MODEL EXPERIMENTS FOR THE DESIGN
OF A
SIXTY INCH WATER TUNNEL

PART I

DESCRIPTION OF APPARATUS
AND TEST PROCEDURES

by

St. Anthony Falls Hydraulic Laboratory
University of Minnesota

Project Report No. 10

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PREFACE TO REPORT SERIES

Contract NObs-34208 between the University of Minnesota and the Bureau of Ships, Department of the Navy, provides for making hydrodynamic studies in compliance with specific task orders issued by the David Taylor Model Basin calling for services to be rendered by the St. Anthony Falls Hydraulic Laboratory. Certain of these task orders related to model experiments for the design of a 60-in. water tunnel.

The end result of the studies related to the 60-in. water tunnel proposed eventually to be constructed at the David Taylor Model Basin was crystallized as a series of six project reports, each issued under separate cover as follows:

Part I	DESCRIPTION OF APPARATUS AND TEST PROCEDURES (Project Report No. 10)
Part II	CONTRACTION STUDIES (Project Report No. 11)
Part III	TEST SECTION AND CAVITATION INDEX STUDIES (Project Report No. 12)
Part IV	DIFFUSER STUDIES (Project Report No. 13)
Part V	VANED ELBOW STUDIES (Project Report No. 14)
Part VI	PUMP STUDIES (Project Report No. 15)

The investigational program was under the general direction of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory, and the work was supervised by John F. Ripken, Associate Professor of Hydraulics.

PREFACE TO PART I

Part I of the report series was prepared in accord with Task Order 2 of Contract NObs-34208.

This report was written by Harry D. Purdy, Research Fellow, who was assisted in manuscript preparation by Ethel Swan and Elaine Hulbert.

The report describes apparatus designs which were largely evolved by John F. Ripken, Associate Professor of Hydraulics; James S. Holdhusen, Research Fellow, was project leader and developed test procedures. Frank Dressel was in charge of the physical construction of the equipment.

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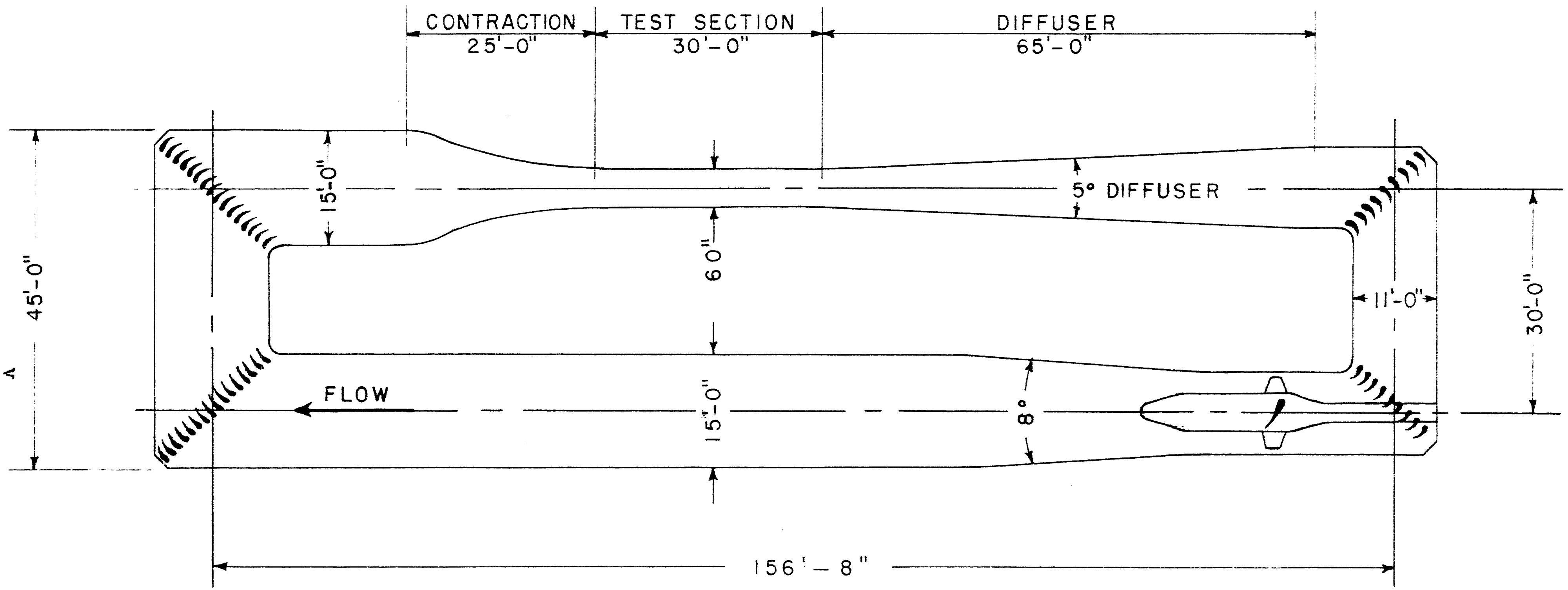

PROPOSED 60" WATER TUNNEL

DESCRIPTION OF APPARATUS AND TEST PROCEDURES

I. DESCRIPTION OF THE MODEL WATER TUNNEL AND CONTROL FEATURES

In order to execute an experimental analysis of the proposed 60-in. water tunnel design as shown in Fig. 1, a 1:10 scale model was constructed and tested at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota in the form shown in Figs. 2 and 3.

It is intended that this report shall serve as a detailed description of the model facility and its test accessories, and that it shall serve as an introductory reference to those later reports which discuss the detailed test data of the separate flow components which compose the tunnel.

A. Water Tunnel Conduits

The tunnel conduit was fabricated from aluminum castings and galvanized steel weldments. Aluminum castings were used in the critical high velocity regions including the contraction cone, test section, first section of the diffuser, and also in the structurally difficult vane frames for the miter elbows. To reduce the excessive costs incurred by construction with castings, the remainder of the tunnel conduit was fabricated of steel weldments.

Aluminum castings were used because (1) they could be readily obtained locally; (2) they could be carefully bored to the specified dimensions and finish; and (3) aluminum is resistant to corrosion and does not require a protective coating.

The contraction cone, test section, and first diffuser section were originally cast and machined in a contract shop and later rebored in the Laboratory shop with a template-following lathe set-up. The magnitude and effect of slight imperfections resulting from the machining are discussed in other Laboratory reports which deal with the separate tunnel components.

The other conduit sections were fabricated from sheet steel, which in most cases had a wall thickness of 3/16 inch. The developed sections were cut out in the Laboratory shop and rolled to the proper radius by a contract shop. The joints were then welded in the Laboratory and flanges were cut out and welded to the conduit. The inner surfaces were ground smooth manually and the flange connections were machine-faced. As a result of the inherent inaccuracies of the welding process, some of the sections were slightly out of round, and after a shop erection some joints were found to be out of alignment and were ground to give a smooth transition. As a protective coating for the inner surfaces, paint was found unsatisfactory in other tunnel installations because it peeled off. Cadmium plating would have been employed, since it gives a smooth surface which is like that of steel and is not affected by galvanic corrosion with the aluminum castings. However, since postwar procurement difficulties made the use of cadmium inexpedient, a hot-dip galvanized coating was used. This coating, although as satisfactory as cadmium would have been with respect to galvanic corrosion, is considerably rougher than the bare or plated steel. The imperfections caused by the galvanizing process were smoothed as much as possible by filing and grinding without breaking the coating, but the wall of the galvanized conduit was not as smooth as was desired.

The tunnel sections were bolted together with steel bolts and sealed with rubber "O" rings or rubber gaskets.

The aluminum castings for the vane frames were cast of Alcoa alloy No. 43 in a local foundry and finished in the shop. The aluminum vanes were formed by a special extrusion die produced by the Aluminum Company of America, and were cut and fitted in the Laboratory shop. The vanes were attached to aluminum trunnions which passed through the frame casting so that they could be set at any desired angle. The castings were grooved for rubber "O" ring seals and tapped for assembly with the other tunnel sections with machine screws.

The tunnel was supported by steel brackets mounted on a steel frame. Leveling screws spaced at frequent intervals permitted careful adjustment of the frame to accommodate variations in the level of the concrete floor on which the tunnel rested.

B. Fluid

Water used in the tunnel was taken from the city water supply of Minneapolis. After the tunnel had been in use for some time, it was disassembled in order that additional piezometer taps might be added. At this time, it was discovered that a thin layer of a yellow, sludge-like material had coated the steel sections, and that the galvanized surface had corroded in spots from 1/16 inch to 1/8 inch in diameter, leaving a white crust over each spot. No appreciable deposit of this material occurred on the aluminum surfaces. The Minnesota Department of Sanitation reported that the sludge deposition in the tunnel was probably a chemical residue left in the water as a result of the water softening process employed by the city. It was believed to have deposited as a result of the elevated temperatures occasioned by continuous tunnel operations and by extremely low (cavitation) pressures. These temperatures varied from 70° to 124° F. Monopyropentametaphosphate was recommended and later procured for use as a stabilizer to prevent deposition and to dissolve any $CaCO_3$ or alumina salts.

C. Pump

For a study of this kind, the most satisfactory pump installation would have been one especially designed and custom-built to provide the best possible head-discharge relation. However, since a primary purpose of the project was to determine the unknown head-discharge relation and to study the characteristics of the tunnel rather than those of the pump, and since postwar procurement conditions precluded the possibility of obtaining the "ideal" pump in a reasonable length of time, it was decided to use a pump of standard manufacture. Examination of the available postwar procurement conditions disclosed that a commercial pump unit satisfactory for use in the water tunnel could not be obtained in less than six months. Therefore, arrangements were made to procure the impeller unit of the most nearly suitable standard design, and to fabricate the remainder of the pump in the Laboratory shop.

The pump installed (Fig. 4) was an axial flow propeller type provided with both suction and diffuser vanes designed to produce a discharge stream substantially free of rotation. The axial flow type of pump has been used on most water tunnels, since it has less disturbing effect on the flow pattern than other types and has head-discharge characteristics in accord with tunnel head-loss characteristics. The pump characteristics desired here were determined by estimating the losses, the possibility of cavitation at the impeller, and the discharge requirements. The designed prototype impeller diameter of 11 ft called for a model pump diameter of 13.2 inches. Since the impeller obtained had a diameter of 11.96 in., it was necessary to make certain modifications in the construction of the housings for the impeller and pump diffuser.

The impeller (Fig. 5) was a bronze, three-bladed propeller type. Its dimensions were:

O D = 11.96 in.
hub length = 3 1/2 in.
hub diameter at suction = 5 3/8 in.
hub diameter at discharge = 6 1/2 in.
vane chord length at O D = 8 1/4 in.
angle of vane with shaft at O D = 12.5°

Shape of vane at O D approximated airfoil NACA 4406.

Straight suction vanes (Fig. 6) were used, since time limitations and the Laboratory fabricating facilities did not conveniently permit constructing a more desirable and complex form; in addition, the fact that the required head-discharge relations of the pump were unknown prevented the use of a more precise design. Four vanes were chosen to facilitate assembly and to prevent the possibility of synchronism of pulsing when used with the three-bladed impeller. The vane shape and chord length were selected so that the vanes could be fabricated from 1/2-in. steel flat stock by simple milling and hand-filing operations. The vanes were welded to the end of the impeller shaft housing tube, and the ends of the vanes were lathe-turned about the hub axis to give a snug fit with the conical impeller housing. The vane tips were attached to the impeller housing by bolts, and the shaft bearing was centered in the housing tube by set screws so that the vane assembly acted as the inboard shaft bearing support. The trailing edge of the vanes was arbitrarily spaced 1 1/2 in. ahead of the leading edge of the impeller blades to allow some space for flow to accommodate the unknown flow vectors without a too severe curvature.

The diffuser vanes (Fig. 7) were made straight for the same reasons that the suction vanes were made straight. Their design was based on Collar's report[*] in which he concluded that radial vanes with axial alignment provide adequate straightening if the vane is an airfoil section operating at less than the stall angle, and if it is of varying chord length so that the ratio

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[*] A. R. Collar, "Cascade Theory and the Design of Fan Straighteners," BRITISH AERONAUTICAL RESEARCH COMMITTEE REPORTS AND MEMORANDA, No. 1885.

of peripheral vane spacing to chord is unity. A spacing ratio of 0.5 gives better results, but little flow quality is sacrificed if a ratio of 1.0 is used, and the structure is thereby simplified. Therefore, a ratio of 1.0 was employed in designing the diffuser vanes. An approximate analysis showed that the impeller would probably operate with little discharge angle in the flow, so that the possibility of a stalling condition at the diffuser vanes would be remote.

Seven diffuser vanes were constructed of 1/2-in. steel flat stock. They were 6 in. wide at the outside diameter and tapered toward a point on the hub axis at a rate which gave the required ratio: $\frac{\text{peripheral spacing}}{\text{chord}} = 1.$ Seven vanes were arbitrarily chosen to give a rather short chord length and to prevent pulse flow owing to synchronism with the three-bladed impeller. The vanes were welded to the diffuser hub fairing (Fig. 7), and their ends were tapered to fit the conical diffuser housing. The assembly was held in the housing by bolts through the vane ends, so that the diffuser vanes served to support the impeller hub diffuser fairing.

The diffuser hub fairing (Fig. 7) was constructed of steel. It faired out from the impeller hub to a diameter of 6 5/8 in. for a length of 6 in., where the diffuser vanes were welded to it, and then arbitrarily faired down on a circular arc of 36-in. radius to a hemispherical end with a one-inch radius. The fairing head piece was constructed of steel pipe and was plug-welded to the tail piece, which was turned from solid steel bar. Both diffuser assemblies were rustproofed by cadmium plating.

The impeller shaft was fabricated from a 2-in. diameter 303 stainless steel rod. The shaft was threaded at the impeller to receive a retainer nut and retainer washer and was slotted for keying to the impeller hub. The shaft was grooved ahead of the impeller to hold a brass thrust ring which transferred the impeller thrust to the shaft. A bronze bearing sleeve was placed ahead of the thrust ring. This bearing was lubricated by the tunnel water and was seated in a cylindrical recess in the shaft housing. The shaft housing was supported at this point by the inboard shaft bearing support previously described and shown in Fig. 6.

The shaft was sealed at the outboard end by a lantern ring and by packing rings which were held in a cylindrical recess in the shaft housing by a packing gland bolted to a collar welded to the shaft housing. Sealing water was supplied to the lantern ring by a tap from the city water supply. The outboard end of the shaft was machined to receive the outboard bearing assembly and flexible drive shaft coupling (Fig. 5). A sealed ball bearing served as the outboard shaft bearing and acted as a combined thrust and radial bearing. The coupling was provided with insulating discs and a contact blade for use as an adjustable contact for the stroboscope, which was used in observing the impeller while in operation.

The impeller shaft was housed in a seamless steel tube 2 7/8 in. O D with a 1/4-in. wall (Fig. 5). The housing was supported at the inboard end by the inboard shaft bearing support and at the outboard end by a steel flange welded to the housing and bolted ~~to~~ a supporting frame, which was welded to the main tunnel support frame. A shaft fairing (Fig. 6) was provided to reduce flow disturbance around the impeller shaft housing. It was fabricated from 1/16-in. sheet aluminum with a chord length of 10 1/4 in., and a faired profile made up of a semicircular nose, a straight section, and a tapered tail formed of circular arcs. Space and flow considerations resulted in a final design in which the nose and tail surfaces were parallel to the plane of the miter.

Since the tunnel design called for an impeller diameter of 13.2 in. and the impeller used was 11.96 inches in diameter, special impeller and diffuser housings were required for transitions from the 13.2-in. diameter tunnel conduit to the 12-in. diameter impeller housing. The impeller and diffuser housings (Figs. 6, 7) were formed from 14-in. O D, one-inch wall, steel pipe by boring to form a smooth-tapered transition. The housings were provided with transparent viewing ports for cavitation observations, one located opposite the impeller tips and one opposite the diffuser vanes. Ports 3 1/4 inches in diameter were formed from lucite, their inner surfaces machined flush with the housing inner surfaces and bolted to flanges welded to the housing wall at a 45° angle from the vertical.

D. Pump Drive

The driving power for the pump was provided by a "Reeves" variable speed V-belt drive unit powered by a 15 hp electric motor. The mechanical principles of this drive are described in a later section of this report, Section I,F. Since any pump speed between 250 and 1500 rpm was available, a test section velocity range of about one to six could be achieved. The speed was controlled by push buttons on the control panel mounted on the pressure control mechanism and velometer housing, also described in Section I,F.

E. Pressure Measurement and Control

Existing water tunnel facilities for varying the test pressure have taken a wide variety of forms. The original Hamburg tunnel employed a vacuum pump or compressor and dual throttling control valves. The University of Iowa tunnel employed an aspirator energized by water from an elevated constant-level tank, and controlled by a throttling valve to produce relative pressure heads at the test section of +30 to -29 ft of water. The California Institute of Technology tunnel employed a regulating circuit pump, a pressure tank, and a bypass valve placed at a low level, which regulated the pressure. Cavitation conditions could be maintained in the test section for any desired test section velocity. The Massachusetts Institute of Technology tunnel employed a tilting pipe which led from the test section to the atmosphere. The free liquid surface in the atmospheric end of the pipe could be varied in elevation by tilting the pipe. The pressure in the open jet tunnel at the David Taylor Model Basin is manually controlled by a needle valve on a vacuum line.

In view of the accuracy and simplicity inherent in the use of a water manometer, and because of the unobstructed vertical space available in the St. Anthony Falls Hydraulic Laboratory (Fig. 18), it was decided to employ a modified version of the Massachusetts Institute of Technology pressure system. This mechanism permitted direct measurement and control at any of several pressure taps along the test section. The particular pressure tap employed was connected by suitable piping and flexible hose to a pan with a free surface at atmospheric pressure. Water level in the pan was maintained by a supply from the city water mains with the excess overflowing to a waste pipe; the overflow was minimized by a manual control. The pan was raised or lowered mechanically and pressure was determined by measuring the distance of the pan water surface above or below the test section to the nearest 0.01 ft of water. Pressures from +16 to -31 ft of water could be maintained at the chosen section.

There are two factors in the normal operating functions of a tunnel which may have rather large effects on the volume of tunnel fluid, and consequently on control of fluid pressure. These are the changes of volume due to absorption or release of gases in the liquid, and changes due to the loss or addition of water at the pump seal. A pressurized water seal employing a lantern ring and a city water supply outlet was used on the pump. The city water pressure at the pump seal was greater than the tunnel pressure at the pump seal under all operating conditions, and thus there was a slight flow of water into the tunnel.

Like the Massachusetts Institute of Technology tunnel, this tunnel was maintained completely full of water at all times. This was accomplished by removing all free air through float-type air vents located at the natural collection points (upstream of the contraction cone, downstream of the diffuser, and downstream of the pump diffuser [as shown in Fig. 2]). These valves were connected to a vacuum pump but were open to the tunnel only while drawing accumulated air, and thus did not establish the tunnel pressure. The dome assembly is shown in Fig. 8.

These changes in volume required a device to control the amount of water in the tunnel. The pressure control and measurement mechanism performed this function. Thus, the pressure mechanism gauge lines also acted as conduits for the tunnel supply water, which would seem to introduce a possibility of error in the manometer readings. However, since the rate of change in volume was small and the gauge lines were purposely kept large, the velocity in the gauge lines was small, and hence the friction head-loss error was never greater than the least graduation on the pressure measurement scale (0.01 ft).

The pressure measurement and control mechanism constructed for the model study was fabricated as a pilot model with a view toward studying its functional operation rather than establishing the best mechanical design. Consequently, certain components could bear considerable improvement, as will be noted. For the model study, a pressure manifold 1 1/2 in. upstream from the downstream end of the contraction cone was used as the control section. Four 1/32-in. diameter piezometer taps, carefully rounded and cleared of burrs, were located at the extremities of the horizontal and vertical diameters and were connected to the pressure manifold. Since the piezometer taps also acted to supply water to the tunnel, it should be noted that if only one tap had been used it would have had to be considerably larger than 1/32-in. to prevent a high head loss in the gauge line when flow occurred through the tap.

The manifold was connected through a valve to copper tubing which led to the pressure measurement and control mechanism and velometer housing; this housing was a 12-in., galvanized steel, spiral-welded pipe which supported and housed the pressure measurement and control mechanism and the velometer. The copper tubing, which was placed without loops to permit effective air drainage, was connected to a rubber hose within the housing. The hose was connected to a tap in the bottom of an aluminum cylindrical pan which had a free surface open to atmospheric pressure. The hose was long enough to permit raising or lowering the pan to relative heights of +16 and -31 ft, and was prevented from kinking by a pulley and weight which rode on the hose. This general arrangement is shown in Fig. 9.

Water was supplied to the pan by a separate rubber hose connected to a tap in the bottom of the pan. The supply water was obtained from a pipe to the city water supply system, to which the supply hose was connected through a valve on the side of the housing. The supply hose, as well as the connecting hose, was prevented from kinking by a pulley and weight.

For structural reasons and in order to confine the overflow waste water, the pan was mounted in a lucite cylinder, the cover of which was perforated to maintain atmospheric pressure on the free surface of the pan. Lucite was chosen for its transparency so that the graduated steel tape used to measure the position of the pan could be zeroed with the free surface of the pan. Overflow from the pan was wasted through two taps in the bottom of the lucite cylinder. The cylinder was supported by a galvanized steel cable, fastened to its cover and running to a pulley at the top of the housing and back down to an electric winch at the tunnel level, which served to raise and lower the pan. The electric winch used for the model study was provided with automatic limit stops but had no brake or inching mechanism. Consequently, run-over could not be controlled readily, and precise adjustment was obtained only by repeated raising and lowering of the pan. In a prototype installation of this character, it would be advisable to have a winch with an inertia brake and an inching mechanism.

The pan elevation was determined by means of a continuous steel tape, graduated to 0.01 ft, which ran on pulleys fastened to the top and bottom of the housing. This tape was fastened to the lucite cylinder within which the free surface pan was mounted, so that it moved with the pan. The tape was read by means of a lucite index mounted on the housing at the elevation of the center line of the test section. The tape was zeroed at the free surface of the pan, so that the reading on the tape gave the pressure head at the test section in axis in feet of water above or below atmospheric pressure. The general arrangements of this reading assembly are schematically drawn in Fig. 9 and photographed in Fig. 10.

Lateral movement of the pan was restrained by an aluminum wire guide, on each side of the lucite cylinder, running through holes in aluminum bars attached to the top and bottom of the lucite cylinder. The guide wires were tied at either end of the housing. However, with this arrangement, the pan could move laterally far enough to knock against the wall of the housing. This effect might be alleviated by using steel wire or steel rods as guides, or by using a track and trolley arrangement.

At the test section level, there was an opening in the pressure measurement and control mechanism and velometer housing which was used as a maintenance and viewing port (Fig. 10). Brackets bolted to the housing served to support the electric winch and other appurtenances.

This mechanism worked satisfactorily. The component parts were simply constructed and no complex valving or controls were required. Pressure control was positive and practically invariant, and accuracy of the pressure measurement was good. The tape was graduated to 0.01 ft so that all settings greater than one foot of water in magnitude were accurate to within one per cent.

F. Speed Measurement and Control

The four most common methods of measuring test section flow speed in water tunnels are:

1. Using the differential pressure drop across the contraction cone as measured through wall piezometer taps,

2. Using a fixed pitot tube mounted in the flow stream near the test body,

3. Using calibrated current meters or propellers mounted near the test body, and

4. Using pressure differentials in other parts of the circuit.

The first method was chosen for the model tunnel because it is probably the simplest and usually yields good results for the following reasons:

1. The pressure differential across the contraction is capable under proper conditions of yielding a reasonably accurate speed value without benefit of calibration.

2. The metering taps are located at points where the local turbulence is the most favorable in the entire circuit.

3. The metering point is adjacent to the tunnel operating station and involves minimum gauge line lengths.

4. The pressure drop can be made suitable to the available indicating gauges by placing a series of piezometer taps axially along the contraction wall and selecting the desired pressure range for use.

The differential gauge used in this tunnel to measure the pressure drop across the contraction cone was a specially built inverted U-tube, air-water manometer, as shown in Figs. 10 and 11. It could be used to measure pressure differentials up to 17 ft of water, with a least reading of 0.01 ft. Since the principal purpose of this manometer was for use in determining the velocity, it is herein called the velometer.

The pressure taps for speed determination consisted of pressure manifolds at the upstream end, midpoint, and downstream end of the contraction cone. For each manifold, there were four 1/32-in. diameter piezometer taps, carefully rounded and cleared of burrs, located at the extremities of the horizontal and vertical diameters. These enlarged to 1/8-in. pipe taps for connection to the manifolds. To avoid locating the upstream piezometer tap in the region of potential flow separation which exists near the contraction entrance, the tap was placed as far upstream as the casting structure permitted, which in the case of the model was 1 1/2 in. from the end of the casting. Subsequent boundary streamline experiments in this model contraction cone (Part II, CONTRACTION STUDIES) indicated a possible zone of separation at the upstream manifold. For this reason, it would be advisable to locate the upstream piezometer taps above the beginning of the contraction in the prototype. The middle manifold was located 17 in. downstream of the beginning of the contraction and was used whenever the differential head between the upstream and downstream manifolds was greater than 17 ft, the limit of the manometer apparatus. The downstream manifold was located 1 1/2 in. upstream of the downstream end of the contraction at a point where the minimum diameter (test section diameter) had been attained. This was the same pressure manifold generally employed for the pressure measurement and control mechanism.

The pressure manifolds were connected to the differential manometer (velometer) by copper tubing placed without loops and, wherever possible, at slopes greater than one to five, in order to provide adequate air drainage. The copper tubing was of sufficient diameter to prevent excessive damping and head loss. The copper tubes from the contraction manifolds were connected to the velometer housing, which also served as the housing for the pressure measuring and control equipment.

The general arrangement of the velometer elements is shown schematically in Fig. 11 and is described in the following text.

The downstream pressure connection was to a float chamber mounted on the outside of the velometer housing. The float chamber contained float valves controlling a compressed air and a vacuum supply so that a certain water level could be maintained in the float chamber. Compressed air and vacuum were provided by a compressor and a vacuum pump. If the free surface in the float chamber rose above a certain level, the compressed air float valve was opened, raising the air pressure in the float chamber and lowering the free surface. If the free surface fell below a certain level, the vacuum float valve opened, reducing the pressure and raising the free surface. Both valves were closed within a one-inch range at center height in the float chamber.

The copper tube leading from the downstream manifold was also connected to a large lucite cylinder, which served as the low pressure leg of the manometer. A pressure equalizer pipe connected the top of the large lucite cylinder to the top of the float chamber so that the same air pressure, and consequently the same elevation of the free surface, was maintained in both. The copper tube leading from the upstream and middle manifolds was connected to a small lucite pipe, which was mounted co-axially with the large lucite cylinder but was sealed from it. The small lucite pipe was joined to galvanized iron pipe at its top and bottom just above and just below the large lucite cylinder, as shown in Fig. 10. The lucite and iron pipe acted as the high pressure leg of the manometer.

The lower section of iron pipe extended to the bottom of the housing where it was supported by the housing. The upper section of galvanized iron pipe extended to the top of the velometer housing, where it was joined to a return elbow which housed an electrically insulated pulley. A galvanized iron pipe led from the other side of the elbow down within the velometer housing to the viewing port level, where it was connected to a pressure-sealed lucite housing containing a winch. The winch was operated by a hand-wheel on the control panel. A pressure equalizer pipe extended from the top of the large lucite cylinder forming the low pressure leg to the winch housing, so that the same air pressure above the free surface was maintained in the high pressure leg, the low pressure leg, and the float chamber.

A steel cable ran from the winch, which was electrically insulated by the lucite housing, up through the galvanized pipe to the insulated pulley with the return elbow, and then down the high pressure leg. There it was connected to an electric point contact, and, by means of an insulated guide block which prevented the cable from contacting the pipe, was connected to the zero end of a steel tape graduated to 0.01 ft. The point contact was at the elevation of the tape zero.

Two 45-volt "B" batteries, mounted on the velometer housing, supplied the electromotive force for the electrical point gauge circuit. Ninety volts were necessary to overcome the resistance of the water, which acted as part of the circuit. One battery lead was grounded to the velometer housing. The other lead ran to a neon indicator light bulb mounted in the viewing port of the velometer housing, then to the winch, through the winch to the cable, and through the cable to the point contact. Thus, when the point contact touched the free surface in the high pressure leg of the manometer, the electric circuit was closed through the water and housing, causing the indicator bulb to light.

The graduated tape, which was 25 ft in length, had a weight attached to its lower end to overcome the effect of buoyancy and keep it taut. The tape passed through a slotted guide at the base of the lucite pipe so that it could not twist. Since the tape was zeroed at the contact point, the differential head was obtained by reading the tape at the low pressure leg meniscus through the transparent lucite cylinders. The tape was graduated to 0.01 ft, so that the probable error of reading would be less than one per cent for all test section speeds greater than approximately 9 ft per sec.

Some time was required for the manometer to reach equilibrium after speed changes, and fluctuations of 0.05 ft were observed owing to the hunting action of the float valves. After equilibrium was established, the differential head could be established to the nearest tape graduation (0.01 ft).

Experience with this velometer established that the general method of using a direct-reading water manometer for velocity determinations was satisfactory, but certain mechanical refinements were necessary to assure long-time, trouble-free operation.

Speed control of the electric motor driving the pump unit was obtained by a Reeves variable diameter V-belt transmission which gave an infinitely variable output speed between 250 and 1500 rpm, corresponding to test section velocities of 8 to 50 ft per sec. Variable speed was obtained by means of a V-belt driving between two pairs of cone-shaped discs, which were adjustable to form an infinite number of driving and driven diameters. The discs were mounted on parallel shafts. One shaft received power at constant speed from the electric motor. The other shaft delivered power at infinitely adjustable speeds as the V-belt assumed different diameters of contact against each set of discs.

Push buttons for starting and stopping the drive motor and the electric motor controlling the movable disc positions were located on the panel above the viewing port of the pressure control and measurement mechanism and the velometer housing (Fig. 10). A tachometer indicating pump shaft speed was also mounted here and served to give approximate values for establishing the test section speed, with more precise values being read on the slower acting velometer.

This speed control mechanism worked satisfactorily; any speed within the drive range could be readily obtained by push-button control of the variable speed transmission.

II. TEST APPARATUS

The main features of the test program involved making velocity traverses at different cross sections of the tunnel circuit and determining the tunnel pressure gradient under different rates of flow. The following section describes the test apparatus and procedure used in the course of the experimental work.

A. Pitot Cylinders

Pitot cylinders were used to determine velocity distributions at various tunnel cross sections. Two types of pitot cylinders were used: the "cantilevered" pitot cylinder, which is so-called because it is supported from the insertion point in only one duct wall (Fig. 12); and the "long" pitot cylinder, which completely spans the duct on a diameter and has physical support at each of the two points where it breaches the duct wall (Fig. 13). The direction of flow was determined by orienting the pitot cylinder so that the pressure at the two metering holes was the same. Velocity was determined by measuring the total head on one metering hole when it was pointed directly into the stream.

The pitot cylinders were not calibrated for this study. A study made at the St. Anthony Falls Hydraulic Laboratory* indicated that neglect of the pitot cylinder coefficient introduced an error of less than one-half per cent in obtaining the average energy over a cross section.

1. The Cantilevered Pitot Cylinder

For the purpose of analyzing the energy conditions in the principal tunnel components, pitot traverse stations were constructed at strategic points along the tunnel circuit. The location of these stations is shown in Fig. 14.

Every traverse station, except the two in the test section and the one immediately upstream of the pump, consisted of a ball-and-socket mounting and three 3/8-in. taps (Fig. 12). The station immediately upstream of the pump consisted of four 3/8-in. taps. The cantilevered pitot cylinders were designed for use at all stations except the two in the test section. The principal cantilevered pitot cylinder (Figs. 15, 16) was designed primarily for use in the ball-and-socket mountings. The barrel of this pitot cylinder was constructed of 3/8-in. OD, 0.032-in. wall, brass tubing; the nose was constructed from a 3/8-in. brass rod 1 1/2 in. long, machined at the end to a hemisphere of 3/16-in. radius. Two No. 32 drill holes were drilled axially in it, and, in order to intersect these axial holes, the metering

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*THE PITOT CYLINDER, Circular No. 1, St. Anthony Falls Hydraulic Laboratory, October, 1947.

holes were drilled radially at a central angle of 80°, at a point two barrel diameters (3/4 in.) from the end of the nose. The nose piece was turned to give a push fit in the bore of the 3/8-in. barrel.

The two pressure passages in the barrel of the pitot cylinder were formed by threading two rubber rods 1/8 in. O D through the No. 32 holes in the nose piece and continuing them through the pitot barrel and out the open end. With the tube in a vertical position and the rubber rods stretched taut to avoid contact with each other, the tube was poured full of molten "Cerrobend" (a commercial alloy similar to Wood's metal and having a melting point of 158° F.). After cooling, the rubber rods were pulled free and the No. 32 holes in the tip of the nose piece were sealed.

The method of "casting in" pressure passages by use of a removable rubber rod is believed an innovation and has proved very satisfactory.

The pitot barrel was hard soldered to the pitot slider (Fig. 15), a 2-in. diameter brass disc bored axially to a slide fit on the pitot support tubes, and bored radially with two 3/16-in. holes to intersect the barrel pressure passages. These 3/16-in. holes enlarged to 1/8-in. pipe taps to receive brass cocks to which the gauge lines could be connected. The pitot support tubes were two 5/8-in. O D, 0.032-in. wall, brass tubes hard soldered at each end to two 2-in. O D brass discs, the pitot supports. A scale having 0.10-in. intervals was scribed on one of the pitot support tubes to form Scale A, which was used to determine the distance from the metering holes to the tunnel wall. The outer face of the pitot slider was the index for Scale A.

The inner pitot support was fitted to a brass sleeve, which was drilled axially to a sliding fit with the barrel of the pitot cylinder and turned to fit the spherical trunnion. A 180° transparent protractor was mounted on the inner face of the inner pitot support and served as Scale C, which was used to determine the direction of the flow. It was read by an index scribed on the spherical trunnion.

The spherical trunnion served as a ball-and-socket mounting for the pitot cylinder. It was fabricated from a 2-in. steel ball bearing and was drilled radially to receive a shaft, the pitot barrel, and the inner pitot support. A rubber "O" ring sealed the pitot barrel and spherical trunnion. The spherical trunnion was seated in a brass base plate bolted to the tunnel.

The spherical trunnion shaft turned in a brass bearing at either side of the trunnion. A 90° protractor was mounted on one of the bearings and served as Scale B, which was used to give the angle of the pitot barrel from the horizontal. Scale B was read by means of a transparent index attached to the spherical trunnion.

The mechanism functioned so that the pitot cylinder openings could be placed at any point in the traverse station cross section, except for a small area adjacent to the boundary of the cross section. At each section, in addition to the ball-and-socket mounting, a 3/4-in. steel boss drilled with a 3/8-in. hole was welded to the tunnel at the other three 90° points. The nipples were bored to a sliding fit with the 3/8-in. cantilevered pitot cylinders, so that the cantilevered pitot cylinders could be traversed on a diameter through these mountings, as well as swung on the trunnion mounting.

The cantilevered pitot cylinders had one major defect: at certain speeds when the barrel extended into the flow a distance of from one-half to two-thirds of the tunnel cross section diameter, the cylinder vibrated to such an extent (amplitudes up to one inch) that it could not be used. At other settings, however, the pitot cylinder did not vibrate appreciably. The pitot cylinder was also deficient in that the drag force occasioned by high velocities caused an elastic deflection of the cantilever such that the tip was not normal to the tunnel axis. Although care was exercised in the construction of the pitot cylinders and their indexes, it is believed that, even under ideal tunnel conditions, the angularity of flow measurements was accurate to only 1 1/2°.

Aside from these characteristics, the cantilevered pitot cylinders functioned satisfactorily. However, the cantilevered cylinders (Fig. 17 [a] and [b]), which were similar to the principal pitot cylinder except for not having pitot support tubes, failed after continued use. In each case, they failed at one of the rings which had been scribed on the pitot cylinder barrel to form Scale A. The fractures were probably due to progressive cracking at these breaks in the surface, caused by continued vibration and crystallization of the hard-drawn brass tube.

2. The Long Pitot Cylinder

Velocity traverses at the upstream and downstream ends of the test section were obtained with a long pitot cylinder (Fig. 17 [c] and Fig. 13).

The pitot cylinder barrel was constructed of a 0.257-in. O D, 0.050-in. wall, stainless steel tube. The center piece of the pitot cylinder was constructed of a one-inch long stainless steel rod. The ends of the rod were turned to a snug fit in the barrel of the tubes. The 0.0225-in. diameter metering holes were drilled radially in the center piece at a central angle of 80° to intersect 1/32-in. drill holes bored from each end of the center piece. A scale graduated to 0.05 in. was scribed on the barrel to serve as Scale A, used in determining the distance of the metering holes from the tunnel wall. Near one of the extremities of the barrel, a 5 1/2-in. long 1/4-in. brass tube was hard soldered to the pitot barrel at right angles for use in determining flow direction. The pitot cylinder was aligned in the upstream direction by adjusting the cylinder so that the brass tube was parallel to the flange at the end of the test section. The rubber tubes leading to the differential gauge were connected to either end of the cylinder barrel.

The long pitot cylinder was mounted in a one-inch steel disc machined to fit as a flange at either end of the test section (Fig. 13). A hole was drilled radially through the flange to a sliding fit with the pitot cylinder barrel. The hole was enlarged at either end and tapped to receive 3/4-in. brass retainer nuts, which served to retain and seal the pitot cylinder barrel in the steel disc. A transparent lucite protractor, Scale C, was mounted on the steel flange plate to give the angularity of flow. The top of Scale C served as an index for Scale A. A scribed line on a lucite strip, mounted on a brass sleeve sliding on the pitot cylinder barrel, served as an index for Scale C.

This pitot cylinder functioned satisfactorily. However, another cylinder of this type had been previously constructed of 3/16-in. diameter drawn brass tubing, and it failed after approximately 10 hours usage at a test section velocity of 30 ft per sec, when the cylinder fractured near the center piece. The failure was probably due to progressive cracking caused by the high rate of vibration and metal fatigue.

The central angle of 80° between metering holes used for the pitot cylinders was chosen for the reason that the pressure curve for flow around a cylinder is very steep at points at central angles of 40° from the stagnation point, and consequently a small directional change would cause a large pressure change (measurement shows a change of 5 to 10 per cent of the velocity head per degree in this region). The position of the metering holes takes advantage of this steep gradient to increase directional sensitivity.

For the cantilevered pitot cylinder, proximity of the measuring hole to the tip of the cylinder may affect the pressure at the metering hole. At a Reynolds number of approximately 30,000, a hole at a distance of two diameters from the tip will result in an error of less than one per cent. This distance was adopted in the design of the cantilevered pitot cylinders.*

B. Manometers

Two types of manometers were used in connection with the pitot cylinders: a 50-in. glass U-tube manometer, and an inverted U-tube water micromanometer (Fig. 3). The micromanometer was used wherever the differential head was less than 6 in. of water; in all other cases the 50-in. glass U-tube manometer was used. Four different metering fluids--carbon tetrachloride, ethylene bromide, bromoform, and mercury--were used in the 50-in. manometer. The metering fluid giving the maximum permissible deflection was used for a particular traverse.

The micromanometer was an inverted U-tube with an air loop. It was read by two micrometer depth gauges, which were used as inverted point gauges carefully set at the same elevation; they could be read to the nearest 0.001 inch. Water levels and air pressure in the micromanometer were controlled by a hand pump and bleed-off valve.

III. TEST PROCEDURE

Testing of the water tunnel consisted of calibrating the velometer and speed control, making velocity traverses at the different tunnel sections, making wall pressure traverses around the tunnel circuit, and determining the cavitation index.

A. Calibration of the Velometer and Speed Control

Calibration of the velometer and pump speed-test section speed relations was accomplished by a primary weight discharge measurement. The apparatus used is shown in Fig. 18. Water was supplied by tapping existing piping from the main Laboratory supply channel, which takes water from the

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* *Ibid.*

Mississippi River. Discharge was piped to the Laboratory weighing tanks where it was weighed by the twin tank method.

The Laboratory's twin weighing tanks, having a capacity of 40,000 lb per tank accurate to 5 lb, can be used to measure flows up to 12 cu ft per sec. The accuracy of the weighing tanks was checked through weight measurements by use of a smaller tank and platform scales (Fig. 18) before the calibration was begun. Since, by the twin tank method, each discharge measurement can be made over as long a time as desired, thus eliminating the timing error, the accuracy is principally dependent on the scale error, which in this case is very small.

Twenty-two runs were made; their durations varied from 30 min for low discharges to 15 min for high discharges. Test section velocities from 9 to 47 ft per sec were obtained. The number of tanks used per run varied from 4 tanks for the low discharges to 18 tanks for the high discharges. During each run, the velometer (using the upstream and middle contraction pressure manifolds alternately wherever possible), the motor rpm, the speed ratio indicator, and the tachometer were read. Using these data, velometer-test section velocity and tachometer-test section velocity relations were obtained, and a tachometer dial reading in test section velocity was constructed.

The function of the velometer depends on the transformation of pressure energy to kinetic energy in the contraction in accord with:

$$\frac{p_{12}}{\gamma} + \alpha_{12}\frac{\bar{V}_{12}^2}{2g} = \frac{p_1}{\gamma} + \alpha_1\frac{\bar{V}_1^2}{2g} + h_f \tag{1}$$

where

$\frac{p_{12}}{\gamma}$ = pressure head at Station 12 (upstream of contraction)

$\frac{p_1}{\gamma}$ = pressure head at Station 1 (downstream of contraction)

$\bar{V}_{12}$ = average velocity at Station 12

$\bar{V}_1$ = average velocity at Station 1

$\alpha = \frac{\Sigma V^3 dA}{A \bar{V}^3}$

V = local velocity at an increment of area

A = cross-sectional area of flow

It was necessary to determine whether this transformation of energy would be affected by recirculating the flow, that is, whether the values of α would be different for non-recirculating flow used during testing. Entrance conditions for the non-recirculating flow (Fig. 18) involved an inlet pipe at an angle to the plane of the tunnel connected to the tunnel by a 90° elbow. Measurements determined that this resulted in a contortion of flow which persisted through the tunnel, as shown in Fig. 19.

For this reason, velocity traverses were made at Sections 12 and 1 at test section velocities of 30 ft per sec for non-recirculating flow (Figs. 19, 20), and at test section velocities of 18, 30, and 50 ft per sec for recirculating flow. The latter traverses are shown in Part III, TEST SECTION AND CAVITATION INDEX STUDIES. α values were then computed, the summation being made by finite increments. The resulting α values (Table I) indicate that the difference in α values for the two flow conditions is negligible at Station 12 and that the two are the same for Station 1. Consequently, the difference in α values was neglected and the calibration of the velometer for non-recirculating flow was assumed to apply to the recirculating flow. From Eq. (1) [neglecting h_f for purposes of comparison],

$$\frac{p_{12} - p_1}{\gamma} = \alpha_1 \frac{\bar{V}_1^2}{2g} - \alpha_{12} \frac{\bar{V}^2}{2g}$$

From continuity and section area relations,

$$\bar{V}_{12}^2 = 0.0123\, \bar{V}_1^2$$

Then,

$$\frac{p_{12} - p_1}{\gamma} = (\alpha_1 - 0.0123\, \alpha_{12}) \frac{\bar{V}_1^2}{2g}$$

Considering the assumption that the calibration is applicable to both types of flow (α values assumed equal), then for equal indicated values of

$$\frac{p_{12} - p_1}{\gamma},$$

$$\frac{\bar{V}_{1_g}^{\,2} \left(\alpha_{1_g} - 0.0123\ \alpha_{12_g}\right)}{V_{1_c}^{\,2} \left(\alpha_{1_c} - 0.0123\ \alpha_{12_c}\right)} = 1$$

where the subscript g refers to non-recirculating flow and the subscript c refers to circulating flow, and

$$\frac{\bar{V}_{1_g}}{\bar{V}_{1_c}} = \sqrt{\frac{\alpha_{1_c} - 0.0123\ \alpha_{12_c}}{\alpha_{1_g} - 0.0123\ \alpha_{12_g}}} \tag{2}$$

If the α values are inserted in Eq. (2), a ratio is obtained which will show the error resulting from this assumption. Then, for $\bar{V}_1 = 30$ ft per sec,

$$\frac{\bar{V}_{1_g}}{\bar{V}_{1_c}} = \sqrt{\frac{1.0022 - 0.0123 \times 1.071}{1.0022 - 0.0123 \times 1.058}} = 0.99992$$

(α_{12} for $V_1 = 50$ ft per sec had to be used since α_{12_c} for $V_1 = 30$ ft per sec was not determined.) Thus, the error in measured velocity introduced by neglecting the change in the flow pattern between the recirculating and non-recirculating flow is estimated at only 0.008 per cent.

The calibration data (pressure drop versus mean velocity of flow) were plotted to a large scale, and the equation of the line of best fit was computed by the method of least squares. The data are presented in graphical form in Fig. 21.

Table I

Values of α for Stations 12 and 1

Test Section Velocity	Station No.	α Non-recirculating Flow	α Recirculating Flow
18 ft per sec	12		
	1		1.0012
30 ft per sec	12	1.058	
	1	1.0022	1.0022
50 ft per sec	12		1.071
	1		1.0010

B. Velocity Traverses

Velocity traverses for purposes of analysis were taken at the various tunnel stations at test section speeds of 18, 30, and 50 ft per sec, depending on the need. The procedure for taking velocity traverses depended on whether the ball-and-socket mounting or the pipe nipple mounting was used with the pitot cylinder. A definite pattern of points where readings were to be taken was established for use with the ball-and-socket mountings so that a complete picture of velocity distribution would be obtained within the limits of the apparatus. When the other mountings were used for taking velocity traverses along a diameter, the points of measurement were determined by the character of the particular station.

Before each series of measurements was taken, the tunnel speed had to be established. If measurements were to be made at Stations 12, 1, and 2, the tunnel speed was established before the pitot cylinder was inserted in the flow, since the flow disturbance it caused would affect the velometer readings. For measurements at other stations, the speed could be controlled while the pitot cylinder was inserted into the tunnel.

After the pitot cylinder had been examined to see that its metering holes and passages were clear, it was inserted in the tunnel and connected to the manometer by rubber tubing. Since flow disturbance caused by insertion of the pitot cylinder would affect any nearby piezometer taps, a station either upstream or downstream was selected as a static pressure reference. One leg of the manometer was provided with two connections and the static pressure tap was connected to one of these by rubber tubing.

When all connections had been made, the pressure pan was raised to a high level and the gauge lines were bled of air individually and examined for leaks. Then the manometer was checked to see that it zeroed properly for all combinations of pressure connections to be used. Next, the pan was set at an elevation which would produce wherever possible a static pressure approximating atmospheric at the measuring stations, and finally, the pump was started and the traverse was begun.

The cantilevered type pitot cylinder, when used in the ball-and-socket mounting (Fig. 12), was inserted into the tunnel by placing the nose of the pitot cylinder in the spherical trunnion, rotating the trunnion, and pushing the pitot cylinder into the tunnel by means of the pitot slider. The desired distance of the metering holes from the wall was determined by use of Scale A (Fig. 16), since, for the ball-and-socket mountings, the reading on Scale A for the metering holes at the wall had been determined by observation before assembly of the tunnel. The angular difference between the pitot cylinder and the diameter through the trunnion was set on Scale B (Fig. 16), and the angularity of flow was then determined.

This was accomplished by opening the two gauge lines from the pitot cylinder to the manometer, and rotating the pitot cylinder about its axis until the manometer was zeroed, that is, equal pressure existed in both legs. At this point the pitot cylinder faced into the flow, and the angularity of flow was read on Scale C (Fig. 16). The pitot cylinder was then rotated 40° so that one of the metering holes faced into the flow, and then, with the gauge line from the other metering holes closed and the gauge line from the pressure reference tap opened, the indicated deflection of the manometer was read as the apparent velocity head. The procedure was then repeated for the other points in the traverse. In order to give the true velocity head for computing velocities, the apparent velocity heads were corrected for the difference in static pressure between the station being traversed and the reference station.

Operation of the cantilevered pitot cylinder in the pipe nipple mounting was similar to its operation in the ball-and-socket mounting. Since only the diameter could be traversed for these mountings, Scale B was not used. Scale C was read by means of a brass index bolted to the tunnel. The pitot cylinder was placed in the tunnel by lowering the pressure pan until a vacuum condition existed at the mounting, removing the mounting cap, and then inserting the pitot cylinder. A coupling screwed to the mounting and the inner pitot support held the pitot cylinder in place. The reading on Scale A when the metering holes were at the wall was determined by moving the nose into the tunnel in small increments and observing the reaction of the manometer to a rotation of the cylinder. The first point at which the manometer responded was taken as the wall reading.

The cantilevered pitot cylinders which were not equipped with pitot support tubes were held in the mounting by a retainer nut which acted as an index for Scale A. For these pitot cylinders, Scale C was fastened to a brass collar which rode on the barrel, and the pitot cylinder was oriented by means of a brass pointer soldered to the pitot barrel so that it was parallel to station. These data were used to compute wall pressure traverses and energy relations around the tunnel, and they are further discussed in Part VI, PUMP STUDIES.

LIST OF ILLUSTRATIONS

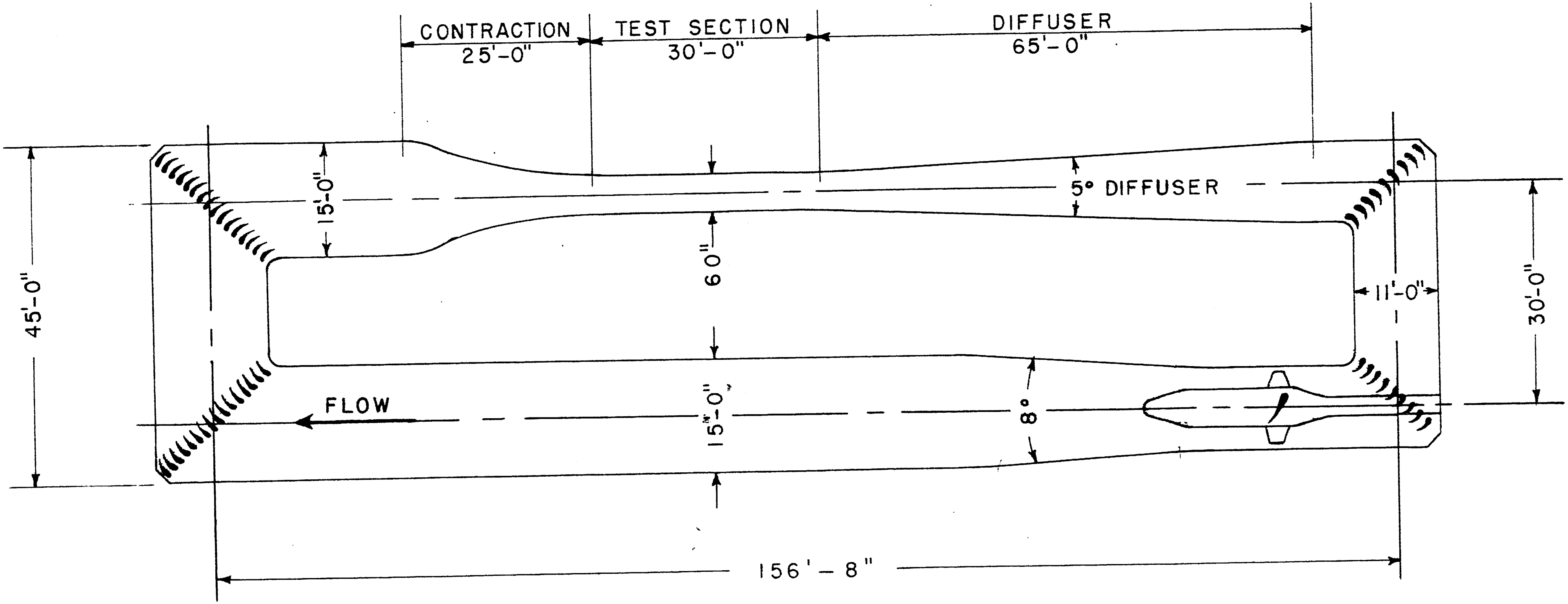


FIG. 1
PROPOSED 60" WATER TUNNEL

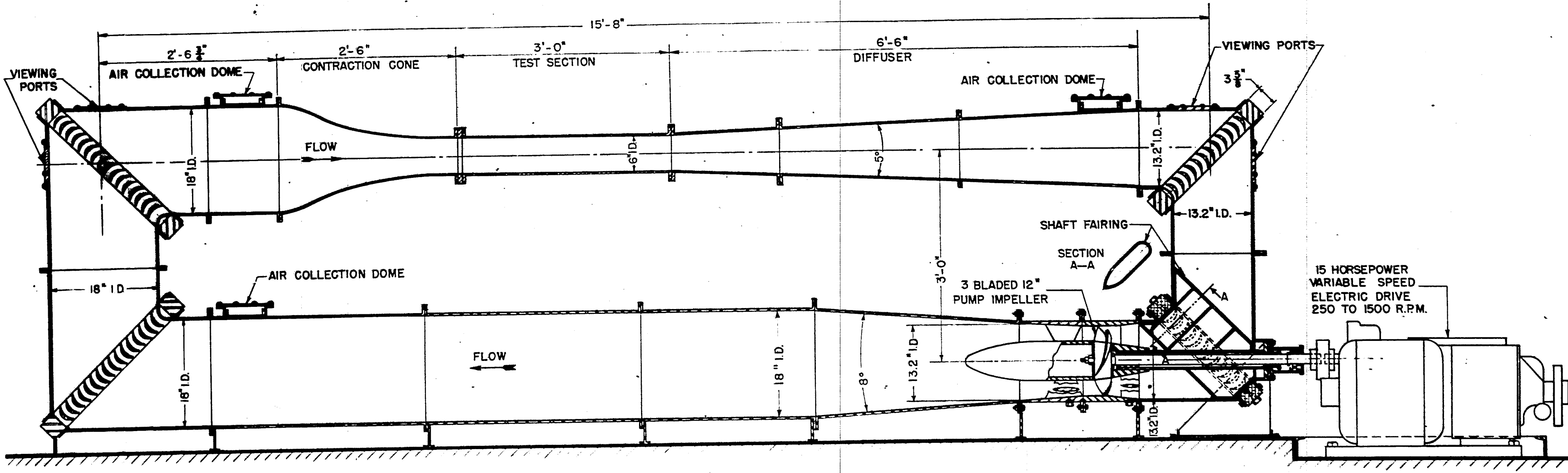


FIG. 2 SCHEMATIC DRAWING OF 6 IN MODEL WATER TUNNEL

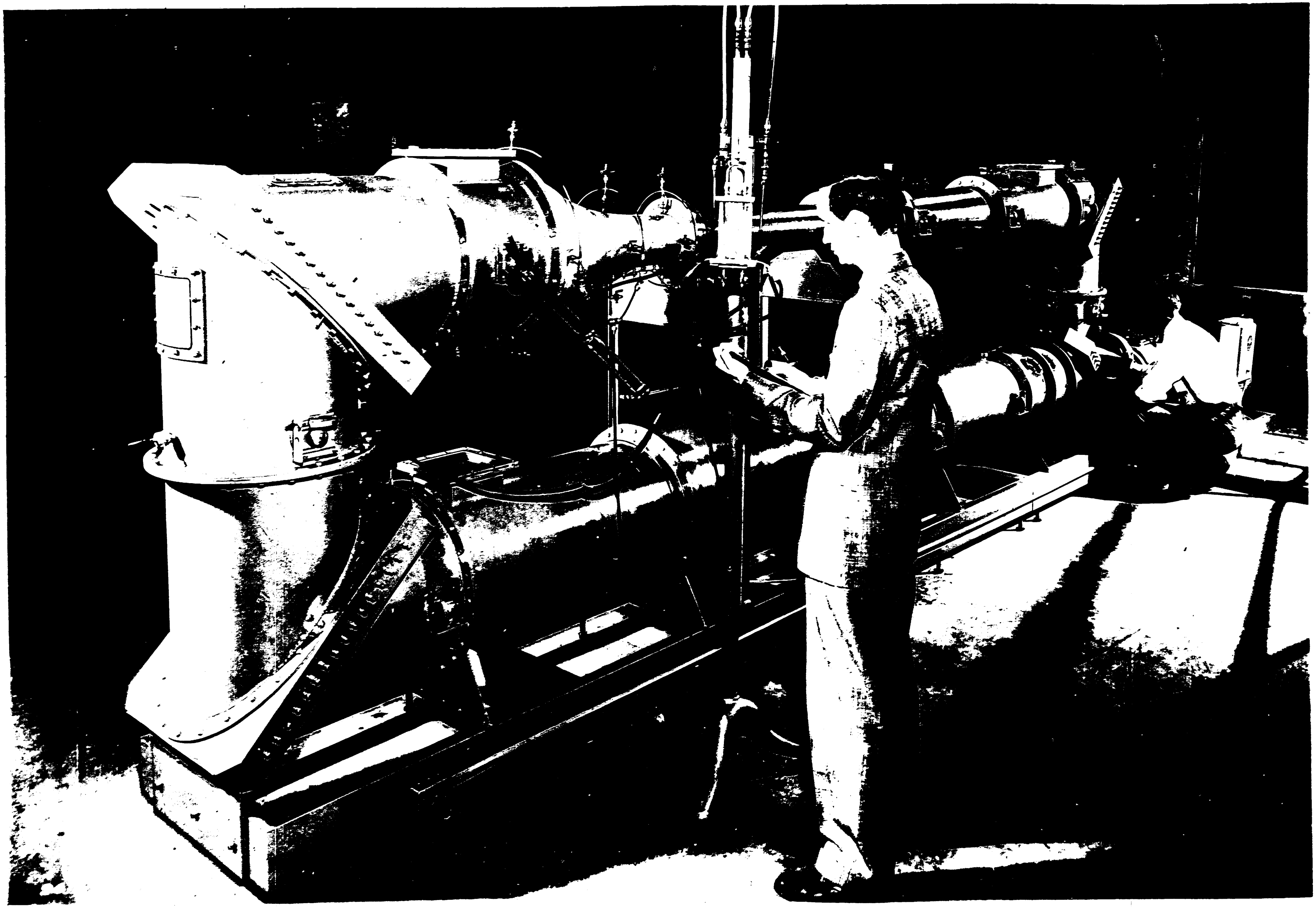


Fig. 3. General View of Tunnel

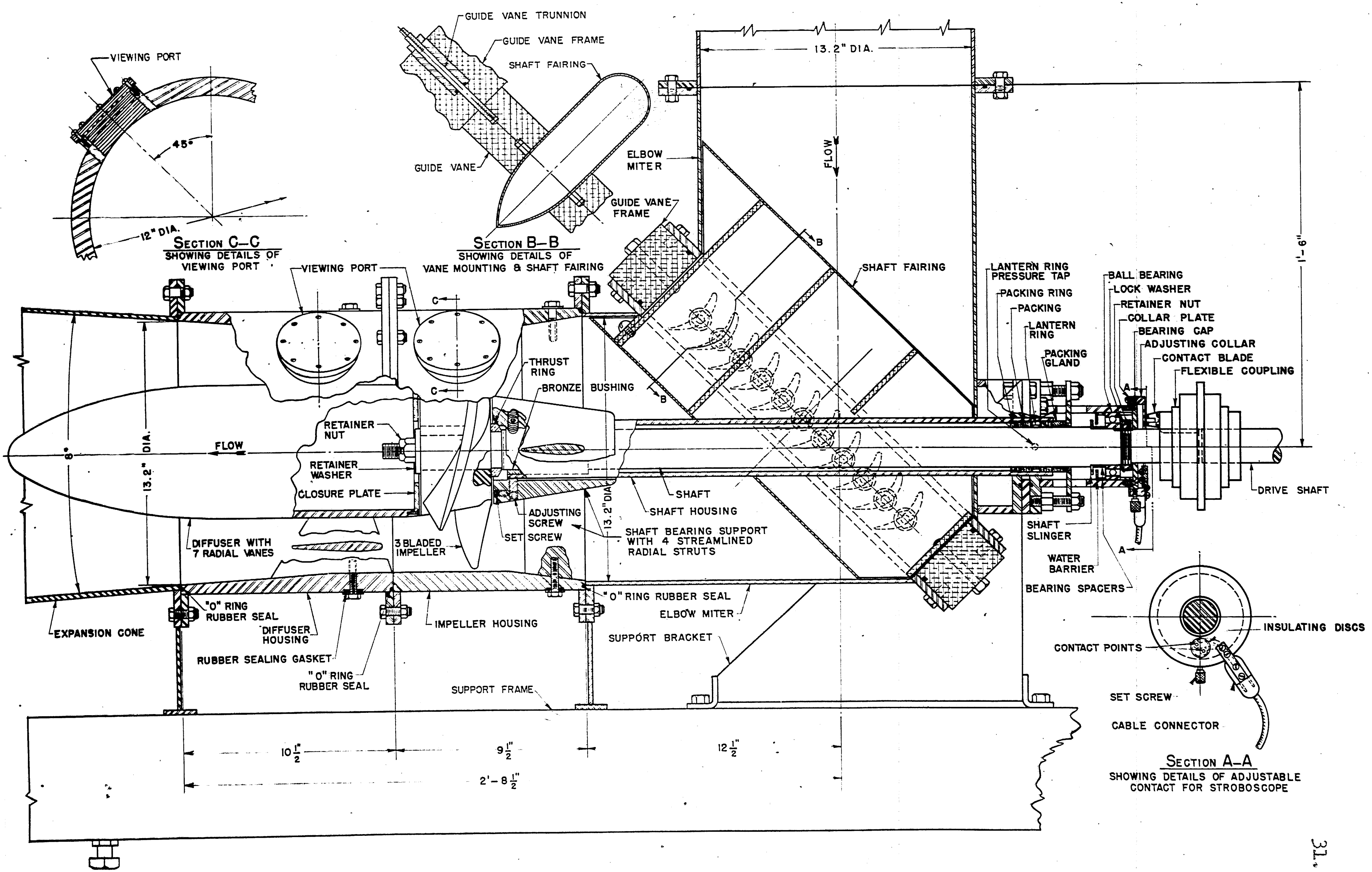


FIG. 4 PUMP ASSEMBLY

Fig. 5. Impeller Shaft and Drive Unit

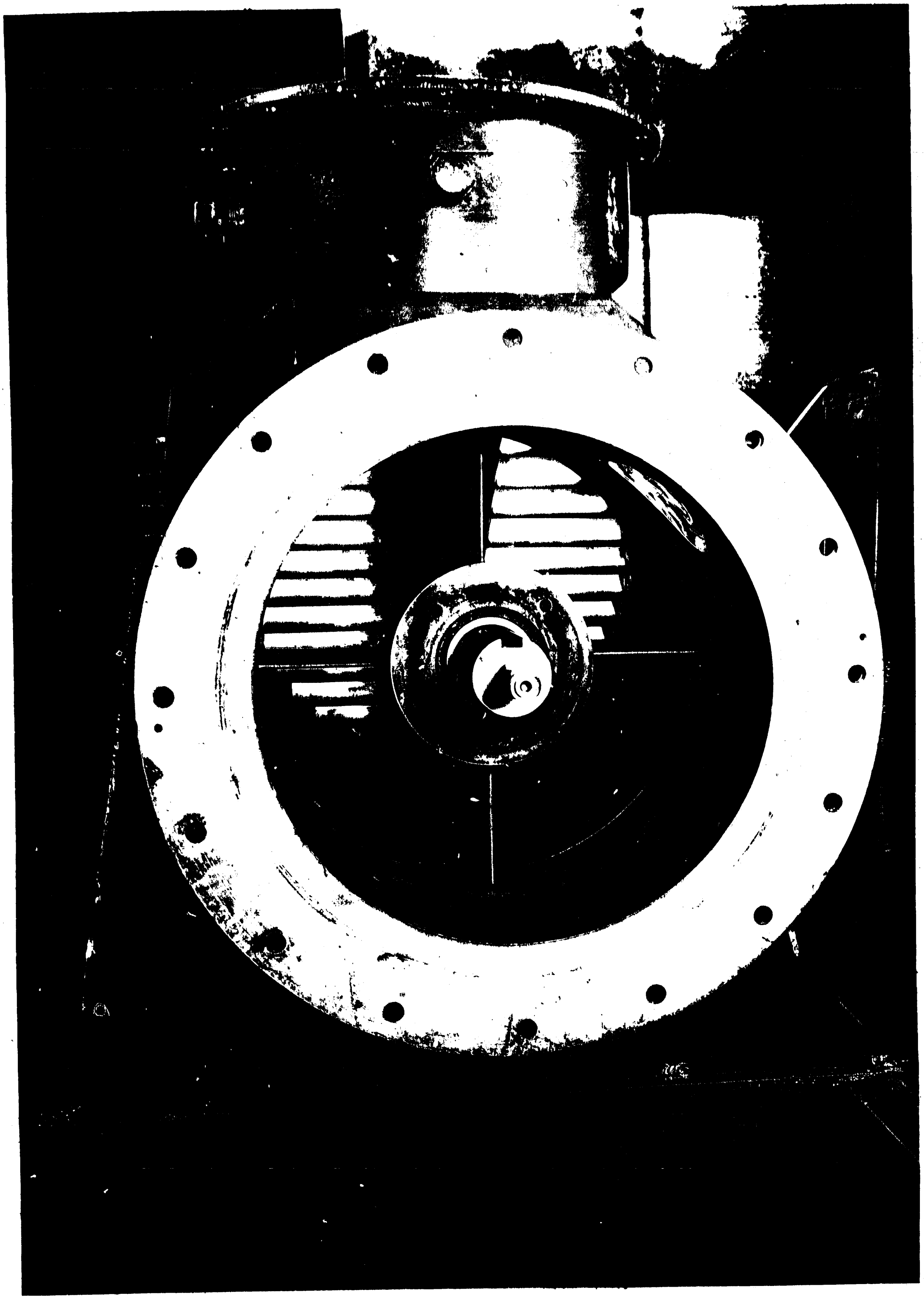


Fig. 6. Suction Vanes, Elbow, and Shaft Fairing

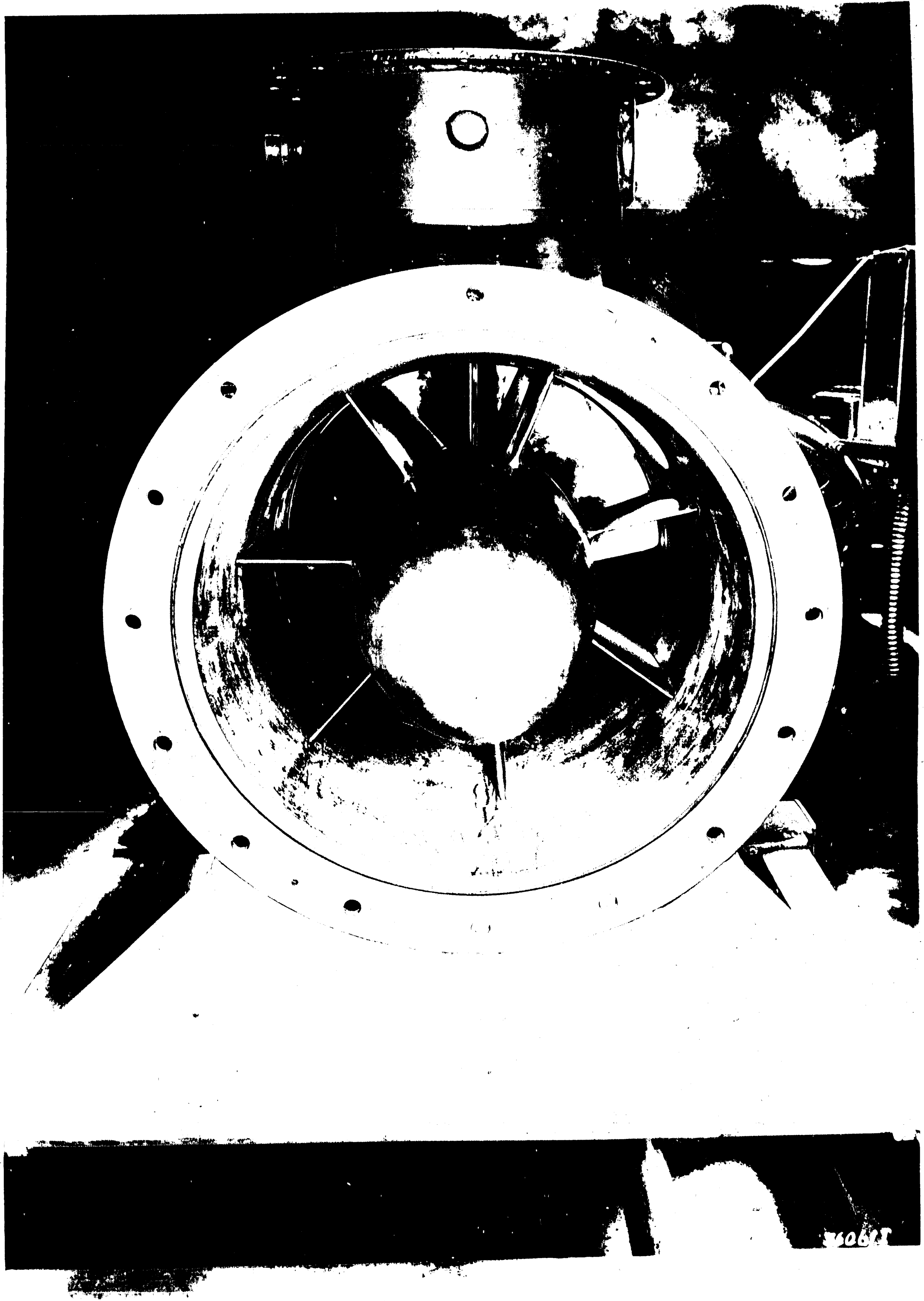


Fig. 7. Pump Diffuser and Housing

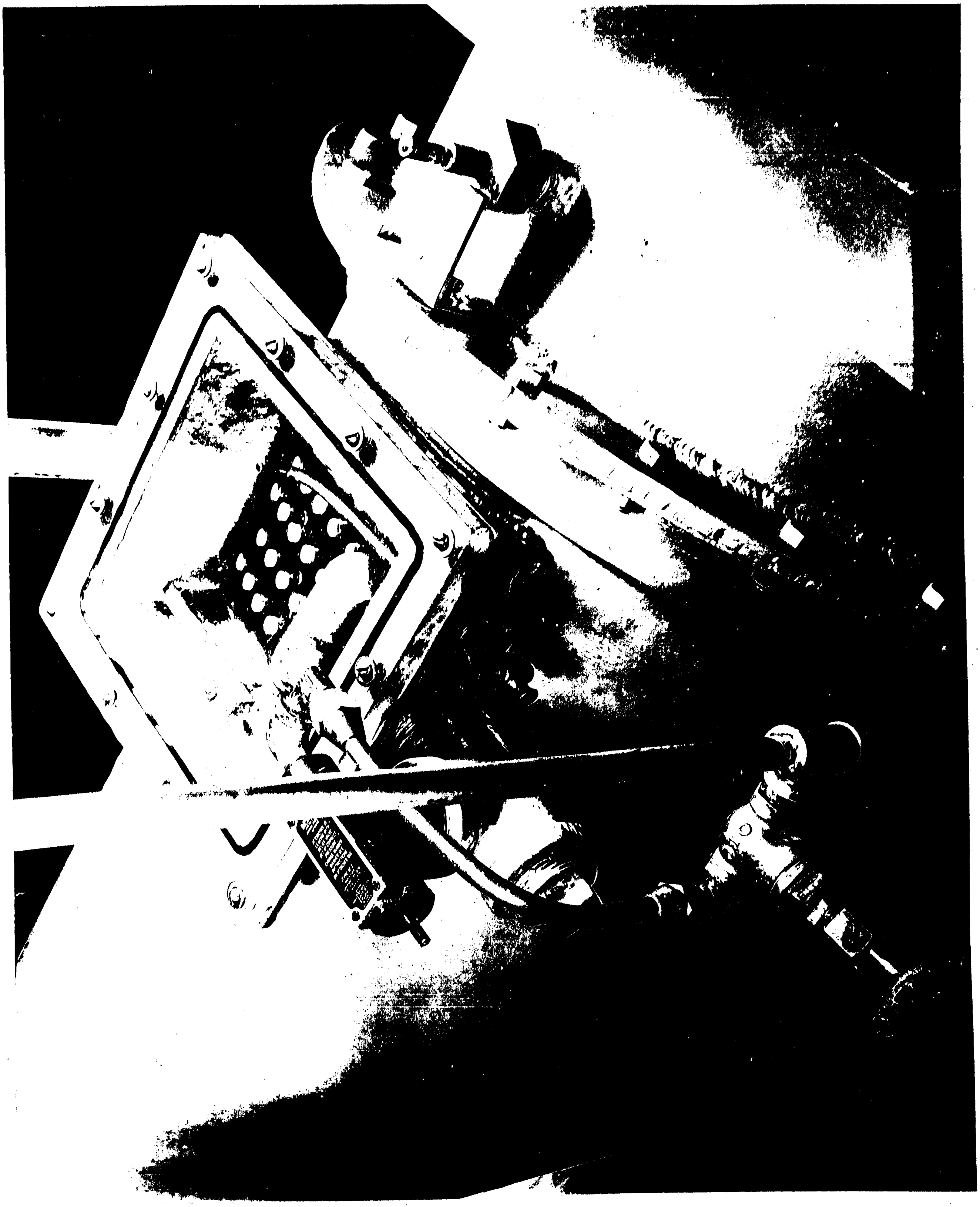


Fig. 8. Air Collector Dome

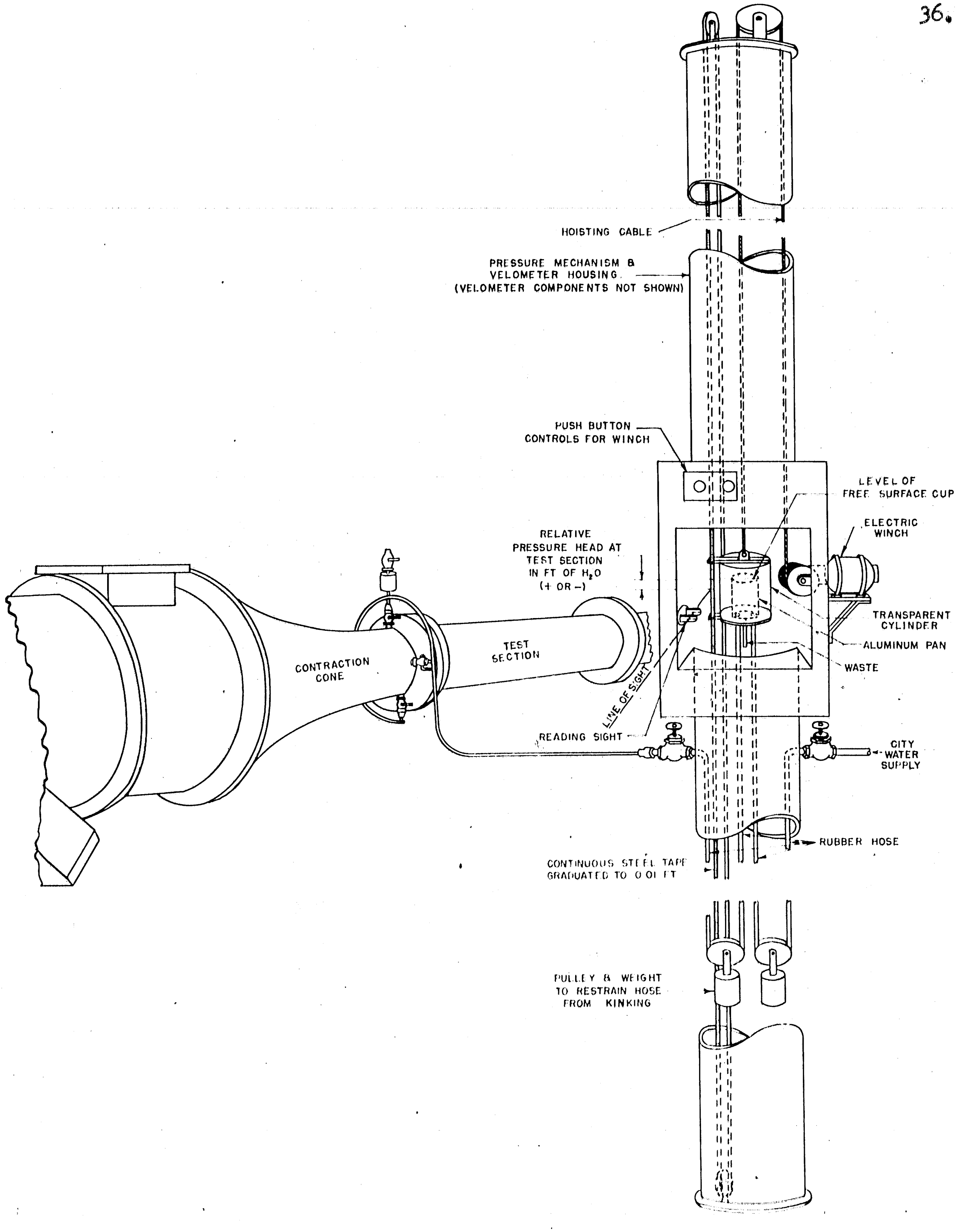


FIG. 9

PRESSURE CONTROL AND MEASUREMENT MECHANISM

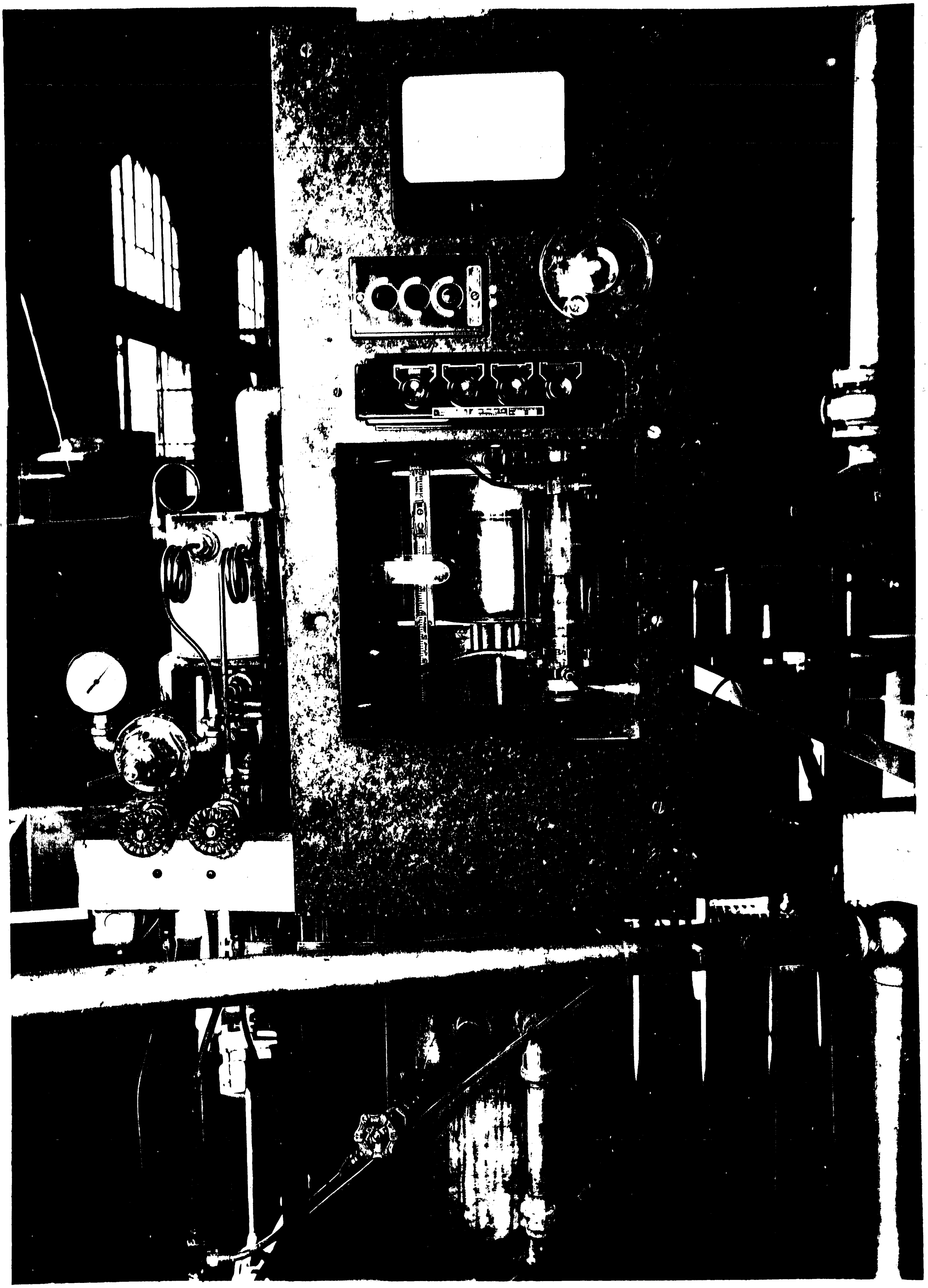


Fig. 10. Velometer Controls, and Speed Regulating and Pressure Regulating Mechanisms

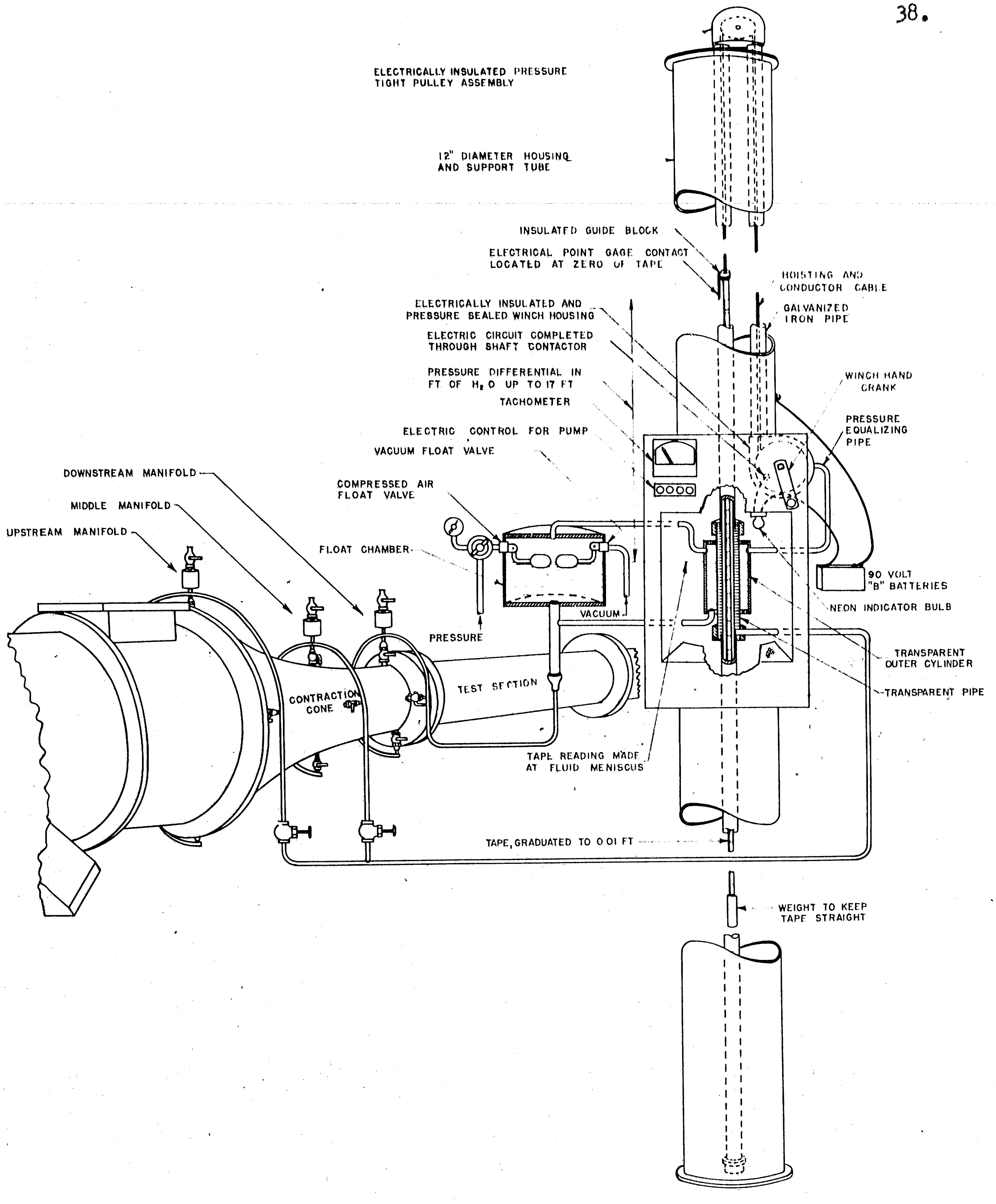


FIG. 11

SCHEMATIC DRAWING OF VELOMETER

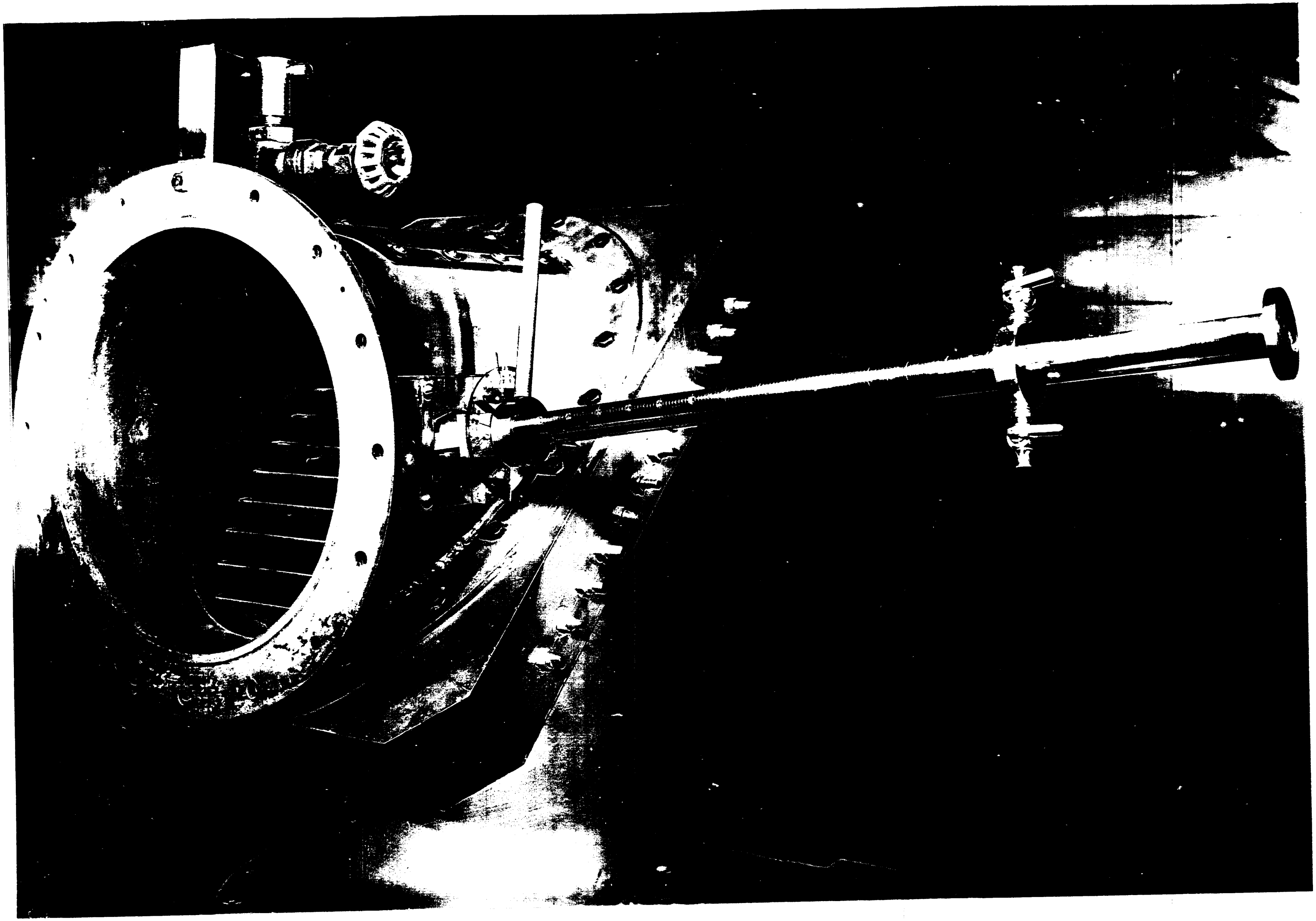


Fig. 12 Pitot Cylinder in Main Mounting at Station 5

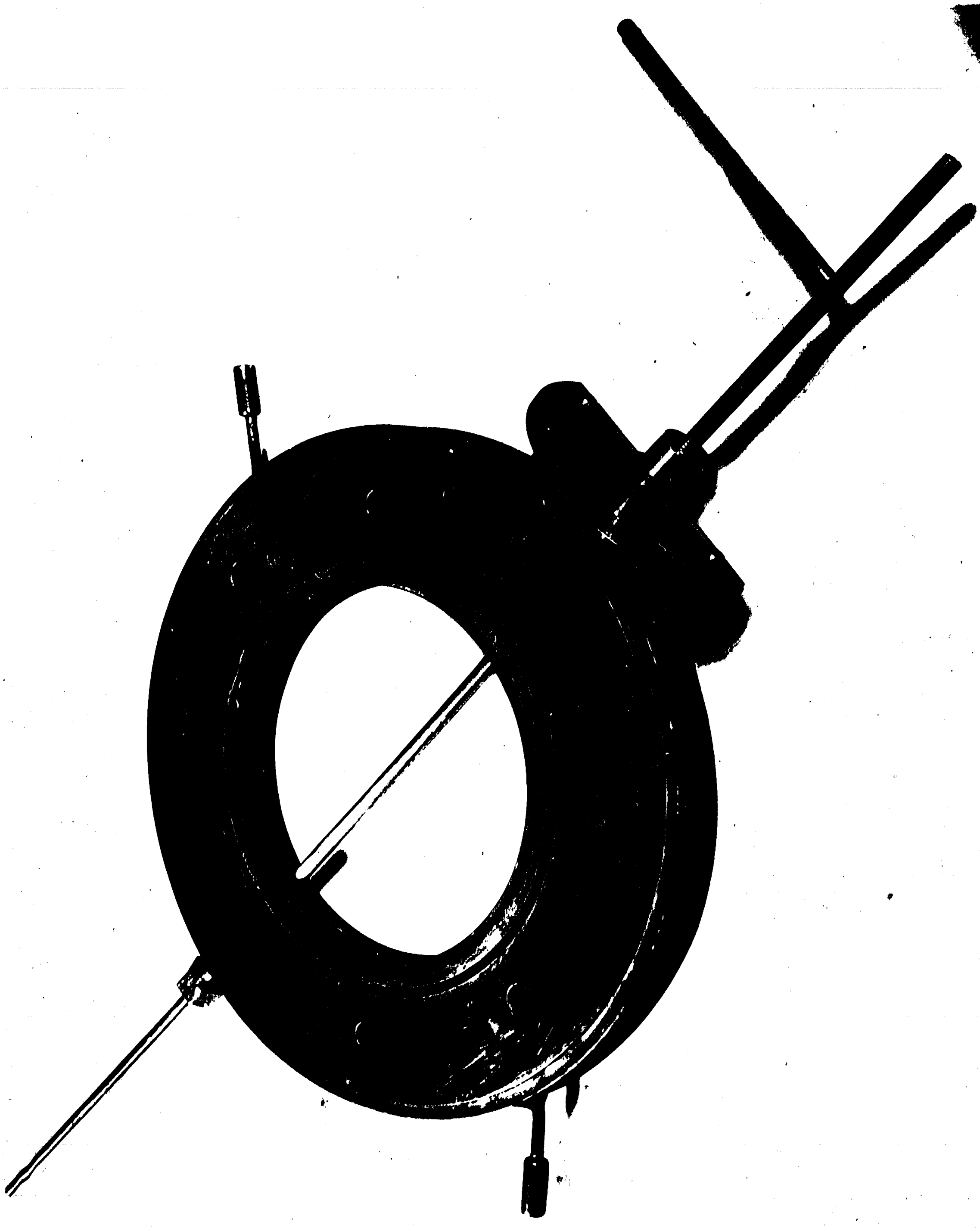


Fig. 13. Long Pitot Cylinder in Adapter Flange

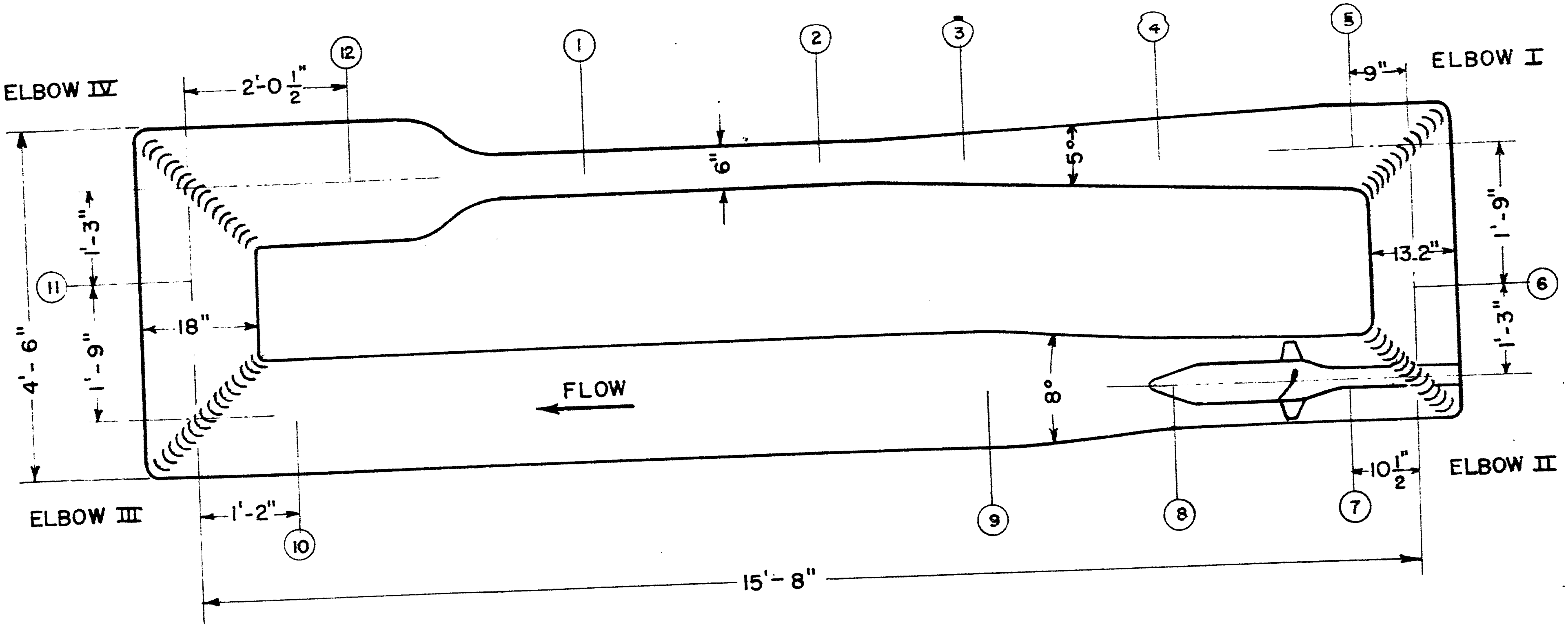


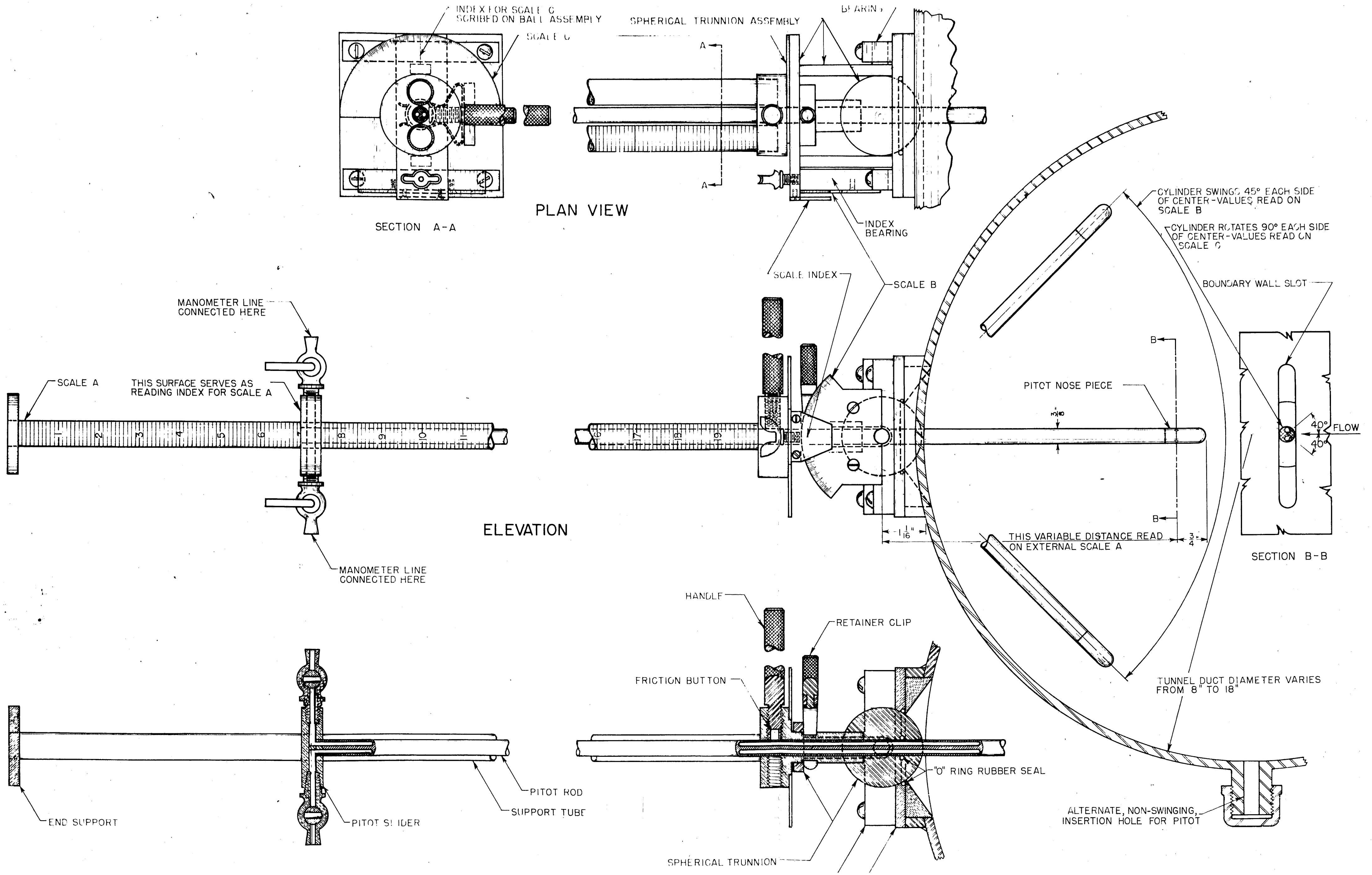
FIG. 14

DESIGNATION OF VANED TURNS AND VELOCITY TRAVERSE STATIONS

Fig. 15. Cantilevered Pitot Cylinder

Fig. 16

Pitot Cylinder and Mounting


INDEX FOR SCALE C SCRIBED ON BALL ASSEMBLY
SCALE C
SPHERICAL TRUNNION ASSEMBLY
BEARINGS
A
A
SECTION A-A
PLAN VIEW
INDEX BEARING
SCALE INDEX
SCALE B
CYLINDER SWINGS 45° EACH SIDE OF CENTER-VALUES READ ON SCALE B
CYLINDER ROTATES 90° EACH SIDE OF CENTER-VALUES READ ON SCALE C
BOUNDARY WALL SLOT
MANOMETER LINE CONNECTED HERE
SCALE A
THIS SURFACE SERVES AS READING INDEX FOR SCALE A
1
2
3
4
5
6
8
9
10
11
16
17
18
19
PITOT NOSE PIECE
3/8
B
B
40°
40°
FLOW
ELEVATION
1 1/16"
THIS VARIABLE DISTANCE READ ON EXTERNAL SCALE A
3/4
SECTION B-B
MANOMETER LINE CONNECTED HERE
HANDLE
RETAINER CLIP
FRICTION BUTTON
"O" RING RUBBER SEAL
TUNNEL DUCT DIAMETER VARIES FROM 8" TO 18"
END SUPPORT
PITOT SLIDER
PITOT ROD
SUPPORT TUBE
SPHERICAL TRUNNION
ALTERNATE, NON-SWINGING, INSERTION HOLE FOR PITOT

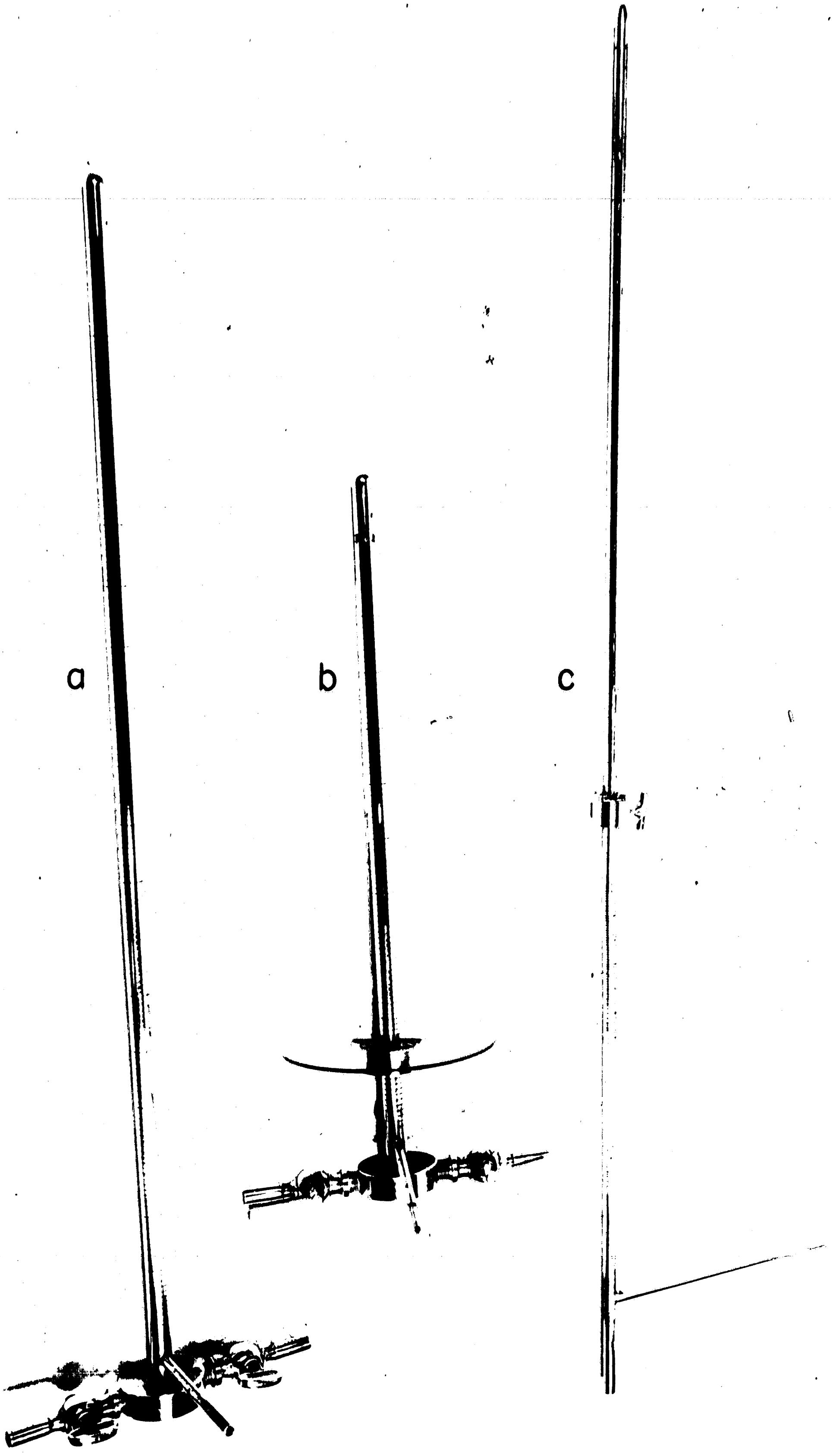


Fig. 17. Pitot Cylinders

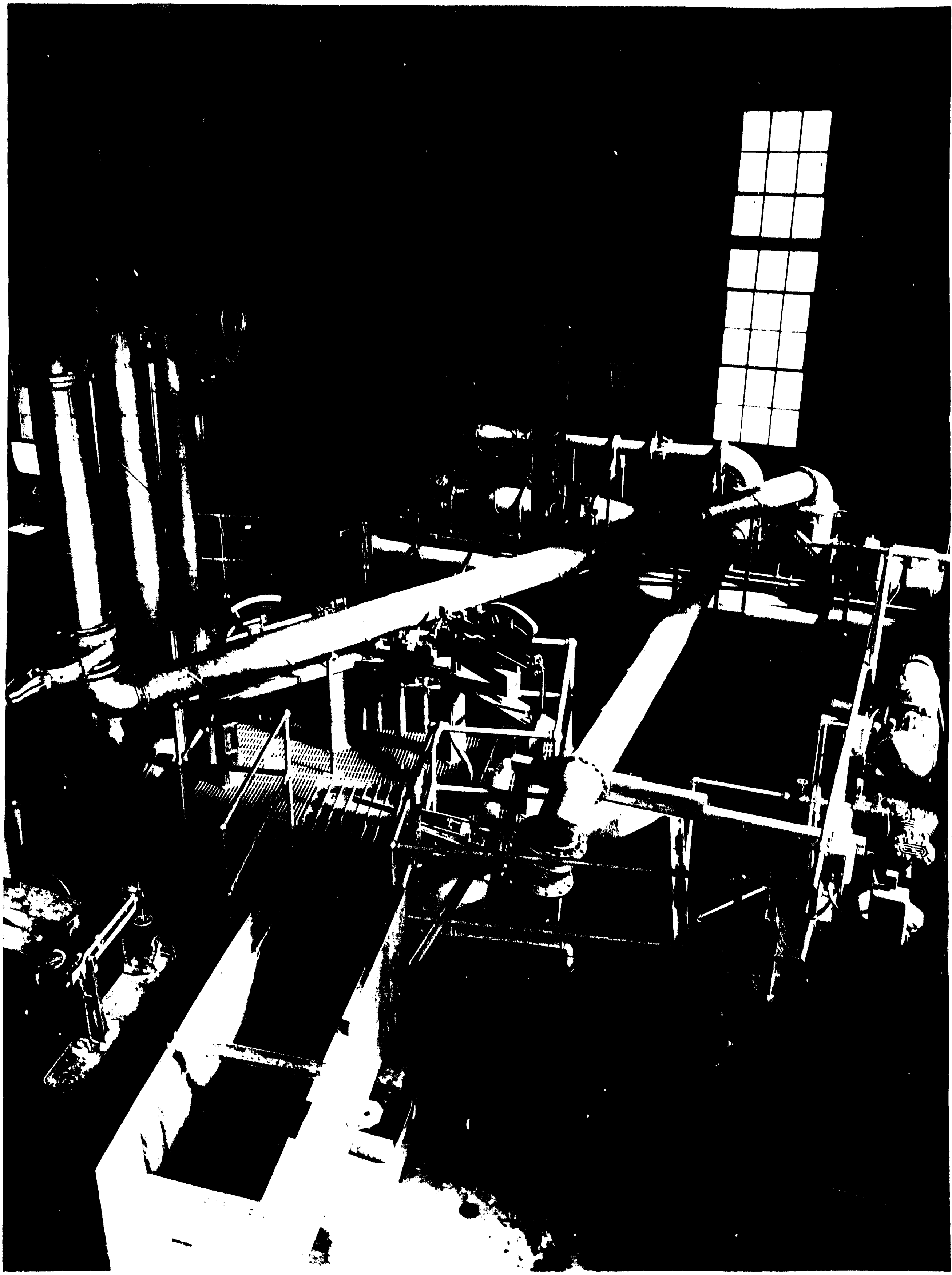


Fig. 18. Apparatus for Velometer Calibration

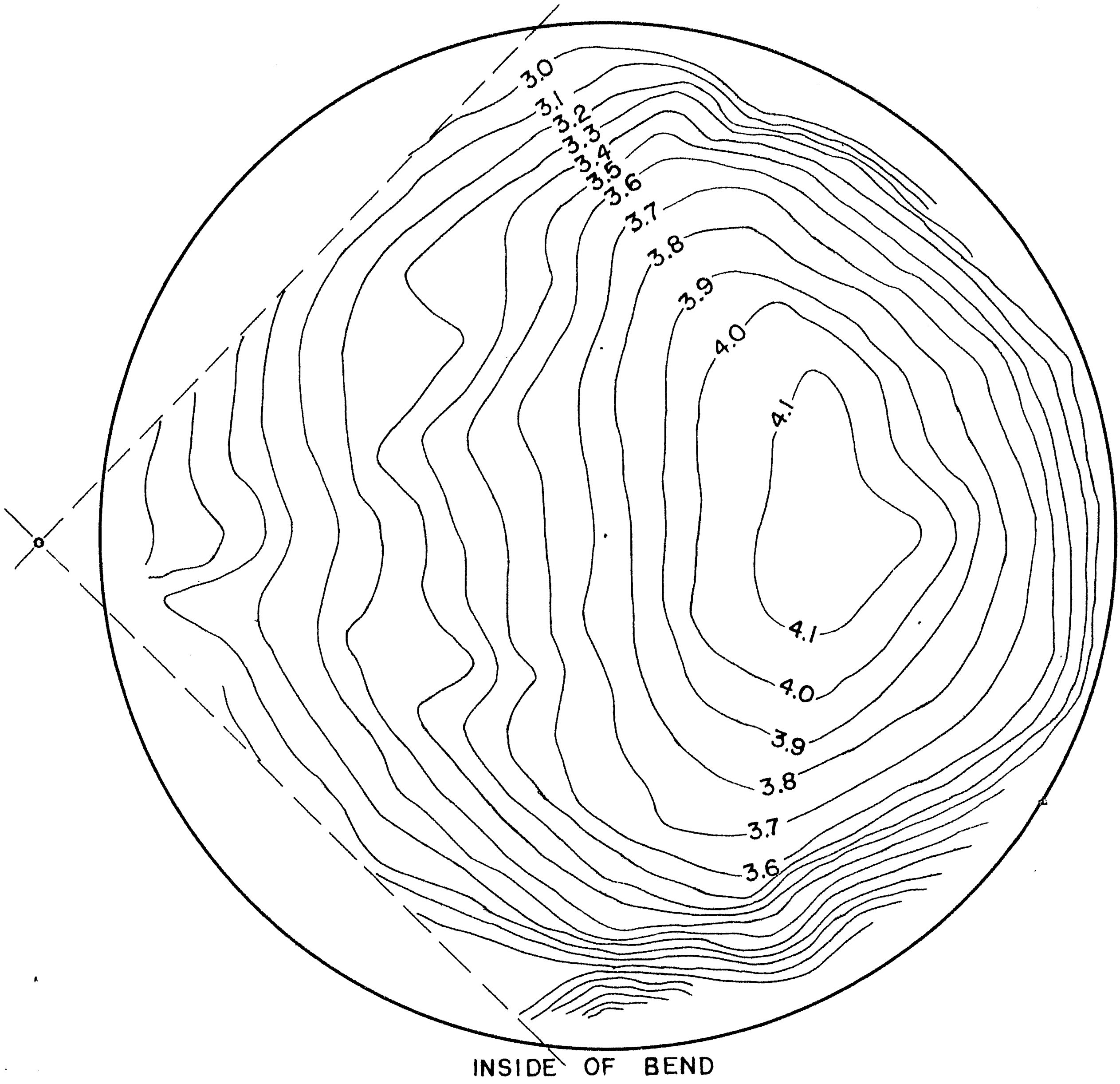
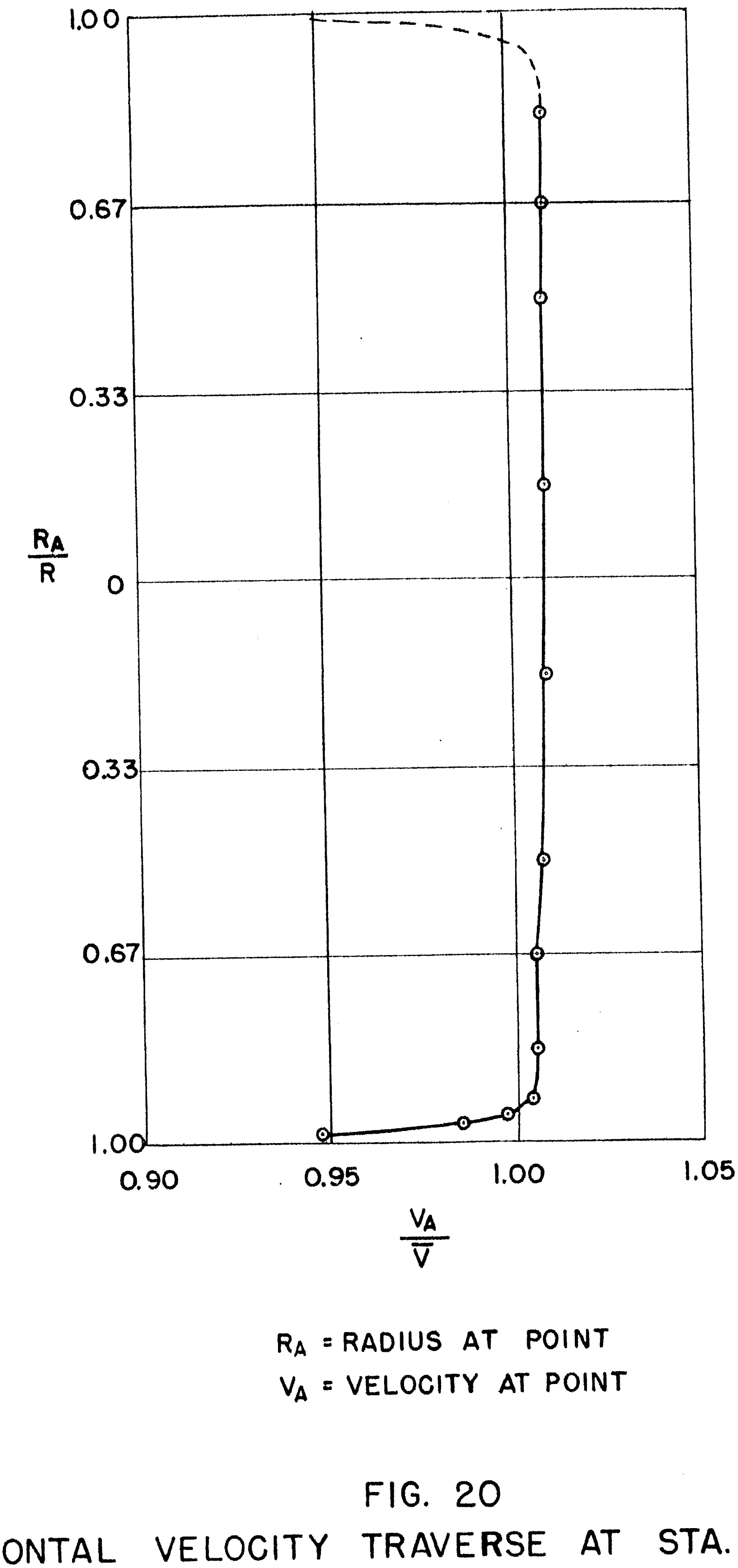


FIG. 19

VELOCITY TRAVERSE AT STATION 12

NON-RECIRCULATING FLOW
VELOCITY IN TEST SECTION = 30 f.p.s.
ISOVEL INTERVAL = 0.1 f.p.s.
VANE STAGGER = 96°



R_A = RADIUS AT POINT
V_A = VELOCITY AT POINT

FIG. 20
HORIZONTAL VELOCITY TRAVERSE AT STA. I

TEST SECTION VELOCITY = 29.72 f.p.s.
NON-RECIRCULATING FLOW

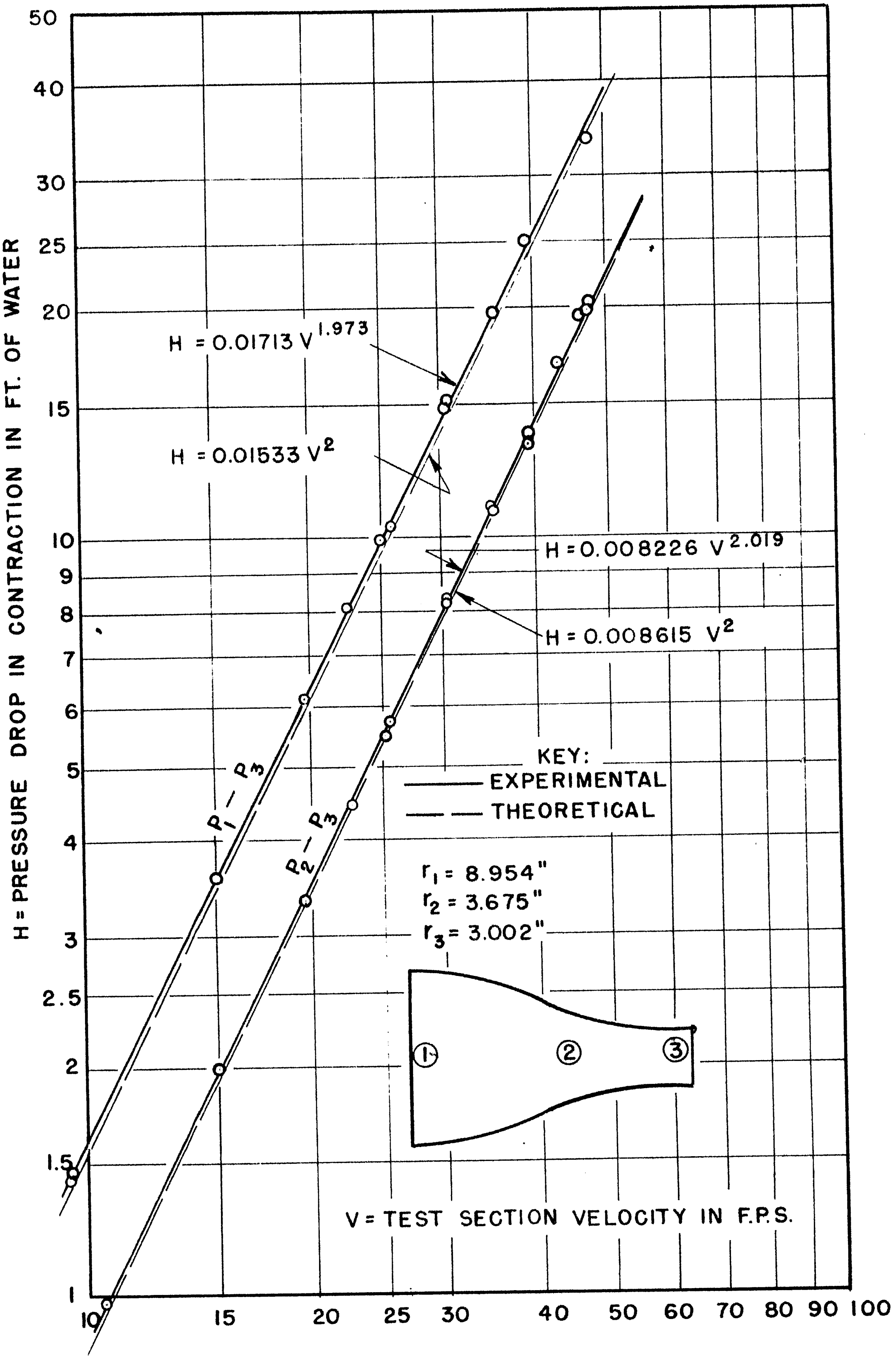


FIG. 21

VELOMETER CALIBRATION

Report No 10 .

Press. meas. and control : pp 7-8 - (M.I.T.)

Twin - tank method : 40,000 lb / tank

Error ± 5 lb

6" diam

$$\frac{\pi \left(\frac{1}{2}\right)^2}{4} = \frac{\pi}{16} \text{ ft}^2$$

$V_{max} = 47$ ft/sec $\quad Q_{max} = \frac{(\pi)\, 47}{16} \sim 9.23$ c

(18 tanks used)

$$\text{Vol} = \frac{18{,}160 \text{ kgf}}{10^3 \text{ kgf/m}^3} = 18.16 \text{ m}^3$$

Square side ~ $\boxed{2.62 \text{ m}}$

9.23 CFS ~ 262 l/s. MAX 12 CFS ~ 350 l/