ST. ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

Project Report No. 35

DESCRIPTION OF A TEN-INCH FREE-JET WATER TUNNEL

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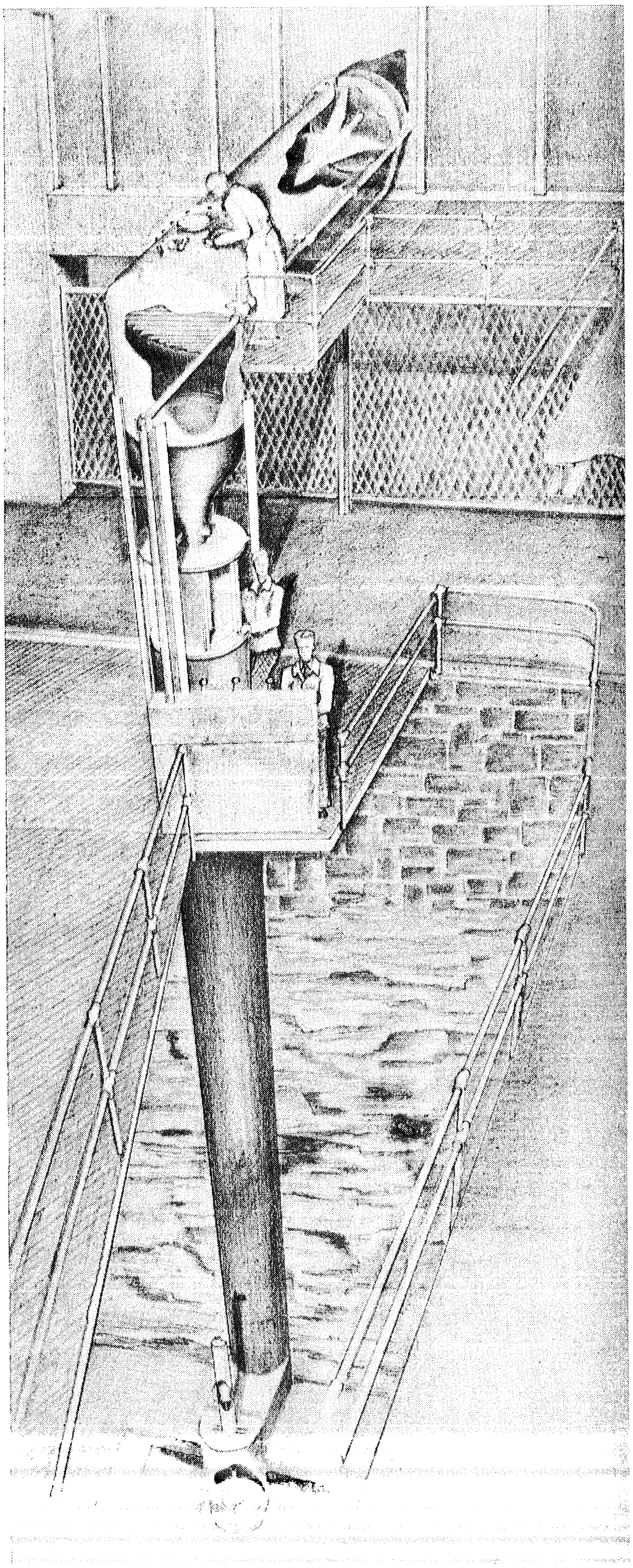

PREFACE

A free-jet water tunnel can be defined as a water tunnel in which the test stream is bounded over the greater part of its surface by a gaseous jacket. A test facility of this type has been designed and constructed at the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota as part of a program of study sponsored by the Office of Naval Research, Department of the Navy.

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The construction of this tunnel represents the second phase of studies concerning the design and operating characteristics of free-jet water tunnels; the first phase consisted of general pilot model studies of the tunnel type. A technical report covering these earlier studies has been prepared and published as St. Anthony Falls Hydraulic Laboratory Project Report No. 25. A summary of the results and conclusions taken from the above are included in this report, along with a discussion of further desirable experimental investigations.

The structure described in this report was designed by John F. Ripken and Charles D. Christopherson under the general supervision of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory. The structural drafting was done by K. N. Chen and Ernst Elguther, and the physical construction of the tunnel was supervised by Frank R. Dressel. This report was critically reviewed by Reuben M. Olson and adapted for publication by Loyal A. Johnson. The manuscript was edited and typed for reproduction by Marilyn F. Larson.

ABSTRACT

A water tunnel is a device used in hydraulic research and design studies for the purpose of observing the relative motion between a solid body and a liquid and the effect which this motion has on the body. Its basic function is the production of a test stream of water of uniform and controllable pressure and velocity in which solid bodies can be supported under varying conditions. The free-jet type of water tunnel has a test stream which, ideally, is surrounded by a gaseous medium and which, practically, has only a partial solid-contact boundary required to permit observation of the interior of the stream. This type of tunnel thus differs from conventional water tunnels such as the closed-jet water tunnel, which has a test stream completely surrounded by a solid-contact surface, and the open-jet water tunnel, which has a test stream surrounded by water and which thus resembles a submerged jet. The essentially unbounded nature of the test stream of the free-jet water tunnel permits deformation of the test stream and avoids formation of adverse pressure and velocity gradients which form in conventional water tunnels because of gravitational effects and boundary layer formation; the result is that in the free-jet water tunnel, natural cavitation about solid bodies in the test stream can be studied at lower cavitation indices and with less influence due to the finite extent of the test stream than is possible in conventional tunnels.

As a phase in its physical development and the study of its operating characteristics, a free-jet type of water tunnel has been constructed at the St. Anthony Falls Hydraulic Laboratory. This water tunnel has a non-recirculating flow which aspirates the test section in passing through it, thus providing a convenient means of obtaining reduced test-stream pressures; pressure control is obtained by bleeding air from the atmosphere into the test section at the desired rate. The test stream itself has a circular cross section 10 inches in diameter, a length of 4 diameters, and is directed vertically downward. The test section is composed of two components: the steel outer test-section barrel, which is 24 inches in diameter, has four equally spaced longitudinal transparent plastic viewing windows, and can be opened or closed by vertical movement of the entire barrel; and the inner test section, which has two longitudinal viewing windows that can be oriented in line with any of the outer viewing windows and that contact the test stream on their innermost surface. The maximum test-stream velocity attainable in the tunnel is 50 fps, and the minimum cavitation index attainable is of the order of 0.01.

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*St. Anthony Falls

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I. INTRODUCTION

In order to make a comprehensive experimental study of the effect which the characteristics of free-jet water tunnel test streams (as distinguished from test streams of "open-jet" and "closed-jet" water tunnels) have on the results of steady-state cavitation studies made therein, a water tunnel of this type has been constructed at the St. Anthony Falls Hydraulic Laboratory. It is the purpose of this report to describe the development and the physical and hydraulic characteristics of this structure (Fig. 1) as a reference for future reports which will be primarily concerned with the description and results of its use as a test facility.

II. DEVELOPMENT

A. Conventional Water Tunnels

The nature of the flow cavities, or discontinuities, created in the region near a solid boundary when the relative velocity between a liquid and the boundary becomes sufficiently high to cause local pressures to fall below the cavitating pressure of the liquid, and the influence which such cavities have on the dynamics of the flow about the body, have long been of interest and recognized importance in a number of phases of fluid mechanics. Of the numerous devices which have been developed for the purpose of studying one or more phases of the cavitation phenomena, the water tunnel developed for the applied design study of cavitation about submerged bodies has been one of the most useful. A water tunnel can be simply described as a device in which a liquid test stream of nearly uniform velocity can be impressed upon a stationary (or rotating, as in the case of propellor studies) solid body in such a way that the undisturbed velocity and static pressure of the test stream can be controlled by an operator. Thus, the degree of cavitation about the body and its relation to the cavitation index of the flow can be studied. This index is defined in general as

$$\sigma = \left(\frac{p_o - p_c}{1/2 \rho U_o^2} \right)$$

where σ = cavitation index,

p_o = the absolute static pressure in the undisturbed test stream,

p_c = the absolute cavitation pressure, taken as the pressure within the cavity for steady-state cavitation,

ρ = the density of the liquid, and

U_o = the mean velocity of the undisturbed test stream.

The flow path in a conventional water tunnel consists of a vertical, rectangular, closed loop in which the flow is continuously recirculated, as shown schematically in Fig. 2, a sketch of a typical conventional water tunnel. The basic elements comprising this loop are the pump, or power supply, in the lower horizontal leg; the contraction, test section, and diffuser in the upper horizontal leg; and the necessary connecting conduit, elbows, and auxiliary appendages. In order to minimize energy losses in the system, the connecting conduit is made as large as practical, thus reducing the velocity of the flow in these elements. Further, the simplest method available for achieving a nearly uniform velocity profile in a flow is to contract this flow just upstream of the point at which the uniform velocity is desired. Hence, the contraction component of the water tunnel serves a dual purpose: it contracts the circulating flow into a high-velocity test stream and at the same time flattens its velocity profile. Similarly, the diffuser serves a dual purpose: it recovers the dynamic energy of the test stream and re-expands the flow cross section to that of the connecting elements. Detailed information concerning the design of conventional water tunnels is available (for example, reference [1 and 2]*), but is beyond the scope of this paper.

There are a number of types of water tunnels which are generally categorized according to the degree of test-stream confinement as indicated by their test-section design. Thus, the closed-jet water tunnel is a type in which the test stream is confined by a cylindrical—or slightly flared [3]—solid boundary, whereas the open-jet water tunnel is a type in which the test stream is confined by a water-filled barrel which has a cross section considerably larger than that of the test stream. In the free-surface water tunnel, the upper surface of the test stream is unconfined; it may be exposed to the atmosphere or exist as a free surface within a pressure-controlled chamber. It is to be noted that it is characteristic of all of these test-section types that a hydrostatic pressure gradient exists in the test stream, and a boundary layer of retarded flow exists along its confining surfaces.

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*Numbers in brackets refer to references listed on page 20.

B. Origin of a Free-Jet Water Tunnel

A free-jet type of water tunnel was constructed in Germany during World War II when it was found desirable to make steady-state cavitation studies at cavitation indices below those obtainable in conventional water tunnels. In order to carry out the desired studies, an existing water tunnel was slightly modified to form what was at the time an innovation in water tunnel design. This facility, described in a number of papers by H. Reichardt [4 and 5], was basically very similar to a conventional tunnel; that is, the test stream discharged horizontally in the upper leg of a vertical, rectangular, flow loop in which the flow was recirculated by a pump in the lower horizontal leg. The design of the test section, however, was unique.

The unusual layout of the test region of this modified tunnel was characterized by a reduction in test-stream confinement with respect to conventional tunnels. The test stream was rectangular in cross section and was bounded by flat plates only on the two vertical sides, one of which was transparent to permit viewing the interior of the stream. The upper and lower surfaces of the test stream were unconfined except that the entire stream was enclosed within a pressure-controlled chamber. Thus, the test-stream hydrostatic pressure gradient inherent in conventional tunnels was entirely eliminated, and the region and effects of retarded flow along confining boundaries were considerably reduced. However, as a result of this test-section design, a second basic modification in the tunnel structure was also necessary. The unconfined boundaries of the test stream made it impossible to recover efficiently the energy of the test stream by directing it into a diffuser, hence it was discharged instead into a large vertical conduit in which there was a horizontal free-water surface slightly below the test-section level. This conduit thus formed a stilling basin for the impinging test-stream flow and a supply tank from which water for the stream was continuously pumped. The components and flow path for a tunnel of the type described above are shown schematically in Fig. 3.

The performance characteristics of the original free-jet water tunnel, taken from Reichardt's papers, indicate that the maximum velocity obtainable in this tunnel was about 33 fps, and that the minimum cavitation index attainable for natural cavitation (the ambient test-stream pressure was reduced by means of a vacuum pump connected to the test section) was about

0.018—considerably below that obtainable in any existing conventional tunnel. Although this tunnel proved to be an extremely useful research tool, it has not been in active use since the end of the war.

C. Initial Free-Jet Water Tunnel Research at St. Anthony Falls Hydraulic Laboratory

In order to obtain further information concerning the design and operating characteristics of free-jet water tunnels, a program of experimental study of this type of water tunnel was initiated at the St. Anthony Falls Hydraulic Laboratory. To instrument this study in its initial stages, a small free-jet water tunnel was built with a test stream of circular cross section 2 inches in diameter and 6 diameters long which could be oriented to discharge either vertically upward, vertically downward, or horizontally. This facility, whose test region is shown in Fig. 4 (in which the test stream is discharging vertically downward), was not designed as a geometrical model of a proposed prototype design, but rather as a device for producing an unconfined test stream whose characteristics could be observed under controlled situations.

A complete description of this facility, with the test procedures used and the results obtained in studies of its characteristics, is given in Project Report No. 25 of the St. Anthony Falls Hydraulic Laboratory [6]. As the conclusions drawn in this earlier report were significant considerations in the design of the free-jet water tunnel described in Section III of this report, they have been included here in the following summary:

1. The free-jet water tunnel is a practical device for implementing studies involving steady-state cavitation bubbles at low cavitation indices.

2. It is preferable that the energy of the jet in a free-jet water tunnel be allowable as an energy loss, however a part of this energy could be regained if the jet were directed vertically upward.

3. The flow through the test section should preferably be of a one-pass nature (i.e., non-recirculating) in order that (a) the necessity for separating entrained air from the flow be eliminated, and (b) the rapid temperature rise of the water resulting from dissipation of the jet energy be eliminated.

4. Viewing windows in contact with the jet are essential for viewing the interior of the jet.

5. No conclusion could be reached regarding the effect of gravity on the steady-state cavitation bubbles, which investigation was made by noting changes in bubble configuration with changes in jet direction.

6. The jet of a free-jet water tunnel should preferably be directed vertically downward (unless the jet energy is to be regained) as this design results in (a) minimum spray effects and natural drainage from the test section, (b) efficient natural aspiration of the air within the test section when the flow is non-recirculating, (c) minimum symmetrical gravitational effects which do not give rise to the pressure and velocity gradients which occur in the non-symmetrical distortion of a horizontal free jet, and (d) an advantageous effect of gravity on the reentrant jet of the steady-state cavitation bubbles.

7. The test stream, with diametrically located viewing windows in place, consisted of a core flow of nearly constant total head surrounded by a boundary layer composed of two parts: (a) the boundary layer opposite the viewing windows consisted of a region of retarded flow due to viscous shear action between the jet and the windows, and (b) the boundary layer at the free surface consisted of an "apparent" retarded flow due to air entrained into the flow through this surface. Both were of the same order of magnitude at any given distance downstream of the contraction and within a normal test-section length.

D. Studies of Free-Jet Boundary Influence

Although considerable useful information was gathered from the initial studies mentioned above, it was at the same time obvious that if a thorough investigation were to be made of the effects which viewing windows and the finite extent of the test stream have on the results of cavitation studies made in free-jet water tunnels, a larger test facility was needed. The free-jet water tunnel has been shown by Reichardt's studies to be particularly well adapted to the study of steady-state cavitation flows about solid bodies. In such studies the parameters of interest are C_d, the coefficient of body drag; d_m/d, the ratio of some significant lateral cavity dimension to a corresponding body dimension; and ℓ/d, the ratio of the cavity length to some significant lateral body dimension. Further, the shape of the cavity itself may be of primary interest in particular cases in which the cavity surface is taken as the basis for the design of a body shape which would have a given maximum super velocity. It is common practice to relate these factors of interest to the cavitation index for a given body shape, and it is generally desirable to do this for the situation in which a solid body is moving in an infinite liquid because practical problems are usually a close approximation of this case. However, as model studies must of necessity be made in test streams which are finite both axially and laterally, boundary corrections must be applied to their results in order to reduce them to the case in which the fluid is infinite.

A number of mathematical analyses have been devoted to the determination of these correction factors for test streams with various degrees of confinement [7, 8, and 9]. Although it is beyond the scope of this paper to review these analyses in detail, it should be noted that mathematical methods thus far used have limited rigorous solutions of the problem to special cases of two-dimensional flow which can only indicate trends and orders of magnitude for practical three-dimensional flow problems. Among the interesting and significant conclusions that can be drawn from these analyses, however, are (a) that boundary corrections for studies made in a free stream will be considerably smaller than those for studies made in a confined stream, (b) that the first-order correction to the drag coefficient of a body which is positioned to be at least one stream diameter from either end of the test stream can reasonably be expected to be zero if the stream is unconfined, and (c) that the correction factors for C_d, d_m/d, and ℓ/d are not of the same order of magnitude for any particular case (i.e., a cavity flow at $\sigma = \sigma_1$ in the finite stream cannot be expected to conform identically to a cavity flow at $\sigma = \sigma_2 \neq \sigma_1$ in an infinite stream).

The experimental investigation of these correction factors requires a test stream of dimensions large enough to permit test bodies whose significant dimensions vary over a considerable range to be inserted into it at different axial locations and under different cavitation conditions. A basic investigation of this type can logically be carried out on the rotationally symmetric flow about flat disks in which the controllable variables are the number and orientation of the viewing windows which contact the test stream, σ, d/D, and L/D (where L is the axial distance from the tunnel contraction to the test body, and D is the test stream diameter); the dependent variables would then be C_d, ℓ/d, and d_m/d. Thus, relations can be determined experimentally which will indicate either directly (if the smallest disk tested requires zero corrections) or indirectly (if the results must be extrapolated to the case of infinite flow) what the boundary corrections for particular cases must be; or, in a broader sense, the limitations of the test stream due to its finite extent can be experimentally defined.

To facilitate such a study, a free-jet water tunnel has been designed and constructed at the St. Anthony Falls Hydraulic Laboratory based on the results of the initial studies mentioned above and the natural facilities available at the Laboratory. The remainder of this paper is concerned with a detailed description of this tunnel and the preliminary checks made on its operating characteristics.

III. DESCRIPTION

A. General Characteristics

The basic structure of the 10-in. free-jet water tunnel is shown in Figs. 1 and 5. It is located in the south corner region of the Laboratory between the weighing tanks and high-speed flume, extending vertically from one floor above the Laboratory's main experimental floor level three floors downward to the turbine room floor level [10]. The test section, which covers a vertical distance of about 3-1/2 ft, is conveniently located in eye-level range above the main experimental floor level of the Laboratory.

The path of flow through the tunnel, as indicated on Fig. 5, is non-recirculating. Water is taken from the main supply channel of the Laboratory (which is connected directly to the headwater pool of St. Anthony Falls) into a horizontal conduit, through a vaned miter elbow which turns it downward, through the contraction, test section, vertical conduit, and discharge valve into the Laboratory tailrace (which is connected directly to the tailwater pool of St. Anthony Falls). Thus, the water for the tunnel is supplied directly from the Mississippi River and the power required to operate the tunnel is supplied by the natural 50-ft head at St. Anthony Falls; i.e., there is no motor-driven impeller in the circuit.

The test stream, which is circular in cross section, with a 10-in. diameter and a length of 4 diameters, is directed vertically downward. The circular cross section was chosen as the most stable and logical form for use in the study of axially symmetric flows. By directing it vertically downward, the test section is made self-aspirating because of the entrainment of air not only through the stream surface, but more particularly at a point downstream of the test section where the test stream strikes the water level in the vertical conduit. Further, with a circular-stream cross section, a vertical test stream is practically mandatory if contact-viewing windows are to be at all efficient over a range of velocities; i.e., nonsymmetrical distortions are eliminated.

The advantages of this overall design are readily discernible from the simplicity of the structure. The non-recirculating flow eliminates all concern for temperature variation due to energy dissipation and air entrainment in the flow downstream of the test section. The available natural head eliminates the necessity of having an artificial power supply in the circuit; the fact that the dynamic energy of the test stream cannot be conserved in the free-jet water tunnel makes this a particularly significant factor. The vertically downward-directed, self-aspirating test stream eliminates the necessity of having a vacuum pump in the circuit to give test-section pressure control; (pressure control is actually achieved by controlling the amount of air bled into the test section). Conversely, the simplified structure and flow system permit neither close control of the water being used in the tunnel nor independent control of the test-stream velocity and pressure.

The tunnel is operated by opening the inlet valve in the supply channel to let water into the tunnel, and the discharge valve at the downstream end of the tunnel to let it out. The water passing through the tunnel entrains the interior air and carries it out of the structure, thus reducing the test-section pressure. The test-section pressure is raised or lowered by adjusting the opening in the test-section air bleed valve, the maximum pressure obtainable being atmospheric. As the total head which causes flow from the supply channel to the test section, where the test stream is unconfined, is the sum of the differences in elevation and pressure head between these two points, the test-stream velocity is controlled or influenced both by the inlet valve opening and by the air bleed valve opening. Further, by adjusting the discharge valve opening, the water level in the vertical conduit can be controlled for given discharges; and by closing it sufficiently, the test section itself can be flooded or submerged so that the test region then closely resembles that of the open-jet type of water tunnel.

Preliminary runs for which the cavitation index was computed, using vapor pressure as the cavity pressure, indicated that the maximum test-stream velocity obtainable in the tunnel is about 50 fps and the minimum cavitation index is in the neighborhood of 0.01 to 0.02.

B. Physical Structure

1. Conduits

There are two principal elements of the tunnel structure which serve the sole purpose of conducting the flow along a substantially straight line from one point to another. These are the horizontal conduit, which is located just downstream of the inlet valve, and the vertical conduit, located just downstream of the test section. For the relative location of these elements, and others to be described later, the reader is referred again to Fig. 5.

The vertical conduit is formed essentially of standard 24-in. OD steel pipe which has a 1/2-in. wall thickness. At its uppermost end is bolted a seal ring which forms part of the test section. Near the upper end, four evenly spaced vertical 4 by 4 by 1/2-in. structural steel angles which extend upward to support the test section, contraction, and miter elbow are bolted to the pipe. Also near its top the conduit is tied to the limestone walls of the turbine room by means of two lateral 4 by 4 by 1/2-in. structural steel angles welded to the conduit and anchor-bolted to the walls. At its lower end, the pipe rests on a grouted limestone ledge to which it is securely anchor-bolted. At this point the flow path is turned through a right angle into a short rectangular conduit (fabricated from 1/2-in. structural steel plate at the Laboratory), which carries it out over this ledge; it is then turned vertically downward again into a final section of circular conduit just upstream of the discharge valve. (It is to be noted that the final vertical section does not extend into the tailrace except during high-water seasons, i.e., the flow is intended to discharge into the atmosphere at this point.) It was not necessary to be particularly concerned with the surface roughness of this conduit because it is downstream of the test section, and only obstructions large enough to cause flooding of the test section are significant. Hence, the surfaces of this element were merely cleaned and painted with rust-resisting paint.

The horizontal conduit is formed of a specially rolled section of structural steel plate. The cross section is circular with a 30-in. ID and a 1/2-in. wall thickness. The flanges at both ends were welded onto the conduit at the Laboratory to custom fit the tunnel structure. The upstream flange is bolted to a steel plate which forms one side of the Laboratory supply channel at this point, and the downstream flange is bolted to the upstream flange of the miter elbow. Both the inside and the outside surfaces were sandblasted and the weld beads were removed on the interior of the conduit before painting the entire element with rust-preventative paint. On the underside of the conduit near the downstream end, a slit was cut in the wall 1 in. long (axially) and 9 in. wide (circumferentially); below this slit was welded a small basin with a 1-1/2-in. valve-controlled drain line for draining the inlet valve leakage when the tunnel is not in operation.

Figure 6 shows these elements during construction of the tunnel; the miter elbow has already been attached and one of the four connecting columns is in place.

2. Miter Elbow

The miter elbow, which connects the horizontal conduit just described to the upstream end of the contraction, turns the flow through a right angle and directs it vertically downward. The walls of this element are fabricated from the same section as is the horizontal conduit; a straight section was carefully cut on a miter at the Laboratory, one end reversed, and the two ends welded back together. A flange was welded to the upstream end to permit bolting of the elbow to the horizontal conduit, and the downstream end was machined so that the wall section formed a V-shaped tongue to match a corresponding groove in the upstream end of the contraction. The surfaces of the elbow walls were treated in the same manner as those of the horizontal conduit.

The guide vanes, which form an integral part of the elbow, are of the circular segment type. They are supported along the miter at their outer ends by being tack-welded to the walls of the elbow, and along the elbow axis by being welded to a faired splitter which in turn is welded to the elbow walls at both corners of the bend. Specifications for the vanes and splitter, which are fabricated from stainless steel, are given in Fig. 7. At the top of the horizontal leg of the elbow, a 6-in. circular hand hole has been cut in the elbow wall and covered with a transparent acrylic resin plate. This arrangement permits visual inspection of the guide vanes and easy access to them for cleaning purposes.

The guide vanes in the elbow are shown in Fig. 8, taken just after fabrication was completed. The completed elbow in place in the tunnel circuit is shown in Fig. 6, in which only one of the four support columns mentioned in the last section is in place, and in Fig. 10, in which all four columns have been located and all temporary supports removed.

3. Contraction

The contraction design selected for use in the tunnel is described in detail in Project Report No. 11 of the St. Anthony Falls Hydraulic Laboratory [11]. The considerable experimental testing of this contraction design, noted in the above report, indicated that its wall pressure is a monotonically decreasing function of the distance from its upstream end, and that within the contraction there are no significant zones of flow separation. The dimensionless profile of the original contraction design is given in Fig. 9 along with experimentally observed wall pressures [11]. For use in the free-jet water tunnel, the original design was slightly foreshortened by eliminating the cylindrical section at its downstream end as indicated in the figure; the proper numerical coordinates (to a different scale) are those given on p. 6 of [12], which differ slightly from the originally computed coordinates of [11].

The contraction was rough cast of an aluminum alloy by a local foundry on a contract basis. The original casting did not meet specifications and hence was returned to the foundry for slight modifications. The exterior of the accepted casting was merely hand ground to a smooth finish, whereas the interior surface was carefully machined to the required profile by Laboratory machinists using a template-follower method. A groove was machined in the upstream edge of the contraction in order to form a tongue-and-groove joint with the miter elbow, and the exterior of the downstream end was carefully machined to a push fit with the test-section plate. These joints were both sealed with O-rings, as opposed to the ordinary gasket-type seals used with the flanged joints. Three sets of piezometer taps were carefully machined into the contraction; the first 1-1/2 in., the second 30-1/2 in., and the third 45-3/4 in. from the upstream end. Each set consisted of four taps located at 90° on a circumference, the individual tap specification being given in Fig. 9. Each tap is individually valve controlled and all four taps of each set are connected to a pressure ring which has a single manometer lead.

Figure 10 is a construction photo taken just after the contraction was set in place in the circuit and after the contraction had been anodized to deter corrosion. It is bolted to the miter elbow at its upstream end and to the test-section plate at its downstream end, both of which are in turn bolted to the four columns. The completed contraction, in place and with pressure rings attached, is shown in Fig. 28.

4. Test Section

The test section of the 10-in. free-jet water tunnel consists of two basic parts, a movable section and a stationary section. The movable section consists of the outer test-section barrel and two hydraulic pistons for positioning it; and the stationary section consists of the test-section plate, seal rings, inner viewing-window assembly, and two guide rods for the outer barrel. These components are shown in the sketches in Figs. 11 and 12.

The outer test-section barrel was fabricated primarily from a specially rolled section of structural steel plate. The flanges on each end and the window frames around the torch-cut ports in the barrel were welded in place. The inside surface of the barrel was machined to a uniform diameter of 24-1/2 in. by a local machine shop on a contract basis, the bearing surfaces of the window frames were machined smooth at the Laboratory, and the remaining surfaces were sandblasted. The four viewing windows, formed of flat sheets of transparent acrylic resin 1 in. thick, are equipped with steel angle frames fastened to the barrel by 1/4-in. machine screws. After completion of all machine work, the barrel was cadmium-plated to prevent corrosion. As an auxiliary component, a 3/4-in. cadmium-plated steel plate was fabricated to the same shape as the windows. Three slots were cut in this "window," and each was provided with a brass cover plate. These slots serve to permit introduction of a Pitot-static tube into the test section and to permit attachment of a test-section air bleed device. The latter, shown in place in Fig. 28, is made up essentially of an automobile air intake, a 2-in. gate valve for control, and a baffle plate downstream of the valve to break up the air jet.

The hydraulic cylinders, which position the outer barrel, are units fabricated at the Laboratory. The two cylinders are fastened in the "V's" of two diametrically located support columns and hence are not visually apparent in the structure. With respect to the detail of their construction (shown in Fig. 11), the pistons, shields, and cylinders were all cut from standard steel shapes and were converted into an operable hydraulic system by the addition of the special bronze O-ring collar. The systems are single-acting and are supplied by a high-pressure hydraulic system described later.

The inner viewing windows were fabricated entirely from transparent sheets of acrylic resin at the Laboratory, their construction details being given in Fig. 12. The two windows are identical in every respect, the final machining on both being accomplished by mounting them diametrically opposite on a lathe. The outside edges of the windows were machined to provide a sliding fit with the test-section barrel, and the inside surface was machined to the theoretical free-stream diameter assuming no gravitational effect along the length of the test section (i.e., to the diameter of the downstream end of the contraction). The windows are doweled in place on the test-section plate and supported vertically by the carrier plate, a cadmium-plated structural steel plate supported in turn from the test-section plate by four 1/2-in. stainless steel rods.

The test-section plate was cut from a standard 5/8-in. structural steel plate and cadmium-plated. It forms the key part of the entire test-section assembly by contributing either vertical support or lateral alignment for almost every other part. The seal rings, one of which is fastened to the vertical conduit and the other to the test-section plate, are simply cadmium-plated, lathe-turned, steel hoops, each equipped with two O-rings. One of the O-rings seals the ring against its supporting member and the other furnishes a seal between the ring and the test-section barrel when the latter is in its closed position. The outer barrel guide rods, formed of standard 1-in. steel shafting, are fastened in the "V's" of the two diametrically located columns not occupied by the hydraulic cylinders.

The assembled test section is shown in Fig. 13, in which the barrel is down and the test section open, and in Fig. 14, in which the barrel is up and the test section closed. The test section is closed by the hydraulic system and opened by its own weight. When closed, the two inner viewing windows are located directly in line with two of the windows in the barrel. Thus, a complete viewing-window assembly for viewing the interior of the test stream consists of a chamber with a flat transparent outer face which contacts the atmosphere, and a curved transparent inner face which contacts the test stream. The inner viewing windows have been mounted diametrically opposite in Fig. 13, however they can be mounted at right angles or one or both completely removed.

Further, provision has been made for filling this window chamber with water; as the refractive index of the acrylic resin and water is nearly the same, this would minimize the optical distortion in the window system.

5. Inlet Valve

The inlet valve of the tunnel is a simple disk valve in which the disk or valve plate is attached to the piston of a hydraulic cylinder. As can be seen from Fig. 15, it is composed of three basic units: the valve plate and hydraulic piston, the hydraulic cylinder and support struts, and the valve seat.

The hydraulic cylinder and piston were fabricated at the Laboratory primarily from standard seamless steel and brass tubing, and lathe-turned steel and bronze accessories. The streamlined projection downstream of the cylinder was attached to minimize the flow disturbance and the unsymmetrical, unsteady forces on the cylinder which would result from its abrupt termination. The cylinder is held on the center line of the conduit by the three struts which were fabricated from structural steel plate, welded to the cylinder, and bolted to the valve seat.

The valve plate or disk was fabricated entirely from structural steel at the Laboratory and welded to the hydraulic piston. The reinforcing struts are provided to limit the deformation—and hence vibration—of the plate under the high dynamic loads which exist when the valve is nearly closed. The pulleys on the valve plate serve as indicator cable guides. One end of a stainless steel cable which passes over the pulleys is fastened to the supply channel wall and the other end is attached to a small piston which moves in a cylinder attached to the exterior of the supply channel. The motion of the valve plate in and out, multiplied by two, is thus indicated by the like motion of this piston. The purpose of this system is described later. The outer edge of the valve plate is covered by a rubber sheet which is both cemented and clamped to the plate. It is this sheet which forms the final seal between the valve plate and the valve seat.

The valve seat is formed from a standard structural steel 3 by 3 by 7/16-in. angle rolled into a hoop. The interior "V" of the angle was filled with mortar which was then molded to the profile shown in Fig. 15, except at the points where the struts were attached. The actual valve seat is formed by the slightly protruding edge of the angle which was ground to match the valve plate after both had been mounted in the circuit.

Figure 16 shows the installation during construction before the valve plate was permanently attached to the piston; Fig. 17 shows the completed valve plate in place. All the components subject to corrosion were either cadmium-plated or carefully painted with rust-preventative paint. The valve is opened by hydraulic pressure and closed by a combination of cable force (which will be discussed later) and dynamic flow forces. The maximum opening to which the valve can be forced by the hydraulic system is limited by a direct connection between the cylinder and the low-pressure side of the hydraulic system which the piston exposes after moving 10-1/2 inches.

6. Discharge Valve

The tunnel discharge valve is composed basically of a valve plate, a valve seat, and a hydraulic cylinder which actuates the valve plate in closing. The valve (a simple disk type) is shown in Fig. 18, in which the components can easily be discerned.

The valve seat is actually the downstream end of the tunnel conduit which has been machined to a smooth, flat surface against which the valve plate, fabricated from structural steel, bears when the valve is closed. To obtain a perfect seal at this valve, it is necessary to put a temporary gasket between the plate and the seat before closing the valve tightly, thus pinching the gasket in place. The hydraulic cylinder, which is hung within an 8-in. standard pipe, is a commercially available unit. The single-acting cylinder piston is connected to a stainless steel rod which is laterally supported by the two bearings and which passes through the tunnel wall through a conventional leather shaft packing. Both bearings are bronze, the downstream bearing being supported by a three-leg spider extending from the conduit walls and fabricated from structural steel. An indicator cable, one end of which is attached to the housing and the other end of which leads out of the housing (and indirectly to the control stand), is passed over a pulley on the hydraulic piston in such a manner that the motion of the valve plate, multiplied by two, is transferred to the cable.

The basic valve structure is shown before installation in Fig. 19, and Fig. 20 shows the completed installation in which only the cylinder housing is readily visible. The valve is closed by hydraulic pressure and opened by a combination of its own weight, cable force, and fluid forces. All corrodible parts were carefully painted with rust-preventative paint.

7. Control and Indicating System

The control stand of the tunnel serves as a base for the convenient and integrated mounting of the tunnel control and indicating equipment, and it also provides space for future auxiliary equipment. The stand itself, shown in Fig. 21, was fabricated from a standard steel storage cabinet which was slightly modified at the Laboratory to form the step top. The basic equipment mounted in the stand consists of the high-pressure hydraulic systems for the test section, inlet valve, and discharge valve, and the indicating mechanisms for the latter two items.

The complete hydraulic system is shown schematically in Fig. 22. The hand pumps (rated at 1500 psi), needle valves, relief valves, filter, storage tank, and necessary special fittings are commercial high-pressure units; whereas the lines are of standard 3/8-in. copper tubing equipped with standard fittings wherever possible. Each of the hydraulically operated elements has its own hydraulic pump which furnishes the power for closing the test section, closing the discharge valve, and opening the inlet valve. By opening the bypass needle valve of each of these elements, the natural forces acting on the elements are permitted to bring about the reverse motions. The complete system, except for the storage tank which is located on the supply channel wall just above the horizontal conduit and the lines leading to the various cylinders, is mounted within the control stand. The pump handles and bypass valves protrude through the desk top of the stand and, hence, are conveniently located for operation.

The indicating systems incorporated into the control stand, shown schematically in Fig. 23, indicate the linear opening of the inlet and discharge valves. As noted in the descriptions of the valves, a 1/8-in. cable is led from each valve to the control stand, which transmits twice the linear movement of the particular valve. In the case of the inlet valve, the cable leading to the stand is attached to the exterior end of a small piston which passes through the supply channel wall to the valve cable within the channel. The exterior cable is led from the supply channel wall horizontally within a 1-1/2-in. standard pipe to a point directly above the control stand. The pipe and cable, by means of a pulley, turn through a right angle at this point and extend downward into the stand. This pipe, which also contains the hydraulic lines leading to the storage tank and inlet valve, serves only as a protective device. The cable from the discharge valve is led directly from the cylinder housing to the control stand along the vertical conduit and through the floor underneath the stand. Within the stand, each cable is wrapped a few turns about a cable drum and then attached to a 200-lb counterweight which insures a positive cable force at all times. The drums are lathe-turned sections of standard pipe equipped with faces welded in place and centered on ball-bearing-supported axes. The bearings are supported in U-frames fabricated from structural steel bar stock and bolted in turn into the stand. The axis of each drum extends through the front of the control stand step and is equipped with an indicator needle at this point. The linear motion of the valves is thus translated into the angular motion of the indicators which have dial faces calibrated to read the valve opening directly.

C. Preliminary Tests

1. Calibration of the Contraction as a Velocity Meter

The contraction of the water tunnel forms a natural velocity meter when equipped with the static pressure-tap system noted in the contraction description, hence it has been calibrated for use as such an instrument in future experimental studies of cavity flows. For this purpose the upstream and downstream pressure rings of the contraction were connected to a 50-in. differential mercury manometer, and the middle and upstream rings were connected to a similar manometer using a commercial gage fluid with a specific gravity of 2.95. All three rings are additionally connected to the high-pressure water supply system of the Laboratory (90 psi municipal water supply) as shown in the schematic layout of the manometry system in Fig. 24. The valving system employed permits independent control of both manometers, and use of the high-pressure supply system to flush the pressure lines into the contraction. A convenient method such as this for clearing air from pressure lines is necessary in a free-jet water tunnel because the contraction is always dewatered except when the tunnel is in actual use.

The contraction was calibrated by directing the flow through the tunnel contraction into the gravimetric measuring tanks of the Laboratory. These tanks are located adjacent to the tunnel in the turbine room area of the Laboratory with their indicating scales on the same level as the tunnel test section. The system consists basically of two tanks with a common headbox into which the flow from the apparatus to be calibrated is discharged and from which it is discharged into either one, but not both simultaneously, of the two tanks. Hence, by using a continuous alternating-tank fill-weigh-empty method of measurement, a total discharge weight and a total discharge time can be achieved which are large enough to give any desired degree of accuracy in the time-discharge relation being determined, within the accuracy of the weighing tanks (which are accurate and sensitive to 10 lb in 40,000, their maximum capacity). In using the weighing tanks to calibrate the tunnel contraction, the headbox of the weighing tanks was connected to the vertical conduit of the tunnel by a short horizontal 12-in. pipe about 9 ft below the tunnel test section. The headbox end of the pipe was equipped with a butterfly valve which could be controlled from the test-section level by means of an extension to the control wheel. The contraction was calibrated by sealing the discharge valve, opening the inlet valve, and controlling the flow through the contraction and into the weighing tanks by means of a butterfly valve. Because the headbox is only slightly below the test section, the discharge through the tunnel is limited, the limiting flow, however, being almost identical with the maximum flow rate measurable in the weighing tank system.

The results of the calibration are shown in Fig. 25, in which the test-stream velocity V_o (defined as Q/A_o, where Q is the discharge rate and A_o the area of the downstream end of the contraction) is given as a function of manometer deflection. As the maximum attainable velocity in the tunnel is about 50 fps, the calibration of the mercury manometer has been extrapolated to this point. The errors in cavitation studies resulting from such an extrapolation will not be significant.

2. Determination of the Test-Stream Velocity Profile

Although extensive pressure-velocity measurements within the test stream of the new tunnel are planned in order to aid in the evaluation of various boundary effects, it was of immediate interest on completion of the tunnel to examine the velocity profile of the stream as it leaves the contraction. A special Pitot-static tube was constructed at the Laboratory for use with the tunnel, as shown in Figs. 26 and 27. The hydraulic design of this device is basically the same as that of the National Physical Laboratory Standard [13]; the second leg has been added to increase the structural stability of the instrument and is also used to transmit the stagnation pressure, the static pressure being transmitted by the usual leg. The device, as a unit, can be mounted in any one of the three slots of the dummy window described in Section III-B-4, and the head of the instrument can then be moved linearly back and forth on a radius a total of 11 in., or from side to side on an arc a total of 60°. Both motions are controlled by small hand wheels, and the angular motion is indicated directly by the position of an indicating needle on an angular scale, while the radial motion is given by the distance the legs extend from their sockets. This design permits taking measurements at any point across the test stream in three horizontal planes. The tests reported here were made in the uppermost plane, in which the nose of the Pitot-static tube is 2-3/4 in. downstream of the contraction exit, with the inner viewing windows mounted diametrically opposite each other and at right angles to the location of the Pitot-static tube. The stagnation and static pressures were led to a 50-in. differential mercury manometer equipped with an air-collecting dome for each leg, as shown in Fig. 28.

A cross-sectional layout of the points of measurement in the test stream is given in Fig. 29 along with the results of the measurements. The charts in this figure give the ratio of the mean velocity V_o, as indicated by the pressure drop through the contraction, to the apparent velocity indicated by the Pitot-static tube at each point. This latter value of the velocity is given by the expression $(2gH)^{1/2}$ where H, the dynamic head, is taken as the difference between the total head and the static head at any point as measured by the Pitot-static tube. The velocity is seen to be nearly constant over the entire measurable cross section; the mean value of $V_o/(2gH)^{1/2}$ can be taken as 0.98+. On this basis, the value of the Pitot-static tube coefficient can be taken as 0.985 without introducing an error greater than the inherent inability of the instrument to detect and indicate in turbulent flows.

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APPENDIX

FIGURES 1 to 29

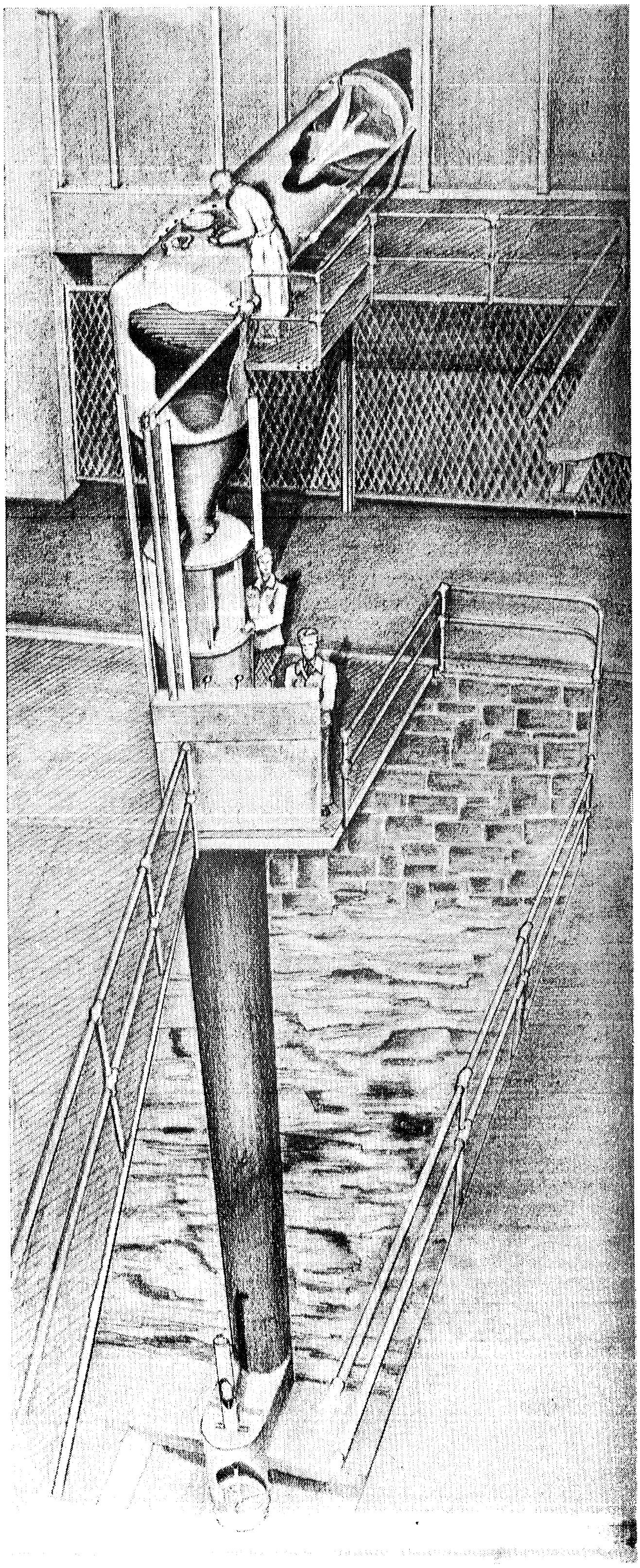


Fig. I-The Ten-Inch Free-Jet Water Tunnel

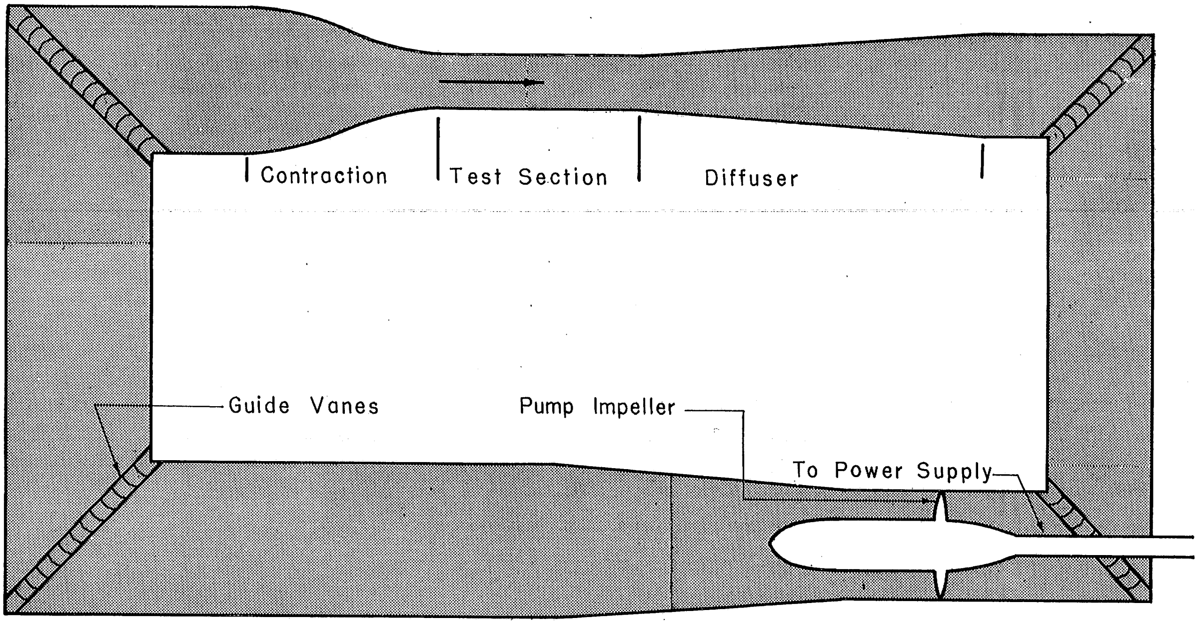


Fig. 2–A Conventional Water Tunnel with a Closed–Jet Test Section

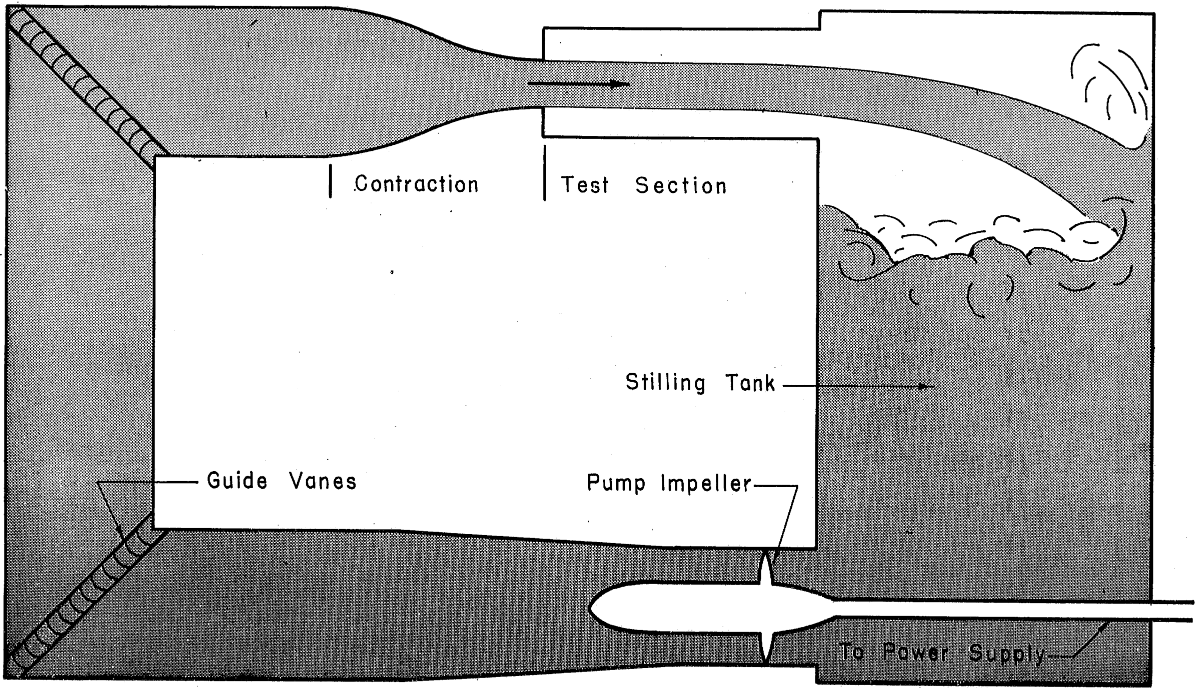


Fig. 3– A Conventional Water Tunnel Modified to Form a Reichardt Free-Jet Water Tunnel

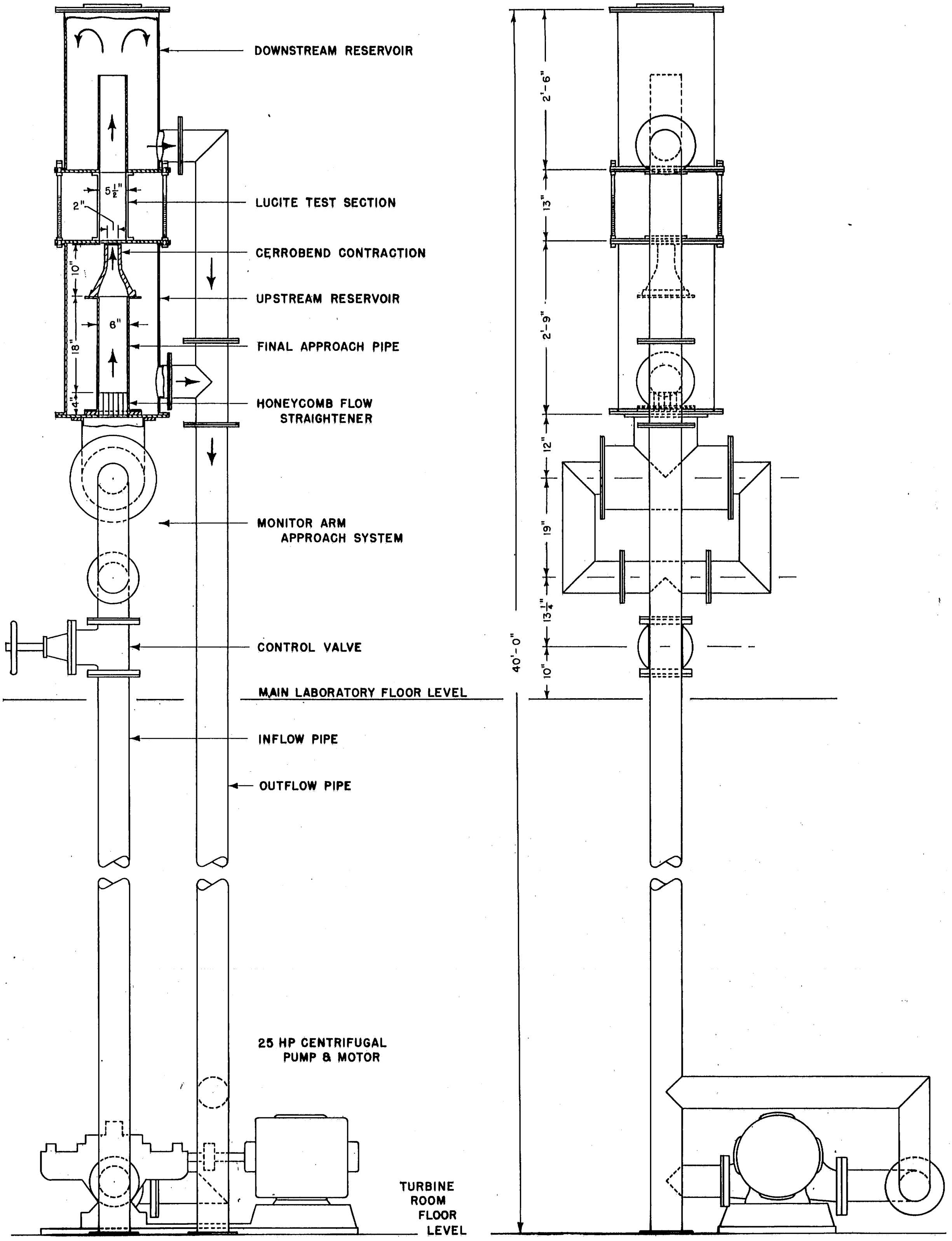


Fig. 4-The SAF Two-Inch Free-Jet Water Tunnel with Test Stream Directed Vertically Upward

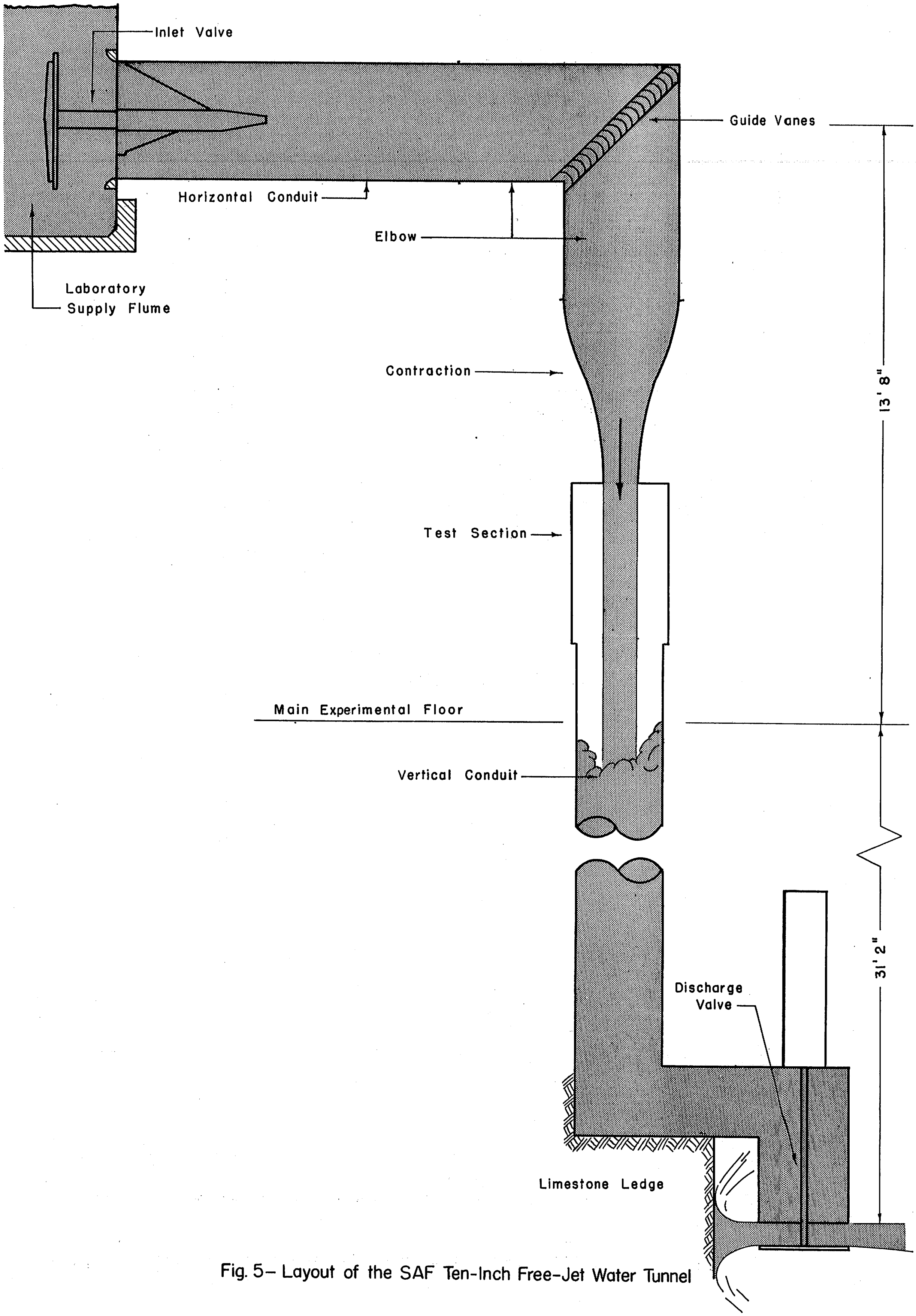


Fig. 5– Layout of the SAF Ten-Inch Free-Jet Water Tunnel

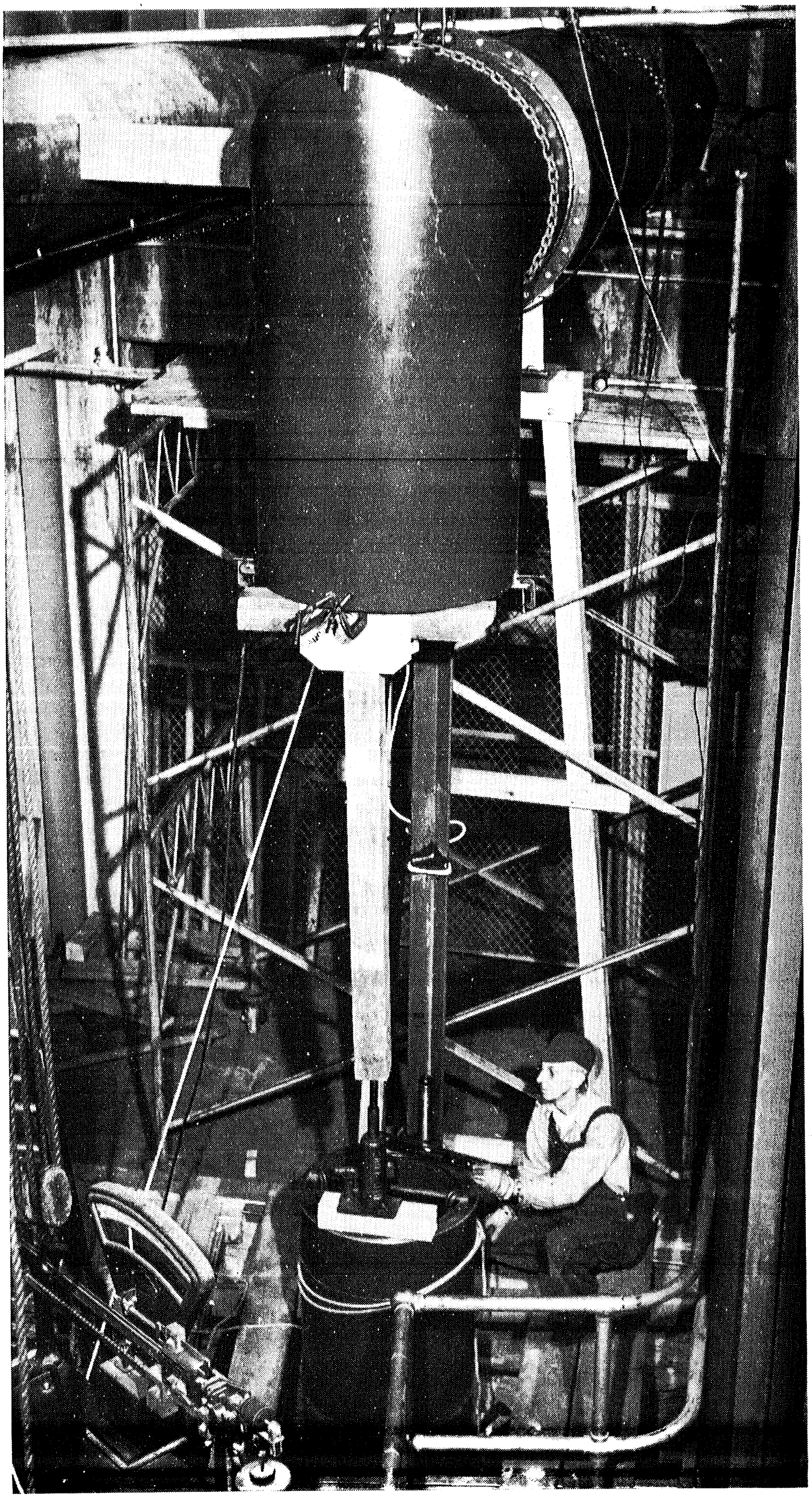
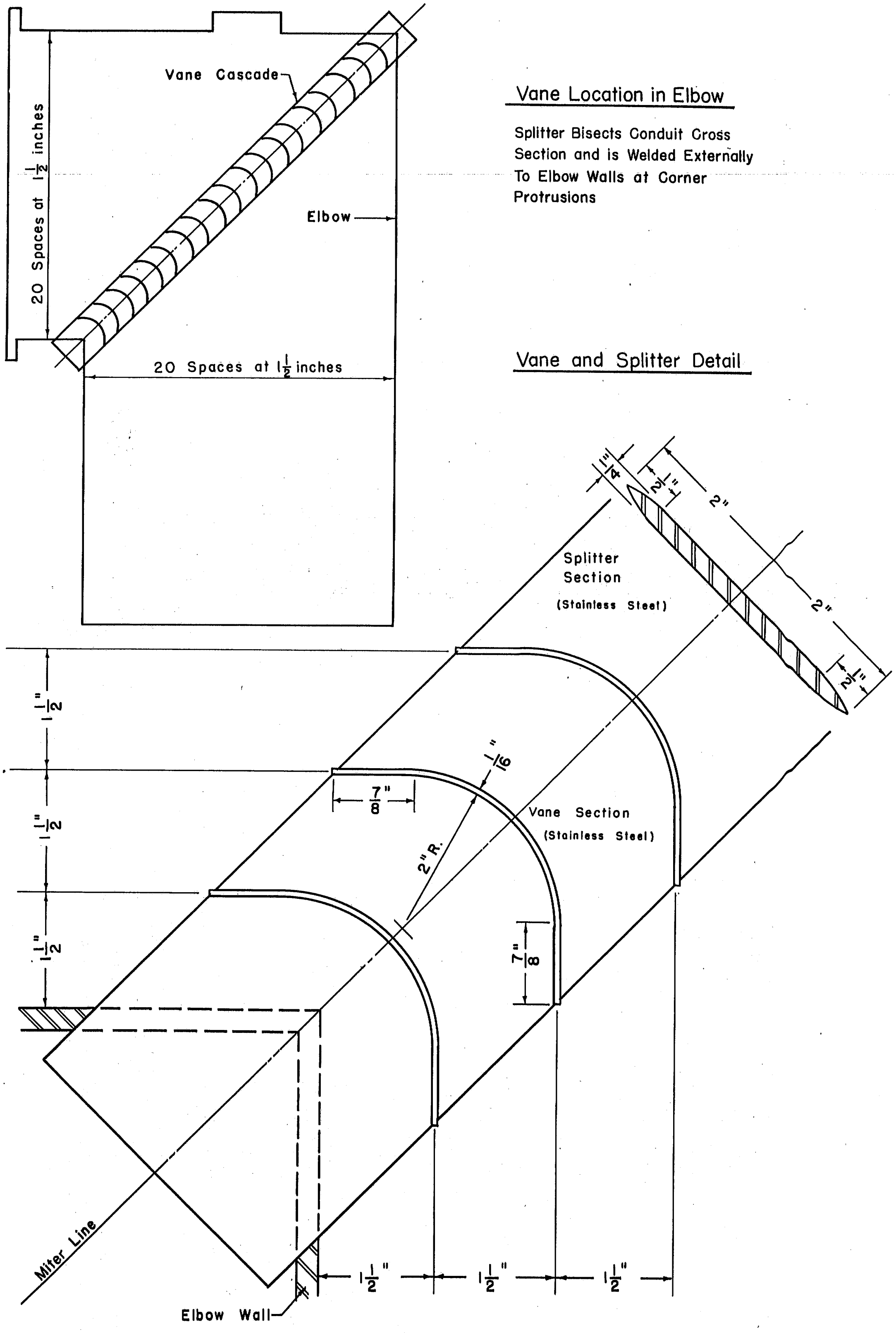


Fig. 6--Installation of the Tunnel Inlet Conduit and Miter Elbow



Vane Location in Elbow

Splitter Bisects Conduit Cross Section and is Welded Externally To Elbow Walls at Corner Protrusions

Vane and Splitter Detail

Fig. 7– Details of Miter Elbow Guide Vanes

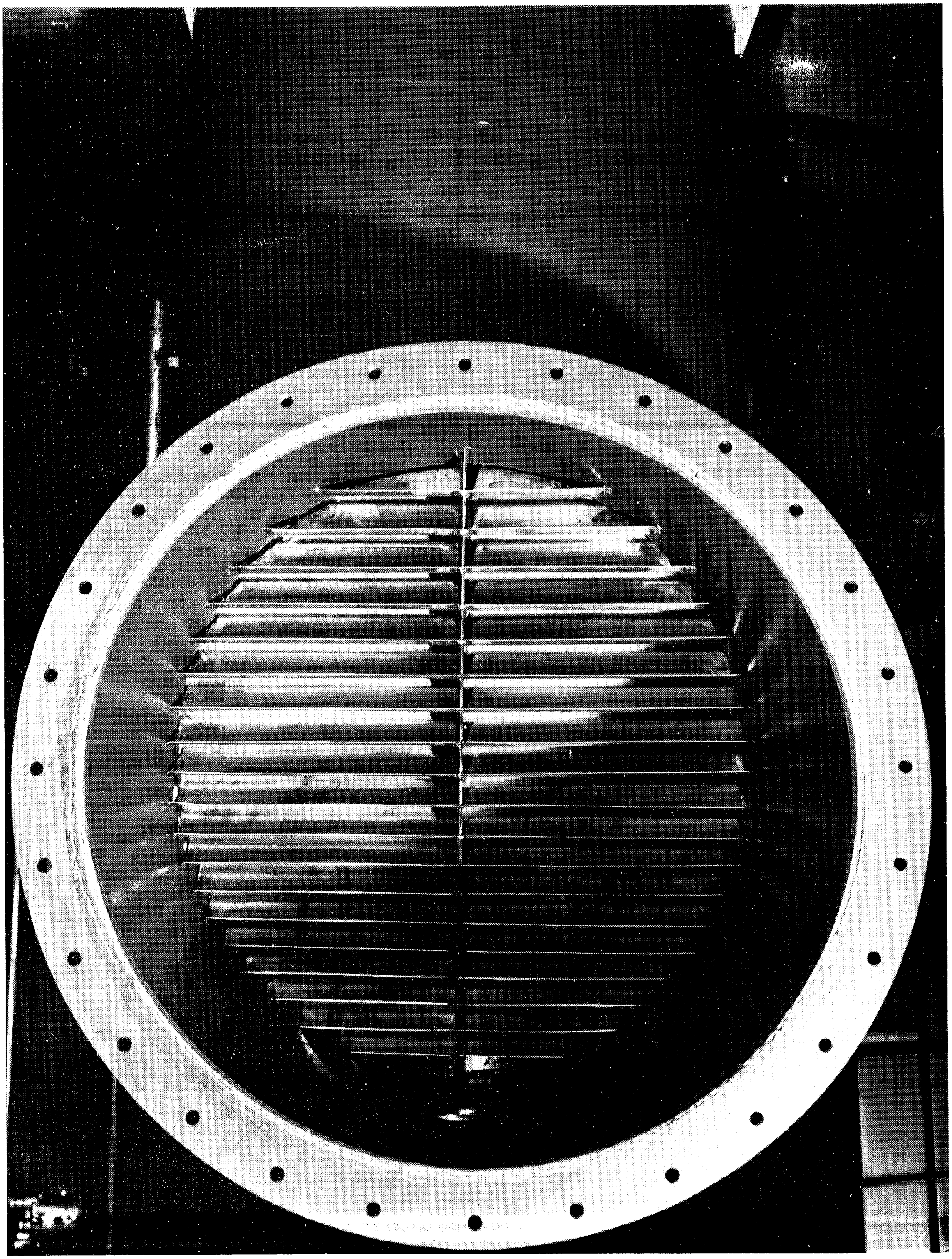


Fig. 8 Installation of Guide Vanes in Tunnel Miter Elbow

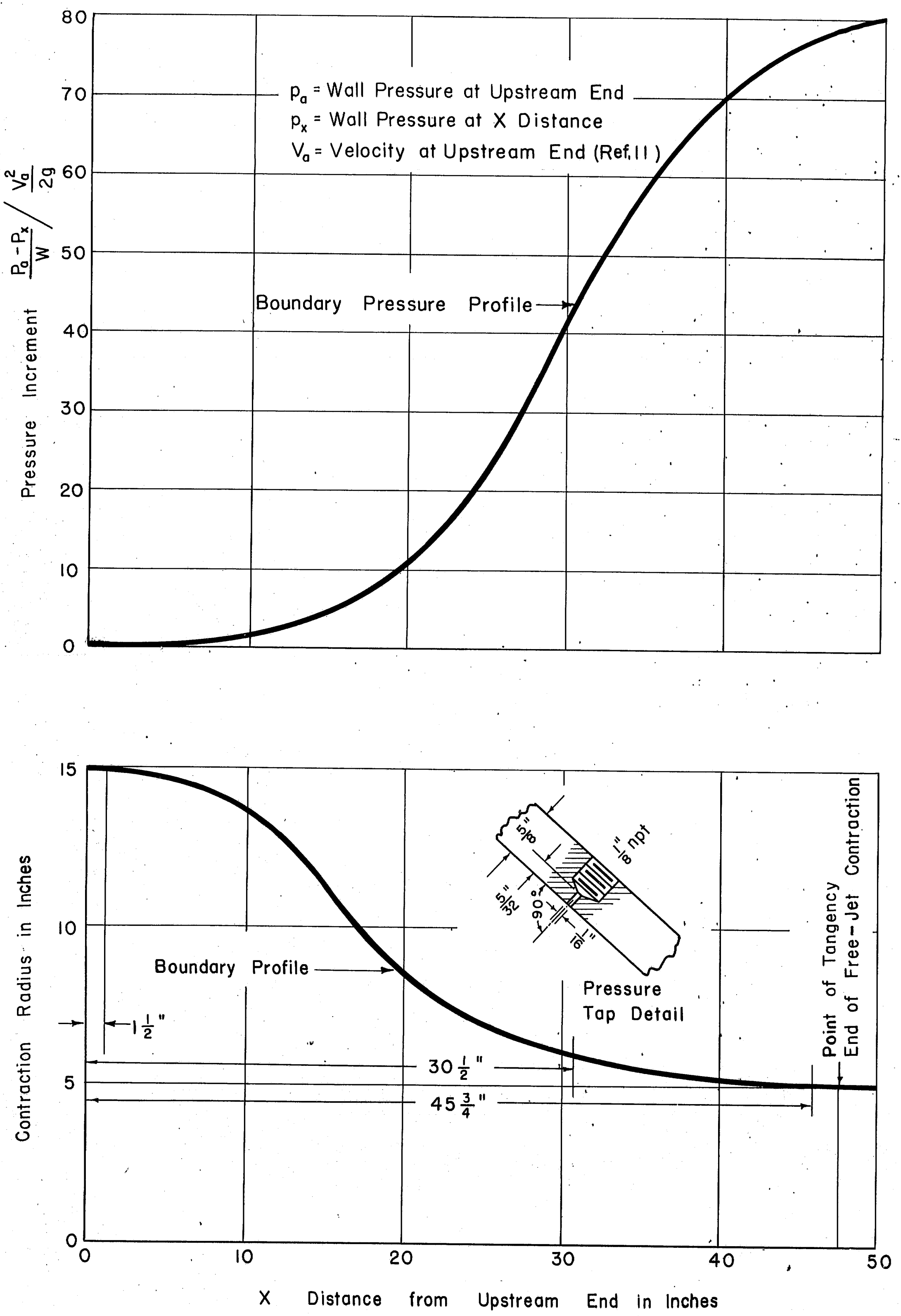


Fig. 9 – Boundary Profile and Boundary-Pressure Profile for the Tunnel Contraction

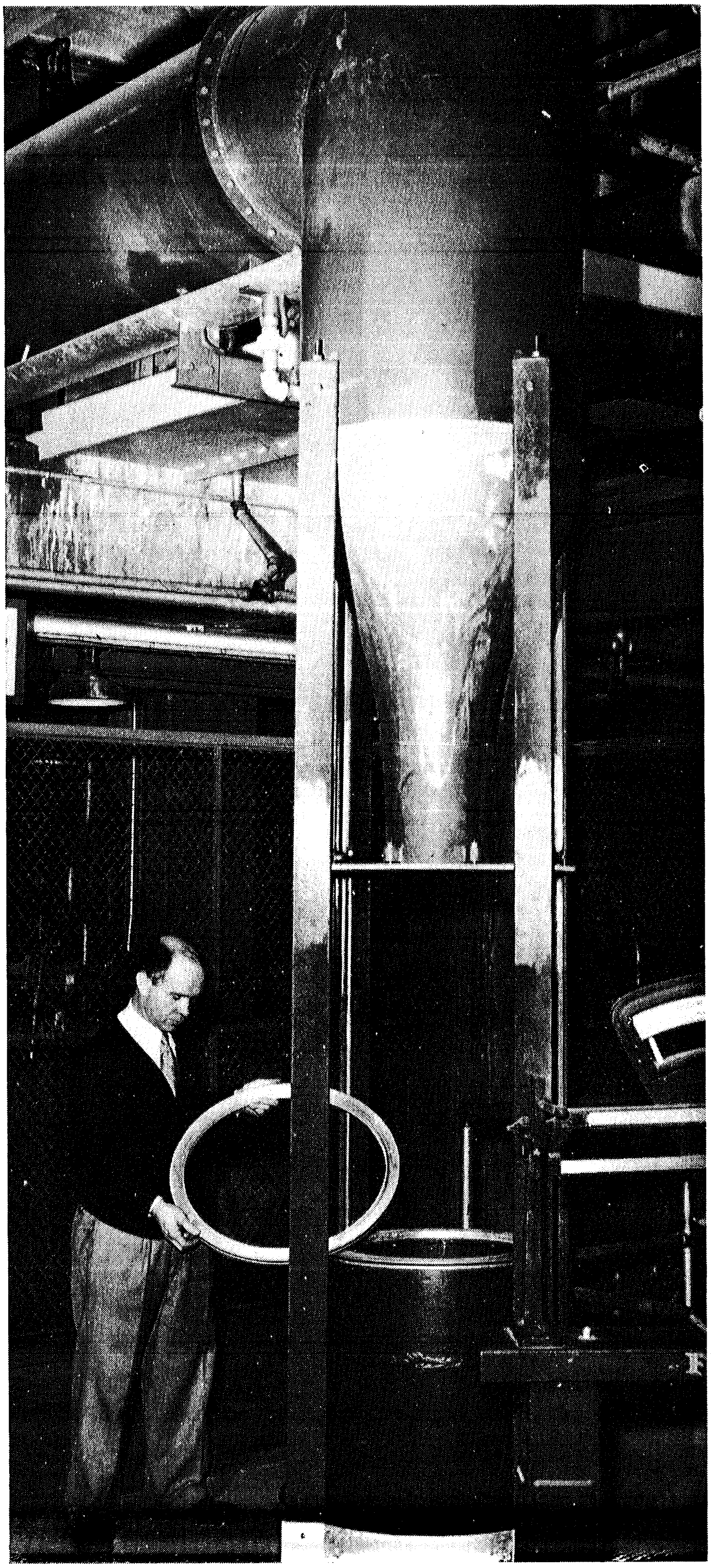
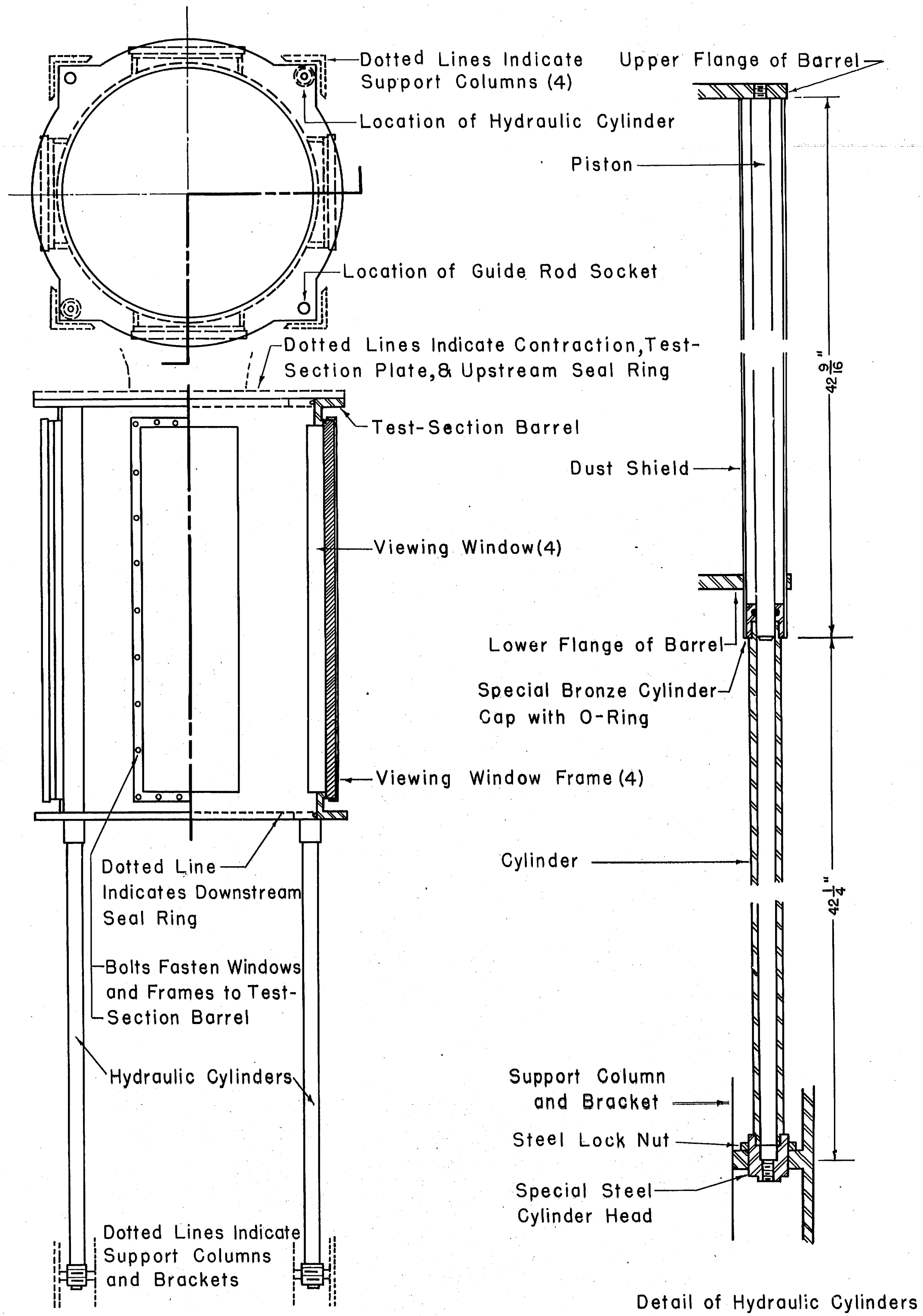


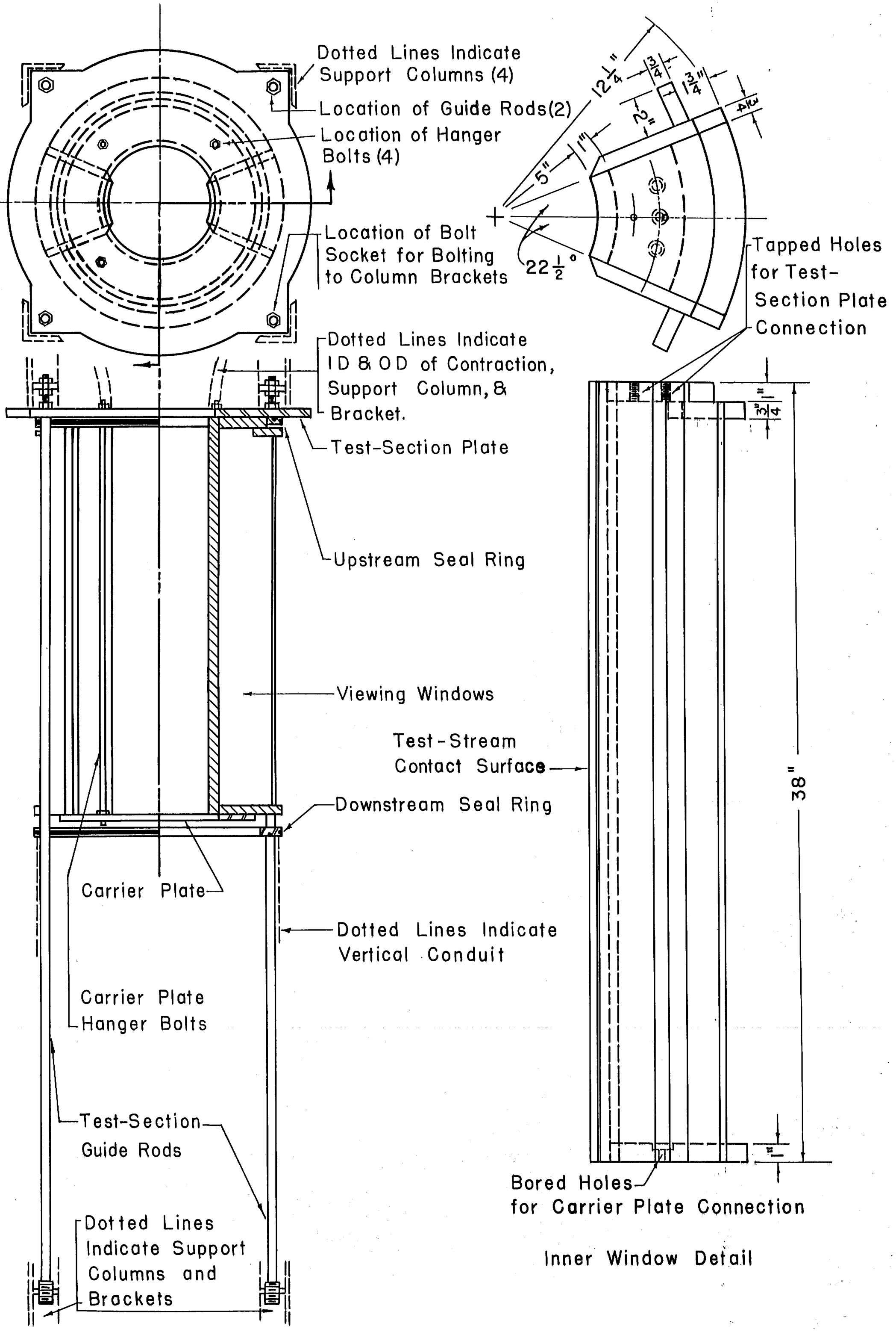
Fig. 10- Installation of the Tunnel Contraction

Shop Foreman Is Holding Upstream Test-Section Seal Ring



Detail of Hydraulic Cylinders
(Test Section Closed)

Fig. 11– Outer Test-Section Components



Inner Window Detail

Fig. 12– Inner Test-Section Components

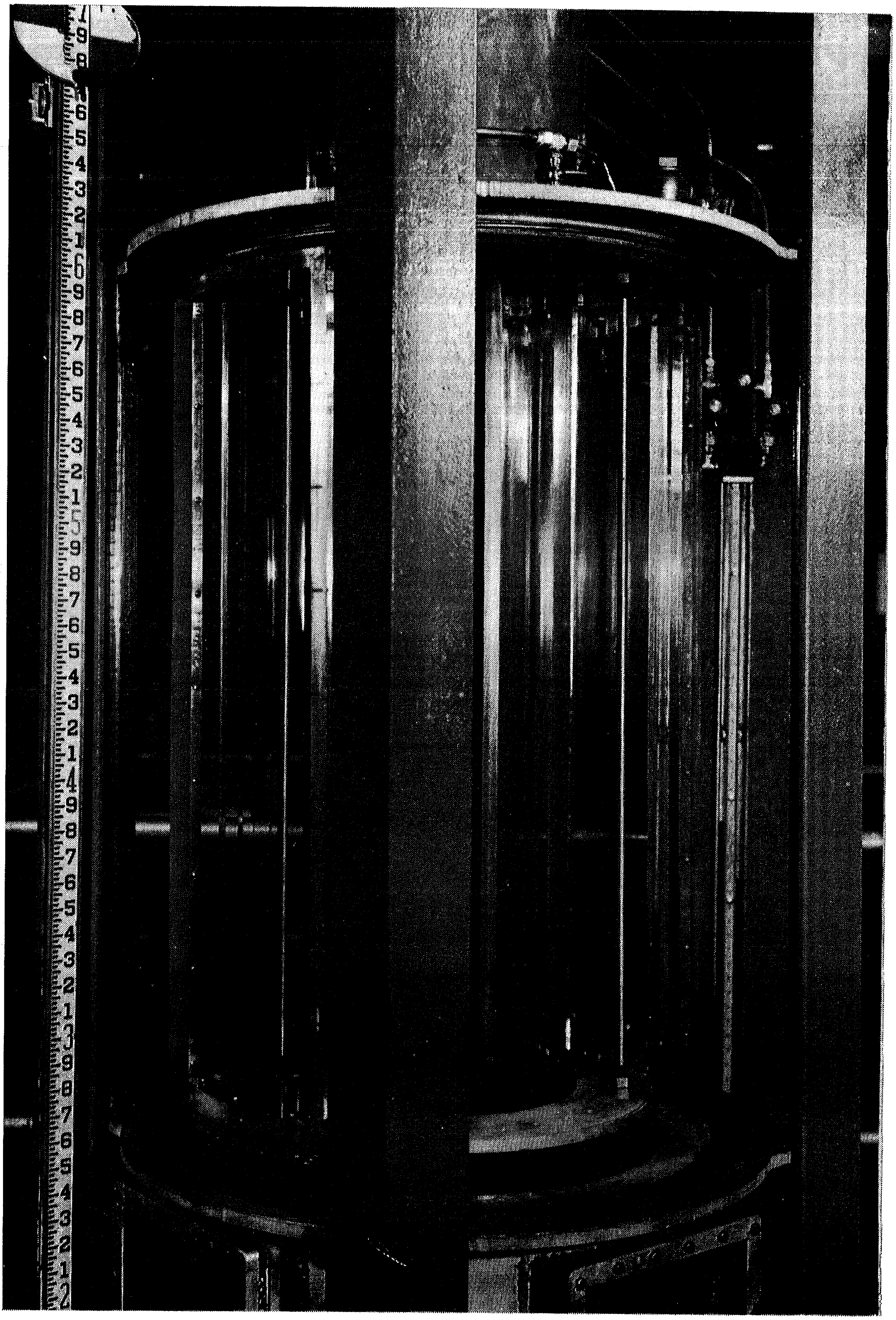


Fig. 13–The Test Section in Open Position

Fig. 14–The Test Section in Closed Position

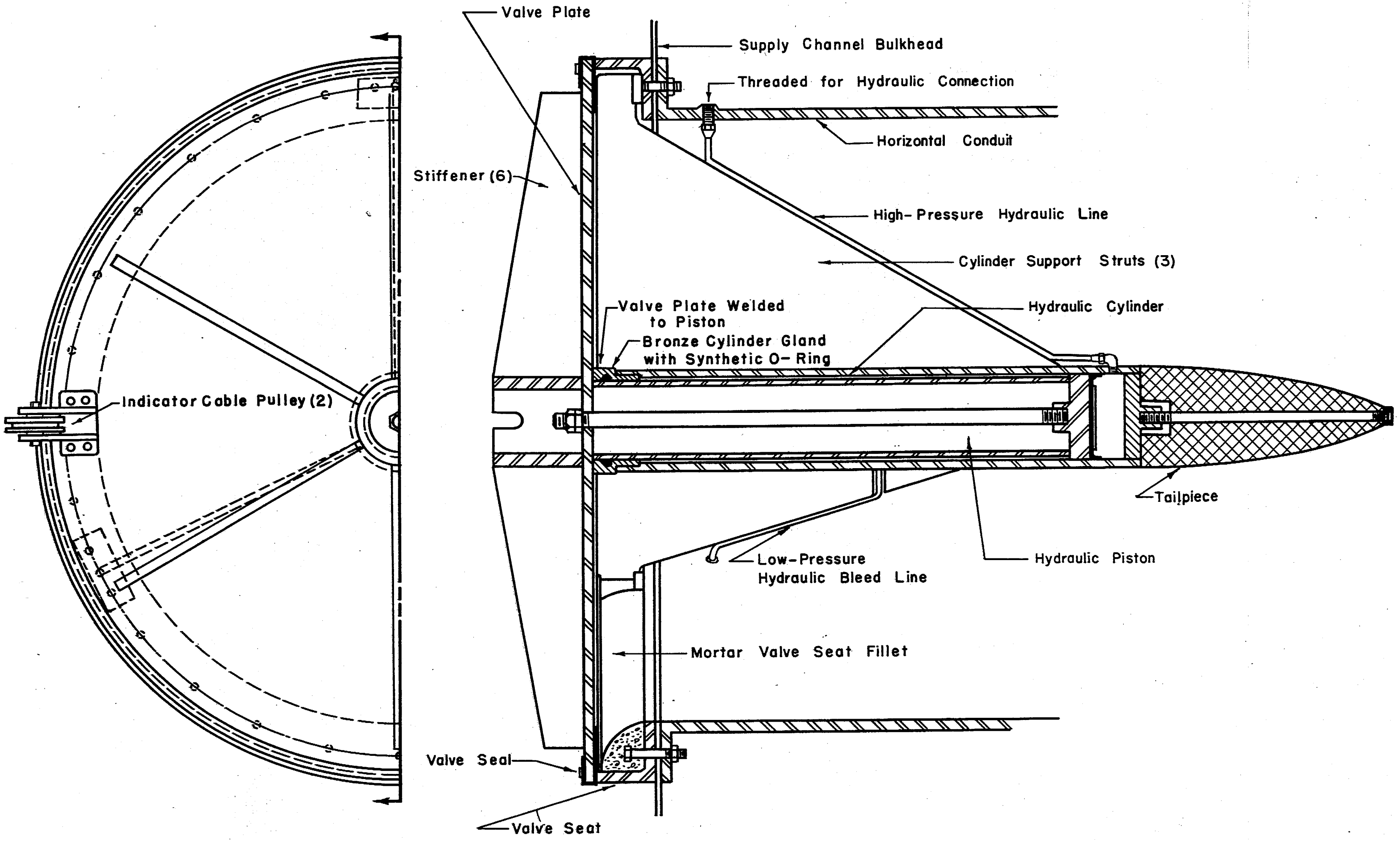


Fig. 15– Inlet Valve Components and Assembly
Valve Is Shown in Closed Position

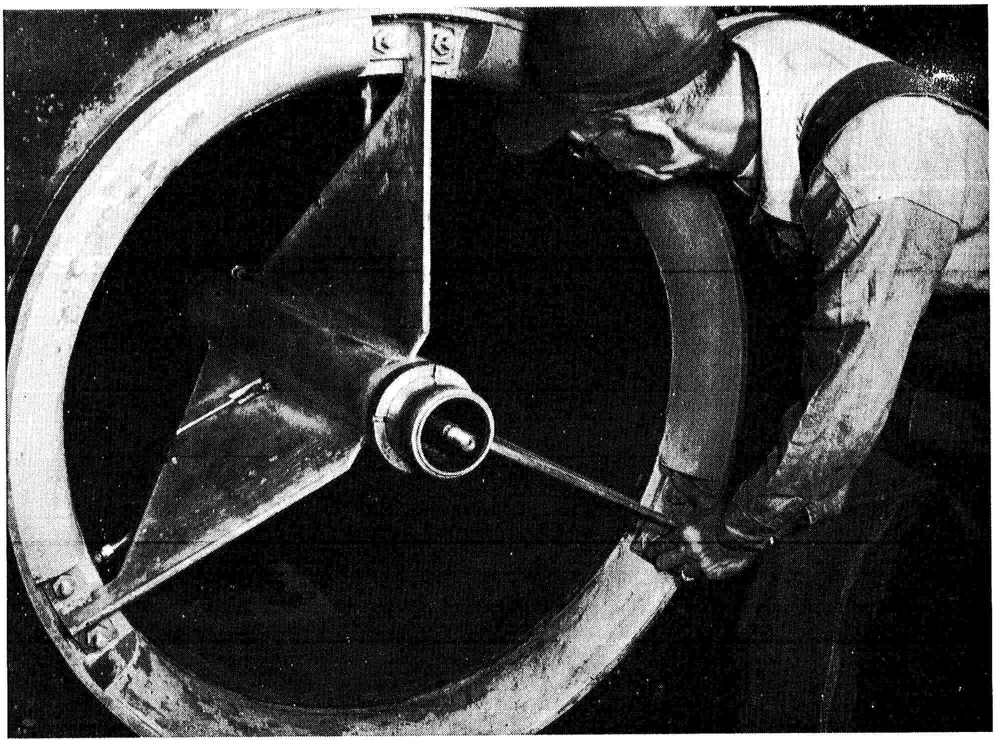


Fig. 16– Inlet Valve During Assembly

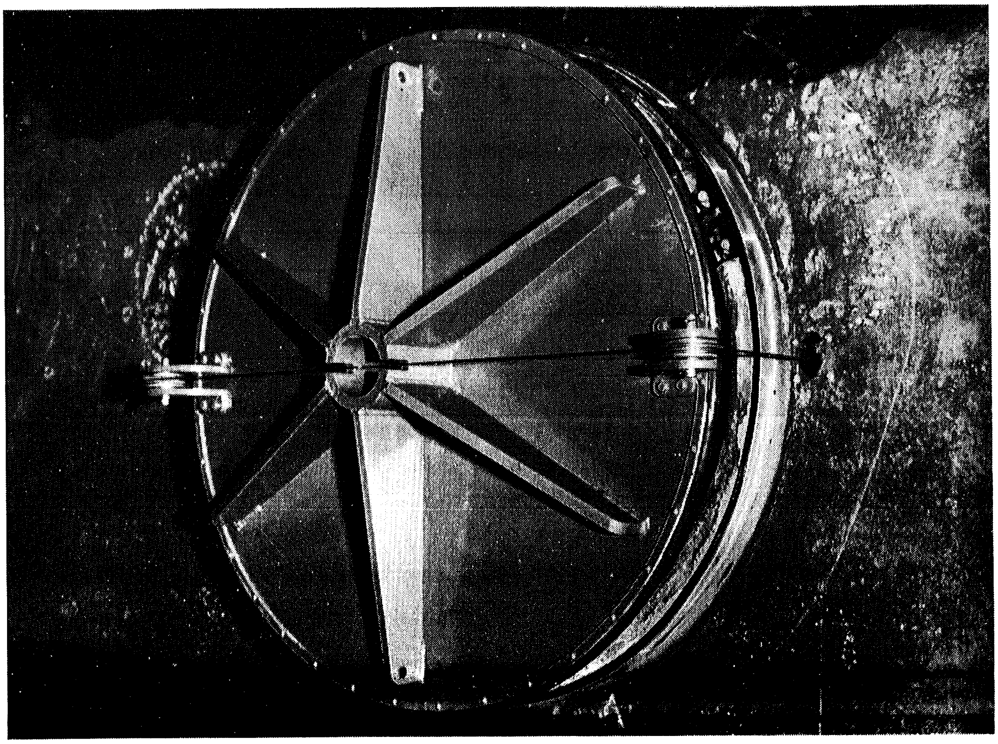


Fig. 17– Inlet Valve in Operation

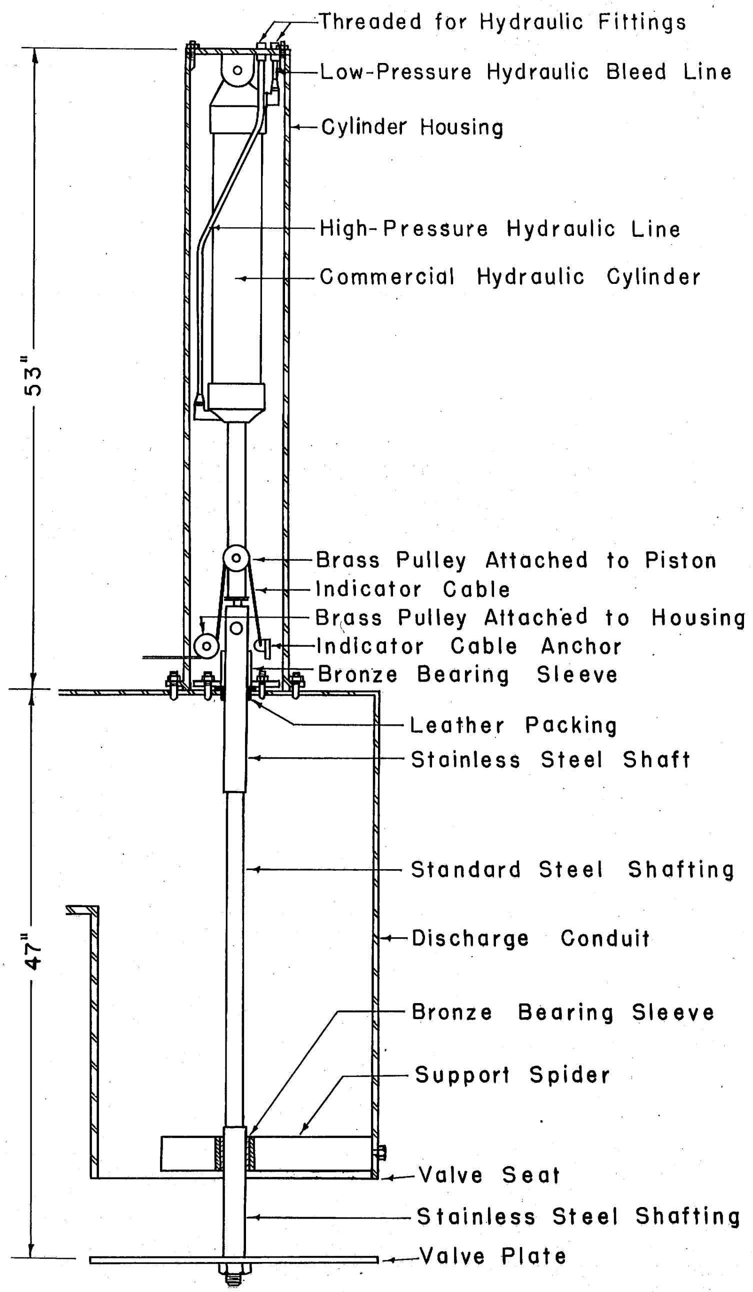


Fig. 18 - Discharge Valve Components and Assembly

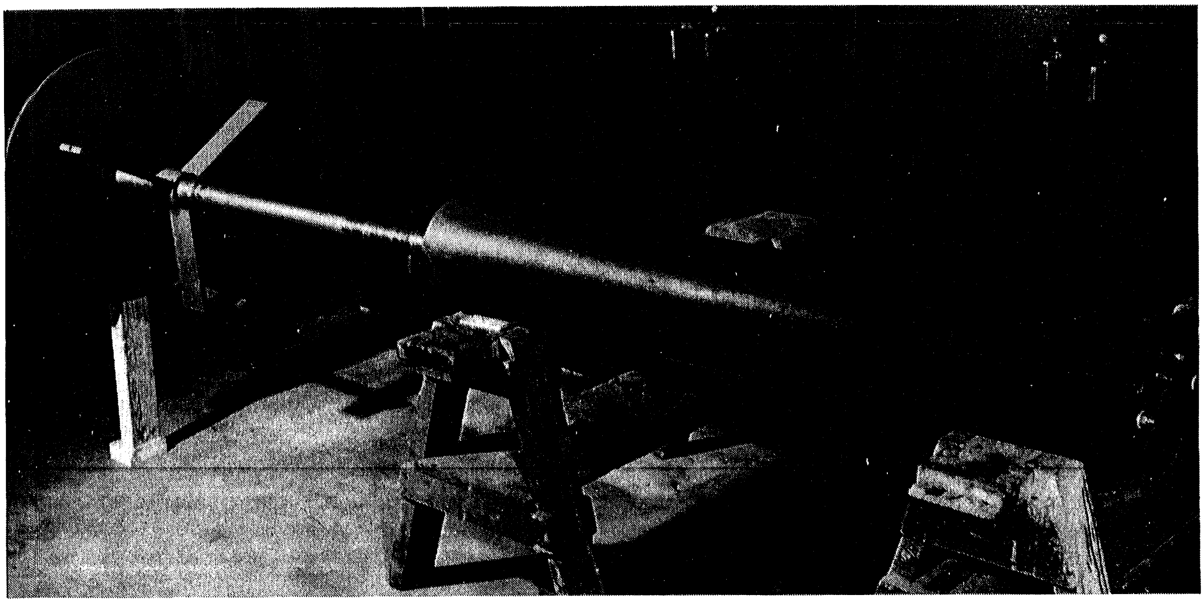


Fig. 19– Discharge Valve During Assembly

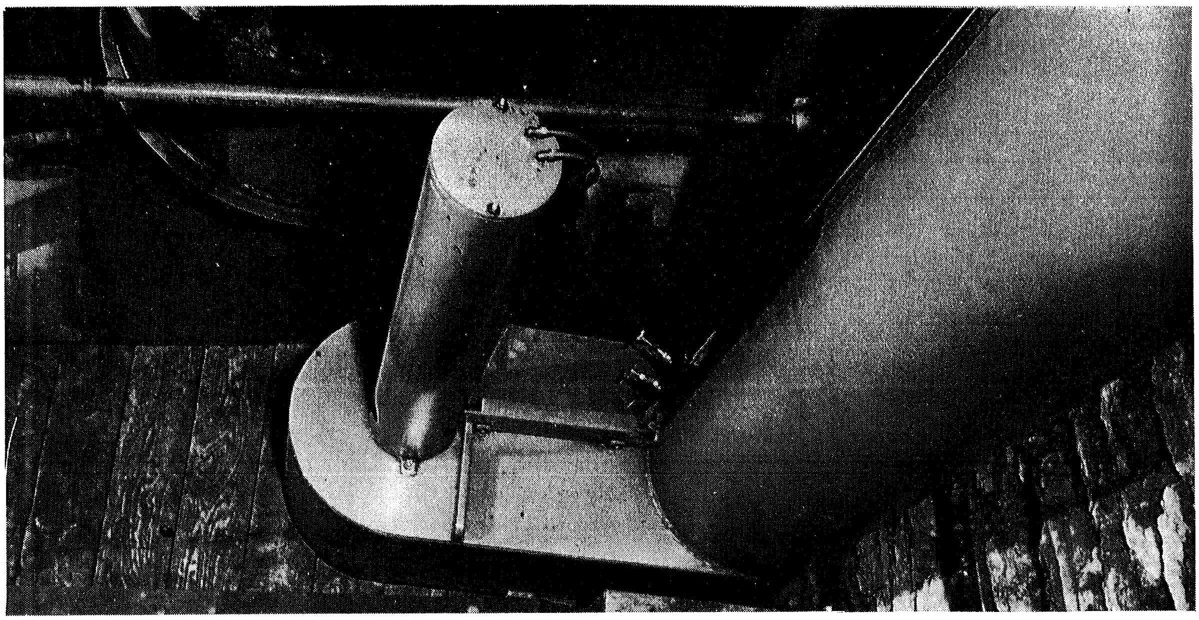


Fig. 20– Discharge Valve Installation

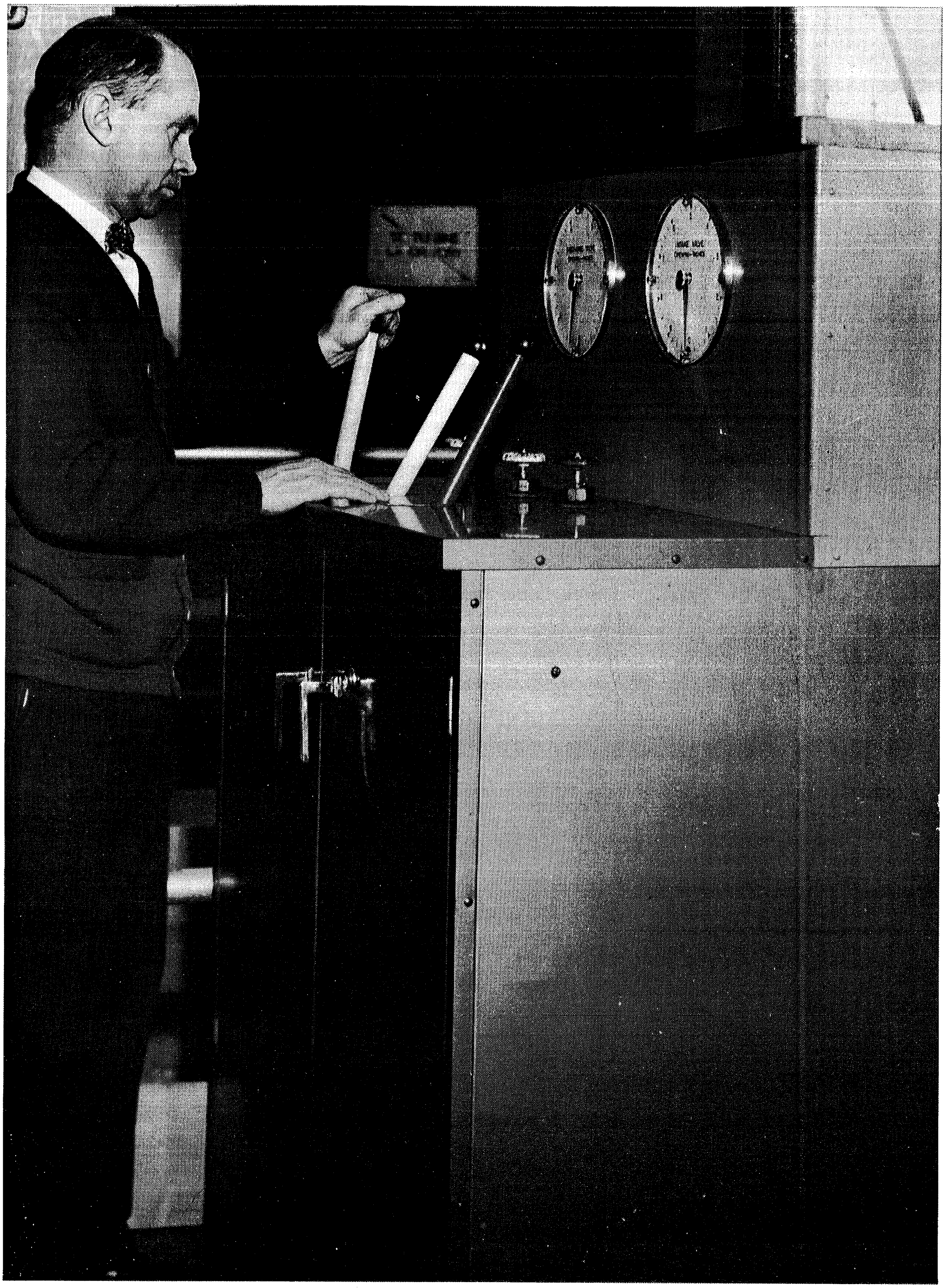


Fig. 21–The Control Stand

Shop Foreman Is Testing Indicating Equipment

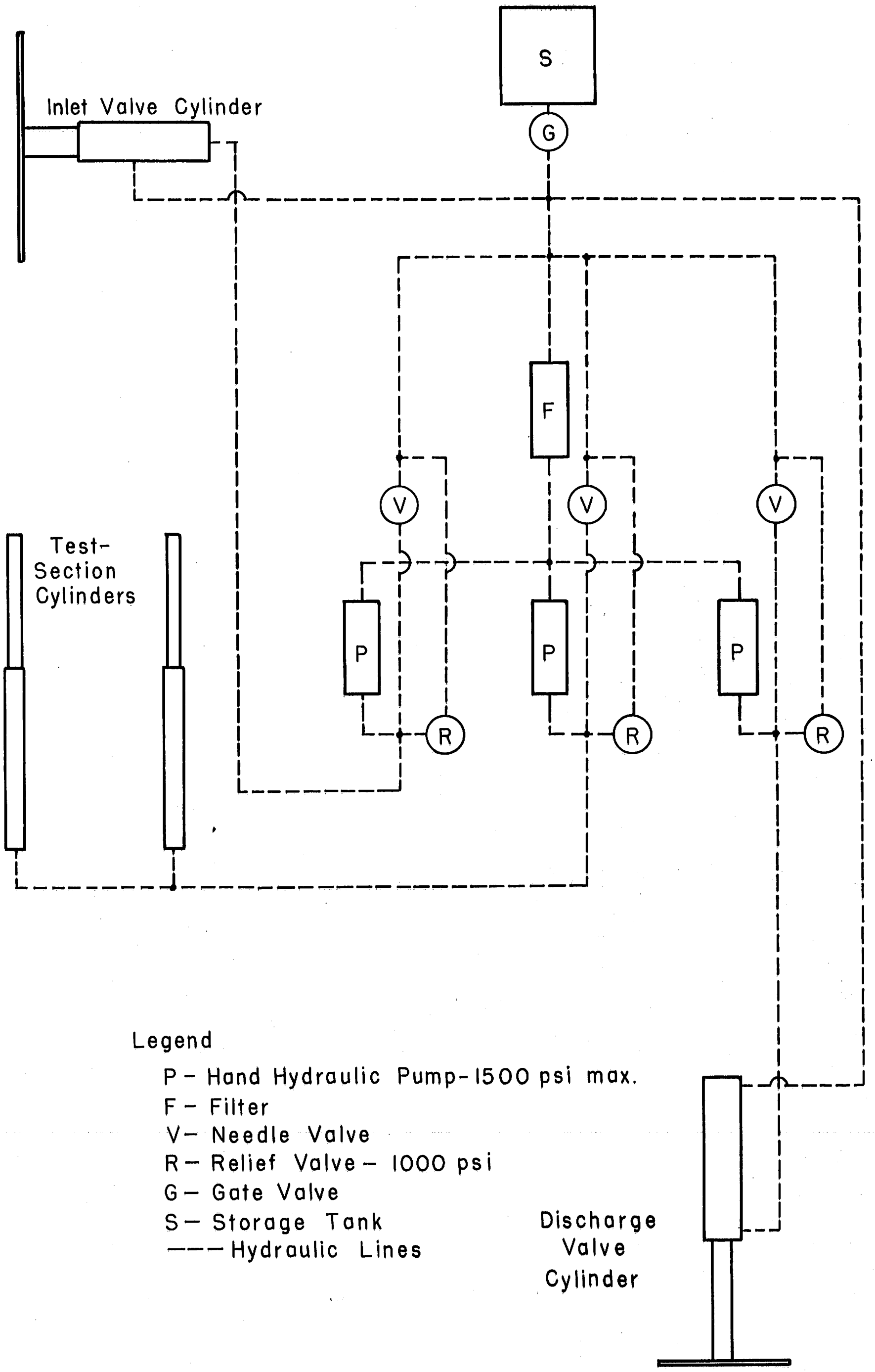


Fig. 22- Schematic Layout of the Hydraulic Control System

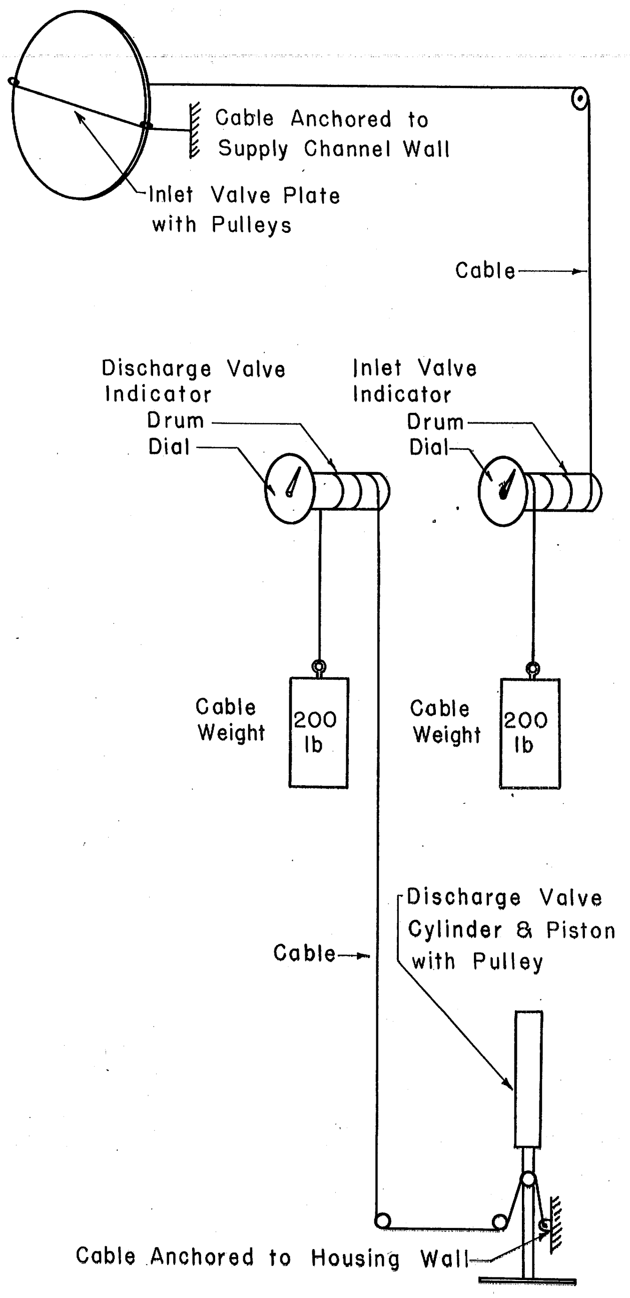


Fig. 23– Schematic Layout of the Cable-Indicating System

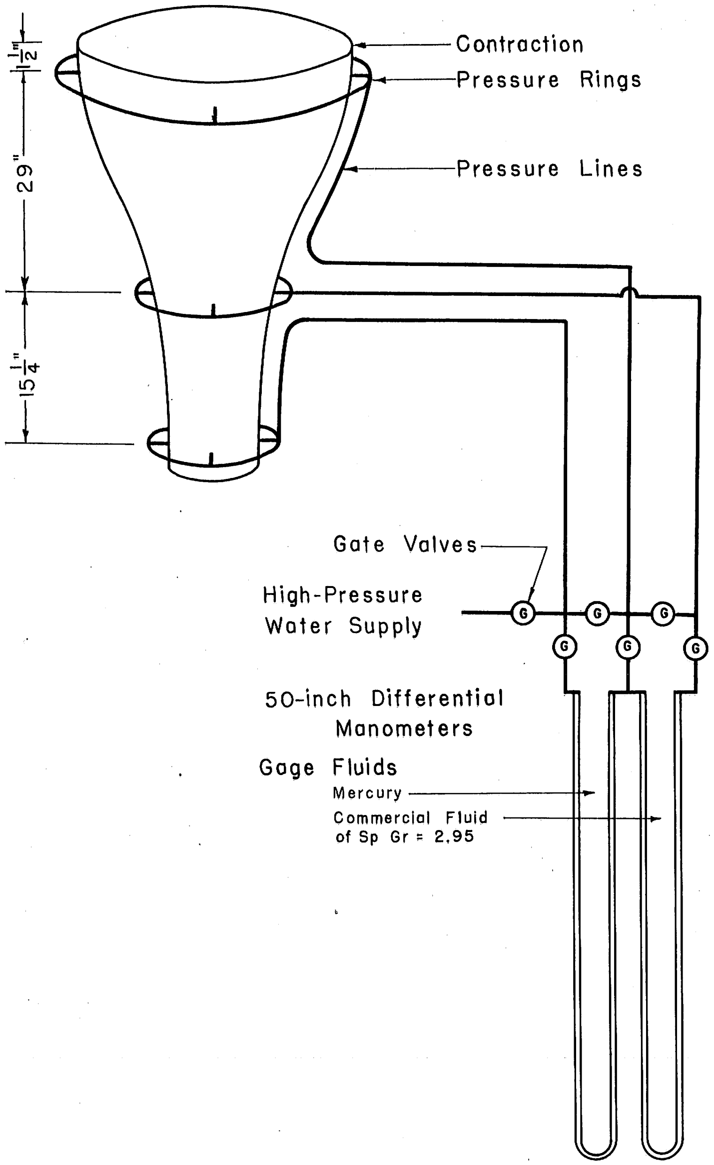


Fig. 24– Schematic Layout of the Contraction Manometry

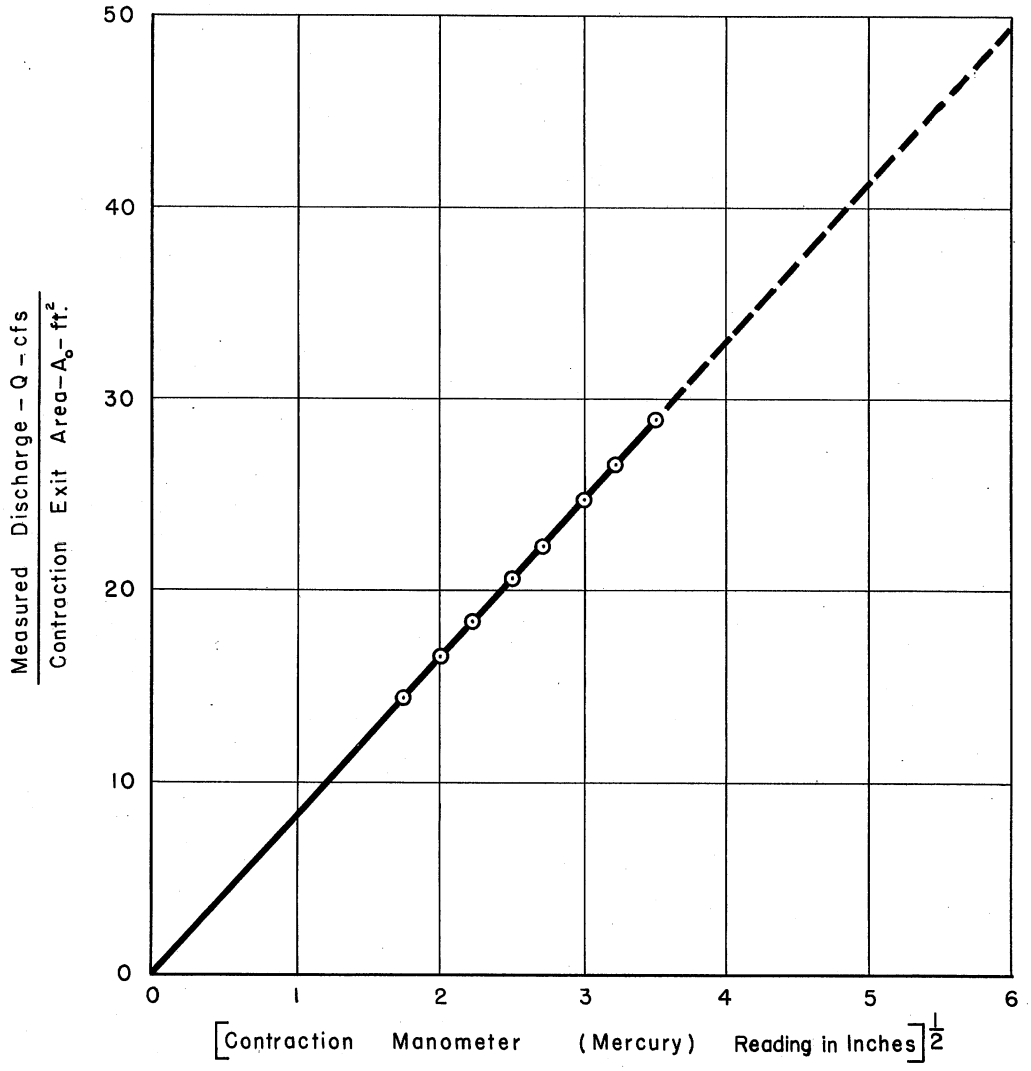


Fig. 25- Results of Contraction Calibration

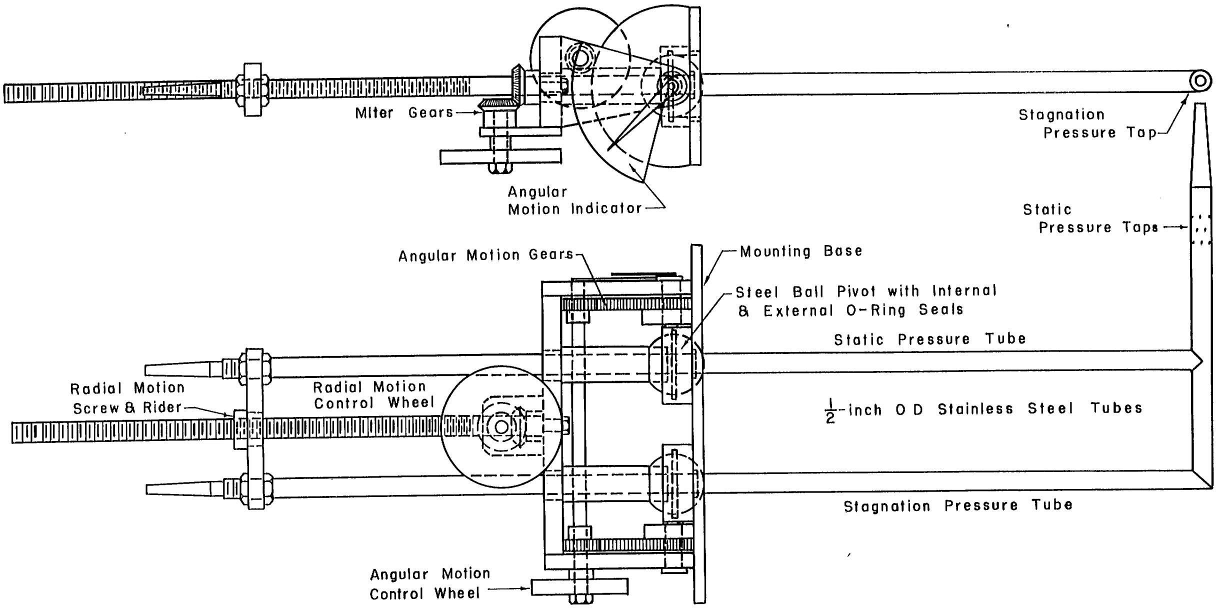


Fig. 26– Pitot-Tube Components and Assembly

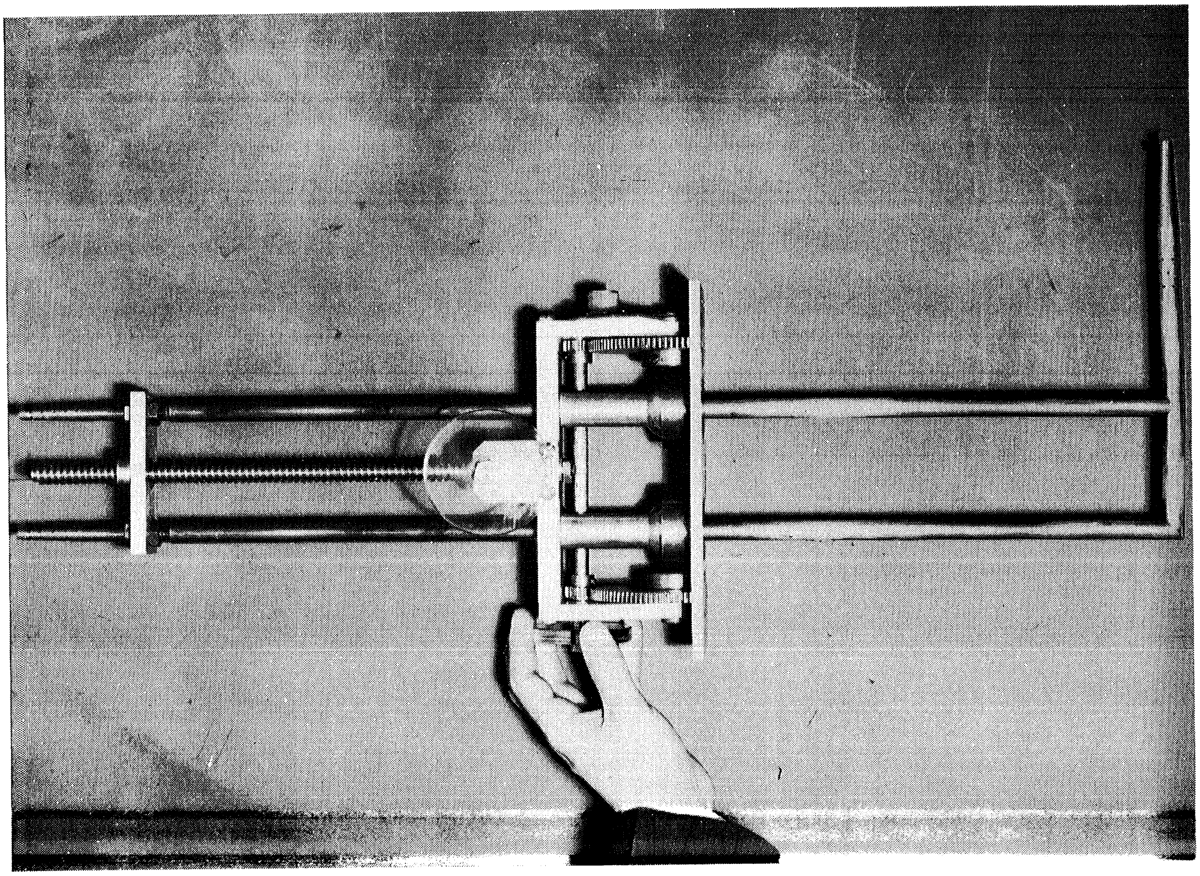


Fig. 27–The Completed Pitot Tube

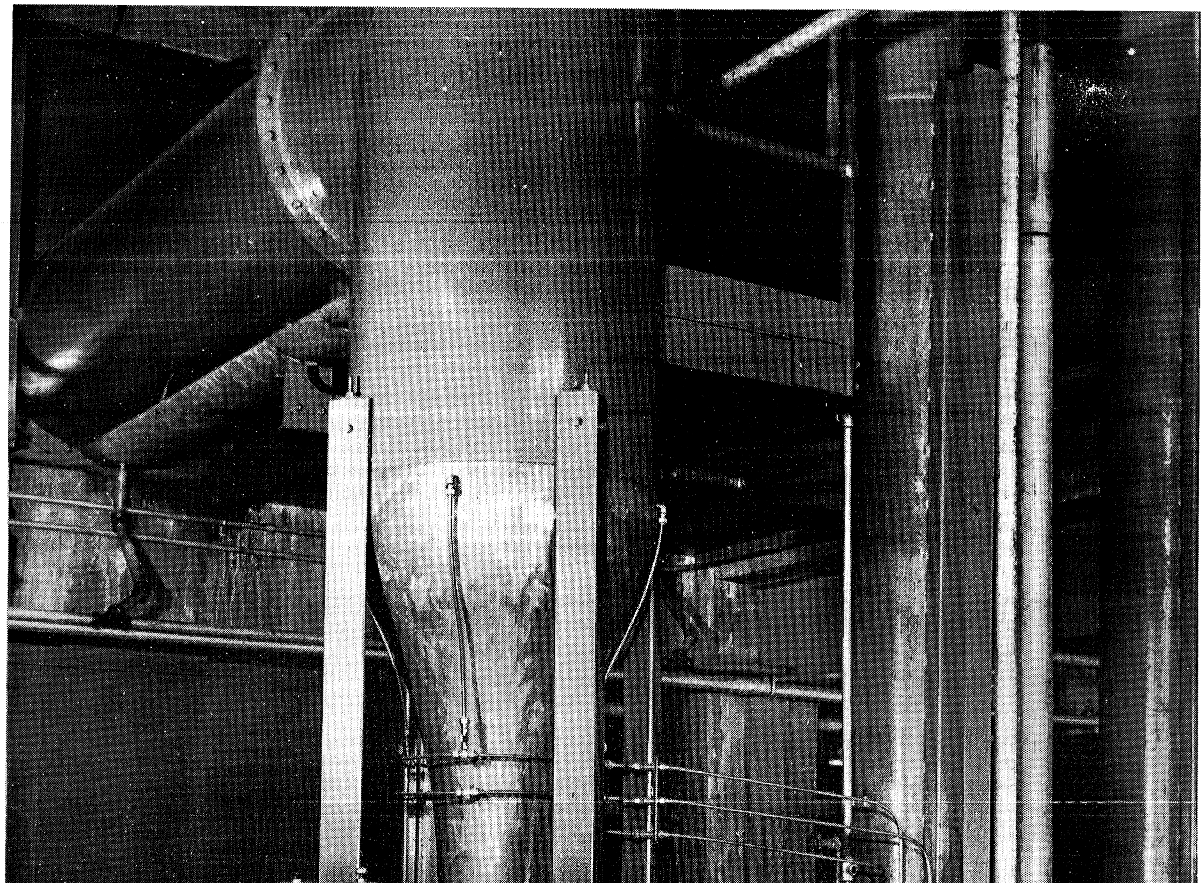
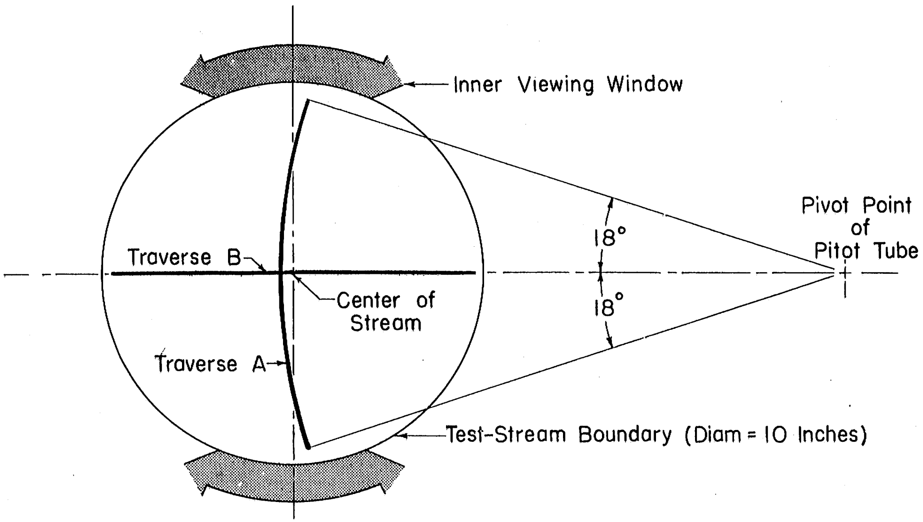


Fig. 28–The Test-Section Region of the Completed Tunnel
With Pitot Tube Installed in the Steel Bulkhead



Plan of Traverses of the Test Stream
(Vertical Location – $2\frac{3}{4}$ Inches Below Contraction Exit)

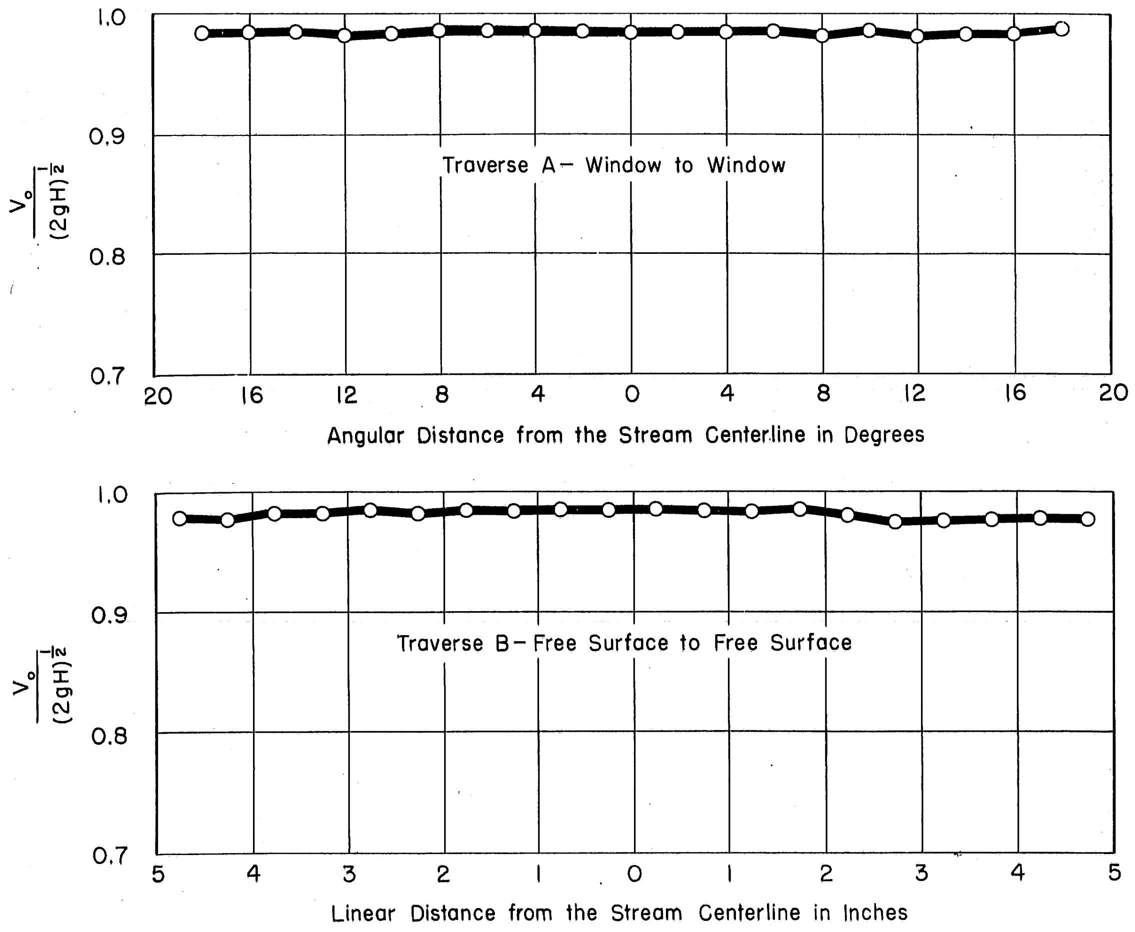


Fig. 29– Results of Test-Stream Velocity Survey

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