

CALIBRATION OF VORTEX TUNNEL

by. A. W. Wright

Jan 1956.

accepted for the Degree
of
Master of Engineering Science

1. SUMMARY.

A description is given of the installation layout of the tunnel in its temporary building on the University site at Sandy Bay.

Investigation of the tunnel flow has revealed that it is satisfactory from the points of view of symmetry and freedom from separation for the proposed blade testing. Curves for mass flow versus intake pressure drop have been drawn.

An initial deflection in one piece of the drive shaft causes considerable vibrations in the outlet section at approximately 400 r.p.m. away from that speed the vibrations are negligible.

Suggestions are made within for future improvement in instrumentation to obtain the three dimensional flow ^{measurement} in the working section.

I N D E X

	<u>Heading</u>	<u>Page</u>
1.	<u>Summary.</u>	1
2.	<u>Introduction.</u>	4
	2.1. General Layout.	4
	2.2. Purpose of Tests.	5
3.	<u>Erection and Preliminary Running Notes.</u>	6
	3.1. Condition on Arrival.	6
	3.2. Erection.	6
	3.3. Initial Running.	8
4.	<u>Instrumentation.</u>	9
	4.1. Introduction.	9
	4.2. Electric Tachometer.	10
	4.3. Revolution Counter	11
	4.4. Torquemeter.	12
	4.5. Vane Anemometer.	15
	4.6. Cylindrical Yawmeter.	16
	4.7. Pitot Tube.	18
	4.8. Barometer.	20
5.	<u>Entry Flow.</u>	21
	5.1.1. Test Condition.	21
	5.1.2. Test Procedure.	21
	5.1.3. Results.	22
	5.2.1. Readings.	23
	5.2.2. Results.	23
	5.3.1. Frame Modifications.	23
	5.4.1. Entry Gauze.	24
	5.4.2. Results.	24

I N D E X (Cont'd)

	<u>Heading</u>	<u>Page</u>
6.	<u>Mass Flow Calibration.</u>	25
	6.1. Test Method.	25
	6.2. Velocity Profiles.	25
	6.3. Mass Flow Curves.	27
	6.4. Non Dimensional Plotting.	27
7.	<u>Diffuser Flow.</u>	29
	7.1. Instrumentation.	29
	7.2. Test Procedure.	29
	7.3. Results.	30
	7.3.1. Behind Outlet Guide Vanes.	30
	7.3.2. At the Beginning of the Diffuser.	31
	7.3.3. Mid-diffuser.	32
	7.3.4. Radial Diffuser Exit.	33
	7.4. General Description of Flow in the Diffuser.	35
8.	<u>Conclusions.</u>	37
	8.1. Instrumentation.	37
	8.2. Entry Flow.	38
	8.3. Mass Flow Calibration.	38
	8.4. Diffuser Flow.	38

2. INTRODUCTION.

This paper is concerned with the work carried out under the direction and supervision of Mr. E. Szomanski^x since the arrival of the Vortex Tunnel in Tasmania in June 1954 until the conclusion of the tests to determine the general flow conditions in the tunnel. (in December 1955.)

2.1. General Layout.

The tunnel and auxilliary gear was assembled in the temporary building erected for it on the new University site at Sandy Bay. For a detailed layout of this building see Fig. No.1. It has four rooms, including the main tunnel room and a combined motor room and workshop, both with concrete floors and also two offices for the research staff.

Since this is an open circuit tunnel, no windows were provided in the main hall, to reduce the number of external leaks; this also helped in dust and sound proofing.

A full description of the tunnel may be found in M.E. 196^{xx}. It was placed with its axis parallel to the side wall and six feet six inches away from it, giving three feet minimum clearance on the motor room side, and providing a clear nine feet passage on the other.

An overhead monorail transporter, of $\frac{1}{2}$ ton capacity, using a rolled steel joist as a rail, runs from the main door parallel to the tunnel as far as the working section where it turns across to a turntable directly above the tunnel axis. From there, two branches parallel to the tunnel serve the working and intake sections.

The separate power supply enters the building at the south western end through appropriate fuses and isolating switches, as required by H.E.C.

^x Senior Lecturer in Fluid Dynamics, University of Tasmania.

^{xx} M.E. 196 A.R.L. by P. V. Crooks and W. Howard.

regulations, to the main switch, which is mounted on the tunnel room wall adjacent to the motor room door. From there it passes through the wall to the motor-generator set, the D.C. output of which is carried to the tunnel motor through the control panel (housing resistances) and an isolating box, both standing at the outlet end of the tunnel.

The 40 H.P. D.C. motor, which is supported on spherical bearings, drives the rotor by means of a three piece shaft. Torque reaction from the motor is transferred by an arm fixed to the motor casing, to the weighing head of a set of scales standing alongside.

2.2. Purpose of Tests.

The tests which lead to the determination of the velocity profiles at different stations, along the tunnel, were conducted to obtain its flow characteristic.

To maintain uniform conditions for the future testing of blades, it is desirable to have velocity profiles as uniform as practicable. Several steps were taken in the design of the tunnel to achieve this end:

- (i) Provision was made for a gauze to be fitted around the peripheral intake.
- (ii) To ensure an accelerated flow into the working section, the entry consisted of a contracting annular passage.
- (iii) No braces or supports were placed in the inlet passage.
- (iv) The driving motor was placed at the outlet end of the tunnel.

It was anticipated that if any large regions of separation occurred in the diffuser, these could be removed by the insertion of the gauze screens.

3. ERECTION AND PRELIMINARY RUNNING NOTES.

3.1. Condition on Arrival.

The general condition of the tunnel on arrival was good, with the exception of the inner contraction piece. The laminations there were soaked with salt water and gradually began to peel. Owing to the extent of the damage it was considered advisable to replace several panels in this section. They were those which were first to be fabricated from the wood laminations, at which stage the glueing technique had not been perfected. New panels have since been installed.

A ball race on the inlet carrying trolley was fractured probably due to
(i) an overload on the race due to the proximity of the clamp,
(ii) a jar at some stage during transit.

The race was replaced with one of the 12 m.m. Hoffman type, since a Federal D5 was unavailable.

3.2. Erection.

During erection, one piece of the main shaft was set on blocks in the core. This was accidentally bumped and the end near the centre bearing burst the plywood core. A former was fashioned from pine and the torn pieces were drawn back together by screws.

In bedding the structure down it was found that the floor was poorly cast, air pockets being found in abundance. However the eight $\frac{7}{8}$ " Loxins provided ample anchorage. Since the floor was uneven, wedges were hammered under the frame at several places to remove some of the vibrations in the tunnel. These were most effective in removing vibrations in the inlet section. Likewise the motor room floor was uneven and the bedplate was packed to take up the variations.

The hood over the parallel section was removed and left standing for a short period while fitting was being attended to. On replacing it, considerable

warping was evident, and a lot of trouble in the final fitting of it was experienced.

Presumably due to the colder temperatures, it was found that the differential contraction between the cast aluminium and steel in the outlet guide vane ring assembly, the roots of nearly all these blades fouled with the shell piece. This was remedied by filing the shoulders down a little.

Alignment of the inner contraction piece was generally a difficult task. The first part of this assembly to be fitted was the spigot on the main tunnel piece, into the groove on the outer contraction piece. The outer contraction piece was set completely free from the inner piece, and by use of packing strips, was adjusted to match the spigot. All the tierods to the inner piece were set at that position and it was found that the inlet guide vanes were fouling with the core. Any attempt to rectify this with the tierods produced a strain in the outer contraction piece which in turn put it out of alignment with the spigot. The clearance between the rotor and the inner contraction piece was also controlled by the tierod adjustment. The setting of the unit is thus a process of trial and error, which usually takes about three quarters of an hour. Several modifications were suggested to remove some of the above difficulties:-

- (i) Increase the number of tierods to eight, to hold the core piece more firmly.
- (ii) Remake the cylindrical core piece on the upstream side of the rotor, from wood laminations. This will allow a lighter construction.
- (iii) Fix a rolled angle to the rotor shoulder wide enough to remove any overhang of the blade roots. The core piece will be made correspondingly shorter in length. This modification will eliminate the two clearances at the rotor blade row, which will be replaced by a single axial clearance upstream of the blade row, between the new core piece and the rotor body.

Of these modifications, only the first has been carried out, the second one has been fabricated, but as yet is not fitted since the rotor alterations to be made by A.R.L. are still outstanding. It has been agreed to make the rotor

lip integral on two new rotors instead of modifying the present rotor. See Fig. No.2.

3.3. Initial Running.

The crimped oil stubs, after the first run were found to leak due to the fine oil used. These were removed and the ends soldered.

Owing to the radial clearance, necessary for rotational movement, between the shell piece and inlet guide vane carrying ring, operation of the worm drive transfers the clearance from side to side according to the rotational direction. This effects the clearance between the blades and the hub.

During the early runs, a disturbing knock was observed in the tunnel motor. After several attempts to locate it, the noise was found to come from the interference of the cooling fan with a small spot of weld left on one of the end plates during fabrication. This interference occurred only when the speed of the motor, which incidentally, was well away from the normal operating range, caused the particular deflection in the fan.

A short test was conducted by the H.E.C. to determine the line voltage drop and the current drawn on starting the motor. A voltage drop of 36 volts from 220 volts to 184 volts was accompanied by a peak current of 29½ amps.

4. INSTRUMENTATION

4.1. Introduction

The Rotary Cascade or Vortex Tunnel is one of the test units built by the Aeronautical Research Laboratories for compressor blade research, designed for the investigation of three-dimensional effects at low Mach numbers.

In this open circuit tunnel, air enters the peripheral intake through a wire mesh, and is turned and accelerated through an unrestricted annular passage to the inlet guide vanes, rotor and stator. Downstream from the working section, there is a short parallel annular passage, containing three bearing and transfer case supports of the aerofoil section, and an annular diffuser, having a constant inner diameter up to the outlet section, where a fairing is provided to obtain a radial outlet. Midway down the diffuser the shaft centre bearing is supported on two cylindrical struts. A sliding throttle is fitted at the diffuser outlet to vary the mass flow through the tunnel at constant rotational speed.

Investigation of the general tunnel flow was carried out with the sand-cast and hand-cleaned S1. blades based on the C4 profile.

Estimates of the velocity distribution at the intake, and diffuser outlet, were made with the vane anemometer. Mass flow and velocity profile measurements in front of the inlet guide vanes were made with two Pitot tubes, whilst estimates of velocity distribution throughout the remainder of the tunnel were made with the cylindrical yawmeter.

Pressures from the yawmeter and Pitot tubes were registered on a multi-tube inclined manometer and a single tube inclined manometer, each using methyl alcohol as the balancing liquid. The multitube manometer was supplied with the tunnel and the single tube unit was fabricated at the University of Tasmania.

Reynolds' numbers up to 2.5×10^5 may be obtained using the three inch chord blades.*

Some assistance in above experimental work was given by R. D. Cuthbert^{xxx} and D. A. Frith.^{xxxx}

4.2. Electric Tachometer^{xxxxx}

As an electric tachometer, a standard unit of the type fitted in Mustang fighters, was used. The counter was driven by its own separate generator, which was attached in this case to the motor support frame. A flat, half-inch, fibre belt was used to drive the generator from the shaft end coupling, used as a pulley.

4.2.1. Principle of Operation. The generator output was carried to the tachometer register where it drove a small electric motor. On the end of the motor shaft was carried a small circular magnetic disc, which ran inside a copper cage, attached to the register needle. A bias spring stopped the rotation of the cage, which was induced by the magnet, at the corresponding register position.

4.2.2. Calibration Procedure. Previous to this set of tests, runs with the tunnel had been confined to mechanical checking and testing of components.

Calibration of the electric tachometer and torquemeter was completed during test runs from 21st to 28th January 1955, and checked during subsequent

* For calculations and further description see M.E. 196 (A.R.L.) by P. V. Crooks and W. Howard.

xx Research Assistant, University of Tasmania.

xxx Hydraulics Demonstrator, University of Tasmania.

xxxx Counter No. 563 M^k. V^A G6A/3352.

Generator 43 - 46076.

runs, all of them carried out with throttle fully open.

The calibration was obtained by comparison of the electric tachometer readings with true shaft speed as measured by a direct counting device.*

It was noted during the course of the test that the electric tachometer first registered at a true shaft speed of approximately 180 r.p.m. When the motor had settled down to a steady speed, readings were taken of the torque, current, voltage, tachometer and true shaft speed. The speed was then altered by adjusting the Ward Leonard resistance. The motor was again allowed to settle to a steady speed before readings were taken. Breaks occurred in the tests at 252 r.p.m. and 444 r.p.m, when they were held over till the following day.

4.2.3. Calibration Curve. This was obtained by joining observed points by a smooth curve; which was nearly a straight line except for several small consistent waves. The maximum variation of these waves from the straight line was approximately $\pm 1\%$ of the value at the point in question.

Later readings, plotted on the same graph, were found to fall on the original curve. See Fig. No. 3.

4.3. Revolution Counter.

A direct mechanical revolution counter^{xxx} was used to calibrate the electric tachometer.

4.3.1. Principle of Operation. The instrument consisted of a main shaft which drove, through a one hundred to one reduction worm, a drum upon which was an indicating mark. This drum rotated in a casing scribed with one hundred divisions.

A connection to the rotating member was obtained by means of a rubber cone pressed into the hole at the end of the main shaft.

* No. 106 See page 11.

xxx No. 106 made by L. S. Starrett Co. Athol. Mass. U.S.A.
(on loan from Hydraulic Laboratory)

The indicating mark on the drum could be set in any desired position since a spring loaded clutch connected the drum to the work wheel.

Readings obtained from this instrument were revolutions and when used in conjunction with a stop watch, revolutions per minute were obtained.

Three readings of a particular shaft speed were used to obtain a mean speed that was correct to within one half of a per cent. This was checked by comparison with an electric tachometer.*

Due to this high accuracy, the speed of the shaft as read with the revolution counter No. 106, was taken as the basic measurement for the tachometer calibration.

4.4. Torquemeter.

A set of springless scales^{xxx} formed the measuring section of the torquemeter. They were placed alongside the tunnel drive motor.

4.4.1. Principle of Operation. The floating driving motor, which was suspended on two spherical bearings was fitted with two radial arms, one on each side. The motor's reaction torque was carried through one of these to the weighing head of the scales. To the other arm, a balance pan was attached.

The scale range of the torquemeter was 150 ft. lbs. and with the help of a bias weight, readings up to 300 ft. lbs. could be taken. In addition, a weight scale reading 0-50 lbs or 50-100 lbs. with the bias weight, was marked, the length of the torque meter arm being 3 ft.

4.4.2. Calibration. Readings for this were taken at the same time as those for the tachometer calibration. When the torque readings were plotted against shaft speed as given by the direct reading instrument No. 106. several notable characteristics were observed. The most important of these was the

* Ser. No. 196 (on loan from Electrical Eng. Dept.)

xxx No. S5173 made by Toleberk.

severe discontinuity over the break in the run from 21st to January 24th. This at first suggested a zero error in the torque readings, and consequently a check reading was carried out. It was considered that a running up time of five minutes before readings were taken was necessary to heat up the oil seals and bearings to a steady running temperature.

The waviness in the torque curve at approximately 400 r.p.m. was expected to be due to the vibrations in the shell piece existing at that speed. From the torque readings and the speed the shaft horsepower delivered from the motor was calculated at each speed. The electrical input horsepower was obtained from readings of the current and voltage. Each of these two variables were plotted against the speed so that a comparison could be drawn.

From the continuity of the electrical input horsepower curve in the 400-450 r.p.m. range, compared with that of the shaft horsepower, it was more apparent that a zero error had been made with the torque readings.

However the more general inconsistency of the electrical input curve could be expected, due to the small scale movements used for recording the electrical components. Nevertheless it gave an approximately continuous curve over the break. On the 25th January 1955, a single unbroken run over the top section of the range was carried out and used in conjunction with a more carefully read value for the zero torque, to obtain a comparison with the first set of graphs. The following day, the lower speed range of this series was tabulated.

The tachometer readings were plotted on the original curve and no variations were found. The torque curve showed a smooth trace in comparison with the first run, with very much smaller fluctuations in the vicinity of 450 r.p.m.s. The zero speed torque reading was slightly higher than for the previous run and conversely the torque at 600 r.p.m.s. was slightly lower.

The curves of both shaft and electrical input horsepower were very

much the same as the previous plot, the higher speed values of horsepower being slightly lower in the latter case. Since the mean zero torque was obtained as the mean of several readings, all different, it was considered that a segmental variation may have been present, due to perhaps some magnetic effect in the motor or an eccentricity of the coil. For this reason, it was decided to compare the zero torque readings at different rotational stations.

On 27th January, 1955, using eight equally spaced stations about the periphery of the coupling to the shaft, the corresponding torque values were read. The stations were approached slowly so as not to overshoot the mark and they were all approached from the same direction of rotation. This process was followed several times, using both directions of rotation.

It became apparent immediately, that rotational position had no effect on zero torque, since an erratic set of results was obtained in each case. However the rotational direction made a considerable difference. This could be accounted for by the fact that the spherical bearings supporting the motor had a noticeable static friction. This exerts a restraining torque on the motor, which must be overcome before the motor can move in either direction. A difference is thus obtained in the zero torque according to the direction of rotation and a zero torque reading may be obtained anywhere between the limits of static friction. In one case, the limits were 5.7 ft. lbs. and 7.8 ft. lbs. and these of course depended on the scale setting. The choice of zero torque was then considered.

The static friction was assumed equal in each direction, so that the true zero torque was taken midway between the maximum and minimum readings of the static torque. In order to turn the shaft from that position a torque would be built up but the motor casing would not move until the maximum zero torque had been exceeded. Up to that stage, the reaction was carried by the static friction in the bearings.

A new torque curve was obtained from readings taken on February 1st 1955

of torque versus speed using the new value for zero torque which was found with the stationary motor positions. Because the curve appeared rather erratic, a second run was carried out the following day.

The same value of zero torque was obtained on each occasion, and the curve for the second set of results was much more consistent than the first, except for the region from 430-500 r.p.m. over which the torque was considerably lower than expected. This effect was spread over the latter part and continued past the first range of vibrations.

4.4.3. Calibration Curve. For each particular air density, a calibration curve for the torque will exist. A typical curve is shown in the graph.^x Its shape was approximately parabolic and passed through a value of zero speed torque of approximately 6 ft. lbs. which was due to the static friction in the oil seals and bearings.

The rate of increase steepened as the speed increased.

4.5. Vane Anemometer^{xx}

This meter was used for velocity estimations at the radial entry and diffuser exit.

4.5.1. Construction. The outer cylindrical tube, approximately 1.6 inches long, had a diameter of slightly more than four inches. Coaxially mounted on two sets of three solid spokes were the blade rotor and the counting device, the latter having a maximum diameter of 2.1 inches. The rotor had eight sheet aluminium blades of approximately one inch span, rivetted to eight integral spider arms carried on the central shaft. The blades were tapered from tip to root.

4.5.2. Principle of Operation. The rotor drove the counter through a disengaging bevel clutch to register on four dials, the feet, the hundreds of feet,

x Fig. 4.

xx No. C12338 made by Short and Mason, London England, N. H. Seward, Melbourne (Agency) on loan from A.R.L.

the thousands of feet, and the tens of thousands of feet of air which passed through the meter. It was thus an integrating type which measured the cumulative amount of air that passed through it. In order to estimate the velocity, it was used in conjunction with a stop watch.

All the dials of the meter could be reset to zero with a small switch located at the top of the periphery near the suspending handle. Situated alongside this switch was the clutch lever. Readings were taken with the dial facing downstream.^x

Owing to the necessarily flimsy construction of this type of meter, it was not intended for use of a repetitive nature, rather for occasional spot readings. The continuous use of the meter may have been a contributing factor to the clutch breakdown.

By taking a series of readings of the same air flow, a scatter of values was obtained. This scatter was distributed over a range of approximately $\pm 5\%$ of the mean value. For that reason repeat readings were essential for results within two per cent. The instrument was built for air velocities from 200 to 3,000 ft. per minute.

4.6. Cylindrical Yawmeter.^{xx}

The yawmeter, which was fabricated in Melbourne at the A.R.L. workshops, was used to estimate the velocity profiles in the working section and diffuser of the tunnel.

4.6.1. Construction. The instrument consisted primarily of a one quarter inch diameter steel tube, approximately 34 inches in length and plugged at each end. Ten inches from one end were the pressure holes in a short brass section one and one half inches in length. From the openings the air pressures were lead through internal tubes to the take off nipples, some six

inches from the end of the tube. Five inches from that end a parallel bar six
^x Ref. V.P. Tunnel staff A.R.L. per W. Howard. ^{xx} Y.No. - 1

inches in length and one inch wide was fixed to the tube as a directional datum. Initially the yawmeter was put together with solder which after some weeks of use, broke down at several joints, causing erroneous pressure readings. It was then despatched to A.R.L. Melbourne, where it was completely dismantled, cleaned off, and remade using silver solder throughout.

4.6.2. Calibration. After the remaking, a new calibration for the zero yaw angle with reference to the datum bar was carried out. The calibration was performed at A.R.L. using the Low Speed Cascade Tunnel as a parallel air supply on August 25th 1955.

The yawmeter was placed in the chuck attachment on the yaw traverse rig of the Low Speed Cascade Tunnel, with the pressure holes about midway across the air stream.

The indexing head was moved until the datum bar of the meter was approximately horizontal. The levelling of this bar was carried out by placing a spirit level on it and finely adjusting the indexing head. The average zero bar angle was found from several separate readings.

The tunnel was then run up to a speed of approximately 80 ft./sec. The indexing head was used to adjust the direction of the tube until equal pressures were obtained from the 45° tappings, these being compared on an inclined tube alcohol manometer. Then the angle on the index register was read. A sample of four or so readings of this value were taken and the mean value was found.

In the second part of the experiment the meter in the traverse rig was removed as a unit and replaced with the index head on the other side of the tunnel. The same procedure for angle measurements was followed for the yawmeter in its new position. The second part of the experiment was carried out to

eliminate the error due to a difference in the absolute air angle from the horizontal.

From the results, the zero bar angle was found to be 7.19° .

4.7. Pitot Tube^x

The pitot tube, which was used for mass flow measurements, was fabricated at the Engineering Workshops of the University of Tasmania.

4.7.1. Construction. The seven static pressure holes were drilled one inch back from the total pressure hole on the two inch probe. The arm of the Pitot tube was fifteen inches long from the probe to the clamping block. Joints were sweated and silver soldered throughout.

4.7.2. Calibration. Since each Pitot tube may have slight variations from the standard due to, for example, inaccurate tip shape, misalignment of the probe, surface finish of the probe, etc., a calibration run of the locally made Pitot tube against a substandard Pitot Tube^{xx} on loan from A.R.L. Variable Pressure Tunnel, was carried out.

After having conducted a traverse with the locally made tube in front of the inlet guide vanes the results were examined to compare the total static pressure difference at various stations across the stream. Since this difference was practically constant across the stream, at least from one inch clear of the walls, it was decided to take simultaneous readings with the two tubes. They were mounted from inside the core and were held in position by means of a wood clamp so that the total head holes were at the same axial position.

The standard tube was placed in such a way that the probe was parallel to the axial stream and two and one half inches from the outside wall, whilst the locally made tube was three and one quarter inches from the outside wall.

^x EA3 - No. 1

^{xx} C 298124 Made by C.I. Co. Ltd.

The distance between the tubes was thus three quarters of an inch.

The pressures were taken to the multi-tube inclined manometer which was set at an angle of arcsine 0.25.

With the throttle full open, a condition in which the velocity distribution across the section did not vary appreciably with shaft speed, this speed was set at a particular value, and the total and static pressures for each instrument were recorded.

The tubes were then interchanged and further readings were recorded. Finally a traverse was done with each tube at a set speed of 3930 r.p.m.

4.7.3. Calculations. By equating the static-total pressure difference to the manometric pressure difference for the standard Pitot tube, we obtain

$$P_T - (P_T - \frac{V_\infty^2}{2g} \gamma_{AIR}) = \frac{\gamma_{AIC} \Delta h}{48}$$

$$V_\infty = \sqrt{\frac{2g \gamma_{AIC}}{48} \times \frac{\Delta h}{\gamma_{AIR}}}$$

$$V_\infty = \frac{8.184}{\sqrt{\gamma_{AIR}}} \times \sqrt{\Delta h} \quad (\text{STANDARD})$$

The results from the local Pitot tube gave in general a lower value of the velocity so that the calibration coefficient was increased. The equation for the local tube became

$$V_\infty = \frac{8.3338}{\sqrt{\gamma_{AIR}}} \sqrt{\Delta h} \quad (\text{Local}).$$

It was seen from the equation that the value of the velocity depended largely upon the ambient air density. For that reason, it was essential that the ambient temperature and pressure were known, so that, by reference to a chart, the air density could be selected. The effect of humidity was neglected

as a second order quantity.^x A sample of the variation is given below.

∅ AIR	0.074 lbs/cuft.	V_{∞}	=	30.660	$\sqrt{\Delta h}$
∅ AIR	0.076 lbs/cuft.	V_{∞}	=	30.228	$\sqrt{\Delta h}$
∅ AIR	0.078 lbs/cuft.	V_{∞}	=	29.830	$\sqrt{\Delta h}$

4.8 Barometer.

Owing to the considerable effect of the air pressure and temperature upon velocity readings with the Pitot tube etc., it was decided to install a barometer with a thermometer mounted beside it.

4.8.1. Construction. A sawn-off glass jar two and one half inches high and two and one quarter inches external diameter, with one quarter inch wall thickness was chosen as a reservoir. The frame consisted of a one quarter inch mild steel bar three and one quarter inches wide and thirty four and one half inches long, at the end of which was welded a platform to carry the reservoir. The tube was supported on three blocks out from the main frame. A perspex scale, graduated in tenths from twenty eight to thirty two inches, was bolted to the upper support block.

A zero indicator was screwed through the reservoir lid in order that level fluctuations could be adjusted by means of a threaded plunger adjacent to the pointer. The reservoir cover plate was held in place by four bolts anchored in the reservoir bracket.

A thermometer, graduated from minus ten to one hundred and ten degrees Centigrade was cemented to the barometer frame next to the barometer scale.

The unit was screwed to the tunnel wall directly opposite to the working section of the tunnel, with the scales at eye level.

^x See Pankhurst and Holder: Wind Tunnel Technique.

5. ENTRY FLOW.

To estimate the velocity distribution at the inlet to the tunnel, the rotational speed and throttle opening were maintained for the tests from February 3rd 1955 till February 14th 1955.

5.1.1. Test Condition. The blades installed in the tunnel were, as originally supplied, of the sand cast S1 type, incorporating the standard C4 profile. The runs were carried out with full open throttle. At this stage the inlet gauze and its clamping rings (of Dee-section) were not fitted. Four radial stations were chosen for the tests close to the four adjusting rods tying the core to the shell. The radial deviation from the quadrant points of the anemometer for each station was calculated:-

Station A: 4° below the quadrant bar.

Station B: 4° back from bar towards station A.

Station C: 4° below the quadrant bar.

Station D: 4° on towards station A.

See Fig.

5.1.2. Test Procedure. Having set the shaft speed at some predetermined value, the anemometer (for description of which see 4.5.) was placed for each of the stations at one of the seven, axial, equally-spaced positions. They were three inches apart, but since the entry width is 23.25 inches the last position was slightly less, i.e. 2.25 inches.

Because the anemometer gave readings in feet of air that pass through it, the velocity was measured in conjunction with a stop watch. A constant time interval of one minute was chosen, the result being a direct reading on the instrument of feet per minute. Initially four readings were taken that gave a repeat result within some 3%, and the averages of these readings were used for the profile plotting.

A second speed was selected and the velocities at the seven positions on

the same bar were measured, care being taken to maintain the same shaft speed for all the stations.

Once a comprehensive picture of the velocity distribution was obtained for various speeds, of which five selected values were taken, the corresponding distributions for the same speeds were obtained at the other three radial stations.

5.1.3. Results. The velocity distribution obtained at the first bar (A) confirmed expectations, a maximum near the outer shell lip, tailing off to a minimum at the inner core lip. This was shown to conform very closely to the distribution for a free vortex flow. Assuming the space between each station was one unit of radius and that a centre existed four units on the downstream side of the station nearest the outer shell lip, we obtained the product $v.r$ at each station.

Station	1	2	3	4	5	6	7
$v.r$	3000	3100	3120	3080	2960	2970	3000

The product was practically constant right across the stream which indicated that a free vortex motion was present.

The distribution at bar B (the bottom station) was affected by the severe sheilding of the floor and framework. The profile at the three velocities tested, showed a distinct peak at the midspan position, falling sharply to either side. It was hoped that the modifications to the framework and placing of the gauze and beadings at the inlet would smooth the flow out considerably from its uneven condition.

At bar C the distribution was definitely influenced by the proximity of the tunnel to the building wall. This had the effect of blocking off the return flow to a certain extent on that side in comparison to the flow on the

passage side of the tunnel. The nett effect on the velocity distribution at bar C was to reduce the peak value near the inner lip and to increase slightly the velocity nearer the outer lip.

A very similar effect was noted with regard to the top station D, with slightly less marked increase in the low velocity region near the outer lip.

5.2.1. Beadings. On February 17th 1955 a new series of readings were started so that a comparison could be drawn for the values of air entry velocity with the beadings in place, with the previous set of readings. The difference would indicate the amount of modification effected by the addition of the beadings (Dee-section ring fairings) only. The gauze was still not placed in position. The tests were suspended for a time (pending completion of repairs) due to the break down of the anemometer. They were resumed on March 24th 1955. A check run over the speed of 333 r.p.m. (1440 on register dial) was made to compare the new results with those obtained before the instrument's break down.

5.2.2. Results. In all four stations at the tested speeds it was found that the velocity profiles were altered slightly in the same manner after mounting of the beading. The peak velocity near the shell lip was reduced and the region of low velocity had an increased flow. In other words, the beading produced a levelling effect on the velocity profiles.

5.3.1. Frame Modifications. The main crossbrace which sheilded the entry, at the bottom station, was replaced by two lighter braces not directly in the stream. This modification has been noted on the drawing of the tunnel frame members No. E602. It had a marked effect on the velocity profile, removing the very pronounced peak near the mid entry position at bar B, and generally producing a distribution very similar to those of the other three stations. The velocities were, however, still lower in this region owing to

the severe shielding by the floor.

5.4.1. Entry Gauze. The gauze was then placed in position around the entry and clamped by the beadings. A new set of readings was conducted at 393 r.p.m. (1,700 on the register dial) to determine the effect on the entry velocity distributions.

5.4.2. Results. A further improvement to the velocity distribution was evident. At all four stations the distribution was now very even, e.g. at station A, the velocity values across the entry from the shell lip to the core lip varied in the form:

SHELL						CORE
700	670	630	620	590	540	475

This provided a very slowly drooping velocity profile from the shell lip to the region of the core lip, where the slope became much steeper.

A similar pattern was observed in all four stations and the quantitative values varied little except at the bottom station, where it was approximately two thirds of the value at the other three.

It was noted that the gauze was very effective in evening up the distribution. See Fig. Nos. 5,6,8.

6. MASS FLOW CALIBRATION.

The object of the calibration was to obtain curves for the mass flow at the working section for given inlet pressure readings.

6.1. Test Method.

As a forerunner to the main calibration and as a part of it, velocity profiles for various speeds and throttle openings were tabulated. The radial traverse was taken at the start of the parallel section in front of the inlet guide vanes. At such a station the flow was predominantly axial and was assumed free from the effect of the inlet guide vanes, being a distance of three chord lengths upstream from the blades.

Eight stations across the stream at one inch spacings were chosen to give a good representation of the velocity profile. The outside stations were each one inch from the walls, since the blade chord was 9". The first set of profiles were recorded for full throttle opening, corresponding to thirty-two inches of axial movement of the sliding valve.

Having set the throttle at full open, the shaft speed was selected and held constant while the static and total pressures were recorded.

This process was repeated for various throttle openings ranging from the 32" ("full open") down to 4" and 3" openings.

Substantially the same rotational speeds were used for each throttle opening in order that a more comprehensive picture could be obtained.

6.2. Velocity Profiles.

In general the velocity profiles were extremely flat, with a variation of approximately $\pm 5\%$ from the mean value, in the extreme cases. That corresponded to a high rotational speed and a small throttle opening, in which case the secondary circulation became marked. However as a sample, the variation for 440 r.p.m. at 6" throttle opening was -1% to $+0.7\%$ with a mean

velocity of 38.45 ft. pci. In all cases the velocity had a maximum value in the vicinity of the inner wall and a minimum near the outer wall.

In order to calculate the average velocity at the section, the mean velocity had to be calculated, having regard to the radius of each station.

$$\frac{\sum vr}{\sum r} = \bar{v} \quad \text{was computed as the mean velocity.}$$

This value of the mean velocity was found to vary from a mean value calculated as $\frac{\sum v}{n}$, where n was the number of stations selected, by extremely small amounts. For example at 667 r.p.m. and at 16" throttle opening, $\frac{\sum vr}{\sum r} = 81.08$ while $\frac{\sum v}{n} = 81.14$ which corresponded to a percentage error of 0.08%. This was entirely negligible considering the accuracy of the individual readings. For this reason the mean velocity was referred to throughout as the value corresponding to $\frac{\sum v}{n}$.

The pressure difference $P_t - P_s$ corresponding to this mean velocity was now compared with the pressure difference values in each case and it was found that without exception the value lay between the values obtained between stations 5 and 7, with a predominance of the value at station 6. The difference between the mean pressure difference and the value for station 6 was at all times far less than one per cent, and again in view of the possible discrepancy for the pressure readings it was considered satisfactory to adopt station 6 as being a representative station for all combinations of throttle opening and speed within the range tested. This range was limited in the lower velocity values by the accuracy of the pressure readings. Thus a minimum throttle opening of 4 inches was chosen. Shaft rotational speed provided the upper limit which in no case lead to an onset of surge except with the very small throttle openings below 4 inches. It seemed certain that the tunnel would not surge at any of the greater openings since the first signs of surge appeared only at 4 inches throttle, far less than 32" throttle.

6. 3. Mass Flow Curves.

So that a picture of results could be easily checked, curves for mass flow against speed, at the various throttel openings were plotted. These resulted in almost linear variations and enabled check results to be compared quickly.

Since the curve for mass flow versus inlet pressure drop was the most important one, it was drawn up for the pressures at station 6. The curve was a predominantly smooth parabola with a marked scatter of values. The derivation of mass flow was then examined and found to depend on the ambient air density. As a result the characteristic curve was drawn for three specific ambient densities, 0.074, 0.076 and 0.078 pounds per cubic foot.

Thus, knowing the ambient density we may immediately read the mass flow for a given pressure difference. Intermediate density values are found by extrapolation.

6.4. Non Dimensional Plotting.

All results were reduced to a non dimensional form so that curves for

$$\frac{\frac{ND}{\sqrt{T_0}}}{\frac{M}{P_0} \frac{\sqrt{T_0}}{D^2}} \text{ and } \frac{P_d}{P_0} \text{ could be drawn where}$$

N - speed in revs/sec.
 D - Characteristic diameter
 T_0 inlet air temperature
 P_0 inlet air pressure
 P_d outlet pressure at measuring station.

The important P_d was the total pressure value (at the station in question) and this was dealt with more fully than the static value.

The total pressure was at all times less than the ambient pressure P_0 , so that $\frac{P_{dt}}{P_0}$ was always less than unity. Similarly $\frac{P_{ds}}{P_0}$ was always less than unity. (P_{dt} total pressure at the station. These two conditions P_{ds} static pressure at the station)

corresponded to turbine running state. In most compressor work P_{d_s} and P_{d_t} was measured after some work had been supplied so that $\frac{P_{d_s}}{P_o}$ and $\frac{P_{d_t}}{P_o}$ were generally greater than unity.

However since primary interest was centred in the inlet calibration and discharge pressures were unavailable, values of $\frac{P_{d_t}}{P_o}$ and $\frac{P_{d_s}}{P_o}$ less than unity, were accepted.

Further, the drop in total pressure from P_o to P_{d_t} represented the total head loss up to the station at all times. The greatest drop corresponded to approximately $\frac{1}{4}$ " of water.

The velocity was represented by a function of the pressure difference, namely $\frac{P_{d_t} - P_{d_s}}{P_o}$. Examination of the curves for $\frac{ND}{\sqrt{T_o}}$ constant showed them to be coincident for the various plots of $M \frac{\sqrt{T_o}}{P_o D^2}$ versus $\frac{P_{d_t}}{P_o}$, which was to be expected since no head was supplied to the fluid up to the test station.

To check the effect of the inlet guide vanes on the flow at the test section, 3 chords upstream the pressure readings at station 6 were recorded for several settings of the inlet guide vanes. No significant change in pressure readings was noted.

7. DIFFUSER FLOW.

In order to examine the flow in the diffuser, with a view to find out whether gauzes were necessary to remove separation, a series of runs were made to determine the velocity distribution at several stations within the diffuser section. In some cases the flow direction was also estimated to obtain a clearer picture of the flow.

7.1. Instrumentation.

The probe used for the examination was the yawmeter YNO-1, which by equalising the two 45° tubes gave the stream direction, the 45° pressure readings and the total head.

The rate of change of pressure on the surface of a cylinder in a fluid stream, reached a maximum close to 45° . For that reason the value of the pressure at that position was likely to be slightly inaccurate and variable. It would however give a lead as to the order of the velocity, but the results should not be considered qualitatively. Also since the indexing head for the yawmeter was not available, no accurate readings for the flow swirl direction were recorded, rather estimates than readings were recorded.

7.2. Test Procedure.

The investigation was carried out in two main stages

- (i) when the inlet gauze was not in place
- (ii) with the inlet gauze in place.

Further variations in these two conditions were shaft speed and throttle opening.

The pressure readings were observed on the multi tube inclined manometer at an angle of $\text{Arcsine } \frac{1}{4}$. The readings were taken in four axial positions with four circumferential stations at each. These circumferential stations were lettered A, B, C, D corresponding respectively to the mid open side of the tunnel house, bottom, mid narrow side of tunnel house and top.

The four axial stations were, running down stream, as follows:

- (i) Behind outlet guide vanes
- (ii) At end of parallel section.
- (iii) At mid diffuser.
- (iv) At outlet.

Readings of velocity at outlet were radial velocity measured with the vane anemometer, which has been described.

The general pattern followed was to choose a particular shaft speed, (i.e. 1,700 r.p.m. on the electric tachometer), and take readings of the pressures at all stations. Variations of speed and the throttle opening were then examined with regard to some particular stations, sufficient to recognise any large disturbance in the flow.

The results were examined in full for each axial position, followed by an overall description.

7.3. Results.

7.3.1. Behind outlet Guide Vanes.

(a) Without Inlet Guaze.

At this axial station only one of the four circumferential positions was investigated, owing to the fact that the aluminium casing was slotted in only one circumferential station A. Readings were taken $1\frac{1}{2}$ chord lengths behind the outlet guide vanes, midway between the wakes of two adjacent outlet guide vanes.

At the standard speed (1,700 on the electric tachometer) the velocity distribution was rather uneven, rising from a value slightly below the mean at the outer casing to a peak value approximately one quarter span from the inner wall. From the peak value it dropped rapidly towards the wall. This was

probably due to three effects

(i) a flow separation from the core

(ii) an interference due to the slot

in the core (iii) a carry over of root effects from the blades upstream.

Reduction of tunnel speed tended to reduce the peak velocity and give a more even velocity distribution, nevertheless its basic character was not changed.

(b) With the inlet gauze in place.

Apart from an approximate 4:3 scale down of values, no change in velocity distribution occurred when the gauze was placed. The peak velocity occurred in much the same position $\frac{1}{4}$ span from the core wall. Since it was found that the alteration of throttle opening does not alter the shape of the velocity distribution at a point up stream (in front of the inlet guide vanes) it was assumed that no substantial change occurred behind the outlet guide vanes.

7.3.2. At the beginning of the Diffuser.

(a) Without the inlet gauze.

Four $\frac{5}{16}$ " holes were drilled at the circumferential stations A, B, C and D at the beginning of the diffuser. Readings were taken at each of these stations with the tachometer registering 1,700 r.p.m. and with full throttle opening.

At station A the velocity distribution had changed considerably from that up stream at A behind the outlet guide vanes. The maximum value had shifted to the mid span position and the drop to the core was considerably less abrupt. Towards the outer shell the velocity dropped to a value of approximately $\frac{7}{8}$ of the maximum, neglecting of course the boundary layer.

A change in the distribution was apparent at position B. At this

position the mean velocity was lower than at A and the peak had shifted even further towards the outer shell, being at nearly $\frac{3}{4}$ span. It was similarly characterised by a larger drop to the inner wall than the outer wall.

The distribution at C was very similar to that at B except that the peak velocity lay nearly at mid span and the drop towards the core was steeper. The mean value was approximately the same as at B and each were less than at A.

Examination of the profile at D, showed that a very large change had taken place. The maximum velocity lay close to the core and the profile drooped considerably towards the outer shell. The mean value was much the same as for B and C.

The velocity profile at A was studied for variation in shaft speed. Increase in the speed from the 393 r.p.m. value to 526 r.p.m. caused a considerable jump in the peak velocity, though its mid span position remained unchanged. The boundary effect near the outer wall was much enlarged, and near the core wall, the readings showed a small blip in the profile, though it was considered that that may be due to an external error.

At the lower speed of 270 r.p.m. (corresponding to 1,200) on the electric tachometer, the profile had become very flat with little wall effect.

(b) With the inlet gauze in place.

The effect of the inlet gauze at A was to reduce the velocity to about $\frac{3}{4}$ of its previous value, with only slight modification to the profile shape. The peak value was made more predominant by a slightly increased slope towards the outer shell.

7.3.3. Mid Diffuser.

(a) Without the Inlet Gauze in Place.

The profile at position A resembled very much the one for D at the

beginning of the diffuser, having regard to the diffusion that had taken place. This would be expected if a swirl of the order of ten to twelve degrees remained in the tunnel past the outlet guide vanes. Estimations of swirl were then carried out using the yawmeter and a bubble protractor, and in fact were found to be of that order. Thus the peak velocity lay close to the core wall and the profile tailed away to about $2/3$ of the peak value near the outer shell.

The rotational displacement of the velocity was found to occur at each of the four circumferential stations so that position B corresponded to the previous station A, C to B, and D to C.

Apart from the rotation, very little modification to the profiles was apparent.

The effect of increasing the shaft speed was very closely similar to the effect at the previous station namely a more predominant velocity peak. Also the reduction of speed gave a practically flat profile.

(b) With the Inlet Gauze in Place.

At station A the gauze caused the velocity to drop to about $2/3$ its value without the gauze. The profile remained similar with a flow concentration near the inner wall.

7.3.4. Radial Diffuser Exit.

(a) Without the Inlet Gauze in Place.

Tests at the diffuser exit were rather extensive and as it has been noted before, were carried out with the vane anemometer No. C 12 338.

At 1,700 r.p.m. on the electric tachometer the flow at all four stations was characterised by a concentration near the extension flange of the core wall, dropping back to no flow at about $2/3$ of the distance from this core wall to the throttle shell. Closer towards the throttle shell a back flow existed

but owing to the very low velocities, no readings could be recorded.

At position A the velocity remained practically constant for about $1/3$ the opening from the core flair then dropped abruptly to zero at about $2/3$ span.

In comparison, the profile at B fell steadily from a higher maximum adjacent to the core to zero in much the same position as A.

The profile at C was similar to that at B except that the peak velocity occurred slightly away from the wall.

An average of the profiles at C and A would give a profile very similar to the one at D. This consisted of a distribution, gradually dropping from a maximum near the wall to about $\frac{1}{2}$ span, followed by a quicker drop.

As with the previous station, a rotational change had taken place with the profiles, consistent with the residual swirl. The effect of speed change at both A and C which were the stations investigated for this change, was found to be one of almost pure scaling down or up from the basic speed of 393 r.p.m. The distributions themselves did not change to any measureable degree. The effect of throttle opening was also investigated in conjunction with changes in speed.

The throttle opening was measured as the axial movement of the throttle shell from the fully closed position up to 32" for fully open.

The effects were studied by taking the distribution at full open, then closing the throttle further for each set of readings.

On closing the throttle the first effect noted was a slight reduction in the values of the main body of flow with no noticeable change near the back flow or dead water region. The flow still terminated in the vicinity of 18" opening. Further closing of the throttle, involving something less than 18" opening, caused an increase in the high velocity region accompanied of

course by a much more abrupt drop towards the throttle shell. Even though a velocity increase did take place, the overall mass flow dropped.

The velocities continued to rise with closing the throttle until the small openings, in which condition the tunnel will not be run for blade tests, did not allow the use of the anemometer.

(b) With the inlet Gauze in place.

Introduction of the inlet gauze made very little difference to the velocity distribution at full throttle and 393 r.p.m. (corresponding to 1,700 on the electric tachometer). The distribution was made more even round the four stations, except for station C which had a marked drop compared with the other three. The wake of one mid bearing support may be the cause of the drop.

The effect of speed on the distribution, as well as the effect of throttle opening were found to be closely similar to the case for no gauze i.e. pure scaling down for speed and little effect down to 18" opening followed by velocity increases on closing the throttle.

7.4. General Description of Flow in the Diffuser.

In the original condition with no inlet gauze, the flow in the diffuser was characterised by channelling of the flow due to regions of separation.

Considering the flow in the consecutive stations from outlet guide vanes to radial exit, a separation at the core was probably influenced by the presence of the yawmeter slots in the core. This separated region was apparently coiled round the tunnel core by a residual swirl from the outlet guide vanes (stators), since the velocity distribution down the tunnel showed a marked resemblance when a rotational displacement was accounted for.

When the throttle was opened wide, the flow at the exit was governed by the lip of the shell and the core body. The throttle valve had no

measurable effect until it was closed to something of the order of 18"-20" opening.

A more evenly graduated change would be obtained, should the throttle valve diameter be reduced to nearer the shell diameter. That would involve removal of the shell stiffening ring or at least a considerable reduction in its thickness.

As it was usually the case in a diffusing section the velocity profiles were characterised in most cases by a flow concentration away from the walls. That was not the case at the exit, at which point the flow was separated from the throttle valve and was concentrated against the diffuser core fairing.

After the inlet gauze was placed, no severe modifications to the diffuser flow were apparent. In general the values at each profile were reduced in proportion except at the exit, where a change in the distributions were present. The general tendency at the exit was to reduce the flow near the core and increase the flow, in comparison, further towards mid stream.

Flow at position C of the exit, was distinctly reduced. An increase of the swirl when the gauze was placed may have been the cause, since a small separated region may have been displaced around to the measuring station.

In conclusion, it may be stated that, for the present purposes, the flow in the diffuser is satisfactory with a reasonably even flow distribution.

8. CONCLUSIONS.

8.1. Instrumentation.

To investigate the velocity in the working section, it appears essential that a velocity measuring instrument with a very much smaller head than the unit EA3. No. 1 be used. A hot wire instrument may be most satisfactory in this application^{*}, as it may be designed to yield directional readings as well.

The present yawmeter gives readings of flow direction, assuming no radial flow components whatsoever. It is realised that the assumption is incorrect, and it is probably in the investigation of radial components that the tunnel would yield most useful results.

Whilst the mounting of a hot wire instrument would be difficult, the manipulation of a spherical-head yawmeter would be extremely difficult. Either a parallel link or segmental traversing gear may be used with the three dimensional yawmeter^{**}. The type of tests for which the tunnel is used will dictate the instrumentation necessary.

Since the substandard Pitot tube was accepted as a calibrating standard for velocity readings with other instruments, it is considered that a recalibration would be advantageous.

The yawmeter indexing head arrived during December 1955 and has since been assembled. The existing yawmeter (Y. No. 1) cannot be used with this carriage to give a full cover of the working section. A yawmeter of similar construction but with modified dimensions has been requested. Mr. Frith has proceeded using the present yawmeter in the available region to determine test

* N.A.C.A. Report 1168, Secondary Flows and Boundary Layer Accumulations in Turbine Nozzles. By Rohlik, Kofskey, Allen & Herzig.

** Pankhurst & Holder Wind Tunnel Technique.

procedure.

8.2. Entry Flow.

The entry flow has been modified by frame alterations and the use of an entry gauze, to a stage where the distribution round the intake is even enough for the proposed blade tests. In front of the inlet guide vanes at station A (where some measurements will be taken) the profile across the stream one inch clear of the walls is particularly even. A range of $\pm 1\%$ of the mean velocity is representative of the variation.

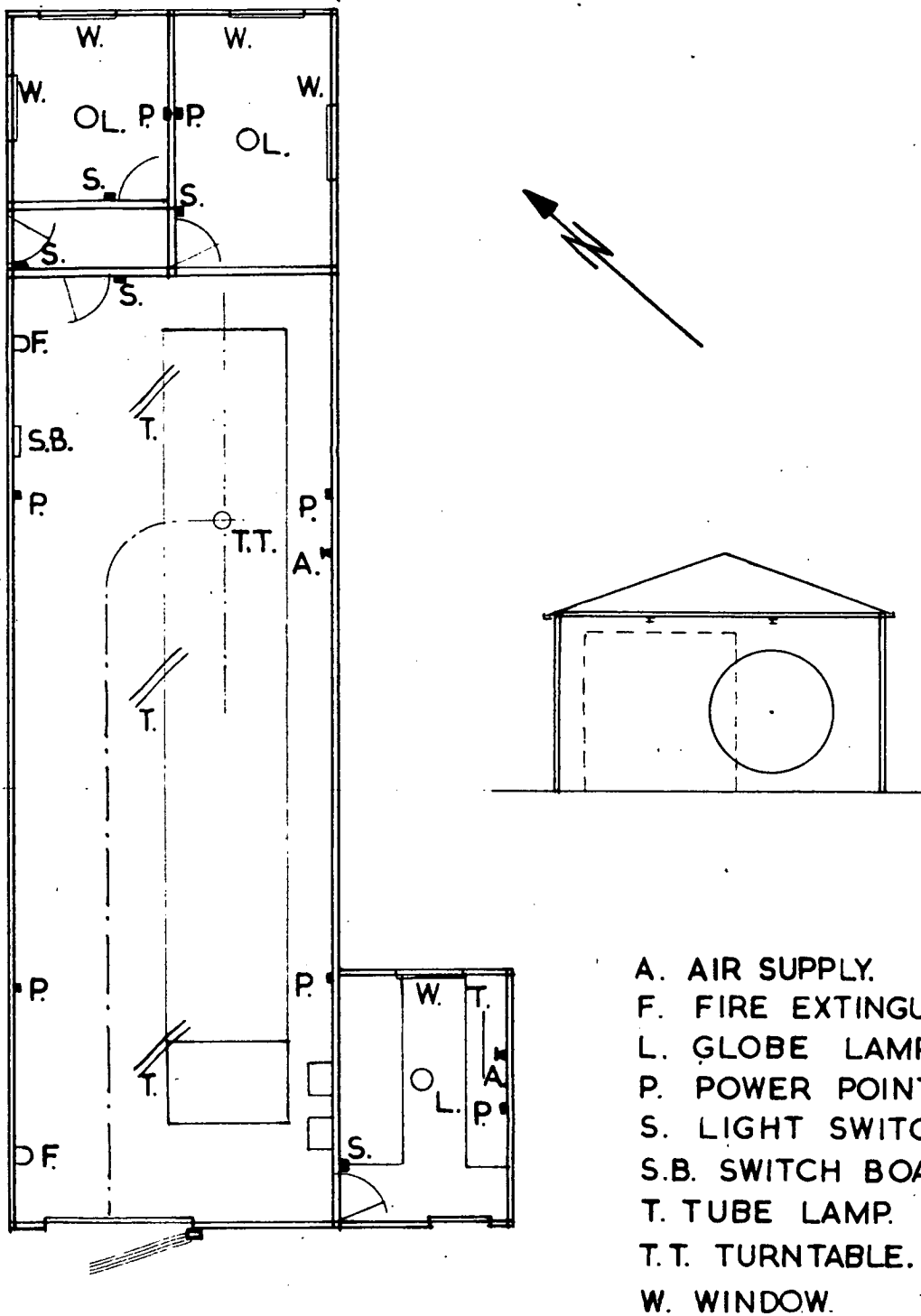
8.3. Mass Flow Calibration.

Curves for mass flow versus velocity head at position 6, station A, (Fig. N°10) in front of the inlet guide vanes, have been prepared from the velocity profiles for various rotational speeds. The reading of velocity head at that position, when used in conjunction with an air density chart, yields the mass flow through the annular working section. It may be more convenient later to consider the mass flow per unit area in the working section. This will be found by dividing the total mass flow by the area of the working section.

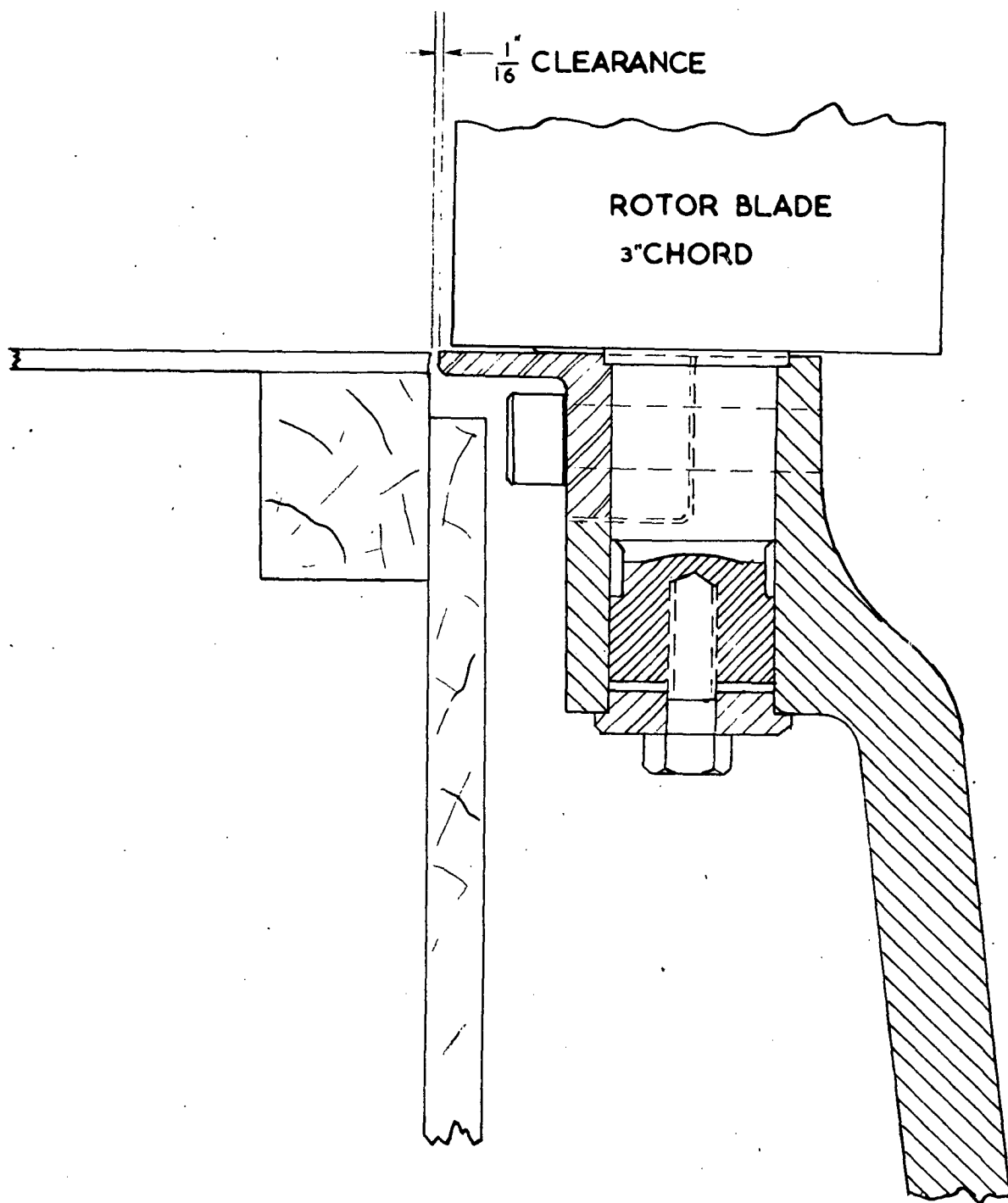
8.4. Diffuser Flow.

The flow in the diffuser is subject to a residual swirl after having passed the outlet guide vanes (stator). Small disturbances in the flow e.g. the wakes from the three faired transfer case supports are handed round the tunnel as the flow progresses to the outlet.

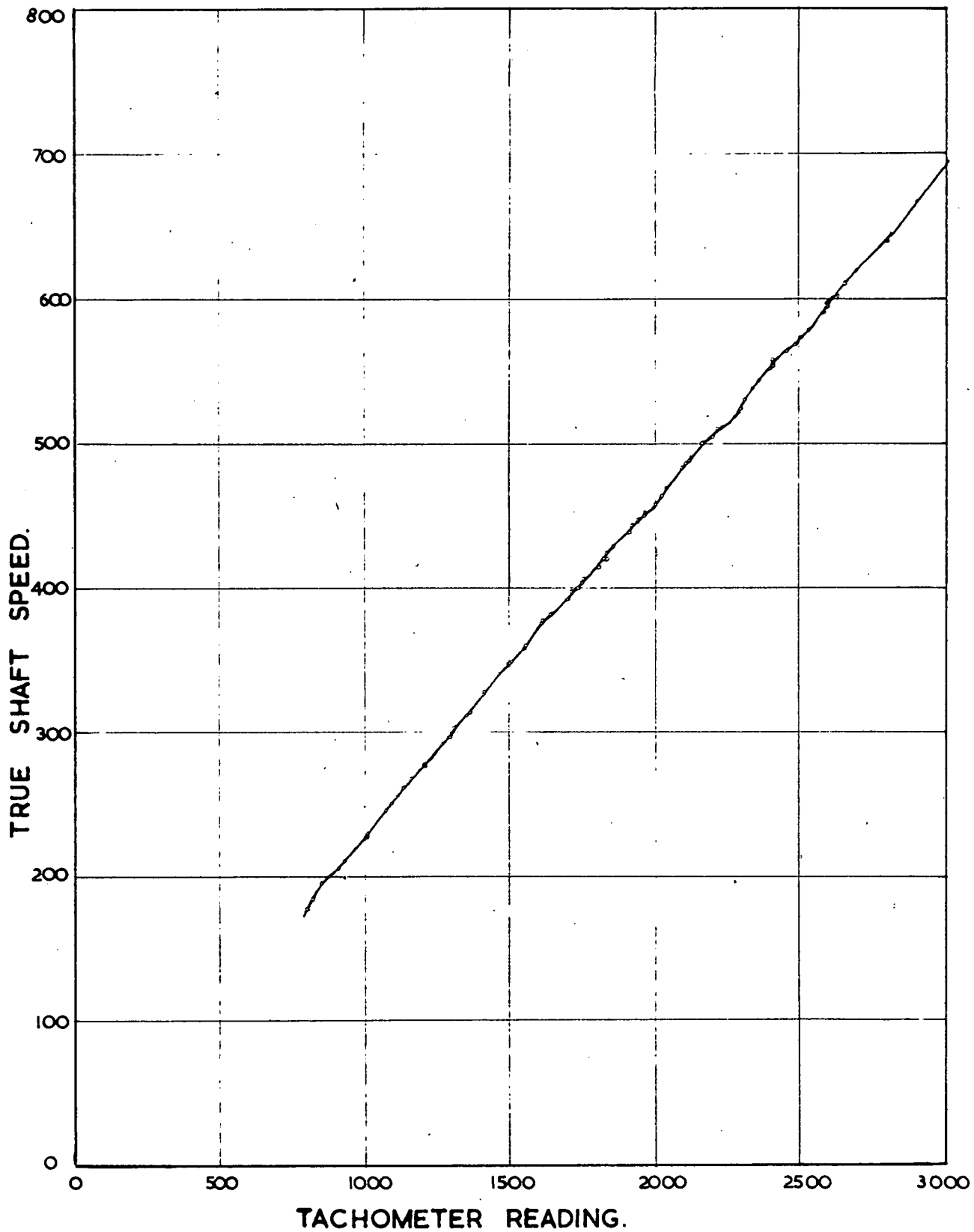
However no serious separation appears to be present and there is no necessity of inserting the gauze in the diffuser section. The inlet gauze and frame alterations considerably improved the flow in the diffuser.



GENERAL LAYOUT OF VORTEX TUNNEL BUILDING.

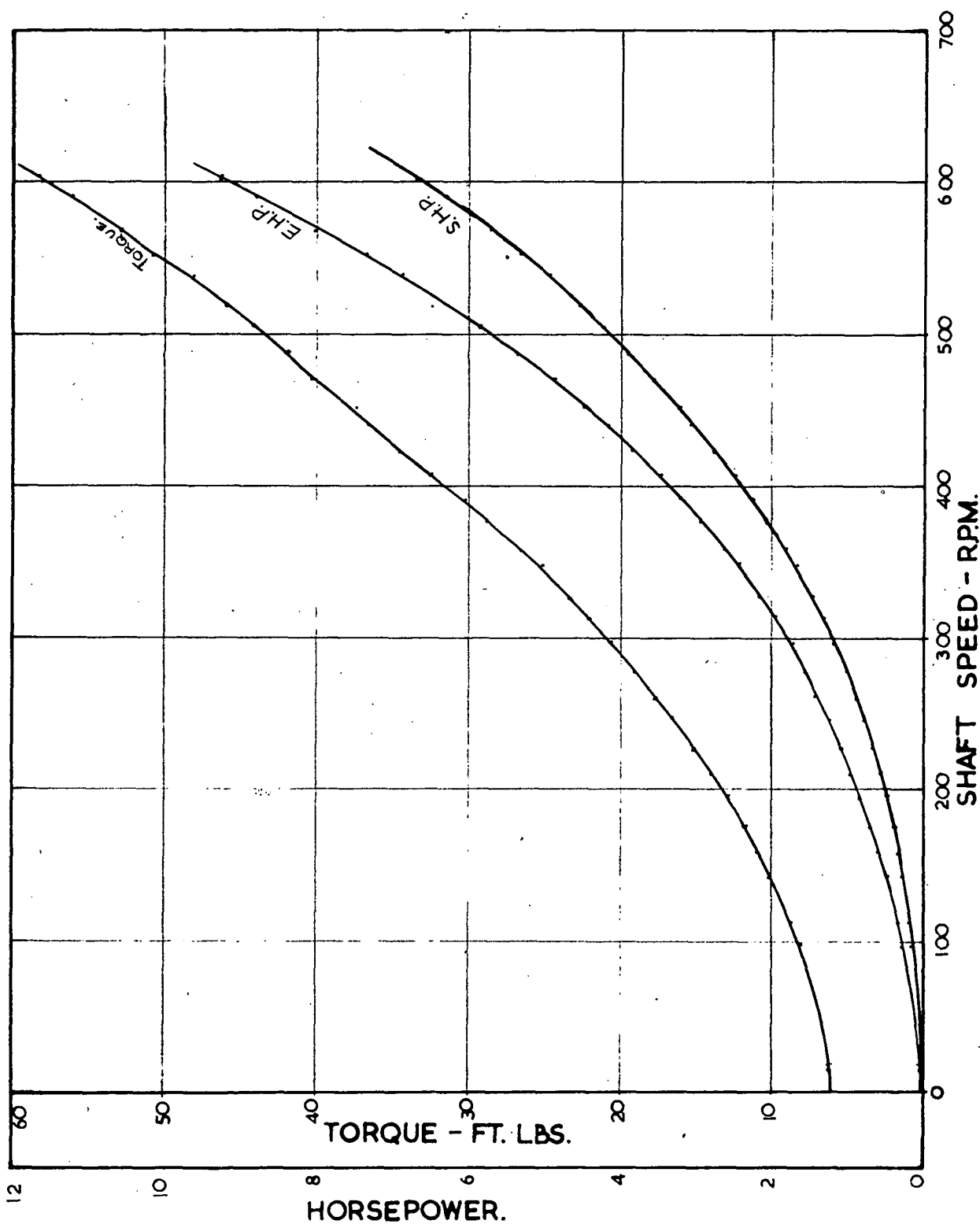


SKETCH OF PROPOSED ROTOR & INNER CASE PIECE.



CALIBRATION CURVE OF ELECTRIC TACHOMETER.

FIG. NO. 4.



TORQUE , SHAFT H.P. , ELECTRICAL H.P. , VERSUS SHAFT SPEED.

CORE LIP OF ENTRY.

SHELL LIP OF ENTRY.

UPSTREAM OF I.G.VANES.

UPSTREAM FACE OF ROTOR.

BEHIND OUTLET GUIDE VANES.

BEGINNING OF DIFFUSER.

MID-DIFFUSER.

SHELL LIP OF RADIAL EXIT

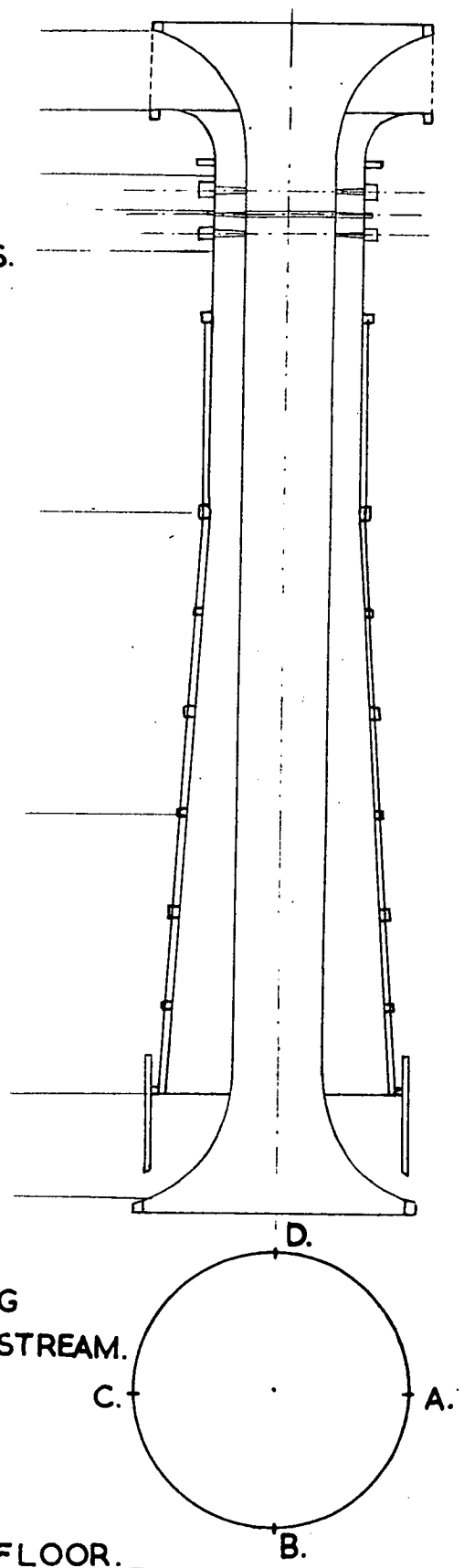
CORE LIP OF RADIAL EXIT.

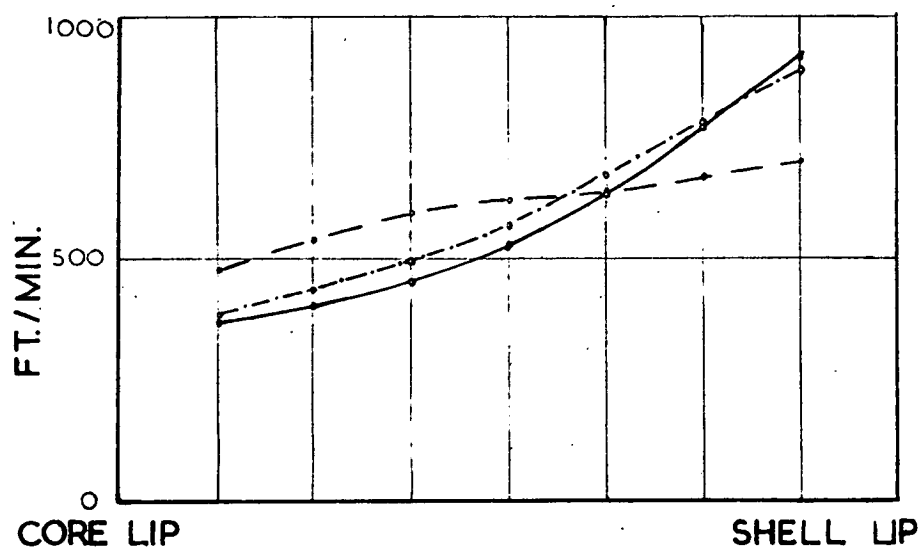
SCALE 1" = 4.4'

FACING
DOWNSTREAM.

FLOOR.

RELATIVE POSITION OF TEST STATIONS.



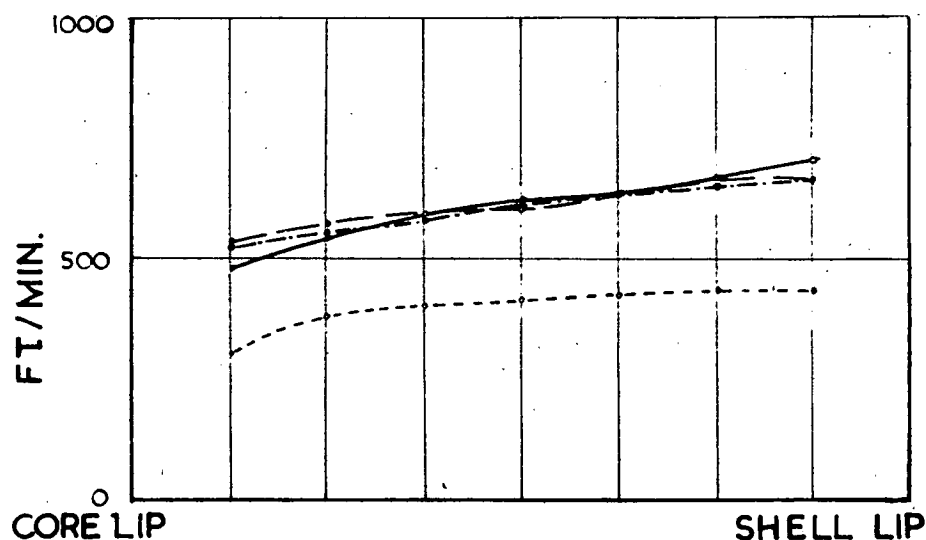


VELOCITY PROFILES AT STATION A.

- NO BEADING, NO GAUZE.
 - - - BEADING, NO GAUZE.
 - . - BEADING & GAUZE.

SHAFT SPEED 393 RPM.

FIG. NO. 6.



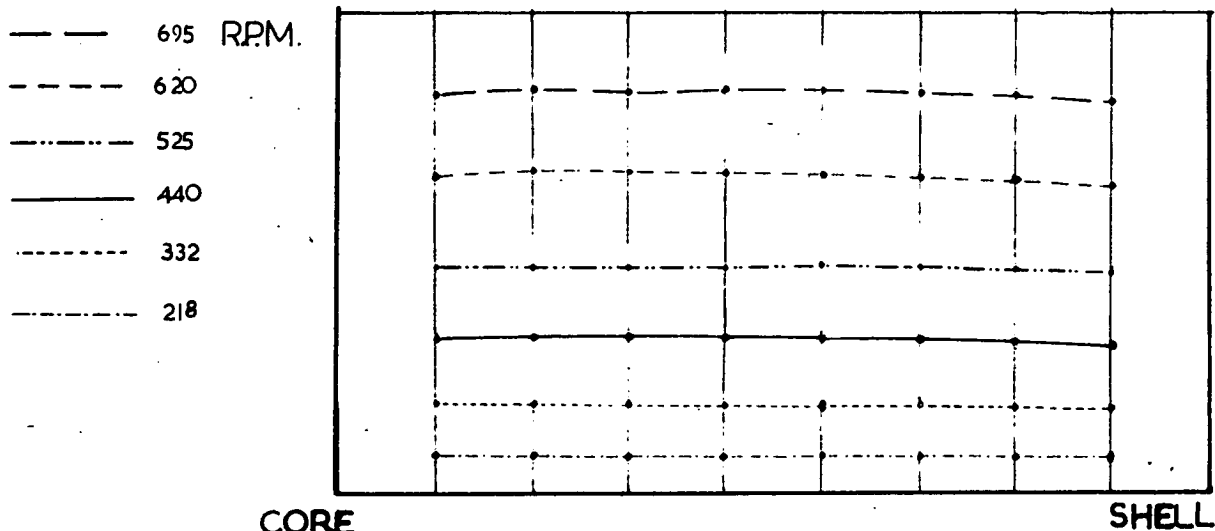
VELOCITY PROFILES AROUND ENTRY.

- STATION A.
 - - - STATION B.
 - . - STATION C.
 - - - STATION D.
- } GAUZE IN PLACE.

SHAFT SPEED 393 RPM.

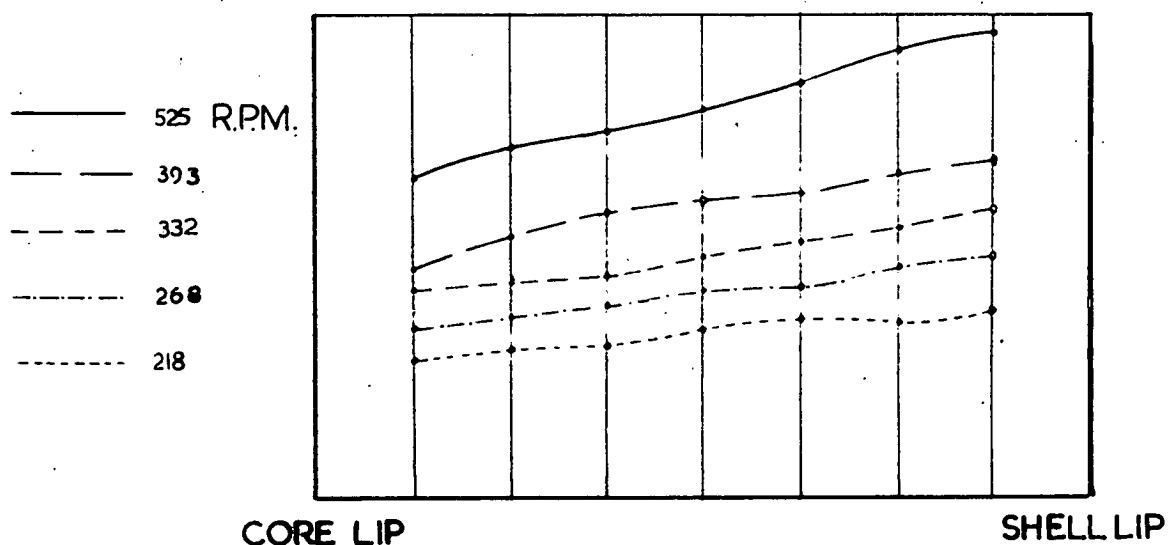
ENTRY VELOCITY PROFILES.

FIG. NO. 7.



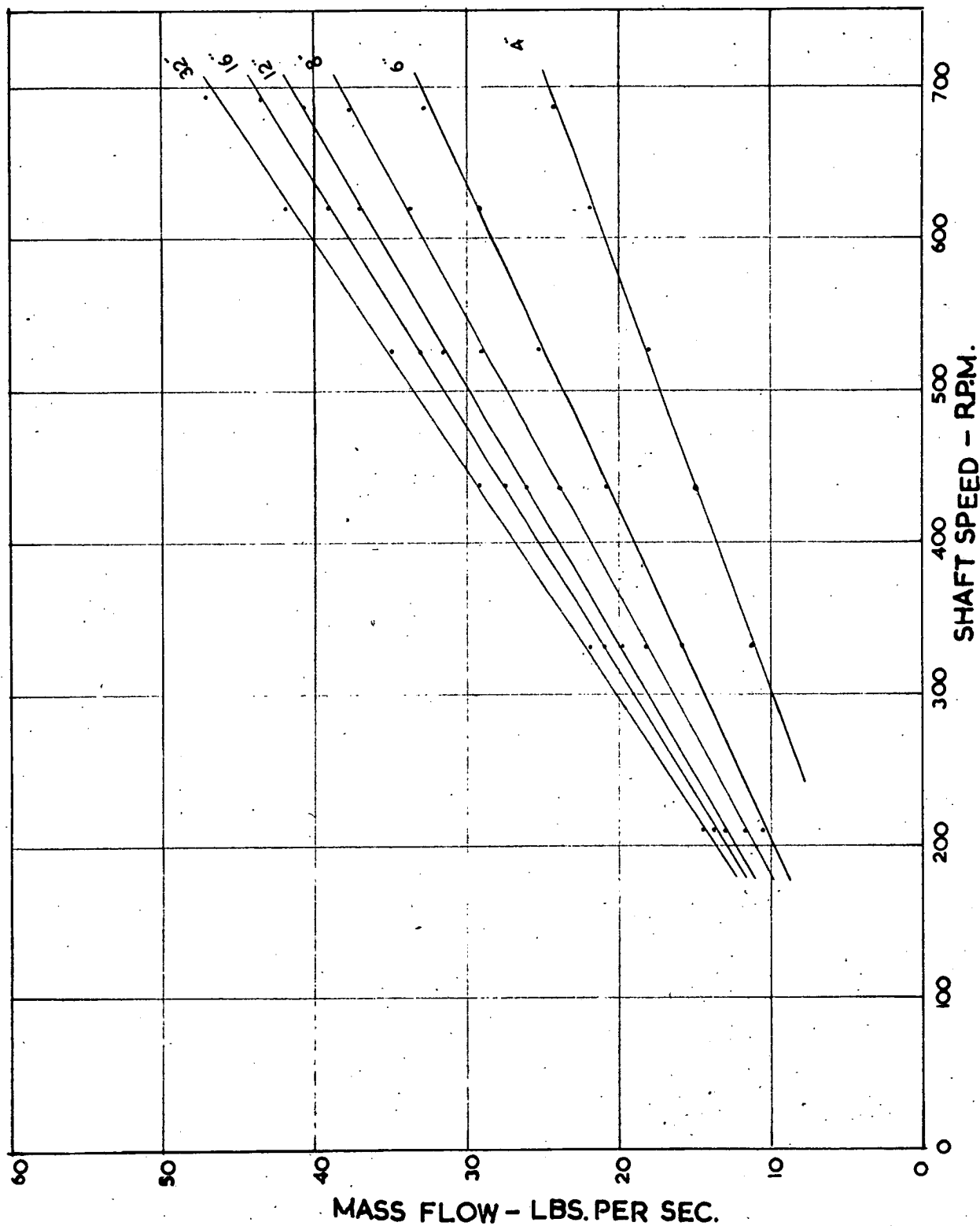
VELOCITY HEAD AT STATION A.
UPSTREAM OF INLET GUIDE VANES.
VARIOUS SHAFT SPEEDS.
GAUZE IN PLACE.

FIG. NO. 8.



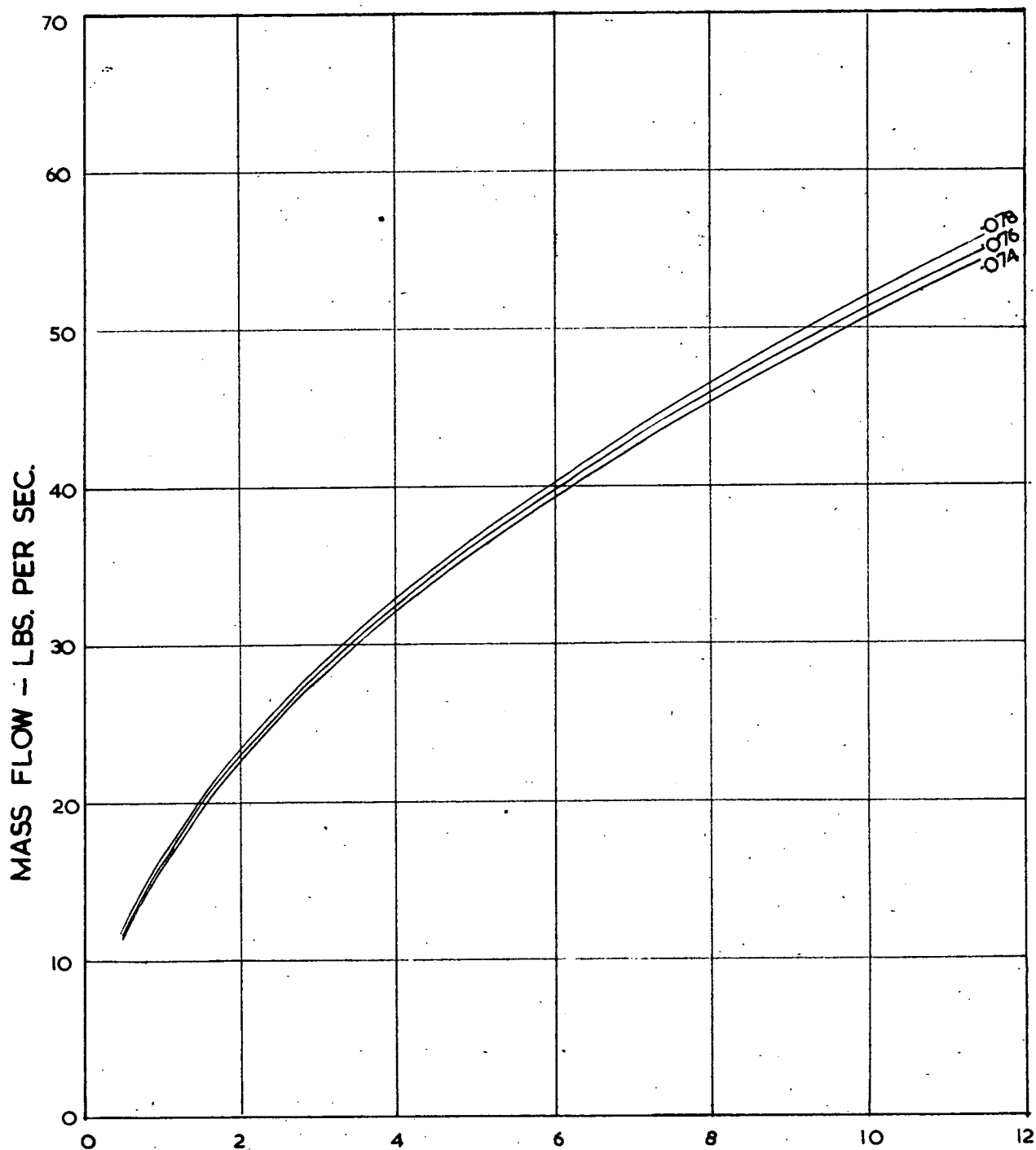
VELOCITY PROFILES AT ENTRY STATION A.
FOR VARIOUS SHAFT SPEEDS.
GAUZE IN PLACE.

FIG. NO. 9.



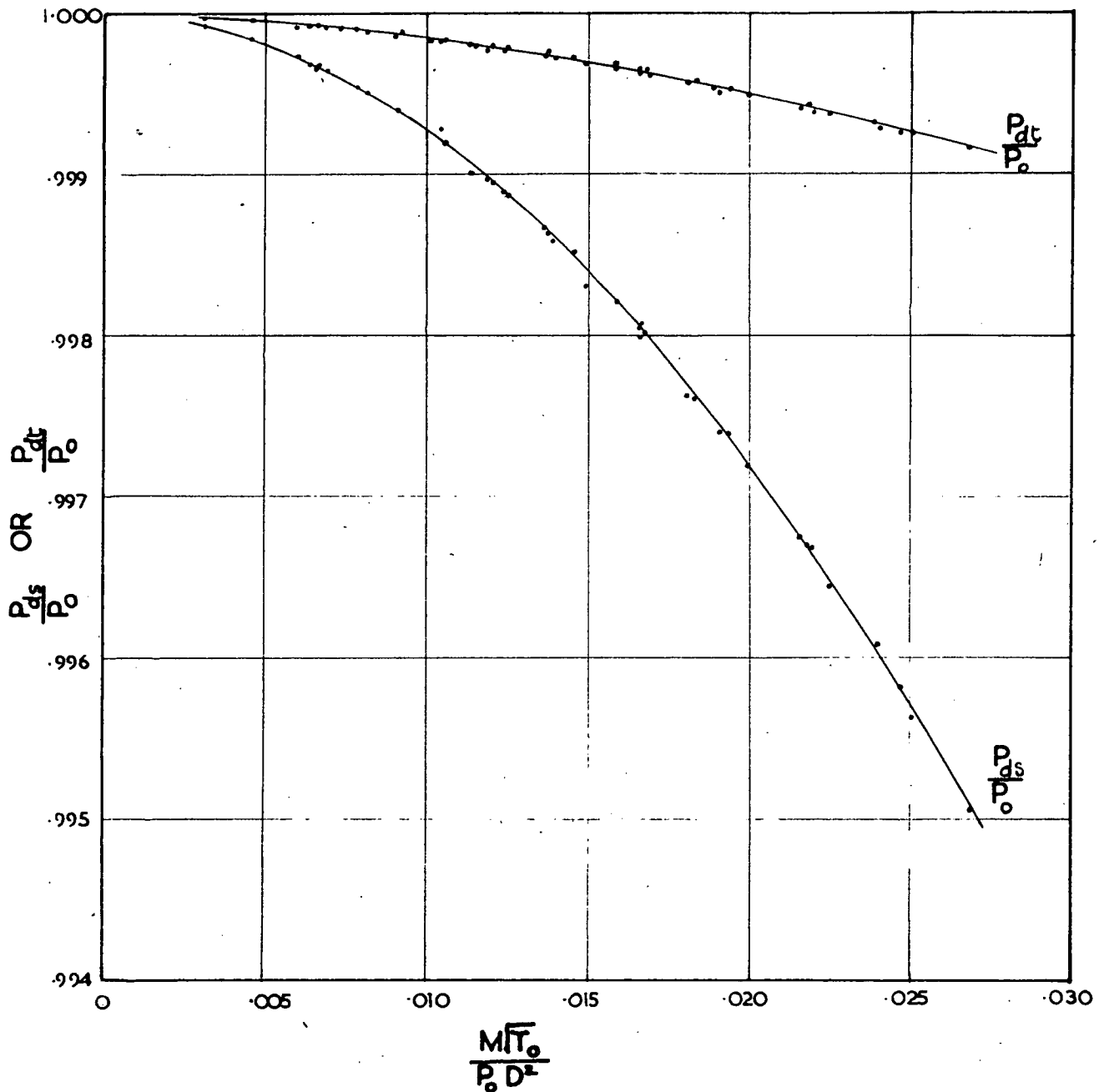
MASS FLOW VERSUS R.P.M. . VARIOUS THROTTLE OPENINGS

FIG. NO. 10.

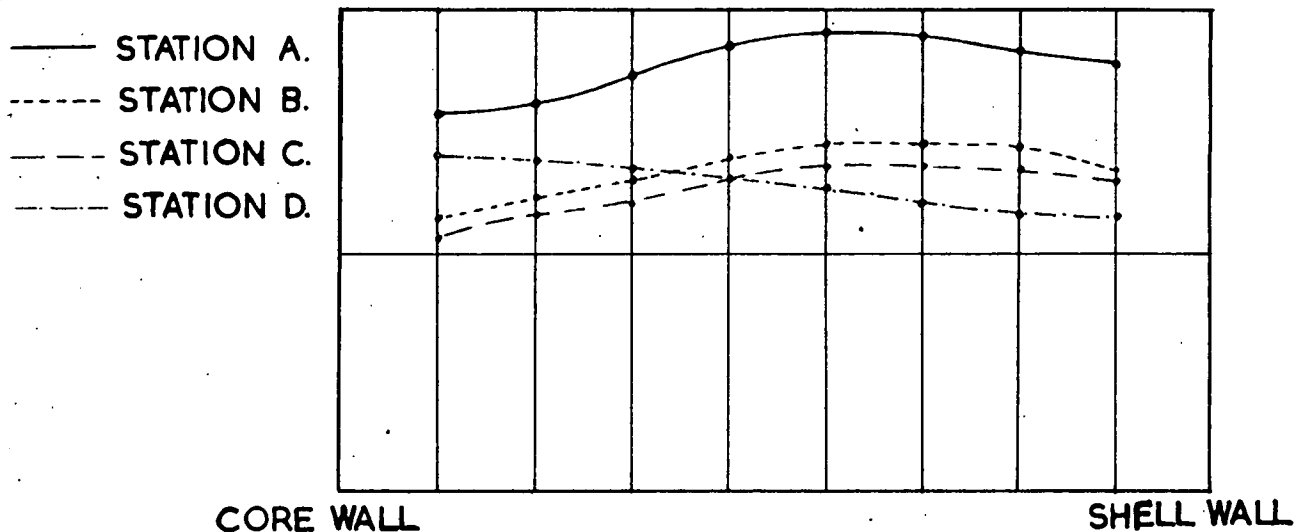


MASS FLOW VERSUS INTAKE PRESSURE DROP
FOR THREE AIR DENSITIES.

FIG. NO. 11.

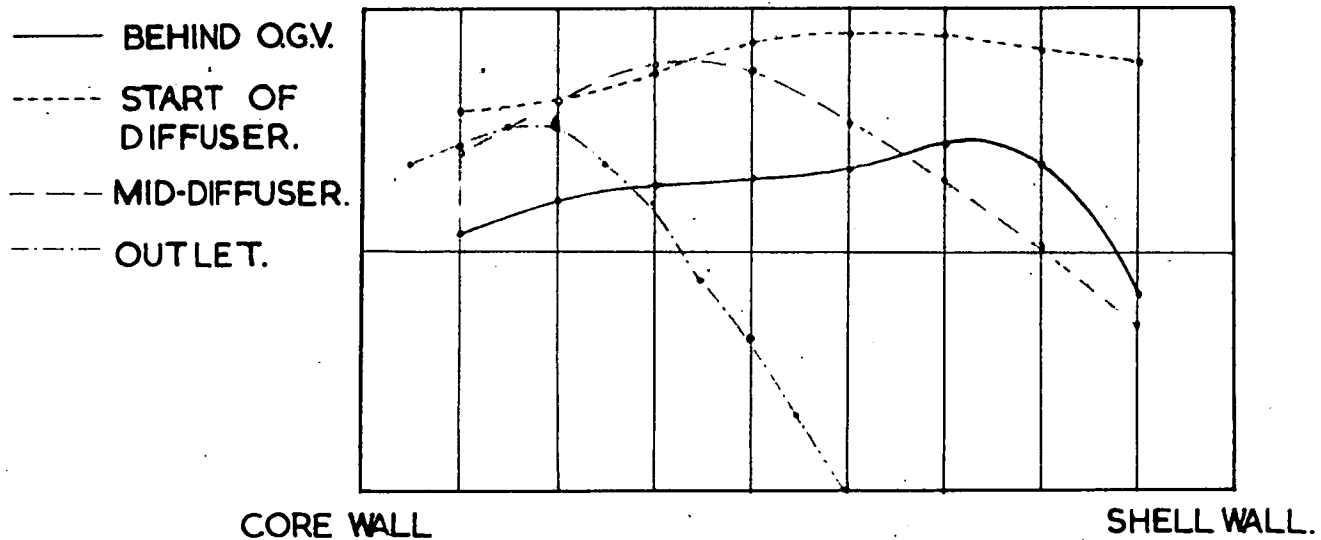


MASS FLOW VERSUS PRESSURE RATIO. (NON-DIMENSIONAL)



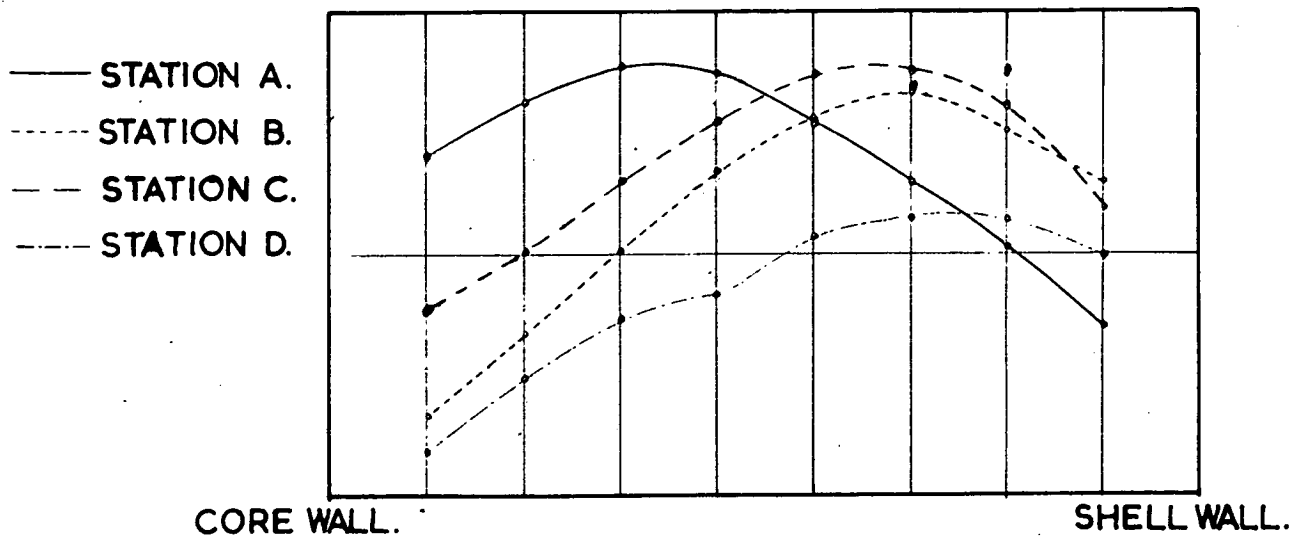
VELOCITY PROFILES AT START OF DIFFUSER.
GAUZE IN PLACE. SHAFT SPEED 393 R.P.M.
FULL OPEN THROTTLE. YAWMETER READINGS.

FIG. NO. 13.



VELOCITY PROFILES ALONG TUNNEL.
GAUZE IN PLACE. SHAFT SPEED 393 R.P.M.
POSITION A. FULL OPEN THROTTLE.

FIG. NO. 14.



VELOCITY PROFILES AT MID-DIFFUSER.

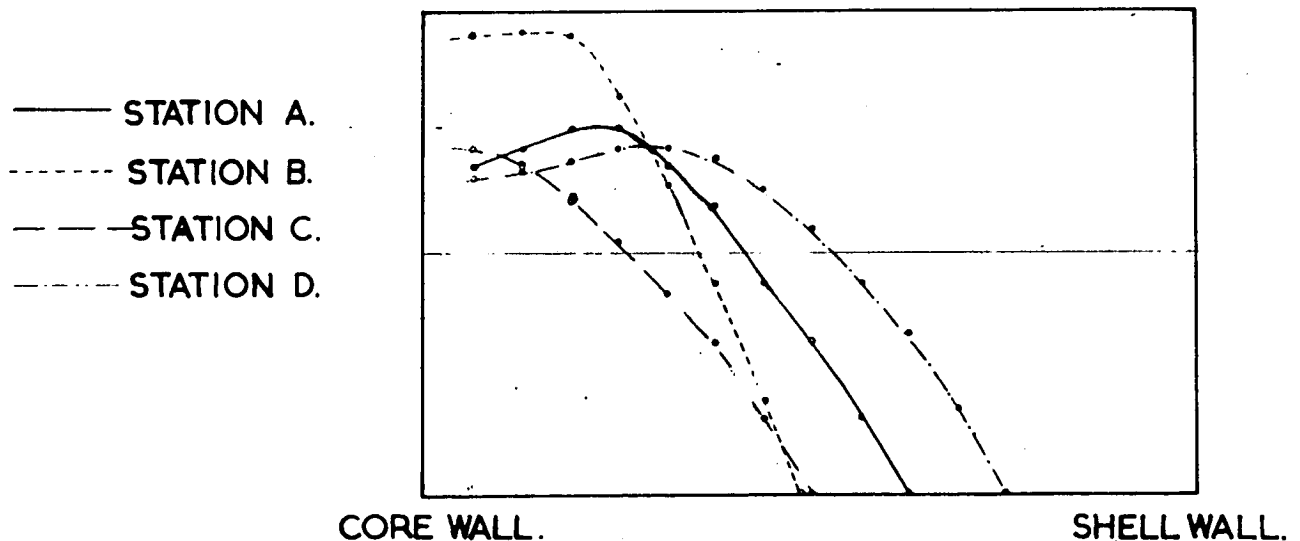
SHAFT SPEED 393 R.P.M.

FULL OPEN THROTTLE.

GAUZE IN PLACE.

YAWMETER READINGS.

FIG. NO. 15.



VELOCITY PROFILES AT DIFFUSER OUTLET.

SHAFT SPEED 393 R.P.M.

FULL OPEN THROTTLE. GAUZE IN PLACE.

ANEMOMETER READINGS.