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The Imperial College Graphite Heated Hypersonic Windtunnel

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Summary.

This report describes the design and development of a graphite-heated, continuous running, Mach 20 windtunnel which operates with Reynolds numbers between 6×10^4 and 5×10^6 per metre.

Preliminary calibrations are presented for a contoured and a conical nozzle and for the performance of the centrefbody diffuser. An electron beam probe is used to measure test section conditions.

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Detachable Abstract Cards

1. Introduction.

The earliest hypersonic test facilities used Helium as a test gas. Being monatomic it is not representative of flight in our atmosphere, but it does avoid problems with condensation of the test gas as it expands through the nozzle to reach high Mach numbers. Diatomic gases can be used to simulate atmospheric conditions and the problems of gas condensation in the test section may be avoided by heating the gas. To give a workable pressure in the test section the tunnel has to operate with a high pressure gas supply. The major problem in the design of a hypersonic test facility is one of producing high pressure, high temperature gas at the nozzle throat.

Intermittent tunnels, such as shock tubes and gun tunnels, have been constructed. These use a strong normal shock wave to compress and heat the test gas, but unfortunately the testing times for these facilities are very short. To overcome this, continuous running "blowdown" tunnels have been built which exhaust high pressure gas into a vacuum system and achieve a given Mach number at a greatly reduced operating pressure. These tunnels usually have heaters or heat exchangers, the material of which limits the performance of the facility. One form of heat exchanger which operates at very high temperatures is the graphite resistance heater and wind tunnels using these operate with nitrogen at pressures up to 10,000 psi (68.95 MN/m²) and temperatures of 3,000°K (Ref. 1).

The Nitrogen Tunnel to be described in this report utilises a graphite heater and is one of the hypersonic wind tunnels available in the Aeronautics Department of Imperial College. Its performance envelope lies between that of the Plasma Jet and the Number One and Number Two Gun Tunnels (Fig. 1a). The test section Mach number with a conical nozzle is 22, and the tunnel stagnation conditions vary over a range of pressure from 500 (3.447 MN/m²) to 10,000 psi (68.95 MN/m²) and temperatures up to 3,000°K. This gives a Reynolds number range from $2 \times 10^4/\text{ft}$ ($6.56 \times 10^4/\text{m}$) to $1.5 \times 10^6/\text{ft}$ ($4.92 \times 10^6/\text{m}$). In terms of simulation of aerospace vehicles this corresponds to Mach 20 flight at altitudes between 110,000 ft (33,367 m) and 210,000 ft (63,700 m) in the Earth's atmosphere.

The Nitrogen Tunnel operates between certain bounds. There is a lower limit on temperature to avoid condensation effects in the test section (Ref. 11), and an upper limit on the temperature at which the heater can operate. There is a designed maximum pressure, and a minimum pressure below which the tunnel will stall. A further limitation is the vacuum pump performance. These limits are shown in Fig. 1b, superimposed on a grid showing Mach number and Reynolds number.

To ensure constant flow conditions during the nominally unlimited running time of the facility, two servo systems are used; one controlling the gas flow to maintain a constant stagnation pressure, the other ensuring a constant current through the heater which effectively controls the stagnation temperature.

This windtunnel has been constructed primarily to investigate viscous hypersonic phenomena for which rarefaction effects are significant and the flow over a flat plate typifies the problems that can be studied. Several flow regimes are associated with the flat plate leading edge problem and these are defined by the rarefaction parameter, \bar{V}_∞ , and the viscous interaction parameter $\bar{\chi}_\infty$. The variation of these two parameters over a typical flat plate in the Nitrogen tunnel test section is shown in Fig. 2. The strong interaction regime is characterised by $\bar{X}_{\infty,x}$ of 0(10) and in this facility this condition is reached 6 in. (150 mm) or more back from the leading edge. Strong interaction flow is characterised by large streamline deflection and pressure gradient terms of the same order as viscous stress terms in the boundary layer. Further forward, with $\bar{V}_{\infty,x} \sim 0.2$, merging of the shock and viscous layers occurs; slip and temperature jump become important and the shock waves are thickened. Between the strong interaction and merged layer regimes, shock curvature appears and the shock front can no longer be treated as a discontinuity. Nearer to the leading edge, within a few free-stream mean free paths, there is a region of near free molecular flow. The free-stream mean free path in this facility is of the order of 2×10^{-3} inch (5×10^{-2} mm) and any such region would be too small for any measurements to be made in this windtunnel. There is also a region of upstream influence ahead of the leading edge which has been investigated using an electron beam probe (Ref. 5).

There are two liquid nitrogen cooled nozzles available, each with an exit diameter of 6 in. The conical nozzle is used with 6 in. diameter test sections and this gives a nominal test section Mach number of 20. The second nozzle is contoured and it may be fitted with a boundary layer blowing ring at its exit and

this increases the test section diameter to 8 in. (203.2 mm) and the flow Mach number to 25. Facilities are provided so that pitot tube probes can be used to investigate flow around bodies and as the test section pressures are sufficiently low, the tunnel is equipped with an electron beam probe. This is used to measure density and temperature distributions while causing no significant disturbance to the flow fields (Ref. 5).

2. Nitrogen Tunnel Components

The Nitrogen Tunnel is a blowdown tunnel which is supplied with high pressure gas by a bank of compressors. The gas flow is regulated by a servo valve which maintains a constant reservoir pressure before the expansion through the nozzle. The high pressure gas is heated by a graphite resistance heater contained within a pressure vessel and expanded through a throat to a test section. Pressure is recovered with a centrebody diffuser and the gas cooled by heat exchangers before entering the vacuum pumps. The layout of the facility is shown in the line drawing of Fig. 3.

The present section covers the construction of the facility and the individual components from servo valves to heat exchangers. The electron beam, compressors, vacuum system and laboratory are described in subsequent sections.

2.1 Heater.

The graphite resistance heater is made in two parts; an outer shell and a separate inner spiral. It is identical to that used in the Princeton University N3 tunnel (Ref. 3). The heater assembly is shown in Fig. 5. The material for the heater is ZTA, supplied by British Acheson Electrodes, and the two parts are machined from the solid and finally fitted together in the Aeronautics Department workshops. There must be good electrical contact between the two parts of the heater along the whole length of the spiral, and this can only be achieved by very careful hand fitting. The heater is housed within a pressure vessel and thus it is only subjected to stresses resulting from its own internal pressure drop, of the order of 100 psi (689.5 KN/m²). The spiral passage inside the heater improves heat transfer to the gas by increasing the effective length and by adding swirl. The cross section of the heater varies along its length to increase the dissipation of electrical power at the cold end where greater heat transfer can be achieved. The average heater life is better than 20 hours.

The heater is supported within a stainless steel tube and is surrounded by a radiation shield made of 'Graphoil' material (supplied by British Acheson Electrodes). This assembly is detailed in Fig. 6. The cold end of the heater is clamped to a water-cooled support with graphite collets, and insulated from the supporting steel tube by three ceramic inserts. Power is fed into the heater at the cold end through a water-cooled lead which is insulated from the heater vessel by a thin layer of Araldite. The hot end of the heater is held in contact with the throat insert by graphite collets. This insert, which includes a small settling chamber has a slightly raised ring of metal which effects the gas seal between heater and nozzle and ensures good electrical contact. The return electrical circuit from the heater is made by connection to the exterior of the pressure vessel at the nozzle end.

The high pressure vessel containing the heater is constructed in two sections, clamped together with a nut and externally water-cooled. By keeping the overall diameter of the heater assembly to a minimum it has been possible to design a pressure vessel of modest dimensions. The complete heater assembly is entirely supported from the nozzle end of the vessel which ensures an intimate contact with the throat section despite any distortions due to the extremes of pressure and temperature.

2.2 Nozzle.

Two nozzles have so far been used on the Nitrogen Tunnel, both designed for a test section Mach number of 20. Nozzle calibrations are presented in the section on preliminary results.

2.2.1. *Conical nozzle.* The conical nozzle has an exit diameter of 6 in. (152.4 mm), a throat diameter of 0.040 in. (1.00 mm) and a total included angle of 20 degrees. It is made in three sections. A beryllium copper throat insert is followed by a stainless steel section which forms part of the high pressure vessel. The final section is a two-part aluminium alloy nozzle. The throat insert is water-cooled; the other

sections can be used with either liquid nitrogen or water as the coolant. All seals subjected to cryogenic conditions are supplied by the Aeroquip Corporation.

Some work is described below where the effects of cooling part, or all, of the final nozzle are investigated. Cooling of the nozzle walls thins the boundary layers and there is evidence that if the cooling on the final section is omitted, more rapid growth of the boundary layer over that part of the nozzle results in the flow being more nearly parallel in the test section with a corresponding improvement in the axial gradient. The measured test section Mach number is 21 and the nozzle operates satisfactorily over the full Reynolds number range. Nozzle calibrations are presented below. There is provision to extend the nozzle to a test section diameter of 8 in. (203.2 mm) using a conical expansion section.

2.2.2. Contoured nozzle. Conical nozzles usually have a divergent flow at their exit plane which causes an axial Mach number gradient in the test section. Contoured nozzles are designed for a parallel flow at the exit plane and therefore should have no axial gradients. The contoured nozzle for this tunnel is designed for a Mach 20 flow and 8 in. (203.2 mm) test section diameter. A Bristol Aeroplane (now BAC) programme was used to design the inviscid shape using a characteristics method giving a minimum length nozzle. The correction for boundary layer growth was made by applying the method of Burke and Bird. In order to keep to a nozzle of reasonable length it has been truncated to give a nozzle exit diameter of 6 in. (152.4 mm). This nozzle is constructed in the same way as the conical nozzle; the throat diameter being 0.032 in. (0.81 mm). The measured test section Mach number is 25 which would indicate that the boundary layer estimation predicted a less rapid growth than actually occurs.

With the basic contoured nozzle the flow separates from the walls when the flow conditions fall below a certain Reynolds number and the nozzle is useful only over a limited range of stagnation conditions. It is thought that disturbances travel upstream through the thick boundary layers from the diffuser to the nozzle and cause a breakdown of the flow.

To counter this a blowing ring has been introduced as a barrier separating the nozzle and diffuser. (Ref. 18). Nitrogen gas which is fed into an annular plenum chamber, passes through a set of discrete holes, equispaced around the circumference of the nozzle. It then expands along a 10 degree included angle duct to exhaust as an annular jet around the nozzle exit, blowing along the tunnel walls. The contour of the nozzle is continued within this section to give an exit diameter of 7 in. in a 8 in. tunnel section, the remaining space being taken up by the blowing ring. (See Fig. 25.)

It is hoped that this addition will allow the nozzle to run successfully over the full Reynolds number range of the tunnel with a uniform flow and negligible axial Mach number gradients characteristic of contoured nozzles.

2.3 Test Section.

The nozzle exits into the tunnel working section which is water-cooled on the outside and can be of 6 in. (152.4 mm) or 8 in. (203.2 mm) diameter, there being an expansion piece to extend the conical nozzle to the larger diameter. Test probes and models are mounted in this working section, which has access ports at the top, bottom and on either side. The overall length of the tunnel may be altered by adding parallel tunnel sections between the test section and the diffuser, the addition of these sections effectively changing the layout of the diffuser.

The electron beam equipment is mounted on top of this test section and the Faraday Cup opposite, on the bottom port. To allow the model to be precisely aligned with the beam a flexible bellows section is mounted just behind the test section. This allows the model, which is supported from downstream, to be moved through 1.6 in. (40.6 mm) fore and aft. Three telescopic sliding joints equispaced around the circumference ensure that the end faces of the bellows remain parallel when adjustments are made. Spacers of different thickness are used to position the model roughly below the electron beam; final adjustments of position are done using the flexible bellows.

2.4 Diffuser.

Some work has been completed to investigate the performance of the diffuser in the Nitrogen Tunnel. It acts as a link between the test section pressure, which depends on stagnation pressure and Mach number, and the entry pressure required by the approximately constant volume vacuum system.

The diffuser is of a centrebody type and is made from sections which may be easily changed. The effect of individual features of the centrebody diffuser on the overall performance can be easily investigated. The tunnel sections upstream are an integral part of the diffuser and influence its performance. All the tunnel sections are water-cooled. At the entrance to the diffuser the tunnel outside diameter changes from 6 in. (152.4 mm) to 8 in. (203.2 mm) through a 15 degree expansion section.

Tests so far have been concerned with the position of the centrebody relative to the change in diameter of the outer casing, or second throat length, and the semi-angle of the diffuser front cone. The present centrebody is made of aluminium alloy and is cooled only at its supported end. The diffuser geometry is shown in Fig. 7 and the performance of a 15 degree and 7½ degree semi-angle front cone diffuser is compared in Fig. 8. These results are for a liquid nitrogen cooled nozzle and further work is planned.

2.5 Heat Exchangers.

The vacuum pumps have a constant volumetric displacement and so their performance is dependent on the temperature of the gas passing through them. It is therefore necessary to cool the flow before it leaves the tunnel. A 15 degree section expands the 8 in. (203.2 mm) diameter diffuser exit to 14 in. (355.6 mm) at the entrance to the cooler which is constructed to take up to five rows of finned copper tube heat exchangers. A 10 in. (254.0 mm) diameter pipe connects the tunnel, via two gate valves, to the vacuum pumps.

2.6 Construction.

The tunnel components are mounted on rails on top of the concrete support and can be easily moved to change the layout of the tunnel, which is rigidly clamped to the concrete base by supports at the heat exchanger box, the heater end being free to move along the rails. Each component is supported on rollers which allow the tunnel to be accurately aligned vertically and from side to side to ensure that vacuum faces come together exactly. These general features are illustrated by Fig. 4 which shows the tunnel during construction and a view of the laboratory in its present state with 8 in. test section, the nozzle blowing unit and the one-dimensional traverse.

3. Control and Operation.

The instrumentation which is described in this section relates to that which is necessary to run the tunnel; any other instrumentation for a particular test will be described elsewhere. The Nitrogen Tunnel is controlled from the panel in the blast-proof control room, and all basic tunnel instrumentation is read out on this panel.

High pressure nitrogen is fed into the heater through an hydraulic servo valve system which controls the tunnel total pressure downstream of the heater. The system (see Fig. 9) comprises two servo-controlled needle valves arranged in parallel in the high pressure gas supply line. The tunnel mass flow is measured by two turbine flow meters, one in each gas line. In one side of the system there is a coarse valve and flowmeter used for initially filling the heater pressure vessel. On the other side, a fine valve is capable of controlling the tunnel steady mass flow precisely. Automatic change-over from one valve to another is effected by monitoring the signals from the flow-meters. Each valve is constructed with an hydraulic actuator controlled by a "Moog" servo valve. A displacement transducer and an operational amplifier complete the position servo for each valve. The actuator system was supplied by Dowty. The needle valves are our own precision reconstruction of PPI valves. A photograph of the assembly is shown in Fig. 10.

The signal for servo-controlling the valves is derived from a precision pressure transducer which measures total pressure (p_0) in the stagnation chamber. Another transducer measures the gas pressure after the servo valves. This, together with the gas temperature is necessary to calculate the mass flow, since the turbine flow meter measures the volumetric flow rate. The difference between the two pressure transducer readings is a measure of the pressure drop across the heater which, in turn, is a good indication of its condition.

Because of the high total temperature of the gas in the small stagnation chamber of the Imperial College graphite heated hypersonic windtunnel, it is not possible to make direct measurement of total temperature—for example by using a thermocouple. The temperature is calculated, using a real gas calculation, from a knowledge of mass flow rate (\dot{m}), stagnation pressure (p_0) and the nozzle throat diameter. It is assumed that the influence of compressibility and vibrational relaxation, while not negligible, are sufficiently small for their effects to be treated separately.

The following method for the calculation of stagnation temperature (T_0) is suggested by Vincente and Kruger (Ref. 14).

The adiabatic flow of a real gas, in equilibrium, through a nozzle is represented by the following five equations:—

Nozzle geometry	$A = A(x)$	(1)
Conservation of mass	$\dot{m} = \rho AU$	(2)
Energy equation	$h_0 = h + \frac{1}{2}U^2$	(3)
Isentropic process	$s = \text{constant}$	(4)
and Equation of state	$p = Z\rho RT$	(5)

The unknown quantity of the equation set is $\rho(h, s)$ which may be represented by the Mollier Diagram for Nitrogen.

An initial guess for T_0 is based on the perfect gas equation for \dot{m} ; p_0 is known. The entropy and enthalpy of the real gas are calculated using the method of Woolley (Ref. 15). At the throat, A is a minimum so ρU must have a maximum value. Knowing the entropy and stagnation enthalpy of the flow, the problem is one of moving along a line of constant entropy in the Mollier Diagram by varying the enthalpy. This corresponds to stepping towards the throat from the stagnation chamber. For each value of h , ρU is calculated using equation (3) above. When ρU reaches a maximum the mass flow through the nozzle is known.

This mass flow is then corrected for vibrational freezing, assuming a finite value of the rate parameter. The correction is obtained by fitting a curve to computed data for the flow through a hyperbolic nozzle with 45 degree semi-angle and 0.032 in. (0.81 mm) throat. The curve was computed by Schofield and Wilson of N.P.L., with data given by Sebacher (Ref. 13).

This value is compared with the actual mass flow through the Nitrogen Tunnel during a particular test run. If the two mass flow rates are different the assumed value of T_0 is modified—so moving to a different constant entropy line—and the mass flow re-calculated. This process is continued until the difference in mass flow ratio is such that the corrections needed to uprate T_0 are less than 1 degree K.

At this time, p_0 , T_0 , \dot{m} and the thermodynamic properties of the real gas are known. Using the method of Wilson and Regan (Ref. 6) or Culotta and Richards (Ref. 16) an equivalent perfect gas is calculated from the real gas properties. The equivalent perfect gas pressure and temperature (P_{EQ} , T_{EQ}) and the measured test section pitot pressure are used in the equations for the isentropic flow of a perfect gas to calculate the test section Mach number. The measured pitot pressure is corrected for viscosity effects using the method of Schaaf (Ref. 17), based on the Reynolds number of pitot tube behind a normal shock, and the test section Mach number re-calculated until the changes in test section conditions are less than 0.01 per cent. The parameters relevant to hypersonic rarefied gas flows, \bar{V} , the rarefaction parameter and $\bar{\chi}$, the viscous interaction parameter, are calculated from the known test section conditions.

The change in p_0 , and T_0 over the period of a typical test have been carefully measured and representative variation are ± 5 p.s.i. in 1300 p.s.i. and ± 10 degrees K respectively. The total pressure can be checked against a Heise pressure gauge, which has a resolution of 5 p.s.i. It is not possible to check the total temperature directly, but aerodynamic measurements known to be strongly dependent on T_0 are repeatable.

The power input to the heater is regulated from the control panel and is indicated on volt and current meters. Positions of valves are shown by semaphore repeaters on a line diagram of the tunnel and lights

give a warning if any part of the tunnel casing overheats. Two television monitors on the control panel are used to view any part of the laboratory. The controls for the high pressure compressors are also on this panel, as are those for the electron beam apparatus.

Two probe traversing mechanisms can be mounted on the tunnel. The smaller is a one-dimensional traverse, which can be attached to any of the ports and carries a pitot tube in a transverse direction across the flow. The mechanism is driven by an electric motor and a linear potentiometer indicates the position of the probe. This can be used in conjunction with a plotter to give a continuous pitot pressure traverse.

The three dimensional traverse is mounted as a tunnel section, downstream of the bellows. Models can be mounted on ports in this traverse section and probes, which are carried on an insulated mounting, can be positioned to 0.001 in. (0.025 mm) within a volume $9 \times 6 \times 3$ in. ($228 \times 152 \times 76$ mm). Three separate driver systems are used, each consisting of a stepping motor and double-start lead screw. The motors are driven by a series of pulses, and the pitch of the lead screw is such that each pulse represents a movement of 0.001 in. (0.025 mm) and one revolution a movement of 0.2 in. (5.08 mm). A bi-directional counter counts the number of pulses and gives a direct read out of position on each axis. At each complete revolution of the lead screw a disc, carried at its end, gives a synchronising signal which triggers the electronics to interrogate a binary coded strip which has 0.2 in. (5.08 mm) increments. This positional information is automatically checked against that displayed by the bi-directional counters and any fault is indicated. This same system is used to initially set up the counter when the equipment is turned on. The probe is introduced into the flow through a long slot in a rotating tunnel liner within the traverse, and touch wires near the edge of the slot signal the liner to rotate when the probe is moved sideways. The whole assembly, which was designed and built within the Aeronautics Department, is contained within a vacuum box. Fig. 12 illustrates the construction of this traverse.

For flow visualisation a glow discharge attachment is available as a unit which is placed between the nozzle exit and the test section. Two aluminium electrodes are mounted in a recessed tunnel section and are excited at 2 kV, 50 Hz. This unit produces a stable afterglow in the test section and is similar to the system used on the N.P.L. Low Density Tunnel (Ref. 12). A yawmeter has been built to measure the divergence of the flow from a conical nozzle. A photograph is shown as Fig. 24. Experiments have confirmed that the flow from the conical nozzle is divergent in the test section.

The present tests are concerned with measuring pressure distributions over models with forward facing steps and on waverider wings. Surface pressures are measured by a bank of 11 transducers—supplied by Pace Engineering Company and Datametrics Inc. The high level output signals are sent to the control room along permanent cables which are terminated in a panel carrying a potential divider on each channel.

The outputs from the pressure transducers, flow meters and any other measured quantity are fed into a 16 way multiplexer, designed and built by the Department and having the facility of extension to 32 channels by the addition of a slave unit. The output of the multiplexer is digitised by a Hewlett Packard Digital Volt Meter, Model 3460B, which forms one input to a Hewlett Packard Model 2570A Coupler/Controller. This system produces a punched data tape compatible with the College's CDC 6400 computer for on-line data reduction via a remote terminal close by the laboratory. A Texas Instruments Model 720 Teleprinter is used to control the system and is also used to input or output relevant alphanumeric information such as run number and model geometrical data. Positional information derived from the three dimensional or other traversing mechanisms constitute another possible digital input source for the computer/controller. Output information may be routed via a Hewlett Packard Model 5050B Digital Recorder to give an immediate hard copy of experimental information.

4. Electron Beam Probe.

Electron beam measurements have been made in low density wind tunnels since the early 'sixties. They provide an accurate method of examining flow conditions, with negligible interference to the flow. High energy electrons cause gas molecules to become excited and the decay of these molecules results in fluorescence of the nitrogen. The density can be inferred from the intensity of this fluorescence and the rotational and vibrational temperatures obtained by a detailed examination of the relative intensities of the spectral lines in various bands. For nitrogen the first negative band is chosen (Ref. 4).

The present electron beam probe, which has also been used on the N.P.L. low density Mach 6 tunnel, was designed by Lillicrap and a full description appears in his Thesis (Ref. 5). Fig. 13 is a schematic drawing of the electron beam arrangements.

The electron gun is a commercial electron microscope unit and uses tungsten hairpin filaments. The initial focussing is electrostatic and may be controlled by a variable grid bias resistor. It is possible to align the beam by mechanically adjusting the head of the gun but the final alignment is done using two deflection coils, positioned below the head of the gun. Two magnetic lenses are used to obtain a narrow, parallel beam about 0.040 in. (1 mm) diameter which is directed across the test section through a narrow drift tube connecting the gun to the underside of the model. This is used to match the pressure at the beam exit hole on the model to the pressure in the drift tube, ensuring that there is no gas flow into or out of the hole in the model surface, which would modify the flow being traversed. An additional pair of deflection coils correct any slight misalignment of the beam before it enters the drift tube. The focussing and deflection coils are powered by six Advance PM44 power supplies, rated at 1 amp constant current with less than 0.1 per cent variation between load and no-load conditions. The electron gun provides an electron beam of 1 mA at 30 keV.

The pressure within the electron gun must be maintained below 5×10^{-4} mm Hg to prevent the filament burning out but at the same time it is necessary to provide an unimpaired path for the electrons to reach the test section where the pressure is at least an order of magnitude higher. The open path is provided by using a 'dynamic valve', an orifice 0.040 in. (1 mm) diameter by 1 in. (25.4 mm), which impedes the flow into the gun sufficiently for the diffusion pump to maintain the required level of vacuum.

The beam is scanned through a window in one side of the test section by a motor-driven two-dimensional optical traverse which can be positioned within an area $2\frac{1}{2} \times 1$ in. (63.5×25.4 mm) with an accuracy better than 0.001 in. (0.025 mm). Light from a point in the flow field is passed through a fibre optic supplied by H. V. Skan and made of quartz to transmit the required wave lengths. This light is fed either directly to a photomultiplier for density measurements, or via a lens system to a spectrometer for temperature measurement. The fibre optic provides a flexible path between the traverse and the spectrometer, thus avoiding the use of double mirrors. The photomultipliers used are EMI type 6256S in cryogenic cases (supplied by The Oxford Instrument Company) and the spectrometer is a 3/4 metre Spex instrument.

5. Tunnel Calibration.

The initial work has been concerned with calibrating the nozzles over their working Reynolds number range. Tests have also been done to investigate the performance of the centrebody diffuser and the nozzle blowing ring. The contoured nozzle and the conical nozzle have been calibrated using the three dimensional traverse carrying a pitot tube. The Reynolds number based on pitot tube diameter is such that corrections for viscous effects are small, even at the worst flow conditions (Ref. 7). These calculations are included in the computer program used to calculate tunnel test section conditions.

5.1 Conical Nozzle.

In a report such as this it is not practical to present complete calibrations and so only a few typical results for the conical nozzle flow are shown in Figs. 19–23. Fig. 19 shows the axial Mach number gradient for constant total pressure and temperature. The working core is seen to be $4\frac{1}{2}$ in. (114.3 mm) with $p_0 = 2500$ p.s.i. (17.235 MN/m^2) and $T_0 = 1000$ degrees K. The Mach number axial gradient is about 0.35 per inch (13.8 per metre) under these supply conditions. Fig. 20 shows the variation of Mach number at distances away from the nozzle exit for a fixed value of p_0 , T_0 and γ . This indicates a Mach number gradient of 0.45 per inch (17.7 per metre) for $p_0 = 970$ p.s.i. (6.687 MN/m^2), $T_0 = 1000$ degrees K. There appears to be a variation of axial gradient with total pressure, the nozzle having an optimum supply pressure. This is illustrated by Fig. 21 which shows that Mach number profiles, at a given station and fixed T_0 , are dependent on the total pressure. The effects of temperature on Mach number profiles for a given p_0 at a fixed station are shown in Figs. 22 and 23 for $p_0 = 970$ (6.687 MN/m^2) and 2500 p.s.i. (17.235 MN/m^2) respectively.

The conical nozzle is made in two sections, each section having its own cooling jacket. Some tests have been done to investigate the effect of liquid nitrogen cooling the whole nozzle or the first section only. Results show that the Mach number variation over the working core is reduced when only the first section is cooled, although the size of core is unchanged. The tunnel has run satisfactorily with a fully cooled conical nozzle at the low p_0 of 500 p.s.i. (3.447 MN/m^2) at $T_0 = 2000$ degrees K, which yields a Reynolds number of $1.98 \times 10^4/\text{foot}$ ($6.5 \times 10^4/\text{metre}$).

5.2 Contoured Nozzle.

A limited amount of work has been done to investigate the performance of the contoured nozzle. The Mach number profiles were seen to be much flatter than for the conical nozzle at the same values of p_0 , but the flow stalled at a Reynolds number of $3.5 \times 10^5/\text{foot}$ ($1.148 \times 10^6/\text{metre}$), when operating with water-cooled walls. Although this nozzle operates with flatter profiles it can only be used over a limited Reynolds number range and further work is intended to investigate the effects of liquid nitrogen cooling and improved diffuser performance. Preliminary results indicate that the blowing ring and liquid nitrogen cooling will prevent this flow breakdown.

5.3 Diffuser.

The purpose of the centrebody diffuser is to match the test section pressure to the inlet pressure for the vacuum pumps. Some small amount of work has been done to investigate diffuser performance which illustrates that it is satisfactory. Results of the preliminary investigation are presented in Fig. 8. There are two sets of data; one for the contoured nozzle with a 15 degree semi-angle front cone; the other for the conical nozzle with a $7\frac{1}{2}$ semi-angle centrebody. Both diffusers are uncooled and in both cases the nozzles were fully liquid nitrogen cooled. The curves show that the diffuser is efficient in matching test section to vacuum pump conditions. The correct limiting performance can only be obtained with a leak introduced downstream of the diffuser.

6. Tunnel Services.

6.1 High Pressure Gas Supply.

The Nitrogen gas supply and the four stage compressor bank are common to the Nitrogen Tunnel and the Number 2 Gun Tunnel (Ref. 8). The pipework associated with the high pressure gas supply is shown in Fig. 14.

High purity nitrogen is stored as a liquid outside the laboratory building. The liquid is passed through air-cooled evaporators and the gas is then fed to 'De-oxo' units which remove oxygen to maintain a purity well within the required standard of 2 parts per million total impurity. The only permissible impurities are inert gases. Nitrogen gas is supplied to the 1st stage compressor at up to 30 p.s.i. (206.82 KN/m^2), the inlet pressure being controlled from a regulator in the control room. Nitrogen can also be supplied from gas bottles in an adjacent store.

The four stage compressors are all of the diaphragm type in order to maintain the high purity of the gas. They are housed in the laboratory on a floating concrete slab mounted on a spring-damper anti-vibration system (Fig. 15). The maximum outlet pressures of the four stages are 250, 1,000, 5,000 and 15,000 p.s.i. respectively ($1.724, 6.894, 34.470, 103.410 \text{ MN/m}^2$). In general the Nitrogen Tunnel uses only the first three stages with a maximum gas pressure of 5,000 p.s.i. (34.470 MN/m^2). All four compressors are manufactured by Pressure Products Incorporated (U.K.) Ltd. The first and second stages are combined in a Model 729 0160 2-stage diaphragm compressor; the third stage is a Model 7104, and the fourth stage a Model 7078. The power consumption of the four stages is 48 kW.

6.2 Vacuum Plant.

The required low pressure downstream of the wind tunnel is produced by a vacuum system supplied by Leybold-Heraeus Ltd., the pumping speed of which is $2 \times 10^4 \text{ m}^3/\text{hr}$ under the tunnel operating condition. The full performance curve is shown in Fig. 17.

The plant consists of two large Roots pumps (Ruvac 59's) running in parallel, followed by an intermediate single Roots pump (Ruvac 46) and finally backed by two parallel rotary piston pumps (type S800). The pumps are isolated from the tunnel sections by two VAT pneumatic gate valves. The layout of the vacuum system is shown in Fig. 16. The two S800 pumps are mounted on the floating compressor slab and may be seen in Fig. 15. The power consumption of the vacuum plant is 100 kW.

6.3 Heater Power Supply.

Power for the resistance heater is supplied from Ferranti constant current rectifier equipment with a D.C. output rated at 120 kW. The working current is between 0 and 3,000 amps with voltages from 40 to 160 volts at full load. Low ripple on the output is achieved by polyphase rectification, using one star and one delta connected transformer and adding their full wave rectified outputs. The specified total harmonic distortion under full load is 4.28 per cent r.m.s., of which 2.25 per cent is at the 12th and lowest harmonic of the 50 Hz supply.

The equipment, which is fully solid state, comprises three units, plus a small supply transformer:—

- (i) 3 phase oil immersed saturable-core reactor;
- (ii) an oil filled transformer—rectifier tank containing two 3 phase transformers and four rectifier assemblies which can be connected in series, series-parallel or parallel to give different output voltages;
- (iii) the feedback control unit maintaining the heater constant current, which is monitored by a current transformer and set by a fader and ten-turn potentiometer on the control panel.

The power supply is connected to the heater by two underfloor, water-cooled, copper conductors and is housed within the laboratory.

6.4 Control Valves.

The high pressure gas and the vacuum systems are controlled by pneumatic valves actuated by solenoid switches. Semaphores on the control panel indicate the position of each valve. In the event of a failure of compressed air services in the laboratory, a stand-by compressor in the plant room is switched on automatically to maintain line pressure. The valves are arranged such that when electrical power is switched off, the system is left in a safe state. The control valves are shown in the layout drawings for the high pressure and vacuum systems, Figs. 14 and 16.

6.5 Cooling Water.

The compressors, vacuum pumps, heater power supply and tunnel cooling are all linked to the same closed circuit water system. If the water pump fails all equipment turns off and a solenoid valve dumps water from the supply tank, via the plant, into a drain, thus protecting vital parts of the tunnel from overheating. Models are cooled by a separate water system.

6.6 Building.

The Nitrogen Tunnel and the Gun Tunnel are housed in the Hypersonics Laboratory at the rear of the Roderic Hill Building.

The laboratory was designed to explosion standards to fulfil two requirements:—

- (i) Hydrogen proof to allow for the possible construction of a third intermittent combustion driven windtunnel. Particular care is taken to eliminate sparks from electrical equipment or moving parts.
- (ii) Explosion proof, to contain the damage resulting from the explosion of large volumes of 15,000 p.s.i. (103.410 MN/m^2) non-combustible gas. This would be a much more powerful explosion than one due to hydrogen; it may have been triggered by a combustion explosion.

The ground plan of the laboratory is shown in Fig. 18. The roof has glass fibre blow out panels held in a solid roof framework and the walls are wood-lined to arrest fragments. The control room is built on to one side of the laboratory and is air conditioned.

7. Conclusions.

The Nitrogen Tunnel has been designed and built to operate with a test section Mach number of 20. The conical nozzle runs successfully over the full range of stagnation conditions and gives a Mach number 22 flow in 6 in. diameter tunnel sections. It suffers from flow divergence and the resulting axial Mach number gradients. The contoured nozzle runs at a higher Mach number over a limited range of flow conditions. With the aid of boundary layer control and liquid nitrogen cooling it is hoped that the nozzle will run over the full range of stagnation conditions with a test section Mach number of 25.

The conical nozzle can operate with reservoir pressures up to 10,000 p.s.i. (68.948 MN/m^2) and temperatures of up to 3,000 degrees K giving test section Reynolds numbers ranging from 2×10^4 to 1.5×10^6 per foot (6.56×10^4 to 4.92×10^6 per metre). The test section static pressure is typically 10^{-4} atmospheres and the static temperatures range from 10 to 40 degrees K. Pitot pressure traverses indicate that the test section Mach number varied ± 1 per cent over a $4\frac{1}{2}$ in. (114.3 mm) core for $p_0 = 2,500$ p.s.i. (17.235 MN/m^2) and $T_0 = 1,000$ degrees K. The axial Mach number gradient under these conditions was 0.35/in. (13.8/metre). These stagnation conditions produce rarefied and viscous hypersonic flows characterised by the merged layer and strong interaction regimes.

The current research program is concerned with viscous and separated flows at very high Mach numbers. Much of the emphasis will be on flows with low stagnation pressures and much of this work will use the electron beam test probe. The models at present being tested are flat-plate and axisymmetric step models and Caret Wings.

LIST OF SYMBOLS

h	Enthalpy
s	Entropy
\bar{V}	Rarefaction parameter
$\bar{\chi}$	Viscous interaction parameter
Re	Reynolds number
p	Pressure
\dot{m}	Mass flow rate
T	Temperature
M	Mach number
x	Distance from the nozzle exit
y	Distance above or below centre line
A	Area of tunnel cross section
ρ	Density
U	Gas velocity
z	Compressibility factor
R	Gas constant
<i>Subscripts</i>	
∞	Free-stream conditions
0	Conditions in the stagnation chamber

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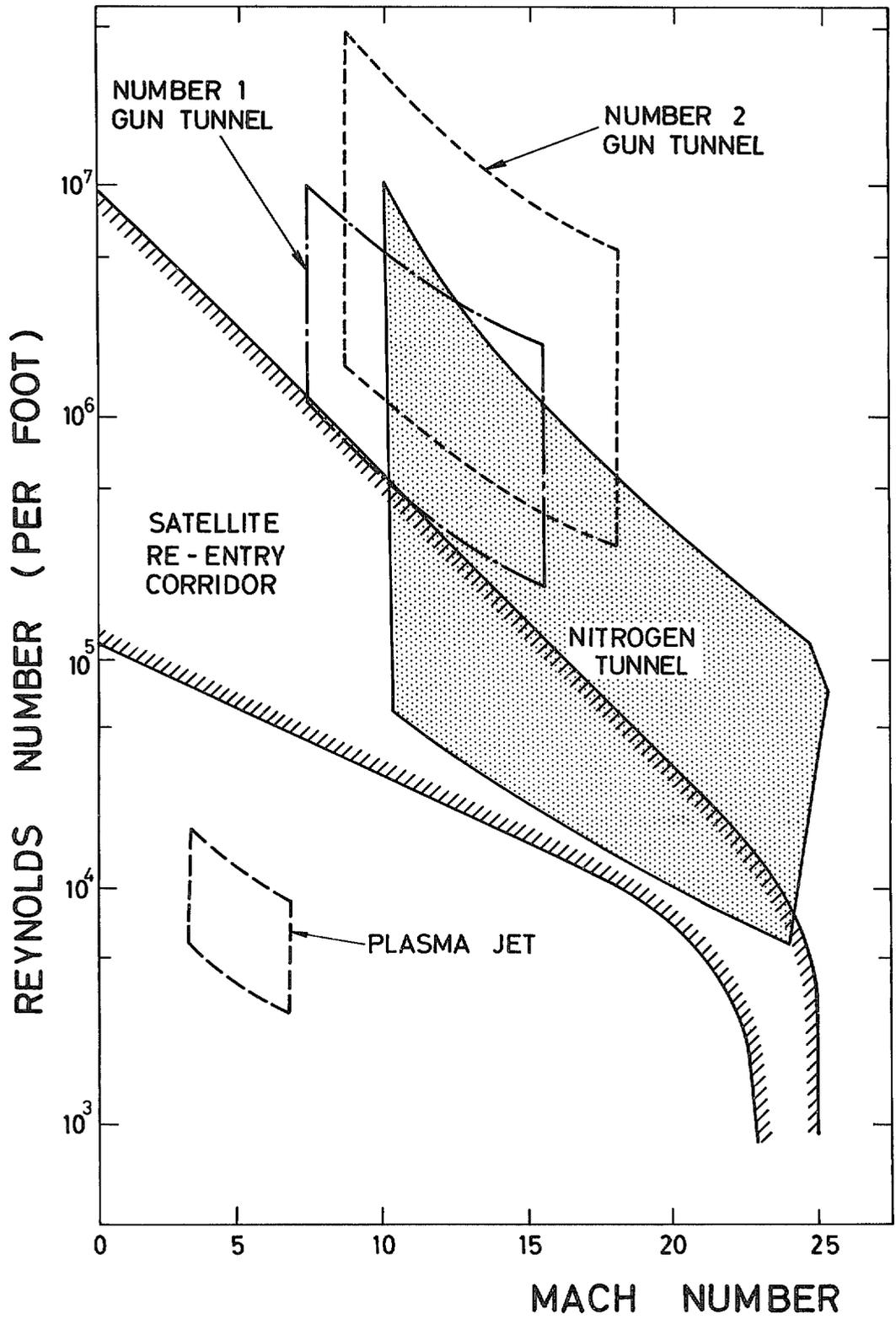


FIG. 1a. Comparison of hypersonic facilities in the Aeronautics Department of Imperial College.

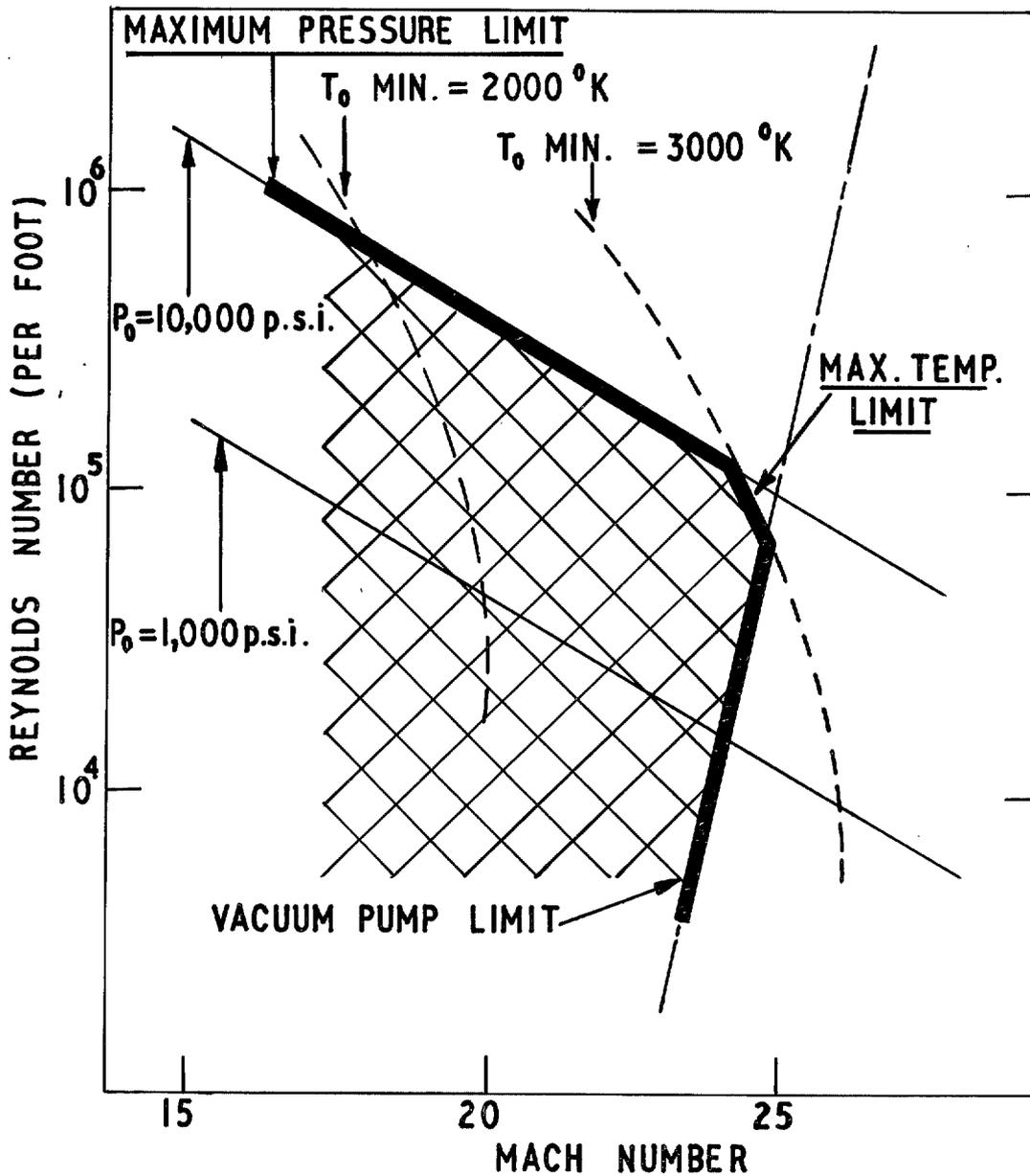
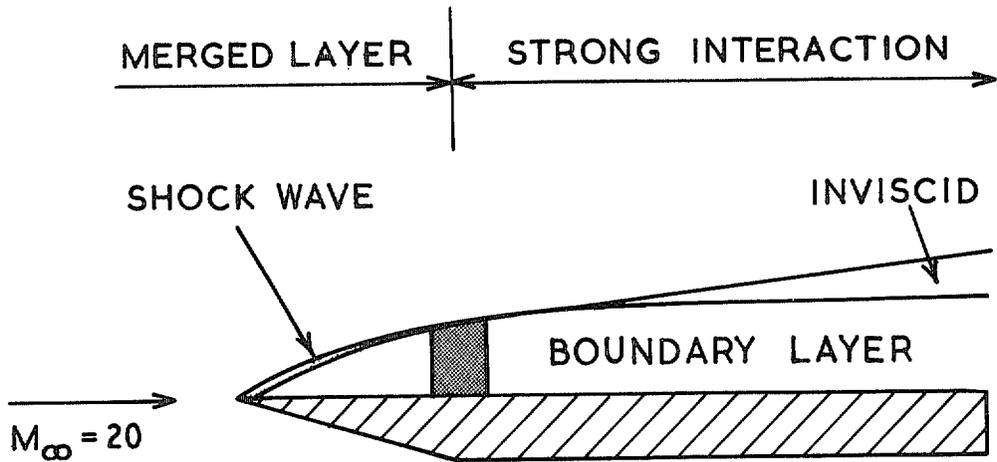


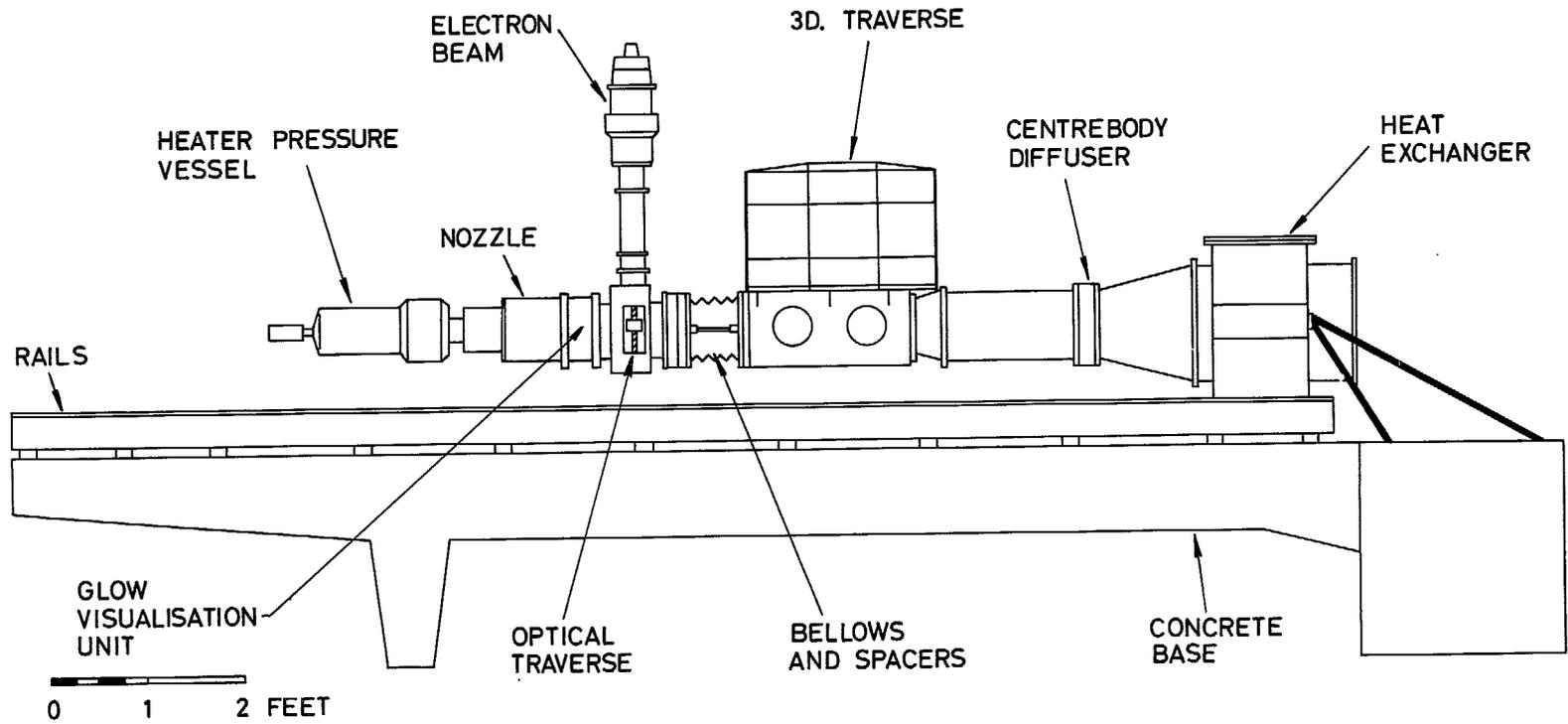
FIG. 1b. Nitrogen tunnel operating boundaries and minimum stagnation temperatures to avoid condensation of the test gas.

$$Re = 2 \times 10^5 / FT.$$



	0	0.5	1	2	3	4	5	6	x (in.)
∞	0.20	0.15		0.11	0.09	0.08	0.07	0.06	\bar{V}_{∞}
∞	80.1	60.4		42.8	34.8	30.0	27.2	25.2	$\bar{\chi}_{\infty}$

FIG. 2. 6 in. flat plate model in a Mach 20 rarefied hypersonic flow.



NOTE:
TROLLEYS ARE OMITTED
FOR CLARITY.

FIG. 3. Nitrogen tunnel layout.

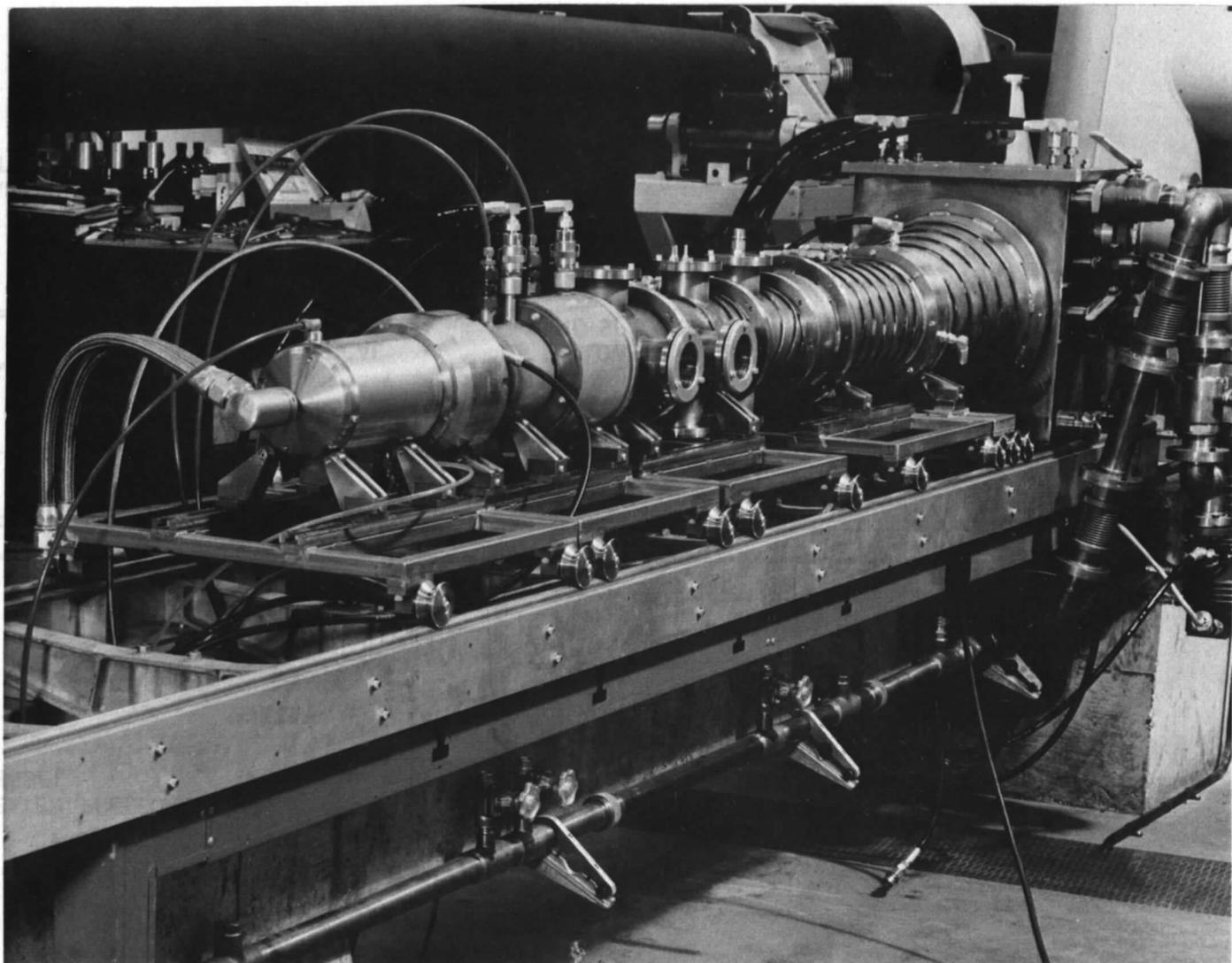


FIG. 4a. Tunnel during construction.

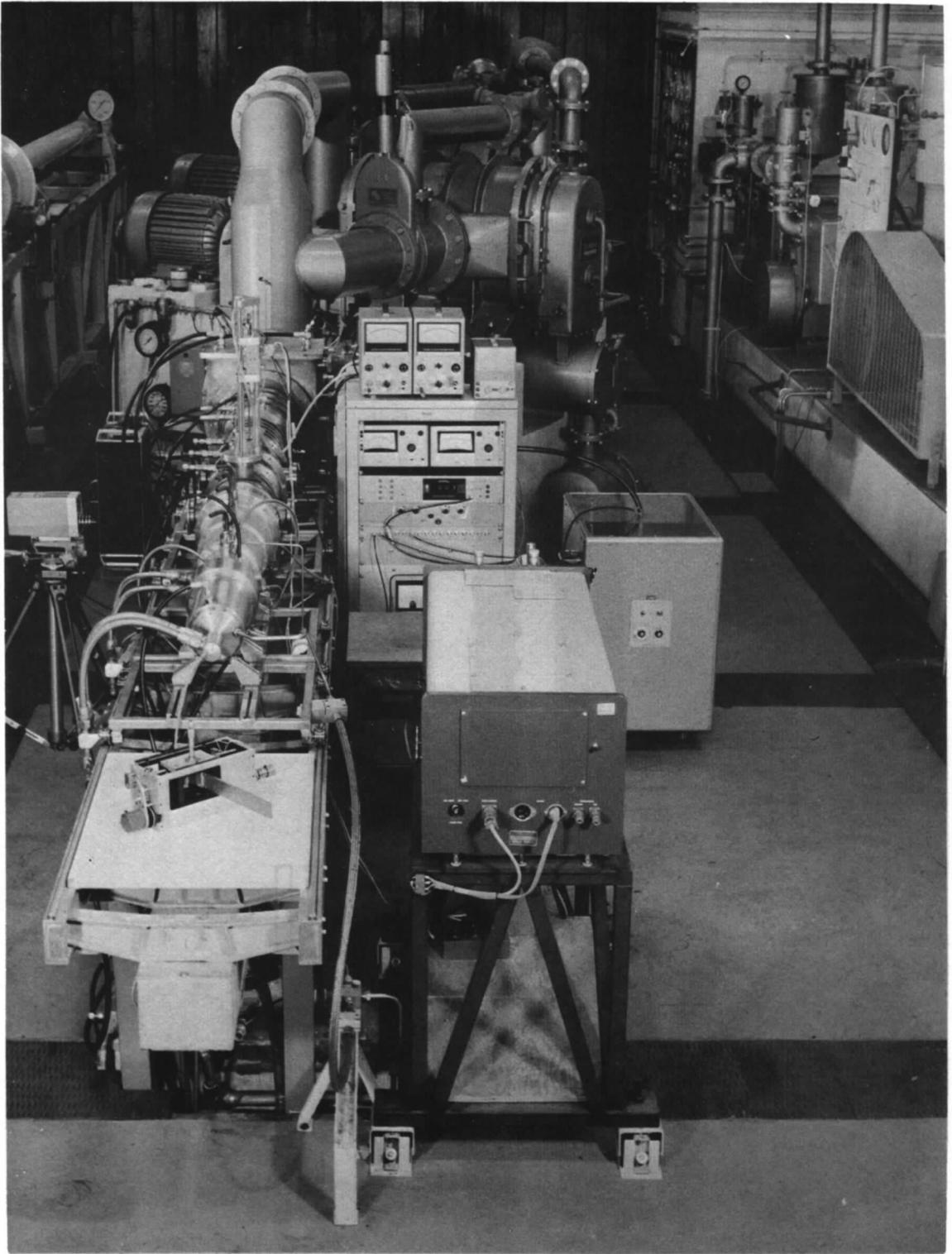


FIG. 4b. General view of laboratory.

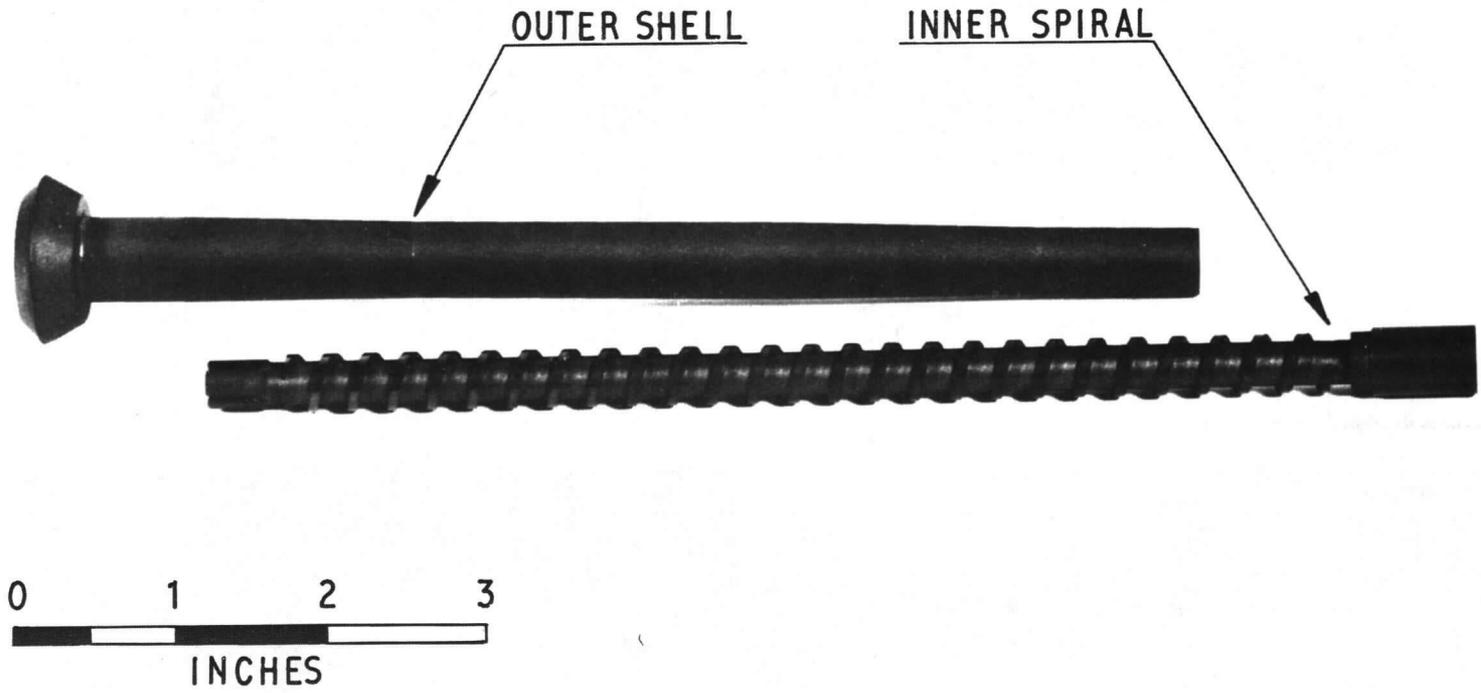


FIG. 5. Heater assembly.

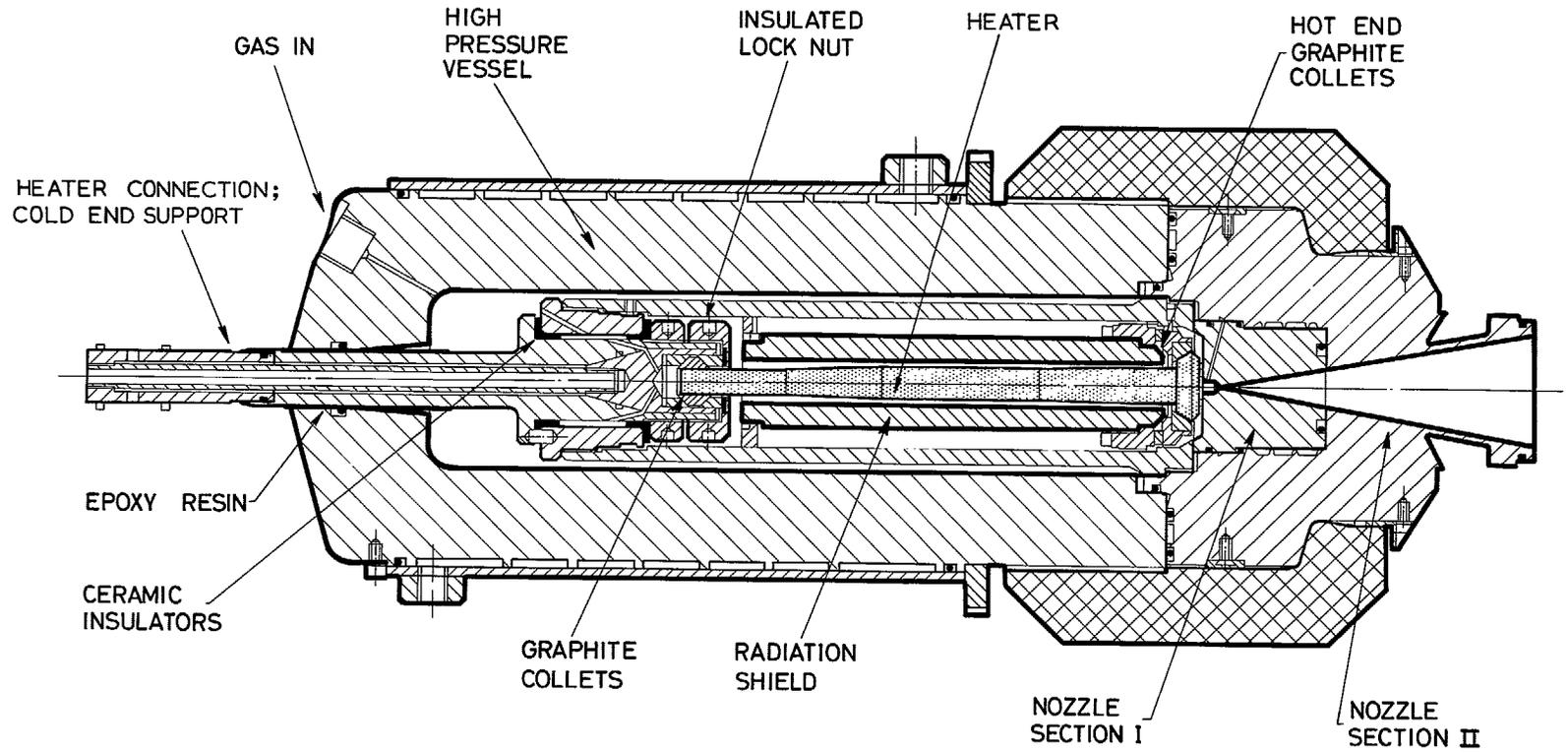


FIG. 6. Heater and pressure vessel.

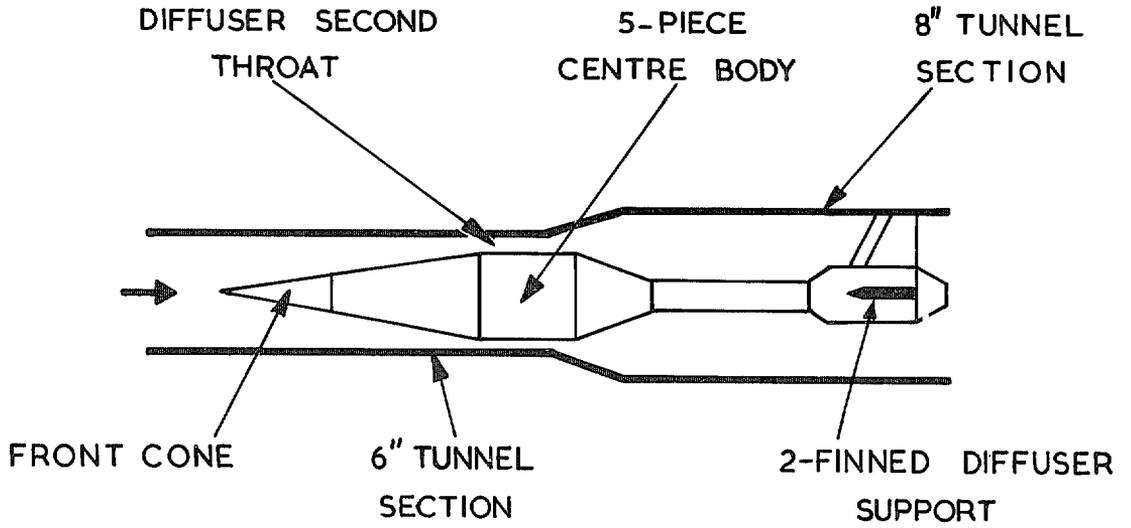


FIG. 8. Diffuser construction.

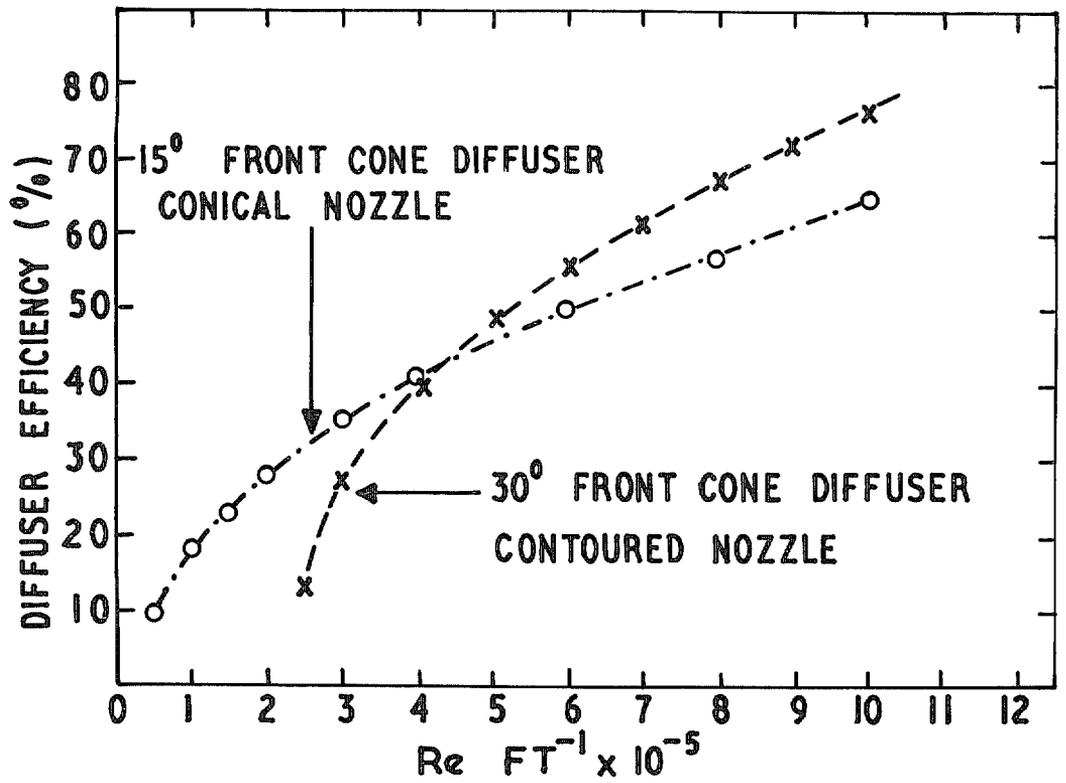


FIG. 8. Diffuser performance curve.

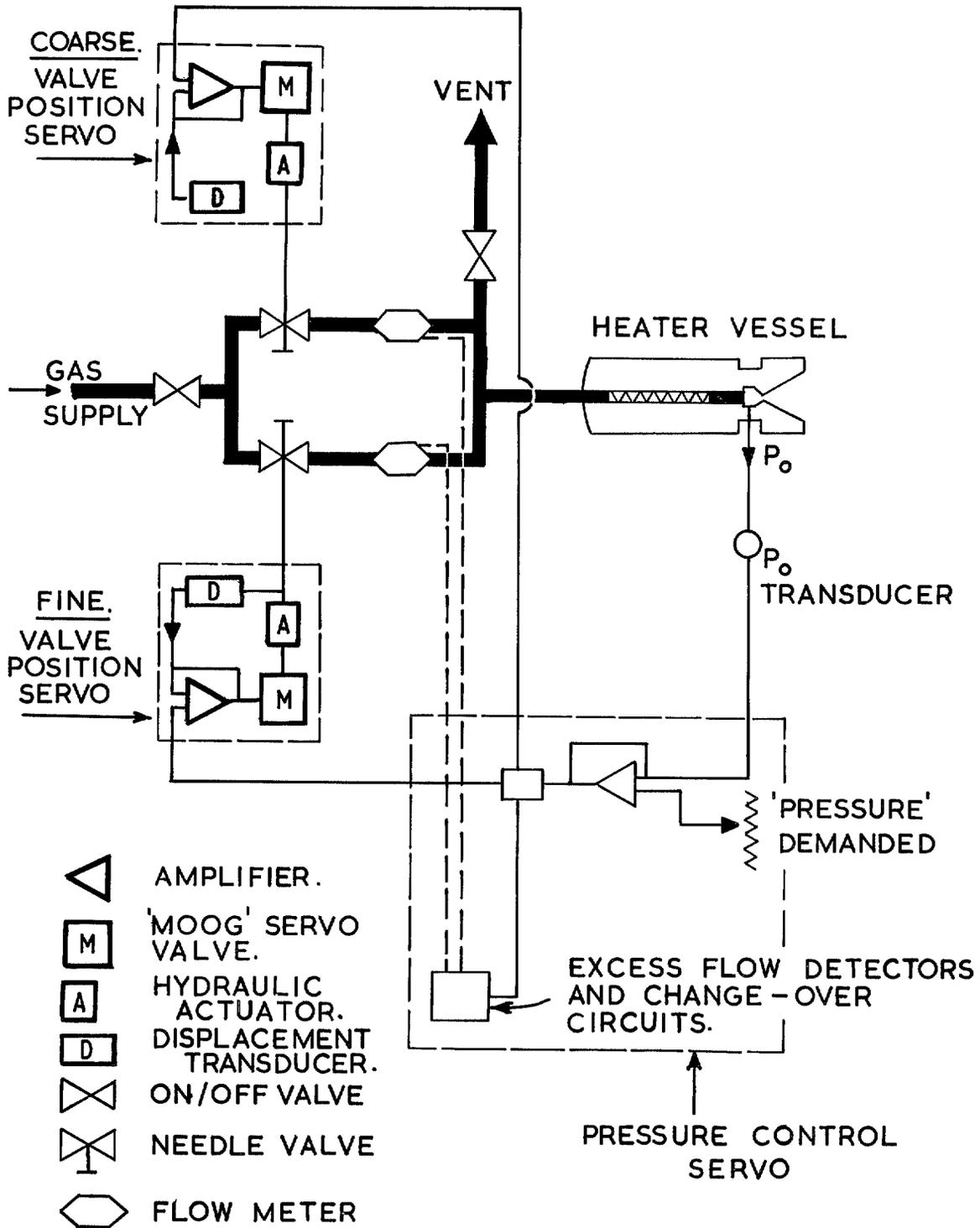


FIG. 9. Supply pressure servo valves.

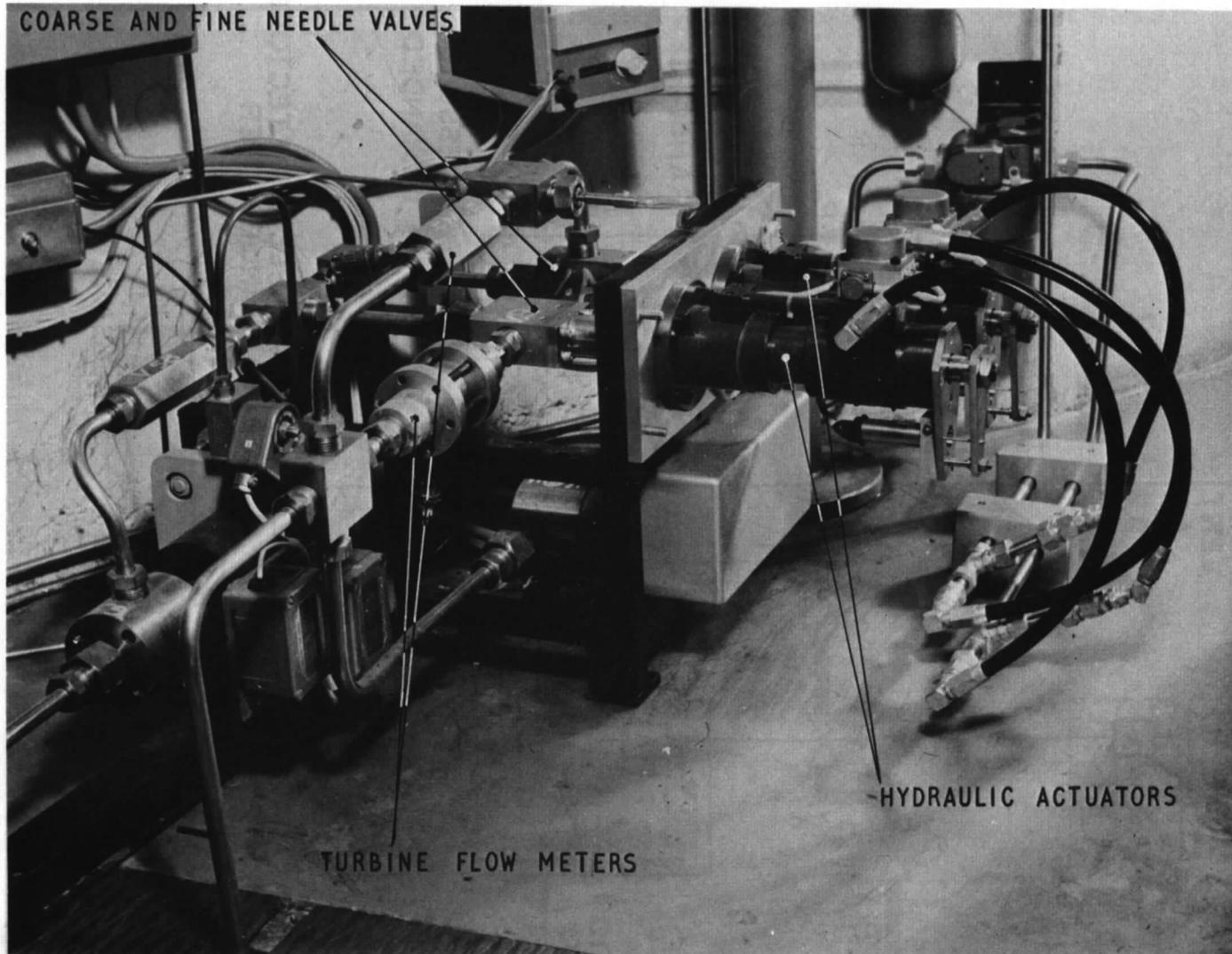


FIG. 10. Servo valves.

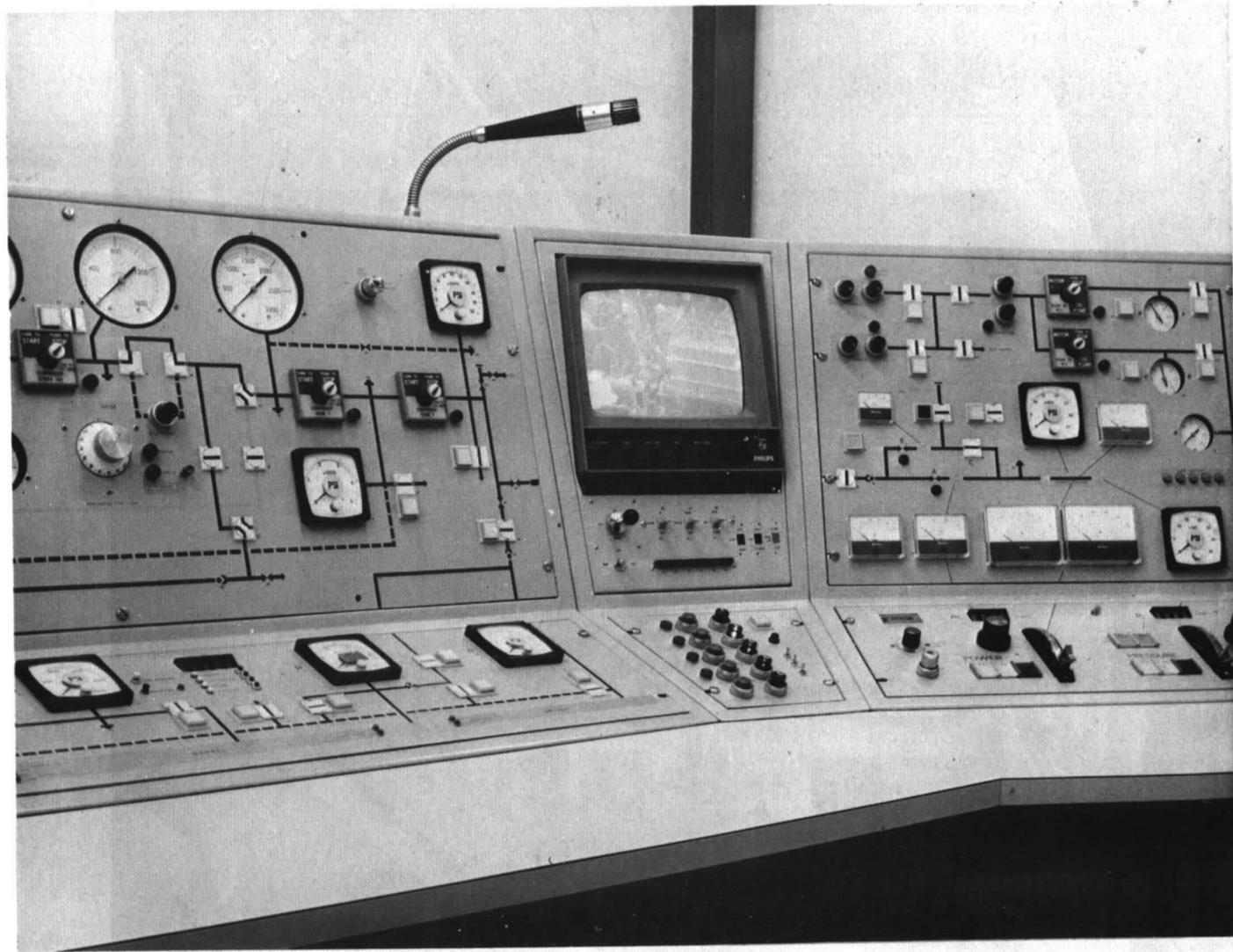


FIG. 11. Control panel.

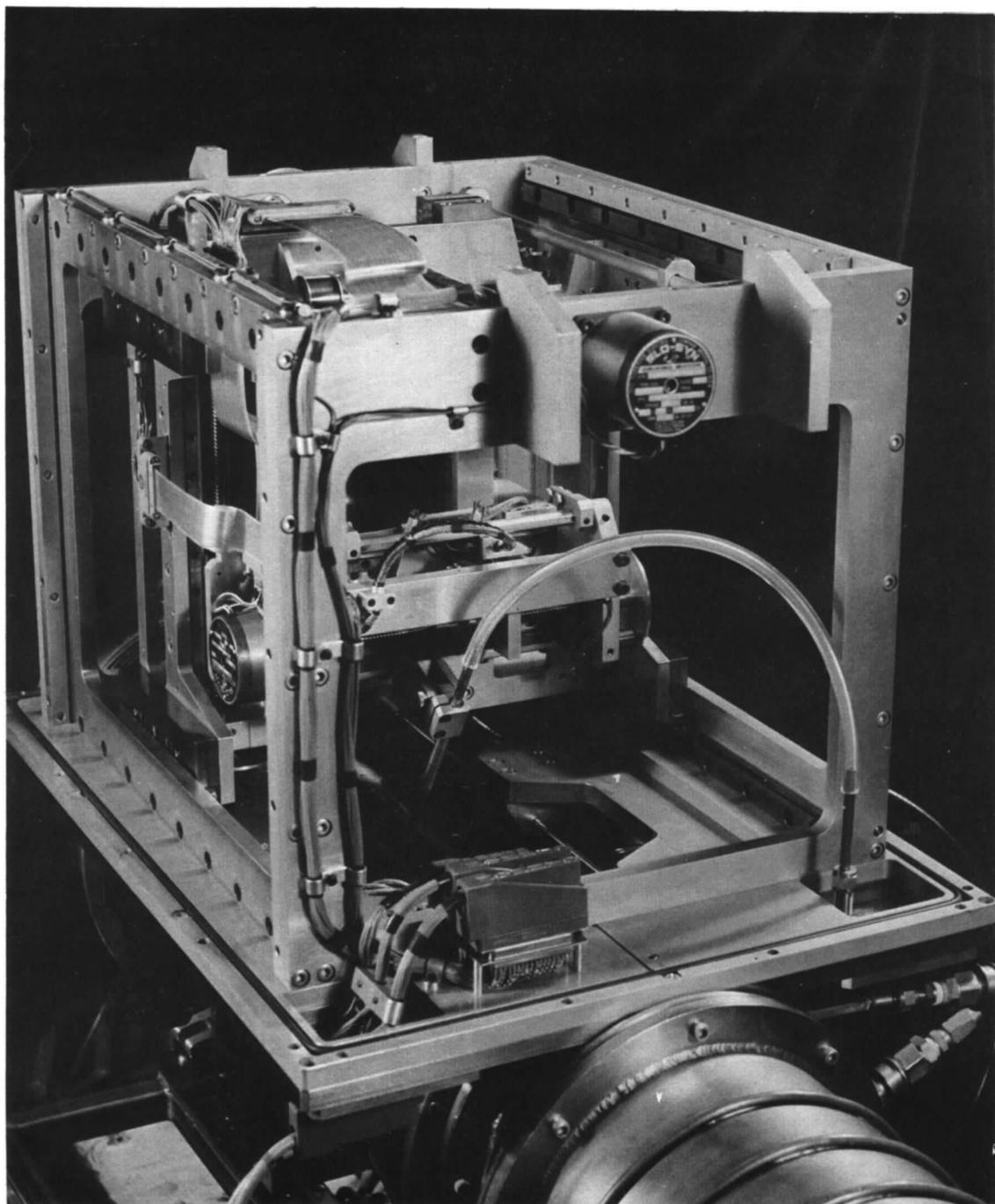


FIG. 12. Three dimensional traverse.

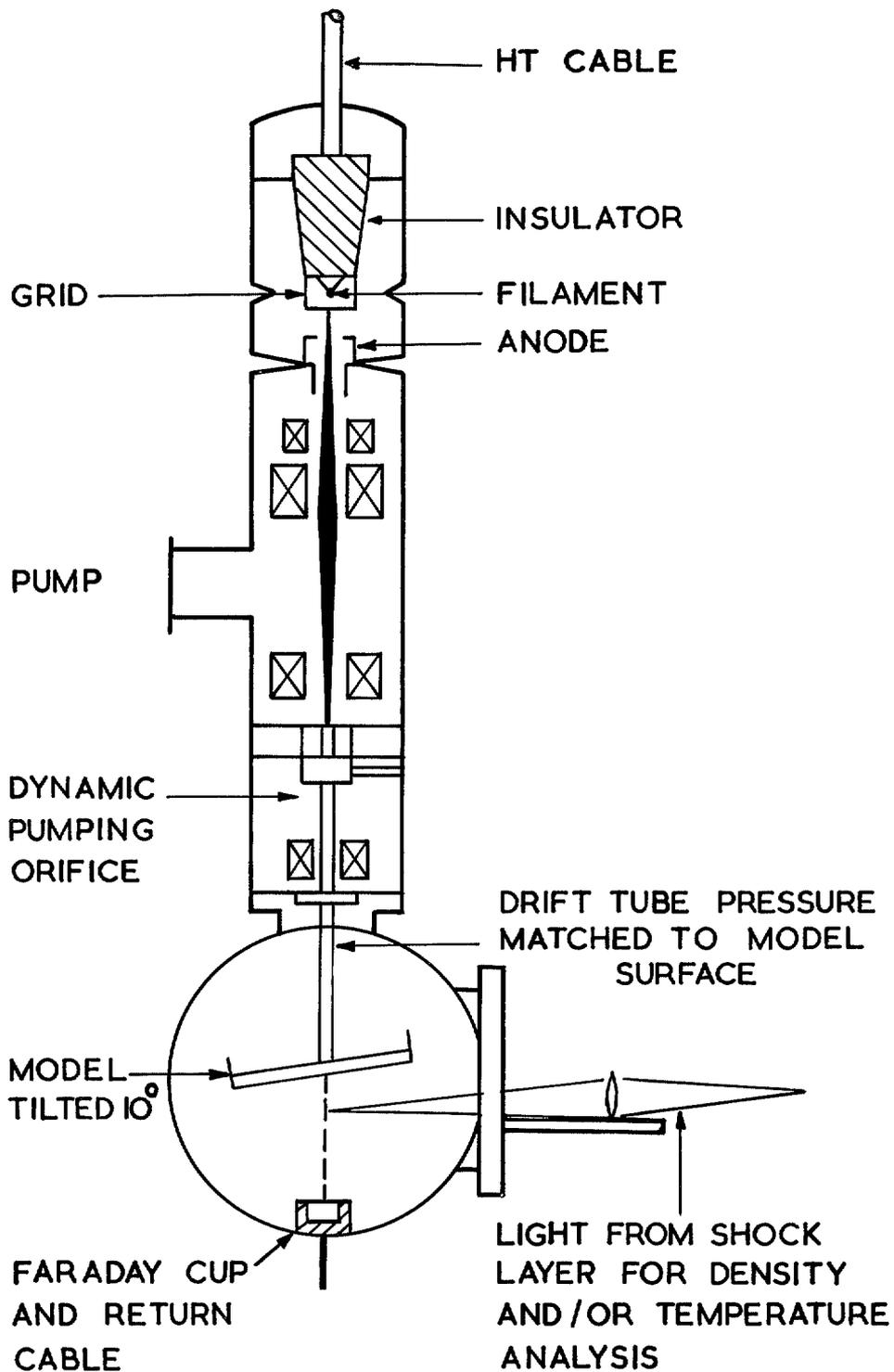


FIG. 13. Layout of electron beam.

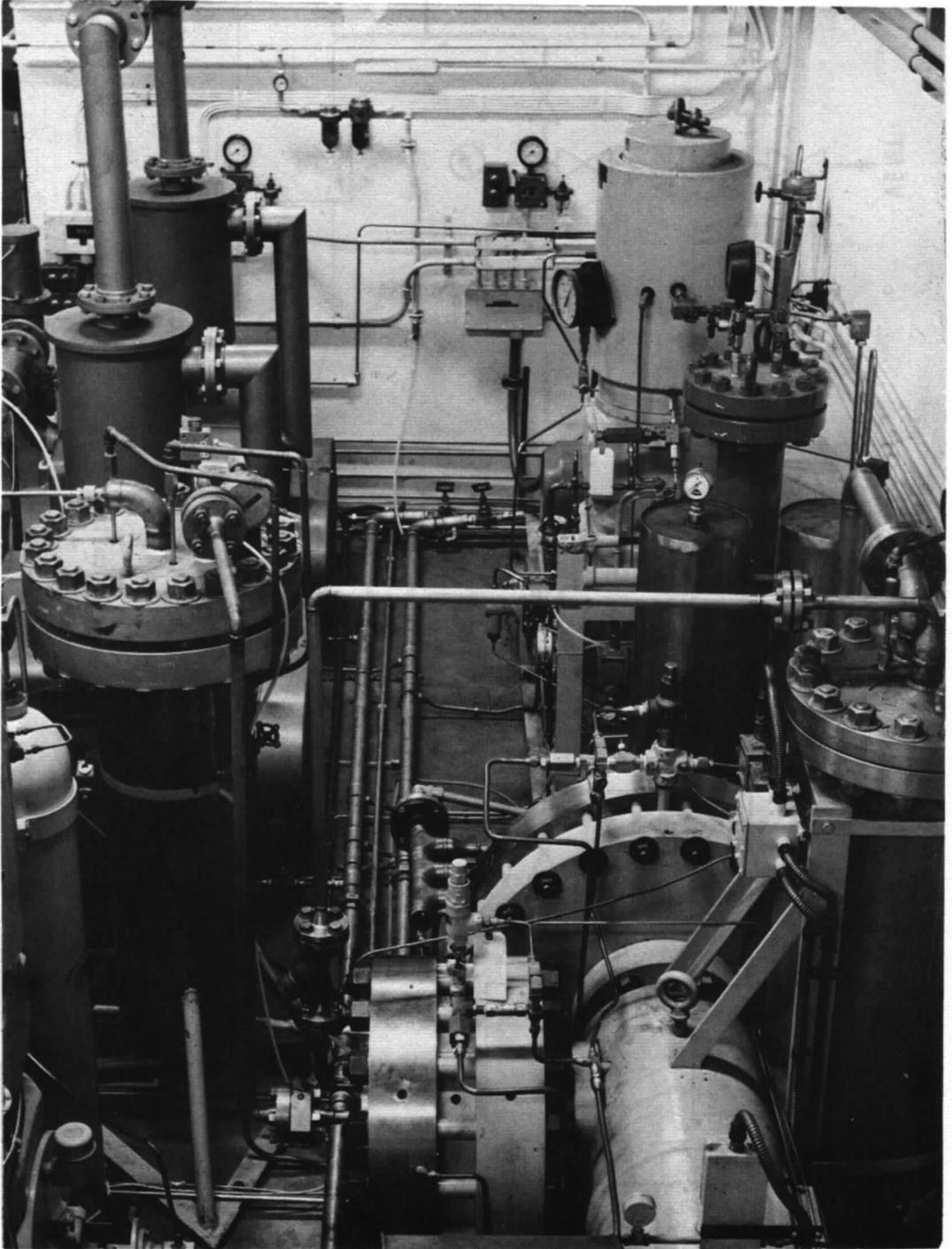


FIG. 15. Compressors on the floating slab.

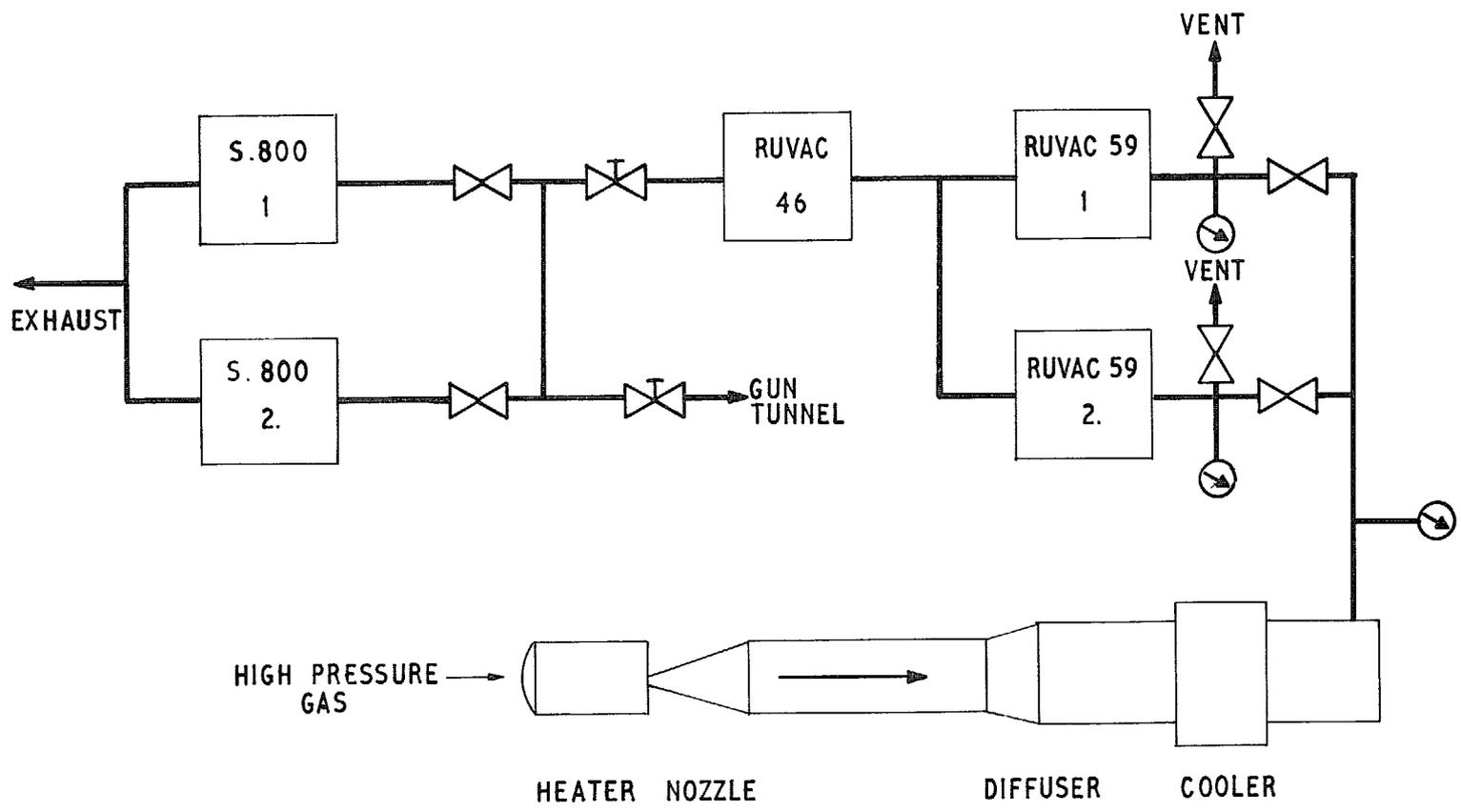


FIG. 16. Vacuum system layout.

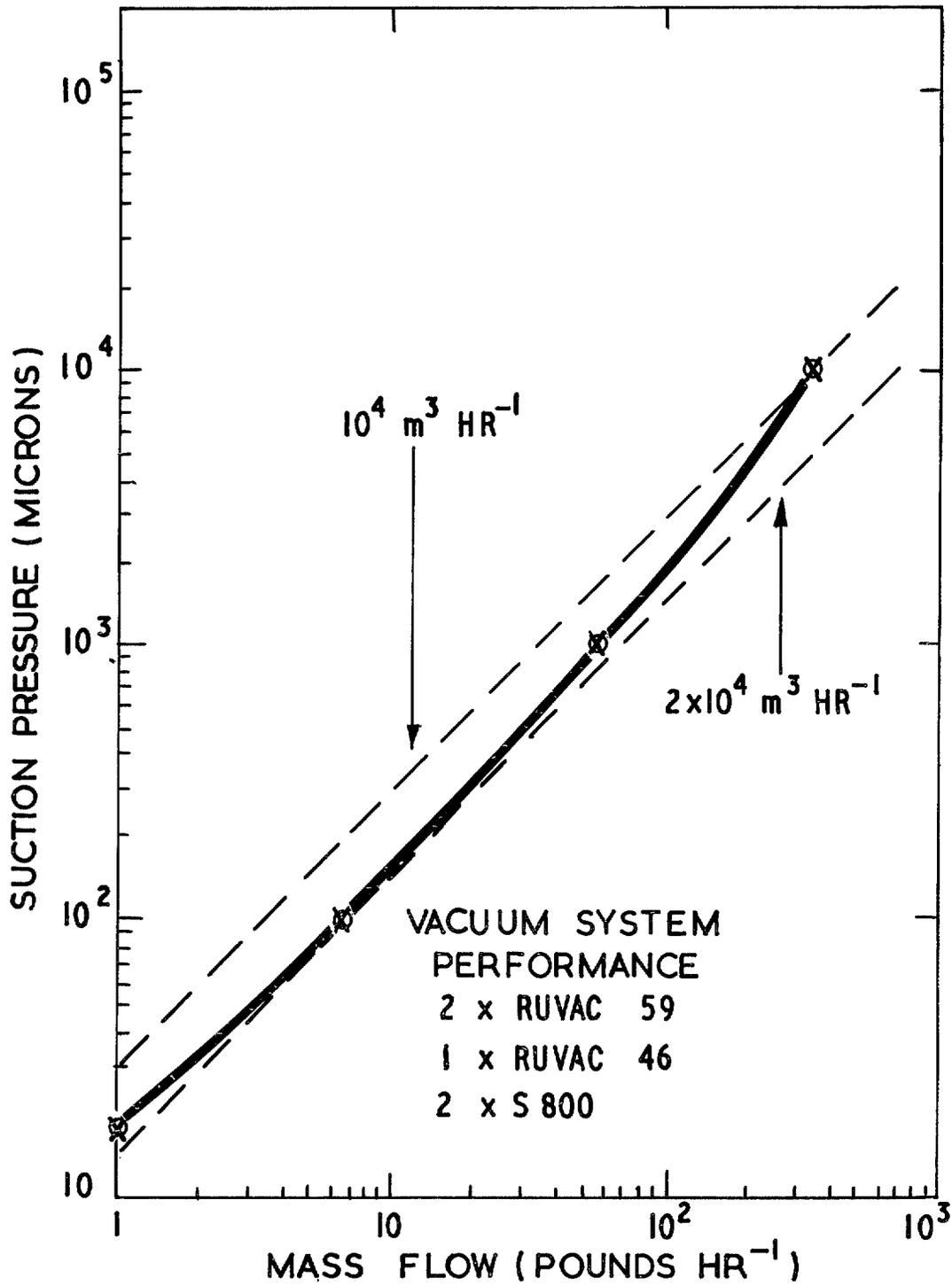


FIG. 17. Vacuum system performance curve.

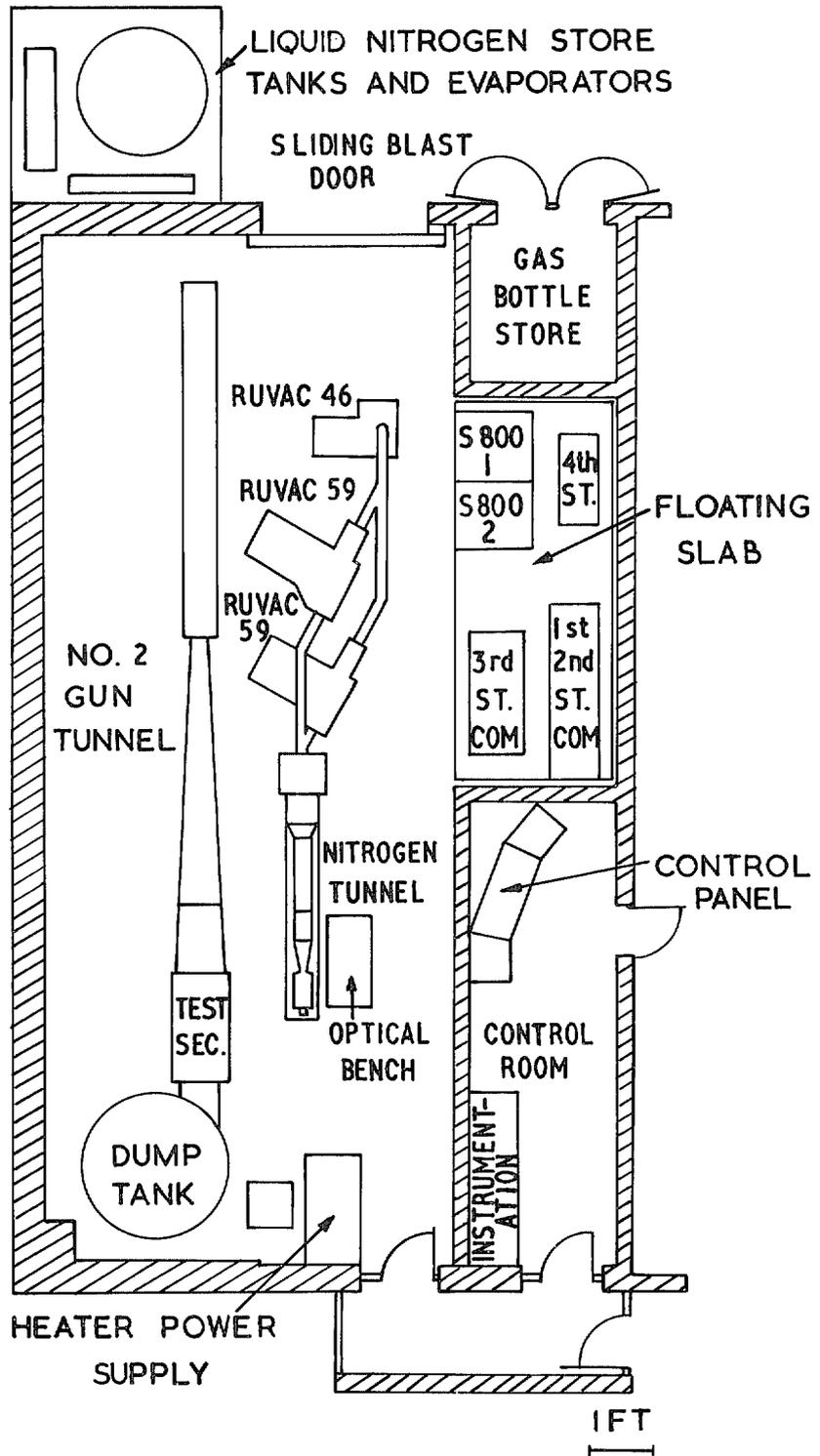


FIG. 18. Laboratory ground plan.

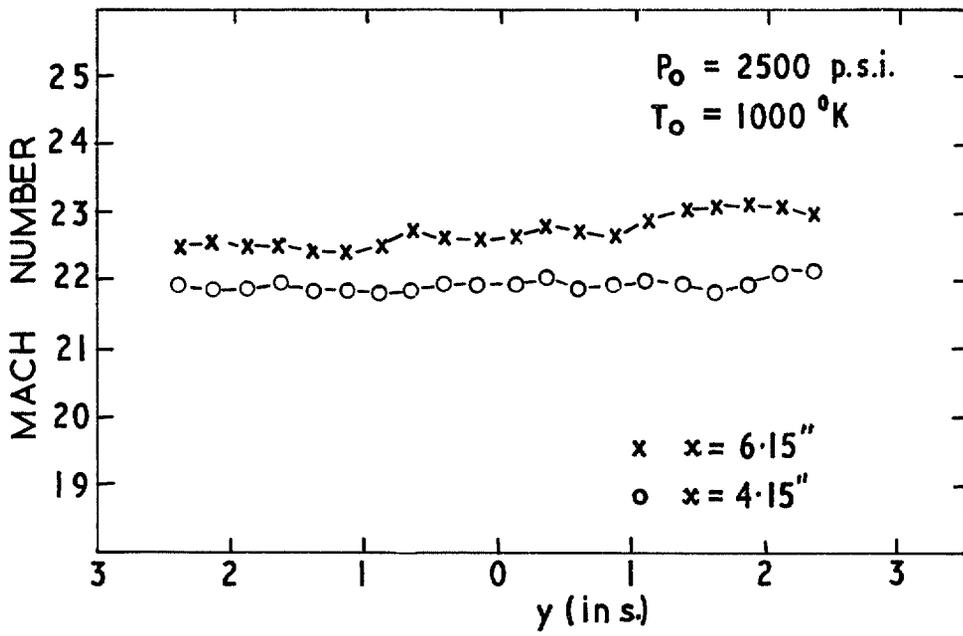


FIG. 19. Mach number. Distribution at two axial stations.

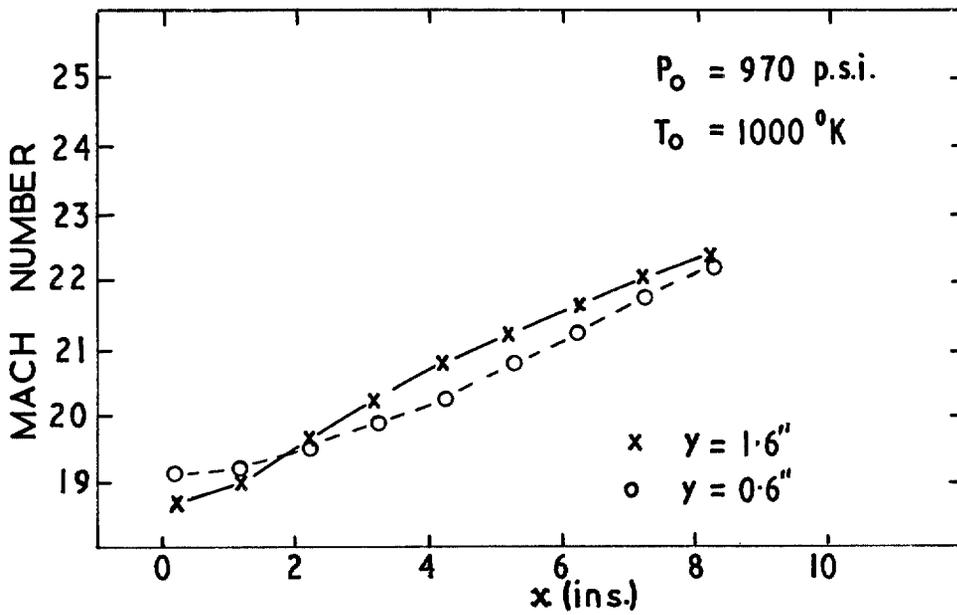


FIG. 20. Axial Mach number variation.

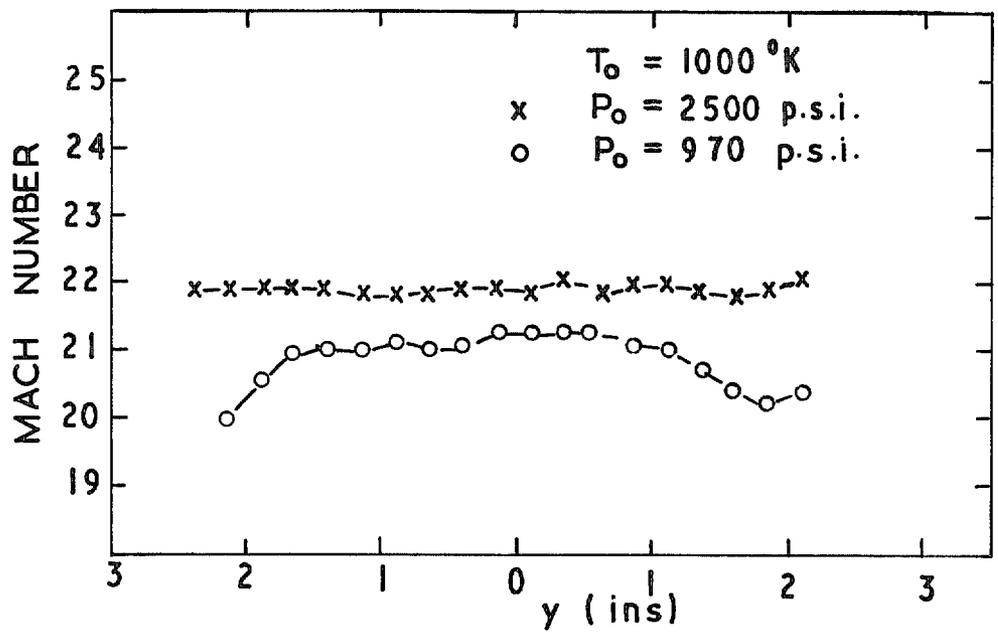


FIG. 21. Mach number variation with p_0 at $x=4.15 \text{ ins.}$

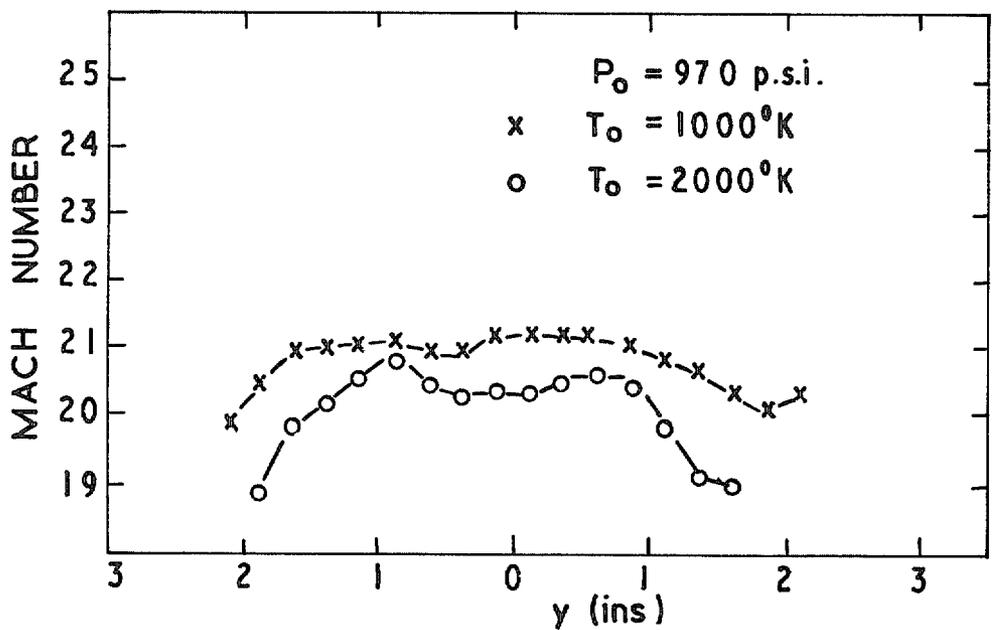


FIG. 22. Mach number variation with T_0 , $p_0=970 \text{ p.s.i.}$ at $x=4.15 \text{ ins.}$

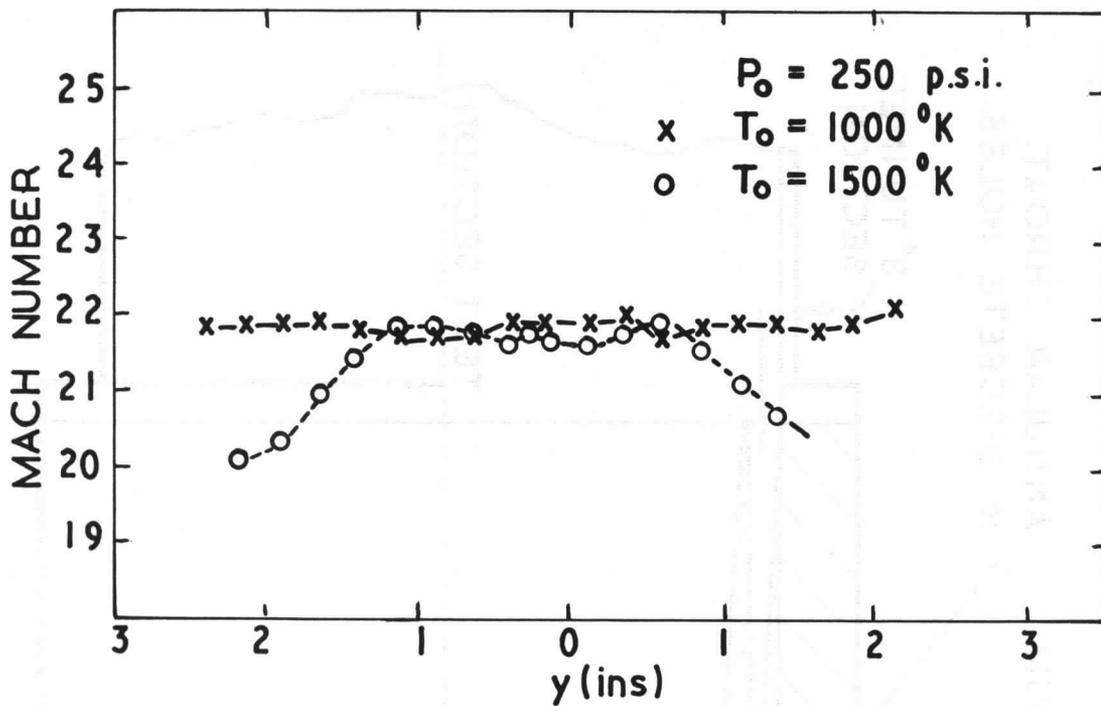


FIG. 23. Mach number variation with T_0 , $p_0=2500 \text{ p.s.i.}$ at $x=4.15 \text{ ins.}$

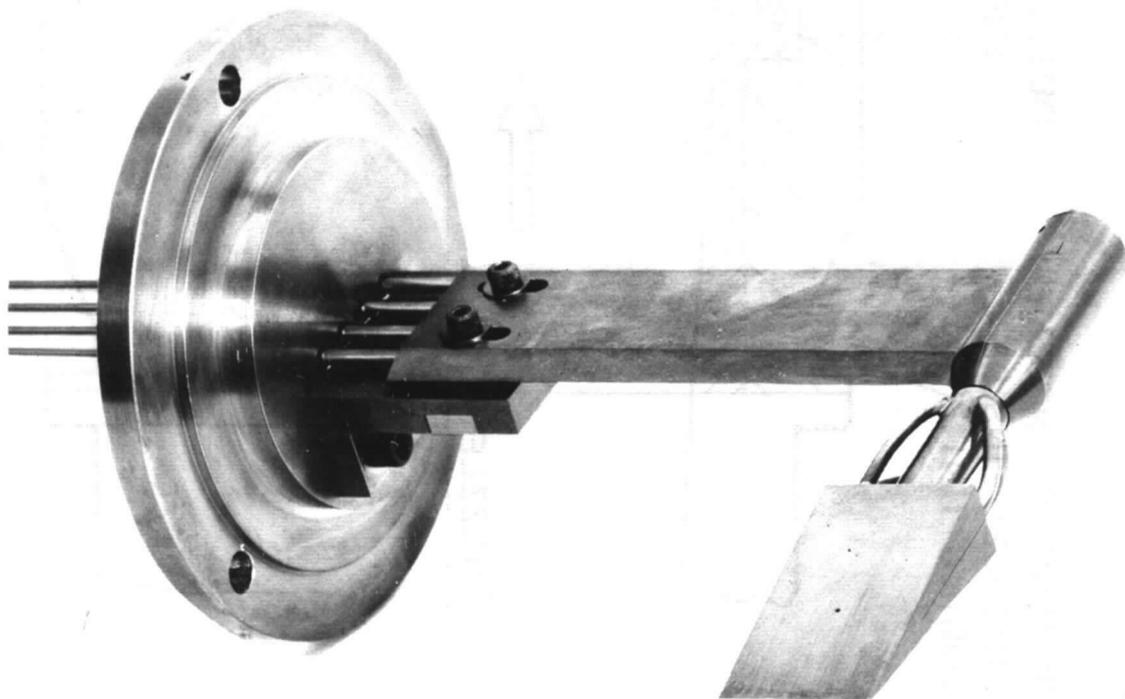


FIG. 24. Illustration of the yawmeter.

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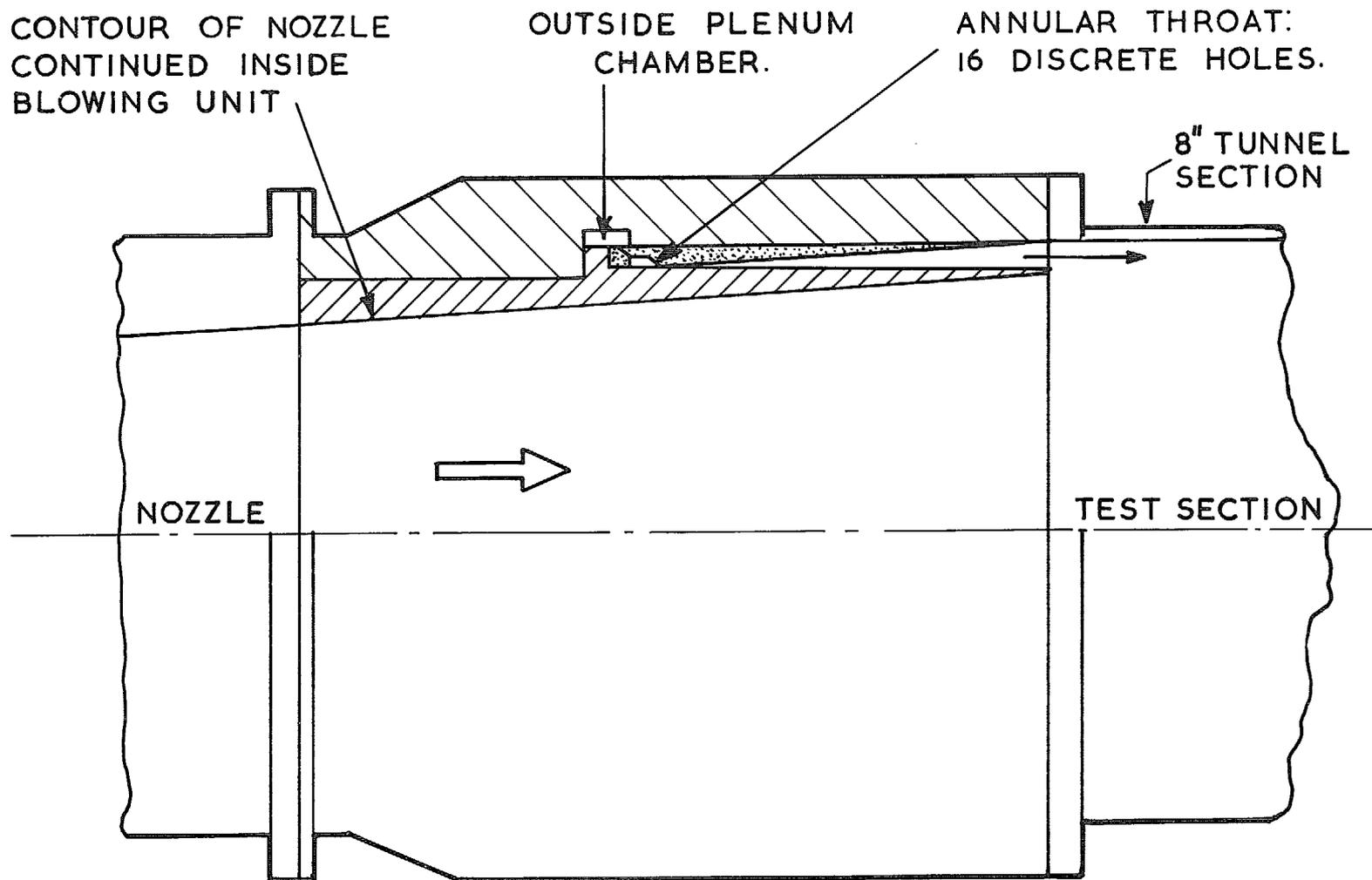


FIG. 25. Boundary layer blowing unit.

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