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Design and Operating Features of the N.P.L. 6 in. Shock Tunnel

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Summary.

Engineering aspects of the shock tunnel facility are described. Details of gas services and routine instrumentation are given. The performance envelope of the tunnel is discussed and routine measurements presented.

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* Approved on behalf of Director, N.P.L. by Dr. R. C. Pankhurst, Superintendent of Aerodynamics Division.
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1. *Design and Operating Features of the N.P.L. 6 in. Shock Tunnel.*

1.1. *Introduction.*

During 1956 interest was stimulated at the N.P.L. to pursue aerodynamic studies in the high-temperature, high-velocity regime of hypersonic flight. Any attempt to produce the flow and environmental conditions prevailing in free flight at Mach numbers above 5 for the prolonged testing periods available in subsonic and supersonic wind tunnels imposed severe mechanical and metallurgical problems in design.

It was realised that no one facility would produce all the necessary conditions, and plans were made to equip a small laboratory with a range of apparatus for studying hypersonic and low-density flows of a fundamental nature, in character with other work of the Aerodynamics Division.

At that time much work on flow phenomena in shock tubes had been carried out by other workers so it was decided to give initial emphasis on the immediate development of a shock tube to gain experience of instrumentation and operation. This NPL 3 in. shock tube was progressively improved and an expanded working section incorporated until it has now become a useful tool in its own right.

Much experience and useful experimental work has flowed from it since early 1957. (References 1 to 5). From this experience and knowledge plans to build a larger shock tunnel were made.

This large shock tunnel (now called the N.P.L. 6 in. shock tunnel) was completed during 1960 and the first runs with hydrogen driver gas were made in December 1960. The tunnel has completed over 1000 runs to date.

The tunnel was designed primarily for operation with driver gases at room temperature. It is a conventional reflected shock tunnel consisting of a high-pressure driver section, interchangeable nozzles and a constant area working section with an added dump chamber. (Fig. 1).

1.2. *Mechanical Design.*

1.2.1. *Driver and diaphragm sections.*—The driver section has two possible diaphragm stations, one section being 6 ft long and the other 12·5 ft long. (Fig. 2).

The 6 ft section was designed and tested to operate with driver gases up to 15 000 p.s.i. and the 12·5 ft section to operate at 7 500 p.s.i.

The short, high-pressure section has not been used for routine reflected-shock running since the ratio of driver to channel lengths (8:1) was designed for possible straight-through operation. Using only the second diaphragm station gives an overall driver length of 18·5 ft, and the reflected expansion originating at this station gives acceptable running times for all driver gases used (Figs. 25, 26 and 27).

The driver sections are made from gun barrel with an inside nominal diameter of 6 in. and a wall thickness of 3 in. The inside surfaces are plated with 'Kanigen'* to prevent corrosion and also to provide a smooth surface.

A valve assembly is mounted on top of the driver section and is designed to admit and contain gases up to 15 000 p.s.i. In this assembly there is a mushroom shaped valve that is used for connection to a vacuum pump for pre-evacuation of air from the driver section before the driver gas is admitted. This valve gives a leak-tight seal against the driver pressure. These valves are remotely operated by nitrogen feed lines at 100 p.s.i. (Section 5.1).

A separate 1 in. diameter dump valve for emergency use is mounted on the driver section and can be operated rapidly from the gas control room by a 2000 p.s.i. nitrogen feed line which gives a 3:1 mechanical advantage on a piston actuator.

1.2.2. *The diaphragm stations.*—Each diaphragm station is operated by means of a breech mechanism (Fig. 3) and horizontal slide operated by a hydraulic ram and feed lines at a pressure of 2000 p.s.i.

The hydraulic system is actuated electrically. It rotates a breech until the splines are released, a hydraulic ram then retracts the whole drive chamber from the channel, allowing easy access for diaphragm loading. Rectangular transition pieces have been fitted to both driver and driven sections to allow uniform petalling of the diaphragms on bursting, (Fig. 3).

'O' rings are recessed in the bolster plates (various thickness of bolster plates can be fitted to accommodate changes in diaphragm thickness) and these have given a good vacuum seal and have been tested in position with nitrogen up to a pressure of 7 500 p.s.i.

The driver and driven sections are mounted on steel rollers to allow for longitudinal recoil. The hydraulic pressure is left on when strong shock waves are produced, to prevent excessive recoil. With nitrogen driving nitrogen at a gas driver pressure of 3000 p.s.i., the maximum recoil is 4 in. without the assistance of the hydraulic system and $\frac{1}{2}$ in. with the system on at 2000 p.s.i.

A thorough maintenance is carried out every 25 runs which includes alignment of the breach mechanism and slide gear, renewal of all 'O' seals, 'pulling through' driver and driven sections and general oiling and greasing of moving parts. This has resulted in almost trouble-free operation of the mechanical aspects.

1.2.3. *Diaphragms.*—Apart from a few trial runs with EN 58 stainless steel, where scatter up to 400 p.s.i. in bursting pressures of 3000 p.s.i. was experienced, mild steel has been used as the diaphragm material.

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* Chemically deposited nickel.

The initial runs on the shock tunnel were made with diaphragms 0·125 in. thick and 'V' groved to about 0·010 in. depth to give 4 petals at right angles on bursting. These burst fairly consistently at 3000 p.s.i. but the petals reflected back, tearing off small particles of steel which had to be removed from the channel after each run. The thickness of the mild steel and the depth of the milled slots were increased until the diaphragm opened completely on bursting but did not reflect back at all. A material thickness of 0·25 in. (Fig. 4) was required to give this control and bursting pressures between 2000 to 3000 p.s.i. were obtained by varying the depth of the milled slot from 0·110 in. to 0·090 in. (Fig. 37).

The material used is to specification E.N.2., hot rolled, cold mangled and of folding quality. To obtain maximum uniformity of material a single billet of 7 to 8 tons weight is rolled to produce plates of thickness 0·265 in. + 0·24 in. − 0 in. 8 feet by 4 feet plates are supplied from the mills and these are gas cut to produce 16 in. diameter discs. Each disc is carefully heat treated to 650°C for 5 hours to remove all stresses and strains and is allowed to cool in the oven in order to obtain good bending quality. Both surfaces are ground to remove scaling, to give an accurate overall thickness of 0·25 in. ± ·001 in. and to produce suitable surface flatness and finish to ensure adequate sealing on the 'O' ring when clamped in position. V-grooves are cut at right angles to one another using a 60° cutter having a tip radius of 0·020 in. to produce the stress concentrations necessary to ensure good petalling without fragmentation. A close inspection of the V-groove formation is made and the cutter is reground or rejected when wear is evident; feed rate and depth of cut are also carefully controlled as variations in these affect the bursting pressures. This care in manufacture has given clean consistent bursts and contributed to the excellent repeatability of shock tunnel flow conditions.

The consistency of bursting pressure is strongly related to the time duration and rate of pressurising of the diaphragm. It has been observed that by deliberately halting the pressurising at 1000 p.s.i., and holding for 5 minutes, that the bursting pressure is railed from 2700 p.s.i. to 3000 p.s.i. for a specific diaphragm thickness and slot.

The diaphragm opening time has not been measured experimentally, but accurate measurement of the shock velocity at 6 detector stations along the channel shows very little attenuation. Measurements of shock attenuation are reported in Section 2.2.

1.2.4. *Shock tube channel.*—The channel or driven tube is 38 ft 6 in. long and has a constant diameter of 5·5 in. and wall thickness of 2·75 in. The bore is plated with 'Kanigen' and the finish is smooth. This section can be operated as a shock tube up to a pressure of 7 500 p.s.i.

There are accurately shaped mounts and plugs for 8 shockwave detector stations and 4 pressure-gauge points distributed along the tube. The mounts form a flush part of the inner wall of the tube and do not disturb the shock tube flow. A resistance thermometer assembly is shown in Fig. 20.

The whole of the tube is supported on rollers and may be driven hydraulically apart from the nozzle to allow the insertion of a Mylar diaphragm at the nozzle throat. (Figs. 5 and 6).

There is a shaped nozzle sealing bush screwed into the nozzle end of the driven tube which has a set of chevron seals and 'O' rings sliding over the nozzle on closing and sealing it for vacuum and pressure. This provides a telescopic joint, without leaks, under all present recoil conditions. Details of the joint for the 1 in. throat nozzle are in Fig. 6b.

1.2.5. *Shock tunnel nozzles.*—The tunnel was designed for 'straight through' operation as well as for reflected-shock operation. The obvious advantages gained by using the reflected-shock method around 'tailored' conditions has lead to the abandonment of the 'straight-through' configuration and the tunnel is not now connected for this operation. In Fig. 6 can be seen the disconnected flange for the nozzle boundary-layer bleed which would be used for 'straight-through' operation.

Four sets of detachable conical nozzle sections and bushes give a range of flow Mach numbers from $M\infty = 5 \cdot 0$ to $M\infty = 12 \cdot 0$. (Fig. 7). The throats are 0·2 in. ½ in. 1 in. and 2 in. diameter. The total expansion angle is 11° 25′, and the nozzle exit diameter is 16 ins. At the throat of each nozzle there is a screwed diaphragm holder which can be easily removed for the insertion of Mylar diaphragms. (Fig. 6b).

A Mylar diaphragm 0·002 in. thick is capable of holding a vacuum of 1 micron Hg in the working section and an opposing pressure of 15 p.s.i.a., in the channel. 0·005 in. thick Mylar has been used up to 60 p.s.i.a. in the channel with the same vacuum conditions. Discs of Mylar are used since they vaporise during running and so do not bombard the models which are on the centre line of the nozzle.

1.2.6. *Model support in working section.*—In an impulsively-driven wind tunnel the acceleration loads are transferred through the tunnel structure and nozzle assembly at a velocity of around 16 000 ft/sec. and thus generally precede the shock wave that is to heat and pressurise the wind tunnel nozzle. The presence of acceleration loads is invariably shown by the occurrence of oscillations on the output of the test section transducers before the wind load occurs on the model. The magnitude of these accelerations can be several 'g's and can cause transducer signals that may be comparable with the magnitude of those to be measured. The accuracy is thereby greatly reduced and the mechanical loading can damage the transducer.

In the N.P.L. 16 in. test section, the sting is firmly attached to a floor-mounted, vertical steel pillar that is not in contact with the shock-tunnel test section. The sting quadrant or traverse beam is mechanically supported by the pillar through metallic bellows that are vacuum and pressure sealed. In Fig. 9 the lower flange only of the quadrant support is shown, and in Fig. 8 the upper flange of the completely assembled sting support is visible together with the attachment to the vertical steel pillar directly behind the test section.

1.3. *High Pressure Plant and Services.*

1.3.1. *Storage of gases* (Reference should be made to Fig. 10).—The nitrogen gas is stored in standard high-pressure bottles in banks of 30 on mobile trailers at pressures up to 4000 p.s.i. This nitrogen gas, when required as the driver, can be admitted directly to the driver section *via* a manual valve. The nitrogen gas is also used to charge the channel section to the required pressure ratio across the main diaphragm. A further use is to bring the whole of the tunnel and dump tank back to atmospheric pressure after a helium run since the tunnel is reduced to 3 p.s.i.a. during the helium reclamation process. (Section 1.3.2.) Since the use of hydrogen as a driver-gas for the tunnel has been abandoned, helium is the next most suitable for obtaining moderate (i.e., 2000°K) reservoir temperatures.

Helium is purchased in bottles at a pressure of approximately 2200 p.s.i. Sixty of these bottles are stored in two rooms adjacent to the gas control room. A Corblin A4C 1000 diaphragm compressor is used to compress the helium gas to 15 000 p.s.i. 9 cu. ft of storage at this pressure is available in 12 stainless steel bottles. The bottles and the compressor are situated in a separate, safety-designed building.

1.3.2. *Helium recovery plant* (Reference should be made to Fig. 11).—As pointed out in Section 2.1. the cost of each run would be very high if the gas were allowed to be dumped to atmosphere. After a run, the helium/nitrogen mixture in the shock tunnel will occupy 370 cu. ft at about 3 atm. absolute pressure. As much as possible of this mixture needs to be reclaimed, purified and recompressed.

A plant to meet these requirements has been designed by N.P.L. Aerodynamics Division and Ministry of Public Buildings and Works staff and is now in operation.

The plant has a two stage A4C V type compressor with a booster A4C 150 compressor.

During the first stage of reclamation the two A4CV compressors are used in parallel so that large volumetric flow is attained. A reducing valve is located in the circuit so that the suction side of the compressor varies from about 3 atmospheres absolute (equilisation pressure) to 1 atmosphere absolute and the outlet does not exceed 16 atmospheres absolute. The swept volume of both stages in this configuration is 70 cu. ft min. Volumetric efficiency obtained from test curves is about 50 per cent and hence the total flow of both stages in parallel is 35 standard cu. ft/min. The amount of free helium and nitrogen mixture used when bursting diaphragms around 3000 p.s.i., is about 900 cu. ft. Thus the time for the first operation of recovery is (900—370)/35 mins. i.e. approximately 15 mins.

In the second stage of reclamation (commencing at 1 atmosphere absolute) the A4CV compressors are used in series to obtain the necessary compression ratio that will reduce the tunnel pressure to an acceptable value of about 0·3 atm. abs. The delivery of the first stage is 18 cu. ft/min, and the average suction pressure is $\frac{1}{2}(1 + 0{\cdot}3) = 0{\cdot}65$ atm. abs. Therefore the average flow is approximately 11·5 cu. ft/min, and the time taken for this second operation (remembering that 370 cu. ft of helium/nitrogen mixture remains at 1 ats. abs) is $370 \times 0{\cdot}7^{*}/11{\cdot}5$ mins. i.e. approximately 23 mins.

The time for the 2nd operation is a constant since the equalisation pressure will be above 1 atm. abs. for normal shock tunnel running operation with bursting pressures in excess of 1000 p.s.i. Hence the total time of reclamation was designed to be about 35 to 40 mins. for 3000 p.s.i., driver condition. The first stage operation takes less if the bursting pressure is reduced and of course will be increased for higher bursting pressures. This has proved to be so during the runs so far carried out.

Lower suction pressures have been obtained when the compressors have been left running but the efficiency is poor. It is therefore, accepted that some helium (say 5 per cent) is to be lost each run if the reclamation time is to be of the order of 45 mins.

1.3.3. *Helium purification.*—The third-stage A4C150 compressor (which is fed from the second stage compressor) passes the helium/nitrogen mixture either to a purifier or to storage bottles for later purification. If the gas mixture is directed to the purifier (under pressure up to 2000 p.s.i.) it first passes through a heat exchanger to reduce the temperature of the gas and to remove any water vapour should this be present. The helium and nitrogen gas used have frost points lower than −100°F., and hence the water-vapour content is not troublesome. The gas next enters a liquid-nitrogen cooled condenser coil. This 3 in. diameter, 36 ft long coil is filled with activated charcoal. Wire mesh filters are fitted at each end of the coil to prevent any of the charcoal entering the gas stream. Any air or nitrogen present in the gas is liquefied and absorbed by the charcoal. The gas

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* About 0·3 atm abs of helium/nitrogen mixture is lost each run, therefore, the volume reclaimed during the 2nd operation is 0·7 × 370 cu. ft, i.e. about 260 cu. ft.

then flows from the purifier through another heat exchanger to pass on to the pure helium gas storage cylinders. All materials used in the construction of this purifier are EN58 stainless steel.

The purifier is capable of handling about 10 000 cu. ft of gas before reactivation of the charcoal is necessary. This is automatically carried out over night by passing hot compressed air over the charcoal for a period of about 8 hours.

A purity monitor is used to check continuously the purity of the helium as it enters the storage bank. The operation of the meter depends on the measurement of the thermal conductivity of the gas. Four wires are connected as a Wheatstone bridge and are heated by an electric current. Two of the wires sense pure helium in two sealed chambers and the other two are exposed to the gas to be measured. Any out of balance of the Wheatstone bridge records, on a direct reading dial, the percentage of purity. The range of the meter is from 98 to 100 per cent pure.

1.3.4. *Gas feed to driver chamber.*—Pressurising of the driver section is carried out from a separate control room. (Fig. 14). A stainless steel valve assembly is situated on the driver section capable of admitting gases up to 1000 atm pressure. The valves of this assembly are activated remotely by pneumatic lines operated from the gas control room. A continuous measurement of the pressure being admitted to the driver section is made by two J. Langham Thompson pressure transducers. One transducer is situated in the flexible line feeding the gases and the other in the driver section near the diaphragm station. This system allows recording of high pressures to be made without the need of high pressure lines to the control room. A fuller description of the driver pressure measurement is given in Section 1.6.1.

1.4. *Vacuum Plant and Services.*

The dump tank and working section are evacuated to low pressures to assist rapid flow establishment in the test section. This back pressure needs to be kept below 500 μHg. if smooth establishment of the flow is to be obtained well within the useful running time of the tunnel. The normal operation of the tunnel is to evacuate the nozzle and test section to 1 μHg. total pressure. These factors necessitate very good vacuum leak-tightness and good-quality castings for the tunnel. The measured leak rate of the dump and working section is about 2 μHg. per minute.

The vacuum pumping plant was supplied by F. Leybold-Elliott and consists of two S180/S6 backing pumps connected in tandem. To increase the speed of evacuation a single stage Roots pump model 35 is brought into the circuit at about 20 mm Hg. (Fig. 15). At pressures above this level the Roots pump is designed to bypass in order to keep the pressure difference between the input and the output at a fixed predetermined value to prevent overheating. The pumping plant is able to evacuate the working section and dump tank to 1 μHg in about 30 minutes.

A sliding disc valve* connects the pumping plant to the tunnel *via* 15 in. diameter pipework. This valve can be opened or closed by an electrically operated remotely controlled pneumatic line. (Fig. 12). The valve is completely leak tight at 1 μHg. Incorporated on the pump side of the valve is a liquid-nitrogen trap. This condenses out any water vapour present in the tunnel and allows the vacuum plant to reach a lower pressure.

A coarse measurement of the vacuum is made by a Macleod gauge† operating on the compression pressure principle. However, this instrument does not record the total pressure. To measure the

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* Camvac. Cambridge Vacuum Instruments.

† Kammerer. Leybold-Elliott, London S.E.10.

total pressure an Alphatron gauge* is used. A record of the pressure from atmospheric to 1 μHg. is continuously displayed on a dial and gives an accurate measurement throughout the required measuring range.

The diameter and thickness of the Mylar diaphragm which separates the channel section from the nozzle and the working section depends on the nozzle being used and the initial pressure required in the channel section. (Section 1.2.5). The channel and driver sections have independent Metrovac rotary vacuum pumps† which can reduce the pressure in the respective sections to less than 1 mm Hg in about 5 minutes.

1.5. *Auxiliary Services.*

1.5.1. *Pneumatic services.* (Reference should be made to Figs. 12 and 16).—The auxiliary services, such as isolator valves, utilise nitrogen at a pressure of 2200 p.s.i. which is stored in cylinders containing 250 cu. ft. at S.T.P.

The system consists of a double feed from twelve bottles, one for the charge circuit and one for the isolator valves etc. They are similar in design using reducing valves of 3600 p.s.i. to 150 p.s.i. output preceded by filters. The output pressure is regulated to 125 p.s.i. and a blow off valve is incorporated for excess pressure above 250 p.s.i. This is considered a useful operating pressure as normal charge pressures to the shock tube channel are 50 p.s.i. and pressure operated indicator lamps trigger at 115 p.s.i. Both systems have several low pressure bottles acting as backing pressure reservoirs between the reducer outputs and the control valves of each system. As the tunnel may be operated using either nitrogen or air as the channel gas there is provision for selecting the nitrogen charging outlet or a low pressure supply of dry filtered air at 350 p.s.i. pressure.

The nitrogen supply services are fed to panels in the two control rooms. The line in the gas charging room energises the isolator inlet port for the driver chamber of the tunnel.

The main control room supply serves a similar purpose as that in the gas charging room but it controls the isolator of the channel and thus driven gas conditions. One additional feature is the operation of the Camvac system to isolate the working system while under vacuum. Both supplies are remotely controlled from the control room using electromagnetic switching.

All ports can be closed instantly and any one particular one opened by toggle switches in the gas charging room. Before charging of the tunnel is commenced all ports should be closed, and with the respective toggle switches in the closed position, the nitrogen service operates pressure switches and lights showing that the tunnel is in a state of readiness.

The only other service is an air operated dump valve for the tunnel. The residual pressure in the tunnel is above atmospheric after a run and can be released by a Saunder's diaphragm valve. An electromagnetic control switch is located in the gas charging room and is conveniently placed for the operator near the main high pressure gas inlet isolator valve. This valve is not used when helium reclamation is required. In case a high overpressure is built up in the tunnel a bursting disc (rated at 100 p.s.i.) is incorporated in a bypass channel around the dump valve.

An emergency dump valve from the high pressure driver chamber ($4\frac{1}{4}$ cu. ft) is incorporated into a 1 in. main isolator valve. A 2000 p.s.i. nitrogen supply through a pressure intensifier opens a mushroom valve normally biased to the closed position. Nitrogen driver gas at 3000 p.s.i. is reduced

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* Leybold-Elliott.

† Metrovac S59. Metropolitan-Vickers.

to 300 p.s.i. in about 8 secs. It would be expected that reducing helium and hydrogen to the same pressure would take approximately 2 secs.

1.5.2. *Hydraulic services.* (Reference should be made to Fig. 13).—The shock tunnel has three chambers which are separated by diaphragms and therefore joints in the structure. These joints must be able to withstand the high pressures that are in use in the chambers on either side while at the same time being able to part easily and quickly.

Referring to Fig. 13, it will be seen that two separate hydraulic circuits exist, namely the main diaphragm station units and a horizontal driving ram. The pump* forces oil into appropriate rams in an order selected by electrically operated solenoid valves. Each station has a single electric push button, biased to the 'off' position, which selects the desired sequence of operation. The system has a key operated interlock in the electric power supply for safety purposes during tube maintenance. Interlocks and pressure switches are incorporated for the three points where diaphragms are selected, and have indicators in both the gas charging room and the main control room which show whether the tube is fully shut or open. The interlocks must be operated in their correct sequence for opening or for closing and must attain completion for any one point before another point may be actuated. For instance, upon opening a diaphragm station, the full rotation must take place before any axial motion commences and similarly the reverse operation upon closing a station.

The mechanism at the first and the second diaphragm stations are similar except for the relative sizes of structure, and therefore the second, which is the main diaphragm station, will be described and is shown in Fig. 3.

The breech mechanism comprises a collar assembly connected to a pair of vertical rams on either side and the mating portion of the tube. The collar is attached to the higher pressure portion of the tube and is free to rotate a quarter of a turn about its axis. It is part of a load bearing structure and is supported on 4 roller bearings resting in a cage which in turn can move axially on rails through a distance of 4 ft. A square section thread is cut inside the collar in the form of a regular pattern of 12 segments alternating with blank spaces. This can be seen in Fig. 3. The lower pressure portion of the tube at this point has a section attached to it in the form of a yoke and also a corresponding mating section of teeth for the collar. A series of lugs are attached for locating the diaphragm in position. The method of sealing the diaphragm on either side is described in Section 1.2.

Assuming the station is fully open, then after inserting a diaphragm and operating the control, the interlocks will only allow the horizontal ram to drive those parts between itself and the opened point along the tunnel axis. A pair of pintles on the cage assembly guide the moving part into the yoke. At the instant when the arranged axial motion has finished, the interlock on the horizontal ram automatically closes and the vertical ram interlock is opened. Oil at 2000 p.s.i. is fed into both pairs of rams to rotate the nut from both sides. Rotation of the nut closes the joint on the teeth until the required degree of clamping has been attained so that the tunnel cannot open axially. An interlock then closes the hydraulic circuit and a pressure switch operates the 'tunnel-closed' lights in the control rooms.

As mentioned in Section 1.2, regarding the sealing of the diaphragms, very slight variation in their thickness relative to a given bolster plate can be accommodated by differing axial measurements, i.e. more or less rotation of the nut and hence pitch movement by adjusting the micro-switch interlock.

The third control point in the system is located at the nozzle diaphragm and can be seen in Fig. 6.

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* Keelavite-Hydraulics, Coventry.

It is much simpler than the other stations since only an axial movement is required. The barrel at this point has on its female portion a series of chevron seals and steps to accommodate the nozzle proper, which with its constant angle of expansion has a series of variable length nozzle cones to give various area ratios. Fig. (7). In practice use is made of a series of removable throat parts which seal into the different steps and chevron seals. An additional seal is formed by an 'O' ring.

The entire moving part of the tunnel is free running on rails with molybdenum disulphide grease over all moving surfaces. During operation of the tunnel at driving pressures above 3000 p.s.i. the tunnel high and low pressure chambers recoil as one unit from the fixed working section by as much as 4 in. with the horizontal ram off. Because of this the hydraulics are kept on to keep the horizontal ram under pressure and thus counteract the recoil force. A mechanical stop prevents overrun by the barrel in axial motion.

1.6. *Routine Instrumentation.* (Reference should be made to Fig. 19.)

All of the runs in this facility have recorded data of diaphragm bursting pressure, initial channel pressure, shock velocity, reflected shock pressure and working section pitot pressure. The stagnation temperature is deduced from real gas tables and the measured shock velocity[6]. Working section conditions, apart from pitot pressure, are calculated using perfect gas nozzle tables[7] and correction factors which account for real gas expansions[8]. The subsequent sub-sections of Section 1.6 detail the equipment used for the routine measurements.

All measurements of shock pressures and working section pressures are taken from oscilloscope traces and are recorded on Polaroid 3000 ASA film. The cameras in general use are Hewlett Packard 196A and Dumont T.302.

1.6.1. *Driver chamber.—The static driver pressure* is measured with a J. Langham Thomson transducer Type B.P.6 in conjunction with a transistorised indicator Type RML 6019. The indicator unit supplies a 2000 c/s carrier signal to the transducer bridge and demodulates the unbalance signal to indicate directly the pressure on a moving coil milliammeter. Transducers are mounted on feeds from the trailers, at the shock tube feed entry and on the storage bottles. The indicators are sited in the Pressurising room. A 'slave' meter is sited in the Control room and is in series with the driver tube pressure indicator. The measurement of such pressures in this way ensures that the reading is not affected by the pipe run and gas feed velocity, and the pressure at which the diaphragm bursts is quite readily observed.

1.6.2. *Shock tube channel.—The initial channel pressure* is read on a Wallace and Tiernen 2 revolution 0 to 50 p.s.i.a. dial gauge Type FA 233. The quoted full scale accuracy is 0·2 per cent.

Incident and reflected shock pressures are measured at points 6 in. and 31 in. from the nozzle entrance. Quartz transducers, Type SLM PZ6 and Kistler 701 and 701A are used, followed by SLM PV17 electrometer amplifiers. The electrometer amplifiers are positioned in the Control room, requiring 50 ft cable runs from the transducer to the PV17. No problem of voltage sensitivity or cable noise arises at these high pressures and consequent high signal levels. Passive CR filters are used directly between the PV17 and the associated oscilloscope. No attempt is made to preserve the true rise time of the shock signal since the routine measurement only requires the level and duration of the 'tailored' run. With the duration of the nominally constant pressure record being approximately 7 mS, overall response times of 0·5 mS are acceptable. Typical stagnation pressure records from a Tektronix 535A are shown in Figs. 33, 34 and 35.

The incident shock velocity is deduced from 6 thin film platinum resistance thermometers set at 2 ft intervals from the nozzle entrance. High gain trigger amplifiers with thyratron lock-out pulse generators feed five separate chronometers having microsecond resolution. Two additional resistance thermometers are spaced at 6 in. intervals and are located within the region behind the reflected shock wave for normal tunnel operation. Examination of the analogue output of these thermometers can give otherwise unobtainable information about the wave interactions in the reflected shock region. The thin films are made by painting Hanovia 05–X platinum colloid onto pyrex rod and heating in a muffle furnace up to 650°C. The technique is as originally described by Vidal[9] and reported in detail by Schultz[10].

The mechanical assembly of the resistance thermometer holder and chevron seals is shown in Fig. 20. The films as used at N.P.L. have a nominal resistance of 40 ohms and are energised from a stabilised dc supply of 350 V *via* a sufficiently large ballast resistor to produce a potential difference across the thin film of 1·0 volt.

The temperature of the shocked gas is not measured, but is deduced from a knowledge of the incident shock velocity and real gas tables[6].

1.6.3. *Nozzle and working section.*—Prior to a shock tunnel run it is essential in the interests of a rapid nozzle flow establishment to have the *working section pressure* in the region of 10^{-3} mm. Hg., read just before the run in the control room on an Alphatron D unit, (as discussed in Section 1.4).

During the run the *pitot pressure* is always measured. If an aerodynamic model is in the test section then the pitot tube occupies a standard position at 5 in. above the centre line and with its probe tip on the same transverse plane as the leading edge of the model. The transducer in standard use is a Kistler 701A, though satisfactory measurements were achieved with the very much larger SLM. PZ 38. Both of these transducers are quartz charge generators and are used in conjunction with SLM PV16 or PV17 electrometer amplifiers.

Free-stream *static pressures* have been measured by a Kistler 701A quartz transducer mounted in a 0·75 in. diameter ogive-cylinder and sampling the cylinder wall pressure at 10 diameters back, from the tip of the ogive. With static pressure levels of less than 10^{-1} p.s.i.a. the charge output of the Kistler 701A is down to 10^{-13}Cb and problems of measuring the signal may arise. Transducer cable lengths are kept as short as possible to keep the shunt capacitance to the transducer to a minimum, and the electrometer amplifiers are sited in the tunnel room adjacent to the working section. The long cable from the output of the electrometer to the oscilloscope in the Control room acts as a low pass filter having a break frequency around 10kc/s. As a precaution against extraneous ‘noise’ the leads in the working section are ducted in copper pipe wherever possible, and the transducers are electrically insulated from the holder and shock tunnel. Acceleration loads are reduced by ensuring that the transducer is mechanically supported by ‘O’ rings or cold-setting rubber.

Mechanical details of the pitot and static pressure probes are shown in Fig. 36.

The working section has two plate glass windows 13 in. diameter and 2 in. thick which have been specially selected and worked to be suitable for a sensitive *single pass schlieren system* (Fig. 21).

The light-source[11] provides continuous illumination by tungsten filament lamp or by an argon jet spark of about 0·2 mS. duration. *Schlieren and direct shadow photographs of the flow* over models have been taken with the spark light source using sensitive graded filters and colour filters[12] made from optical glass.

16mm Fastax films have been made, operating at 6000 frames/sec. and using a 75 watt tungsten filament lamp as the light source. Careful synchronisation of the control of the bursting pressure and starting the camera is necessary since no means of starting the camera by the tunnel shock or flow is possible. The time taken for the camera to reach maximum speed is about 0·5 sec which is of course a far longer time than the shock tunnel flow time. In consequence the camera must be started 0·5 sec before the bursting of the main diaphragm, which is difficult to anticipate.

In order to photograph the short duration flow around free flight models and to be able to measure the movement of these bodies, a rapidly opening shutter is required. In addition the shutter should be capable of operation from a pulse generated by the passage of the primary shock down the shock tube.

The Beckman and Whitley Dynafax high speed framing drum camera has a solenoid operated Compur shutter. This shutter can be set to open for the duration of the selected framing rate. A pulse from a Nagard Pulse Generator is amplified to 100 volts and used to open the shutter within about 5 mS. This is sufficient time to receive a pulse from a resistance thermometer situated near the diaphragm station to open the shutter before the flow is established in the working section.

The light source used is an Osram HB0107/1 high pressure mercury vapour lamp driven by a 60V dc power supply. The light is sufficient to take schlieren photographs of the flow at the maximum speed of the camera (25 000 frames/sec).

Single and multiple flash light sources have been used and the occurrence of the flash is sensed by a silicon photocell whose output is sufficient to provide a marker pip on an oscilloscope. The rise time of these cells is less than 1 μsec and their decay greater than 3 μsecs. This assists the photographing of the trace by oscilloscope camera.

1.6.4. *Calibration of routine pressure instrumentation.*—The indicators of the static driver pressure (Section 1.6.1.) may be readily checked prior to their used by switching a known shunt resistor across one of the strain gauge transducer arms. The deliberate out-of-balance signal is then used as a calibration of the sensitivity and linearity of the indicator.

The quartz pressure transducers referred to in Sections 1.6.2. and 1.6.3. are calibrated by a rapid pneumatic technique. This entails the use of a fast acting solenoid valve to connect the transducer to a relatively large volume of known pressure gas. The electric actuation of the solenoid valve triggers the oscilloscope that is normally connected in the measurement channel. The additional volume of the transducer assembly and valve port makes a negligible effect on the initially adjusted reference pressure.

Two pressure calibration rigs are used. One is for pressures from 15 p.s.i.a. to 4000 p.s.i. which is used for stagnation pressure transducers, and the other for pressures of 1mm Hg. absolute to 760mm Hg. absolute which is used for calibrating the pitot and static pressure probes. In the first case the transducer is unscrewed from the tunnel and screwed into the calibration rig. In the second case a plastic tube is connected to the probe orifice on the pressure probe in its position in the test section. In both instances appropriate reference pressures are applied to the transducers and the oscilloscope traces recorded through the usual Polaroid system. The trace deflection is always arranged to give a reading accuracy of ± 1 per cent.

Calibration with this technique automatically ensures that in-line circuitry is not interfered with, and that d.c. drift of the electrometers does not affect the calibration. Comparison of calibrations by this method and by 'dead-weight' testers show excellent agreement. The pneumatic technique is much more convenient.

2. *Performance of N.P.L. 6 in. Shock Tunnel.*

2.1. *Introduction.*

The N.P.L. 6 in. shock tunnel was intended for routine 'tailored'[13] operation at a shock Mach number of 6, achieving this with hydrogen at room temperature as the driver gas, and using air or nitrogen as the channel gas. Though the maximum gas storage pressure of the high pressure plant is 15 000 p.s.i., the maximum pressure that the 18 ft 6 in. driver section is designed for is 7500 p.s.i., and due to the working rating of the flexible feed lines to the driver chamber (Section 1.3) there is no intention of having static loading pressures much in excess of 5000 p.s.i. This represents 1530 standard cu. ft of driver gas. Only a few runs have been performed at 5000 p.s.i. driver pressure. The driver gas in these cases was nitrogen.

Of the first 1000 runs of the tunnel, approximately 200 were with hydrogen, 700 with nitrogen and 100 with helium as driver gas. Run 205 was the last firing made with hydrogen as the driver gas. A rapid leak at the main diaphragm station ignited and created a strong compression wave that blew down the main doors of the shock tunnel building. No injury was caused to personnel, but estimates of possible damage to adjacent private houses made the continuing use of large quantities of hydrogen unacceptable. A limited number of check runs were made with helium as a driver gas to ensure that the experimental results were in reasonable accord with theory. These tests with helium were made as few as possible since the tunnel was not equipped with any means of recovering the used helium, and the cost in the U.K. was over 40 times the cost of hydrogen gas.

An immediate design of plant for helium recovery and purification was put in hand, and nitrogen gas used to run the shock tunnel for a subsequent 700 runs over the ensuring 2 years. The helium plant was installed and finally tested out in October, 1964, at Run No. 912. Routine operation of the tunnel is now with helium as the driver gas and driving shock Mach numbers of 4 into nitrogen as the channel gas. Up to 95 per cent of the helium is recovered from each run and re-purified.

2.2. *Reflected Shock Tube Performance.*

The measured performance of the shock tunnel is compared with real gas calculations[6] where possible (e.g. pressure ratios across shock waves) though predictions requiring a theoretical value of driver pressure (p_4) utilise the simple theory of diaphragm pressure ratio as found in Reference 16. The following measurements have been used in the performance comparison: diaphragm pressure ratio P_{41}, pressure ratio across the incident shock wave P_{21}, pressure ratio across the reflected shock wave P_{52}, pressure recovery ratio P_{54}, and magnitude of the reflected shock pressure p_5.

2.2.1. *Nitrogen driver gas.*—Reference to Figs. 22 and 24 shows that nitrogen driving into nitrogen is most inefficient as regards pressure recovery and shock Mach number. The capability of the shock tunnel had not been considered in terms of nitrogen as the driver gas until the necessity arose. The x vs. t diagram for $M_s = 2 \cdot 4$ (Fig. 25) shows that 6 mS of reflected shock gas should be available, with no quenching by expansion waves during this time. The minimum shock Mach number is dependent upon the required flow Mach number, so that liquefaction of the test gas is avoided. If we suppose that a stagnation temperature of 700°K is required to expand satisfactorily to $M_\infty = 8 \cdot 0$, then the incident shock Mach number should not be less than $M_s = 2 \cdot 0$.

A compromise has to be made between choosing the maximum stagnation temperature and sufficient reflected shock pressure. In Fig. 23a it can be seen that the initial channel pressure is in the region of a few hundred p.s.i., for $M_s < 2 \cdot 0$ at a driver pressure of 3000 p.s.i. and difficulties arise in providing a nozzle diaphragm that will withstand the initial channel pressure from the nozzle and test section and yet will rapidly and satisfactorily burst without fragmentation when the shock wave is reflected.

Satisfactory operation has been achieved at $M_s = 2 \cdot 3$, which gives a reflected shock temperature of 900°K. The measured shock wave attenuation is $0 \cdot 2$ per cent/ft at $M_s = 2 \cdot 3$ over the last 12 ft of channel.

The duration of the reflected shock pressure is 4mS and its variation with time is depicted in Fig. 33. The reflected shock pressure magnitude at $M_s = 2 \cdot 3$ can be seen in Fig. 24 to be only $0 \cdot 2$ of the driver pressure.

2.2.2. *Helium driver gas.*—Fig. 22 shows that with helium driver gas the simple theory for diaphragm pressure ratio in terms of resulting shock Mach number over-estimates by nearly 30 per cent at Mach $4 \cdot 0$. When real helium gas properties are used to predict conditions at the contact surface as a function of shock Mach number and actual diaphragm pressure ratio, it has been shown by Davies[15] that the normally quoted tailored Mach number of $M_s = 3 \cdot 4$ for helium driving nitrogen is considerably modified.

As a result of the actual diaphragm pressure ratio required to obtain a given shock Mach number being less than predicted by the simple theory, the tailoring Mach number is raised from $M_s = 3 \cdot 4$ to approximately $M_s = 4 \cdot 0$. It is possible to understand how this occurs from Fig. 23b where the magnitudes of p_5 and p_8 are plotted for a given driver pressure and assume the simple theory for the pressure ratio across the diaphragm. Since in fact p_1 will be actually higher than plotted in Fig. 23b, and therefore p_2 and p_5 will be higher, the point of intersection of the curves of p_5 and p_8, which is at $M_s = 3 \cdot 4$ in this figure, will be displaced to the right. This intersection, and hence equality, is of course, the requirement for tailoring.

Reference to the x vs. t diagram of Fig. 26, shows that 7 mS of shocked gas is available at constant pressure before quenching by the reflected expansion wave head. The pressure variation with time is shown in Fig. 34a.

Shock speed measurements over the last 12 ft of shock tube channel show a repeatable attenuation of $0 \cdot 2$ per cent/ft at $M_S = 4 \cdot 0$.

Measured pressure ratios across the reflected shock waves for $3 < M_S < 5$ are within $+10$ per cent of the calculated real gas values.

The reflected shock pressure magnitude at $M_S = 4 \cdot 0$ can be seen in Fig. 24 to be $0 \cdot 8$ to $0 \cdot 9$ times the driver pressure.

2.2.3. *Hydrogen driver gas.*—The x vs. t diagram (Fig. 27) shows that the reflected expansion wave head arrives at the nozzle entrance approximately 6 mS after the incident shock, quenching the shock heated gas. The reflected shock pressure record confirms this estimation (Fig. 35).

The diaphragm pressure ratio to produce a given shock Mach number is approximately 25 per cent greater than ideal theory predicts. (Fig. 22). Tailored shock tunnel operation is achieved at $M_S = 6 \cdot 0$ which is consistent with previously reported experiments[13].

Shock speed measurements over the last 12 ft of shock tube channel show a repeatable attenuation of $0 \cdot 4$ per cent/ft at 35 ft from the diaphragm. Measurements by Jones[14] at N.A.S.A. Langley showed that attenuation at $M_S = 6$ with a hydrogen driver amounted to $0 \cdot 6$ per cent/ft at 60 ft from the diaphragm, reducing to $0 \cdot 3$ per cent/ft at 120 ft from the diaphragm. The attenuation in the N.P.L. 6 in. shock tunnel is clearly less than that at Langley, at a corresponding length to diameter ratio.

Pressure ratios across the incident and reflected shock waves have been measured, and for $5 < M_S < 6$ are within -10 per cent and -4 per cent respectively of the real gas values[6]. The magnitude of the reflected shock pressure appears to be considerably less than theory from Fig. 24, but this is implicitly related to the need for a value of driver pressure greater than the theoretical, to achieve a given shock Mach number, (Fig. 22). It can be seen that at $M_S = 6 \cdot 0$ the reflected shock pressure is about $0 \cdot 8$ of the driver pressure.

2.3. *Shock tunnel performance.*

2.3.1. *Operating conditions of the tunnel.*—Figs. 28 and 29 show the importance of real gas behaviour on the expected values of pitot and static pressure, the three shock Mach numbers of $M_S = 2 \cdot 3$, $4 \cdot 0$ and $6 \cdot 0$ generating respectively reflected shock temperatures of 900°K, 2000°K and 4000°K approximately.

Examination of Fig. 30 illustrates the advantage in operating the shock tunnel at different shock Mach numbers: for a given measured stagnation pressure and expansion to a constant flow Mach number the unit Reynolds number can be varied by a factor of 10 by changing the stagnation temperature by a factor of 4. The three shock Mach numbers shown are $M_S = 2 \cdot 3$, $4 \cdot 0$ and $6 \cdot 0$ and respectively refer to the shock tunnel used with room temperature nitrogen, helium or hydrogen as the driver gas.

The practical limitation to stagnation pressure is imposed by the driver gas pressure, and supposing this to be 5000 p.s.i., then reflected shock pressures for nitrogen, helium and hydrogen drivers respectively might be 1500, 4500 and 4000 p.s.i., at the chosen shock Mach numbers.

It is interesting to draw attention to Figs. 31 and 32 which record the measured free-stream Mach number in the 16 in. diameter test section. In the opinion of the authors no earlier references have reported experimental evidence of the dependence of free-stream Mach number on the stagnation temperature of the nozzle, in a given nozzle geometry. The nozzle calibrations plotted here were obtained from a 16 in. exit diameter, $1 \cdot 0$ in. throat diameter cone having a total angle of 11° 25′ (*see* Section 1.2.5). The nominal free stream Mach number measured varies from $8 \cdot 7$ to $7 \cdot 9$ at 11 in. from the exit of the cone as the stagnation temperature changes from 900°K to 4016°K. Calculations by Bernstein[17] of real nitrogen expansions for this area ratio predict a variation in free-stream Mach number from $8 \cdot 5$ to $7 \cdot 4$ over this range of temperature. The measurement error of the pitot and stagnation pressure is at the most ± 2 per cent, giving a worst error in the ratio of 4 per cent. The effect of 4 per cent error of nozzle pressure ratio is less than 1 per cent in estimation of free-stream Mach number.

The horizontal Mach number gradient, along the nozzle centre line in the window region, for the nitrogen driver case is $0 \cdot 01$/in. over 8 in.; for the helium driver is not measurable and in the case of hydrogen driver is near to $0 \cdot 1$/in., which though 10 times worse than in the first case is quite comparable with measured Mach number gradients in contoured nozzles. The scatter in the measured values in the last case may be due to the fact that the measurements were made during the first 200 shots, when pressure gauge mounting and calibrations were not as reliable, due to inexperience.

2.3.2. *Duration of test-time with helium driver gas.*—The constancy of test-section conditions is usually deduced from the steadiness and duration of stagnation and pitot pressure records. These parameters are unfortunately insensitive to temperature changes, and can therefore give no indication of the fluctuations occuring in the total enthalpy of the flow.

However, if a measurement is made of heat transfer on the surface of a model, then this may be correlated with the total enthalpy of the stream and will therefore give a direct indication of the duration and constancy of the hot flow.

If the duration of the pressure and heat transfer rate is obtained from measuring the time between the arrival of the shock wave and the expansion wave and plotted against shock Mach number as in Fig. 34c, it can be seen that there is a loss of test time above the tailoring Mach number. Davies[18] has shown that there can be a loss of test time when operating above the Mach number for tailoring when using helium driver gas and nitrogen test gas. The times on the graph of Fig. 34c have no theoretical significance and are present to indicate trends.

The oscilloscope record shown in Fig. 34b is the output of a passive C–R analogue network, which for an input voltage proportional to surface temperature gives an output voltage proportional to heat transfer rate. The networks in use at N.P.L. are based on a design by Meyer[19] and have 36 sections, each section having a time constant of 0·1 mS. The signal shown in Fig. 34b was from a thin film platinum thermometer on the surface of a sharp leading-edge plate at 10° incidence to a stream of $M_\infty = 8.5$, the free-stream pressure being 0·1 p.s.i.a.

3. *Acknowledgements*

Mr. M. J. Shilling has assisted with the shock tunnel operation and data reduction. Mrs. M. Marshall and Miss B. Redston calculated the theoretical performance.

The shock tunnel was built by the Royal Ordnance Factory, Woolwich under contract to the Ministry of Public Buildings and Works. The design of the shock tunnel was originated by Drs. D. W. Holder* and D. L. Schultz†.

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† Now Lecturer, Department of Engineering Science, Oxford University.

LIST OF SYMBOLS

atm	Atmosphere
g	Gravitational unit
mS	Millisecond (10^{-3} sec)
M_S	Shock Mach number
M_∞	Free-stream Mach number
p.s.i.a.	Lb per square inch absolute
p_i	Pressure in region i (*see* Fig. 25 for i = 1, 2, 4, 5 and 8)
Pij	$= pi/_{pj}$
μ	Micron (10^{-3} mm)
μS	Micro second (10^{-6} sec).

Notes.

(i) Shock-tube notation is from Ref. 16.

(ii) Real gas values of shock-wave relationships from Ref. 6.

(iii) Nitrogen was used as channel gas in all cases.

REFERENCES

No.	*Author(s)*	*Title, etc.*
1	B. D. Henshall	Experimental results from the N.P.L. hypersonic shock tunnel. NPL Aero Report 372 (February, 1959).
2	D. W. Holder and D. L. Schultz	The duration and properties of the flow in a hypersonic shock tunnel. International Hypersonics Conference MIT Mass. USA (August, 1961).
3	K. C. Lapworth, J. E. G. Townsend and K. Bridgeman	Reservoir temperature measurements in a hypersonic shock tunnel by sodium line reversal. Part I Single beam method. A.R.C. 23,341 December, 1961.
4	J. L. Stollery and J. E. G. Townsend	Temperature, pressure and heat-transfer measurements in the two-dimensional nozzle of a reflected-shock tunnel. A.R.C. C.P. 726 September, 1962.
5	K. C. Lapworth and J. E. G. Townsend	Temperature and pressure studies in the reservoir of a reflected-shock hypersonic tunnel. A.R.C. 26, 110. December, 1964.
6	L. Bernstein	Tabulated solutions of the equilibrium gas properties behind the incident and reflected normal shock-wave in a shock-tube. I. Nitrogen. II. Oxygen. A.R.C. C.P. 626 April, 1961.
7	—	Equations, tables, and charts for compressible flow. Ames Research Staff NACA Report 1135. 1953.
8	J. L. Wilson and J. D. Regan	A simple method for real gas flow calculations. A.R.C. C.P. 772, February 1964.
9	R. J. Vidal	Model instrumentation techniques for heat transfer and force measurements in a hypersonic shock tunnel. Cornell Aeronautical Lab Report AD–917–A–1. (WADC TN 56–315). February, 1956.
10	D. L. Schultz	Thin-film resistance thermometers and calorimeters. Symposium on some development on techniques for temperature measurement by Inst. Mechanical Engineers. April, 1962.
11	R. J. North	A short-duration Argon-jet spark light source system. N.P.L. Aero Note 1008. December, 1962.
12	R. J. North and R. F. Cash	Colour schlieren photography in high speed wind tunnels. N.P.L. Aero Report 383. June, 1959.
13	C. E. Wittliff, M. R. Wilson and A. Hertzberg	The tailored-interface hypersonic shock tunnel. *J. Aero/Space Sci* Vol. 26, 1959, pp 219–228.
14	J. J. Jones	Experimental investigation of attenuation of strong shock waves in a shock tube with hydrogen and helium as driver gases. NACA TN 4072. July, 1957.
15	L. Davies	High pressure real gas drivers and tailoring in shock tunnels. A.R.C. C.P. 770. December 1963.

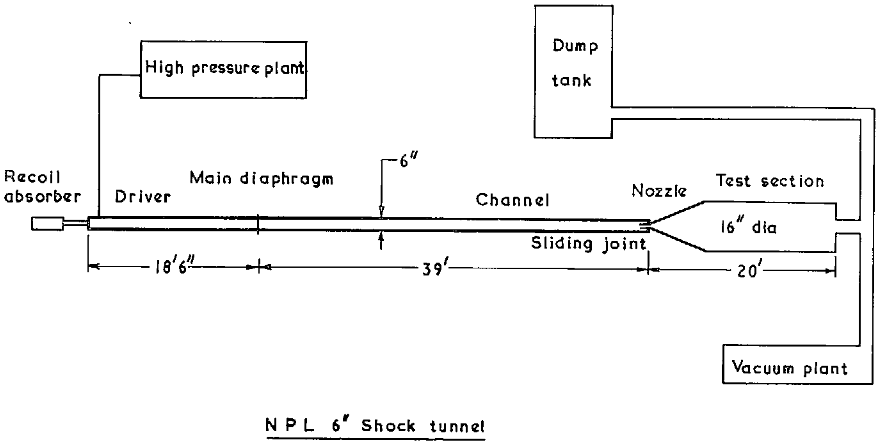


FIG. 1. N.P.L. 6 in. Shock tunnel.

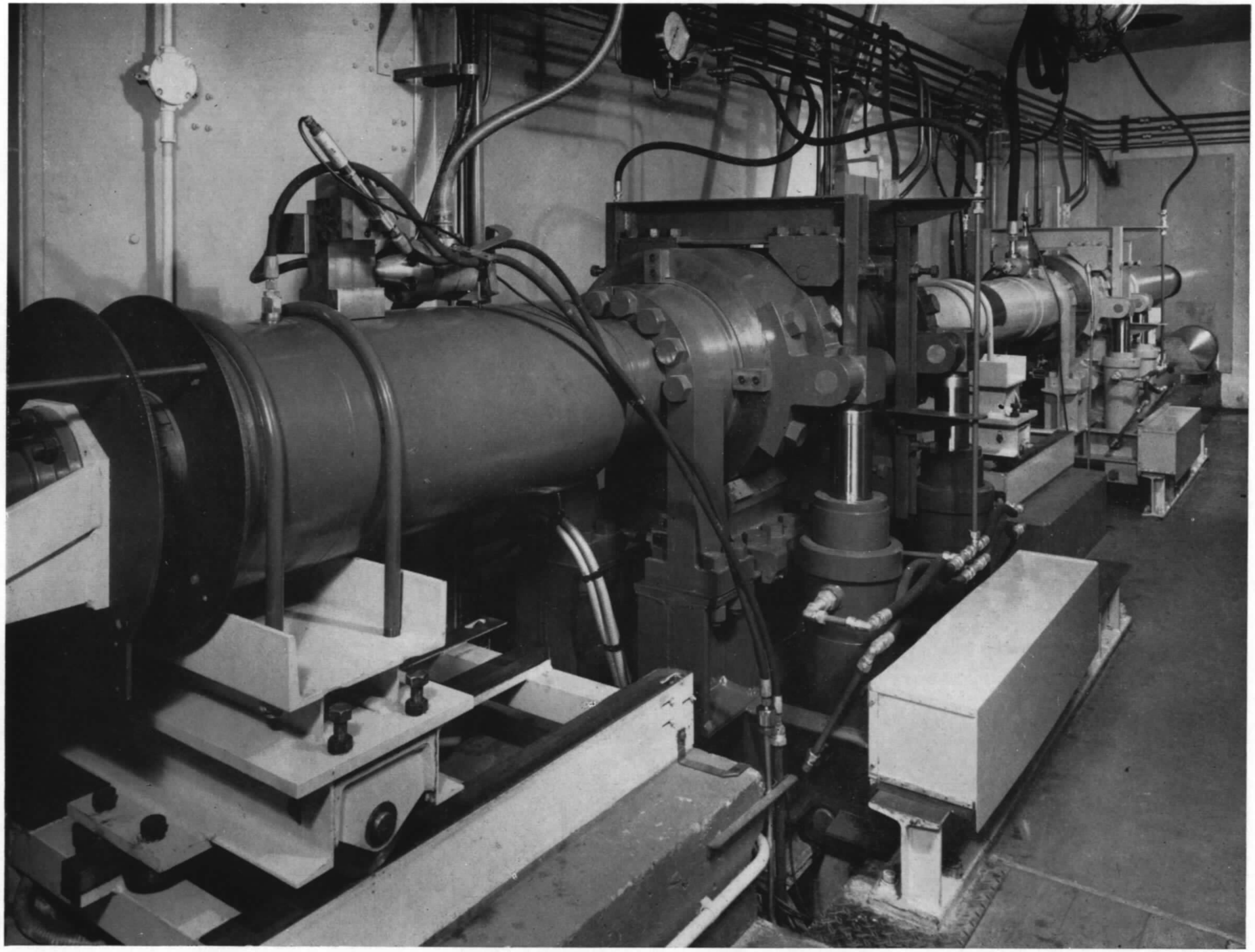


FIG. 2. Driver section of N.P.L. 6 in. shock tunnel.

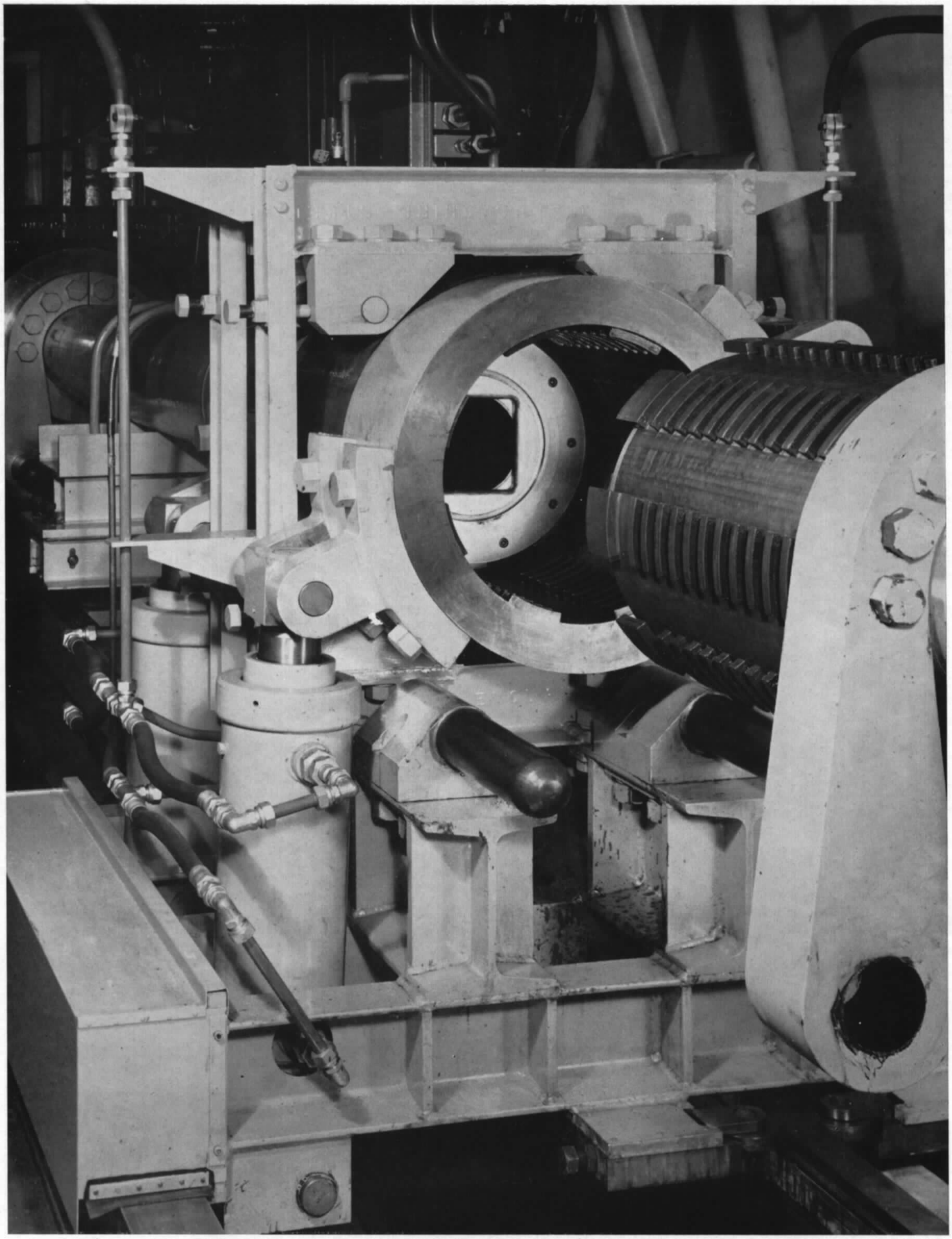


FIG. 3. Main diaphragm station.

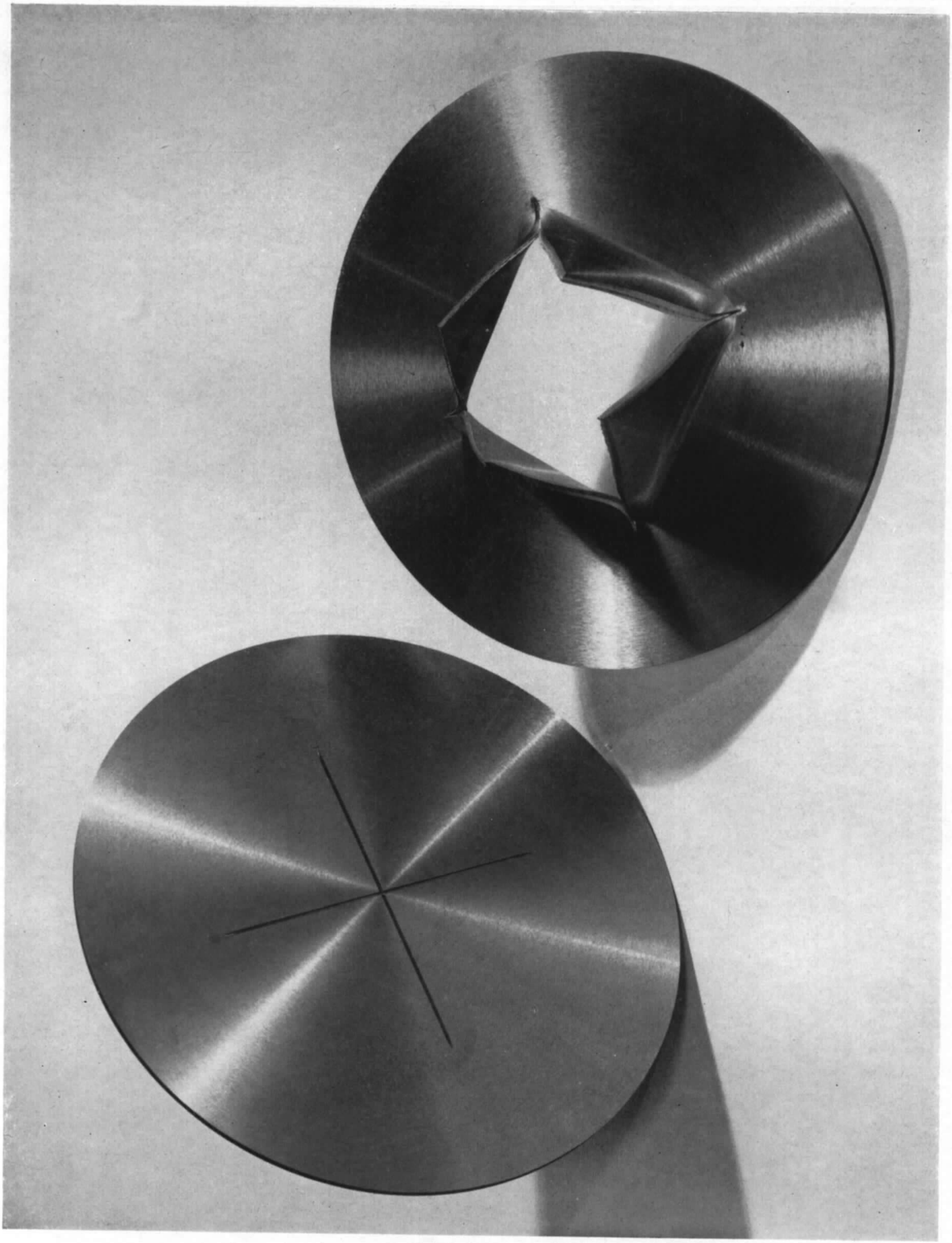


FIG. 4. Mild steel 0·25 in. thick diaphragms.

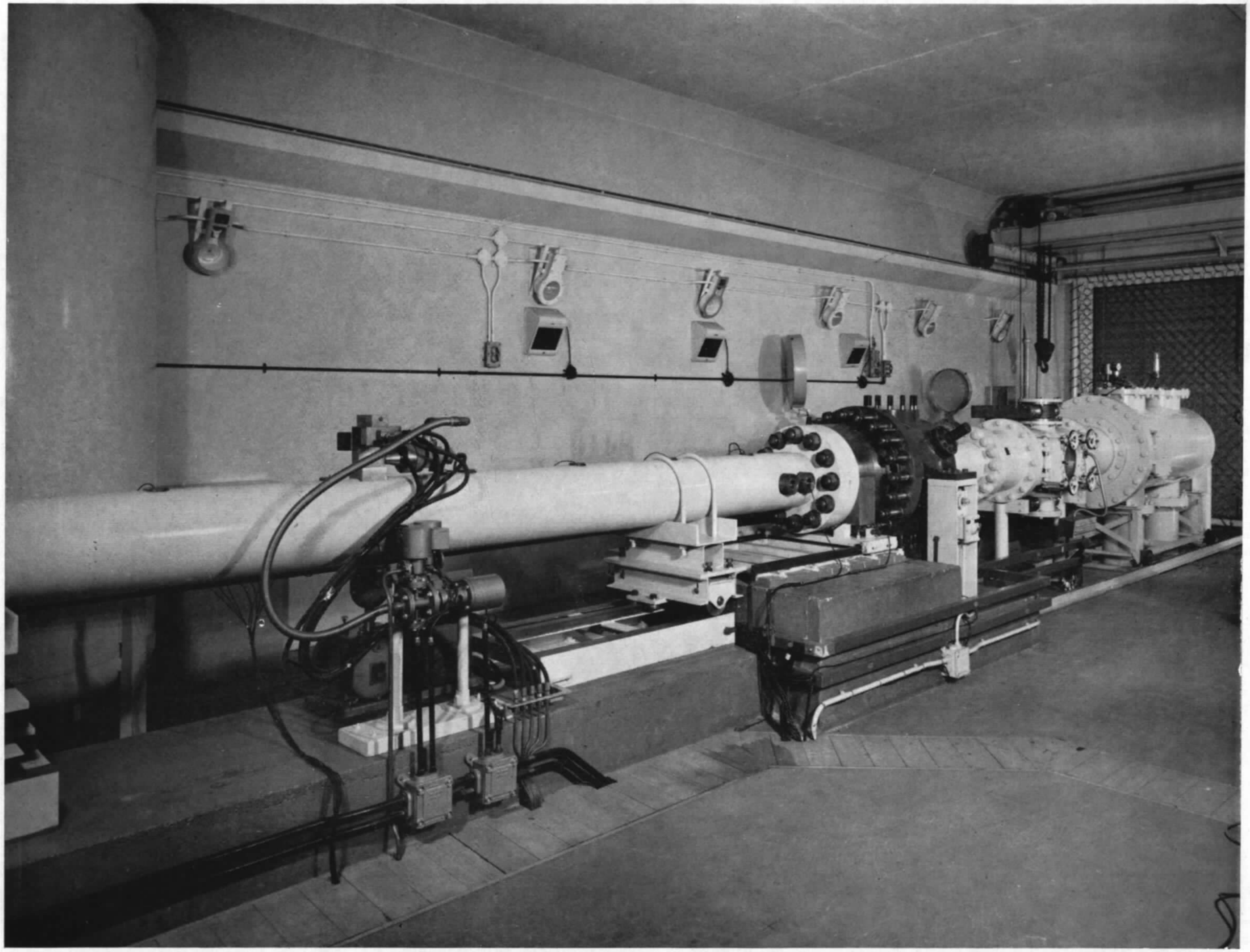


FIG. 5. Shock tunnel channel and nozzle.

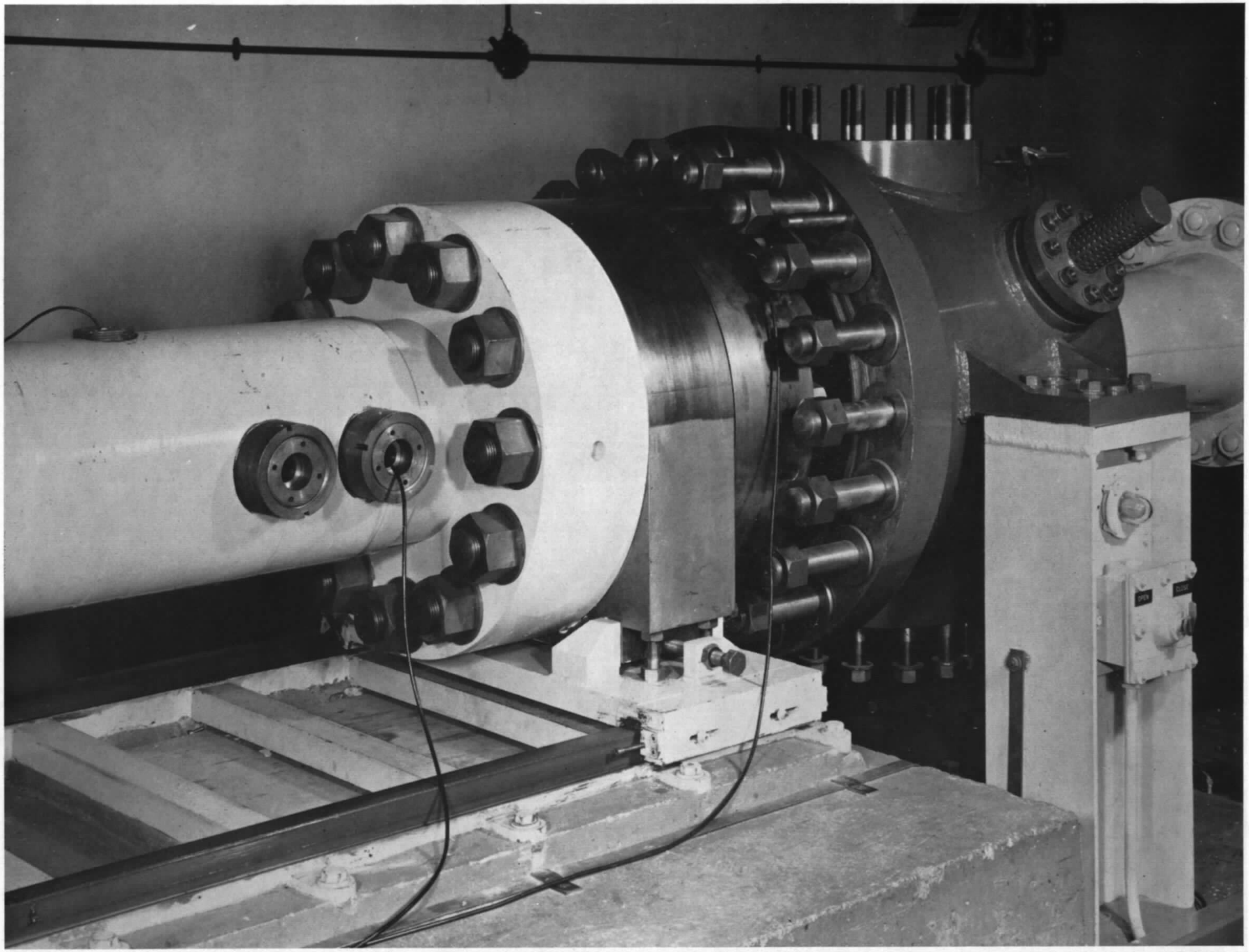


FIG. 6a. Shock tunnel stagnation region.

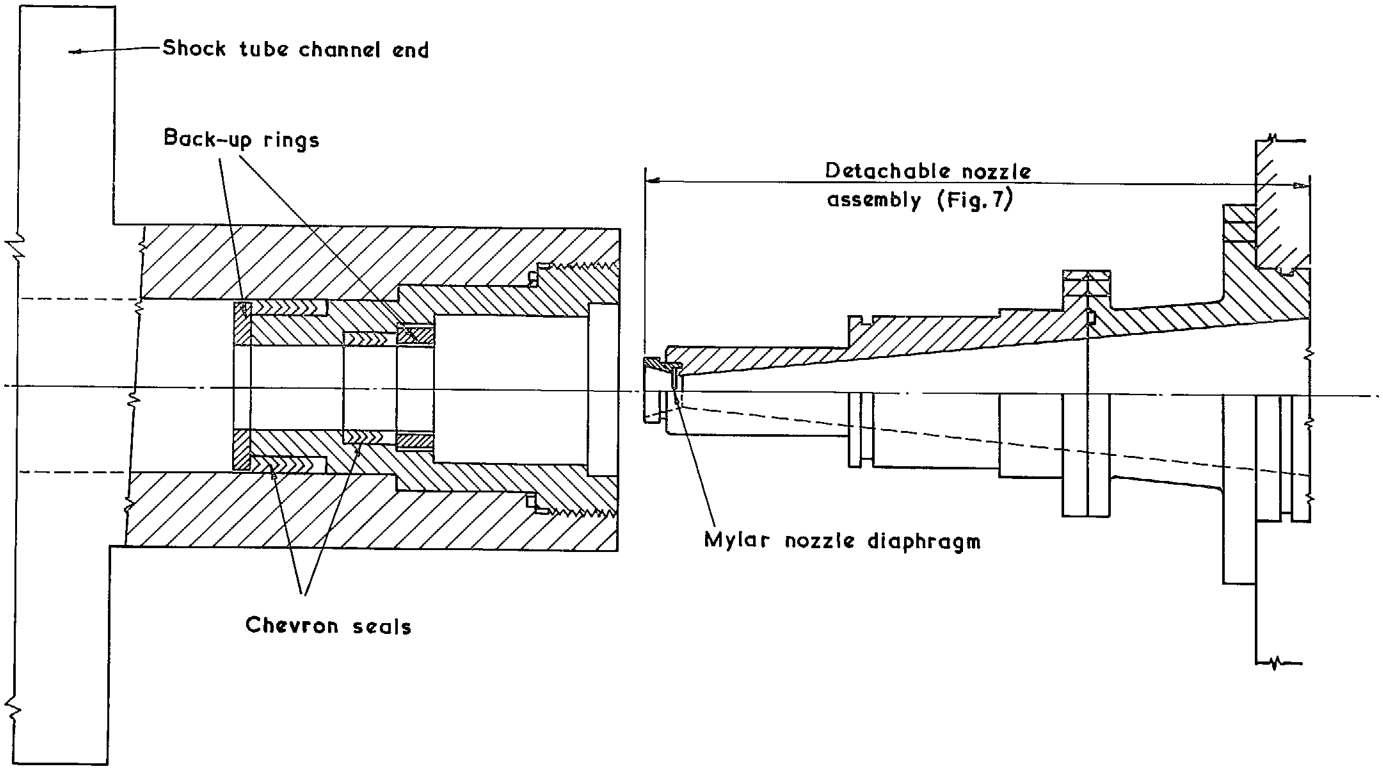


FIG. 6b. Detail of sliding joint in shock tunnel stagnation region.

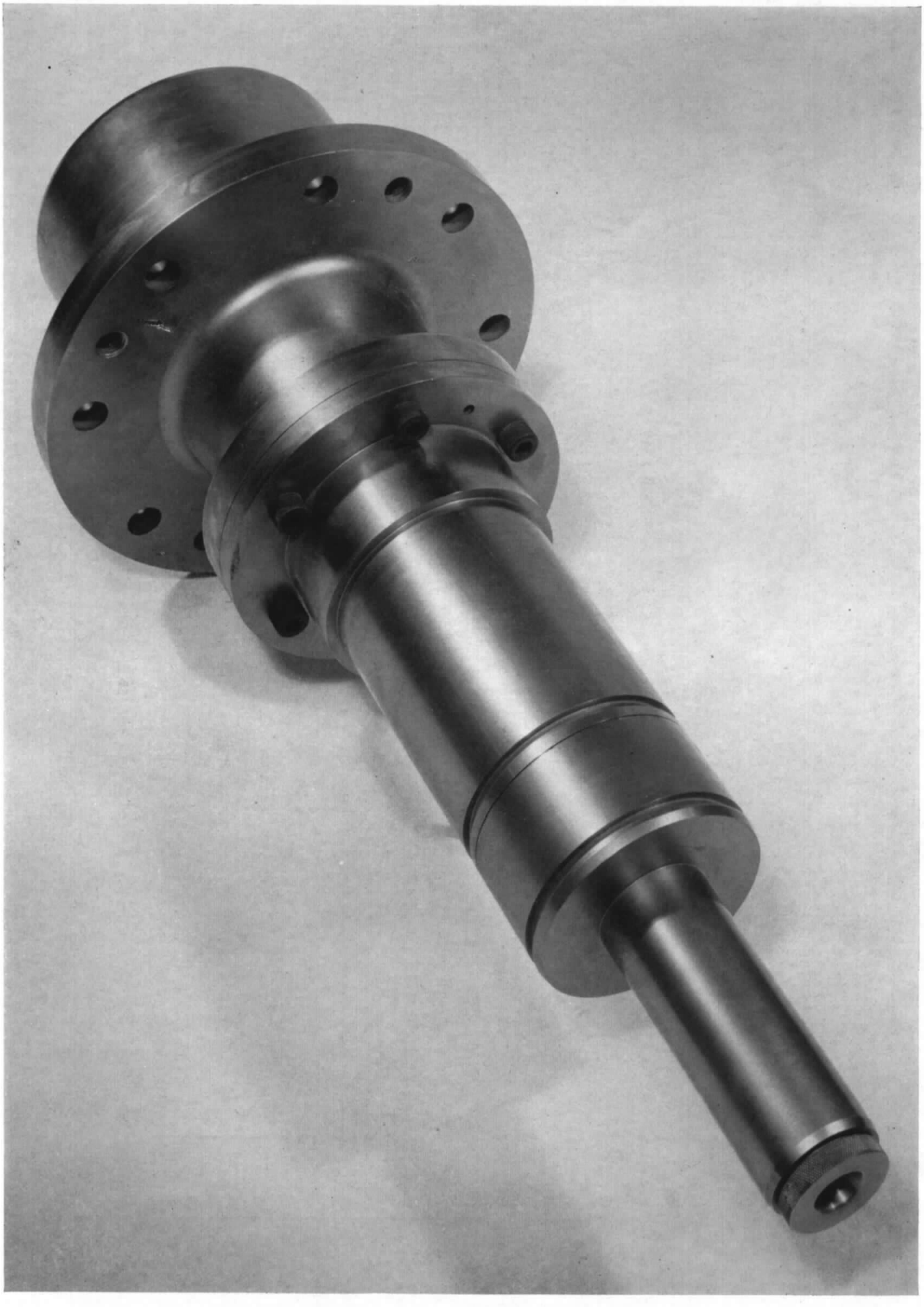


FIG. 7. Replaceable nozzle assembly.

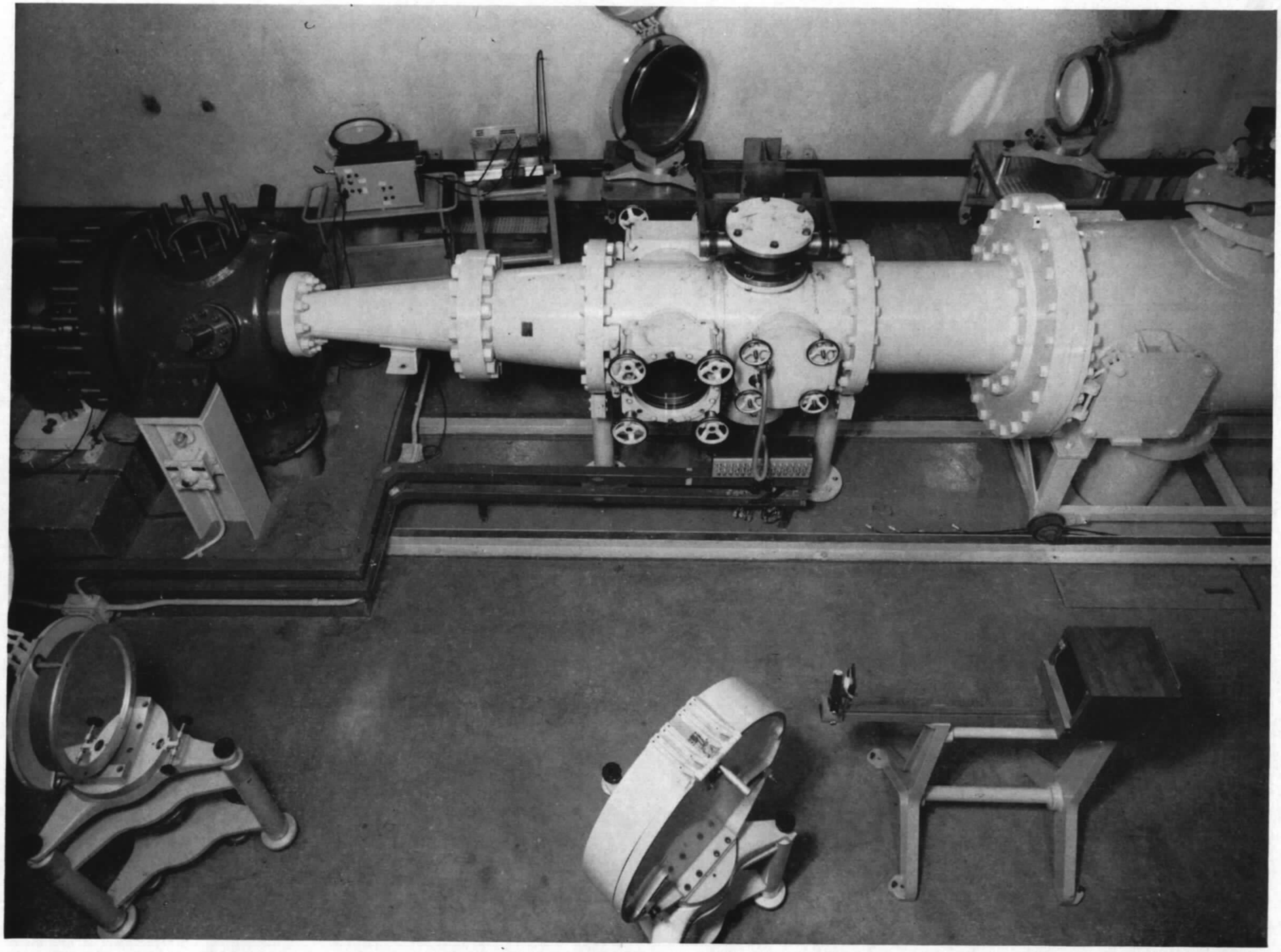


FIG. 8. Shock tunnel test section and schlieren system.

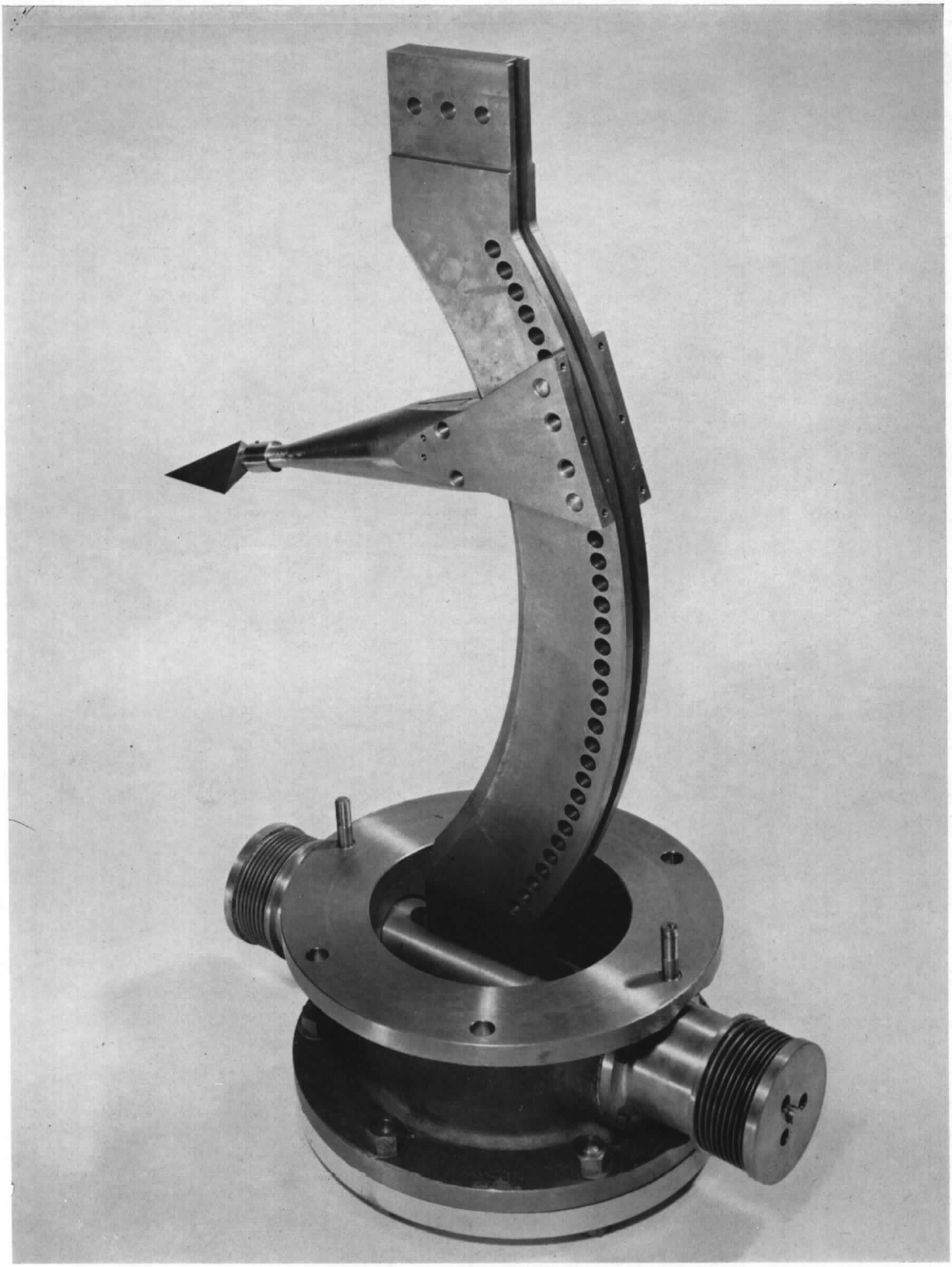


FIG. 9. Model support and quadrant.

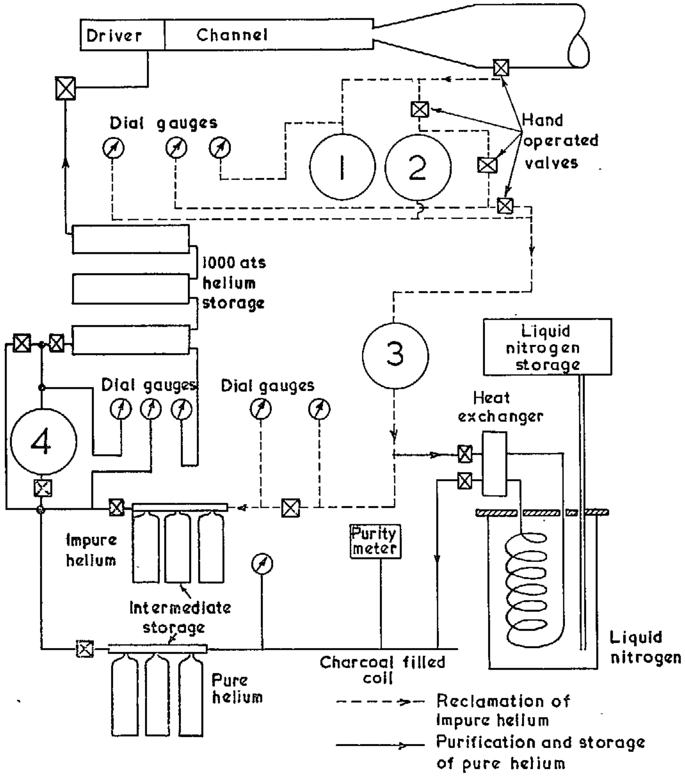


FIG. 10. 6 in. Shock Tunnel helium reclamation, purification and storage plant.

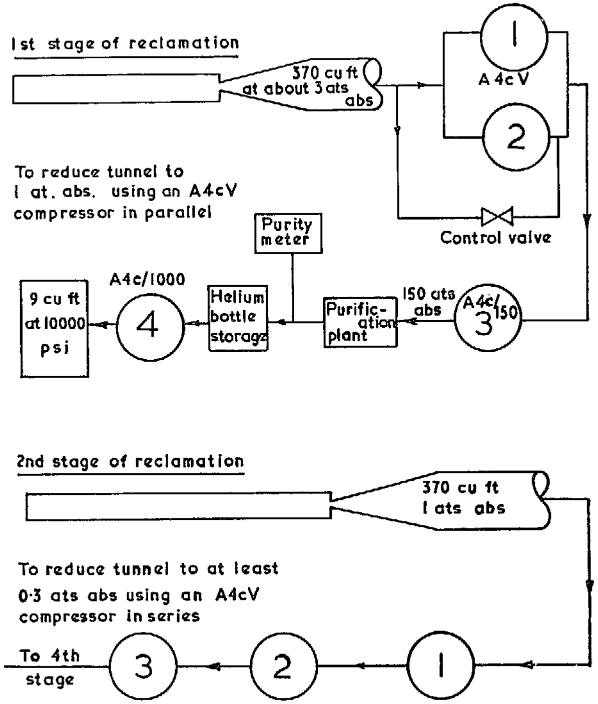


FIG. 11. Phases of helium reclamation.

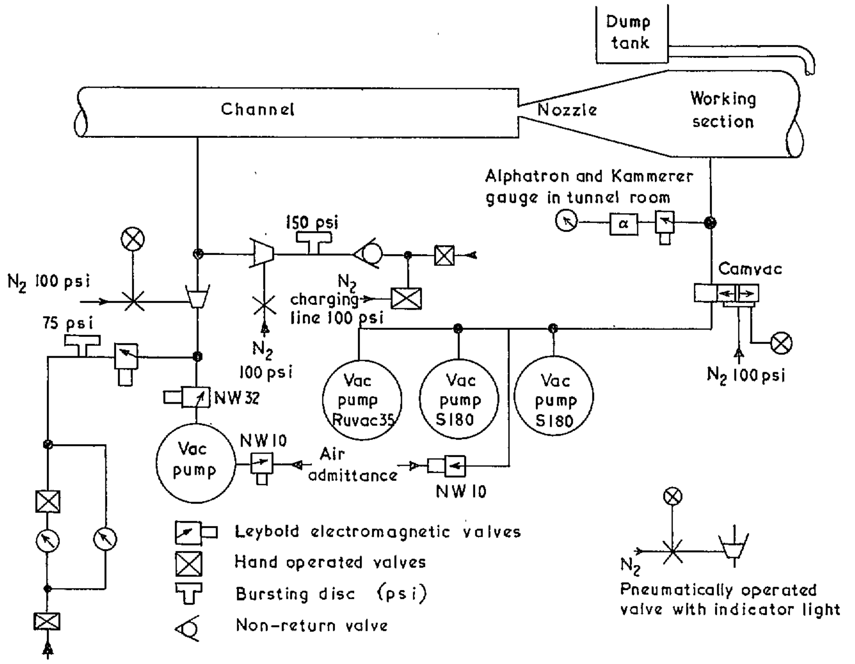


FIG. 12. Channel and working section vacuum and charging plant.

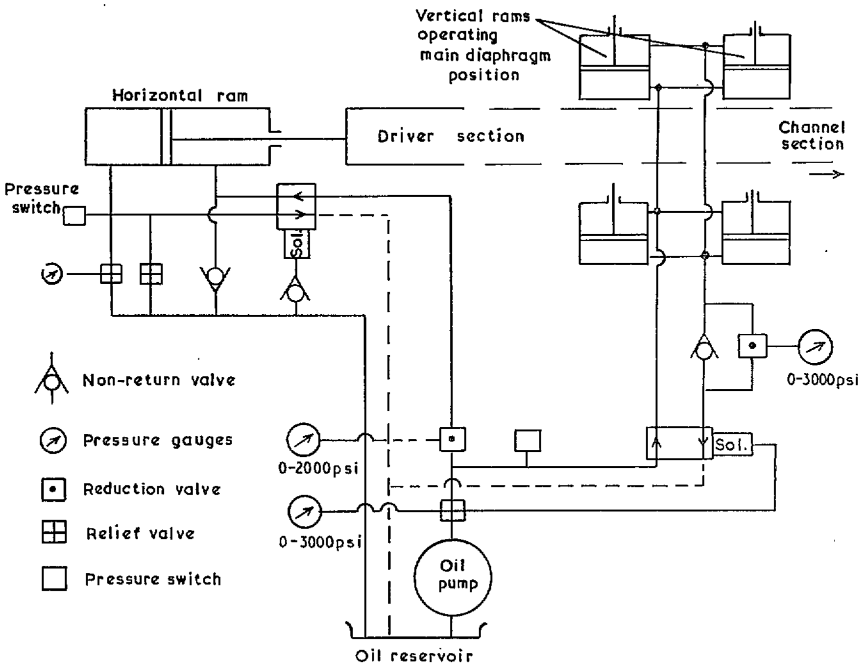


FIG. 13. 6 in. Shock Tunnel hydraulic circuit.

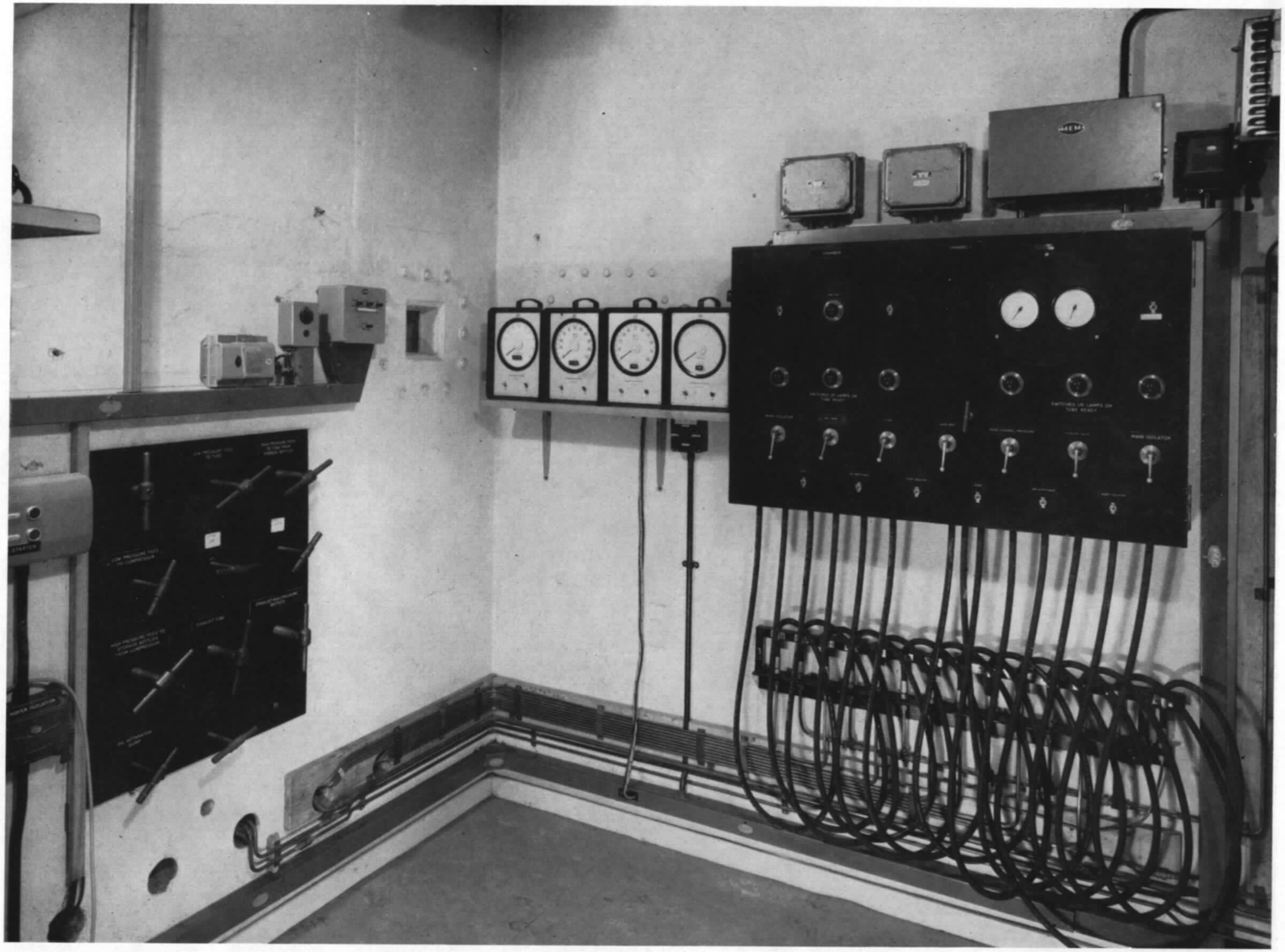


FIG. 14. Shock tunnel pressurising room.

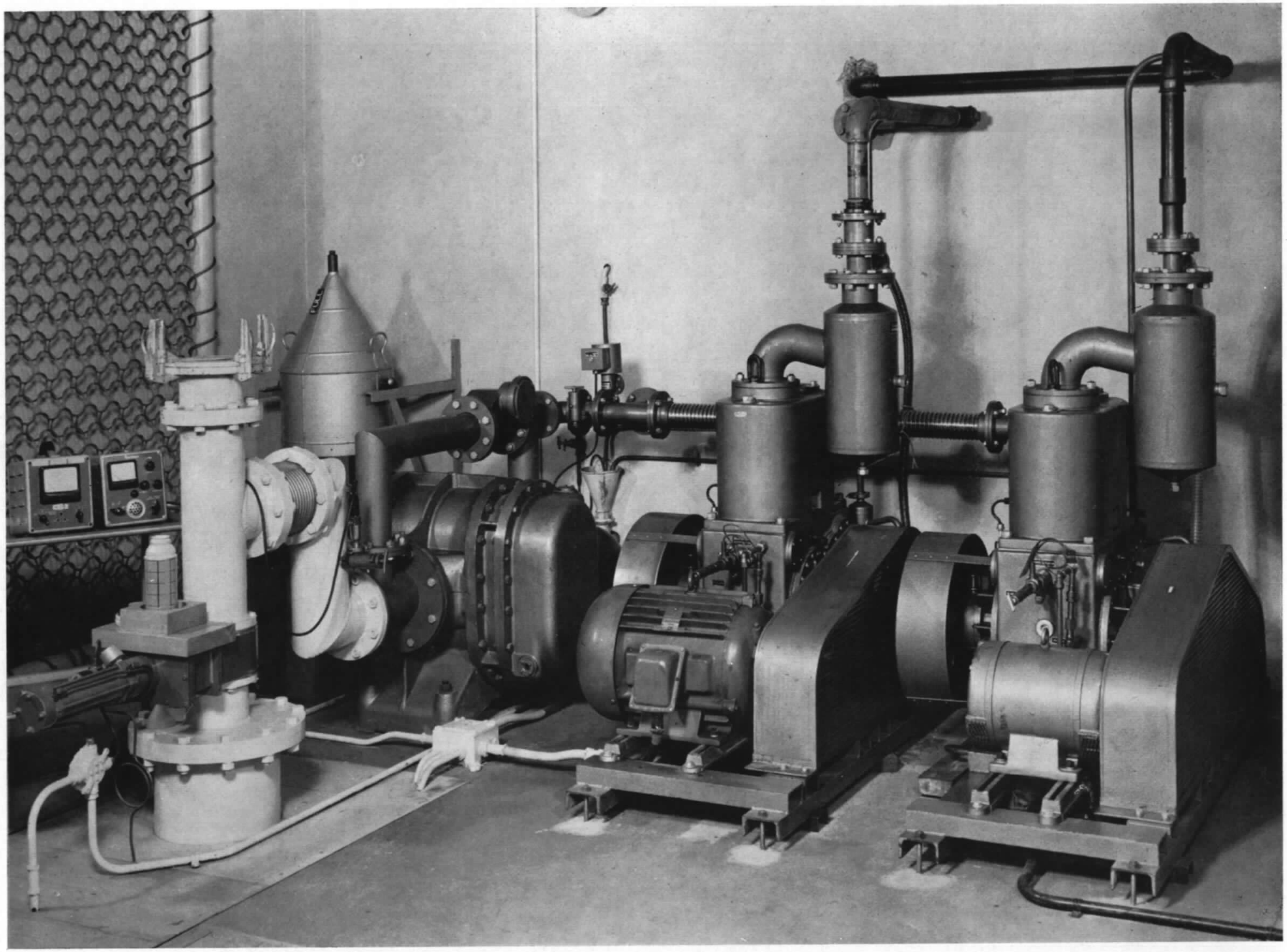


FIG. 15. Vacuum plant for shock tunnel.

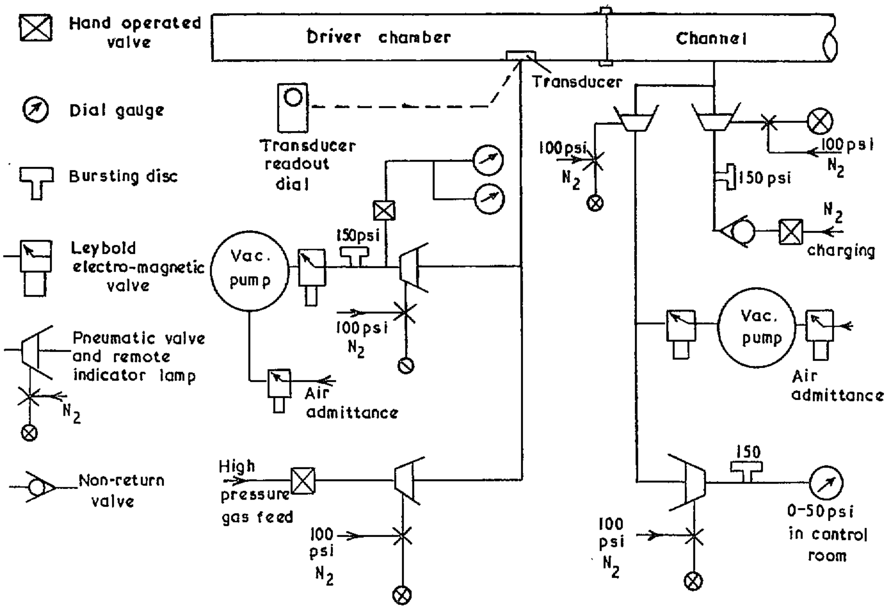


FIG. 16. Gas control services.

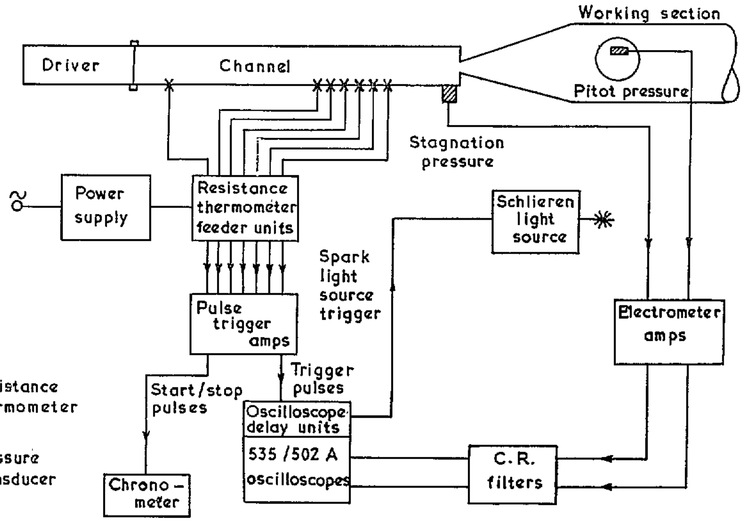
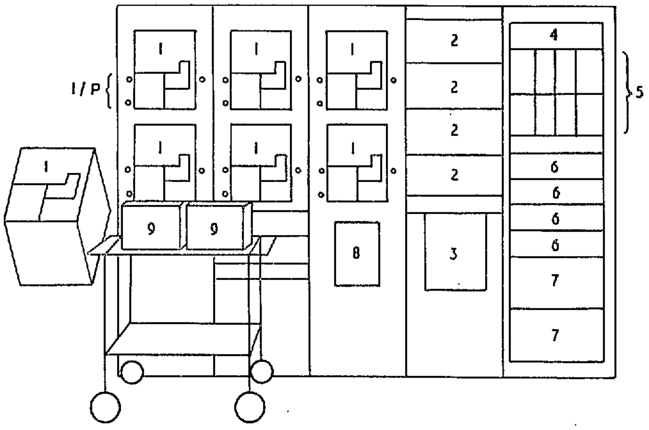


FIG. 17. Routine electronic instrumentation.



1	Tektronix T 535 oscilloscopes with Dumont T302 recording cameras
2	Racal type S.A.45 digital microsecond chronometers
3	Hewlett-Packhard Model 523 B electronic counter
4	Voltmeter panel for resistance thermometers in the tube
5	Two banks of Winston Pulse Trigger amplifiers
6	Preset Resistance Thermometer Feeder Units
7	Regulated power supplies
8	Tektronix T180A Time Mark generator
9	Electrometer amplifiers (mounted on a trolley)

FIG. 18. Control room electronics.

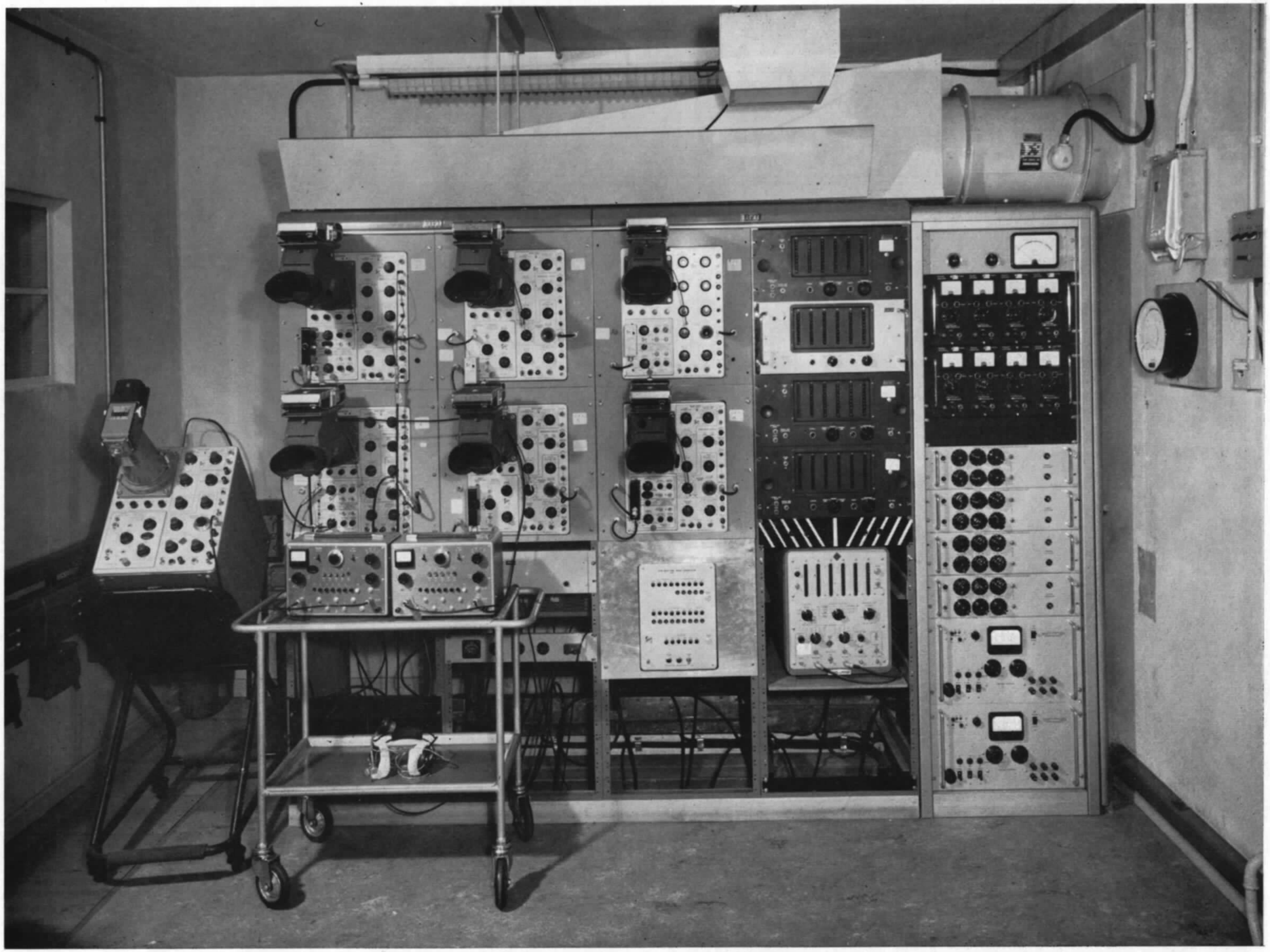


FIG. 19. Instrumentation bay for shock tunnel.

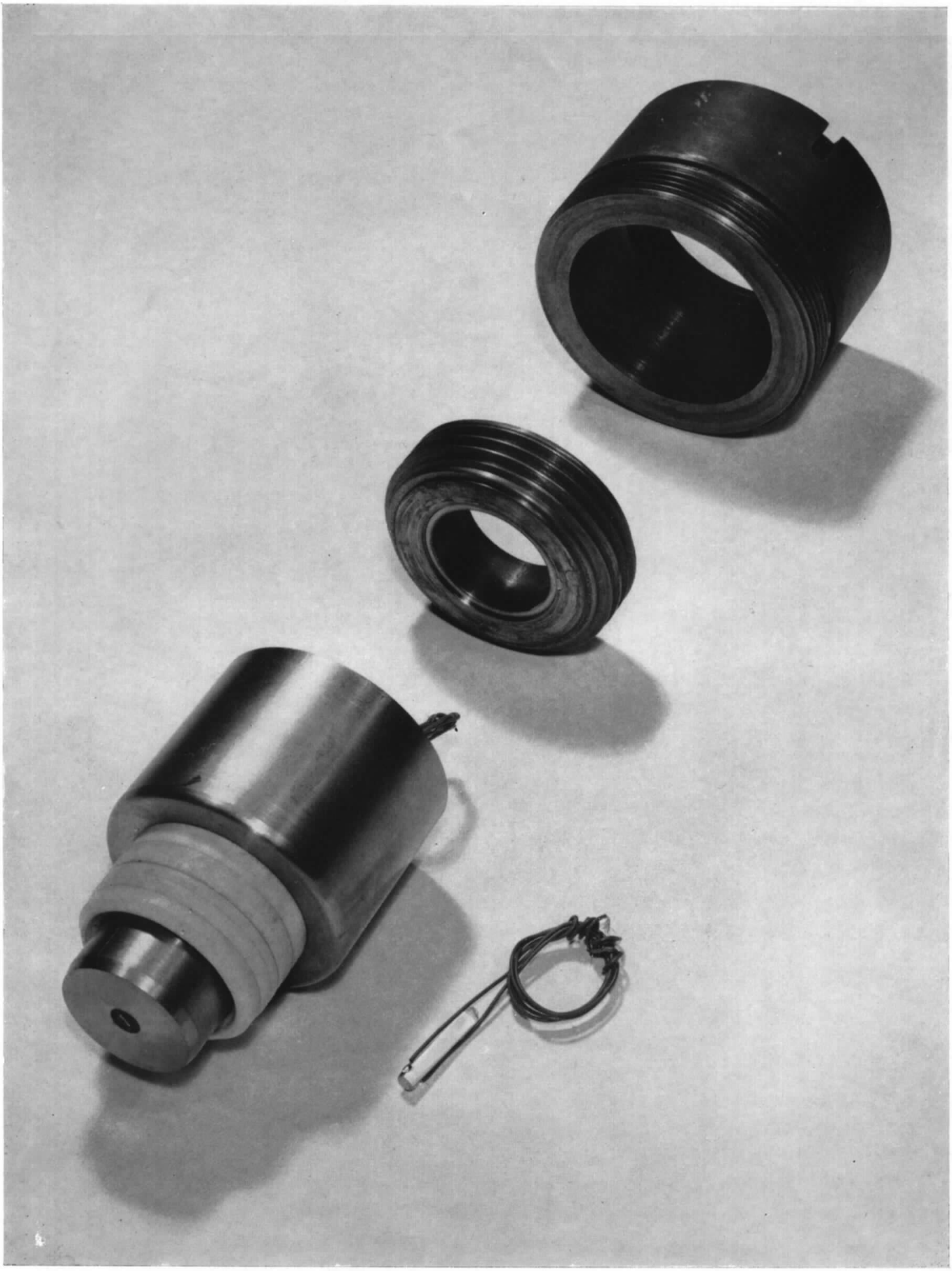


FIG. 20. Resistance thermometer assembly.

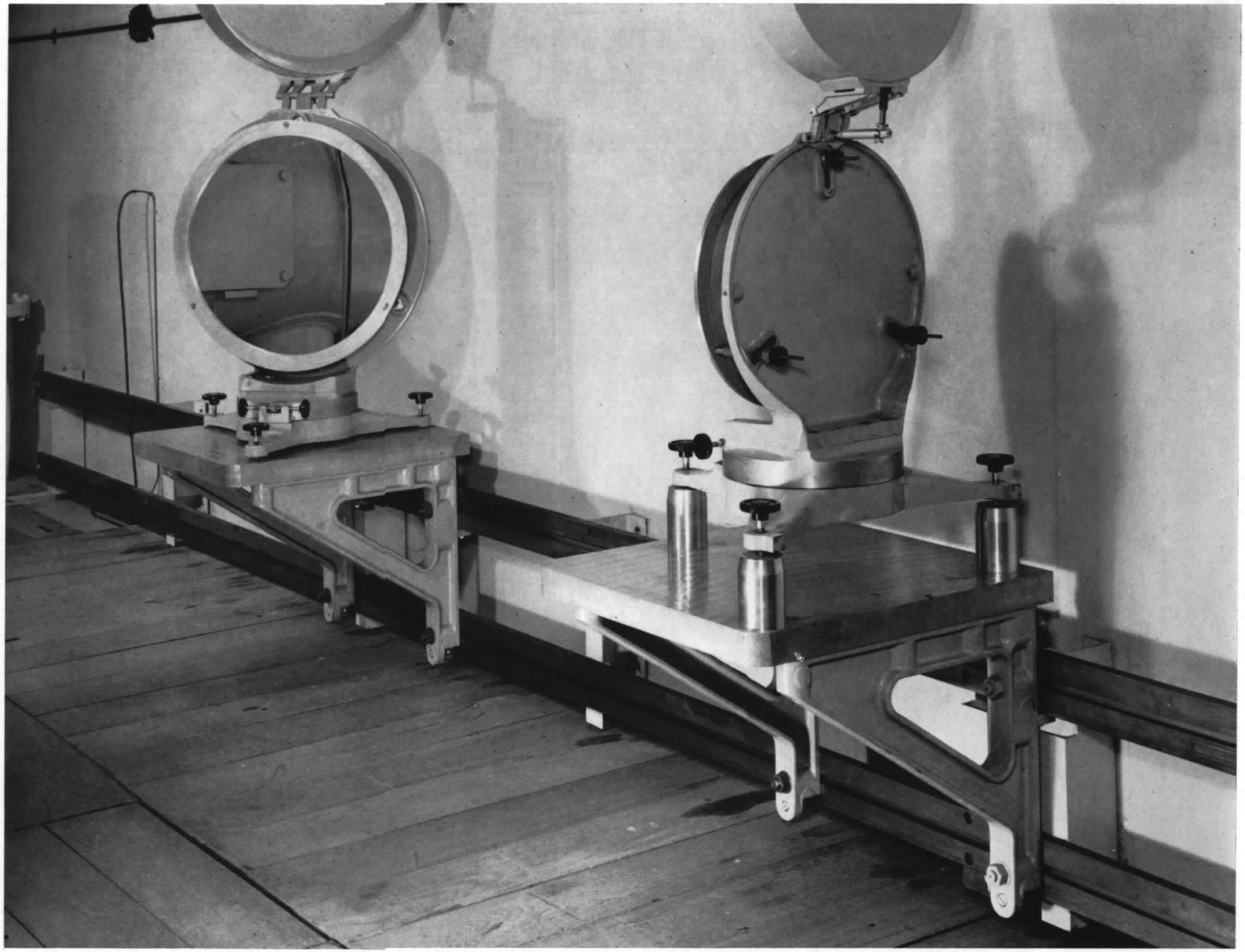


FIG. 21. Part of schlieren system.

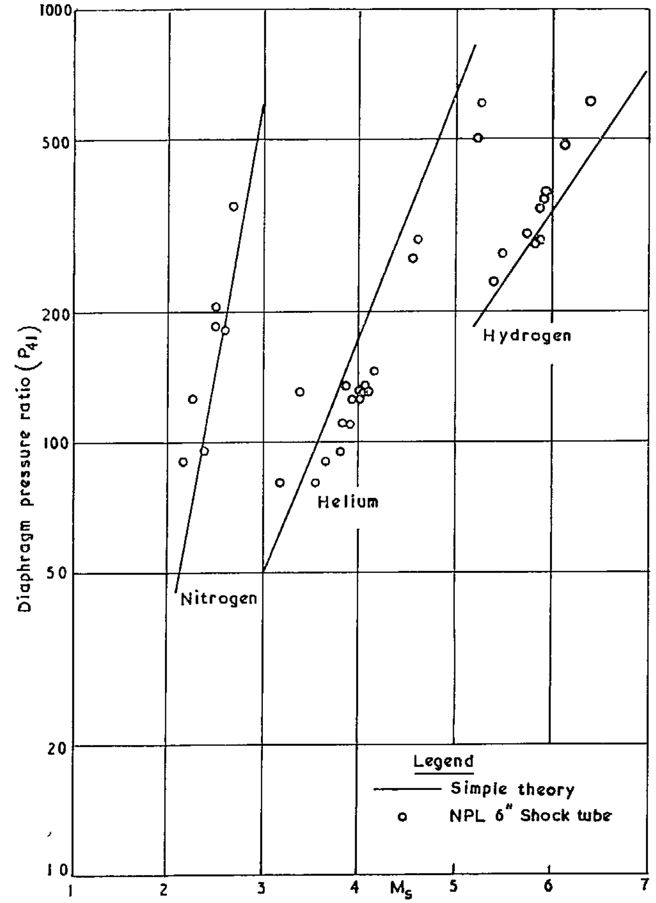


FIG. 22. Diaphragm pressure ratio for various driver gases.

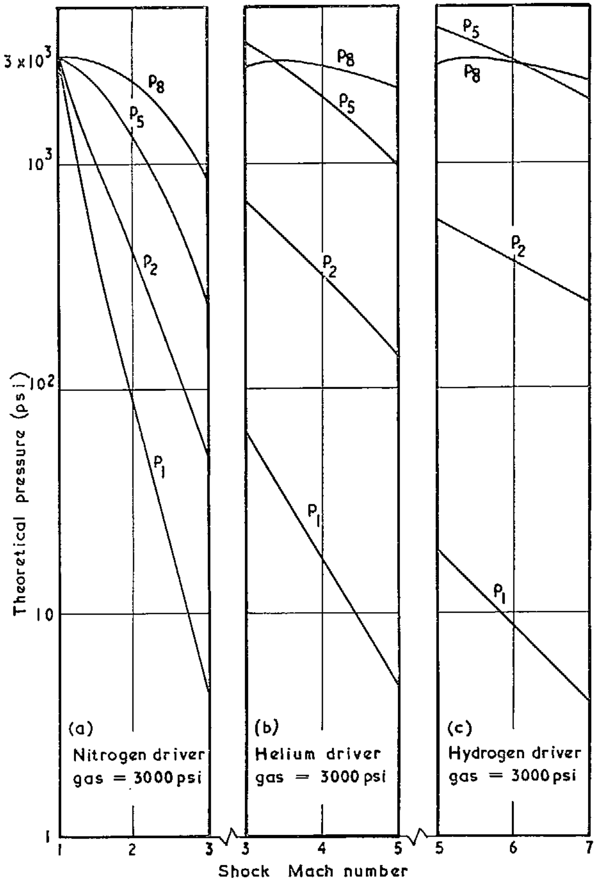


FIG. 23. Theoretical shock tube pressures for constant driver gas pressure.

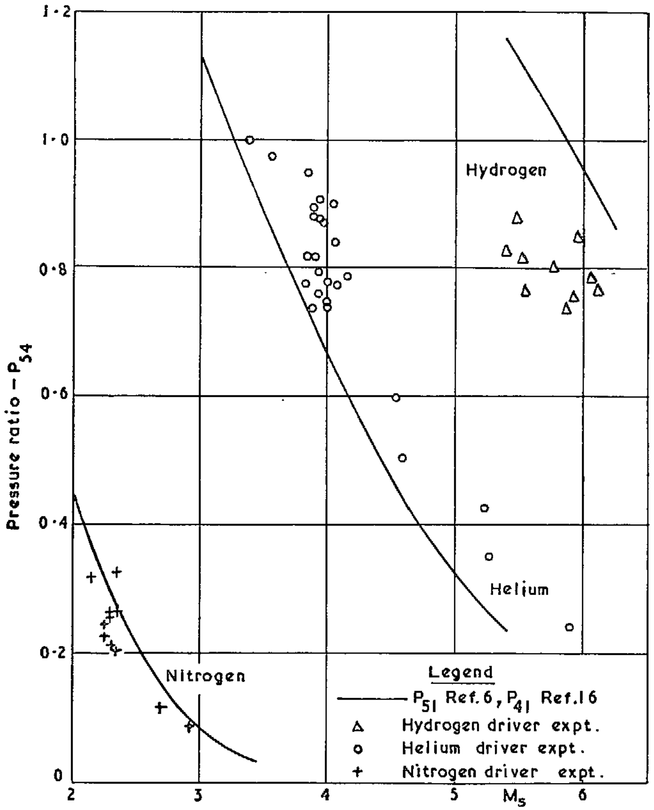


FIG. 24. Experimental pressure recovery for different driver gases.

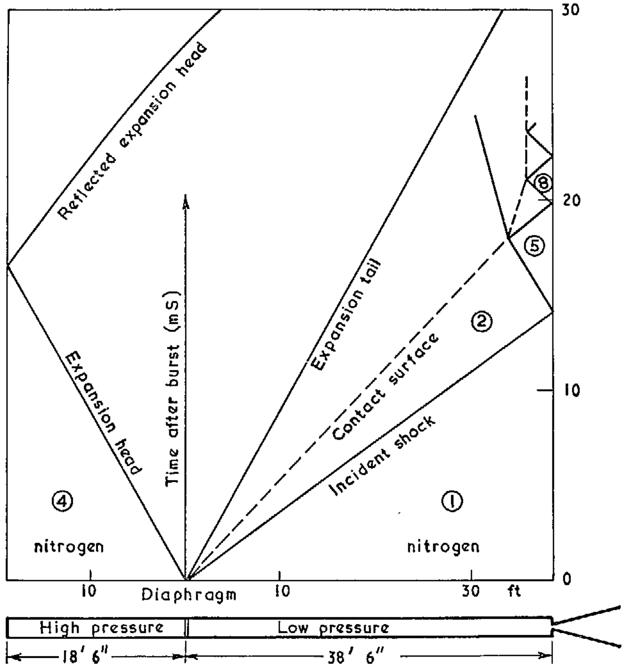


FIG. 25. Wave diagram for nitrogen driver at $M_s = 2{\cdot}4$.

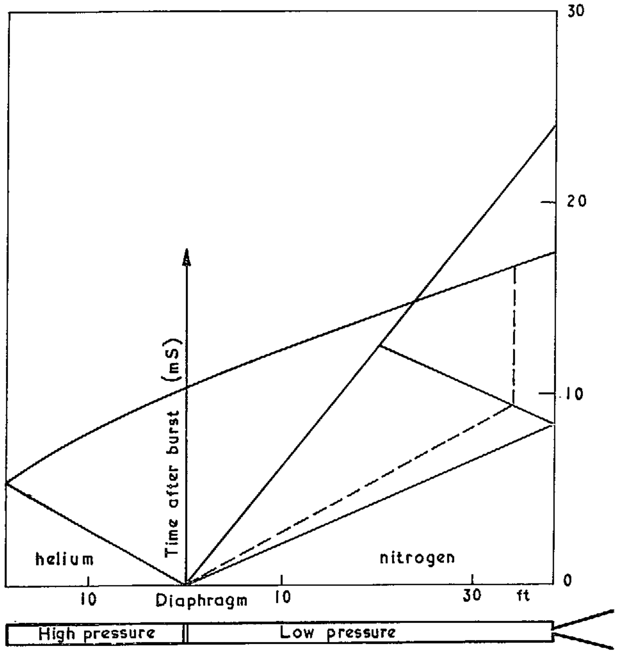


FIG. 26. Wave diagram for helium driver at $M_s = 4{\cdot}1$.

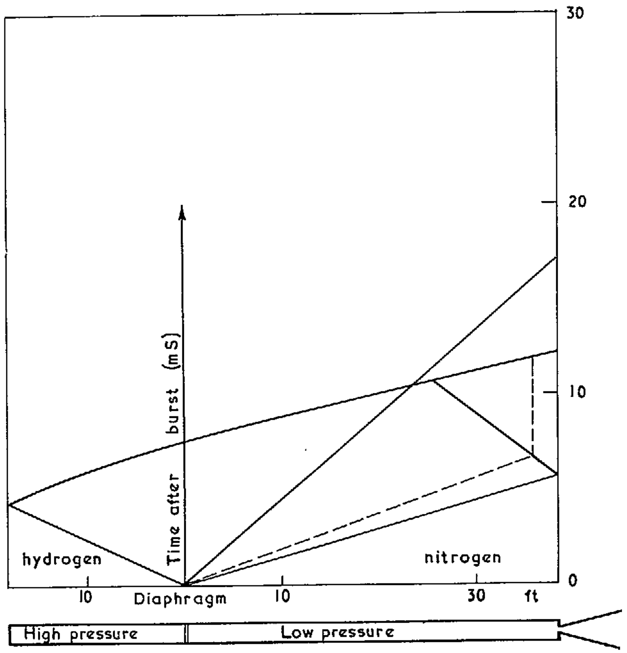


FIG. 27. Wave diagram for hydrogen driver at $M_s = 6{\cdot}0$.

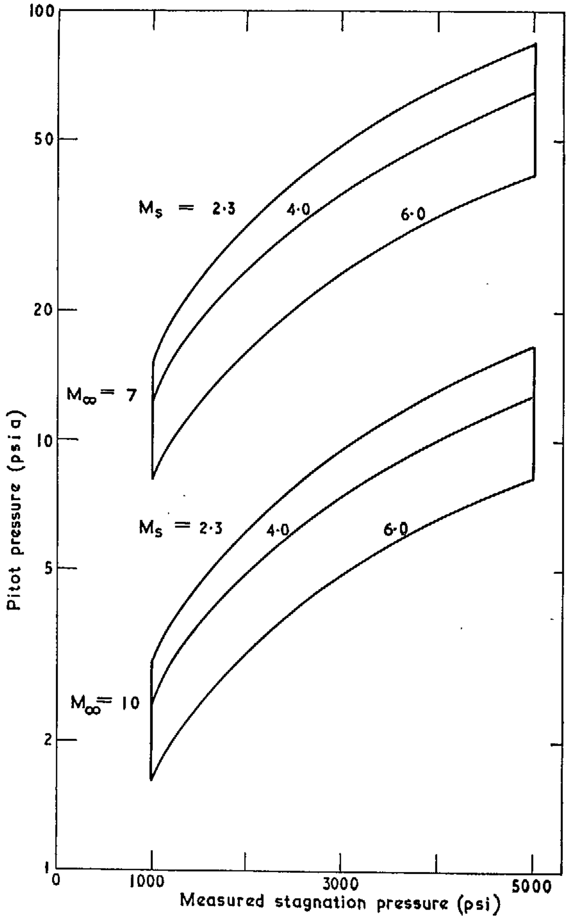


FIG. 28. Variation of pitot pressure with stagnation pressure.

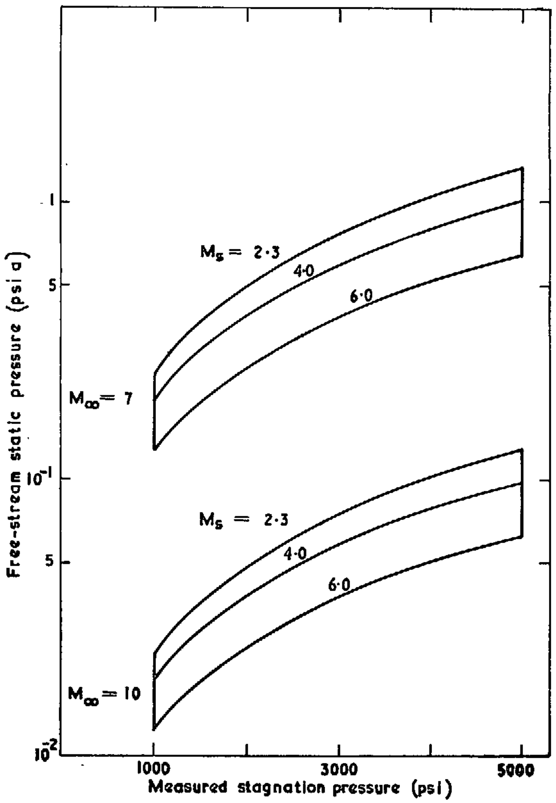


FIG. 29. Variation of free-stream static pressure with stagnation pressure.

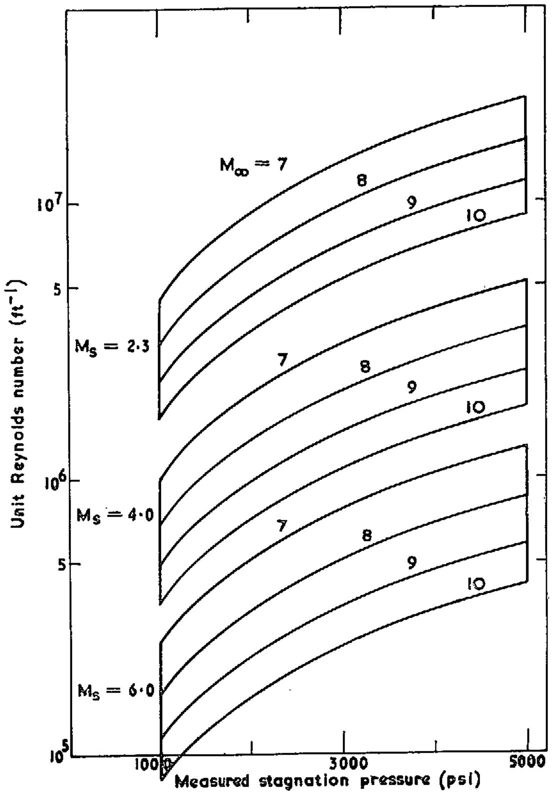


FIG. 30. Variation of unit Reynolds number with stagnation pressure.

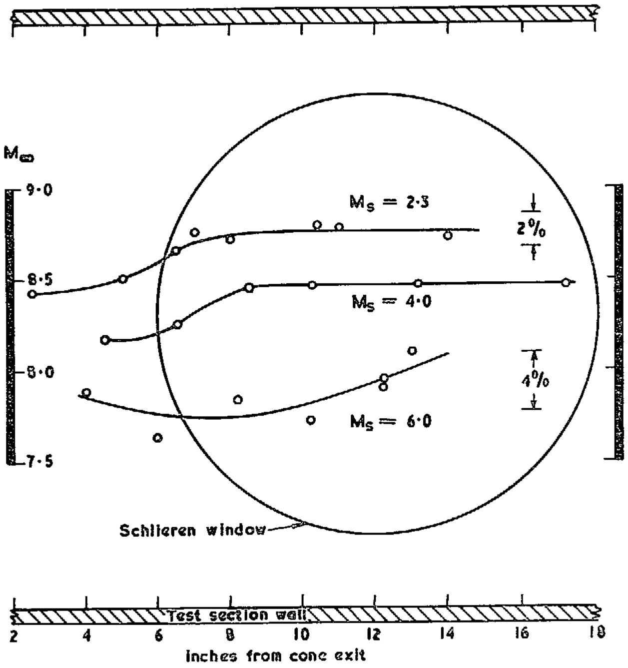


FIG. 31. Horizontal Mach number profile of centre-line of 16 in. test section.

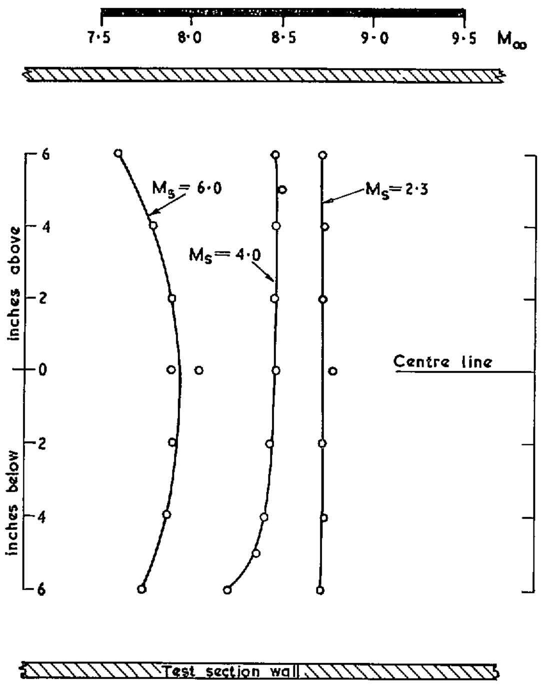


FIG. 32. Vertical Mach number profile of 16 in. test section at 11 in. from cone exit.

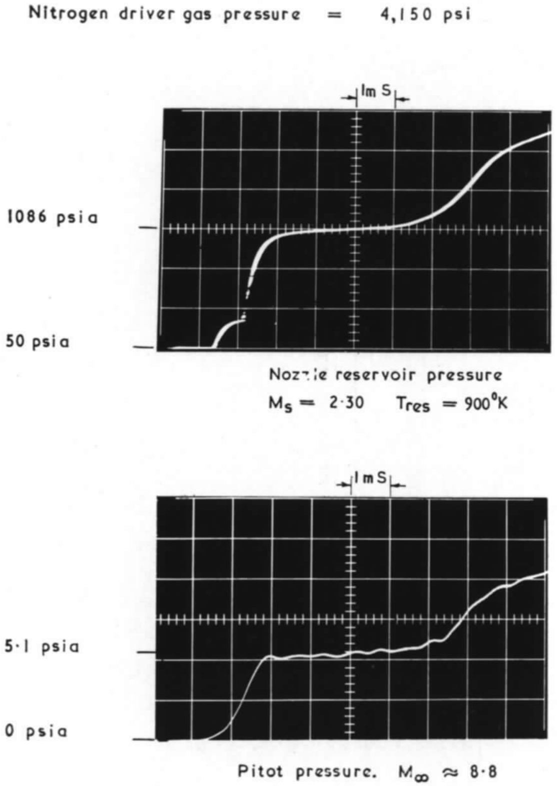


FIG. 33. Shock tunnel pressure records (nitrogen driver).

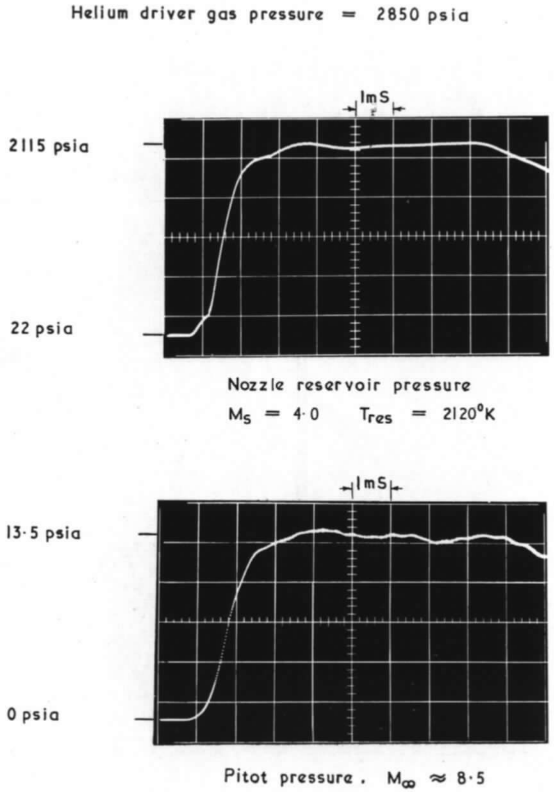


FIG. 34a. Shock tunnel pressure records (helium driver).

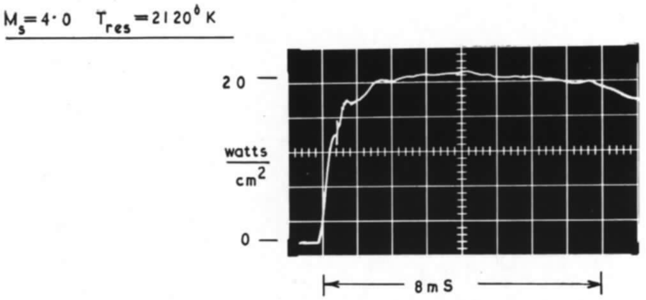


FIG. 34b. Analogue signal of test-section heat transfer rate with helium as driver gas.

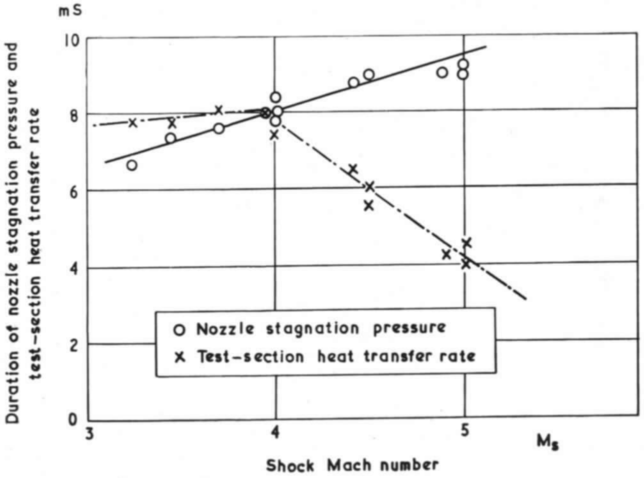


FIG. 34c. Duration of pressure and heat transfer rate with helium as driver gas.

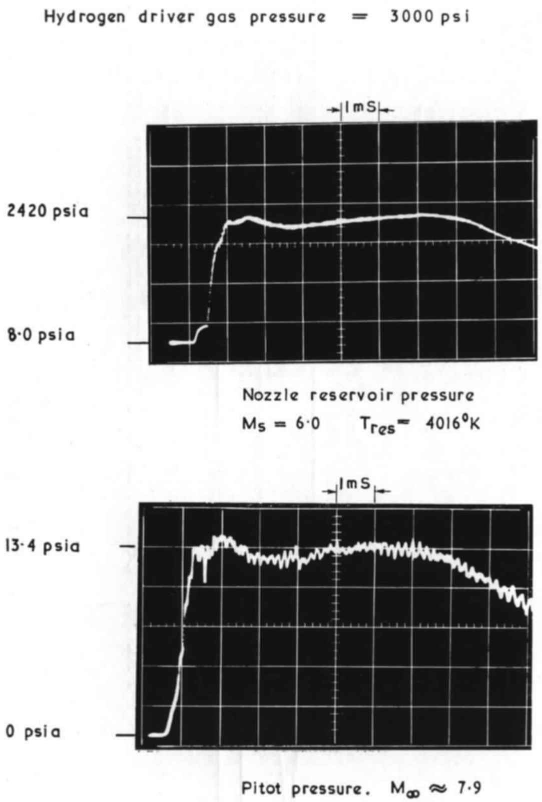


FIG. 35. Shock tunnel pressure records (hydrogen driver).

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