.14 ms	t_{ST} = 0.39 ms	M_{rp} =
p =	t_T = 0.53 ms	t =	
	t =	t =	
	t =		
	t =	Scale : time E : 0.1 ms/div	
		press: 5 psi /div	

p_4 =	200 psig	p_4/p_1 =	132
Patmos =	30.15 " Hg	Station	
Tatmos =	61°F	a_1 =	1117 fps
T tee =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 9

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·665 psi	M_{1p} = 2·53	time^A : 0·1ms /div
T_1 = 61°F		press: 5 psi /div
p_A = 10·5 psi	t_r =	time^D : 0·1ms /div
p_{rA} =	P_2/P_1 = 7·30	press: 1psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·21
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·7 psi	t =	t =	p_{D2}/p_1 = 2·62
p =	t =	t =	Mt = 1·86
p =	t =	t =	Mp = 1·55
p =	t =	t =	M_{part} = 0·88
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·14ms	t_{sT} = 0·40ms	M_{rp} =
p =	t_T = 0·54ms	t =	
	t_{rT} = 0·84ms	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0·1ms/div
			press: 5psi/div

P_4 =	200 psig	P_4/P_1 =	121
P_{atmos} =	30·15" Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 10

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·74 psi	M_{1p} = 2·53	time: 0·1ms/div
T_1 = 61°F		press: 5 psi /div
p_A = 11 psi	t_r =	time: 0·1ms/div
p_{rA} =	P_2/P_1 = 7·32	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·21
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·7 psi	t =	t =	P_{D2}/P_1 = 2·55
p =	t =	t =	Mt = 1·86
p =	t =	t =	Mp = 1·53
p =	t =	t =	M_{part} = 0·88
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t =	t =	M_{rp} =
p =	t_s = 0·15mS	t_{ST} = 0·40 mS	
	t_T = 0·55mS	t =	
	t =		
	t =	Scale :	time: 0·1mS/div (E + HW)
			press: 5psi /div

p_4 =	200 psig	P_4/P_1 =	116
P_{atmos} =	30·15" Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 11

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·85 psi	M_{1p} = 2·54	time^A : 0·1ms /div
T_1 = 61°F		press: 5 psi /div
p_A = 12 psi	t_r =	time^D : 0·1ms/div
p_{rA} =	p_2/p_1 = 7·36	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·21
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 2·5 psi	t =	t =	p_{D2}/p_1 = 2·35
p =	t =	t =	M_t = 1·82
p =	t =	t =	M_p = 1·47
p =	t =	t =	M_{part} = 0·85
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·14mS	t_{ST} = 0·41ms	M_{rp} =
p =	t_T = 0·55mS	t =	
	t_{rT} = 0·85mS	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0·1ms/div
			press: 5psi /div

p_4 = 200 psig		p_4/p_1 =	109
Patmos = 30·15" Hg		Station	
Tatmos = 61°F		a_1 =	1117 fps
T tee = 61°F		a_t =	1117 fps.

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SHOCK TUBE

Run no. R 12

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 2·39 psi	M_{1p} = 2·34	time^{A} : 0·1ms/div
T_1 = 61°F		press: 5 psi /div
p_A = 12·5 psi	t_r =	time^{D} : 0·1ms /div
p_{rA} =	p_2/p_1 = 6·23	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·13
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 3 psi	t =	t =	p_{D2}/p_1 = 2·27
p =	t =	t =	Mt = 1·82
p =	t =	t =	Mp = 1·45
p =	t =	t =	M_{part} = 0·85
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·14 mS	t_{ST} = 0·41 mS	M_{rp} =
p =	t_t = 0·55 mS	t =	
	t_{rT} = 0·86 mS	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0·1mS/div
			press: 5psi/div

p_4 =	200 psig	P_4/P_1 =	88·4
P_{atmos} =	30·15 " Hg	Station	
T_{atmos} =	61° F	a_1 =	1117 fps
T_{tee} =	61° F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 13

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 3·03 psi	M_{1p} = 2·24	time^A : 0·1ms /div
T_1 = 61°F		press: 5 psi /div
p_A = 14 psi	t_r =	time^D : 0·1ms /div
p_{rA} =	p_2/p_1 = 5·70	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·09
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 3·4 psi	t =	t =	p_{D2}/p_1 = 2·13
p =	t =	t =	M_t = 1·78
p =	t =	t =	M_p = 1·40
p =	t =	t =	M_{part} = 0·82
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{1rt} =
p =	t_S = 0·15 ms	t_{ST} = 0·42	M_{1rp} =
p =	t_T = 0·57 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	time^{E+HW}: 0·1mS/div
			press: 5 psi/div

p_4 =	200 psig	p_4/p_1 =	67
p_{atmos} =	30·15"Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 14

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 3·91 psi	M_{IP} = 2·25	time^A: 0·1ms/div
T_1 = 61°F		press: 5 psi /div
p_A = 18·5 psi	t_r =	time^D: 0·1ms/div
p_{rA} =	P_2/p_1 = 5·73	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 1·05
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 4 psi	t =	t =	P_{D2}/p_1 = 2·02
p =	t =	t =	Mt = 1·73
p =	t =	t =	Mp = 1·37
p =	t =	t =	M part = 0·79
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·17ms	t_{ST} = 0·43ms	M_{rp} =
p =	t_T = 0·60ms	t =	
	t =	t =	
	t =		
	t =	Scale : time^{E+HW}: 0·1ms/div	
		press: 5 psi/div	

p_4 =	200 psig	P_4/P_1 =	52
Patmos =	30·15 " Hg	Station	
Tatmos =	61°F	a_1 =	1117 fps
Ttee =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 15

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 5.17 psi	M_{1p} = 2.14	time (A): 0.1 ms/div
T_1 = 61°F		press: 5 psi/div
p_A = 21.5 psi	t_r =	time (D): 0.1 ms/div
p_{rA} =	p_2/p_1 = 5.15	press: 2 psi/div
p_{rare} =	t_{rare} =	M_{part} = 1.04
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 4.4 psi	t =	t =	p_{D2}/p_1 = 1.85
p =	t =	t =	M_t = 1.65
p =	t =	t =	M_p = 1.32
p =	t =	t =	M_{part} = 0.73
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0.18 ms	t_{ST} = 0.45 ms	M_{rp} =
p =	t_T = 0.63 ms	t =	
	t =	t =	
	t =		
	t =	Scale : time ($E+HW$): 0.1 ms/div	
		press: 5 psi/div	

p_4 = 200 psig		p_4/p_1 = 39.7	
P_{atmos} = 30.15 " Hg		Station	
T_{atmos} = 61°F		a_1 = 1117 fps	
T_{tee} = 61°F		a_t = 1117 fps	

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SHOCK TUBE

Run no. R 16

DRIVEN TUBE :

Readings	Derived results	Scale
P_1 = 7·2 psi	M_{IP} = 1·95	time A : 0·1 ms/div
T_1 = 61 °F		press: 5 psi /div
P_A = 23·5 psi	t_r =	time D : 0·1 ms /div
P_{rA} =	P_2/P_1 = 4·26	press: 2 psi /div
P_{rare} =	t_{rare} =	M_{part} = 0·93
TEE	M_{It} =	$t_H - t_A$ =

Readings		Derived results	
P_D = 5 psi	t =	t =	P_{D2}/P_1 = 1·70
P_E = 20 psi	t =	t =	Mt = 1·62
P_{eE} = 15 psi	t =	t =	Mp = 1·27
p =	t =	t =	M_{part} = 0·70
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	Mrt =
p =	t_s = 0·17 ms	t_{ST} = 0·46 ms	Mrp =
p =	t_T = 0·63 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	time E + HW : 0·1 ms/div
			press: 10 psi/div

P_4 = 180 psig	P_4/P_1 = 26		
Patmos = 30·15 " Hg	Station		
Tatmos = 61°F	a_1 = 1117 fps		
Ttee = 61°F	a_t = 1117 fps		

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SHOCK TUBE

Run no. R 17

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 8·44 psi	M_{1p} = 1·92	time^A: 0·1ms/div
T_1 = 61 °F		press: 5 psi /div
p_A = 26·5 psi	t_r =	time^D: 0·1ms/div
p_{rA} =	p_2/p_1 = 4·14	press: 2 psi /div
p_{rare} =	t_{rare} =	M_{part} = 0·92
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 7 psi	t =	t =	p_{D2}/p_1 = 1·83
p =	t =	t =	Mt = 1·62
p =	t =	t =	Mp = 1·31
p =	t =	t =	M_{part} = 0·70
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_S = 0·20ms	t_{ST} = 0·46ms	M_{rp} =
p =	t_T = 0·66ms	t =	
	t =	t =	
	t =		
	t =	Scale : time^{E+HW}: 0·1ms/div	
		press: 10psi/div	

p_4 = 200 psig		p_4/p_1 =	24·7
P_{atmos} = 30·15″ Hg		Station	
T_{atmos} = 61°F		a_1 =	1117 fps
T_{tee} = 61°F		a_t =	1117 fps

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SHOCK TUBE

Run no. R 18

DRIVEN TUBE:

Readings	Derived results	Scale
p_1 = 11.0 psi	M_{1p} = 1.83	time (A + D): 0.1 ms/div
T_1 = 61°F		press: 5 psi /div
p_A = 30 psi	t_r =	time: /div
p_{rA} =	p_2/p_1 = 3.73	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0.86
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 9.5 psi	t =	t =	p_{D2}/p_1 = 1.86
p =	t =	t =	M_t = 1.58
p =	t =	t =	M_p = 1.32
p =	t =	t =	M_{part} = 0.67
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{1t} =
p =	t_s = 0.20 ms	t_{ST} = 0.47 ms	M_{1p} =
p =	t_T = 0.67 ms	t =	
	t =	t =	
	t =		
	t =	Scale: time (E + HW): 0.1 ms/div	
		press: 10 psi/div	

p_4 =	200 psig	P_4/P_1 =	19.2
P_{atmos} =	30.15" Hg	Station	
T_{atmos} =	61°F	a_1 =	1117 fps
T_{tee} =	61°F	a_t =	1117 fps

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SHOCK TUBE

Run no. R 19

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 14·7 psi	M_{1p} = 1·75	time^{A}: 0·2ms/div
T_1 = 62°F		press: 10 psi /div
p_A = 35 psi	t_r =	time : /div
p_{rA} =	P_2/p_1 = 3·38	press: /div
p_{rare} =	t_{rare} =	M_{part} = 0·80
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 15 psi	t =	t =	P_{D2}/p_1 = 2·02
p =	t =	t =	M_t = 1·41
p =	t =	t =	M_p = 1·37
p =	t =	t =	M_{part} = 0·52
p =	t =	t =	
p =	t =	t =	P_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·10mS	t_{ST} = 0·53 mS	M_{rp} =
p =	t_T = 0·63mS	t =	
	t =	t =	
	t =		
	t =	Scale : time$^{D1\ HW}$: 0·1ms/div	
		press: 5 psi/div	
		* Hot wire position check	

p_4 =	200 psig	P_4/P_1 =	14·6
P_{atmos} =	29·9" Hg	Station	
T_{atmos} =	62°F	a_1 =	1118 fps
T_{tee} =	62°F	a_t =	1118 fps

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SHOCK TUBE

Run no. R 20

DRIVEN TUBE :

Readings	Derived results	Scale
p_1 = 1·96 psi	M_{1P} = 2·50	time^{A} : 0·2 ms/div
T_1 = 62°F		press: 5 psi /div
p_A = 12 psi	t_r =	time : /div
p_{rA} =	p_2/p_1 = 7·12	press: /div
p_{rare} =	t_{rare} =	M_{part} = 1·20
TEE	M_{1t} =	$t_H - t_A$ =

Readings		Derived results	
p_D = 3·2 psi	t =	t =	p_{D2}/p_1 = 2·64
p =	t =	t =	Mt = 1·86
p =	t =	t =	Mp = 1·55
p =	t =	t =	M part = 0·88
p =	t =	t =	
p =	t =	t =	p_1/p =
p =	t =	t =	M_{rt} =
p =	t_s = 0·03 ms	t_{ST} = 0·40 ms	M_{rp} =
p =	t_T = 0·43 ms	t =	
	t =	t =	
	t =		
	t =	Scale :	time^{D+HW}: 0·1 ms/div
			press: 2 psi /div
		* Hot-wire position check	

p_4 =	200 psig	P_4/P_1 =	103
P_{atmos} =	29·9" Hg	Station	
T_{atmos} =	62°F	a_1 =	1118 fps
T_{tee} =	62°F	a_t =	1118 fps

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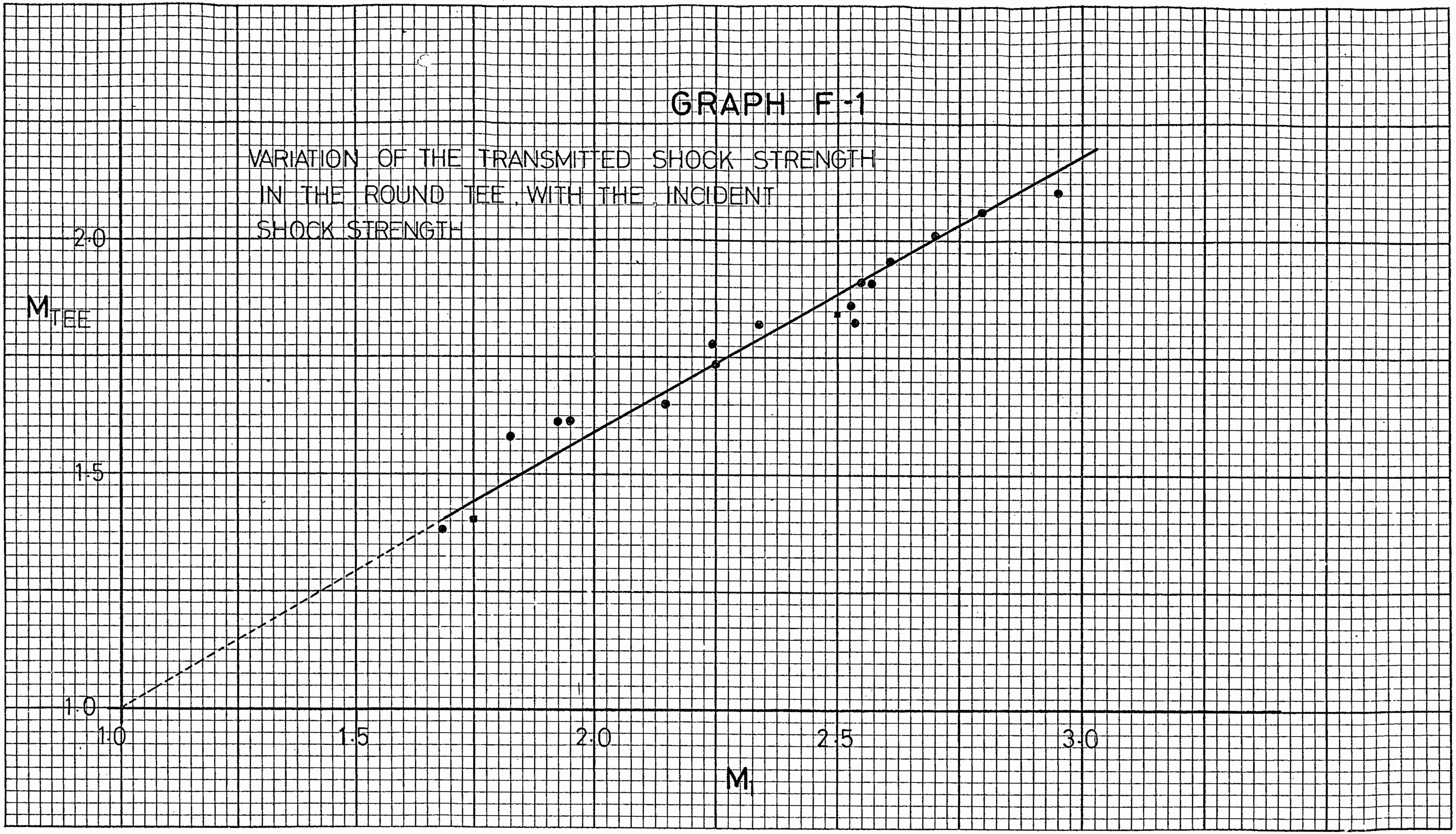
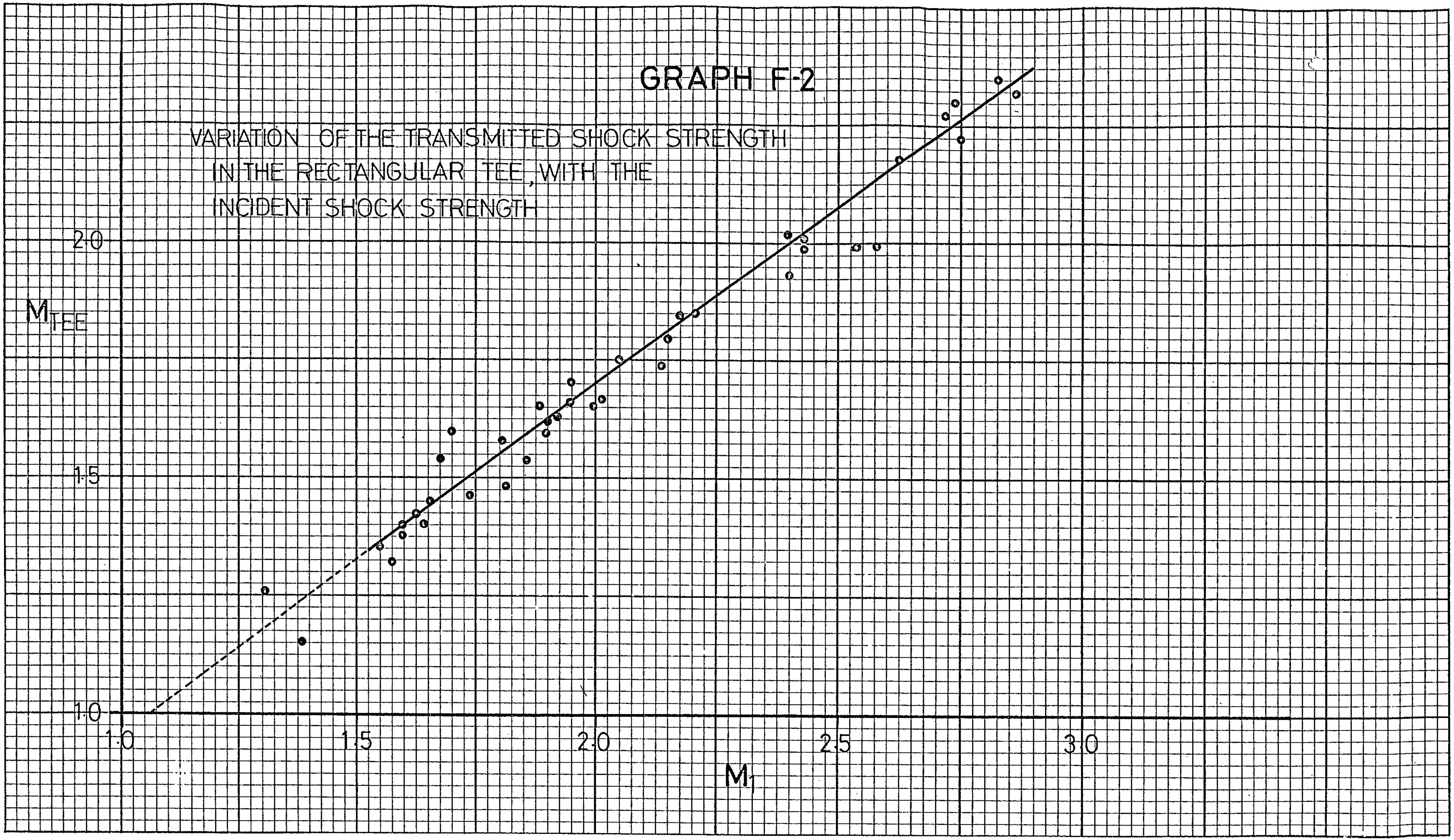
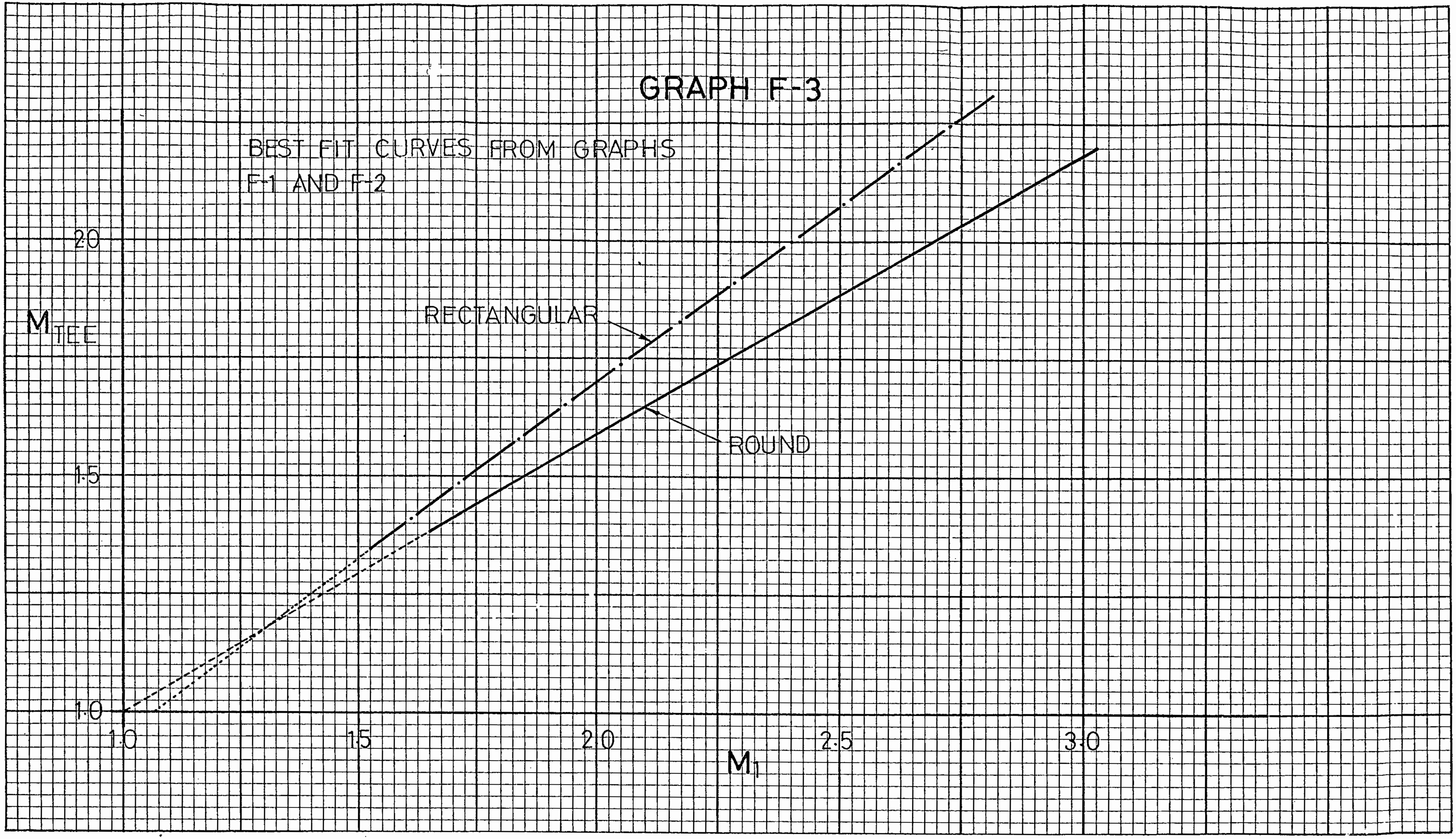
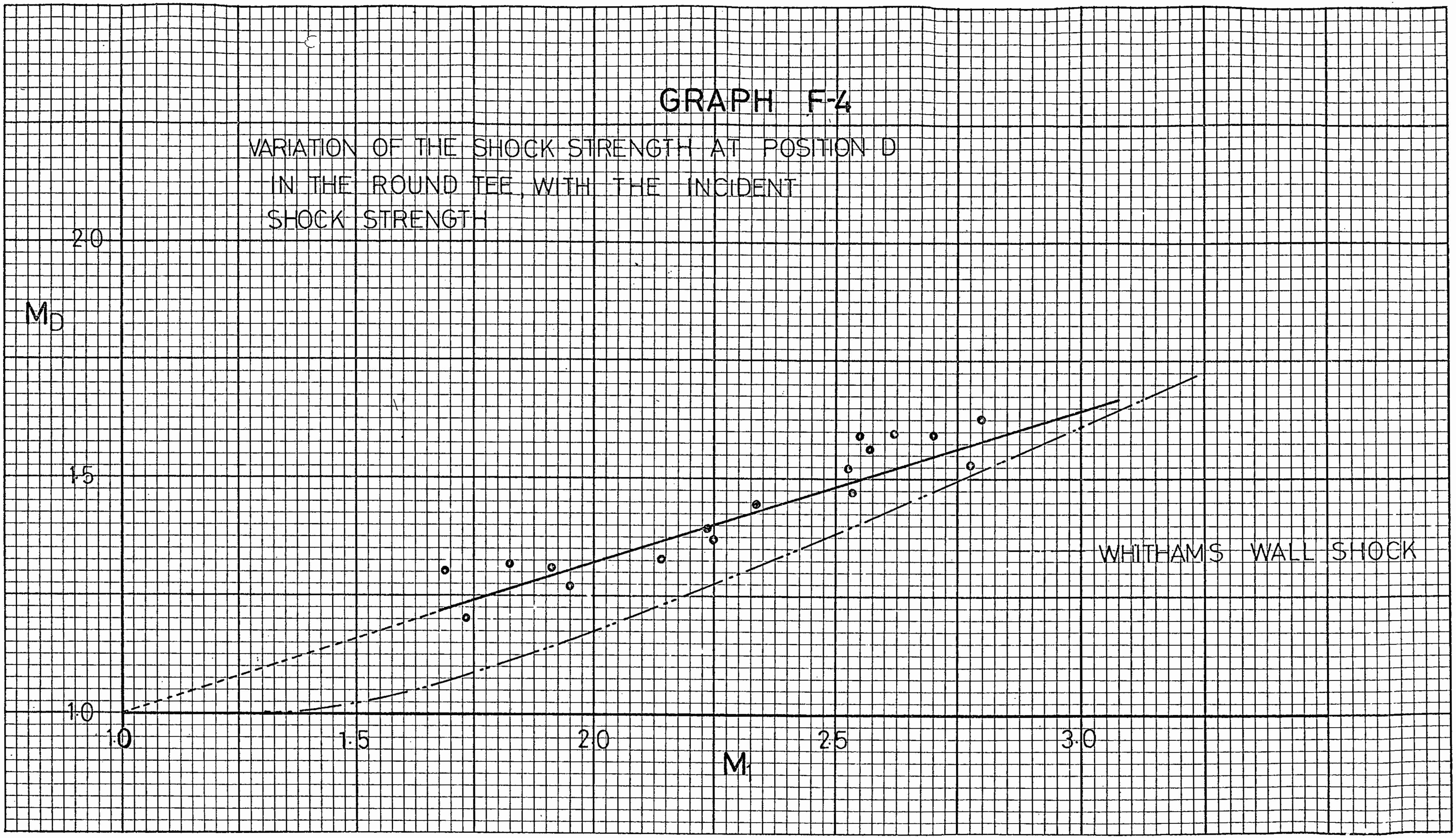

GRAPH F-1
VARIATION OF THE TRANSMITTED SHOCK STRENGTH
IN THE ROUND TEE, WITH THE INCIDENT
SHOCK STRENGTH
M_{TEE}
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0
M_I

REF.: 75/P/502

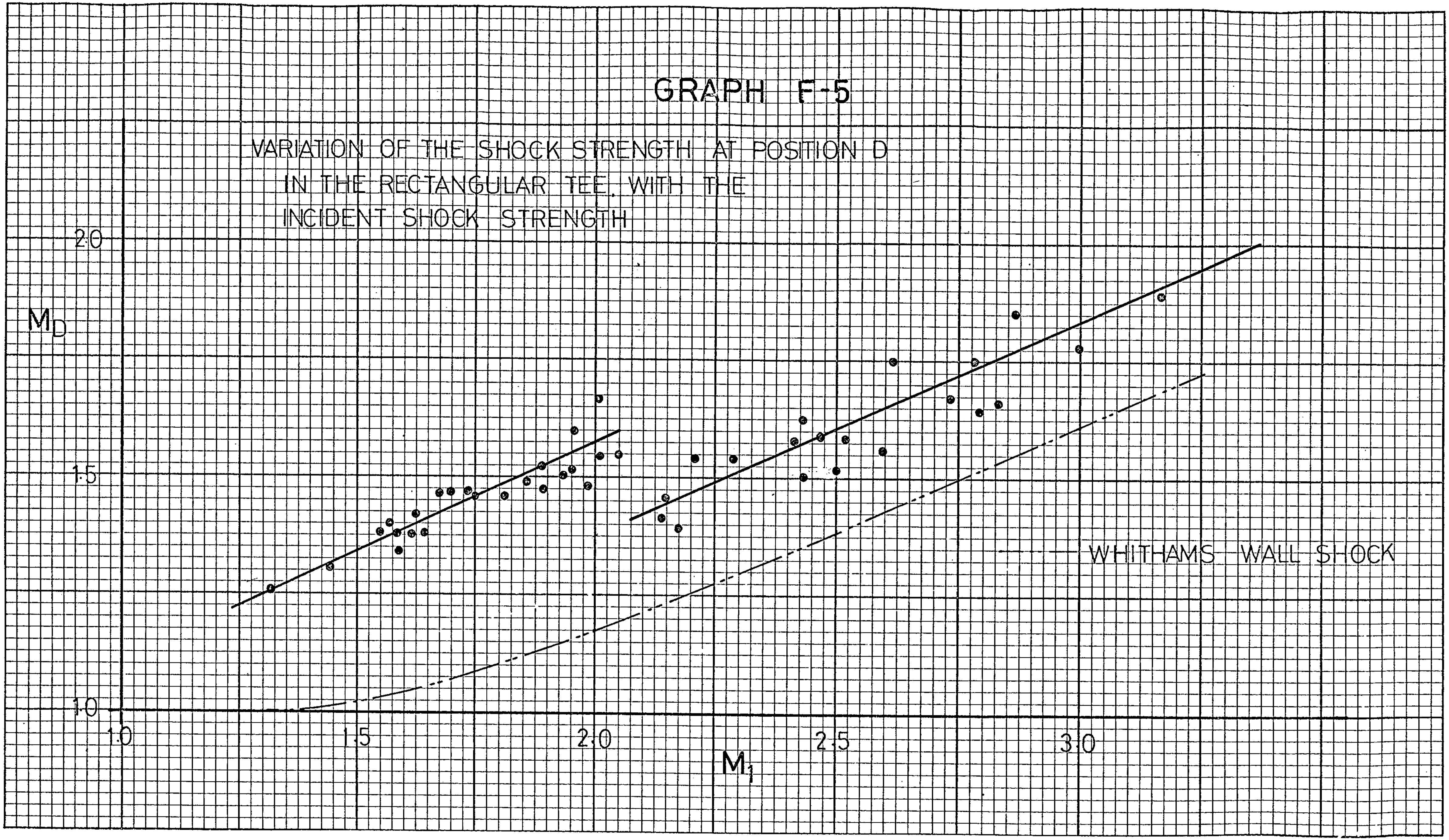

GRAPH F-2
VARIATION OF THE TRANSMITTED SHOCK STRENGTH
IN THE RECTANGULAR TEE, WITH THE
INCIDENT SHOCK STRENGTH
2.0
1.5
1.0
M TEE
1.0
1.5
2.0
2.5
3.0
M 1

REF.: 75/P/502


GRAPH F-3
BEST FIT CURVES FROM GRAPHS
F-1 AND F-2
RECTANGULAR
ROUND
M_{TEE}
2·0
1·5
1·0
1·0
1·5
2·0
2·5
3·0
M_1

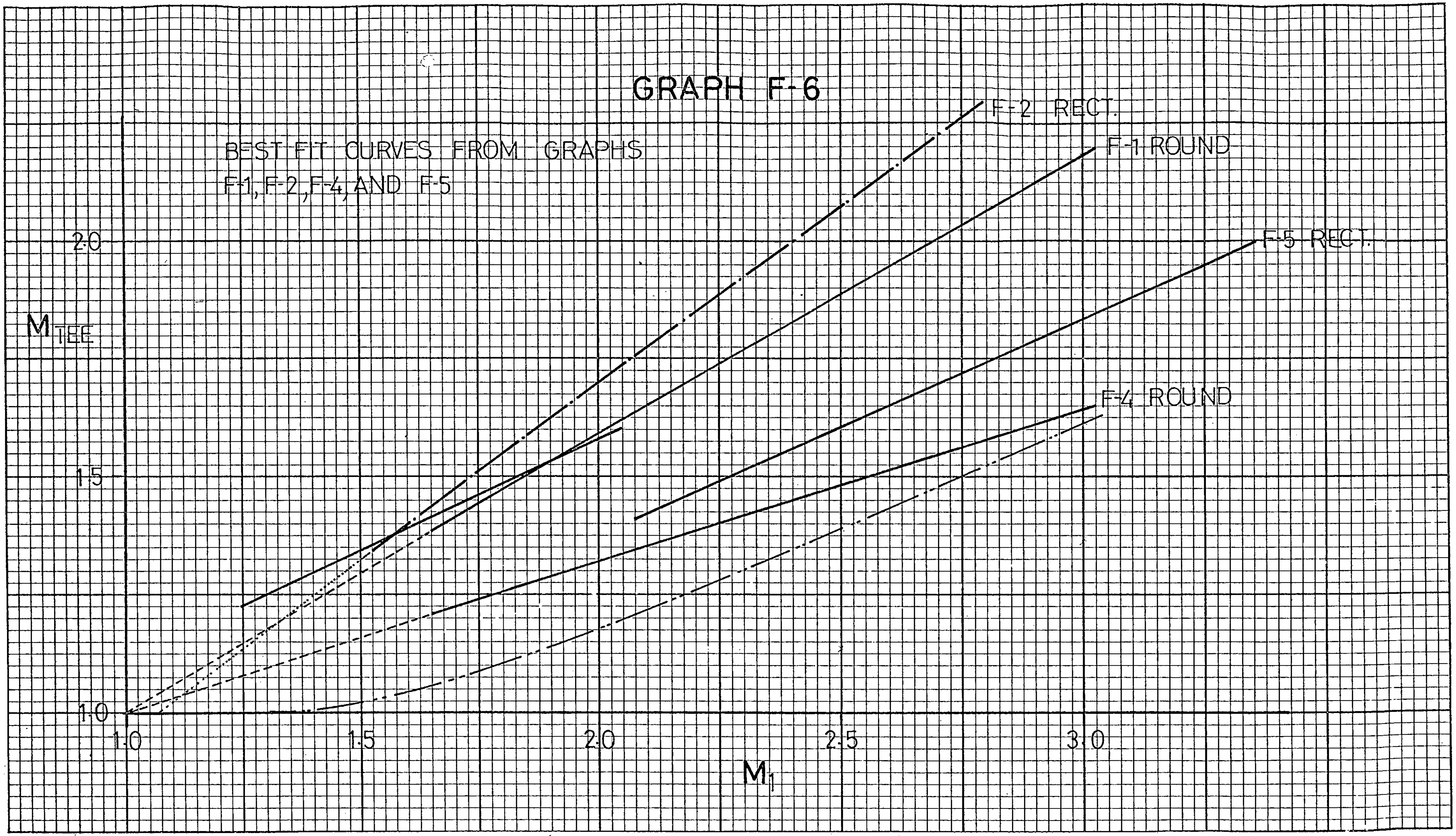

GRAPH F-4
VARIATION OF THE SHOCK STRENGTH AT POSITION D
IN THE ROUND TEE, WITH THE INCIDENT
SHOCK STRENGTH
M_D
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0
M_1
WHITHAMS WALL SHOCK

REF.: 75/P/502

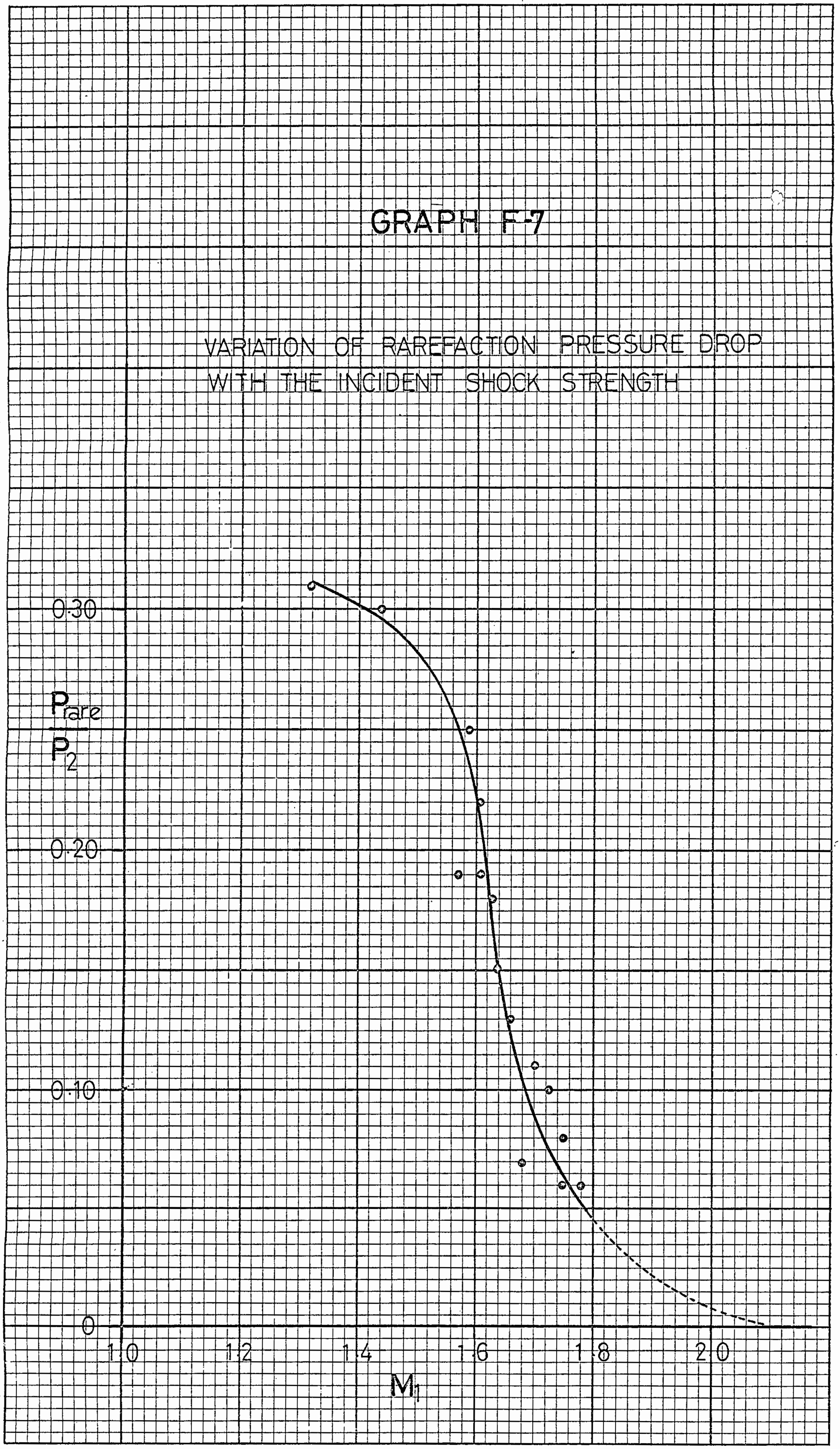


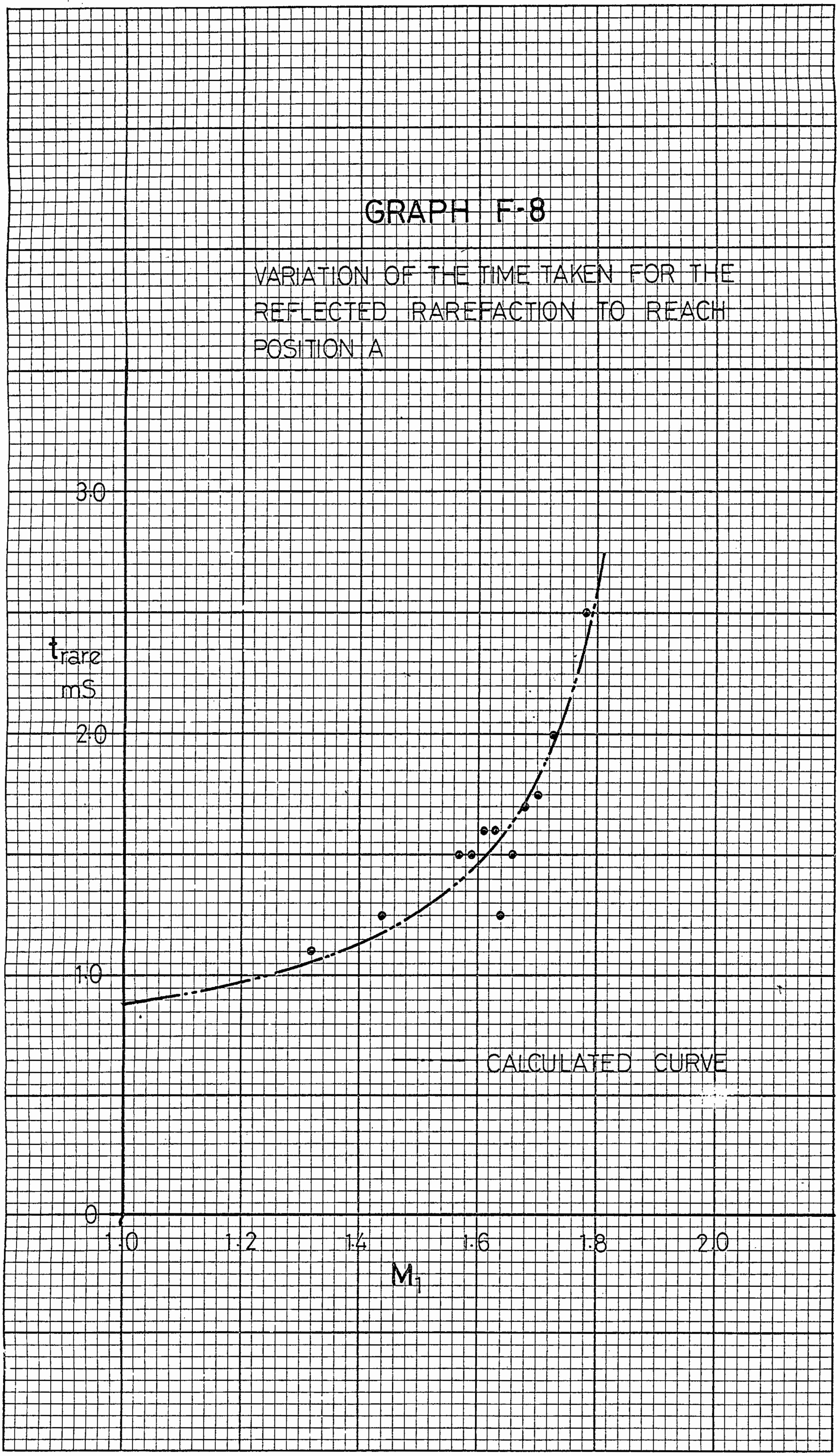
GRAPH F-5
VARIATION OF THE SHOCK STRENGTH AT POSITION D
IN THE RECTANGULAR TEE, WITH THE
INCIDENT SHOCK STRENGTH
WHITHAMS WALL SHOCK
M_D
M_1
2.0
1.5
1.0
1.0
1.5
2.0
2.5
3.0

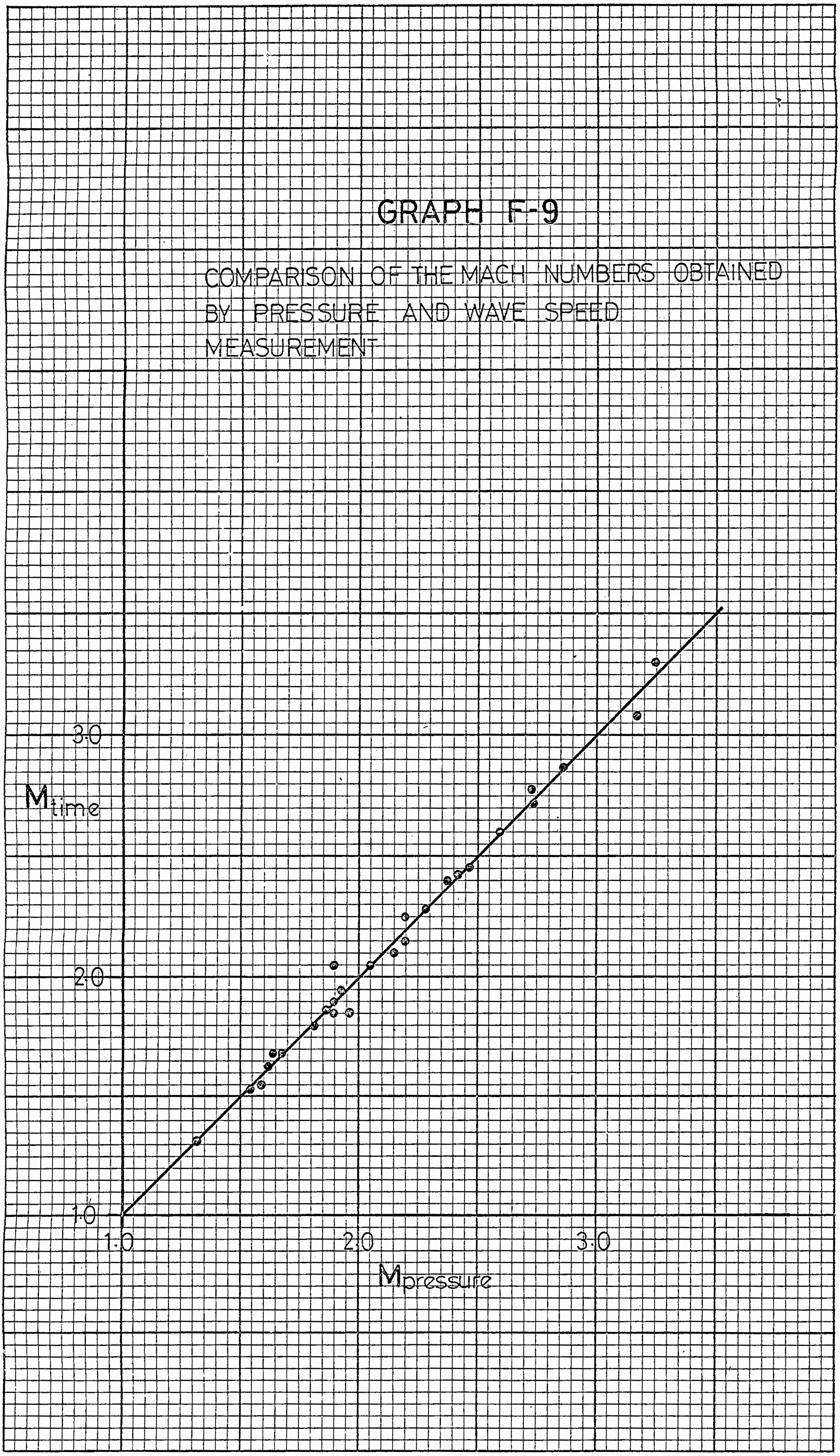
REF.: 75/P/502


GRAPH F-6
BEST FIT CURVES FROM GRAPHS
F-1, F-2, F-4, AND F-5
F-2 RECT.
F-1 ROUND
F-5 RECT.
F-4 ROUND
2.0
1.5
1.0
M TEE
1.0
1.5
2.0
2.5
3.0
M1

REF.: 75/P/502

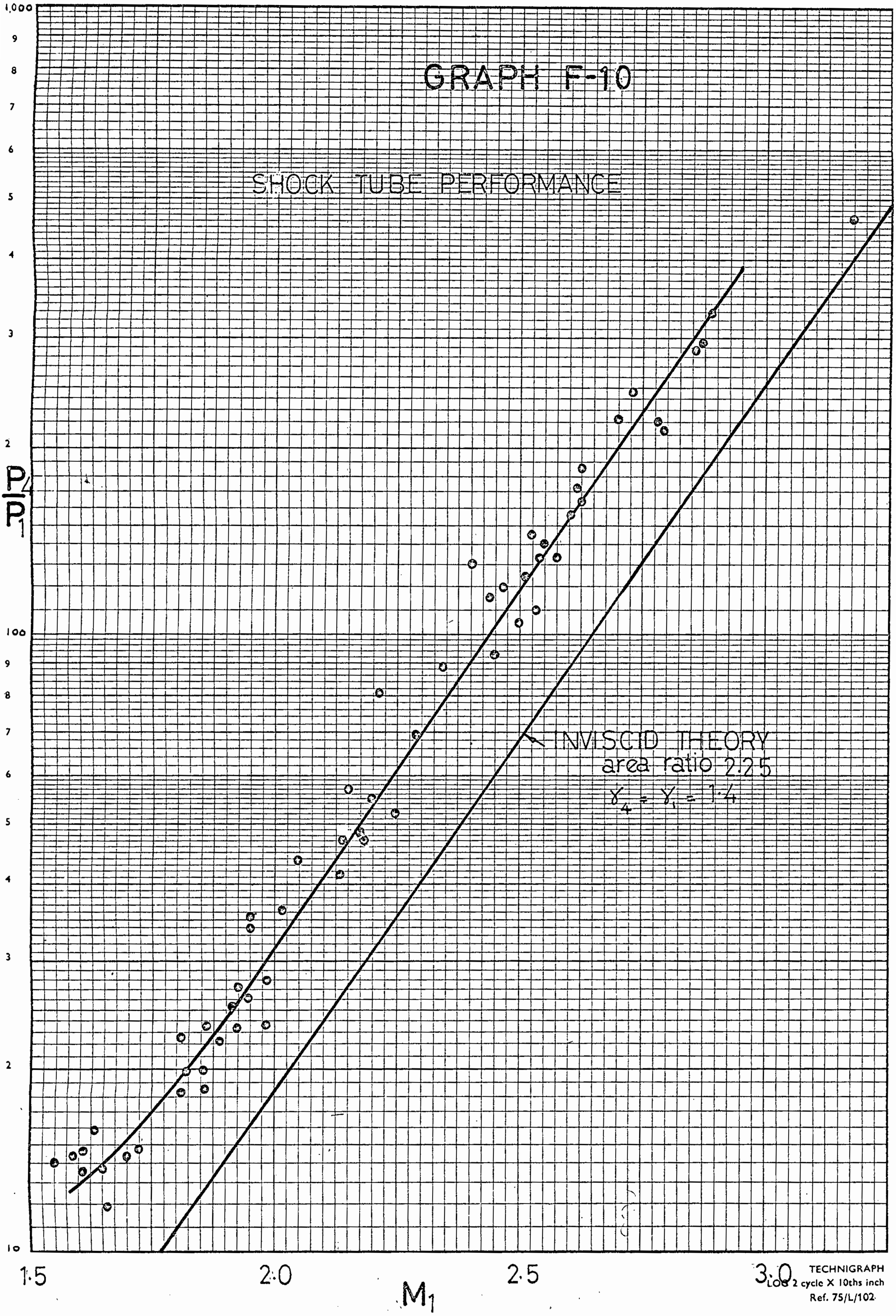

GRAPH F-7
VARIATION OF RAREFACTION PRESSURE DROP
WITH THE INCIDENT SHOCK STRENGTH
0·30
0·20
0·10
0
$\frac{P_{rare}}{P_2}$
1·0
1·2
1·4
1·6
1·8
2·0
M_1


GRAPH F-8
VARIATION OF THE TIME TAKEN FOR THE REFLECTED RAREFACTION TO REACH POSITION A
3.0
2.0
1.0
0
t_{rare} mS
1.0
1.2
1.4
1.6
1.8
2.0
M_1
CALCULATED CURVE



GRAPH F-9

COMPARISON OF THE MACH NUMBERS OBTAINED BY PRESSURE AND WAVE SPEED MEASUREMENT



GRAPH F-10
SHOCK TUBE PERFORMANCE
INVISCID THEORY
area ratio 2.25
$\gamma_4 = \gamma_1 = 1.4$
$\frac{P_4}{P_1}$
1,000
100
10
1·5
2·0
2·5
3·0
M_1
TECHNIGRAPH
LOG 2 cycle X 10ths inch
Ref. 75/L/102

GRAPHS

PROGRAMMES

```
CHAPTERO
PRINT+CO ORDINATES OF THE SHOCK AFTER A 90 DEGREE BEND +
PRINT+ACCORDING TO WHITHAMS THEORY+
NEWLINE4
PRINT+ANGLE RAD  ANGLE DEG          X          Y+
NEWLINE2
C&5.0743
D&ØSQRT(C)
E&C+1
E&ØSQRT(E)
E&E/D
F&ØARCTAN(1ØD)
I&0(1)50
X&-0.01IT
PRINT(X)1Ø5
Y&-1.8I
SPACE
PRINT(Y)2Ø4
G&X/D
G&ØEXP(G)
H&ØSIN(F-X)
A&EGH
SPACE2
PRINT(A)0Ø4
Z&ØCOS(F-X)
B&EGZ
SPACE
PRINT(B)0Ø4
NEWLINE
REPEAT
END
CLOSE
```

CO ORDINATES OF THE SHOCK AFTER A 90 DEGREE BEND ACCORDING TO WHITHAMS

ANGLE RAD	ANGLE DEG	X	Y
0.00000	0.0000	0.1000 / 01	0.4439 / 00
-0.03142	- 1.8000	0.9994 / 00	0.4066 / 00
-0.06283	- 3.6000	0.9977 / 00	0.3698 / 00
-0.09425	- 5.4000	0.9948 / 00	0.3336 / 00
-0.12566	- 7.2000	0.9909 / 00	0.2980 / 00
-0.15708	- 9.0000	0.9859 / 00	0.2630 / 00
-0.18850	-10.8000	0.9799 / 00	0.2287 / 00
-0.21991	-12.6000	0.9730 / 00	0.1951 / 00
-0.25133	-14.4000	0.9651 / 00	0.1622 / 00
-0.28274	-16.2000	0.9563 / 00	0.1299 / 00
-0.31416	-18.0000	0.9466 / 00	0.9845 /-01
-0.34558	-19.8000	0.9361 / 00	0.6772 /-01
-0.37699	-21.6000	0.9247 / 00	0.3775 /-01
-0.40841	-23.4000	0.9126 / 00	0.8566 /-02
-0.43982	-25.2000	0.8998 / 00	-0.1983 /-01
-0.47124	-27.0000	0.8863 / 00	-0.4742 /-01
-0.50265	-28.8000	0.8721 / 00	-0.7419 /-01
-0.53407	-30.6000	0.8573 / 00	-0.1001 / 00
-0.56549	-32.4000	0.8419 / 00	-0.1253 / 00
-0.59690	-34.2000	0.8260 / 00	-0.1495 / 00
-0.62832	-36.0000	0.8095 / 00	-0.1730 / 00
-0.65973	-37.8000	0.7926 / 00	-0.1956 / 00
-0.69115	-39.6000	0.7751 / 00	-0.2173 / 00
-0.72257	-41.4000	0.7573 / 00	-0.2382 / 00
-0.75398	-43.2000	0.7391 / 00	-0.2583 / 00
-0.78540	-45.0000	0.7205 / 00	-0.2775 / 00
-0.81681	-46.8000	0.7015 / 00	-0.2958 / 00
-0.84823	-48.6000	0.6823 / 00	-0.3133 / 00
-0.87965	-50.4000	0.6628 / 00	-0.3299 / 00
-0.91106	-52.2000	0.6431 / 00	-0.3457 / 00
-0.94248	-54.0000	0.6232 / 00	-0.3607 / 00
-0.97389	-55.8000	0.6031 / 00	-0.3748 / 00
-1.00531	-57.6000	0.5828 / 00	-0.3881 / 00
-1.03673	-59.4000	0.5624 / 00	-0.4006 / 00
-1.06814	-61.2000	0.5420 / 00	-0.4123 / 00
-1.09956	-63.0000	0.5214 / 00	-0.4232 / 00
-1.13097	-64.8000	0.5008 / 00	-0.4333 / 00
-1.16239	-66.6000	0.4802 / 00	-0.4426 / 00
-1.19381	-68.4000	0.4596 / 00	-0.4511 / 00
-1.22522	-70.2000	0.4391 / 00	-0.4589 / 00
-1.25664	-72.0000	0.4186 / 00	-0.4659 / 00
-1.28805	-73.8000	0.3981 / 00	-0.4722 / 00
-1.31947	-75.6000	0.3778 / 00	-0.4777 / 00
-1.35088	-77.4000	0.3576 / 00	-0.4826 / 00
-1.38230	-79.2000	0.3375 / 00	-0.4868 / 00
-1.41372	-81.0000	0.3176 / 00	-0.4902 / 00
-1.44513	-82.8000	0.2979 / 00	-0.4930 / 00
-1.47655	-84.6000	0.2783 / 00	-0.4952 / 00
-1.50796	-86.4000	0.2590 / 00	-0.4967 / 00
-1.53938	-88.2000	0.2399 / 00	-0.4976 / 00
-1.57080	-90.0000	0.2210 / 00	-0.4979 / 00

```
0 01  CHAPTERO
  00  F@4
  00  U@4
  00  D@4
0 02  PRINT+SOLUTION OF WHITHAMS THEORY FOR SHOCK STRENGTH AFTER A +
0 02  PRINT+ 90 DEGREE BEND BY SIMPSONS TYPE INTERGRATION+
0 03  NEWLINE4
0 04  PRINT+ MO       MW+
0 05  NEWLINE2
0 06  B&0.005
0 07  K&1(1)24
0 08  A&1.2+0.1K
0 09  PRINT(A)1Ø1
0 10  SPACE2
1 10  Y&0
0 11  I&0(1)400
0 12  U1&A-IB
0 13  U2&U1-B/2
0 14  U3&U1-B
0 15  J&1(1)3
1 15  JUMP2ØUJ&1
0 16  D&0.4UJUJ+2
0 17  E&2.8UJUJ-0.4
0 18  D&D/E
  01  D&ØMOD(D)
0 19  D&ØSQRT(D)
0 20  E&1+0.7014214/D-0.7014214D
0 21  F&2D+1+1/UJ/UJ
0 22  F&EF
0 23  FJ&2/F
0 24  DJ&FJUJUJ-FJ
0 25  DJ&-2/DJ
  02  DJ&ØMOD(DJ)
0 26  DJ&ØSQRT(DJ)
0 27  REPEAT
0 K8  2)X&D1+4D2+D3
0 29  X&0.3333333BX
0 30  Y&Y+X
0 31  JUMP1ØY≮1.5707964
0 32  REPEAT
0 33  1)PRINT(U3)1Ø3
0 34  NEWLINE
0 35  REPEAT
0 36  END
0 37  CLOSE
```