ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Progress Report

TWO-DIMENSIONAL ORIENTATION RESEARCH

G. V. Edmonson

Project 2496

NATIONAL SUPPLY COMPANY
PITTSBURGH, PENNSYLVANIA

April 1957

FOREWORD

This progress report covers the work done during the period February 13, 1956, to April 1, 1957, as Project 2496 of the Engineering Research Institute of The University of Michigan for the National Supply Company.

The project is a portion of the research services provided for industry by the Engineering Research Institute, and uses the facilities of the Mechanical Engineering Department. The investigations are under the direct supervision of G. V. Edmonson, Professor of Mechanical Engineering, The University of Michigan

ABSTRACT

The design and construction of the water tunnel required for the research project is described. Instrumentation selection, calibration, and application is discussed from the viewpoint of its use in obtaining research data. Evaluation of the water-tunnel performance prior to its use in the research program has been completed.

OBJECTIVE

This project has been developed to determine the magnitude of the various flow parameters as effected by a series of known design blade forms when set in a predetermined cascade spacing and orientation.

INTRODUCTION

Following a series of conferences between representatives of the National Supply Company, The University of Michigan Engineering Research Institute staff, and faculty from the College of Engineering at The University of Michigan, a research contract was consummated.

Among those attending these conferences were Messrs. H. L. Willke, Peter Tauson, R. J. Krall, A. J. R. Peterson, J. D. Mitcham, and R. W. Colebrook from the National Supply Company; Professors J. S. McNown, R. C. Porter, G. V. Edmonson, and Mr. F. C. Michelsen from the College of Engineering faculty; and Messrs. J. W. Courtis and H. F. Poehle, and Dr. R. G. Folsom of The University of Michigan Engineering Research Institute.

The contract established the subject of the research program. A time period was estimated for the completion of the work, which presupposes that all items of the research program have been correctly evaluated in advance. The program is also intended to provide information about an activity concerning which existing knowledge is inadequate for design purposes. The project has proceeded as rapidly as possible without premium payments for materials or labor.

The contract established the estimate of cost prior to a library study, the design and building program, the instrumentation program, and the preliminary checking of the research apparatus needed in connection with the future design of torque converters.

The subject of the project as set forth in the contract dated February 10, 1956, was "Two-Dimensional Orientation Research." The project, in substance, required that the magnitude of various flow parameters be established for a series of blade forms under varying conditions of attack angle, varying solidity, and varying spacing between successive cascades. The National Supply Company report of December 13, 1955, generally described the research program. The later submission of the number of blades of varying design, and a following detailed report, not dated, by Mr. Krall, established the particulars of the research investigation.

It was initially agreed that the National Supply Company would furnish the test blades for the cascades to the project, and that the remaining portion of the program would be under the direction of The University of Michigan research team. Close liaison between the sponsor and the research group has been continuously encouraged.

THE RESEARCH PROGRAM

The initial detailed study by the supervisory group on the project indicated four distinct steps in the program, each of which was dependent on the successful completion of the prior development. The possibility of parallel activity on the program steps was not overlooked; however, the hazards of such planning and the costs involved were carefully considered and scheduled accordingly. The project programs in the order of sequence are: (1) The Design and Build Program; (2) Development of Instrumentation; (3) Performance of Test Facility; and (4) The Test Program and Analysis.

1. THE DESIGN AND BUILD PROGRAM

The test program for the proposed research required a special form of water tunnel. Early considerations of the cross-sectional area of the vane cascade test section and the required velocities indicated that pumping capacity was available and was already installed in the Mechanical Engineering Laboratory. The pump had sufficient capacity to provide the flows as established by the program if careful attention were given to the design of the water tunnel. The pump selected was a Worthington, class OS, centrifugal type rated at 5400 gpm at 50 ft lb/lb when operating at 870 rpm. The use of this pump resulted in a considerable saving in the cost of project facilities.

Figure 1 is a scaled assembly drawing of the required water tunnel. The tunnel is a closed circuit. Note that the make-up and supercharging circuit is also shown on this figure. It consists of the following sections, numbering them downstream and starting at the pump discharge: (a) 14 in. to 30 in. at 7° included angle diverging section; (b) a vaned 30-in. mitered bend elbow; (c) a 30-in. to 36-in. diverging section at 7° included angle; (d) a vaned 36-in. mitered bend elbow; (e) a 36-in. straight stilling section provided for diffusion screens, if required; (f) a complex converging section from 36-in. diameter to a 3-in. x 24-in. cross section; (g) a complicated off-set rectangular test section; (h) a transition section from a 3-in. x 24-in. section to a 24-in. round section; and, (i) a series of 24-in. and 18-in. elbow sections to the inlet flange of the pump.

The straight diverging sections, items (a) and (c), and the straight section, item (e), are all designed with detailed knowledge of the behavior of fluids in such passage. Proper consideration with respect to strength to withstand two-atmospheres supercharge pressure was given to the design of these parts.

A certain amount of design research was required in the design of the vaned mitered elbows. The data used were from a report issued by the St. Anthony

Falls Hydraulic Laboratory.[1] Vaned elbows are believed to be absolutely essential for reducing or stopping cross-flow tendencies before fluid enters the converging section of the test facility. For reasons of economy and delivery, it was decided to use a constant cross-section vane rather than a form vane. It was recognized, however, that energy losses would result. Figure 2 shows a typical design of a mitered elbow.

The specifications for the turning vane of the mitered elbow correspond to those for vane shape No. 3 of Klein, Tupper, and Green: the ratio of vane spacing to chord length, $s/c = 0.5$; the angle between the miter axis and the vane chord, $\theta = 90°$; and the vane Reynolds number $Vc/\nu = 2(10^5)$. The symbols used in defining the various design parameters are shown in Fig. 3.

A vane chord of 8-5/8 in. was selected for the vanes in both elbows. The associated vane Reynolds numbers (i.e., using the vane chord as the linear dimension) are sufficiently near the design Reynolds number when the water velocity in the test section is 30 ft/sec to provide good performance.

The converging section, item (f), shown in Figs. 4 and 5, of the tunnel was one of two difficult design requirements of the project. Although it is a generally accepted fact that more freedom of choice exists in designing a converging section than other passages in fluid circuitry, passing from a 36-in.-round section to a 3-in. x 24-in. rectangular section required careful calculation and design to accomplish a uniform rate of change of section. A model of this section along with the drawing detail was prepared for the fabricator. Figure 6 is a detail drawing of the converging section.

The design study of the rectangular off-set test section, item (g), required advanced consideration of all subsequent phases of the project, including the well established fact, brought out in the initial conversation, that unforeseen flow phenomena might well require reconsideration of the data or test conditions as first agreed upon. Figure 7 is a detailed drawing of the test section.

Such considerations as a variable spacing of a flexible guide-vane section; an external mechanism for operating the flexible guide-vane section; a study of the placing of instrumentation, a provision for adequate visual observation of the flow supercharged to two atmospheres; design of false work to direct the flow at top and bottom of the test section, the shape of which was dependent on the particular set of National Supply test vanes being studied; and the requirement of a minimum boundary layer built up within the test area: all were time-consuming and exacting, and of such a nature that very little prior experience could be found in the literature search. Figure 8 shows the location of instrumentation in the test section.

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[1] "Fluid Flow Diversion," Project Report 1, August, 1951, St. Anthony Falls Hydraulic Laboratory.

The success of the facility development depended on a design of a test section where the flow of fluid directed into the test section would be uniform and constant at all times.

Establishing test-vane performance by measurement of exit-flow conditions from the test section required the existence of properly directed off-set passages to the outlet of the test section. The minimum of interference to flow at all test-section boundaries was necessary. All vane-actuating mechanisms had to be located exterior to the flow passage. The guide vanes and test-vane cascade are the only elements in the path of flow.

An uninterrupted transition of flow from the converging nozzle to the test-section entrance was accomplished by telescoping the converging section-outlet nozzle into the test section. The outlet edge of the converging nozzle is adjacent to the guide-vane section side plates.

The requirement of both negative and positive angle of attack of the fluid on any one set of test vanes dictated that a design study of a variable inlet guide-vane section be initiated. A constant fixed direction of the entering edge of the variable guide vanes was a first requirement. The entering edge of the guide vanes had to remain in a fixed position so that the mean line of the vane nose would be tangent to the stream line of the entering flow. The variable position, that is, angle, of the exit edges of the guide vanes required a flexible blade surface connecting the vane nose and trailing edge. Further, the variable guide vane required that a mechanical provision be made so that the longitudinal position of the guide-vane cascade would be adjusted to maintain a constant spacing between the exit of flow of the guide-vane section and the entrance of flow to the test-vane section. The design study indicated that the total range of the flexible guide-vane section could be developed through the use of four sets of guide vanes, each satisfying a predetermined range of conditions and each being self-contained between parallel side plates.

To actuate the flexible vane sets into the many positions, a gear and rack mechanism was conceived and built. Figures 9 and 10 show this vane-actuating mechanism. Because of lack of uniformity of materials in flexure, a degree of periodicity of flutter that developed at the trailing edge of a vane section under relative high load, and back-lash that is inherent in gear systems, the flexible guide vanes have caused trouble. This item will be discussed later in the report.

Two-dimensional flow is required in the rectangular test section which includes the guide-vane section. The outlet of the test section was designed to 0.131 in. wider than the 3-in. inlet passage. This design feature was introduced to negate the consequences of the inevitable boundary-layer thickening which occurs in the direction of flow.

The boundary layer is a region in which the fluid velocity varies with the distance from a solid surface. As the thickness of the boundary layer increases, the distance over which there is a varying velocity profile also increases. If the boundary layer is associated with a flow having essentially a uniform velocity distribution, then a thickening boundary layer on the constant velocity field can be overcome by properly increasing the flow path. Because it was intended that the transverse velocity profile in the test section should not be dependent on the distance from the inlet flange, the sides of the test section were made divergent by a total angle of 0.18 degrees. The top and bottom walls of the test section do not diverge because the 24-in. height of the cross section was considered large in comparison with the expected thickening of the boundary layer.

A plexiglas window 8-1/2 in. x 13-1/2 in. and 1 in. thick is mounted in the front plate of the test section in the region of the test vane cascades. The edges of the window are mitered into the surrounding steel plate of the test section so that the inner face of the glass is flush with the inner wall of the test section. The plexiglas window forms a portion of the test section, and flow patterns as observed through the window can be assumed to be the flow conditions existing within the vane cascades.

All sets of test blades are mounted on a removable plate which forms the back portion of the rectangular test section in the vicinity of the vane cascade. The front edge of this supporting plate as well as the downstream edge are made flush with the adjacent side plates forming the channel passages. Figures 11 and 12 are photographs of the test section showing the test-vane cascade location in the area of the plexiglas window. It will be noticed that the trailing edges of the entering flow guide vanes are likewise visible. The instrument panel is seen to the left of the photograph and the pressure-regulating valve system may be seen on the right.

Drill jigs were designed for each set of test blades and their respective supporting side plates. Figures 13 and 14 are drawings of typical drill jigs. Both the vane and the plate are drilled for dowel location of the leading and trailing edge of the test blade on its support plate so that the entire cascade of any vane shape will be uniformly directed and spaced. Each vane is located on the support plate by two dowels and held in place by a flathead screw.

It will be noted that the test section is off-set downstream of the test-vane cascade. False work of the varying cross section is located in the test section in the vicinity of the section off-set to direct the flow from the trailing edge of the vane cascade into the transition section of the tunnel.

The return piping and elbow attached to the transition section of the tunnel are standard 18-in. and 16-in. welded concuit sections.

The converging nozzle, item (f), and the test section, item (g), are fabricated from stainless steel. The remaining sections of the tunnel, with the exception of the pump casing, are fabricated from normal cold-rolled sheet, the interior of each section being painted with a No. 212 Vinyl primer followed by a Vinyl enamel. As an added protection against corrosion, sodium dichromate in the ratio of one part in ten thousand is added to the water in the closed circuit.

It was particularly important that fabricators of parts be familiar with the requirements of a water tunnel. It was fortunate that the nozzle and test sections could be contracted for at a reasonable price by a supplier who had constructed similar sections for the same general type of facility.

2. DEVELOPMENT OF INSTRUMENTATION

The research proposal required that the vane loading be calculated from measurements of direction of flow at inlet and outlet of the test-vane cascade, and velocity of flow in the determined direction. Simultaneously, measurements of local pressures are required to permit calculation of energy reductions from inlet to outlet. Determinations of energy degradation, in turn, would permit evaluation of the various design parameters that have been established in the project schedule.

Instrumentation of a type and kind which separately establish performance of the tunnel and vane cascade is essential to the successful attack on the research problem. Until such time as the design features of the test section, in particular, could be completed, specifications for instrumentation was not practical.

Two techniques have been established to determine direction of flow. Photographic techniques with the simultaneous use of small suspended reflecting particles provide a record of visual observations of the flow conditions in the area of the vane resulting from flow directions imposed on the vane cascade. The second technique, which will provide quantitative data, is the direction-sensitive stagnation probe. Because of the rigid directional requirements and the close confined space of the section, special sources of supply had to be considered. A certain amount of delay resulted in acquiring the three-prong Pemco, Inc., instruments shown in Figs. 15 and 16. The design of precise probe operating mechanisms and careful calibration of the probes are a necessary part of the instrumentation program.

It was mutually agreed that determination of direction and energy quantities would be determined ahead of and behind the test-vane cascade. It was further decided that evaluation of vane performance would be based upon data taken in the region of the center vane of the vane cascade in all cases.

A complicated probe operating mechanism which would provide for orientation of the probe through the required variable angle about its axis and simultaneously permit movement of the probe through a vertical distance parallel to the vane cascade equal to the length of the maximum vane spacing was designed and built. Figure 17 is a picture of the operating mechanism. The operating mechanism makes possible the precise angle measurements by vernier movement of the probe. It further permits vernier movement of the probe parallel to the vane. The two mechanisms, one ahead of and one behind the vane cascade, return the probe to any position, thereby making it possible to check any data at any time within the period in which the remainder of the tunnel is operated at constant condition.

Calibration of the direction-sensitive stagnation tube has been completed in accordance with the following procedure. The results of the calibration are included.

Each of the stagnation tubes, used to determine flow direction and velocity simultaneously, were calibrated by means of an air jet, a smooth approach nozzle, and a standard pitot-static tube. All the stagnation probes that were tested were of the same design.

The apparatus which was used for this calibration test is illustrated in Fig. 18. The air was supplied by a 3-stage axial-flow fan which discharged into a 12-in. duct. The end of the duct was fitted with a smooth approach nozzle of 1.59-in. internal diameter. A Prandtl-type pitot-static tube was aligned in the air stream with the tip of the tube in the discharge plane of the nozzle. Stagnation pressure readings were taken in 1/8-in. intervals across the nozzle with the expected result that the stagnation pressure was constant across the nozzle opening. Concurrently, the static air pressure was measured in the duct to insure that any set of calibration readings would be made under the same fan-operating conditions. The static duct pressure was subsequently used to compare the readings obtained with the standard pitot-static tube and the stagnation probes that were being calibrated. An examination of the data in Fig. 19 revealed that the ratio of the stagnation pressure at the nozzle exit to the duct static pressure was 1.003.

The stagnation probes which were to be calibrated were fixed in the air stream so as to read the impact pressure in the plane of the nozzle discharge. Again the nozzle opening was traversed and the stagnation pressures and duct static pressures recorded. By using the duct static pressures which were recorded when the nozzle was traversed with the pitot-static tube and with the stagnation probe as a connecting parameter, it was possible to calibrate the stagnation probe against the standard pitot-static tube. A group of simultaneous readings of the impact pressure obtained from the stagnation probe and the pitot-static tube, along with the duct static pressure, substantiated the previous results. By these two means it was determined that the stagnation probes to be used in the water-tunnel tests would measure the impact pressure within 1.5% of the value obtained from a standard pitot-static tube. This is a high degree of "efficiency" for the stagnation probes.

Results of the above calibration tests are presented in Figs. 20, 21, 22, 23, and 24. The fact that the readings increase as the stagnation probe begins to block a larger and larger portion of the nozzle opening was expected. It was found that the presence of the small pitot-static tube in the air stream simultaneously with the stagnation probe did not affect the impact pressure readings (Fig. 25).

Throughout the previous tests the rate of air flow yielded a velocity pressure of between 23 and 24 in. of water. This corresponds to an air velocity of approximately 310 ft/sec, a figure within the range for which incompressibility may be assumed. As the Reynolds number is the similarity parameter for pitot-tube calibration tests, the air velocity that was used would give results that would be comparable to conducting the tests in a water stream of approximately 31 ft/sec. The water tunnel was designed to have a maximum speed of 30 ft/sec in the test section where the probes will be used.

The sensitivity of the stagnation probes was also checked with the air of the air jet. The probe was placed perpendicular to the air stream and each of the outermost (direction-sensing, Fig. 26) tubes of the probe were connected, respectively, to one side of a U-tube manometer that was filled with water. As the alignment of the impact tube with respect to the air stream (i.e., nozzle axis) was varied by rotating the stagnation probe about its axis, readings of the unbalanced pressure existing between the direction-sensing tubes were recorded. The alignment angle of the impact tube was read by means of a protractor mounted on the probe with respect to an arbitrary fiducial angle.

It was found that there was straight line relationship connecting the angle that the impact tube made with the air stream and the pressure difference between the two direction-sensing tubes. This linear variation existed over a 14° range of probe rotation with the flow direction. These calibration data are presented in Figs. 26, 27, 28, 29, and 30. The slope of the lower curves varied slightly for each probe (.673 in. H_2O/deg to .858 in. H_2O/deg). A careful examination of the probes did not reveal a cause for this minor variation. These graphs also present data which show that the impact-pressure reading obtained from the impact tube was unaffected by its alignment with the flow direction over a range of ± 7°. The elimination of the requirement for precise positioning of the probe to obtain accurate flow-velocity readings is important to the reliability of tunnel data.

The stagnation probes were further tested to determine their ability to sense direction in a nonparallel stream. Accordingly, a cylinder of 1-in. diameter was installed perpendicular to the axis of a 5-in. smooth approach nozzle at a distance of 6 in. from the plane of the nozzle exit. The airflow direction was measured with one of the stagnation probes and the results compared with the values calculated from potential flow theory. This theory can predict to a high degree of accuracy the flow velocity and direction upstream of the cylinder. Figures 31 and 32 summarize the results of this test.

Readings were taken as close to the cylinder as possible. An examination of the configuration of the direction-sensing tubes (Fig. 16) led to the belief that the probe would read a direction of flow corresponding to that which existed at the axis of the 1/4-in.-diameter, stagnation probe assembly. Hence, the readings in closest proximity to the cylinder correspond to a distance of 1/8 in. upstream of the cylinder. It will be noted that these readings show a great deal of inconsistency in the measured flow direction. The variation in the data could have been the result of possible inaccuracies in locating exactly the probe for each test run, or errors in the reading of the angle which the impact tube made with the reference direction (Fig. 33). The results shown in Fig. 34 can be partially assigned to the inability of the observer to tell accurately the unique angle when the pressure differential between the direction-sensing tubes is zero. Near the cylinder there was but a minor change in the pressure differential as the impact-tube alignment with the reference direction was changed.

The following conclusions can be drawn concerning the calibration work done on the stagnation probes which will be used in the water-tunnel tests:

a. The impact readings obtained with the probes will be within 1.5% of the values obtained with a standard pitot-static tube.

b. The probe can be used to measure flow direction in a parallel stream. In this case the probe will give a reading which varies linearly with the angle of misalignment of the impact tube with the flow direction.

c. Throughout the range tested, ± 7° from the flow direction, the impact-tube reading was not affected by its alignment with a parallel flow.

d. In flow regions having a rapid change of direction caused by turbulence or nearness of a deflecting vane, the probe may not give an accurate indication of the flow direction at a particular point at a given instant of time. As a result of the calibration work, a recommendation that the center line of the probes be placed no closer than 3/8 in. in front of a test-vane cascade has been made.

The selection and calibration of the direction probes and velocity-determination instrumentation has more than adequately met all reasonable expectations. The research results can be expected to be equally accurate.

Instrumentation to determine that the quantity of fluid flow is constant for any test condition and fluid temperature has been installed in the water tunnel.

It is necessary to know that a constant total quantity of fluid is flowing through the water tunnel during any one flow determination for a given vane cascade. Two pressure taps at entrance and exit to the converging sections of the tunnel have been provided. A differential manometer is connected into the taps and indicates a constant total quantity flow when the manometer reads a constant difference in pressure.

Temperature variations are to be expected in a closed-circuit tunnel where all energy requirements are dissipated in the form of heat. A portion of the total heat is, of course, transferred to the surrounding air and another portion causes a temperature rise. A thermocouple is located downstream of the test section.

3. PERFORMANCE OF THE TEST FACILITY

At the completion of the stagnation probe calibrations against accepted standard conditions, the calibrated instruments were installed in the test section for the purpose of determining the flow conditions in the area of the test section where the test-vane cascades would be located. Neither test-vane cascades nor guide-vane section were installed at the time of the tunnel-performance determinations. A false work designed to change the direction of flow uniformly at the test section off-set was, however, installed.

The result of the vertical and horizontal profile traverses are shown in Figs. 35 and 36. The plotted results follow after several adjustments of the instrument support of the 24-in. long, vertical traverse probe to overcome vibration caused by fluid impact of the tube diameter and interference of the measurements by the support for the impact tube.

There are two particular items to be noted in these data:

a. The velocity profile across the 3-in. width of the test section is very uniform. The side-wall effects caused by boundary layer are somewhat less than had been expected.

b. The velocity distribution in the 24-in. height of the test section indicates the degree that the deflecting off-set false work downstream had on the test-vane cascade upstream. That upstream deflecting effects do take place is important to the understanding of vane loading and degradation of energy. This effect may become more important as the research work proceeds. Certainly, an examination of the effect of each change of false work is dictated.

c. It will further be noted in Fig. 36 that the total energy across the 24-in. height of the test section varies. A portion of the variation is due to the velocity distribution; the other is height difference. The height difference tends to cancel out in the experimental data since measurements of energy quantities are made at nearly constant elevations even for the vane section producing maximum turning.

4. THE TEST PROGRAM AND ANALYSIS

Initial data for the first vane cascade have been taken. The results indicate that the research facility is functioning. Preliminary analysis of these data indicates that considerable information needed for further torque-converter design will be obtained. These data were obtained through use of a series of rigid guide vanes instead of the variable flexible guide-vane system.

As previously indicated, the mechanism to provide external control of the directional characteristic of the flexible guide has caused trouble. It is a complicated mechanism. The trouble is caused from two sources: (1) binding and back-lash; and (2) oscillation of the trailing edge. The oscillations are of the same type as noted at the trailing edge of the aileron of an airplane under steady flight.

To proceed with the research program, it was decided to fabricate a series of fixed guide-vane sections and simultaneously to attempt to redesign the flexible guide-vane section. This work is progressing.

CONCLUSIONS

It must be acknowledged that the project has not moved as rapidly as had initially been estimated. However, some of the problems involved were not completely anticipated. Delivery of special apparatus such as is required for such a project frequently does not meet expectations and the apparatus occasionally does not meet the requirements for research without some time for rework. Unavoidable delays have occurred both in the case of equipment being supplied for the project by the research group and by the sponsor.

In the interest of making maximum use of funds, a supervisor is obligated to regulate the number of employees, based on his best understanding of delivery dates. That this has been done is shown by the fact that the rate of expenditure was not up to the level initially anticipated. It is quite evident, however, that the estimate of costs initially determined is insufficient to complete the research program.

After the date when the test-facility performances were evaluated, a progressively increased number of students have been used to take data and process it. A tight schedule of work has been established through conference with Mr. Krall, who is now located at the research facility. Every effort is being made to maintain this schedule. One of the most important items in the remaining program is the regulation of the data-taking so that evaluations can be completed simultaneously. The hazard of out-of-balance activity is great. All personnel are aware of this possibility.

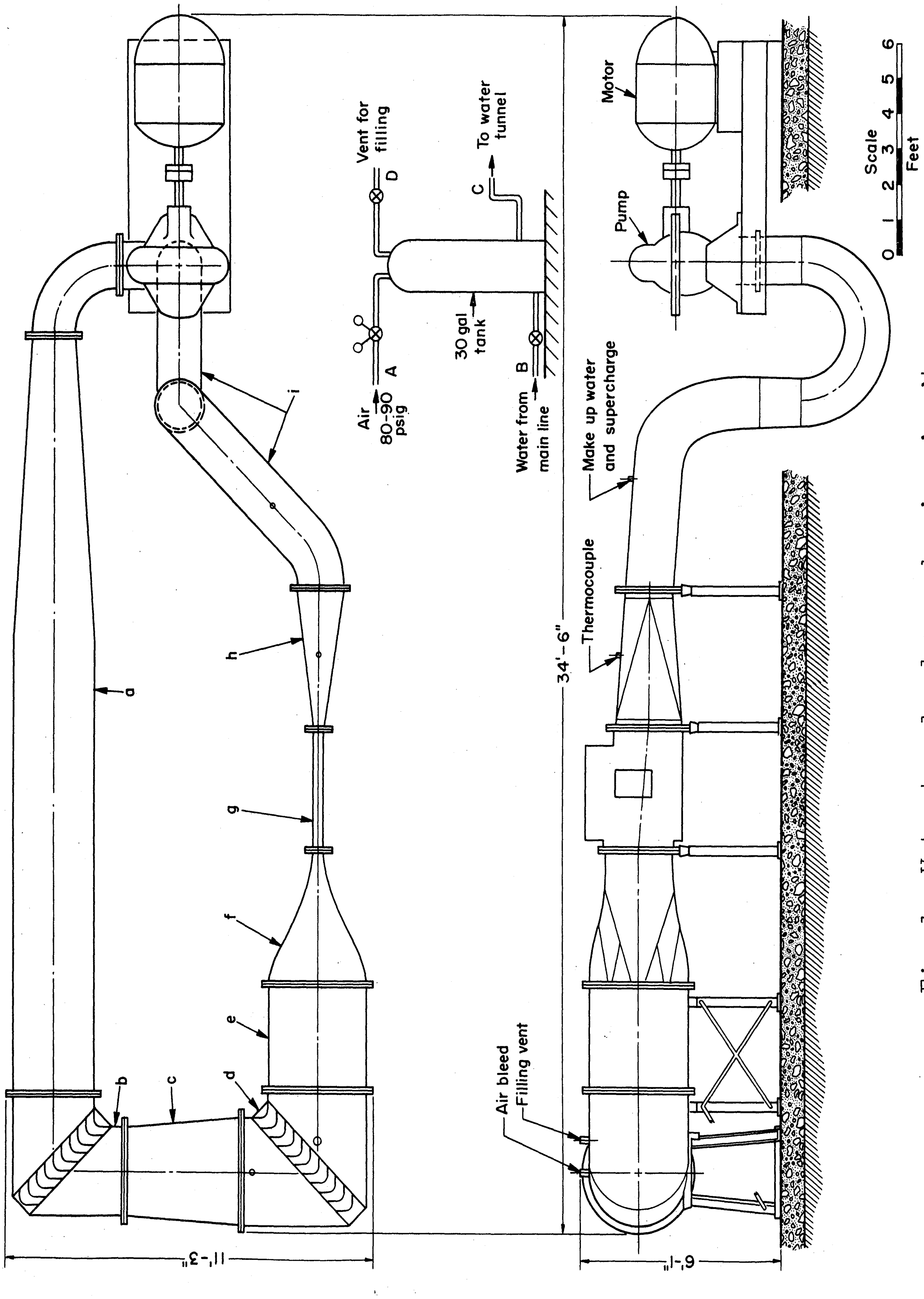


Fig. 1. Water tunnel and supercharging circuit.

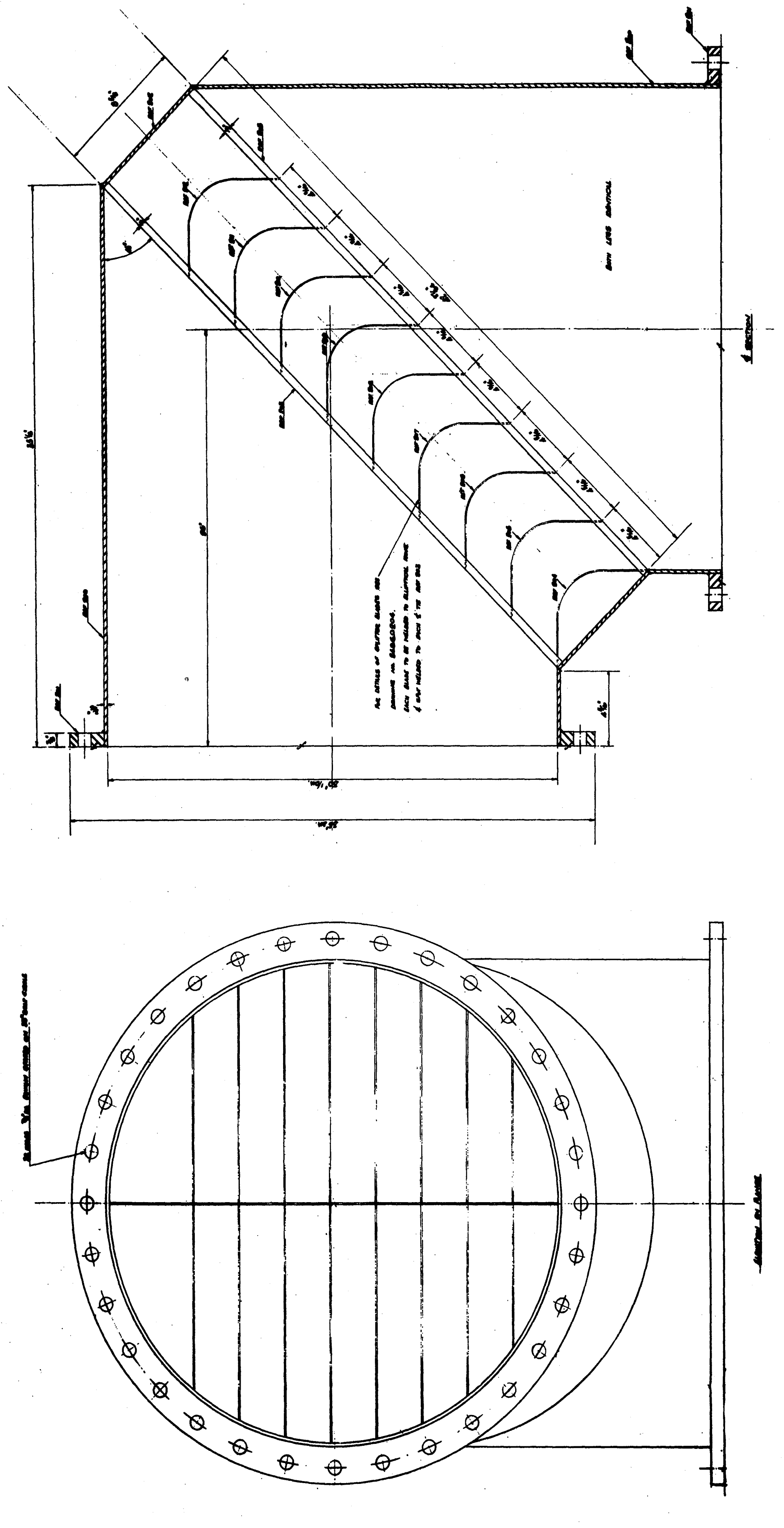


Fig. 2. Typical milateral elbow.

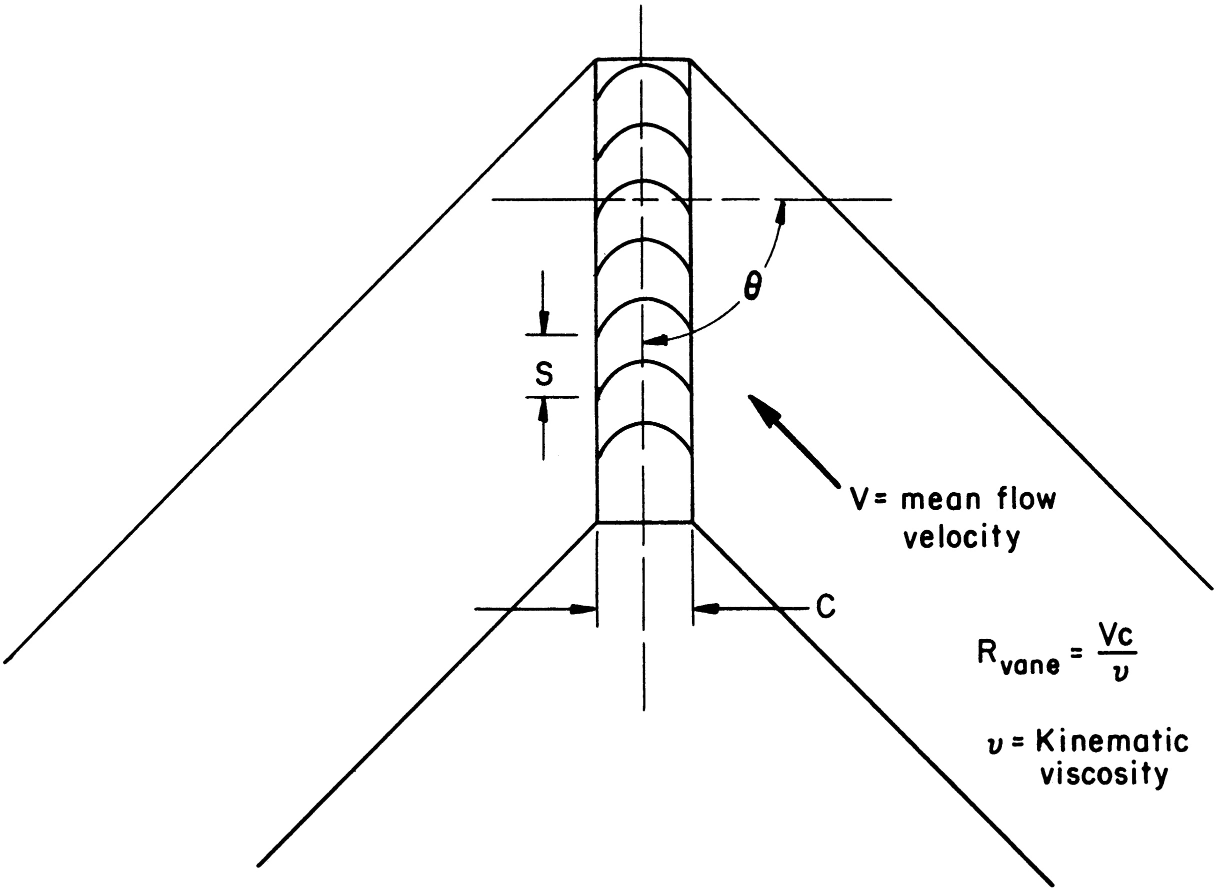


Fig. 3. Mitered elbow. Symbols indicate definitions of design parameters.

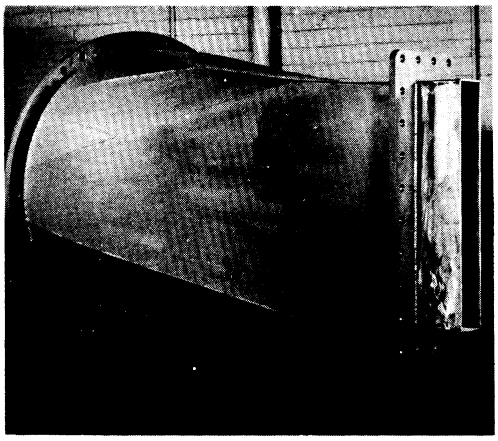


Fig. 4. Converging section shown before installation in tunnel.

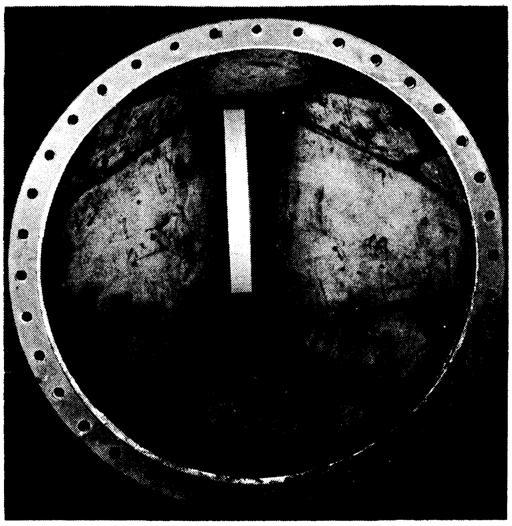


Fig. 5. Inside of converging section, looking downstream.

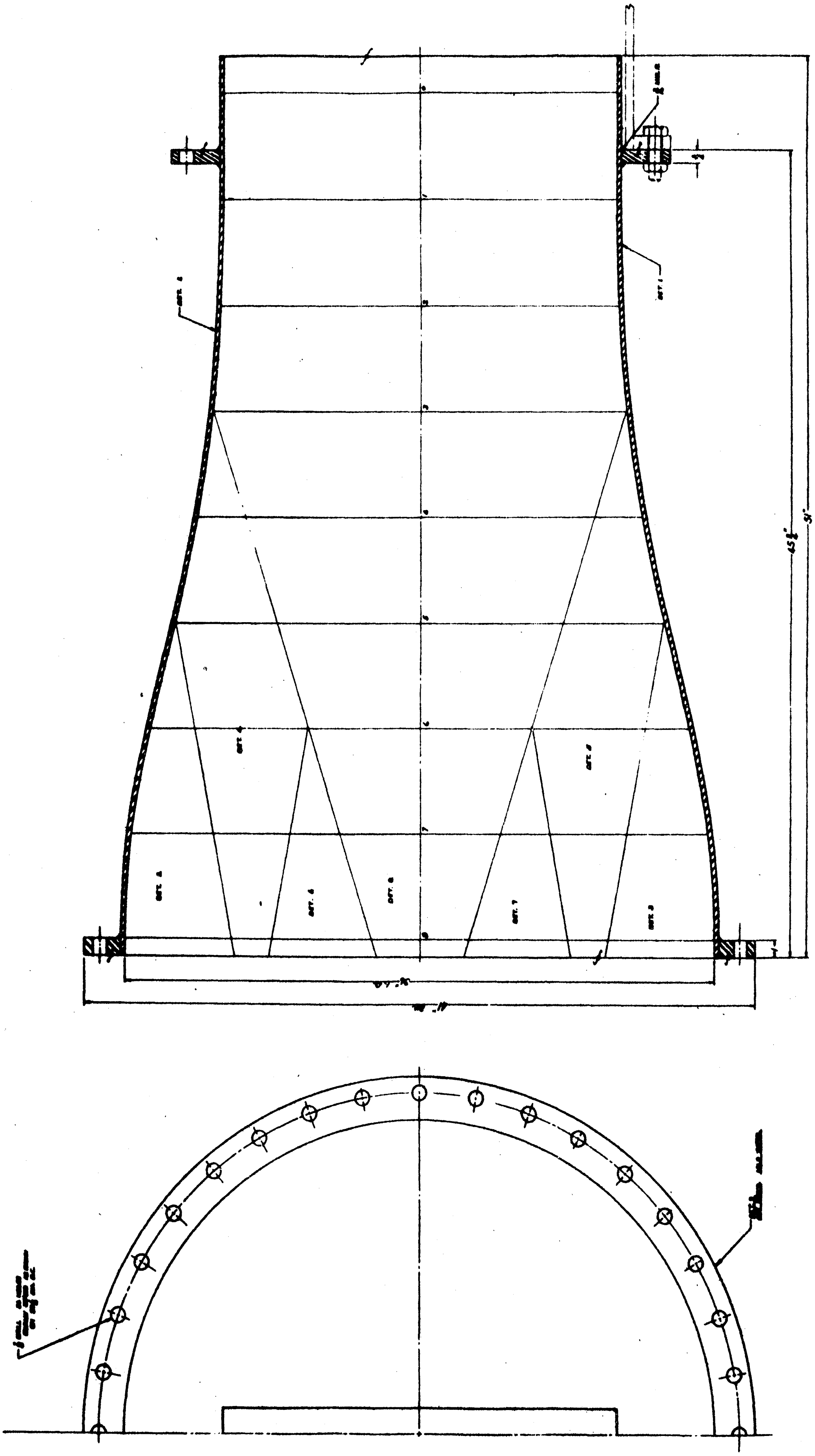


Fig. 6. Detail drawing of stainless steel converging section.

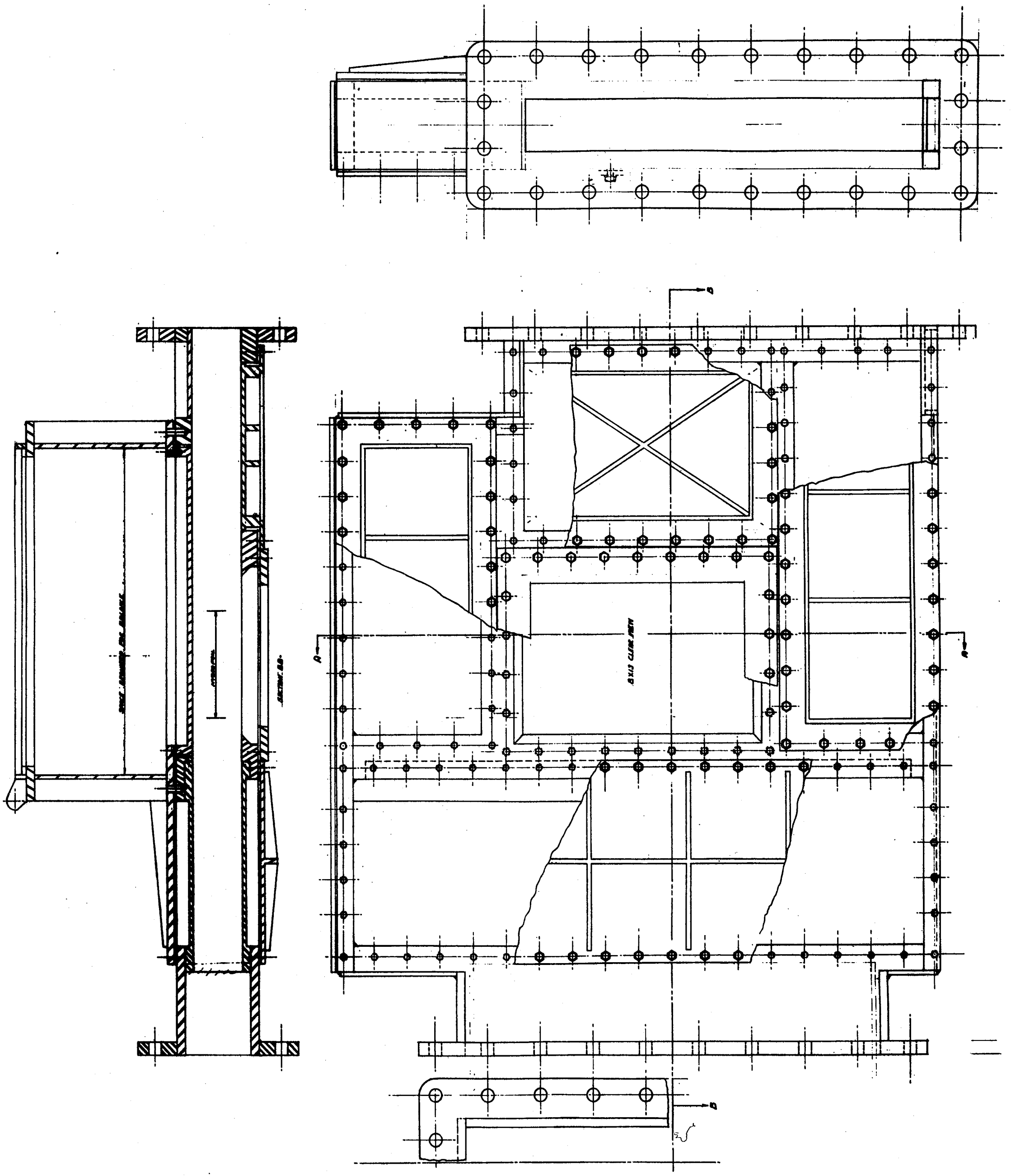


Fig. 7. Assembly drawing of test section.

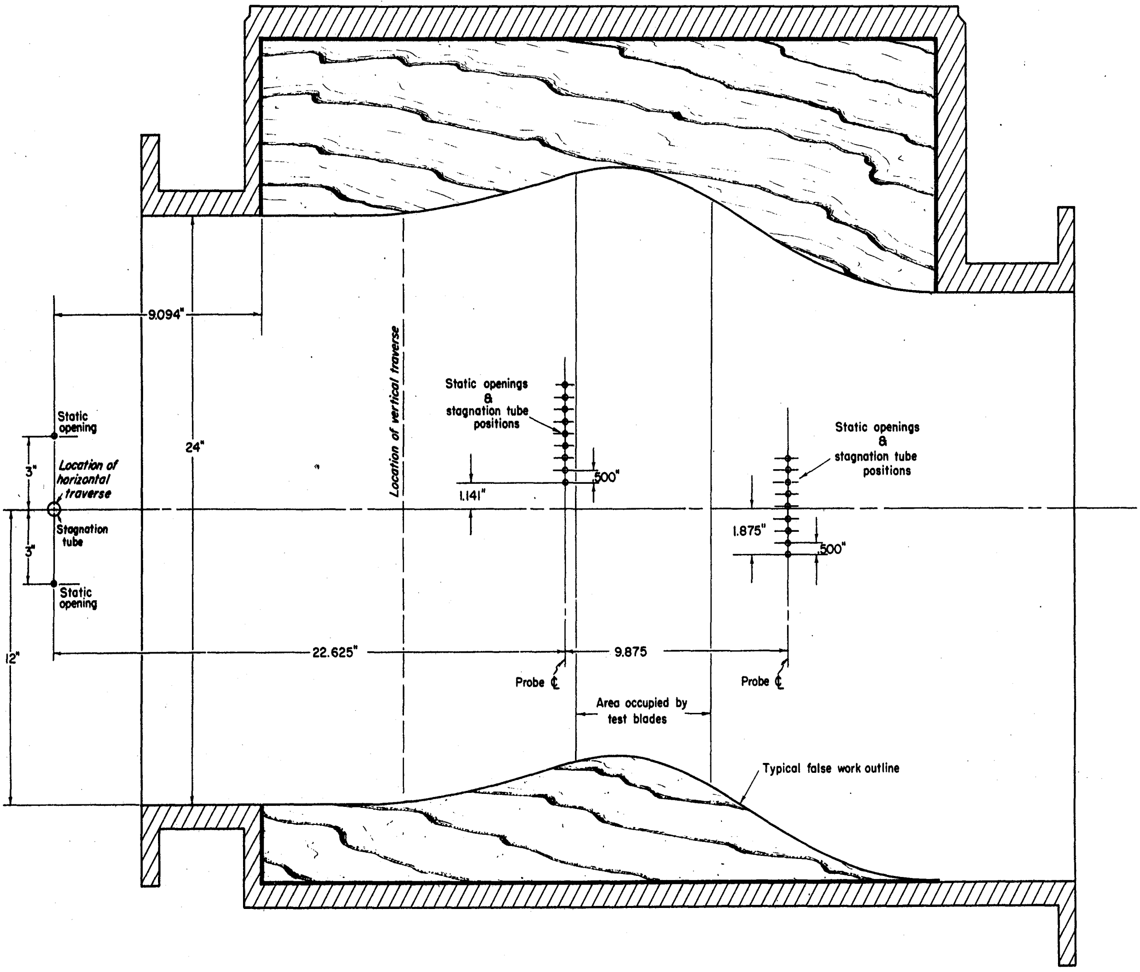


Fig. 8. Location of instrumenter in the test section.

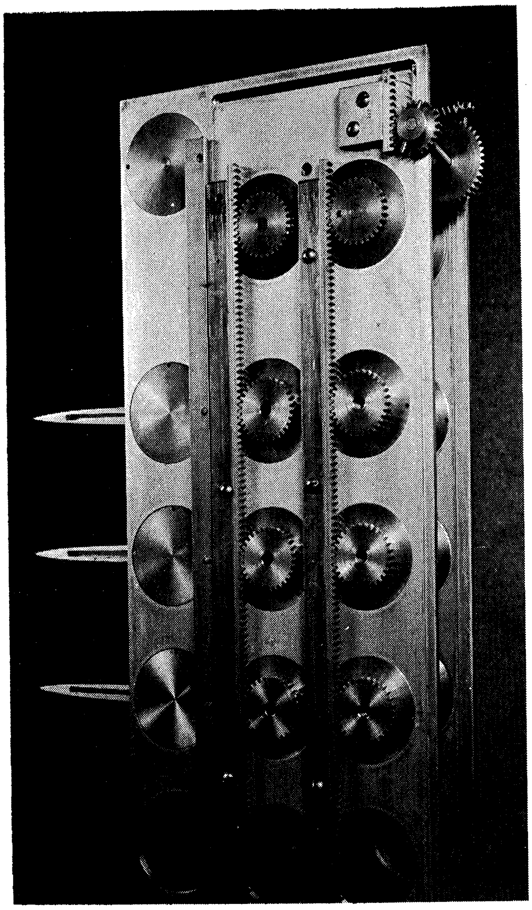


Fig. 9. Side view of guide-vane control mechanism.

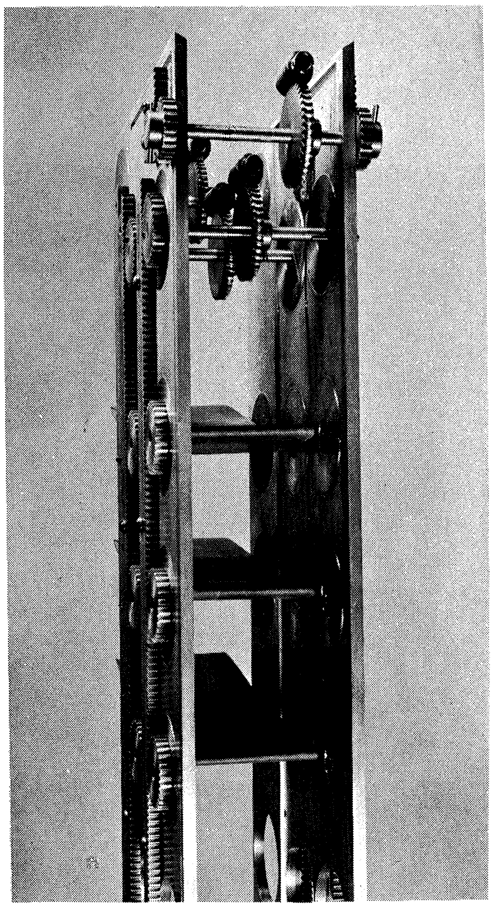


Fig. 10. Upstream end of guide-vane control mechanism.

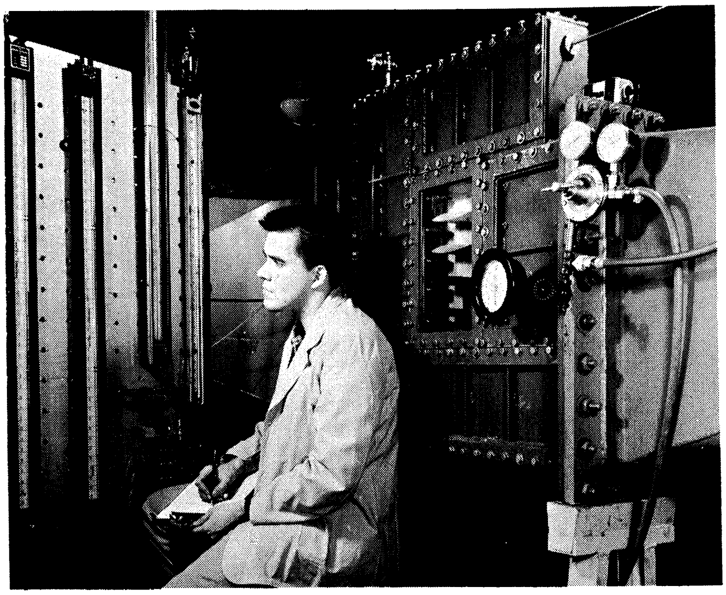


Fig. 11. Test section and instrument panel.

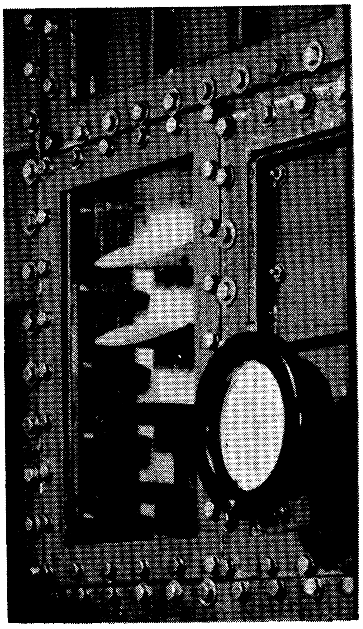


Fig. 12. Test section showing the test-vane cascade location.

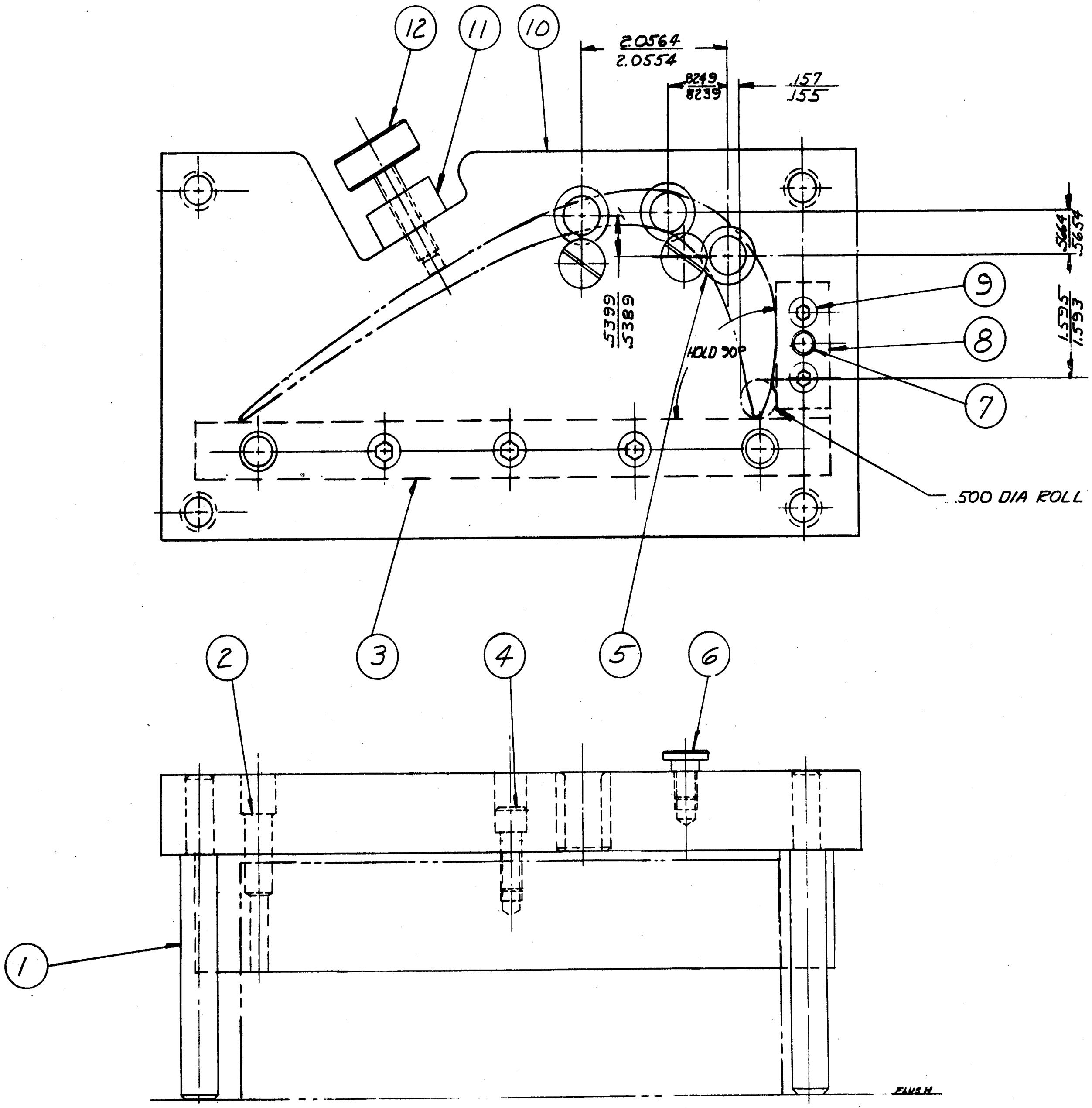


Fig. 13. Typical drill jig for positioning mounting holes in test blade.

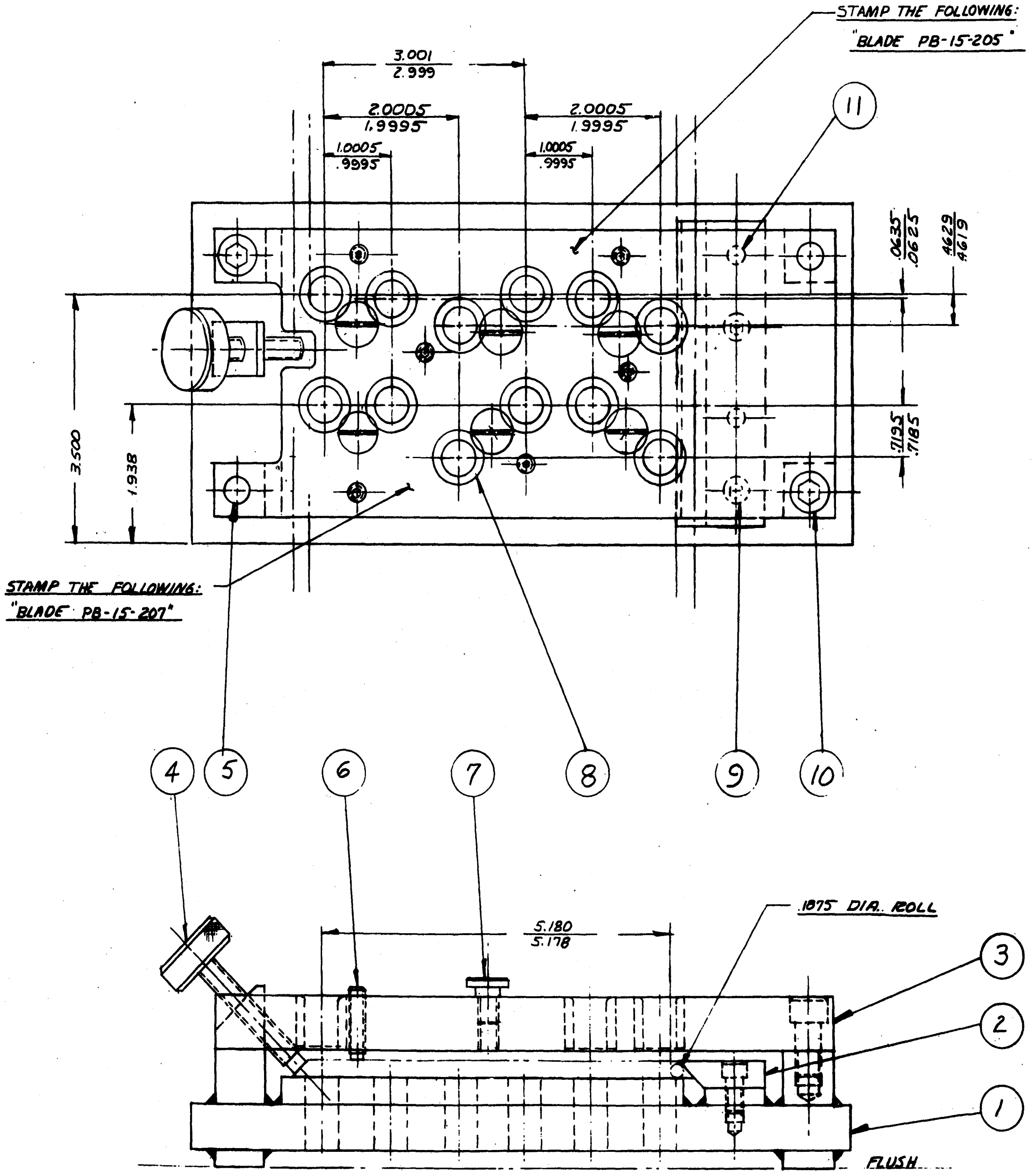


Fig. 14. Typical drill jig for positioning mounting holes in plate.

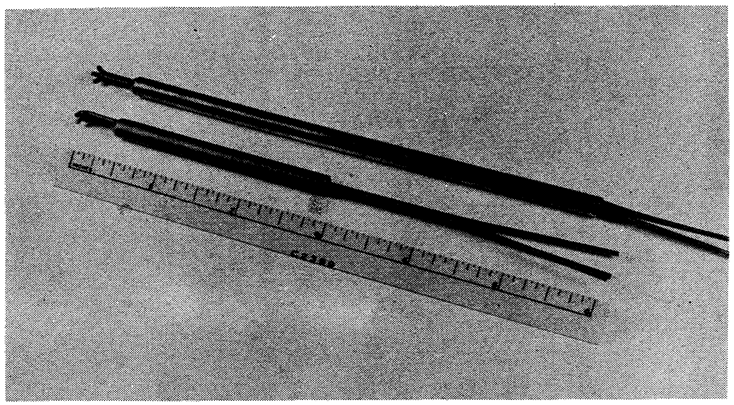


Fig. 15. Direction-sensitive stagnation probes, shown in two lengths.

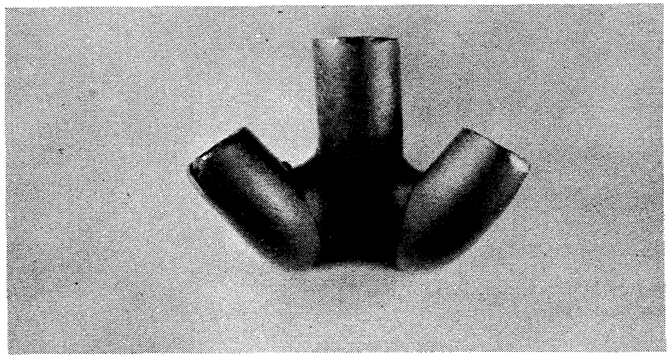


Fig. 16. End view of direction-sensitive stagnation probe.

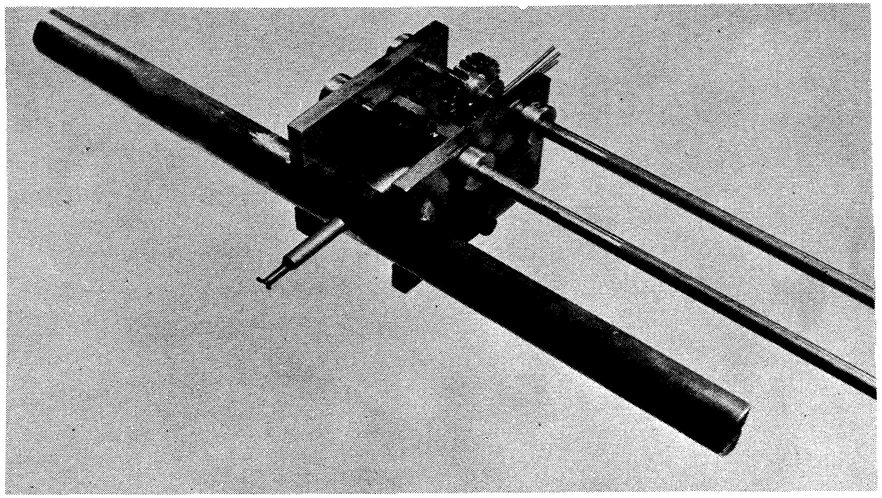


Fig. 17. Gear-driven probe actuating mechanism.

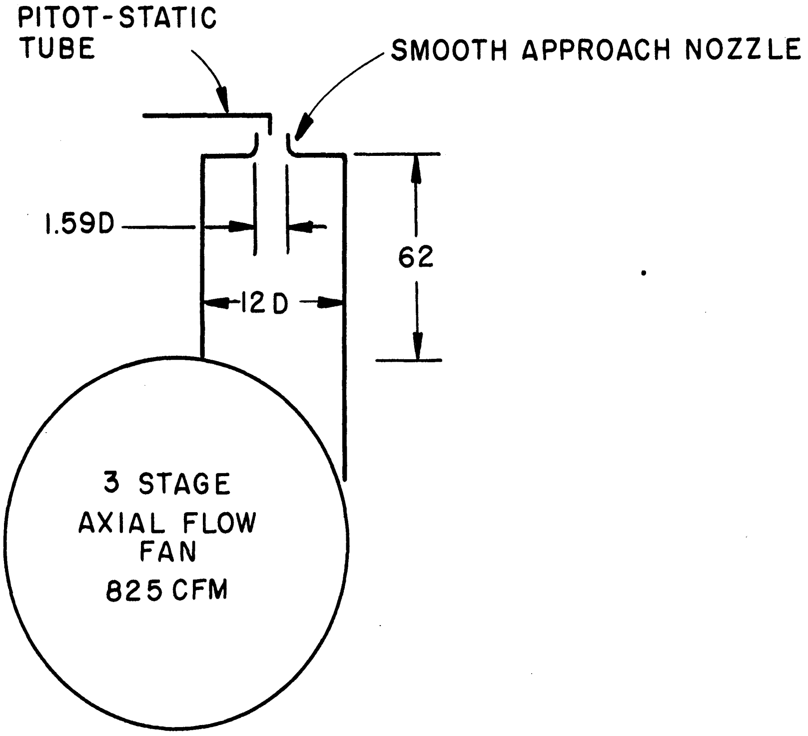
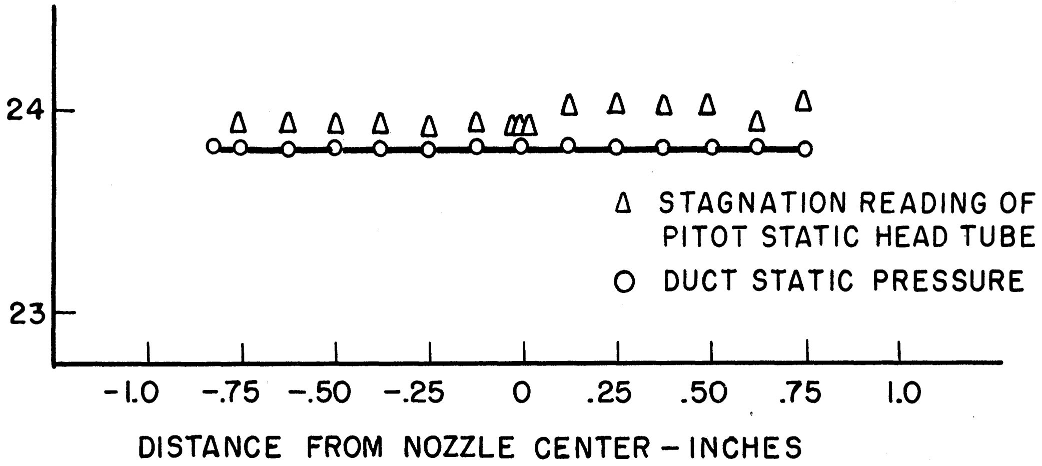


Fig. 18. Schematic drawing of calibration apparatus.



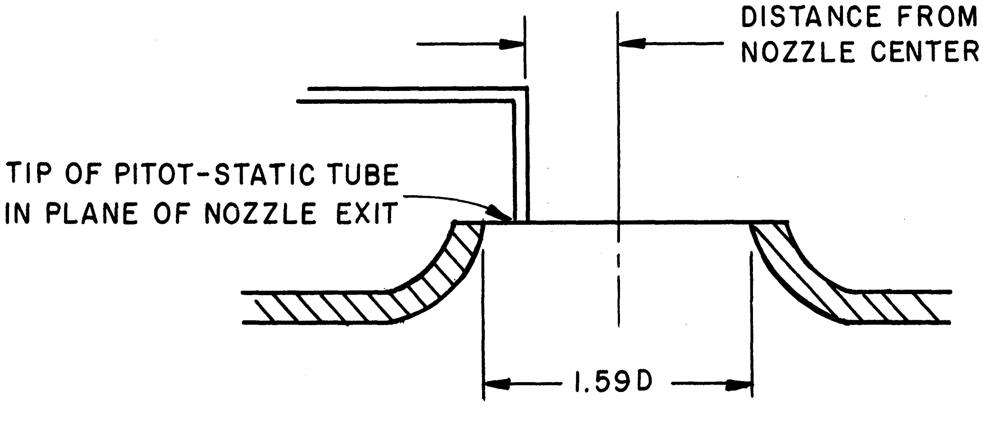


Fig. 19. Velocity profile traverse across nozzle.

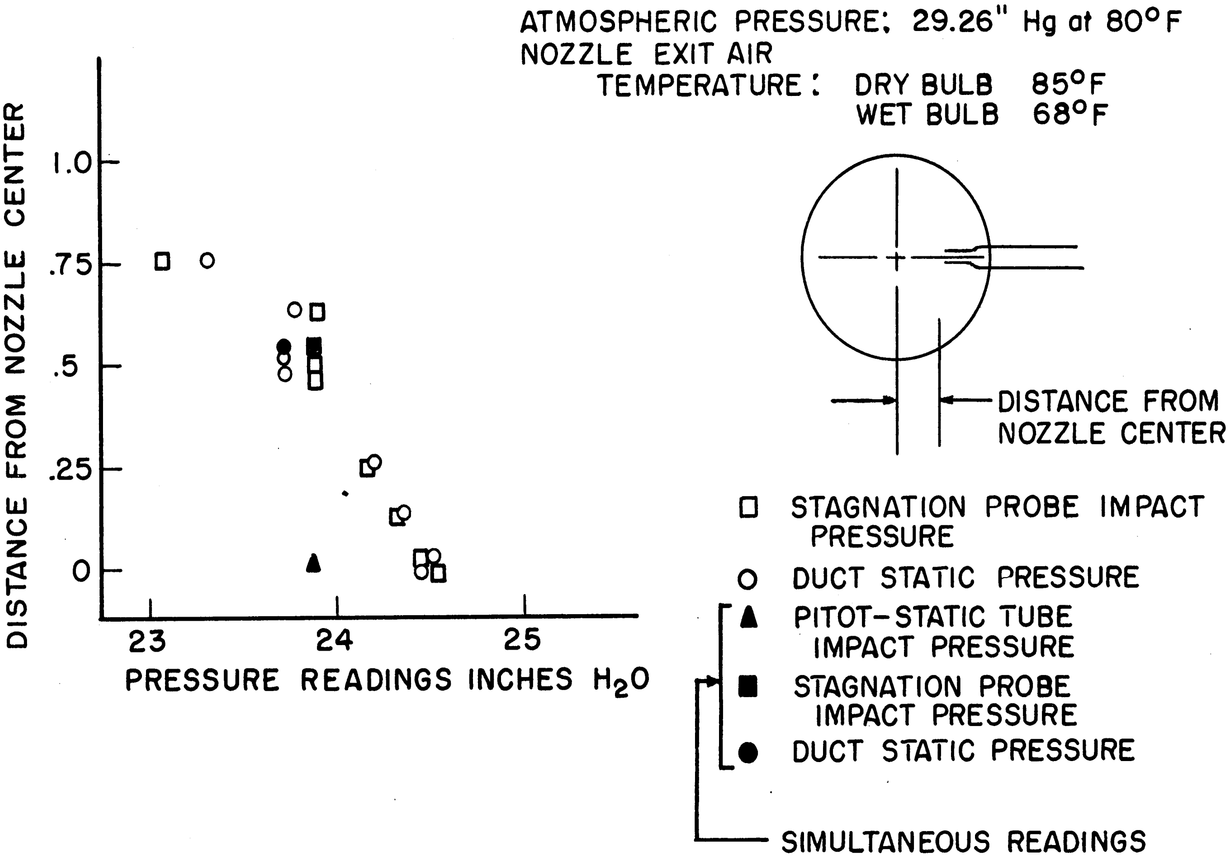


Fig. 20. Stagnation-probe calibration curve for impact pressure. Three-inch length, No. 1 probe.

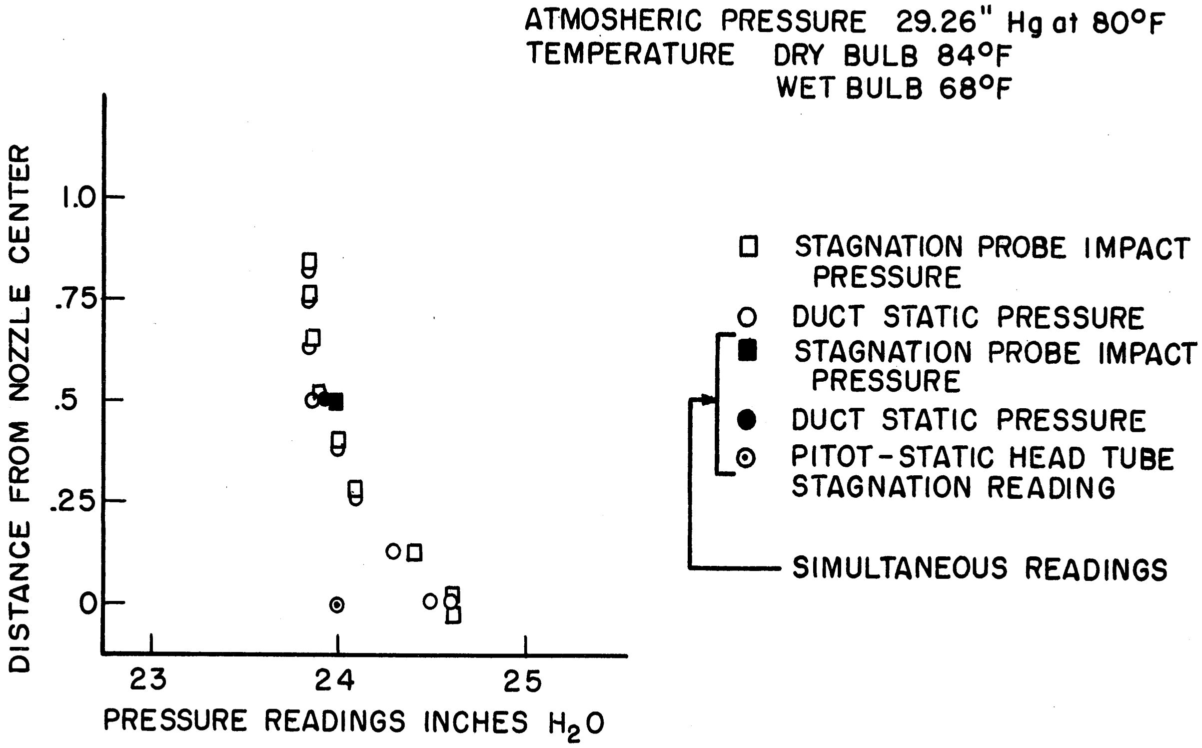


Fig. 21. Three-inch length, No. 2 stagnation tube.

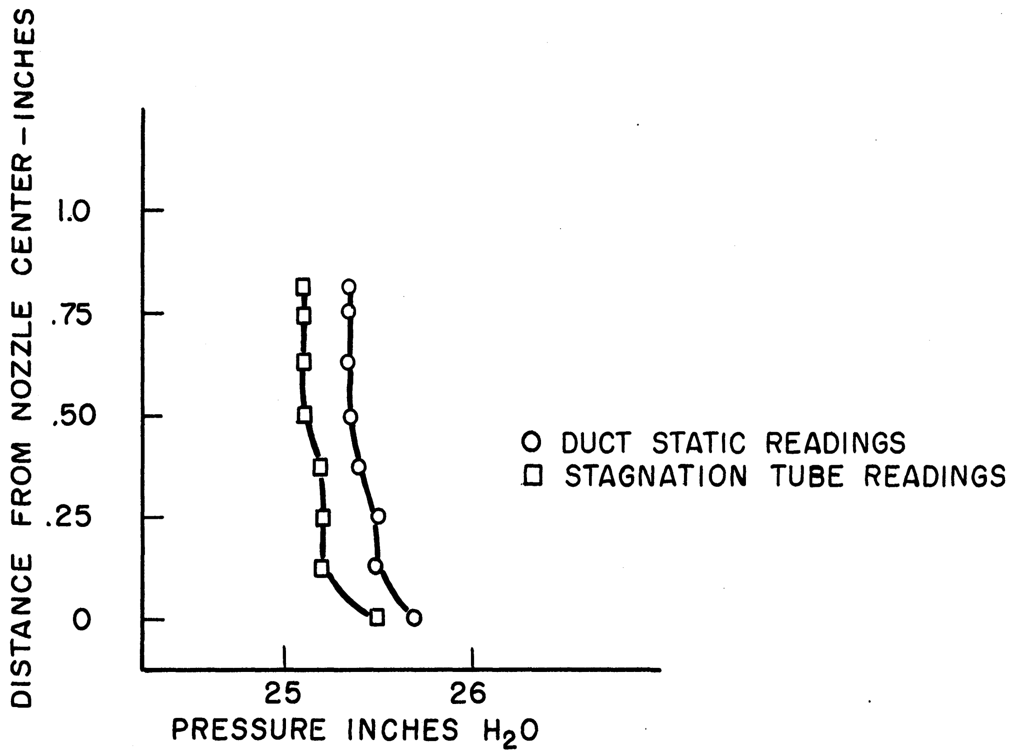


Fig. 22. Nozzle survey with Pemco stagnation probe, 3-inch length, No. 3.

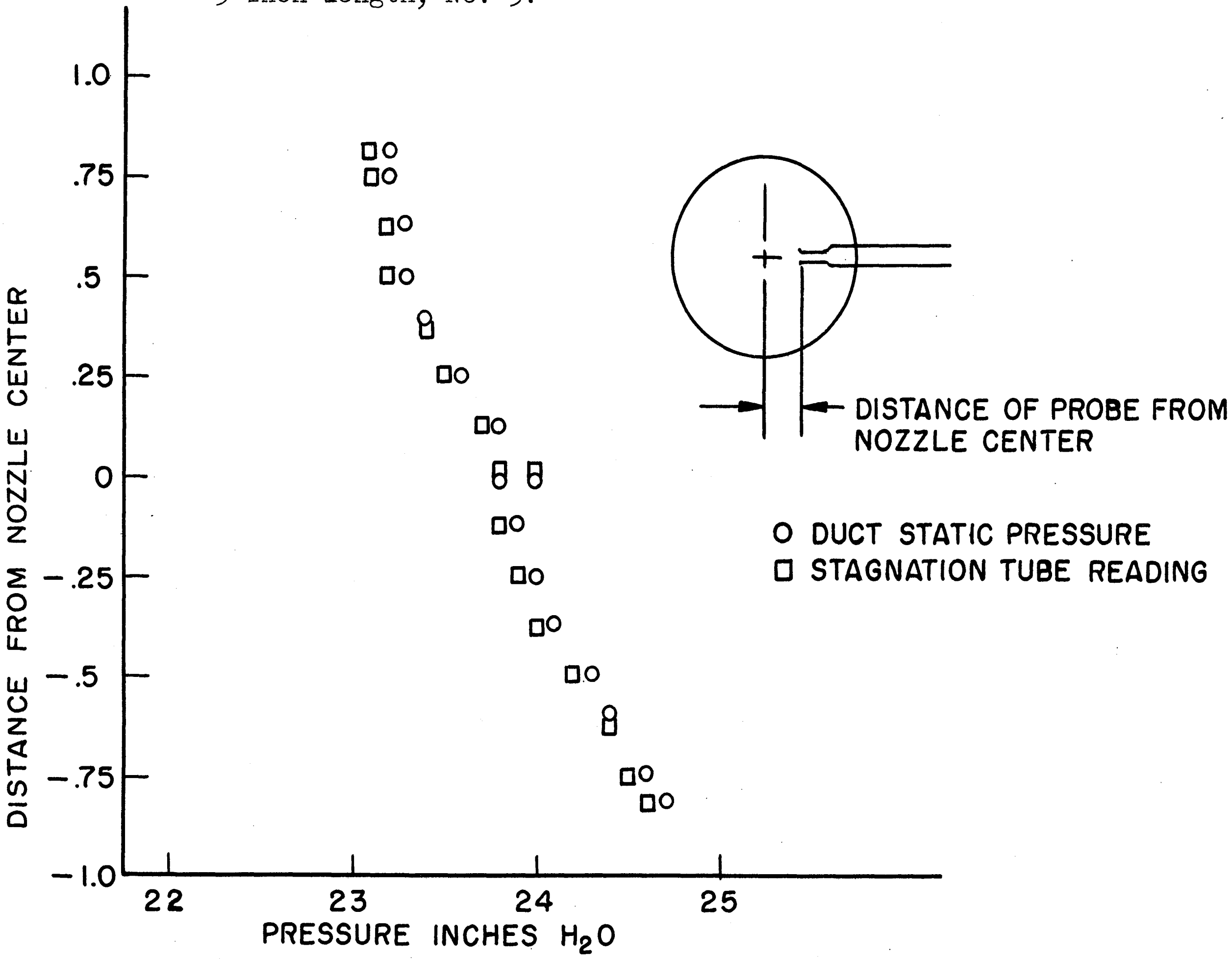


Fig. 23. Stagnation-probe calibration curve, 6-inch length (fluid:air).

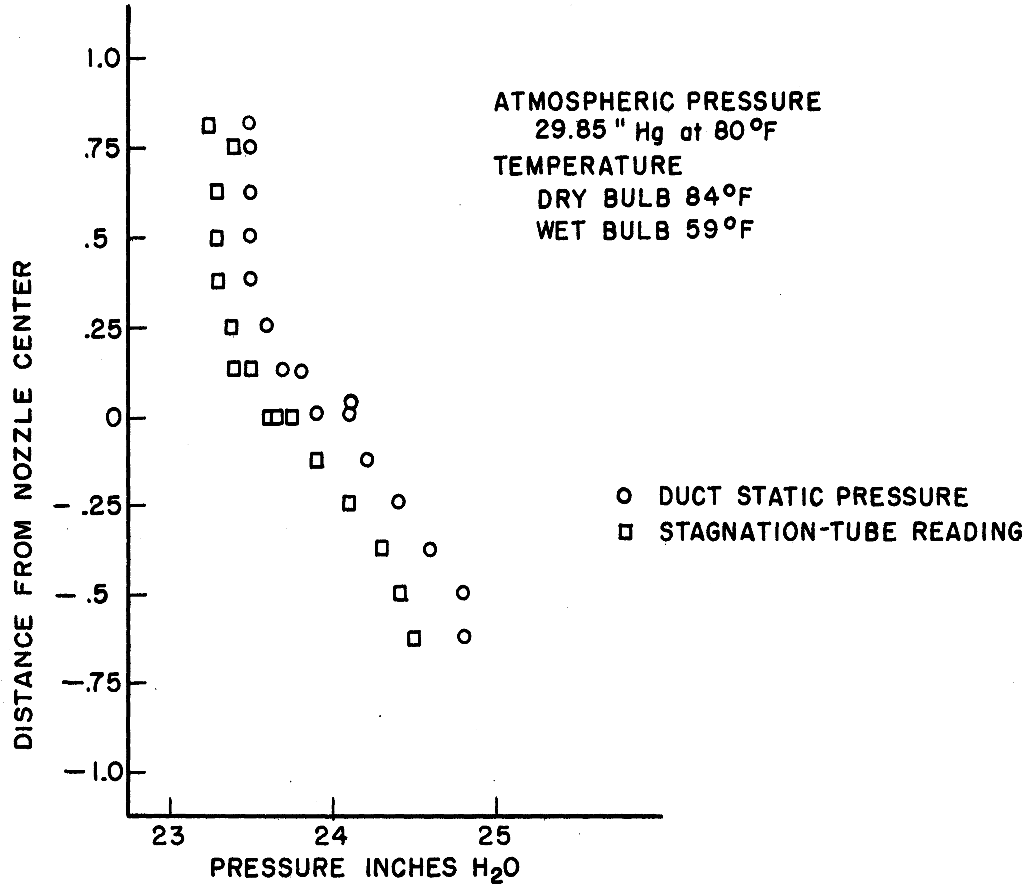


Fig. 24. Stagnation-probe calibration curve, 24-inch length.

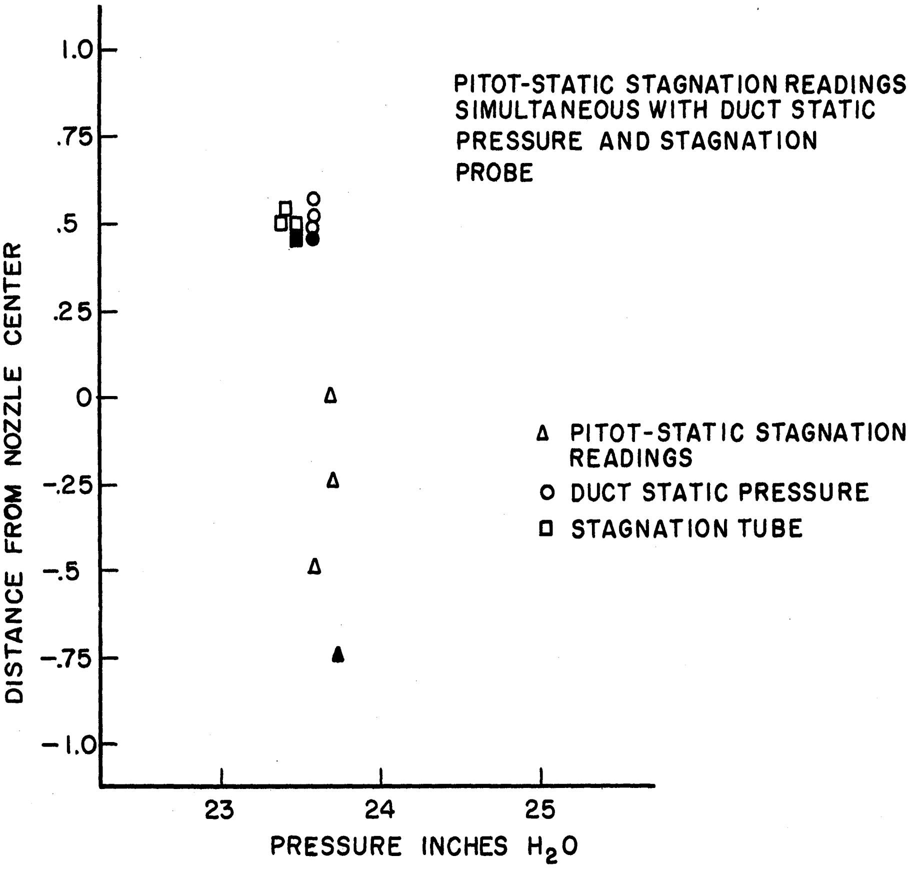


Fig. 25. Influence of pitot-static tube on stagnation-probe readings.

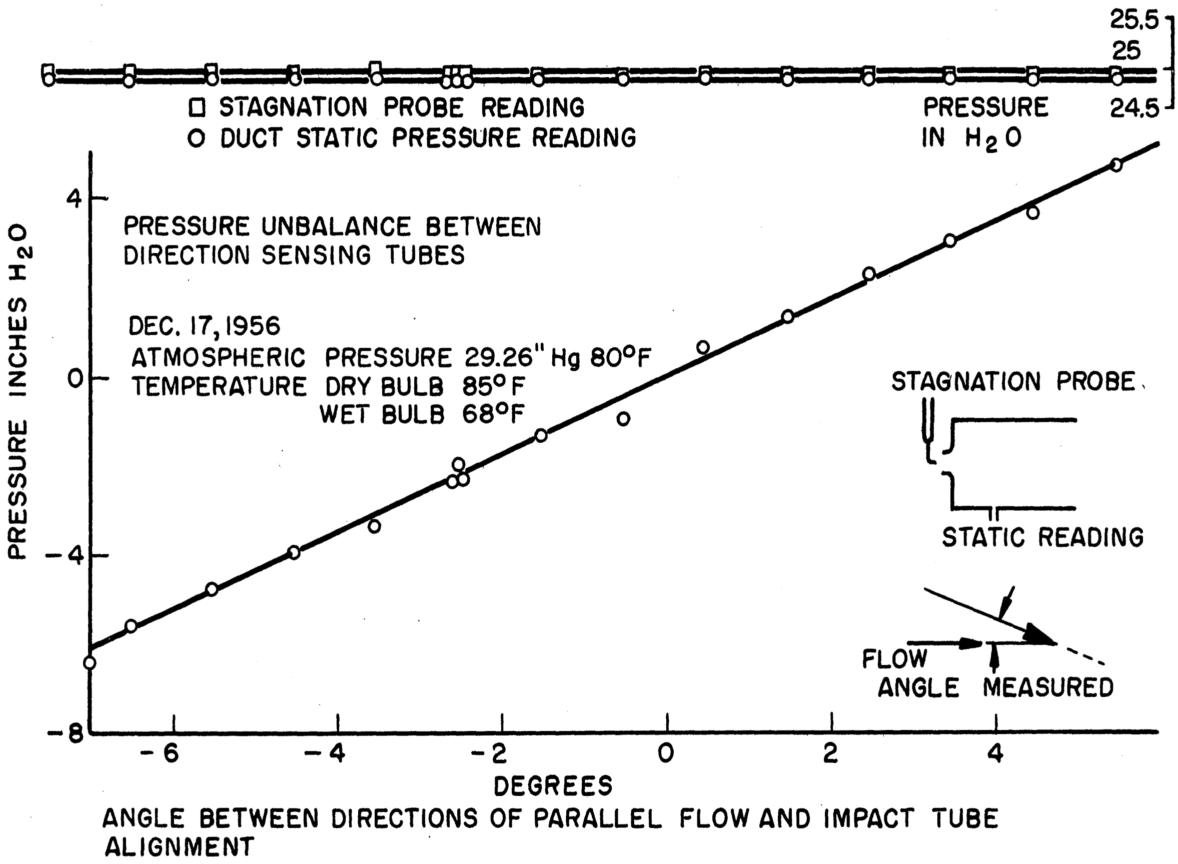


Fig. 26. Calibration curve for No. 1 stagnation probe, 3-inch length.

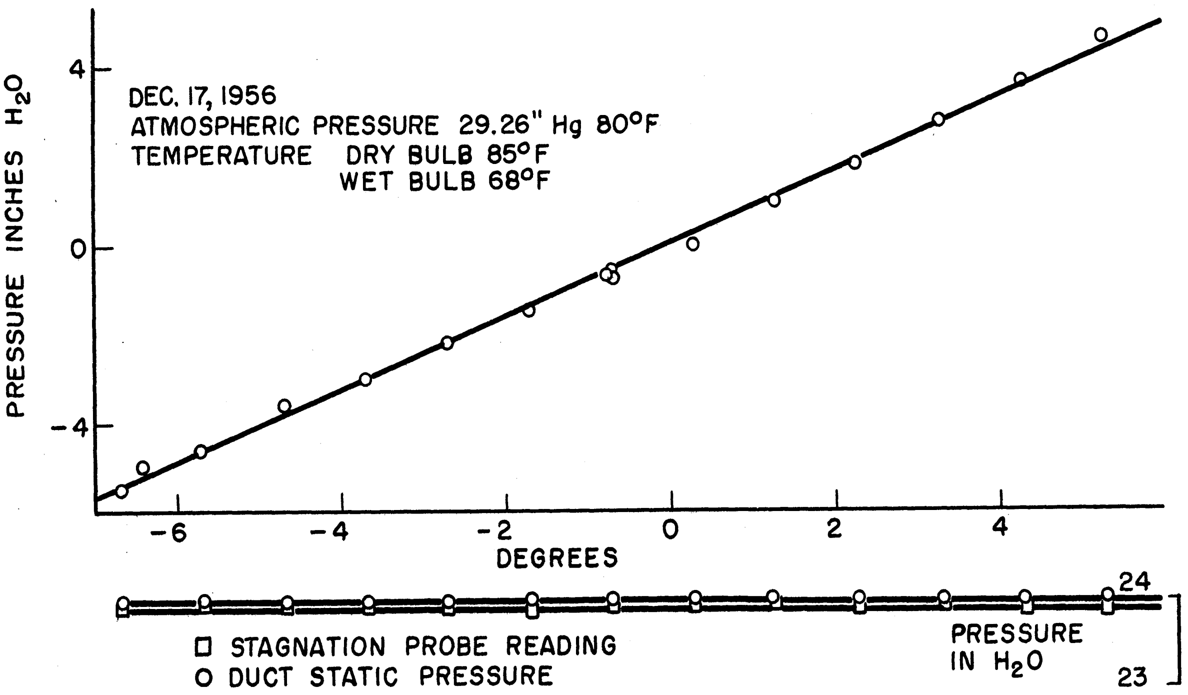


Fig. 27. Calibration curve for No. 2 stagnation probe, 3-inch length.

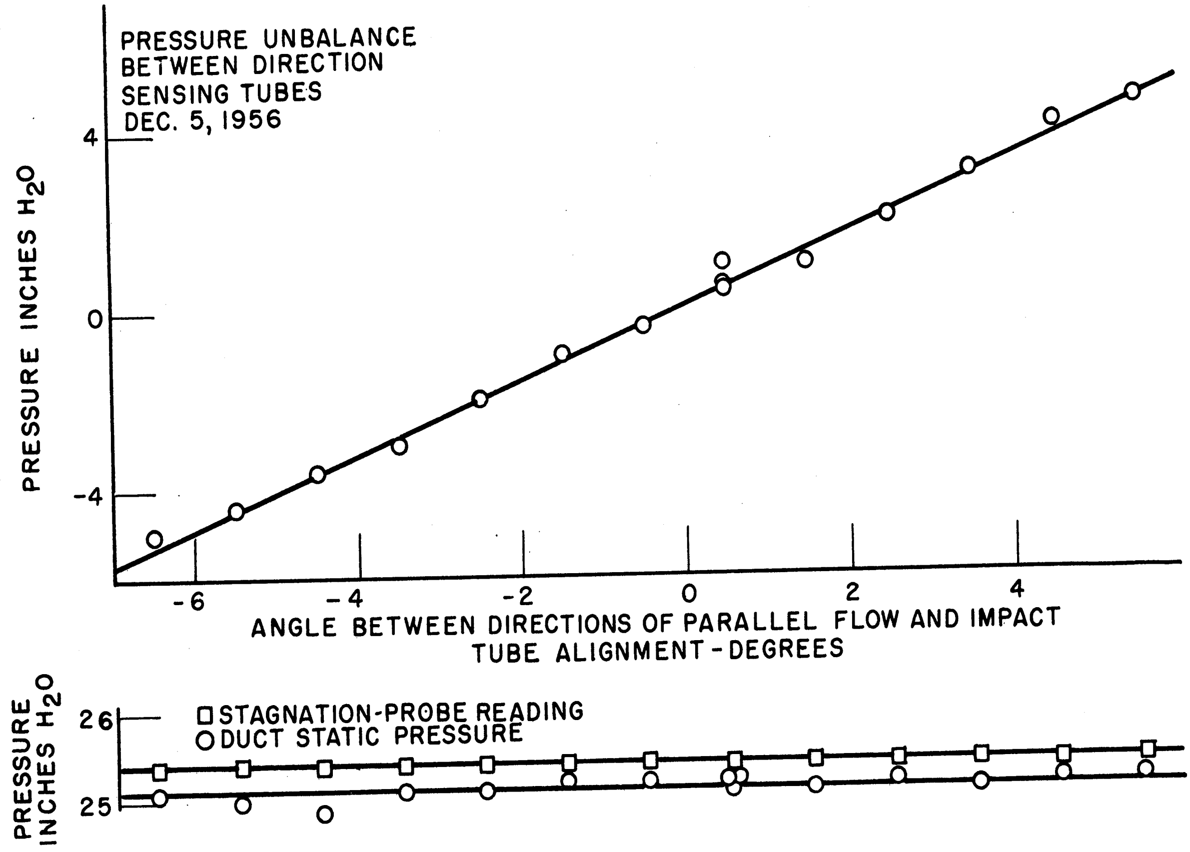


Fig. 28. Calibration curve for No. 3 stagnation probe, 3-inch length.

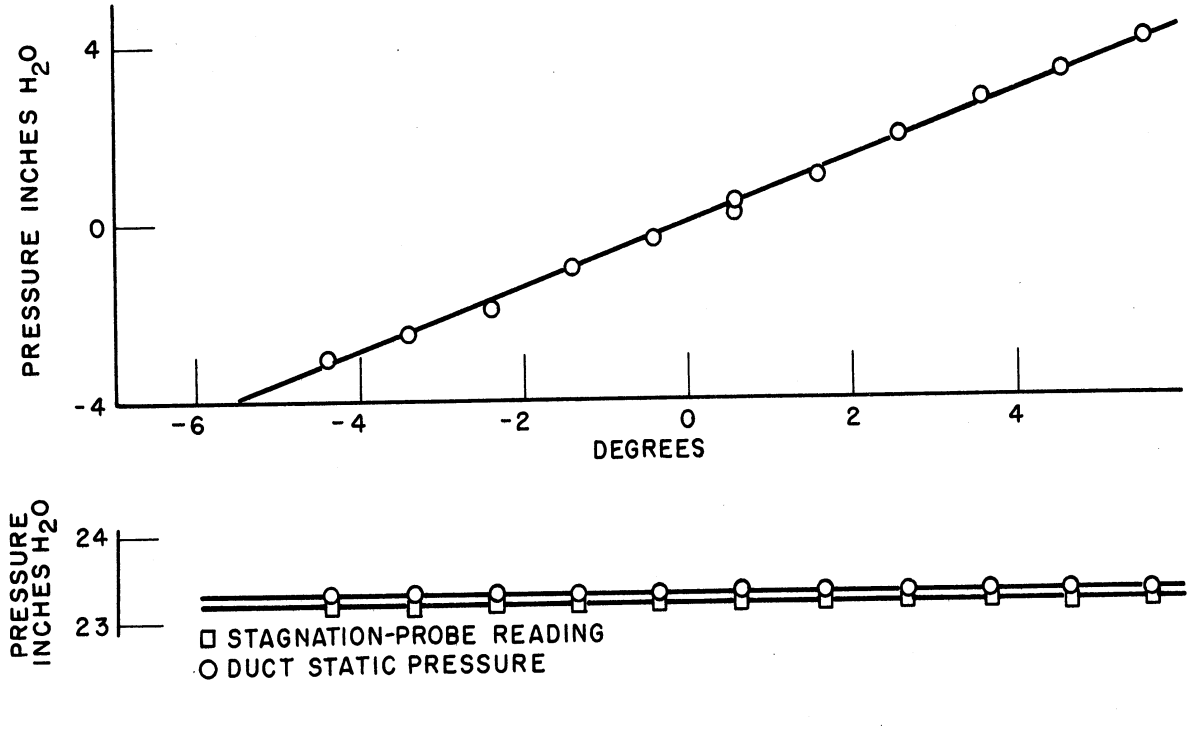


Fig. 29. Calibration curve for 6-inch stagnation probe.

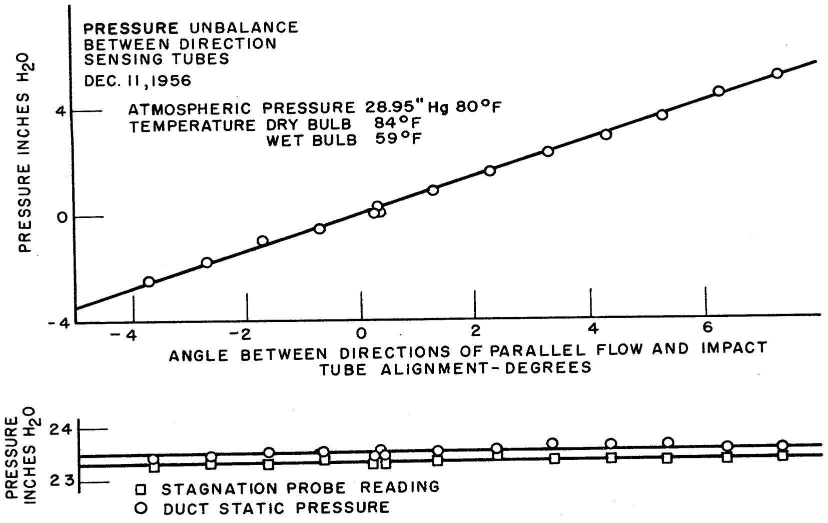


Fig. 30. Calibration curve for 24-inch stagnation probe.

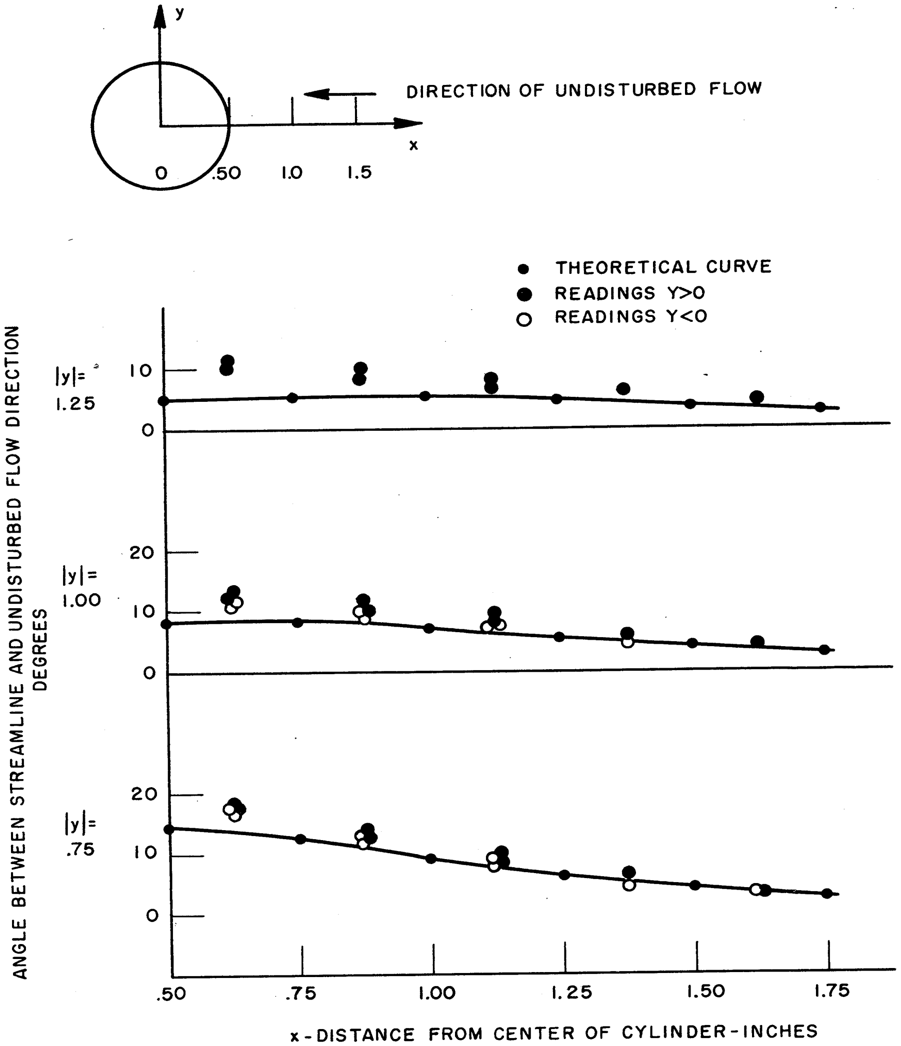


Fig. 31. Theoretical and observed flow directions upstream of a 1-inch circular cylinder with axis perpendicular to air flow from a smooth approach nozzle.

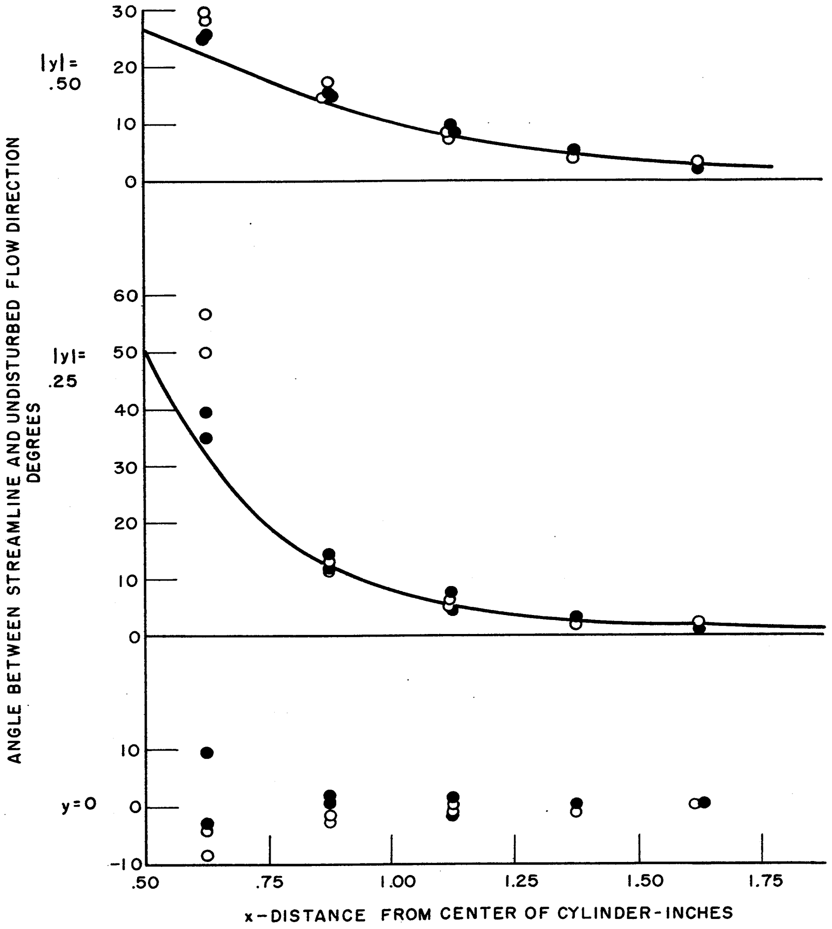


Fig. 32. Flow about a circular cylinder.

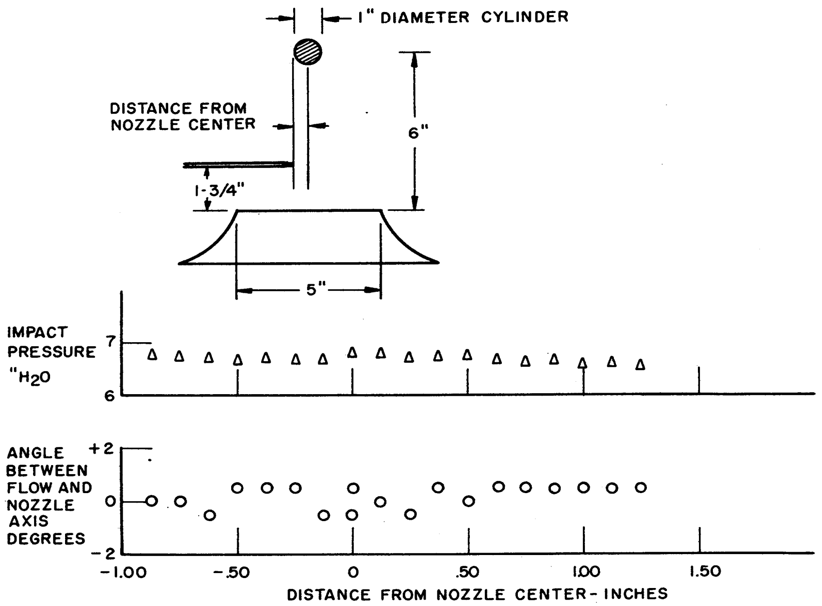


Fig. 33. Nozzle survey with circular cylinder downstream.

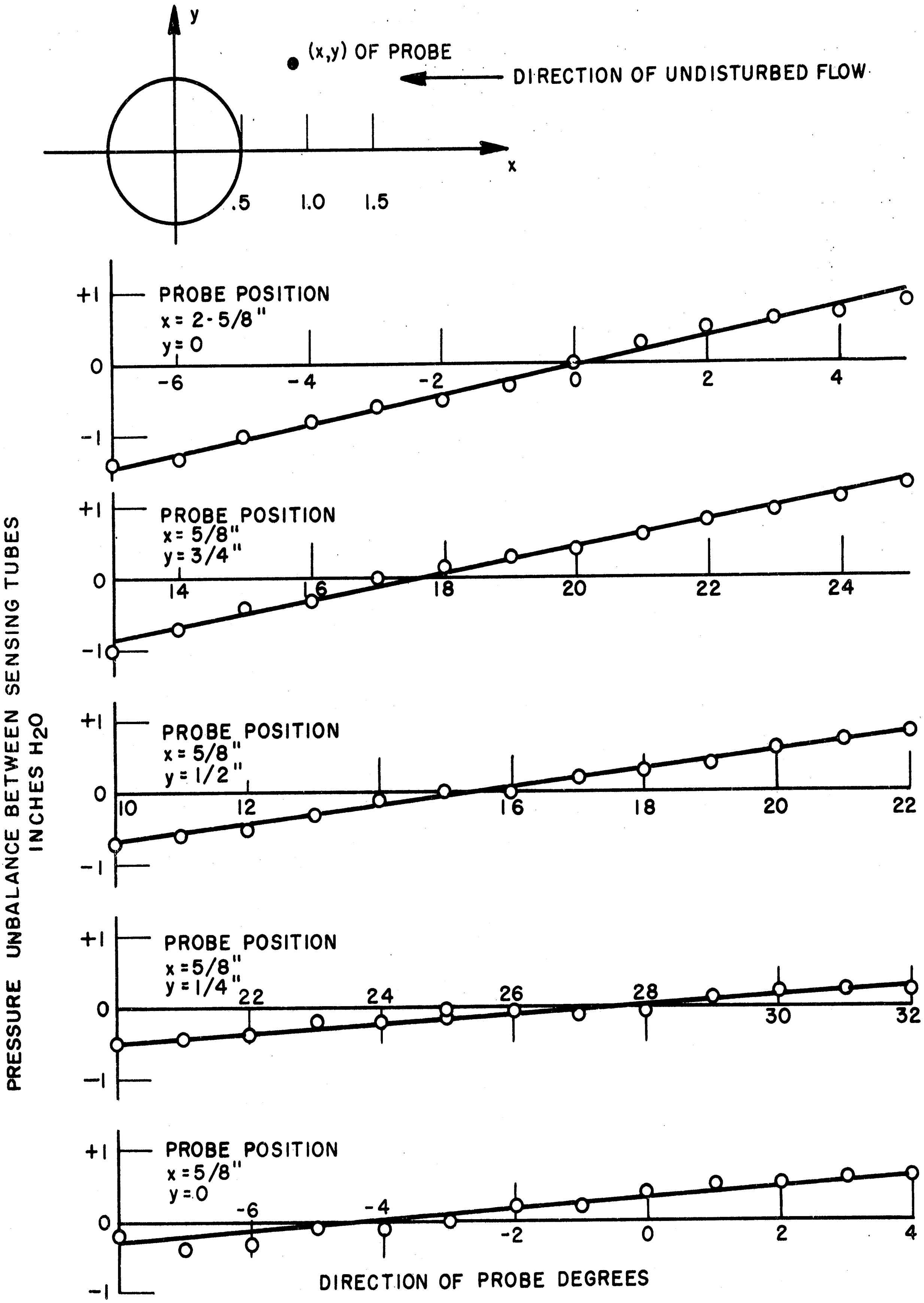


Fig. 34. Sensitivity of direction sensing tubes to rotation of probe in flow past a circular cylinder.

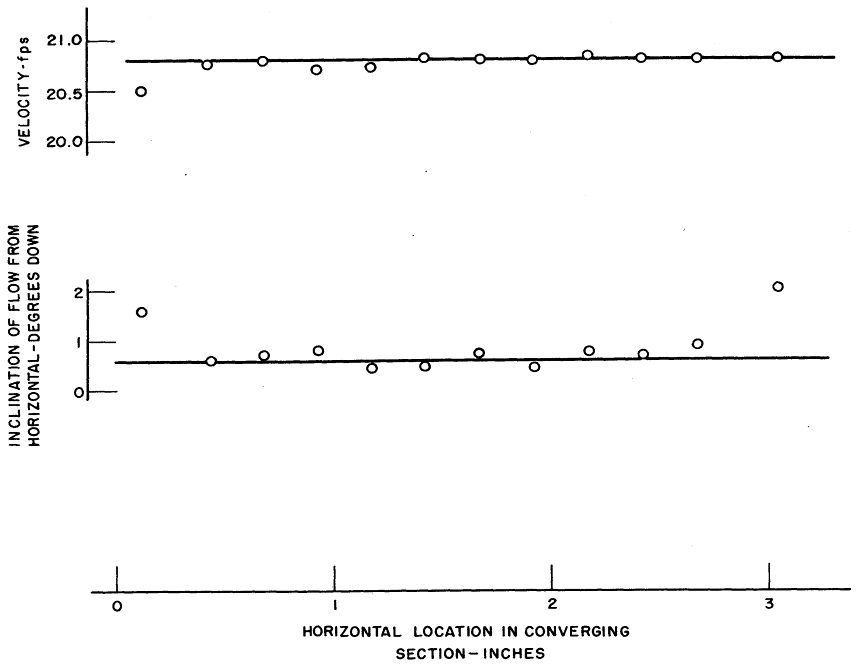


Fig. 35. Horizontal tranverse at entrance to test section.

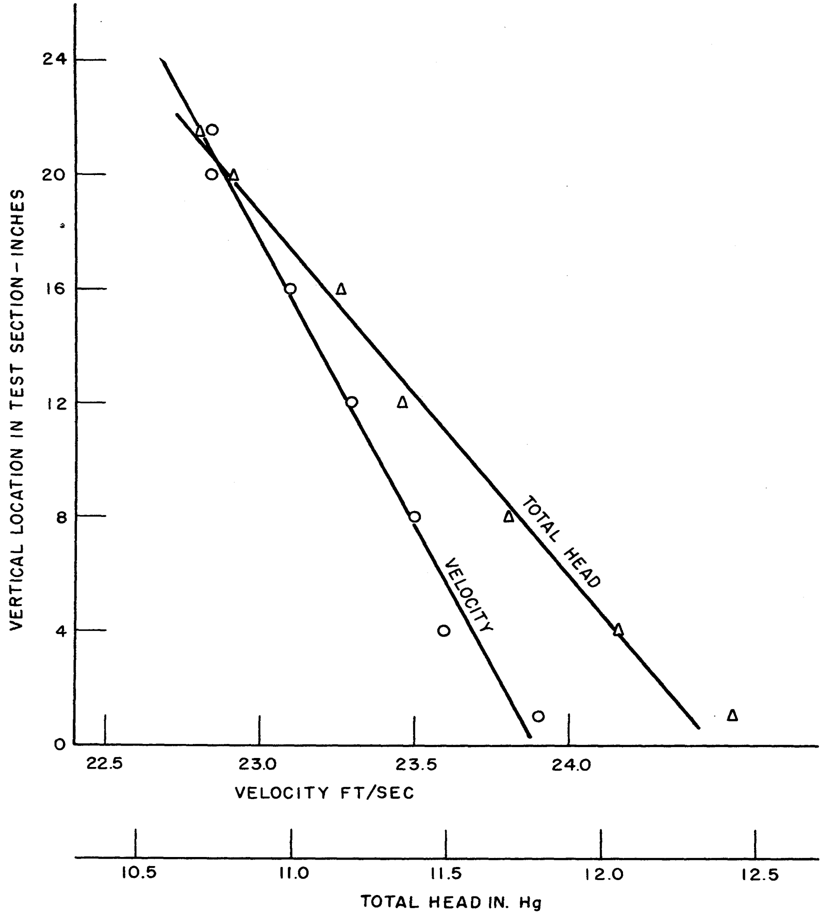


Fig. 36. Vertical traverse showing velocity and total head distribution on a line 29.75 inches from exit of test section.