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THE COLLEGE OF AERONAUTICS

CRANFIELD

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EQUIPMENT USED FOR BOUNDARY LAYER MEASUREMENTS IN FLIGHT

by

F. M. BURROWS

(Prepared under Ministry of Supply Contract 6/Aircraft/9807/CB6a)

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CRANFIELD

A Note on some Equipment used for Boundary Layer Measurements in Flight

Part I

The Design and Construction of a Large Multitube Manometer for Use in Flight

Part II

Two Fixed Head Type Combs for Boundary Layer Investigations

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Acknowledgements

The author wishes to express his gratitude to Mr. Martin and Mr. Farrer of the Department of Flight at the College of Aeronautics; Mr. Farrer for his many helpful suggestions and work in the construction of the manometer unit, and Mr. Martin for his patience and craftsmanship displayed during the construction of the boundary layer combs.

SUMMARY

Some notes are presented relating to the design and construction of a large multitube manometer and to two 'fixed head' type boundary layer combs to be used for the measurement in flight of the boundary layer characteristics of a swept back wing. Although the equipment described was designed with a particular object in view, there is no reason why the designs should not be modified as and where necessary for the construction of similar equipment.

PART I

The Design and Construction of a Large Multitube Manometer For Use in Flight

1.1. Introduction

In Part I of this note brief consideration is given to the design and construction of a large multitube manometer which has been installed in the rear fuselage of an Avro Lancaster (P.A.474). This aircraft is being used as a test vehicle for a series of investigations in flight of the behaviour of the three dimensional boundary layer on a swept back wing (mounted as a fin above the mid upper fuselage of the aircraft) at moderately high Reynolds numbers, and the manometer described was designed to cope with all the aerodynamic measurement requirements to be satisfied under test conditions, and to overcome the difficulties associated with making such observations in flight.

Although the instrument is large, there is no reason why its dimensions should not be scaled down to any size, modifications being made as and where necessary in the particular circumstances.

1.2. General Description of the Manometer

1.2.1. Choice of Dimensions, Manometric Fluids etc.

Consideration of the range of static and dynamic pressures to be met in practice together with the headroom and width available in the rear fuselage of the Lancaster led to the choice of a fifty tube manometer some 7 feet in height, and 30in. wide. It was at first thought that, due to the height restriction of 7 feet, a dense manometric fluid would be necessary and so initially provision was made for using carbon tetrachloride (S.G. = 1.599) in the instrument.

The use of carbon tetrachloride as a manometric fluid does present one or two difficulties. For example, the use of rubber tubing for fluid pipe lines is out of the question since it rapidly tends to perish under the action of the carbon tetrachloride. Plastic (P.V.C.) tubing may however be used with success but it requires that connections be wired and sealed off by means of shellac varnish to completely eliminate leaks. A further difficulty encountered in flight is that of the tendency for the manometric fluid (i.e. carbon tetrachloride) to 'boil' at altitude, due to the reduced atmospheric pressure and temperature and its relation to the liquid vapour pressure.

For such a large manometer, the reservoir size is naturally large (the actual capacity being approximately 4 gallons) and since the installation was within the relatively confined interior of an aircraft fuselage, it was necessary to guard against the toxic effects of carbon tetrachloride upon the operating crew of the aircraft in the advent of tube failure and consequent spillage, by providing an adequate draining system with its outlet to atmosphere. Although, for the initial measurements made using the instrument under discussion the manometric fluid was carbon tetrachloride, it was later found possible to replace this fluid by distilled water using fluorescene as a dye.

Since observations of the manometer are recorded photographically using an F.24 camera, it was necessary to overcome the problem of illumination. This was achieved by a system of back lighting to be described.

1.2.2. The General Arrangement of the Manometer

The general arrangement of the complete manometer unit is shown in figs. 2 and 3. The manometer tube bank is positioned at the front end of a lamphouse, the framework of which is extended to form a rigid structure incorporating the F.24 observer camera. The reservoir is mounted on runners which are attached to the side of the lamphouse, and it may be positioned at any desired height, fixture at the required position being facilitated by a simple clamping arrangement.

The whole assembly forms a very rigid structure and being attached to the aircraft floor via resilient mounts, is free to vibrate as a whole. It has however been observed that under test conditions, little or no perceptible vibration of the instrument occurs, except during the 'ground run up' of the aircraft engines.

1.3. Constructional Details

1.3.1. The Manometer and Lamphouse

An exploded view of the manometer and lamphouse is shown in fig. 4. Basically the unit consists of a box framework constructed of 2in x 2in x 1/8in steel angle with an additional member of 'T' section let into the front face to provide adequate support for the perspex face and tube bank assembly. All joints are welded with the exception of those at the front of the box frame which are bolted. This was to facilitate the removal of the actual manometer observation face and tube assembly, should this prove necessary, within the confined interior of the aircraft fuselage.

The sides of the box frame were covered with 22 S.W.G. light alloy sheet attached by means of No. 6 P.K. screws. The back cover for the frame was constructed of 3/8in. plywood and serves as the mount for the lighting unit which consists of 24, 6V, 24W bayonet cap frosted light bulbs. The lighting unit was wired in series parallel and supplied from one of the 24V power circuits available on the aircraft.

To eliminate concentrations of light corresponding to the bulb filaments appearing on the manometer observation face, small diffusers of 2in diameter were fitted over each bulb. These are not shown in fig. 4, but were very similar to the light traps shown on the top and bottom cover plates. The top and bottom cover plates as attached to the box frame were also of 22 S.W.G. light allow sheet but were provided with heat vents as indicated in fig. 4. To eliminate the possibility of stray reflections from the aircraft fuselage due to light streaming from the heat vents and its consequent effect upon the observer camera, baffle plates were fitted as indicated in fig. 4, thus constituting a light trap. To obtain a maximum degree of diffusion of the available light, the interior of the box assembly was sprayed matt white.

Three tube supports were constructed of 5/8in x 1/4in brass strip and positioned at the top, middle and bottom of the front face of the manometer frame as indicated in fig. 4. These were drilled along their length with 1 c.m. diameter holes to correspond to the manometer tube spacing and then 'split' to form clamping units. Due to variations in the diameter of the tubing used for the manometer it was found that to obtain satisfactory clamping, it was necessary to wire each glass tube to the rear half of the support straps as indicated in fig. 6, the front of each strap being used to 'back up' the assembly.

The front of the box frame was closed in with two 3/16in. thick perspex sheets, the 'inner' faces of which were 'scrubbed' by means of emery cloth to yield a matt finish. They were positioned between the three tube support straps on the manometer frame and attached by means of 2 B.A. countersunk head screws. On the outer faces of these two backing sheets a graticule was engraved, this being simply a system of parallel horizontal lines spaced at $\frac{1}{2}$in. intervals over the entire surfaces of the backing sheets, and coloured alternately black and red for ease of identification. The arrangement of the tube support straps and the two backing sheets was such that when the glass tubes were wired in place they were in contact with the backing sheets throughout their length, and the graticule was thus positioned as close as possible behind the tubes.

Two front cover sheets of 1/8in. thick perspex were fitted over, and in contact with, the glass tube assembly. They were mounted on oak spacing blocks attached to the manometer frame as indicated in fig. 6, and positioned between the tube support straps in the same way as the two perspex backing sheets. Additional clamping of the glass tube bank was then achieved by means of a number of 6 B.A. brass screws passing through from the perspex front covers to the rear of the backing sheets, the screws being tightened so as to lightly sandwich the glass tubes. This arrangement has, so far, proved to be satisfactory.

1.3.2. The Lower Manifold

Interconnection of the manometer tubes and the reservoir was achieved by means of the lower manifold as shown in fig. 5. This was constructed of 2in. O.D. x 20 S.W.G. brass tubing and was fitted with 48 stub tubes suitably staggered to facilitate the fitting of connections to the manometer tubes. The remaining two manometer tubes were separately connected, forming a simple 'U' tube unit to be connected to the aircraft airspeed pitot static system for direct indication of the free stream dynamic head.

Since the manometer tubes were very closely spaced it was necessary to use thin walled P.V.C. tubing (approximately 9m.m. O.D.) for all flexible connections to the glass tubes, and the connections from the lower manifold to the bottom ends of the manometer tubes were accordingly made using this material together with 'elbows' of copper tube fitted as and where necessary to eliminate 'kinking'. The scheme is illustrated in fig. 5.

The lower manifold was fitted with a drain plug and inlet tube together with a screwed plug which could if necessary be used to 'bleed off' any entrapped air, and the whole assembly attached to the manometer box frame as indicated in fig. 5.

1.3.3. The Manometer Reservoir

The manometer reservoir is constructed of 22 S.W.G. Brass Sheet and measures 15in. x 12in. x 6in. Two bearing tubes are let into the tank, and the tank can be moved up and down two 3/4in. diameter Bright Mild Steel guide runners which are attached to the manometer box frame as shown in fig.4.

Fixture of the tank at any desired position on the guide runners is achieved by two simple 'split collar' screw clamps. Connection to the lower manifold is made by means of 1in. diameter P.V.C. tubing, and to prevent this tube 'kinking' it is fitted internally with a close coiled spring of 7/8in. diameter, wound from 18 S.W.G. piano wire. 'Jubilee' clips were used in the attachment of this feeder tube to both the reservoir and the lower manifold.

1.3.4. The Observation Camera Frame

The observation camera frame was constructed of 1in. x 1in. x 1/8in. steel angle throughout. It was built as an extension to the manometer box framework and was designed to be as rigid as possible, this being to ensure that the manometer unit would vibrate as a whole under flight conditions and so not impair the use of the camera as an observer. The arrangement is shown in fig. 2.

1.3.5. Top Tube Connections and Tube Freeze Clamp

Due to the close spacing of the glass tubes in the manometer, it was necessary to make the top tube connections via a junction bar as indicated in fig. 7. The thoroughfare tubes in the junction bar were staggered, to facilitate the connection of the rubber tubes from the required pressure tappings.

The tube freeze clamp is shown in fig. 8. The clamp base was constructed of $1\frac{1}{2}$in. x $1\frac{1}{2}$in. x 3/16in. 'T' section mild steel, attached to the observation camera frame, all joints being welded. A 1in. diameter bright mild steel rod was used for the clamping eccentric, spigots being turned on either end of the rod at centres displaced 1/4in. from the centre line of the rod. Two trunnion bearings for the spigots were attached to the sides of the top members of the ~~camera observation~~ frame and were arranged so that the rod spigot centres were disposed along the centre line of the web of the 'T' section base, and 3/4in. above the flange face. To the end of one spigot a clamping handle was attached (fig. 8).

The rubber tubes from the required pressure tappings were passed through the freeze clamp unit (fig. 8) and by rotation of the clamping handle, all pressures to the manometer could be isolated. There is however a tendency for the clamping eccentric and base to distort under load and it is evident that more effective isolation of the pressures at the manometer could be achieved if the clamping eccentric were to be fitted with a centre bearing in addition to the two trunnions.

1.3.6. The Observer Camera

The observer camera was basically a standard F.24 camera. It was fitted to the manometer frame at the position indicated in fig. 2 by means of a swivelling mount, thus permitting the camera to be 'lined up' on the manometer. Since the manometer face is very much greater in height than in breadth, a considerable film wastage would result from using the full F.24 frame for each observation. To overcome this a standard F.24 magazine was modified so that the film could be wound independently of the camera shutter mechanism. The rear face of the camera was suitably masked so that film records could be obtained of approximately one third of the width of the standard F.24 frame which was adequate for the purpose required. Considerable saving in the use of observer camera film was thus achieved.

1.3.7. The Installation of the Instrument in the Aircraft

Five heavy rubber resilient mounts were fitted to the manometer frame, four at the base of the box frame and one directly under the camera (see fig. 2). The complete installation of the instrument in the aircraft was effected by attaching these mounts to the floor of the rear fuselage, the general arrangement being shown in fig. 1.

The unit as a whole including the manometric fluid weighs approximately 350 lbs. and its design, construction and installation was completed in 8 weeks.

1.4. General Discussion

1.4.1. Behaviour of the Instrument in Flight

Up to the present, the behaviour of the complete manometer unit in flight has been most satisfactory. Although the manometer and observer camera unit are attached to the aircraft via resilient mounts, there is little or no vibration of this assembly in flight and it has been found that, due to the skilful and accurate handling of the aircraft by the pilot, experimental conditions can be set such that the fluctuation of the fluid columns does not exceed 1/32in. This latter has been deduced from careful observation of the behaviour of the fluid columns in the manometer during each of the test runs completed so far.

It has been found that the only noteworthy limitation upon the accuracy of the results obtained is that encountered in the reading of the film records, for whilst true and accurate readings of the required pressures may be displayed upon the manometer, it has so far proved impractical to attempt to read the film records to an accuracy involving less than 0.05in. of manometric fluid. Since the attainable experimental conditions permit greater accuracy in film reading, the film reading technique has accordingly received some consideration, although as yet no definite steps have been taken for its improvement.

1.4.2. Pressure Connections to the Manometer

The 'U' tube unit built into the instrument (para. 1.3.2) is connected to the aircraft pitot static system and thus provides a direct indication of the free stream dynamic head, i.e. when corrected for the aircraft static pressure error.

Two further tubes, one at each side of the manometer face are connected to the aircraft static system and so under test conditions provide a datum to which all measurements may be referred. By this means allowance is made for the effect of small angles of bank occurring during tests and the corresponding settling of the fluid to its gravitational level.

The other available tubes on the manometer are connected in the usual way to the required pressure sources.

1.4.3. Specimen Results

Two specimen observation photographs of the manometer face are shown in figs. 9 and 10. The clarity with which the fluid columns are displayed may be seen and the uniformity and effectiveness of the lighting arrangement is noteworthy. The difficulties encountered, however, in attempting to read the observation film to an accuracy greater than 0.05in. of manometric fluid may be appreciated.

PART II

Two Fixed Head Type Combs for Boundary Layer Investigations

2.1. Introduction

Consideration is now given to the construction of two combs for boundary layer exploration using the 'fixed head' technique. They were designed to meet the needs of the tests, to be performed in flight, on the boundary layer characteristics of a swept back wing (see para. 1.1) in which the primary aim was to study the behaviour of transition with variation in Reynolds number and incidence.

The two types of comb to be used for this work were designed to measure the boundary layer velocity profile and the total head distribution at, near to, and along the wing surface respectively for a fairly wide range of experimental conditions in which the flow could assume any characteristics between those of a thin laminar to a thick turbulent boundary layer, or more remotely, a layer in separated flow.

Although it is possible to make a survey in flight of the boundary layer using a traversing gear, such a survey may be much more easily and rapidly completed using fixed heads of the type to be described provided that the flow is reasonably well ordered. In regions where the flow experiences considerable transverse shear, however, more elaborate techniques are required for measurement.

In this note, separate consideration will be given to each of the two types of comb together with the results of some preliminary test work performed to assess their usefulness.

2.2. The Transition Indicator

2.2.1. General Description

We shall consider first the comb to be used for measuring the total head distribution at, near to, and along the wing surface. This comb will be referred to as the 'transition indicator' since from such measured distributions of total head the position of the transition front may be readily determined (see fig. 11).

The indicator is made up of two pitot tubes and one static tube (to provide a datum pressure to which the pressures recorded by both pitot tubes could be referred) arranged as shown in fig. 12, all three tubes being constructed of 1m.m. O.D.

hypodermic steel tubing. The ends of the pitot tubes are 'flattened' to yield orifice dimensions of approximately 0.50in. x 0.010in.- 0.012in., whilst the static tube is of the usual bullet nosed type having six static vents disposed approximately in line with the ends of the pitot tubes.

The three tubes pass through a hypodermic steel tube of 3m.m. O.D. to which thin brass fixing straps are fitted to facilitate attachment to the wing surface. Adaptors for the pressure leads are fitted to the ends of the pitot and static tubes, all joints being made with soft solder. The arrangement is such that when the fixing straps are firmly in contact with the wing surface, the position of the pitot and static tubes are respectively, resting on, 1/4in. above, and ½in. above the wing surface.

Attachment to the wing surface is accomplished by means of cellotape which provides completely adequate rigidity in fixing although being somewhat utilitarian in nature. This arrangement has so far proved to be perfectly satisfactory under test conditions, and the transition indicator may be attached at any desired position on the wing surface, to the exclusion of those regions where the wing surface curvature is large (e.g. close to the leading edge), without destroying the surface finish.

For the particular tests under consideration (para. 1.1) six such transition indicators were constructed.

2.3. The Boundary Layer Comb

2.3.1. General Description

For measurement of the boundary layer velocity profiles a comb was designed as shown in fig. 13. Five such combs were constructed and each consists of eleven pitot and two static tubes (to provide datum pressures) disposed as shown in fig. 13, only those pitot tubes in the immediate vicinity of the wing surface having flattened ends. The pitot and static tubes were constructed of 1m.m. O.D. hypodermic steel tubing and mounted in two faired brass pedestals. The pedestals were provided with feet for attachment to the wing surface.

A thin brass strap of streamlined section was attached to the comb at approximately 1.1/4in. downstream of the leading edge (tube orifice line) and serves both as a brace and datum fixing for the tube assembly. The arrangement is such that when the base of this strap is held in contact with the wing surface, the tube centres are above the wing surface at the respective heights shown. Contact between the strap base and the wing surface is effected by means of a small moveable brass stirrup which may be positioned as shown in fig. 13.

Adaptors for the pressure leads were fitted to the downstream ends of the pitot and static tubes, and as with the transition indicators all joints were made using soft solder.

The comb is attached to the wing surface at the desired position with cellotape which provides all the rigidity required under test conditions.

2.4. Wind Tunnel Tests

2.4.1. Experimental Equipment

To assess the usefulness of both the transition indicator and the boundary layer comb, some simple experiments were made using the boundary layer flow on a flat plate. These experiments were performed in the College of Aeronautics Göttingen Wind Tunnel. This tunnel is of the return flow, open working section type, the jet being of elliptic cross section with dimensions of the major (horizontal) and minor (vertical) axes of 40in. and 27in. respectively. All pressure measurements were made using a multitube manometer inclined at 30° to the horizontal.

A flat plate of 20in. chord constructed from light alloy was supported between end plates in the tunnel as shown in fig. 14. This plate was some 0.375in. in thickness and was everywhere aerodynamically smooth. Its leading and trailing edges were elliptic in cross section, and there was provision for inclining the plate at small incidences to the mainstream.

For the purpose of comparing the boundary layer velocity profiles as measured by the combs with those resulting from a standard pitot traverse, a pitot tube of 0.030in. O.D. was mounted on a traversing head fitted with micrometer adjustment in the vertical plane. This was arranged as shown in fig. 14.

2.4.2. Details of Tests

With the flat plate set at zero incidence to the mainstream and with free transition, the velocity distribution in the boundary layer at 11.5in. from the leading edge of the plate was determined using the traversing head, for tunnel speeds of 80ft/sec. and 130ft/sec. respectively. For comparison, similar distributions were also measured using a boundary layer comb positioned alongside the traversing pitot as shown in fig. 15.

To determine the position at which transition from laminar to turbulent flow was occurring, a transition indicator was positioned in turn at a number of stations spaced 2in. apart along the plate and the distribution of total head near to and along the plate surface determined for a tunnel speed of 130ft/sec.

For the purpose of assessing the behaviour of the boundary layer comb in a thick fully turbulent boundary layer, a 1/8in. diameter transition wire was fitted 1.5in. from the leading edge of the plate. The velocity profiles at 11.5in. from the leading edge were measured accordingly, both with the comb lined up with the free stream, and also yawed through $\pm 30^\circ$ (in intervals of 10°), this latter being intended to simulate the effect of transverse flow.

2.5. Specimen Results

2.5.1. Boundary Layer Transition

From the pressures recorded by the two pitot tubes on the transition indicator, measured relative to the datum static, the distribution of total head along and 1/4in. above the plate surface was determined. The results obtained are shown in fig. 16, and are plotted as the variation of (u_1/u_o) with distance along the plate surface (where u_1 is the velocity in the boundary layer, and u_o is the free stream velocity).

It can be seen that throughout the traverse the raised pitot (i.e. at 1/4in. from the plate surface) was at no time immersed in the boundary layer and thus recorded no total head loss. The surface pitot readings do however show quite clearly the marked reduction in total head which occurs as the tube passes from the turbulent into the laminar boundary layer and it can be seen that in this particular case transition to fully turbulent flow occurs over a region which is approximately 4in. in length.

2.5.2. Boundary Layer Velocity Profiles

The various boundary layer velocity profiles measured are shown in figs. 17-21. The agreement between the profiles as measured by a standard traverse and those measured with the boundary layer combs is good for each of the tunnel speeds considered, with the exception of those cases in which the comb was yawed relative to the free stream direction. Under these latter conditions it can be seen that the profile is seriously affected, even when the angle of yaw of the comb is as small as 10°.

The test showed that, even with such small pitot tubes, there was no serious lag in the manometer readings for changing flow characteristics. This is a prime requirement for measurements to be made in flight since a time limit is imposed by the ability of the pilot to hold steady any given set of experimental conditions.

2.6. Concluding Remarks

Up to the present only a few tests have been performed in flight using both the boundary layer combs and transition indicators positioned on the surface of a swept back wing. The behaviour of the combs and transition indicators has however been extremely good under all conditions of flight encountered so far, as a result of which a comprehensive boundary layer survey is being made on the above wing for a range of Reynolds numbers and incidences, the incidences being restricted to a range (0° - 10°) in which the changes of flow direction at the wing surface are known from tuft observations, to be very small.

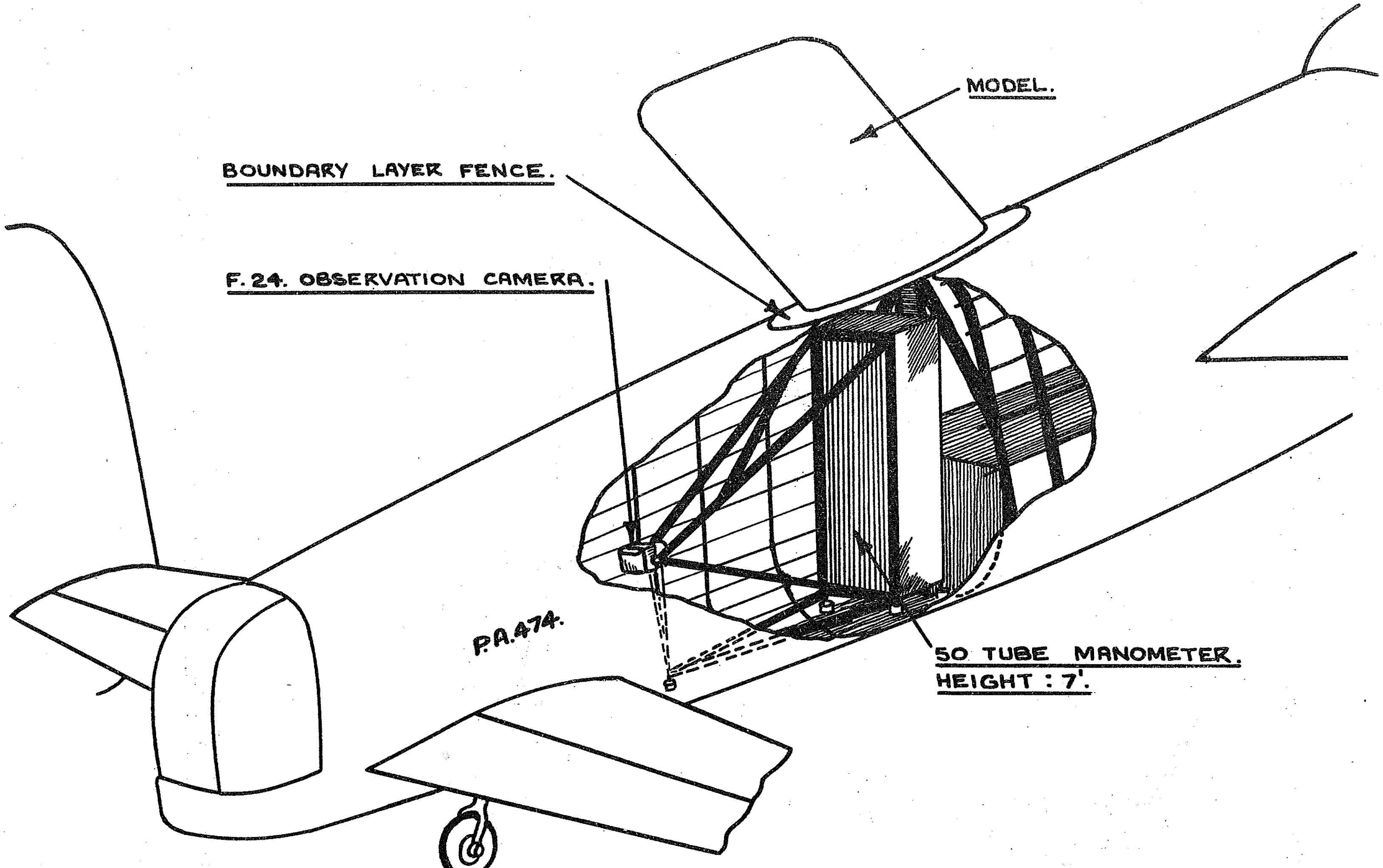

FIG. 1. LAYOUT OF EQUIPMENT IN LANCASTER.

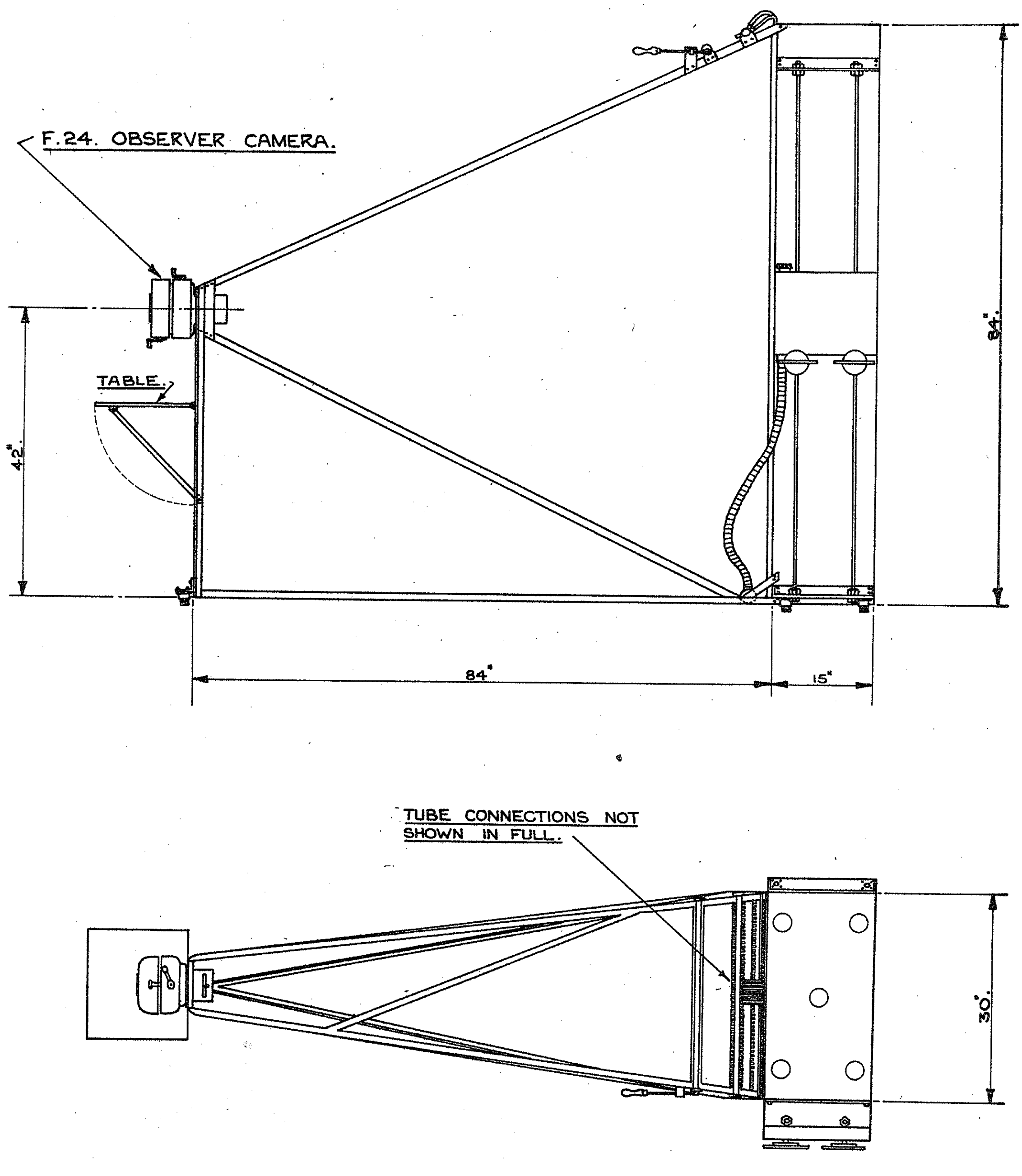

FIG. 2 . GENERAL DIMENSIONS OF MANOMETER.

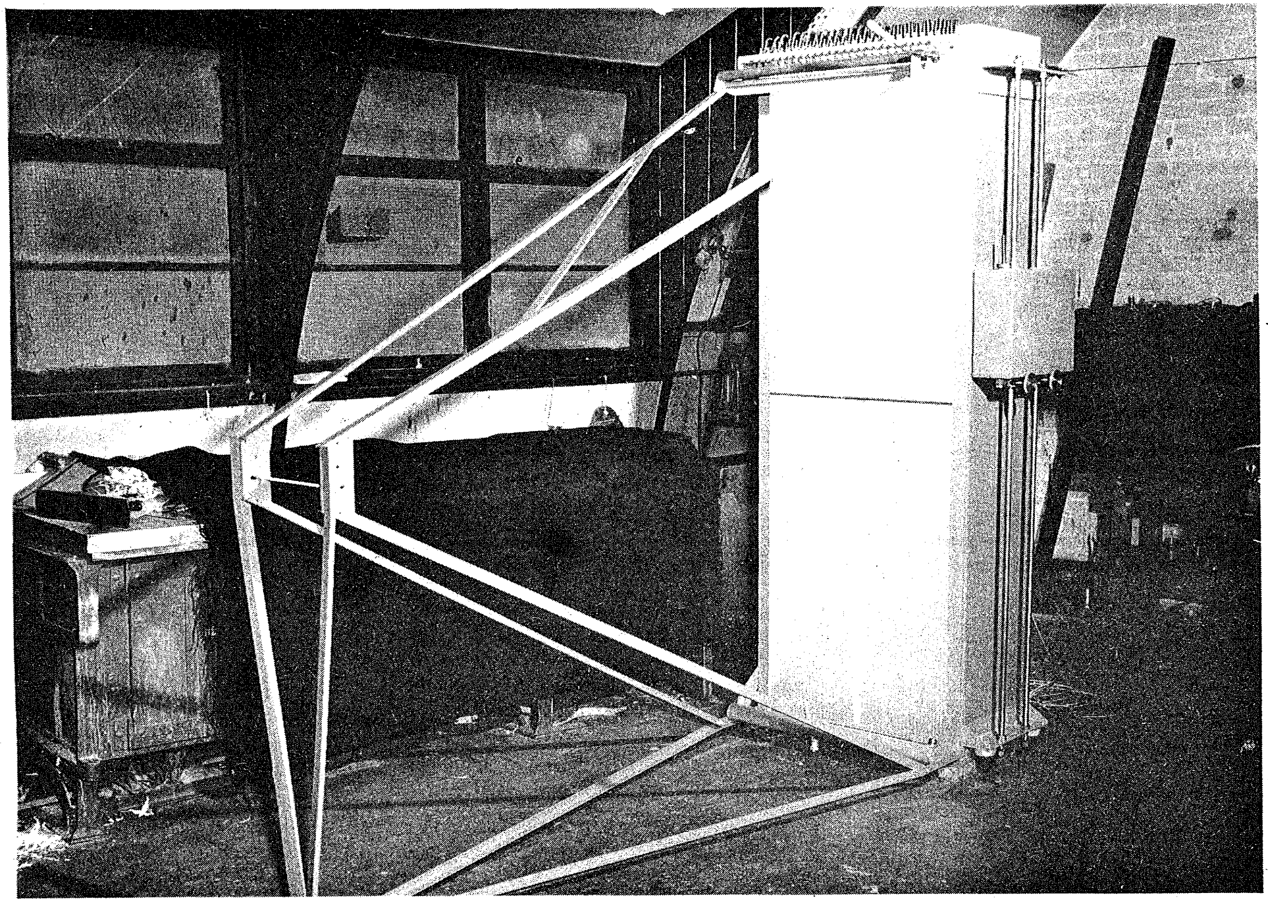

FIGURE 3. THE MANOMETER UNIT NEARING COMPLETION

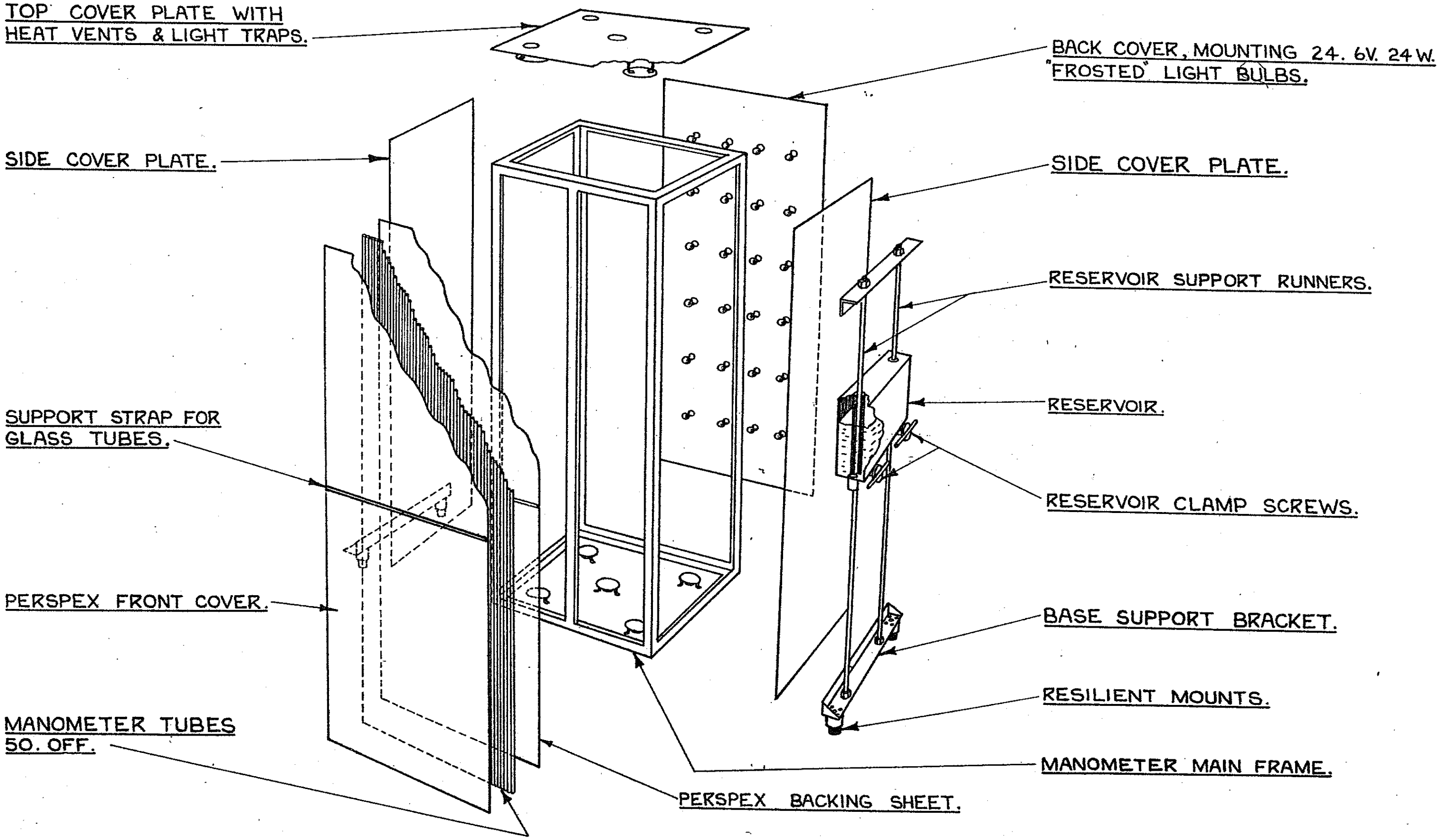

FIG.4 . ARRANGEMENT OF MANOMETER & LAMPHOUSE.

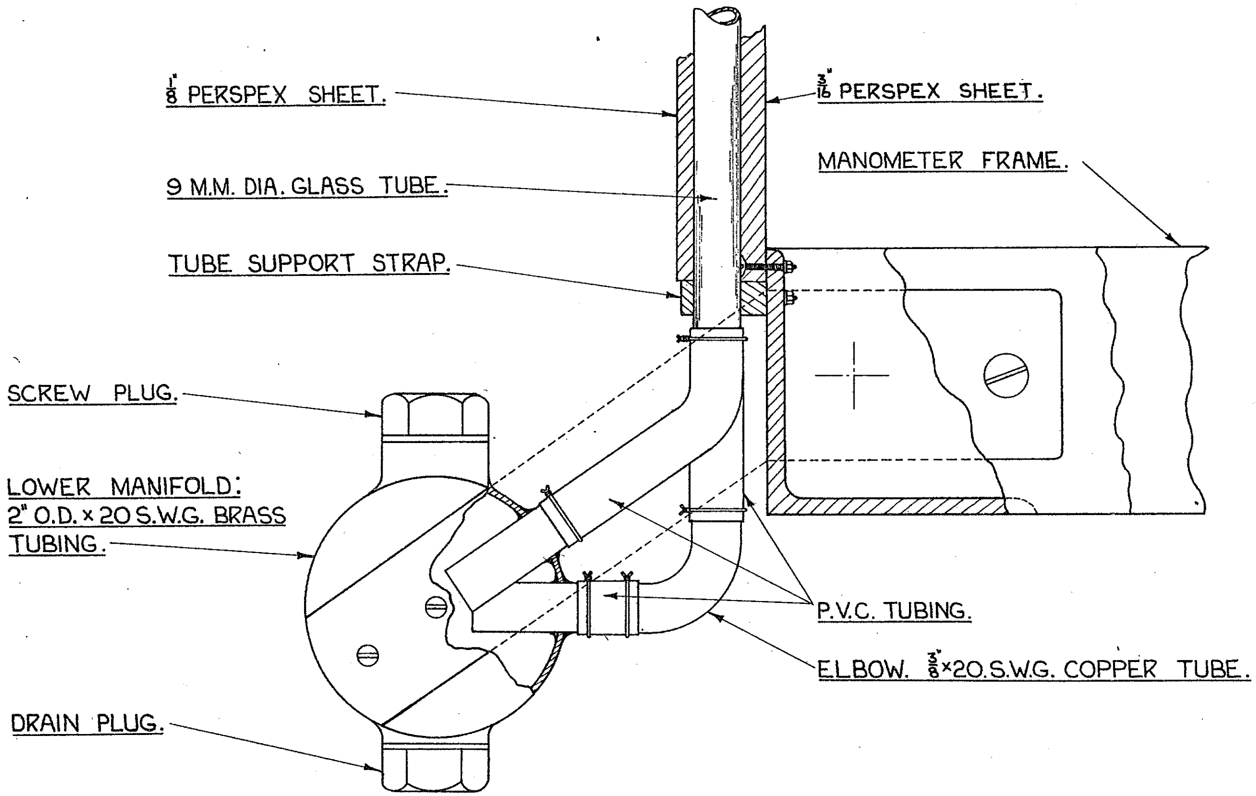

FIG.5. DETAILS OF LOWER MANIFOLD.

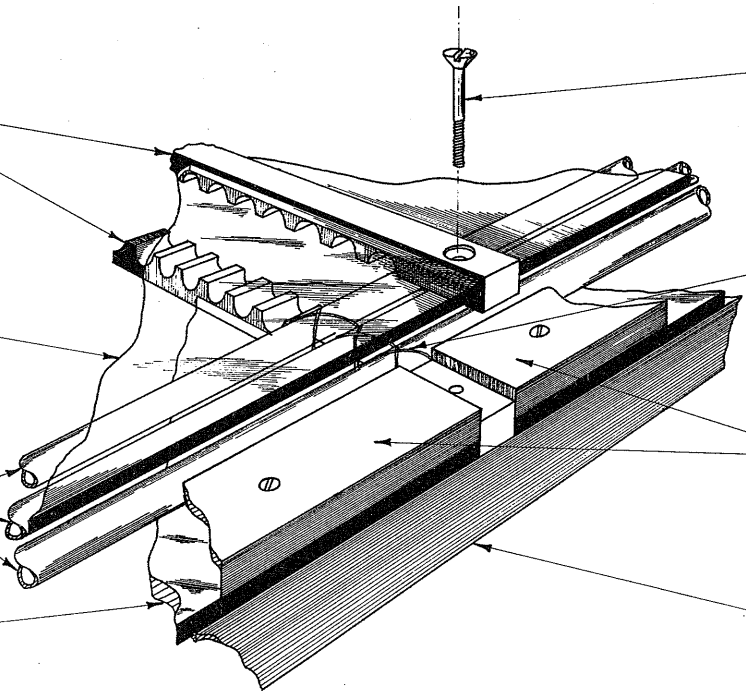

FIG. 6. TUBE & PERSPEX COVER SHEET FIXINGS.

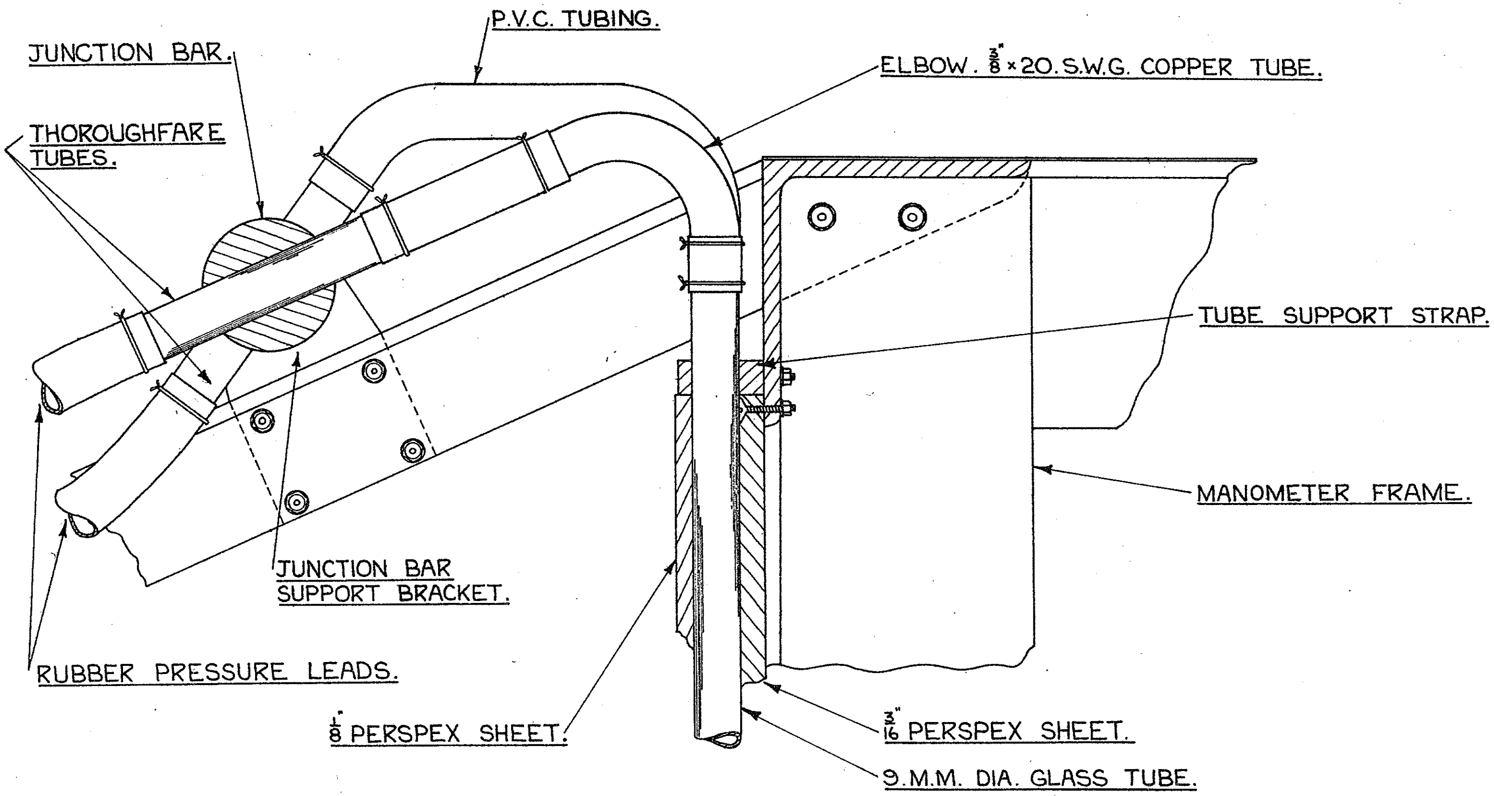

FIG. 7. TOP TUBE CONNECTIONS.

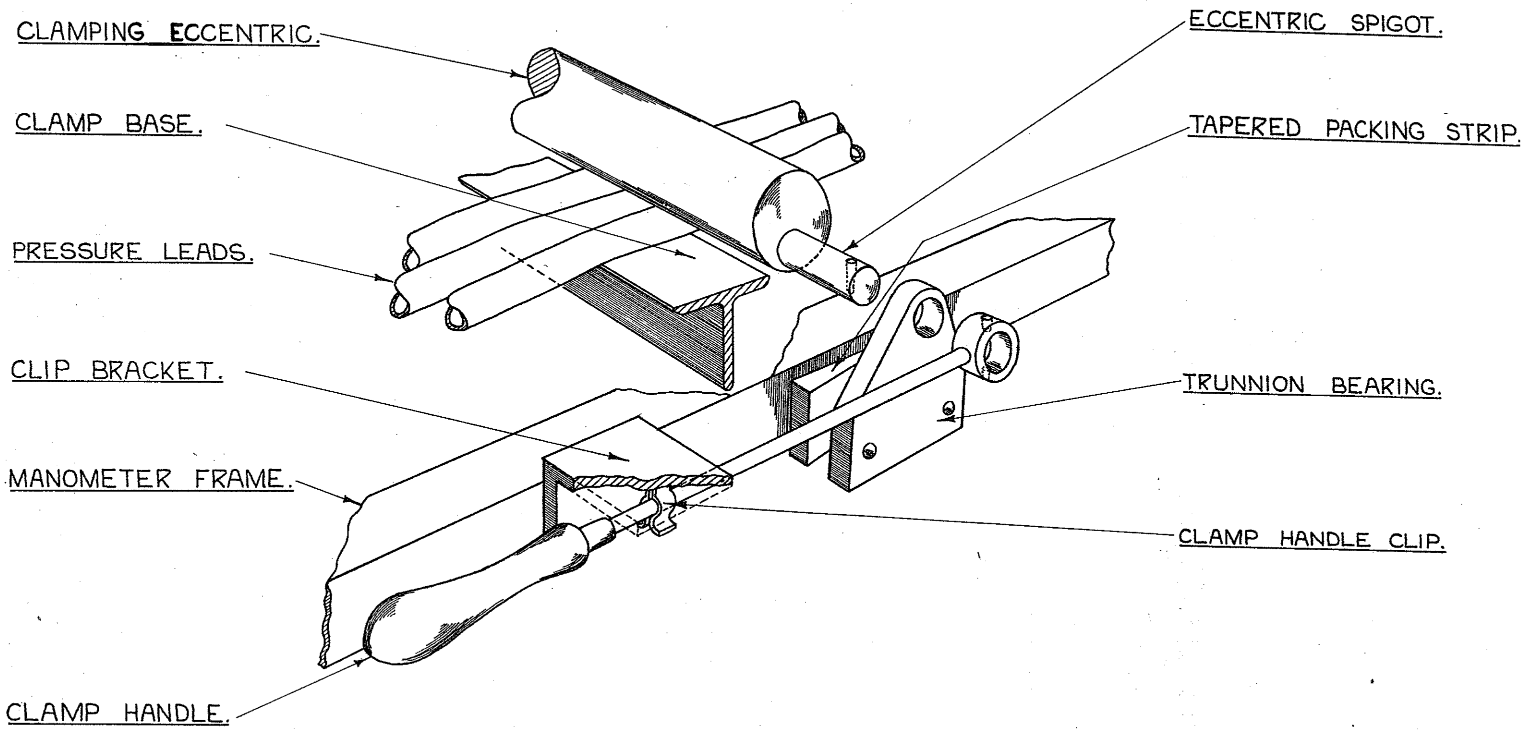

FIG. 8 . TUBE "FREEZE" CLAMP.

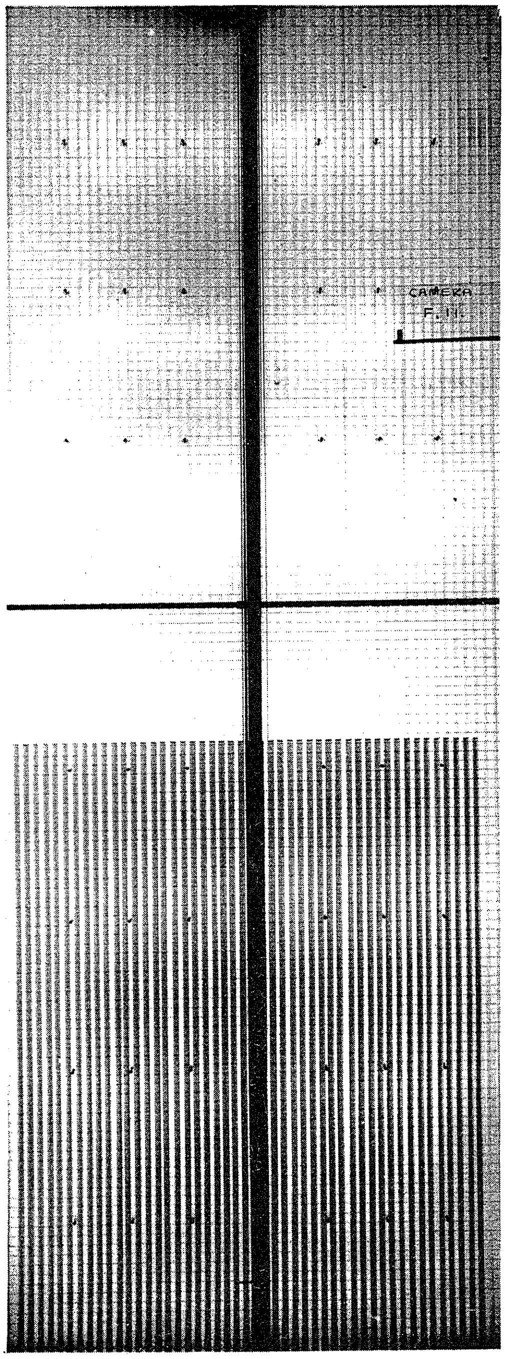

FIGURE 9. THE MANOMETER FACE. (NOTE: THE UNFILLED 'U' TUBE UNIT MAY BE SEEN AT THE EXTREME RIGHT HAND SIDE).

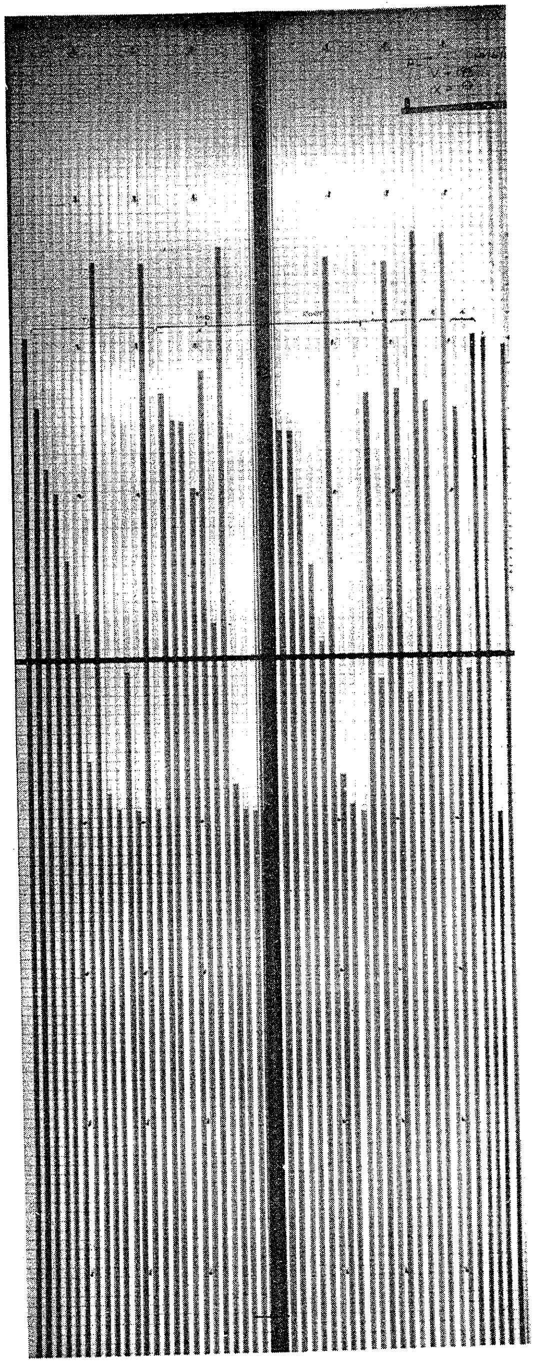

FIGURE 10. THE MANOMETER FACE UNDER TEST CONDITIONS.

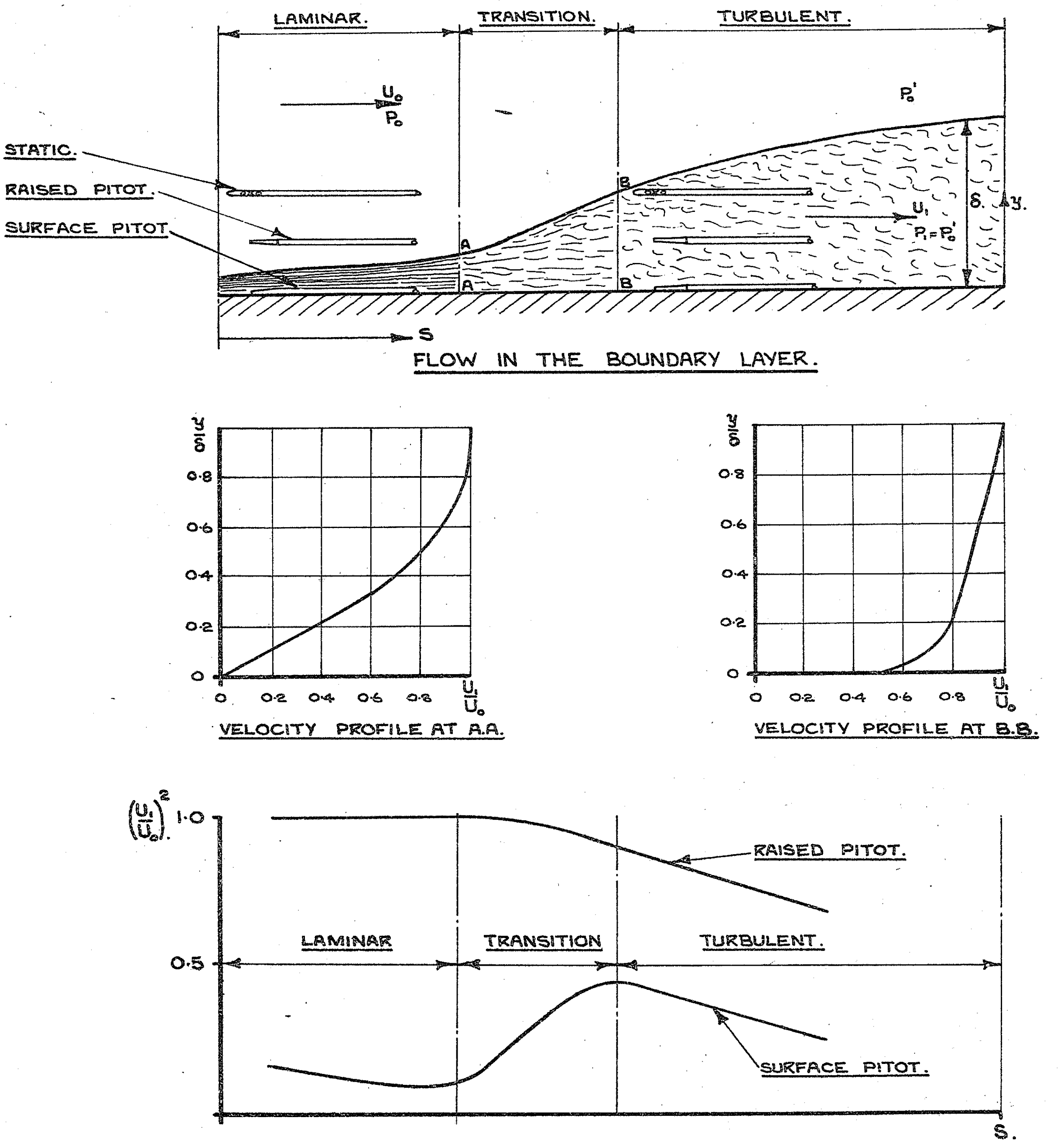

FIG. 11. DIAGRAM SHOWING PRINCIPLE OF TRANSITION LOCATION USING RAISED AND SURFACE PITOT TUBES.

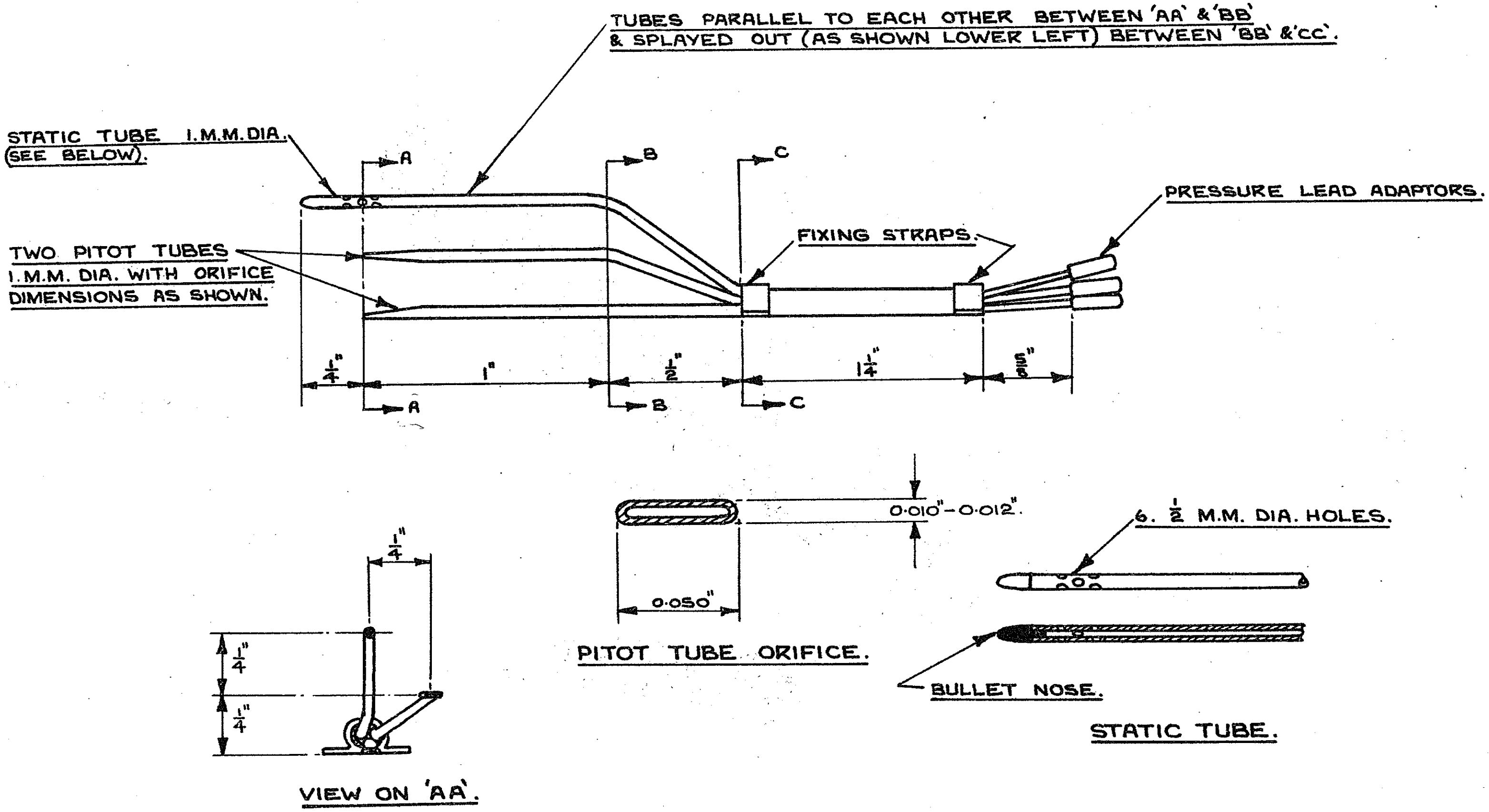

FIG.12. TRANSITION INDICATOR.

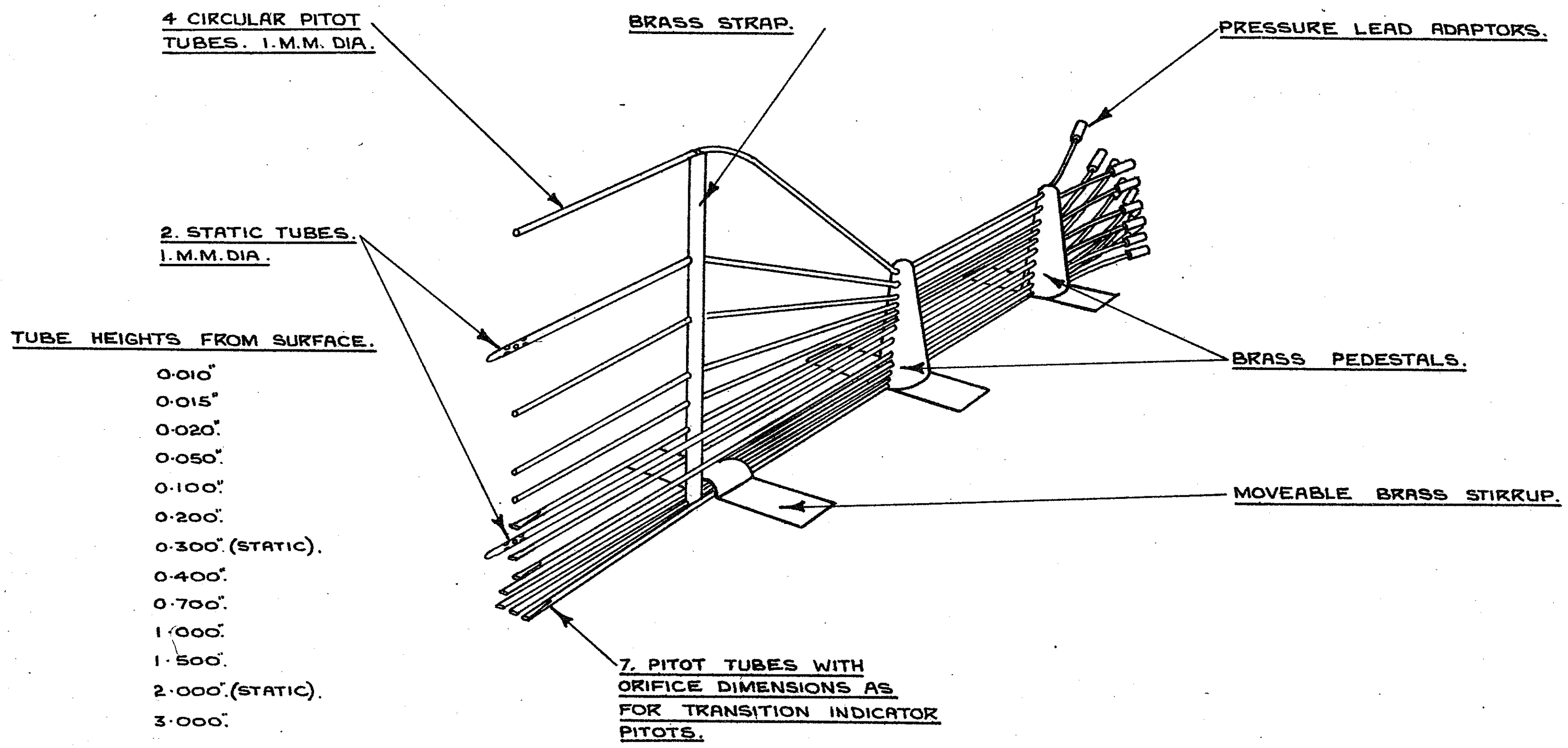

FIG. 13. BOUNDARY LAYER COMB.

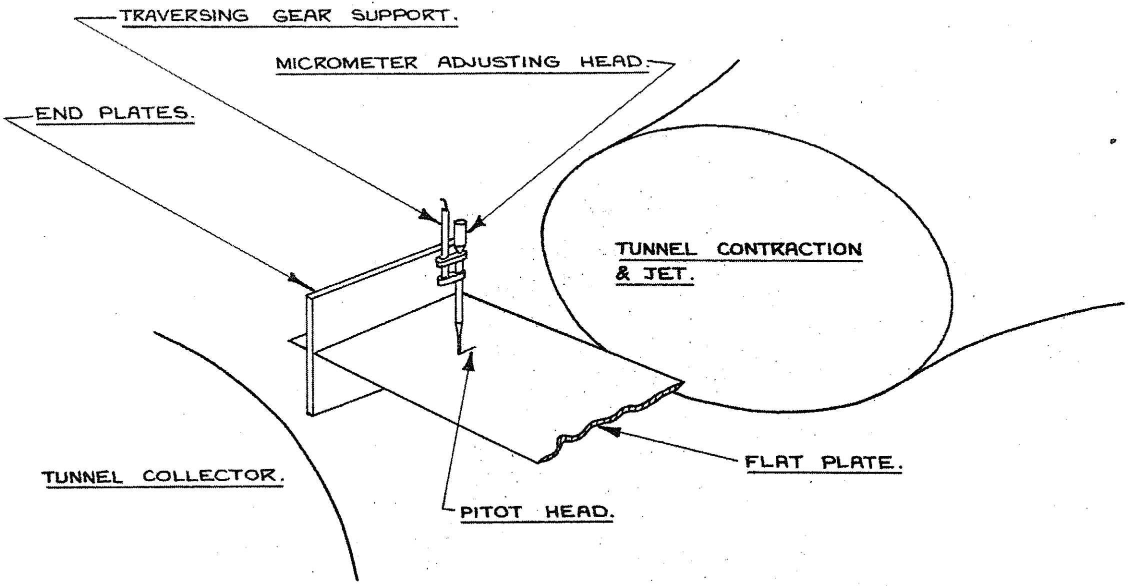

FIG. 14 . ARRANGEMENT OF FLAT PLATE & TRAVERSING GEAR IN WIND TUNNEL.

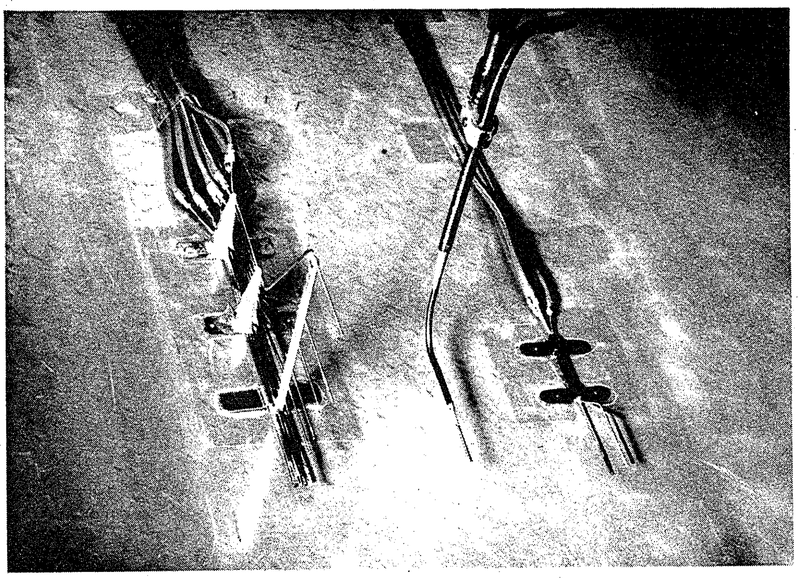

FIGURE 15. ARRANGEMENT OF THE BOUNDARY LAYER COMB, TRANSITION INDICATOR, TRAVERSING PITOT AND FLAT PLATE IN WIND TUNNEL.

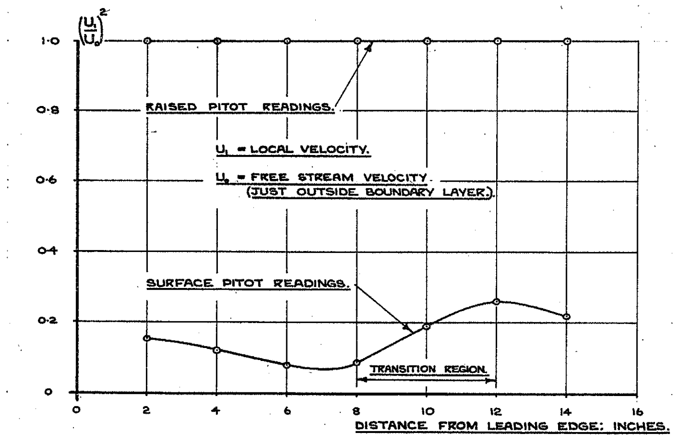

FIG. 16. FREE TRANSITION ON FLAT PLATE FROM TRANSITION INDICATOR READINGS.

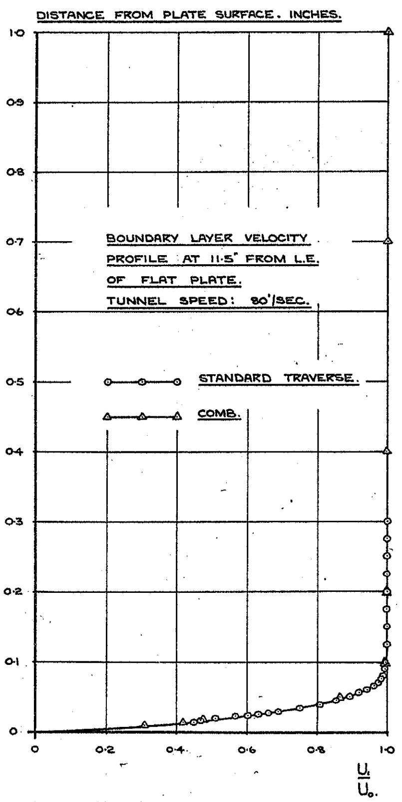

FIG. 17.

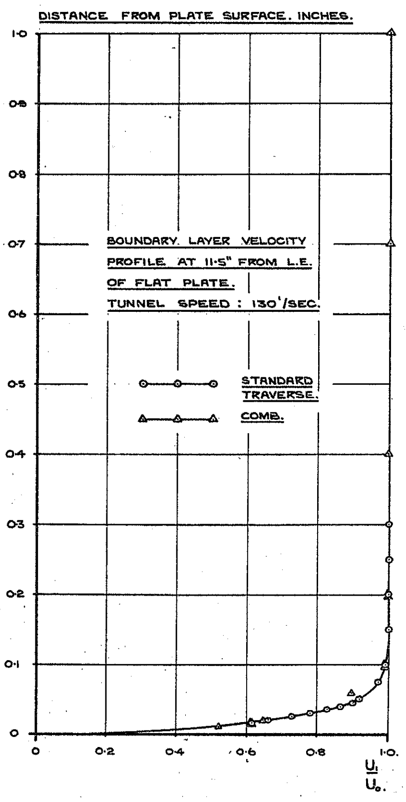

FIG. 18.

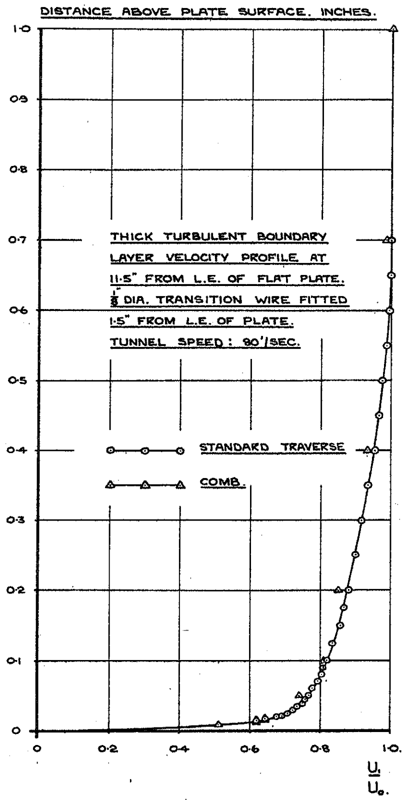

FIG. 19.

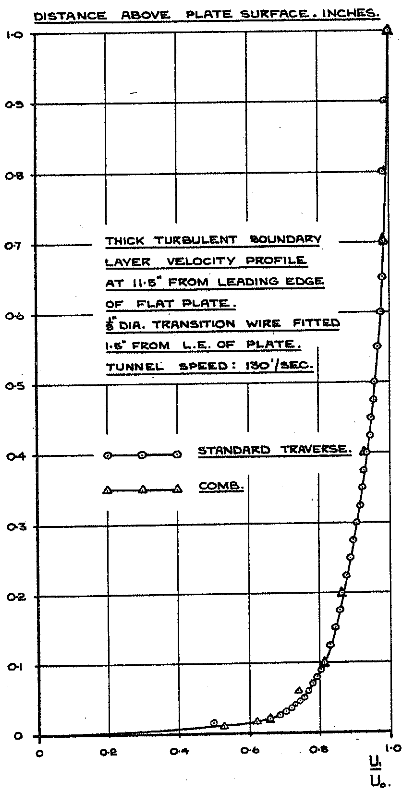

FIG. 20.

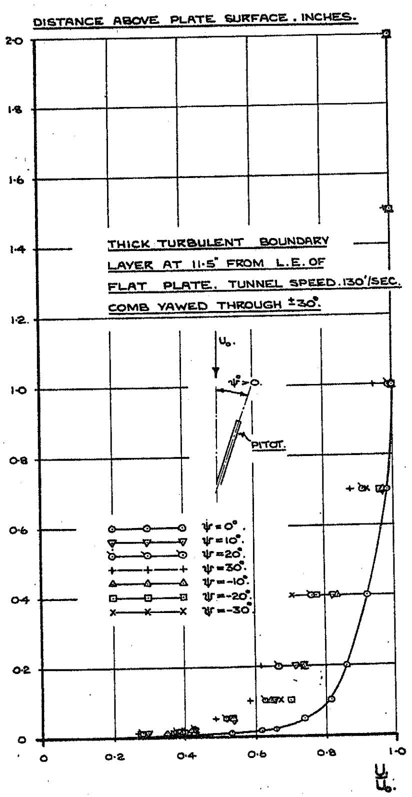

FIG. 21.