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A USER'S GUIDE TO THE LANGLEY 16- BY 24-INCH WATER TUNNEL

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SUMMARY

The Langley 16- By 24-Inch Water Tunnel, located in Building 1234 at the Langley Research Center, Hampton, Virginia, is described in detail, along with all the supporting equipment used in its operation as a flow visualization test facility. These include the lighting systems (laser and incandescent), and the recording systems (photographic, video, and laser fluorescence anemometer) used to make permanent records of the test results. This facility is a closed return water tunnel capable of test section velocities from 0 to 0.75 feet per second with flow through the 16 by 24 inch test section in a downward (vertical) direction. The velocity normally used for testing is 0.25 feet per second where the most uniform flow occurs and is slow enough to easily observe flow phenomena such as vortex flow with the unaided eye. The model support sting can be operated in the pitch and yaw planes of rotation through plus or minus 33 and plus or minus 15 degrees, respectively. The model and sting can be rotated in the sting mount to obtain the maximum deflection angle in either the model yaw or pitch plane, and the best view for observing and photographing the model.

In addition to detailed descriptions of the various systems, this document presents an overview of the operational characteristics, procedures, and capabilities of the water tunnel to potential users of the facility. It is intended that individuals can use this document to determine if the facility meets their needs and then, along with hands-on instruction from a qualified facility operator, be able to perform investigations and record results with minimum assistance or

supervision by others. If the reader believes this facility can meet his needs for an investigation, he should contact the Propulsion Aerodynamics Branch personnel for further information and schedule planning for the test.

Introduction of dye streaks into the flow above the test section during early check out of the flow quality, resulted in facility modifications which produced very smooth flow with little angularity in the test section at the 0.25 feet per second nominal flow velocity.

INTRODUCTION

This document describes in detail the operational characteristics of the Langley 16- By 24-Inch Water Tunnel located in Building 1234 (Room 100) at the Langley Research Center, Hampton, Virginia and the equipment used with this facility. The facility was officially declared operational on June 27, 1988. It is a closed return water tunnel with a clear acrylic sheet 16 inch wide by 24 inch deep by 6 feet 4 inch tall test section incorporating steel angle corner bracing, with downward (vertical) flow, capable of speeds from 0 to approximately 0.75 feet per second. The test section is located so that the model is about eye level above the floor - convenient for photographic purposes. Red, green and blue vegetable dyes, or fluorescent dyes* are injected into the stream flow through a remotely controlled probe mounted from above the test section, and/or from orifices located on the model surfaces, to obtain a visual and, if desired, a photographic record of the flow patterns around the model. Vortex flows are especially suited to this method of flow visualization since the vortex core tends to contain the dye streak, if properly located. Fluorescent dyes are most effective when used in conjunction with the laser light sheet system which uses two galvanometer-mirror devices to orient the light sheet in any desired direction, subject to test section limitations.

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* Dyes other than vegetable types may require a safety permit issued by the Langley Safety Engineering Branch.

The emphasis of research planning in this facility will be on vortex flow phenomena since the low flow velocity and small model size prevent similar flow conditions (i.e., same Reynolds number) to those in air. The purpose of this paper, in addition to detailed descriptions of the various systems, is to present an overview of the operational characteristics, procedures, and capabilities of the water tunnel to potential users of the facility. An abbreviated description of the water tunnel and its capabilities are also given in section XI of reference 1. Due to the simple operating procedures of the water tunnel, this document along with hands-on instruction from a qualified facility operator should allow use of the water tunnel with minimum supervision by others. The various operational procedures will be described in sufficient detail to use the facility in its normal mode with flow velocity of 0.25 feet per second, using the standard angle-of-attack mechanism to mount the model, and with vegetable dye injection from the model or from overhead probes. The 2 1/4 inch by 2 1/4 inch Hasselblad camera and/or video cameras and appropriate lighting equipment can then be used to record flow patterns around the model as desired. A laser fluorescence anemometer is available for flow field studies around models in the water tunnel. The system consists of a 3-component, laser doppler velocimeter with a fourth, concentration-detection component, used in conjunction with fluorescent dye excited by the laser light.

A brief historical background of the water tunnel with important events and milestones will also be presented in a subsequent section. As with any other experimental facility at Langley Research Center, modifications to this facility, its supporting equipment, test hardware, and data recording equipment occur on a continuing basis. Therefore, direct contact with facility personnel should be established prior to model design and construction for entry in the water tunnel. Use of trade names or manufacturer's names in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied by the National Aeronautics and Space Administration.

ABBREVIATIONS AND SYMBOLS

AOA	angle-of attack
AOS	angle of sideslip
DC	direct current
ID	inside diameter
ft./sec.	feet per second
GPM	gallons per minute
hp	horsepower
LDV	laser doppler velocimeter
LFA	laser fluorescence anemometer
m	meter
ma	milliamperes
mm	millimeter
$\dot{m}_i/\dot{m}_\infty$	(inlet mass flow)/(stream mass flow)
in.	inch, inches
OD	outside diameter
PSI	pounds per square inch (also lbs./in.^{2})
PAB	Propulsion Aerodynamics Branch
PVC	polyvinyl chloride
RPM	revolutions per minute
SS	stainless steel
TE	trailing edge
typ	typical
V_j	velocity of exhaust nozzle flow
V_∞	test section freestream velocity
2-D	two dimensional

DESCRIPTION OF FACILITY

Reservoir, Cross-flow Section, and Test Section

The Langley 16- By 24-Inch Water Tunnel is a closed, single return tunnel oriented in a vertical plane so that flow through the 16" by 24" by approximately 6' long test section is in the downward (vertical) direction. Figure 1(a) is a sketch showing the arrangement of the major tunnel components; figure 1(b) shows the important internal dimensions of the flow path; and figure 1(c) shows the arrangement and gives the coordinates of the internal convergent section leading to the test section. The structure of the water tunnel reservoir and cross-over channel consists of W8 × 13 steel I-beams arranged vertically on 16" centers and welded to L6 × 6 × 1/2 steel angles at all edges where the vertical beams meet the horizontal bottom and top of the tank. The containment walls of the tank consist of two layers of 3/4" marine grade plywood and one layer of 1/8" fiberglass sheet (next to the water), all epoxied together inside the steel framework. As shown in figure 1(a), there is a work platform at the top of the tank (over the test section) which provides access to connections from the dye reservoirs to the overhead probe mechanism and the dye tubes leading down to the bottom of the test section. There is also a work platform at an intermediate height for use with the cross-over channel observation window. The cross-over channel can be used for "quick-look" tests where photographic records are not necessary (except possibly from above) or where very low velocities (22.48% of test section velocity) are desired. Models can be mounted on a heavy base which positions the model about 20" to 24" above the channel floor, and the best locations for dye orifices can be determined using a hand held dye probe. Dye orifices already in the model can also be connected to the dye reservoirs as described in later sections of this report.

The water storage tank (reservoir) is 12' 2" long by 14' 6" high, by 3' wide with the water inlet from the main flow pump located near the bottom, centered on the West side. Water is distributed uniformly throughout the bottom of the tank using a 6" ID PVC pipe tee and two 6" diameter extension pipes capped on the outer ends and drilled over their entire length on both sides with 1/4" diameter holes angled downward at 45^{0}. The water is further stabilized by passing through a perforated stainless steel plate with 40% open area that is achieved by using 1/8" diameter holes on staggered 3/16" hole centers (33 holes per square inch). The water then rises up in the reservoir and flows into the cross-over channel where it passes through one honeycomb and foam flow straightener upstream of the observation window and another one downstream of the window. The window, made of clear, type G, 3/4" thick Plexiglass, is 24" high and 18" wide and located 17.50" below the top edge of the tunnel and 50.50" downstream of the reservoir. With the water at its normal operating level (4" below the top edge of the tunnel), the cross-over channel is 47.55" high by 36" wide (cross-sectional area of about 1708 in.^{2}) by 11' long (to test section centerline). Since the cross-sectional area of the test section is 384 in.^{2}, this results in an area contraction ratio of about 4.45 from the cross-flow channel to the test section. After passing horizontally through the last flow straightener in the cross-over channel, the flow makes a 90° turn and flows down into the convergent section and then through the test section. The cross-sectional area at the beginning of the convergent section is 1440 in.^{2} yielding a contraction ratio to the test section of 3.75 : 1. At the top of the test section is a 16" by 24" by 3" thick honeycomb flow straightener that can be used to further improve the test section flow. Since this flow straightener is between the probe traversing mechanism and the test section, it cannot be installed and still use the overhead probe with the traversing mechanism. During check out of the water tunnel, problems with flow separation occurred on the sidewalls triggered by the cross-over channel flow straightener support frames. The separation occurred along the side walls over the test section where the flow makes the 90° turn into the convergent section. This will be discussed in detail in a later section entitled "**MODIFICATIONS TO IMPROVE FLOW QUALITY**".

The vertical arrangement of the test section yields a pressure of 4.3 PSI at the model rotation center, about 2.9 PSI at the top, and 5.6 PSI at the bottom of the test section. Because of this pressure, models used in this facility must be either vented to eliminate pressure differences inside the model, or they must be rigid enough to prevent buckling of the exterior surface shapes. More details on how this can be done is discussed in the "**MODEL REQUIREMENTS AND RECOMMENDATIONS**" section. At the bottom of the test section, the water passes through a perforated plate and diverters, and then into 6" ID PVC pipe for return to the main flow pump. Part of this flow is diverted through a swimming pool filter to remove impurities and improve the water clarity for better viewing and photographic results.

Figure 2(a) is a photograph of the water tunnel showing part of the reservoir section at the left, the cross-over section at the top, and the test section and dye flow control panel at the lower right side of the picture. The observation window described in the previous paragraph can be seen in the middle of the cross-over section, and part of the dye probe traversing mechanism (above the cross-over section and test section) can be seen at the top right in the photograph. As shown in this photograph and in more detail in the close-up view of figure 2(b), 3" by 3" by 1/2" steel angles along each corner support the 1.25" thick acrylic (clear Lucite SAR) walls through which the model is viewed in the 16" by 24" test section. There are also four 2.85" by 1/2" thick steel bars spanning each wall to tie the angles together and also to help prevent bulging of the Plexiglass when the tunnel is filled with water. Figure 2(c) is a photograph of the test section taken from the opposite side (East wall) showing the test section access door in place with an F-15 model mounted on the AOA mechanism. Enclosed between the two I-beams supporting the test section at the bottom of this picture are the flow diverter vanes and the 6" flow return. The return flow pipeline extends under the striped plywood protective cover from the other side (front) of the test section, through a 90° elbow, and out of the picture on the right to the water filter and main flow pumps. The test section access door covers the 3' high by 16" wide opening to the test section and supports the AOA mechanism which is removed along with the model when the access door is removed (see figure 2(d)). Further details on the AOA mechanism can be found in the section titled "**MODEL SUPPORT SYSTEM**". A list of the detailed drawings used in the construction of the water tunnel and its auxiliary equipment are given in **APPENDIX A**.

The total volume of the entire water flow path just described is approximately 700 cubic feet or 5236 gallons.

Tunnel Flow Diagram

Figure 3(a) is a diagram showing the flow paths of the water piping and valves. The circled numbers indicate item numbers shown in the parts list of figure 3(b). The letter-coded numbers correspond to identification tags attached to the valves. These tags are used later in the "**OPERATIONAL START-UP PROCEDURES**" and "**OPERATIONAL SHUT-DOWN PROCEDURES**" sections to aid in identifying and locating the various valves used in these procedures. Flow through the test section is adjusted by manually setting valve W1 and then adding bypass "make-up" flow by manually setting valve W2 to get the desired flow through the main pump.

Main Flow Pump and Controls

The main water-flow pump is a Goulds Model 3196MT centrifugal pump with a 10" diameter, 316 SS impeller driven by a 3 phase, 440 volt, 10 hp electric motor operating at 1150 RPM. Figure 4(a) is a photograph taken at the end of the reservoir opposite the test section, showing the main flow pump at the extreme left in the photograph (electric driver motor is not visible), the water filter and pump at the bottom right in the photograph, and most of the associated plumbing to the two pumps. Water flows from the bottom of the test section via the 6" PVC piping; through the 6" diameter by 24" long Goodall, Model VFC-15 vibration absorber attached to the pump inlet horizontally; out through the top of the pump; and then through another identical vibration absorber mounted vertically. The water goes through an elbow above the main pump and then flows horizontally toward the end of the tunnel. Near the tunnel, the flow turns another 90° horizontally, then 90° down and another 90° to horizontal again. Then the water flows into the bottom of the reservoir near the middle, and exits the distribution manifold through the 1/4" diameter holes into the bottom of the reservoir. The flanged pipe section just to the right of the elbow above the pump contains a 6" diameter Technocheck PVC check valve to prevent backward flow through the pump.

The main circuit breakers for the main water flow and water filter pumps are mounted in a panel (which is numbered P-100 and labeled 440V) on the North wall in the jet exit control room. Figure 4(b) is a photograph showing the electrical panels on the North wall with panel P-100 located at the left side of the picture. The left top switch (1) controls the water filter pump and the right top switch (2) controls the main water flow pump. The two circuit breaker/control panels (shown at the right in figure 4(c)) that are used to control the main water flow and water filter pumps are located on the West wall near the main water flow pump. Shown at the bottom middle of the photograph is the wall mounted processor unit for the Badger Electronic Transmission System (ETS) used to calculate and display the flow rate through the test section. Figure 4(d) is a photograph of the 2" main water supply line, including a back flow preventer ⑭ and shut off valves W6 and W6A. Product instruction manuals and specifications for the equipment used in the main water flow system can be found under items 3 through 15 in the "**Specifications, Installation, Calibration, and Operation Information**" manual dated December 1985.

Minimum Pump Flow Control

Since the main water flow pump is a centrifugal pump, there should always be some flow through the pump to prevent cavitation and bubble formation in the flow. Cavitation in the pump can cause accelerated wear of the impeller vane surfaces, leading to more frequent repair and parts replacement. Both the additional noise generated by cavitation, and the bubbles in the flow rising in the reservoir produce disturbances in an area where vibration and turbulence need to be eliminated.

To eliminate the cavitation, there is a return circuit of flow from the pump outlet to the inlet which is controlled by a manual hand valve (W2 on figure 3(a)) and by a pneumatic flow controller valve (C5 on figure 3(a)). This system keeps the flow through the pump at a preset minimum value (should be set between 500-800 GPM) and helps to stabilize the flow through the test section. A diagram of this flow system is shown in figure 5 along with the various components used to operate the system. Just to the left of the Badger processor, figure 4(c) also shows the Dieterich "Eagle Eye" meter and the

Honeywell UDC controller which are used to maintain a preset minimum flow through the pump.

Water Filter Pump and Controls

The water filter and pump used to remove particulates from the water and improve water clarity is shown at the right in figure 4(a). The filter system is also indicated by the dotted rectangle labelled ② in the schematic of figure 3(a). The filter system includes a Perflex EC-65 System III swimming pool filter which uses diatomaceous earth as the filter media. Using the 3/4 hp, 440V motor and pump, this system will clean about 60 to 80 GPM, depending on the pressure differential through the filter. Details for operation and maintenance of the filter system will be given later in the "**OPERATIONAL START-UP PROCEDURES**" and "**EQUIPMENT MAINTENANCE**" sections. Since the 3/4 hp electric motor used for the filter system is wired for 440V just like the main flow pump motor, the main circuit breakers and control panel are in the same locations as they are for the main pump. Figures 4(b) and 4(c) show these two panels. In each case, the switch controlling the water filter motor is located on the left and the main flow pump switch is located on the right. In general, this system should be operating anytime the main flow pump is on, especially after filling the reservoir when it has been empty. It may be necessary to run the two pumps for about an hour or longer, under the above circumstances, to obtain the water clarity needed for good photography. Instruction manuals and specifications for the equipment used in this system can be found under item number 2 in the "**Specifications, Installation, Calibration and Operation Information**" manual.

Dye Injection System

The three dye injection reservoir bottles, and their needle and shut off valves are arranged on a panel mounted on the water tunnel support structure at the Southwest corner. Figure 6(a) is a schematic showing the dye flow system and related valves and reservoirs, while figure 6(b) is a photograph of the dye flow panel mounted on the tunnel structure and the dye flow/traversing probe control console mounted on a pedestal with casters so that it can be easily moved. The three reservoirs are numbered 1 through 3 from top to bottom and generally contain red, green, and blue dye, respectively. The shut off valves for each reservoir are controlled by the 3 switches on the bottom row of the console (also numbered 1 through 3, left to right). Regulated feed air pressure to the reservoirs should be set between 8 and 10 PSI using the regulating valve next to the shut off valve labelled S13. Flow rate out of the reservoirs is controlled using a combination of feed pressure and needle valve setting (valves N15, N16, and N17 in figure 6(a)) and may vary widely depending on the number of orifices connected to each reservoir. As indicated on figure 6(a), dye can be routed from the reservoirs to dye probes at the top of the test section, or to model orifices connected to manifolds located at the bottom of the test section. Connections can also be made to models located in the cross-over channel from the area over the test section. Since all connections are made from this position, any combinations of reservoirs and dye colors may be used, but experience has shown that only dye colors having the highest contrast, such as red, green, and blue, will give satisfactory results when photographic color film is used as a recording medium.

Figure 6(b) also shows the control switches on the console for the overhead dye probe traversing mechanism. The top row of switches on the control console actuate the up/down, forward/backward, and left/right traversing directions which correspond to switch number 1 on the left to number 3 on the right, respectively. Figure 6(c) is a photograph of the traversing mechanism taken from above, looking down toward the reservoir end of the tunnel. The servo motor in the foreground mounted directly to the tunnel structure controls the left/right movement; the motor mounted on the right end of the tray, which is mounted perpendicular to the length of the tunnel, controls the forward/backward movement; and the motor mounted on the left end of the tray on the small platform controls the up/down movement. The 3 copper tubes that carry the dye from the 3 reservoirs to the top of the test section are also visible at the left side of this photograph. Instruction manuals and specifications for the equipment used in the dye flow system can be found under items 16 through 21 in the "**Specifications, Installation, Calibration, and Operation Information**" manual.

Model Support System

As shown in figure 2(d), the remotely actuated angle-of-attack (AOA) and angle-of sideslip (AOS) mechanism is mounted on the test section access door when in use. With the AOA/AOS mechanism installed in the test section, the useable test section length is reduced from about 6' to about 4.5'.

Angle-of-attack and yaw mechanism. Figure 7(a) is a sketch showing the mechanism support plate and all of the parts that are attached to it. The pitch arc, shown at the bottom of the sketch, produces an AOA range of ±33°. A Pittman Model 9514 DC servo motor is used to drive the belt which rotates the lead screw, driving the pitch arc follower to the desired AOA. The gear on the end of the pitch drive motor is coupled directly to the upper drive belt gear when the AOA/AOS mechanism is assembled to the access door. Figure 7(b) shows this servo drive motor near the middle of the sketch, and the two stand-offs to which the main support plate is attached.

In the yaw direction, the entire assembly shown in figure 7(a), except for the support plate, is rotated through a range of ±15°. When the access door is installed on the back (East) side of the test section, the yaw arc roller (see figure 7(a)) rests on the yaw arc on the West wall of the test section. This assembly is also driven by a Model 9514 Pittman servo motor mounted at the bottom left side of the access door and moved by the yaw drive pin (see figure 7(a)) engaged in the yaw drive slot (see figure 7(b)). The AOA/AOS mechanism is actuated using a hand held controller which normally hangs on the South wall of the room near the test section door (see figure 7(c)). Angles set are determined visually by observing the AOA in degrees, seen on the pitch arc, aligned with the right edge of the slider block; and the AOS is indicated in degrees by the pointer at the top of the yaw arc sector (see figure 7(a)). These angles can be set to within about ±0.25°.

Model mounting methods. When mounting the model on the AOA/AOS mechanism, a sting approximately 1/2" in diameter, which protrudes from the rear of the model far enough to clear the model orifice tubes by a minimum of 2", should be used. The sting is inserted into a slider block (fig. 7(a)) that has a 0.499" diameter by 1.0" deep hole with 2 set screws to hold the model in place. If possible, the sting should be about the right length to position the model lift center near the rotation center (about 16.2" above the lower end of the sting). This will help to prevent the lift center from moving around with changing AOA which can worsen flow distortion around the model. The last 1.50" of the lower end of the sting should have a maximum diameter of 0.498" to prevent binding in the slider block.

An offset sting-mounted plate is also available for mounting larger semispan wings when tip vortex flow studies are desired. Figure 7(d) shows the sting used to mount a straight wing with a serrated TE. The sting/strut connected to the AOA mechanism is visible at the bottom of the photograph, but the 2" wide by 1/8" thick by 24" long wing support plate is hidden behind the test section corner brace at the left of the picture. Other methods for mounting the model can be devised by making a new support plate that mounts on the two stand-offs on the access door (see figure 7(b)), but this will prevent use of the servos to change AOA and AOS. This mounting method will also delay testing while the piece is being fabricated and fitted to the door, and must be coordinated with Propulsion Aerodynamics Branch personnel in the planning stages.

Model Inlet Flow Simulation

Inlet flow can be simulated and controlled by including ducts in the model so that the inlet flow passes through the exhaust nozzles which are connected to hoses. Alternatively, the inlet flow can be exhausted through pipes in the support system. Figure 2(d) shows a typical arrangement for a 1/48 scale F-15 model where the two inlet flows are ducted through the model to tubes in the exhaust nozzles which are connected to rubber surgical tubing to carry the flow down to the bottom of the test section. From there, with the tubing flush against one corner of the test section, the inlet flow goes back up to the top of the water tunnel and then back down on the outside of the tunnel where the connections are made to the panel, shown at the right in the photograph. On this panel, flowmeters are mounted to measure the mass flow rate through each inlet, and needle valves are used to control the flow rate. Water from the outlet side of the tubes at the panel are dumped into the pit under the tunnel since the water pressure inside the test section (about 4 to 5 PSI at the model) should be high enough to produce adequate flow through the inlets. The panel shown in figure 2(d) is sized so that 4 different flows can be measured and controlled simultaneously. Proper simulation of the flow field around the inlet depends on the mass flow through the inlets, so control and measurement of that flow is imperative. Improper simulation in these regions can adversely affect the external flow field and produce erroneous data, and in some cases, even cause flow separation downstream of the inlets. An approximation of the correct flow rate can be calculated using a mass flow ratio ($\dot{m}_I/\dot{m}_\infty$) of about 0.80 and the measured inlet capture area. The duct sizes through the model should be about 0.85 of the inlet capture area to allow for friction losses. More details on incorporating these features in the model will be discussed in the "**MODEL REQUIREMENTS AND RECOMMENDATIONS**" section.

Model Exhaust Flow Simulation

Since the water pressure around the model in the test section is about 5 PSI or higher at the aft (lower) end, exhaust flow must be simulated using water at a higher pressure. For this purpose, regular city tap water may be used and is available at the water tunnel facility. In this case water must be supplied to the model using a hollow sting connected to the water supply, or through external model connections at some other location that will not disturb the flow over that part of the model being studied in the experiment. As in the previous section, the panel shown in figure 2(d) may be used to control and measure up to 4 flows simultaneously, but the experimenter may be required to supply part of the instrumentation, piping, and valves. One word of caution on simulating exhaust flows. City tap water may be at a different temperature (and hence, different density) than water in the facility and is always very turbulent where it exits at the model;

therefore, if you want smooth laminar flow at the exhaust, a way must be devised to accomplish this inside the model.

MODEL REQUIREMENTS AND RECOMMENDATIONS

This section will describe in detail: water tunnel model dimensional requirements and scaling precautions; the methods used in the construction of models and how they are reinforced internally for sting installation; and how internal modifications to incorporate inlet flow or exhaust flow simulation can be made. Details of appropriate adhesives, fillers and surface finishes will also be discussed. Since advances in materials and finishes occur on a continuing basis, contacting the personnel of the Composites & Models Development Section at Langley Research Center is recommended before model fabrication is initiated so that the best materials and techniques can be used.

Model Size/Scale

Since the water tunnel test section width is only 16" when ±33° AOA is being used, model wing span should be limited to about 12". For typical fighter type scale models with normal wing and tails arrangement, a maximum length of about 15" and wing area of 50 in.^{2} (or less) produces about the maximum desirable model size for the water tunnel. These limits should be used for generic models and those models of real aircraft that are built from scratch where the model can be scaled arbitrarily to get the model size desired. For commercially made plastic model kits of fighter aircraft, 1/48 scale models are about the correct size. As aircraft sizes get larger (i.e.

transports, bombers), model scales must get smaller (i.e. 1/72, 1/100, 1/144, etc).

These size limitations are applicable to models that will be tested to large angles of attack, but specialized testing may require models to be larger or to be partial models instead of entire model configurations. The purpose of limiting model size is primarily due to AOA/AOS mechanism loading and the test section flow distortion created by the model lifting surfaces.

Precautions Concerning Model and Flow Scaling

The density of water is 800 times that of air, resulting in the Reynolds number being 15 times that in air for the same scale and velocity. If cavitation is avoided and compressibility effects are negligible, the fluid motions of water and air at the same Reynolds number are dynamically similar. Since the typical test velocity for this water tunnel is only 0.25 ft./sec. and model lengths are around 1 to 1.25 ft., the Reynolds number based on length will only be about 32,000. This is lower by a factor of 10^2 than typical wind tunnel tests and by a factor of 10^3 or 10^4 compared to flight tests of real aircraft. For this reason, care must be taken to insure that the flows on the model in the area of interest are not Reynolds number dependent. For instance, rounded leading edge airfoils are very susceptible to separation at low AOA and Reynolds number, but if the leading edges are sharp and/or the investigation is run at higher angles of attack, the flow will be separated at all Reynolds numbers, except when velocity is so low that Reynolds number is around 1, which corresponds to

Stokes flow or creep flow. These conditions are unlikely to be encountered at the model scales and velocities commonly used in the Langley 16- by 24-Inch Water Tunnel.

Reference 2 describes tests performed on a 1/48 scale F-15 model in the Northrop diagnostic water tunnel in 1978 to determine the effect of AOA, AOS, inlet mass flow, inlet cowl deflection, and forebody shape on the vortex flow patterns over the upper surface of the wing and fuselage. This test demonstrates how model kits can be easily modified by installing inlet ducts for proper flow matching over the model, and using dye orifices in the model to visualize vortex flows over the upper surfaces.

Reference 3 includes a discussion of parameters used for correlation of water tunnel results with wind tunnel and flight data and also includes a literature survey of water tunnel applications. References 4, 5, and 6 include examples of three different type tests run in the Langley 16- By 24-Inch Water Tunnel.

Sting Installation in Model

Since the sting attaches the model to the AOA/AOS mechanism, it must carry all of the forces and moments produced by the water flow over the model. Using a 1/2 inch diameter 6061 aluminum rod as the sting provides more than adequate strength to the sting, but it must also be well supported inside the model to transfer model loads to the sting. This can be accomplished by including two bulkheads in the afterbody of the model, spread apart longitudinally about 2 inches or more. These bulkheads should fit tightly around the sting and properly align the model with the test section centerline. As mentioned earlier, the sting should protrude out the model aft end about 3 to 4 inches so that adequate clearance is achieved for any dye orifices or internal water flow tubes.

Inlet Flow Ducting

Sizing the ducting through the model so that adequate flow can be pumped through the model will depend on the size of the inlet capture area, the angle of attack (for nonaxisymmetric inlets), and Mach number being simulated. At very low Mach numbers, the inlet may be "sucking" flow through it at high engine power settings producing mass flow ratios as high as 2.0 or more, while at high subsonic speeds and cruise engine power settings, mass flow ratios of 0.8 or lower are typical. Also, for 2-D inlet shapes like those on the F-15, increasing angle of attack may substantially increase inlet capture area which decreases mass flow ratio for constant inlet mass flow rates.

For the Langley 16- By 24-Inch Water Tunnel, the water height above the test section produces a pressure head of about 5 PSI so that a duct size equal to or slightly less than the capture area should be more than adequate. In any case, the ducting should be smooth internally and have no sharp turns or sudden shape changes in order to minimize pressure and friction losses. If the engine exhaust nozzles are fixed in the non-afterburning position (for kit built models), they may be too small to allow proper mass flow and should be replaced with "cylindrical" nozzles approximating maximum afterburning nozzle shapes to produce sufficient room for larger tubes that can carry the necessary flow. As an alternative, the inlet flow also may be carried out through a hollow sting or through ducts that exit the model in a location that will prevent distortion in the flow around the areas of interest on the model.

A typical example of flowing inlets in a fighter type aircraft is shown in the 1/48 scale F-15 models used in references 2 and 5. The tubes carrying the flow out of the model were 0.50" ID thin wall copper tubes to which the discharge hoses were attached. Figure 8 is a photograph of this F-15 model showing the two inlet flow discharge tubes protruding out through the exhaust nozzles. As mentioned earlier for sting support, the inlet ducts should also be supported by interior bulkheads so that water pressure against them will not break the seals at any of the joints between parts.

Exhaust Flow Ducting

If the propulsion system exhaust flow(s) must be simulated because of their close location to the region of interest in testing, then some method must be devised to get water under sufficient pressure inside the model so it can be ejected out through the exhaust nozzles at velocity ratios (V_j/V_∞) high enough so that the jet flow will produce external flow conditions on the nozzle boattail(s) similar to those at much higher Reynolds number. Experience has shown that V_j/V_∞ of up to 6 may be necessary to match the boattail flow characteristics between the water tunnel and wind tunnel or flight tests. Figure 9 is a photograph of a 1/72 scale B-1B model used for this type experiment.

Note that the model is supported by a sting faired into the vertical tail/horizontal tail juncture and that the fuselage tail cone has been omitted to accommodate the 2 tubes carrying tap water to the left hand nacelle nozzles. The right hand nacelle had flow-through inlets/exhausts and the left hand nacelle has faired over inlets to accommodate the tubes used to produce the exhaust flow simulation. In this model 1/2" ID copper tubing is used to carry water all the way to the individual nozzles in the nacelle, thus eliminating the possibility of leaks inside the model.

Dye Orifices

For most orifice installations in the model, .040" OD by .020" ID SS tubing provides a size that is easy to install in the model and yields enough dye flow to form highly visible streaks or filaments in the flow. Using smaller diameter tubing such as .020" OD which has about .010" ID may result in clogging when dye is left in the model for several hours, and may also produce thin, less visible streaks in the flow. If a large number of orifices are required on the model and more than about 8-10 tubes are manifolded together for connection to one reservoir, then using the .020" ID tubing may produce widely varying flow rates between the tubes connected to one reservoir. This should be avoided since too low a flow rate renders the streaks nearly invisible, and too high a flow rate will disturb the flow being visualized. The best way to avoid this problem is to minimize the number of orifices and distribute them among as many reservoirs as are available for use. If no probes are being used at the same time as dye orifices on the model, all 3 reservoirs can be used for this purpose.

Experience with models tested in the Langley 16- by 24-Inch Water Tunnel has shown that the best dye flow patterns from the dye orifices are obtained with the orifice tubes installed with the tube tilted downstream (local surface flow direction) at 45° as it comes out of the surface. The tubes should also be epoxied in place for about 2" inside to prevent them from breaking loose and allowing water to leak around them into the model interior. This can happen relatively easily when the tubes are being ground flush with the model surface so be particularly careful during this process.

Dye probes used to survey various areas of the model using the remotely controlled overhead mechanism should be available, but if a special probe is needed, it should be made using 1/8" SS tubing, stepped down to a final size of .060" OD and .042" ID. The probe shape at the tip found to give the best results is a "V" shape with the point of the "V" cut up into the tube (see fig. 10). Further discussion of the development of this probe shape can be found in the "**MODIFICATIONS TO IMPROVE FLOW QUALITY**" section.

Construction Materials, Adhesives, Finish, and Interior Venting

Materials used in the construction of water tunnel models must be impervious to water and not subject to corrosion when immersed in high mineral content water for extended periods of time. Styrene plastics such as those used in commercial model kits are good examples of this type of material, and in addition, are easily cut and shaped using common hobby tools. Two other materials suitable for use are stainless steel and 6061 aluminum, but they are more difficult to shape, and when using them, consideration should be given to the extra weight carried by the AOA/AOS mechanism. In any case, when using metal fasteners and dowel pins during model construction, always use stainless steel types. Since model plastic cements (which contain toluene) actually soften and fuse the plastic parts together, immersion in water will have no effect on this type of joint. If other types of adhesives are used, such as epoxies or alpha cyanoacrylate ("super glue"), these must not be soluble in water or subject to failure when submerged in water for long periods of time.

If commercially-made scale model kits are used, be sure to remove all <u>raised</u> panel joint lines from the model and fill all engraved panel joint lines since they are most likely to be substantially over scale. It may be desirable to leave some engraved details on the model - for instance control surface hinge lines or gaps, and some surface inlet or exhaust apertures that are scale sized - so be careful what is removed or left in place. In general, model surfaces should be smooth and painted flat white to show dye flow filaments to best advantage. For models to be used with the laser light sheet system, flat, medium gray is probably the best color to use, if reference marks will be included on the model. The type of fillers and finish materials used on the model should be determined by calling the Composites & Models Development Section at Langley Research Center to get their latest recommendations.

If the model is hollow, as most model kits are, provisions must be made to completely seal the model so that no leakage can occur, or the model must be vented by drilling holes through internal bulkheads and ribs so that air cannot be trapped inside and can escape through the model near the nose. If the air does not escape quickly, it may seep out slowly through surface cracks, forming air bubbles on the model surface which will interrupt smooth flow and prevent proper dye flow streamlines on the model. If the model is completely sealed, care must be taken to insure no leakage around the dye orifices where they extend through to the surface of the model, or where tubes exit the model for connection to dye tubes. Also, the model surfaces must be sufficiently rigid to prevent "oil canning" of the surfaces, particularly wing and tail surfaces, or any other surfaces, which are nearly flat. Surface movement of this type not only will alter model shape, but will cause cracks at joints in the model parts and eventually lead to water leakage into model cavities, and hence, air leakage out. This effect can be prevented by inserting ribs or frames as needed inside the model to support the model surfaces.

FLOW VISUALIZATION METHODS

One of the main advantages of using water tunnels is the increase in water density (800 times the density of air) making highly reflective dye "streaks" or "filaments" much easier to create, thereby producing flow patterns that are easily observed by eye and recorded using still photography and video recorders. This effect can also be used to advantage when laser equipment is employed to create visible cross-sections of the flow illuminated by laser light sheets.

Dye Probes

The main advantage in using dye probes are their portability relative to the model, making it possible to survey the model surfaces to determine the best locations to properly visualize the flow or to install dye orifices in the model. The disadvantage is the disturbance to the flow upstream of the dye ejection location caused by the probe fixture and connecting tubing to the dye reservoirs. One excellent use for probes is visualization in the flow up to and over an airfoil or nose of the model. Figure 10 is a sketch of a twin probe fixture that is inserted through and supported by the flow straightener at the top of the test section. Figure 10(a) shows details of the probe and figure 10(b) shows how it is installed in the honeycomb flow straightener. One of the blades connecting the two .090" OD SS tubes lays across the wall between two hexagonal flow straightener cells, for support, and may be moved around at will to direct the flow over the model as desired. Figure 11 is a photograph of an example of this type of flow visualization over an airfoil using the twin probe fixture.

Another option is using the overhead dye probe mechanism which can adjust the probe position remotely from the console located conveniently near the test section. The disadvantages of using the probe mechanism are its larger size which may create more flow disturbance, and the necessity of removing the overhead flow straightener. Advantages are the better precision when adjusting the probe position and the ability to adjust it vertically which cannot be done with the twin probe fixture except by making a new fixture. There are several other probes available for use, and probes can be fabricated for specialized uses relatively easily. In most cases, .090" OD SS tubing would be the best choice of material and size.

To introduce the least disturbance while injecting dye into the flow, an inverted "V" shaped tip works best and the dye flow rate should be set to produce a filament approximately the same size as the probe. The condition where least disturbance is created can easily be set, because the exiting filament is obviously very clean and steady.

Model Dye Orifices

As previously mentioned in the "**MODEL REQUIREMENTS AND RECOMMENDATIONS**" section, .040" OD SS tubing should be used for model orifice installations and if possible should be oriented so that the end of the tubes point downstream (local flow direction) at 45° as the dye exits the orifices. Also, the number of tubes manifolded together should be the minimum possible and certainly no more than

6 to 8 per dye reservoir. If too many tubes are connected to one reservoir, setting the proper flow rate from all the orifices will be impossible. Some of the orifices may be flowing too little dye while others may be flowing too much. This effect can be further minimized by using a manifold with the dye inlet tube near the center, and with the orifice tubes equally divided and spaced in the manifold on either side of the inlet tube. It also helps to make all the orifice tubes connected to one manifold the same length. The side of the model the orifices are on (windward or leeward side) can also affect the dye flow balance between orifices since this will affect the back pressure at the orifices. Because of all the above effects, some experimentation with the tube connections on a manifold may be necessary to establish even flow rates from the orifices on one manifold. If vortex flows are to be visualized, it may be necessary to determine orifice locations by testing one model using an external probe to find the vortex core origins, and then build another model with the orifice tubes installed at those positions. The cross flow channel between the water reservoir and test section is a convenient place to perform this preliminary step.

Lights and Support Stands

When using vegetable dyes for flow visualization, two Colortran Multi-6 650 watt, tungsten halogen, 3200° K. flood lights and two Gitzo 105/4 light stands are available to illuminate the test section. Wherever the lights are located, **under no circumstances** should they be placed **closer than 3 feet** from the test section! The lights are very hot and may heat the test section Plexiglass walls to high enough temperatures to cause stress cracking if placed too close! Breakage of the test section wall would require replacement of the broken Plexiglass wall which could take several weeks and cost thousands of dollars! In general, sufficient illumination of the model and dye streaks can be accomplished with one light, or with the two lights about 90° apart and 5 to 6 feet away from the test section. Longer distances, may be required to get uniform illumination of the entire length of the test section, if needed, so individual test requirements will also determine how close the lights are placed. The lights can be adjusted from spot focus of about 20° angle to flood focus of about 68° angle. When locating the lights, care must also be taken to prevent direct reflection of the light images into the camera or video recorder since this will wash out the dye streak images being photographed for permanent test data.

Laser Light Sheet

A laser light sheet system is available for planar flow visualization, using fluorescent dye and a planar sheet of laser light. An example is shown in figure 12 where the laminar wake behind a wing at low Reynolds number was visualized using a laser light sheet oriented perpendicular to the wing span. A number of different methods for creating the light sheet exist, including spreading the laser beam using glass rods and standard positive- and negative-focal length optics. In addition, rapidly scanning a laser beam creates the perception of a sheet of light.

The system currently used consists of a galvanometer-mirror scanning device. Two mirrors are mounted on galvanometer motor shafts that are perpendicular to each other. The high-frequency scan rate produced by the motors can be controlled to place the light sheet, formed by a rapidly-scanning laser beam, in any desired orientation. This system can be used to translate and rotate the sheet as well as change the width and create multiple sheets. Additional details about the system can be found in reference 7. Reference 8 gives details of the various flow visualization and recording techniques in a water tunnel and specifically discusses the uses of laser light sheet systems.

When fluorescent dyes are used for water tunnel investigations, a safety permit issued by the Langley Safety Engineering Branch will be required. This may also be the case for using the laser light sheet equipment. Both these permits should be obtained several weeks before the test since special warning devices and door interlocks must be used to prevent accidental exposure of the eyes and skin to the laser output. A Radiation Worker's Certification Card is also required for all individuals using the laser system in conjunction with the water tunnel. For further information on the above safety requirements contact the 16-Foot Transonic Tunnel Safety Head.

Hydrogen Bubble Generator

A hydrogen bubble generation system has been developed to provide an alternative method of flow visualization in the channel above the test section. The physical principle governing the generation of the visualization media is the electrolysis of water. In essence, the system consists of a voltage source with an electrode connected to each end. These electrodes are immersed in water and a voltage applied. Positively-charged hydrogen ions in the water move toward the negative electrode (cathode), and negatively-charged hydroxyl (OH) ions move toward the positive electrode. The hydrogen ions gain an electron from the electric "current" to form atomic hydrogen, join with other hydrogen atoms, and assemble to form hydrogen gas bubbles at the cathode. The hydroxyl ions lose an electron at the positive electrode. They combine with other hydroxyls to form water and oxygen atoms. These oxygen atoms join to form molecules and appear at the anode as oxygen gas. Twice as much hydrogen gas is formed as oxygen, leading to the use of hydrogen for the flow tracer.

A typical system will use a platinum wire of small diameter (0.001" to 0.005") as the hydrogen-generating cathode. This is connected to the voltage source by a wire and placed in front of the object around which the flow is to be visualized. As the flow passes by the wire, the hydrogen bubbles are pulled off and form a sheet which, when illuminated, appears bright white. As the bubbles flow around an object, the flow patterns are visualized by the bubbles following the flow. Because of their small size, they do not rise significantly due to buoyancy. The anode is placed in a noninterference location close to the cathode. An example of the flow visualized behind a flat plate is shown in figure 13. The flow is moving from left to right and significant reverse flow can be seen moving forward from the wire behind the plate.

The hydrogen bubble system was tested unsuccessfully in the test section of the water tunnel. Since the production rate of hydrogen bubbles is an inverse function of depth below the water surface (reference 9) and the center of the test section is about 10' below the surface, the channel above the test section must be used (maximum speed = 1.85 in/sec). There are many excellent references on the subject of hydrogen bubble generation for flow visualization such as reference 10. One example of quantitative determinations derived from this technique is that by Schraub, et al, reference 11. They used a novel approach to bubble generation in the form of "combined-time-streak markers" to provide the visualization from which velocity information could be derived. If the hydrogen bubble generation technique is used and part of the model will be behind the bubble streaks, it may be necessary to paint the model black so that the bubble streaks will be visible in front of the model.

DATA RECORDING METHODS

Understanding flow phenomena and observing the flow paths is easily done in the water tunnel because of the low velocity and highly visible dye streaks. Movement of the flow is clearly visible and usually slow enough so that no blurring is evident to the eyes. This flow movement, of course, is the most important part of understanding what flow phenomena is occurring, but this cannot be recorded using still cameras. The 2 1/4" by 2 1/4" film size used with the Hasselblad still cameras produces the clearest images of the flow patterns available for the recording systems used on site at the Langley 16- By 24-Inch Water Tunnel. Since movement is so important in understanding the flow phenomena , video recorders are also available, but do not produce nearly as clear images as the Hasselblad cameras. A carefully assembled visual record of a water tunnel investigation may therefore include both still photography to record the streamline patterns and video recordings to depict movement in the flow.

To obtain data on flow velocities around a model in the water tunnel, there is a 3-component, laser doppler velocimeter (LDV) system which can be used by itself, or can be combined with a fourth, concentration-detection component. The disadvantage of using this system is the large amount of data required to obtain an adequate flow survey, and the time required to record the data.

The following sections will describe in detail the equipment available and how each of these systems should be used to obtain good records of the data needed from the investigation.

Film Cameras

Since clear prints of flow patterns are required, the Hasselblad system was chosen for use at the water tunnel because of the 2 1/4" by 2 1/4" (70mm) film size which allows substantial print enlargement while still producing sharp images. Larger cameras could be used, but are not as easy to handle as the Hasselblad cameras. In addition, the 70mm film is readily available and inexpensive compared to other formats such as 4" by 5" or 8" by 10". 35mm single lens reflex cameras can also be used, but the 8" by 10" print size normally used degrades image quality because of magnification of the negative image necessary to get this large print size. Following is a list of the Hasselblad camera equipment available for use at the water tunnel, allowing most any type view of the test subject, limited only by the test section size and external test section brace viewing obstructions.

500 EL/M motor-driven, single-lens reflex camera body
Standard focusing hood and screen
2.5× magnifying focusing hood
80mm, f2.8 Planar lens
120mm, f5.6 S-Planar lens
150mm, f4 Sonnar lens
250mm, f5.6 Sonnar lens
Proxar 0.5, 1.0, and 2.0 close-up lenses
Film magazines A12, A24, and 70
Filter holder for 50mm bayonet mount
Wratten 2B filter

Other equipment available includes 2 ITE T-20A tripods, 1 Gitzo 325 tripod with 372 Rational tripod head, a Sekonic Digilite light meter, and the 2 Gitzo 105/4 light stands mentioned in the "**Lights and Support Stands**" section.

As indicated in the equipment list above, there are 3 different film magazines available for use with the Hasselblad camera. The magazine A12 produces 12 exposures using 120 size film, the magazine A24 produces 24 exposures using 220 size film, and the magazine 70 can be loaded with film cassettes containing up to 15' (70 exposures) of 70mm roll film. In most cases, Kodak Vericolor II, Type L (VPL-120) rated at ASA 100, is best suited for photographing dye streaks illuminated with the halogen lights. For photography with the laser light sheet equipment, Kodak Vericolor VR 400 (CM-120, ASA 400) works well. All of the film rolls mentioned above are 12 exposure rolls, but 220 film (24 exposure) could be substituted if a large number of model and/or flow changes are to be photographed. The reason for staying with the smaller magazines is so prints can be obtained more quickly at the beginning of the investigation to determine if the correct exposure is being used; and to better keep track of flow conditions or model configuration for each frame. The best way to document exposure and flow conditions is to use a label visible in the picture, but away from the location of interest, (see figure 7(d) for example).

Shutter speed and iris (f stop) settings for correct film exposure using ASA 100 film and one halogen light is about f5.6 and 1/60 second. With two lights f stop can be increased to f8 or f11 for the same shutter speed (1/60). For ASA 400 film, f stop can be increased to about f16 (2 stops) or shutter speed increased to 1/500. These are approximate settings to be expected, but more precise exposure values for given light positions and model color can be determined using the light meter.

The close-up lenses listed earlier can be used to study flows in relatively small areas in the flow. With magnification factors from about .04 up to about .77 and focus distances (in air) from 84" down to 13 7/8", most anything that will fit in the water tunnel can be photographed up close in small areas (about 2.9" by 2.9") or further back for over-all views. Figure 14 shows the range of focus distances and magnification factors for the 80mm, f2.8 lens and the 150mm, f4.0 lens. If further information is needed on the operation of the Hasselblad camera, instruction manuals are available from PAB personnel.

Video Equipment

Of course, nothing can beat sitting close to the water tunnel test section with the model well lit and observing the flow patterns around the model along with the motion of the dye streaks, to aid in understanding flow phenomena in the water tunnel. This is fascinating viewing , sometimes, while the test is in progress, but how do you explain a certain flow pattern to someone several months after a test is completed? For recording this motion in the flow in a qualitative manner, there is video equipment available on site for this purpose.

The following equipment is dedicated to use at the water tunnel:

Panasonic NV-8950 VHS recorder
SONY DXC-101 color CCD camera
SONY Auto Iris VCL-08Y, f1.4, 8mm lens
Fujinon H6 × 12.5, f1.4, 12.5mm ⇒ 75mm zoom lens
SONY CMA-D1 camera adapter
Panasonic BT-S1300N color video monitor
Time/date generator
Portable rack mount (contains the recorder, monitor, camera adapter and time/date generator)

The camera can be mounted on one of the tripods, and the portable rack can be rolled around to a convenient location so that both the monitor and the model can be observed simultaneously. There is a time/date generator included with the recorder so this information can also be included in the tape record. The same comments about labels visible in the picture are also important here. Remember, the still camera and video camera may not share the same view, or be taken at the same times, so if possible, be sure to include model configuration and flow conditions on a label that is visible on the video monitor <u>while the recording is being made</u>! Since the video recorder is much more sensitive to light than the color films used with the still cameras, there should be no problem with lighting when making a video recording of any flow phenomena desired. For close-up views, the zoom lens probably offers the most versatility since the camera will not have to be placed very close to the test section to get good detailed views of the flow. The same model colors and dye colors apply for video recordings as those used for still photography purposes.

If use of the video equipment is desired during your planned water tunnel test, be sure to relay this information to Propulsion Aerodynamics Branch personnel when planning for the test is initiated.

Laser Velocimeter And Fluorescence Anemometer

A laser fluorescence anemometer (LFA) is available for flow field studies at the water tunnel. The device consists of a 3-component, laser doppler velocimeter (LDV) system which can be used by itself, or can be combined with a fourth, concentration-detection component. Contractor-designed traverse control electronics, data acquisition electronics and software, and optical configuration are primary components.

The LDV system uses three colors of light from a Coherent Innova 90-6, 6 watt argon laser to measure three perpendicular velocity components in a sample (probe) volume. This sample volume is created at the focused intersection of all of the beams. It is in this sample volume that the fourth concentration component is also measured. This fourth component measures the concentration of a fluorescent dye that is excited by the laser light. The fluorescent light and the scattered light from naturally-occurring seed particles in the flow is collected by receiving optics focused on the sample volume. The light is chromatically separated and converted to electrical signals which are amplified, downmixed, and analyzed to determine the doppler frequency, and is subsequently converted to three velocity values. The fluorescence component is sampled as a digitized analog signal and recorded as voltages. Mean and fluctuating values of all four components are plotted as well as velocity cross-correlations.

A photograph of the laser beam transmission and receiving optics on either side of the water tunnel test section is shown in figure 15. Three pairs of beams are transmitted by the optics on the right side of the figure and the scattered light is collected by the optical equipment on the left side of the figure. This is termed the forward-scatter mode of light collection.

CHANGING MODELS OR CONFIGURATIONS

Model changes for use in the water tunnel require the test section and channel above to be drained so that the test section door may be removed. The water remaining in the storage tank is not drained. Carefully remove the access door and model, placing the door, outside face down, on the support cart (see figure 2(d)). All connections to the model, such as orifice tubes and inlet mass flow tubes connected to the exhaust pipes, should be long enough to leave them connected while the model is being worked on. Before reinstalling the access door and model in the test section, all the dye orifices should be checked to make sure they are not clogged, and then the model should be thoroughly cleaned to remove all dye stains from the surfaces. When a model change is complete, install the access door and torque down the screws as instructed in the **"OPERATIONAL START-UP PROCEDURES"** section, and then add water to the test section and cross-over channel to bring the water level back up to 4" from the top of the storage tank. During the summer, the water temperature in the storage tank stabilizes at about 78° F (25.6° C). This yields a unit Reynolds number of 2.58×10^4 per foot (0.85×10^5 per meter). In the winter, city water temperature drops to about 55° F (13° C) and water tank temperature remains at about 68° F (20° C). These temperature differences (during summer or winter) result in density differences in the water, and will cause turbulence in the water when it is flowing through the test section. This density difference between fresh city water and water remaining in the storage tank is observable in the test section by looking at a light source through the water. By operating the water tunnel, the two masses of water can be mixed over a period of about 20 to 30 minutes to eliminate the turbulence. The mixing can be accelerated by increasing the freestream velocity during the mixing period.

PREOPERATIONAL FLOW SYSTEMS CHECK-OUT

This section gives procedures for setting/checking the operating parameters of the Badger Meter Electronic Transmission System (ETS), and the Honeywell UDC 300 controller. These checks are <u>not</u> made routinely by Propulsion Aerodynamics Branch personnel and <u>never</u> by other individuals using the tunnel. These procedures should be checked at least once before an investigation begins and perhaps also at the end of the test.

A. Check panel P100 (labelled 440V) on North wall of the control room (Room 102) to assure switches 1 (filter pump) and 2 (main pump) are on.

B. Check panel 100A (labelled 208V) in the control room to make sure both upper, labelled switches are on.

C. On West wall near main pump, open air supply valve (S12), then set main water pump bypass valve control pressure regulator to 15 PSI, (may be set at values up to 20 PSI, if needed).

D. Turn on the Honeywell UDC 300 controller, (see products manual - section 5). Perform the following checks:

    1. Open the door below display. If "MAN" indicator is off, press $\boxed{\text{A/M}}$ until LED is on. Controller is now in <u>manual</u> mode.

2. Process variable (PV) will show in upper display and % OUTPUT in lower display, (this is % shut for control valve).
3. Change % OUT to 100 by pressing $\boxed{\Delta}$ or $\boxed{\nabla}$ and $\boxed{\Leftarrow}$ (flashing digit indicates one being changed),and then $\boxed{\text{ENT}}$. Control valve should close fully.
4. Change % OUT to 0 by pressing $\boxed{\nabla}$ and then $\boxed{\text{ENT}}$. Control valve should open fully.
5. Press $\boxed{\text{SP}}$. Set point will be displayed. For smoothest operation, this value should be between 500 and 800. To change, press $\boxed{\Delta}$ or $\boxed{\nabla}$ and $\boxed{\Leftarrow}$, then $\boxed{\text{ENT}}$.

NOTE: When main pump is on, the manual bypass valve (W2) may be adjusted so that controller can maintain constant flow rate, if this is desired.

6. Press $\boxed{\text{DISP}}$ to exit from set point function.
7. Press $\boxed{\text{PARA}}$ until "P" shows in upper display. Lower display shows the value of proportional band (PB). This should be same as value indicated on tag on inside of keyboard door. If different, consult qualified operator.
8. Press $\boxed{\text{PARA}}$ until "I" shows in upper display. Lower display shows the value of integral. This value also appears on the label inside the keyboard door. If different, consult qualified operator before attempting any changes.
9. Press $\boxed{\text{PARA}}$ until "d" shows in upper display. Lower display shows the value of derivative. This value also appears on the label inside the keyboard door. If different, consult a qualified operator before attempting any changes.

10. If all values are set properly, press DISP to exit from parameter setting function. Shown below is a typical keyboard door label:

PB = 210
I = 1
d = 5

11. Press A/M until "MAN" LED goes out. Controller will return to automatic mode. If main pump is off, valve should go to full open position.

E. Turn on the Badger Meter Electronic Transmission System using the switch on the digital read out panel, (see products manual - section 6). Perform the following self test if this is first use for an investigation:

1. Set the TEST/RUN switch to TEST position, the DIVIDER switch to position 4, and the X1/X2 switch to X1 position,(see figure 5-2, page 14 in **Installation, Operation, and Maintenance Manual** for Badger ETS).
2. Press the RESET/START switch to the right of X1/X2 switch and allow the EPU to totalize (about 20 seconds). The totalizer should indicate the setting of the scaler multiplier switches.

3. Press the RESET toggle switch down and release to reset totalizer to zero. Test section flowmeter is now ready for operation.

OPERATIONAL START-UP PROCEDURES

This section should be used only as a checklist. Further details of the various systems, their maintenance, and principles of operation can be found in the product manufacturer's manuals listed in Appendix B, and in other appropriate sections of this user's guide.

1. If a new model configuration is to be tested; when ready, install the test section access door, bottom edge first on dowel pins (at bottom corners), slide in against bottom surface of gasket and then tip forward to seat against entire gasket. Make sure roller at outer end of AOA/AOS yaw arc sector is engaged on curved rail mounted to inside surface of front (West) viewing window.
2. Install sixteen 1/2" × 13 and six 5/16" × 24 SS bolts, washers (2 each bolt), and nuts finger tight on the access door sides. Install eight 5/16" × 18 SS washers and nuts finger tight on the studs at the top and bottom edges of the access door.
3. Starting at the middle of the door, alternating side to side and up and down, torque the 1/2" bolts and nuts to 35 in. lbs. Then torque the 5/16" bolts and nuts to 35 in. lbs., and finally torque the 5/16" nuts on the studs to 35 in. lbs.
4. Repeat the above procedure, in the same order, this time using a torque value of 50 in. lbs.

5. Check power panel P-100 in control room (440V panel in Room 102) to make sure main water pump and filter pump switches are on. (P-102 and P-101).
6. Check power panel L-100 in Room 102 to make sure switch L121 for panel L-100A is on.
7. Check power panel L-100A in Room 102 to make sure "water tunnel/dye probe" and "water tunnel lights" switches are on (L101A and L102A, respectively).
8. If tunnel already has water in it, check water level in tunnel and add water as needed. Open valve W1 about five notches before adding water and/or before starting tunnel.
9. Check water bypass valve W4 (located under stairs). Verify valve is closed (normal position).
10. Open service air shut-off valve S12 and set control pressure regulator on West wall above water fountain (see fig. 5, and 4(c) - middle left) to 15 PSI.
11. Open water bypass valve W2 about 1 turn.

    NOTE: If tunnel is already full, open valve W3 and skip to step 15.
12. Close valve W3 and open valve W6 and W6A to fill test section. Close W6A when test section is full, and check water clarity. If unacceptable, drain test section (drain valve D2) down to perforated plate. Refill by opening W6A. This procedure can be repeated as many times as is necessary to obtain desired water clarity.
13. Open valves W6A and W3 to allow tunnel to fill.

14. Retorque test section door bolts to 50 in. lbs., when water can be seen near the top of the upper level observation window.
15. Close valve W6A when tunnel is full.
16. Open valves W5 and W5A.
17. Open drain lines on high and low pressure lines at transducer on West wall (see fig. 4(c) - top left), and let drain until all air is eliminated, then close both valves securely.
18. Open balance valve between high and low pressure lines at transducer on West wall. Shut valve securely after a brief wait (a few seconds).
19. Check digital output flow rate on Honeywell UDC 300 and reading on GPM meter. Honeywell UDC 300 should read 78 and the GPM meter should read 0. If not, repeat steps 16 to 18.
20. Turn on filter pump and main pump breakers at panel on West wall. Verify red lights are illuminated on panel (see fig. 4(c) - right side).
21. Start filter pump at panel next to test section (see fig. 2(a) - to right of dye panel). Check filter pressure. If pressure is near or exceeds 20 PSI, shut down filter pump and regenerate filter media, (see instructions on filter tank).
22. Check clear glass bowl oil supply for main pump bearing (between driver motor and pump). If oil is not visible, add a high quality turbine-type oil of approximately SAE 20 viscosity.

23. Start main pump at panel next to dye panel. Set desired flow rate at Badger EPU by adjusting valve W1. Set bypass valve W2 and flow control valve
24. For higher test section flow rates, manual bypass valve W2 should be closed and flow control valve should be operated near closed, or closed for maximum flow rate.
25. Check the 3 dye reservoirs to assure they are at least 1/2 to 3/4 full for those systems to be used. If more dye is needed, use a mixture of about 10 ml of dye per 200 ml of water (full reservoir)[1]. Regulated pressure to dye reservoirs should be set at 8-10 PSI.
26 To fill dye reservoirs, close air shut-off valve S13 and open vent valve S14 (see fig. 6(a)) before opening access port on top of reservoir. Replace cap, close the vent, open the air shut-off valve, and set the dye system air pressure regulator to 8 PSI when reservoirs are full.
27. The following systems can now be used to set tunnel and model conditions as desired:
    a. Valve W1 - Tunnel velocity from 0 to 900 GPM (0.75 ft./sec.).
    b. AOA/AOS system - $\alpha = -30°$ to $+30°$
       $\beta = -15°$ to $+15°$

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[1] Only vegetable dyes and Clorox may be added to the water tunnel. Any other chemicals must be checked by the safety office, and may require a safety permit <u>before</u> use, because of dangers to the environment from liquids drained into the storm drain system.

    c. Dye probe system - Note: Use remote probe system only if flow straightener at the top of the test section is removed.
    d. Dye injection system - Three different dyes separately controlled from control box near test section.

28. Tripod mounted flood lights can be used to obtain sufficient light for still photography with the Hasselblad camera, but do not locate flood lights closer than 3 feet to the test section. **(Test section Plexiglass temperature hazard!)**
29. A low power laser (1/2 watt or less) may be used to illuminate fluorescing dye (both require permits) in light sheets as an alternative lighting method. This is especially useful when using video cameras, where less light is required.
30. Use still cameras and/or video cameras to record visual data as desired.

OPERATIONAL SHUT-DOWN PROCEDURES

1. Turn off dye flow at console. Close air shut-off valve (S13 - fig. 6(a)) and open vent valve (S14) to depressurize the dye system.
2. Turn off main pump and filter pump at panel next to dye panel.
3. Turn off main pump and filter pump breakers at panel on West wall,(fig. 4(c)).
4. Close valves W1, W3, W5, and W5A.
5. Close service air shut-off valve (S12 - fig. 5) on West wall.
6. Open test section drain valve D2 and main tank drain valve D1 (see fig. 3(a)). Allow main tank to drain a few inches below upper channel floor level, then close main tank drain valve.
7. Allow test section to drain just below perforated plate in bottom of test section, then close test section drain valve D2.

EQUIPMENT CALIBRATION AND TUNING

The procedures and checks discussed in this section are not routinely performed on the water tunnel equipment and should only be done by Propulsion Aerodynamic Branch personnel familiar with operation of the water tunnel systems. Most of these checks should only be performed if some discrepancies in equipment operation or flow measurements are found. Further details of the calibration and tuning procedures can be found in the individual equipment instruction manuals contained in the **Specifications, Installation, Calibration and Operation Information for The 16" X 24" Water Tunnel Equipment** manual under the item number as indexed in the front of the manual, and indicated on drawing number LD-543351.

Badger Flowmeter and EPT-2 Transmitter

The Badger 4" turbometer including the EPT-2 transmitter used in the 6" diameter return line from the test section (⑥ in figure 3) is calibrated at the factory before shipment to the customer. Since water is used as the test fluid for accuracy checks at the factory and water is used in the water tunnel facility, no accuracy check/adjustment of the mechanical parts of the flowmeter are necessary. A quick check of agreement between the Badger electronic transmission system, the Dieterich Annubar flow sensor/Eagle Eye meter, and the diffused silicon transducer/UDC 300 controller system flow rates can be performed by closing manual valve W2 ⑨ and the minimum flow control valve C5 ⑤, which cuts off the bypass flow through the main pump. Under these conditions, the flow through each of the three measuring systems will equal the flow through the test section, and the measurements should agree with each other. If these values do not agree, then further checks should be done to determine where the problems exist and necessary steps to be taken by PAB personnel to correct them.

Badger Electronic Processor Unit

As defined in the **Installation, Operation and Maintenance Manual,** the water tunnel uses a EPT-2 transmitter from the flowmeter, and a wall-mounted Electronic Processor Unit (EPU) (see figure 4(c)), which together make up the Electronic Transmission System (ETS). For checks on this system, turn back to the **PREOPERATIONAL FLOW SYSTEMS CHECK-OUT**, Section E, for the steps necessary to make sure the system is operating properly. No other checks or calibrations are necessary for this system.

Main Water Pump Minimum Flow Control System

The equipment used to set and control the minimum flow rate through the main water pump (③ on figure 3(a)) are shown on the schematic of figure 5 and described in more detail in the following paragraphs:

<u>Honeywell 2 1/2 inch Model 8105 cage valve.</u> The pneumatically-operated, single seated cage valve (⑤ on figure 5 - tagged C5) is normally open, and is closed by the pneumatic

diaphragm actuator described in the next paragraph and controlled by the electro-pneumatic valve positioner described in the second paragraph. These three units are assembled to produce the remotely actuated minimum flow control valve. No calibration can be performed on the cage valve itself, but cleaning and maintenance of the valve parts can be critical to its operation. These procedures will be discussed in the next section.

Honeywell Type 05 pneumatic diaphragm actuator. The Type 05 actuator is direct acting (air to close) and uses 15 PSI service air pressure to operate the diaphragm actuator. Since the valve is direct acting, the valve will open fully if the service air or the controller (see next paragraph) fails. No adjustments or calibrations are needed for the actuator unless the valve body and actuator are disassembled. See "Operator's Manual for 8105 Cage Valve" in the **"Specifications, Installation, Calibration and Operation Information for 16" X 24" Water Tunnel Equipment Manual"** - Section 5 for details of these procedures.

Honeywell Model 870020 valve positioner. The valve positioner is side-mounted directly to the actuator yoke on the valve. It uses a 15 PSI air supply (㉑S12 on figure 5) and feedback cam to position the 2 1/2" valve in accordance with the current signal (4 to 20 ma) from the Honeywell UDC 300 digital controller. No adjustments or calibrations are necessary for the positioner, unless something fundamental is changed in the valve operating characteristics or in the controller. See the "Operator's Manual for 63-87-25-05 E-P Positioner", also in section 5 of the previously mentioned equipment manual, for details on replacing parts if needed.

Honeywell UDC 300 digital controller. The UDC 300 Universal Digital Controller is a microprocessor-based multi-function type, single loop, digital indicating (on the instrument face) controller which regulates the volume flow rate (GPM) through the 2 1/2" cage valve. The controller uses the signal from the Dieterich ANR-75 Annubar flow sensor, converted to a milliampere current signal by the Honeywell diffused silicon transmitter. Control is achieved using a PID (Proportional, Integral, and Derivative) algorithm with a "current proportioning" output signal fed to the valve positioner. Operation and calibration of the UDC 300 is described in the product manual included in section 5 of the equipment manual previously mentioned. Check-out of the operating parameters for the UDC 300 unit are also given in the **PREOPERATIONAL FLOW SYSTEMS CHECK-OUT** section in this manual.

Rochester SC-1330E square root extractor. The SC-1330E square root extractor is an instrument designed to provide a linear output from square function inputs. These inputs are typically from differential pressure flow transmitters such as the Honeywell differential pressure transducer described in the next paragraph. The output from the SC-1330E is a highly accurate signal that is linearly proportional to the square of the input signal. The range of this unit is 4 to 20 ma input and 4 to 20 ma output. The AC-powered SC-1330E with the "E" option includes a 24 VDC 20 ma current limited power supply to the Honeywell differential pressure transducer. Calibration of the SC-1330E is covered in the "SC-1330 Instruction Manual", also included in section 5 of the equipment manual, but should not be necessary on a routine basis and should only be performed by PAB personnel.

Honeywell diffused silicon differential pressure transducer. The Honeywell, Model 41105 differential pressure transducer senses the pressure differential across the ANR-75 flow sensor ((FE) on figure 3(a)) and converts the signal (which varies from 4 ma at zero flow to 20 ma at 930 GPM) for use by the UDC 300 controller, after passing the signal through the square root extractor. Refer to section 5 of the equipment manual for the operation and calibration procedures for this pressure transducer.

Dieterich ANR-75 Annubar flow sensor. The Model ANR-75-C21-CSS flow sensor is sized for use with 6" ID piping and constructed of 316 SS. It has a 1.0" diameter probe with four orifices on the side facing the flow (Hi pressure side) and one orifice on the side facing away from the flow (Lo pressure side). Shut-off valves are included in both the Hi and Lo lines at the external connections to facilitate servicing of the connecting tubes, if necessary. Calibration of the flow sensor should not be a consideration when trouble shooting flow measurement problems. Refer to section 5 of the equipment manual for information on this flow sensor, also.

Dieterich standard "Eagle Eye" meter. The Model EFW-F1-GPM1000NM is a differential pressure sensing analog meter which reads 0 to 1000 GPM directly from the Hi and Lo pressure lines from the ANR-75 flow sensor (also "teed" to the Honeywell pressure transducer). The Eagle Eye Meter is calibrated at the factory and should not be recalibrated in the field. The full scale calibration point is shown on the back of the meter. Refer to section 5 of the equipment manual for further information.

EQUIPMENT MAINTENANCE

In general, maintenance of the various systems used with the water tunnel are the responsibility of PAB personnel, but if personnel from other branches or organizations are using the facility and notice equipment needing attention, please inform someone familiar with the systems so that corrective action can be taken. For detailed information about maintenance on the various pieces of equipment used with the water tunnel, refer to the specific section via the index in the front of the **"Specifications, Installation, Calibration, and Operation Information for 16" X 24" Water Tunnel Equipment"** (referred to as **Equipment Manual** in the following text), indicated in the paragraph on each item. This information can be used in conjunction with the parts list in figure 3(b), which has corresponding numbers. **APPENDIX B** of this report lists in detail the contents of the **Equipment Manual.**

Perflex Filter

During normal operation of the water tunnel, when the filter pump is running, pressure at the gage near the top of the filter tank should read about 10 PSI. When this pressure exceeds 7-10 PSI above the previously mentioned value, the filter should be "regenerated" by shutting off the pump, then moving the media regeneration (bump) handle down slowly, then up briskly. Repeat 3 times. Restart the pump to continue filtration. The gage pressure should now read near the "precoat" value (clean filter-media coating on filter tube bundle) of approximately 10 PSI. As the filter continues to work, the gage pressure will rise slowly over several days operation until it needs regeneration again. As dirt accumulates in the filter, this recycle time will decrease to the point where a 10 PSI differential pressure from the precoat level will occur in less than a days operation. When this happens, the filter media must be changed as described below:

Draining out old media.

1. Fill the test section with water to 6 inches above the floor of the flow channel (if it doesn't already have water in it) to provide for flushing the pump out.

2. Put the white rectangular container (preferred) or other receptacle under drain.

3. Open inlet valve (W5A) on pump and drain valve (D3) on filter (all other valves in the system should be closed). This will allow old filter media to drain into the receptacle. While the water is draining, pump the media regeneration (bump) handle to shake loose the filter media, (see figure 16).

4. When the receptacle is near full, close valves and dump the old filter media from the receptacle into the pit under the water tunnel.

5. Repeat steps 2-4 until the water draining into the receptacle is relatively clear. The draining process is complete.

6. Close pump inlet valve W5A and add water to the test section if needed to maintain flow level over the cross channel.

7. **CAUTION:** Do not operate filter pump for extended periods without filter media in housing.

Replacing filter media.

1. Open pump outlet valve W5 and valves W1 and W3.

2. Open pump inlet valve W5A about half way. Start the filter pump. Open the top of the vertical PVC pipe for the filter media (see figure 16). Open valve W7 at the base of the pipe and adjust the pump inlet flow valve until the flow up into the pipe has stopped, i.e., the pump is just barely sucking air.

3. Place garden hose end into pipe and turn it on at a low rate. If necessary, adjust the pump inlet flow valve to keep the water level near the bottom of the vertical pipe.

4. With the hose running, put 18 cupfulls (6 lbs.) of filter media (diatomaceous earth) into the pipe, washing the media out of the vertical pipe as necessary.

5. Turn off the hose, close valve W7 below PVC pipe, shut off filter pump, and put top back on the vertical pipe.

6. Filter is now recharged, but should be operated at full capacity (both valves W5 and W5A fully open) for a few minutes to seat the media in the housing screens.

7. After a few minutes of operation, pressure gage on filter housing should read close to 10 PSI.

Over long periods of time the "Flex-Tubes" inside the filter can become clogged with algae or filter media that won't break loose when bumped. This will become evident if replacing the filter media does not drop the gage pressure down to 10 PSI or less. The above condition can be checked by removing the pressure gage and gage port adapter together, and checking the tube bundle by looking into the tank through the port. Refer to **Section 2** in the **Equipment Manual** for details on this procedure.

Goulds Main Flow Pump

Maintenance of the Goulds Model 3196MT 4 × 6 - 10 pump (10" diameter 316 SS open impeller with 6" suction and 4" discharge lines) only requires checking the bearing oiler and stuffing box. The pump has a glass bottle oiler for easy checking and uses a high quality turbine type oil with rust and oxidation inhibitors. Under normal operating conditions, an oil of about SAE 20 weight should be used.

Fill oiler bottle and replace in oiler housing. Repeat until oil remains visible in bottle. Do not add oil through the vent or breather.

The stuffing box should be checked periodically to make sure there is sufficient leakage (40 to 60 drops per minute) through the packing to lubricate and cool the packing and shaft sleeve. Never restrict the leakage from the packing as this will cause damage to both packing and shaft sleeve. Draw up gland nuts slowly and evenly, and only while pump is running.

To insure that bearings and seals are running with proper lubrication, check the temperature of each by hand touch (pump off). Bearings and seals should not be so hot that they cannot be touched! Refer to **Section 3** in the **Equipment Manual** for further details on the above procedures.

Honeywell Digital Controller

The UDC 300 Universal Digital Controller is used to maintain a set flow rate through the main flow pump manually by setting flow rate through the test section (about 300 GPM) using valve W1 ⑦ (see figure 3(a)), and providing additional flow through the manually adjusted bypass flow valve W2⑨. With a combined flow of 600 GPM to 800 GPM through the 3 valves, the automatically controlled valve C5 ⑤ helps to stabilize the flow through the test section. Other than general cleaning of the external display clear window and outside protective case, there are no routine maintenance procedures for the digital controller. However, there are routine calibration checks which should be performed about once a week when the tunnel is being used. These checks are covered in the **EQUIPMENT CALIBRATION AND TUNING** section of this report, and also in the product manual in **Section 5** of the **Equipment Manual**.

Badger 4 Inch Flowmeter

Although routine maintenance is not necessary for the flowmeter and ancillary equipment, there is potential for debris or algae growth to affect the operation of the rotor assembly. Although not considered a likely occurrence, the procedures for removing and inspecting the rotor are included in the product manual in **Section 6** of the **Equipment Manual**. Trouble shooting and maintenance for the Badger Electronic Processing Unit are also included in **Section 6** above.

Dye Injection System

The Norgren L12-400-OPPA Oil-Fog Lubricators which are used for the three dye reservoirs in the water tunnel application should be thoroughly cleaned and flushed out <u>before</u> and <u>after</u> each test and at the end of a work week or before extended periods of non-use (several days). The transparent reservoirs should be cleaned using warm water <u>only</u>. Other parts may be flushed out by filling the reservoirs with water, pressurizing the system, and flushing the water through the system at a high flow rate. Details of the above cleaning methods are described in the product manual in **Section 17** of the **Equipment Manual**.

HISTORY OF FACILITY DEVELOPMENT

In the mid to late 1970's with the high costs of building wind tunnel models and operating complex wind tunnel facilities, other less expensive tools were needed to conduct basic flow visualization studies. Complex three-dimensional flow patterns of recent aircraft designs could not be evaluated by state-of-the-art analytical methods, and still cannot be done cheaply today.

It was determined that a small, inexpensive water tunnel could be useful in performing basic exploratory research in three-dimensional flow patterns. In the late 1970's and early 1980's, design study contracts were issued by NASA at the Langley Research Center to determine the feasibility and costs of building such a facility at the Jet Exit Facility (Building 1234). The studies determined that this could be done at reasonable cost, so a "Request For Proposals" was issued in the early 1980's.

Chronological List of Important Events

Event	**Dates**
Design contract NAS1-17419	
Award	February 1983
CDR	October 23, 1983
Completion	January 30, 1984
Construction contract NAS1-17733 (C)	
Award	April 5, 1984
Completion	April 18, 1986

AOA mechanism	
Design	January 1984
Construction	1984-1985
Installation	February 1985
Access door failure	May 2, 1985
Test section redesign	
Design review	May 23, 1985
Pressure system committee	March 29 1985
Construction	Aug.-Sept. 1985
Installation	Mar.-Apr. 1986
Add restraining bars	Apr.-May 1986
Replace AOA servo motors	July 1986
Tank leaks and repair	
Install rubber membrane coating	April 1985
Install ceramic cladding	June 1986
RTV all visible cracks	Feb. 1987
Modifications to improve flow (see next section)	
Smooth out surfaces above contraction and in throat area	Oct. 1986
Add flow straightener above test section	Aug. 1987
Door gasket replacement	Jul. 86, May 87
Piping repairs	Jan. 1988
Combined Integrated Systems Review and Operational Readiness Review	March 24, 1988
Water tunnel operation final approval	June 27, 1988

MODIFICATIONS TO IMPROVE FLOW QUALITY

Flow quality studies were begun in the channel above the water tunnel test section between the two flow straightener sections. An L-shaped dye tube (0.06" diameter) probe with the base aligned with the freestream flow was used to inject a dye streak into the flow. The dye streak was used as a qualitative indicator of the flow quality. The Reynolds number based on tube diameter at the normal tunnel mass flow rate was 25 in the channel. This condition precluded the shedding of flow-disturbing vortices from the vertical part of the probe.

Significant unsteady flow was observed in the channel. The second (downstream) flow straightener was reoriented so that the foam was on the downstream side of the honeycomb. The unsteady flow entering the downstream flow straightener emerged on the downstream side as a smooth streak and remained smooth until it reached the test section. Upon entering the test section on the far side, the dye streak became contorted on a large scale and experienced small-scale oscillations.

Placing the dye probe in the storage tank upstream of the upstream flow straightener revealed very unsteady flow. This unsteadiness was caused by air bubbles and turbulent flow emerging from the pipe manifold in the bottom of the storage tank. The air bubbles were presumably caused by cavitation aft of the tunnel speed control butterfly valve (W1 ⑦) as it was used to reduce tunnel speed. When tunnel speed was increased by opening the valve, the size and quantity of the bubbles decreased. Unfortunately, at normal tunnel speeds, many air bubbles emerge from the manifold pipe. A vent pipe for air was attached to the manifold at one end and protruded through the water surface above. This allowed most of the air to escape through the vent pipe instead of through the manifold. A reduction in the air bubbles coming through the manifold resulted although significant disturbances still existed. This flow was examined as it migrated downstream.

As the dye passed through the first foam section and exited the honeycomb, it appeared as cell-like streaks which exhibited small wavelength unsteadiness about six inches downstream of the upstream flow straightener. The dye entered the downstream flow straightener and exited smoothly. The orientation of the upstream flow straightener was also reversed, placing the foam downstream of the honeycomb, and resulted in elimination of the flow oscillations.

A dye streak, inserted upstream of the second flow straightener near the channel floor, entered the turn above the test section and moved down into the test section away from the near wall toward the far wall at an angle as shown in figure 17(a). This behavior did not change with tunnel speed. Observations were made of the corner flow in the contraction section above the test section. The flow in the downstream corners was visualized using dye streaks originating near the channel walls about one foot below the water surface at the downstream flow straightener. As shown in the sketches in figure 17, two counter-rotating vortices rotating in a direction appropriate for inducing the test section streakline away from the near wall were observed. The source of the vortices appeared to be the separated flow from the edge of U-shaped brackets holding the honeycomb along its edges in the downstream flow straightener. This vortical, separated flow moved downstream where it was concentrated and organized into corner vortices before descending into the test section.

New, flat honeycomb brackets were installed. Observation of the streak in the test section indicated that the previously observed pitch angularity was gone. However, looking in the plane perpendicular to the pitch plane revealed a curvature of the streakline. Observations in the contraction section above the test section revealed an intermittent rotational flow in the corner of the section on the far wall. In addition, there was rather turbulent flow on the far wall that was transported down into the test section, causing an occasional wiggle in the smooth dye streaks near the center.

Sources for a non-uniform onset flow to the contraction section that might cause the rotational flow in the contraction were hypothesized. One possible source was gaps between the foam and the channel walls. Probing the flow in that area with dye indicated the existence of jets of accelerated flow through the gaps. The foam was adjusted to eliminate the gaps and subsequent probing with dye indicated that the jets were gone.

The dye streaks flowing down into the test section still exhibited some asymmetry. In addition, there was significant flow separation on the channel sidewalls above and in the contraction section. A temporary turning vane in the corner was installed using plastic sheet. Promising results from this modification prompted installation of a permanent turning vane, as shown in figure 18(a), in the far right upper corner of the contraction section. The beneficial effect that the turning vane had on the flow was verified by removing it from the water and watching the streaklines turning into the test section assume a non-symmetric distribution as shown by the solid lines in figure 18(b). When re-inserted, the vane influenced the flow to return to a more symmetric form (dashed lines in figure 18(b)).

Wall flow separation in the section upstream of the contraction was investigated. Since the flow was basically laminar and was in an adverse pressure gradient region caused by the presence of the back wall, it was very sensitive to surface irregularities. The side wall regions were probed with dye tubes to determine the extent of separation.

The separated flow along the walls appeared as shown in figure 19. The effect of increasing tunnel speed was to move the separated flow downstream, but the separation locations did not move. The effect of increasing the mass flow rate from 300 GPM (0.25 ft./sec. test section velocity) to 900 GPM (0,75 ft./sec. test section velocity) is shown in the sketch in figure 19.

The sidewalls were sanded to minimize existing surface irregularities. The surface was then painted with a ceramic coating which provided a very smooth surface. This effort moved the separation locations on the sidewalls downstream. However, the East sidewall separation location was about one foot upstream of the separation location on the West wall as shown in figure 20(a). As figure 20(b) shows, all of the flow marked by dye on the East wall separated and dropped down. However, as shown in figure 20(c), some of the dye streaks on the West wall continued downstream before dropping down. Separation was subsequently fixed on the West wall at the same location that it occurred on the East wall. However. this separated flow did not drop down just downstream of the separation location as it did on the East wall, but moved downstream and dropped down near where it dropped down on the West wall before the separation location had been fixed. This indicated that the flow was being driven further on the West wall than on the East wall, even with the separation location fixed.

These observations, along with a slight counterclockwise rotation of the streaklines as they descended into the test section, implied that a local, residual circulation pattern existed in the contraction. Hypotheses were explored for sources of flow asymmetry. Asymmetry of the walls was an unlikely possibility since the tunnel dimensions are fairly consistent and a rather large asymmetry would be necessary. Elimination of geometrical considerations implied that the source was in the flow field.

If a non-uniform onset flow from upstream was causing the residual circulation, a modification of the onset flow might resolve the problem. Sections of foam were placed on the upstream side of the last honeycomb section in the channel. This was used to selectively retard the flow and counter the circulation. Unfortunately, at the edges of the extra foam sections, vortical flow was generated, likely due to the extreme velocity discontinuity created at the edges. These disturbances moved downstream and greatly reduced flow quality. Foam wedges without abrupt edges might prove more effective, but are difficult to fabricate. Other methods to counter the circulation would likely disturb the flow.

Dye streaks released in the channel between the two honeycomb/foam sections and also downstream of the last honeycomb/foam section showed very little visual difference in translation time and position of the dye as it moved downstream. A non-uniform velocity distribution that is too small to see could possibly be magnified in the contraction, similar to the behavior of a vortex when concentrated. However, another possibility could be the effect of coriolis acceleration since the area of the contraction and test section are essentially a drain system. In addition, since other sources of disturbances had been minimized, such subtle effects could emerge as dominant factors.

A section of honeycomb was inserted downstream (below) the contraction at the entrance to the test section as shown in figure 21. Observations of the dye streaks revealed that they were still in a rotational flow field upstream of the test section. However, after passing through the honeycomb at the test section entrance, the dye streaks remained straight in both viewing directions. A 0.090" dye tube was placed in the honeycomb and dye was released into the flow. The dye streak remained straight and vertical and did not diffuse at a free stream velocity of 0.25 ft./sec. (300 GPM).

This configuration of the water tunnel was chosen as the basic, final configuration for normal tunnel operation. In addition, a set of wire-mesh screens that can be inserted below the honeycomb flow straightener and above the test section is available for reducing disturbances at higher tunnel speeds. A 14-mesh and a 24-mesh screen can be used either together or separately. Depending on the screen configuration, disturbance-free flow can be maintained up to a test section flow velocity of 0.4 ft./sec. (500 GPM).

One other factor that became apparent during testing was the effect of water temperature differences on flow quality. After filling the tunnel with water and starting the pump, very distinct turbulent waviness appeared in the flow in the test section. This was visualized by looking at the tunnel work light through the water and observing the waves. The source of the turbulence was determined to be density differences due to the difference between the temperature of the water in the storage tank and the new water brought in when refilling the tunnel.

Using a submersible water-capturing device with a glass-bulb thermometer, temperature surveys were done at various depths and locations in the tunnel at different times after tunnel refill and start-up. It was found that the larger the initial temperature difference, the stronger the turbulence appeared to be and the longer it took to dissipate by mixing with the warmer water. A period of about 20 to 30 minutes is necessary to assure complete mixing and a uniform temperature distribution. This mixing method is also discussed in the **CHANGING MODELS OR CONFIGURATIONS** section.

FLOW QUALITY IN DAY-TO-DAY OPERATION

There are several factors that can affect flow quality during normal water tunnel operation. As previously mentioned, gaps between the flow-straightener foam and the wall in the channel can cause significant non-uniformity in the flow field. Also, temperature differences must be accounted for. The effect of tunnel speed is manifested by the amount of turbulence caused by the honeycomb and/or screens above the test section. At the highest test section speeds (0.4 to 0.75 ft./sec.), an unsteady free stream flow always exists. If the remotely-controlled, overhead dye probe (without the test section honeycomb) is used, it will shed vortical flow into the test section that will cause unsteady flow around the model. This was verified by releasing dye near the upstream end of the probe and observing it into the test section.

Dye probes fabricated from 0.90" tubing are used to provide a dye streak from the overhead honeycomb section to the model. Three factors affect the steadiness of the dye streak from this probe(s). The orientation of the probe in the honeycomb cell will determine if the probe sheds a significant, unsteady wake. This wake will disturb the dye streak locally and be translated down to the model. Dye flow rate will also affect flow quality. If the probe dye flow rate is too high, an unsteady, vortical jet will emerge and flow to the model.

Another factor related to the orientation of the probe is the tip configuration. As shown in figure 22(a), the standard tube is cut off blunt. This is generally acceptable for low tunnel speeds and dye flow rates, and relatively straight tube orientations. However, at higher dye flow rates, the jet becomes unstable and is also sensitive to angularity due to the blunt base., A hypodermic tip shape, shown in figure 22(b), provides a smooth, stable flow at higher dye flow rates. This shape has also proved to be desirable for tubes attached to models since it provides a less-abrupt transition to the surface and exposes more dye to the flow. This probe is still somewhat sensitive to flow angularity when used at the test section entrance.

A third probe tip was fabricated with a "vee" shape, shown in figure 22(c). The flow from this probe is very smooth and less sensitive to angularity. When at a small angle to the flow, the probe does not have the sharp-edge separation, but the dye streak will spread slightly. This probe tip shape is currently in use at the water tunnel, and is described in detail in figure 10.

APPENDIX A

INDEX OF FACILITY DRAWINGS

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	Water Tunnel Tank and Test Section
LD-543337	Cover Sheet & Drawing List
LD-543338	Water Tunnel Facility Isometric
LD-543339	Test Section
LD-543340	Ground Floor Plan
LD-543341	Sections at Ground Floor
LD-543342	Water Tunnel Elevations
LD-543343	Water Tunnel Framing Elevations & Sections
LD-543344	Supports & Tank Details-Sheet No. 1
LD-543345	Supports & Tank Details-Sheet No. 2
LD-543351	Flow Diagram
LD-543352	Piping Arrangement
LD-543353	Electrical Plans
LD-543354	Electrical Details
LD-543355	West Area Facilities Key Plan
LA-904452	Perforated Plate Support Legs
LC-904453	Turning Vane Support

Dye Injection System

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LD-543347	Dye Injection Traversing Mechanism Sections - Sheet 1
LD-543348	Dye Injection Traversing Mechanism Sections - Sheet 2
LD-543349	Dye Injection Traversing Mechanism Details Sheet 1
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LD-545055	Restraint Locations
LD-528738	Restraint Bars - Test Section
LD-544500	Test Section Sheet 1 - Notes
LD-544501	Test Section Sheet 2 - Assembly Details
LD-544502	Test Section Sheet 3 - End & Door Seals
Un-numbered sketch dtd 7/21/86	Water Tunnel Door Levelling Bar
Un-numbered sketch dtd 10/10/86	Water tunnel Flow Straightener Brackets

APPENDIX B

LIST OF PRODUCT MANUALS

Section Number	Subject of Product Manual
1	Water Tunnel
	Water Tunnel Sketch
	Water Tunnel Specifications
	Flexible Tank Surface Sealant
	Fisher Freeze Alarm Unit
2	Perflex Water Filter
3	Gould Model 3196MT Pump
4	Goodall Vibration Absorber 6" dia By 24" Long
5	Honeywell 2 1/2" Model 8105 Flow Control Valve
	Electro-Pneumatic Valve Positioner
	Honeywell UDC 300 Universal Digital Controller
	Sales Information Sheet (orange)
	Specifications for UDC 300 and UDC 400
	Product Manual for UDC 300
	Honeywell Steam Measurement Pamphlet
	Dieterich Standard Annubar Flow Sensor
	Flomec, Inc. Letter Dated 5/3/84
	Annubar Flow Sensor Chart
	Flow Sensor Installation Sketch

	Standard Eagle Eye Meter Sketches
	Annubar Flow Calculation for 6" ANR-75
	Honeywell Diffused Silicone Differential Pressure Transducer
	Rochester Model SC-1330 Square Root Extractor
	Norgren 1/2" Model F12-400-M3T Air Filter
	Norgren 1/2" Model F45-400- Oil Removal Filters
6	Badger 4" Turbo Meter Instruction Manual
	Sales Brochure
	EPT-1 and EPT-2 Wiring Diagram
	Installation Dimensions Sketch
	Electronic Transmission System Brochure
	ETS Installation, Operation and Maintenance Manual
7	6" ASAHI/America Butterfly Valve
8	6" Technocheck Check Valve
9	3" ASAHI/America Globe Valve
10	2" ASAHI/America Butterfly Valve
11	2" Technocheck Check Valve
12	2" ASAHI/America Ball Valve
13	1" ASAHI/America Globe Valve
14	2" Aergap Reduced Pressure Backflow Preventer
15	ASAHI/America 1 1/2" Ball Valve
16	Norgren 1/2" Pressure Regulator (Dye System)
17	Norgren 1/2" Oil-Fog Lubricators
18	Hoke 1/4" NPT Needle Valve
19	ASCO 1/4" Solenoid Valve
20	Watts 1/2" Bronze Globe Bleed-Off Valve

21 Globe 1/2" Bronze Shut-Off Valve

22 P.P.S. LLC Liquid Level Control

23 P.P.S. 0-100 PSI Gages w/ 1/2" Globe Shut-Off Valves

24 AOA Mechanism Information
    Drawing LE-543591
    Drawings LD-543592 to LD-543595

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5. Neuhart, D. H.; and Rhode, M. N.: Water-Tunnel Investigation of Concepts for Alleviation of Adverse Inlet Spillage Interactions With External Stores. NASA TM-4181, April 1990.
6. Smith, J. W.; Mineck, R. E.; and Neuhart, D. H.: Flow Visualization studies of Blowing Form the Tip of a Swept Wing. NASA TM-4217, November 1990.
7. Rhodes, D. B.; Franke, J. M.; Jones, S. B.; and Leighty, B. D.: A Twin-Mirrored Galvanometer Laser Light Sheet Generator. NASA TM-100587, June 1988.
8. Beckner, C.; and Curry, R. E.: Water Tunnel Flow Visualization Using a Laser. NASA TM-86743, October 1985.
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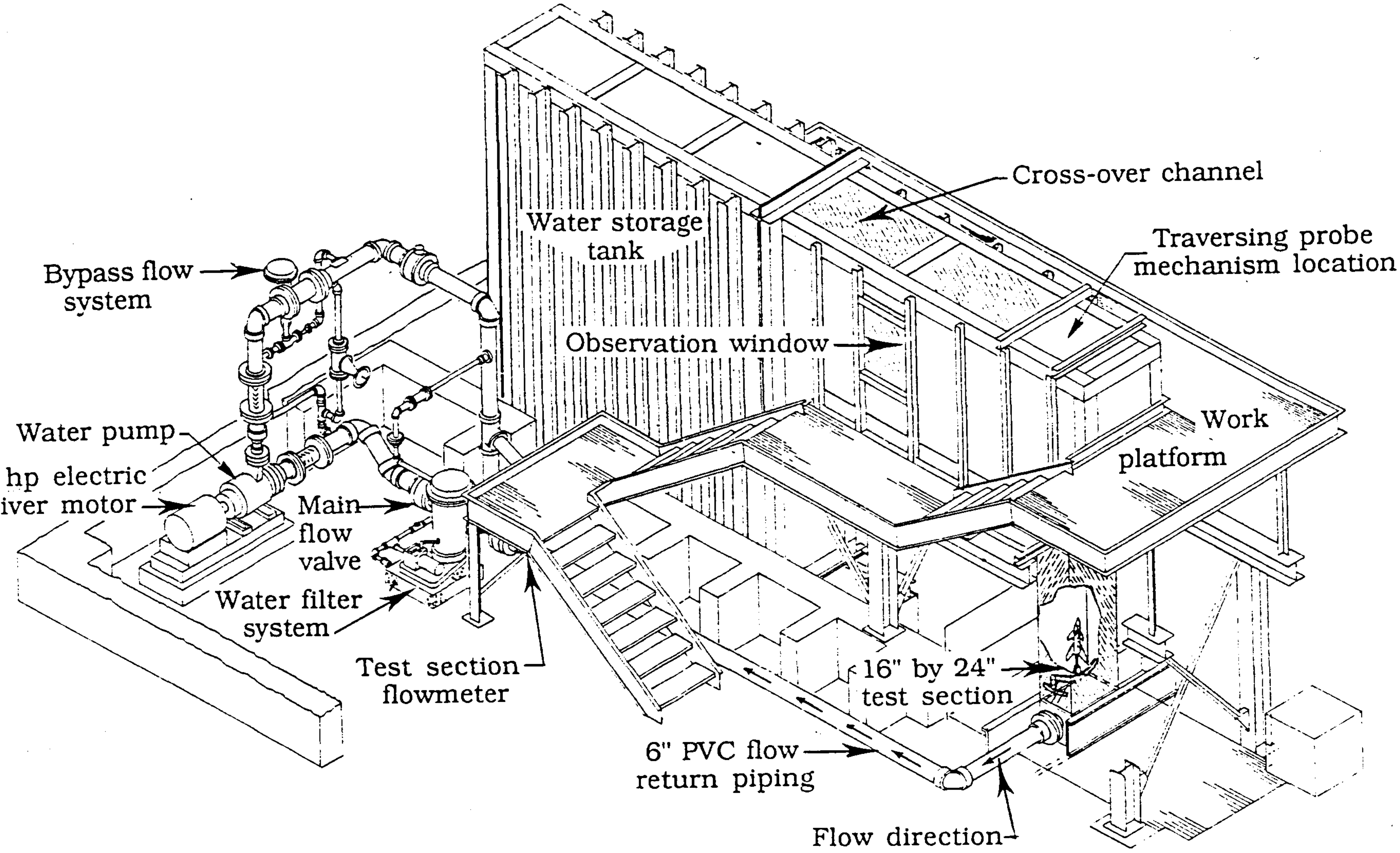
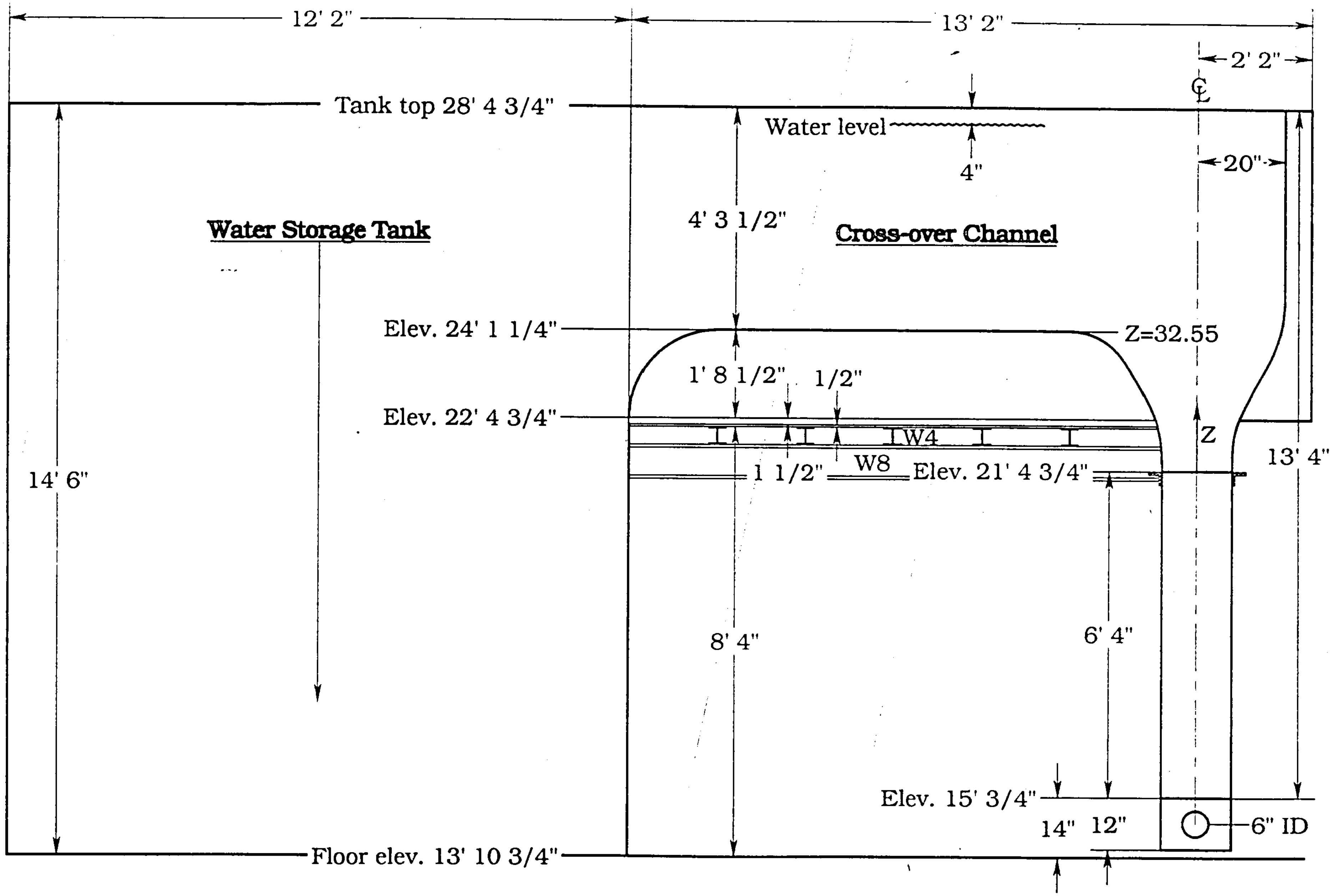
11. Schraub, F. A.; Kline, S. J.; Henry, J.; Runstadler, P. W., Jr.; Littell, A.: Use of Hydrogen Bubbles for Quantative Determination of Time-Dependent Velocity Fields in Low-Speed Water Flows. ASME Journal of Basic Engineering, June 1965.



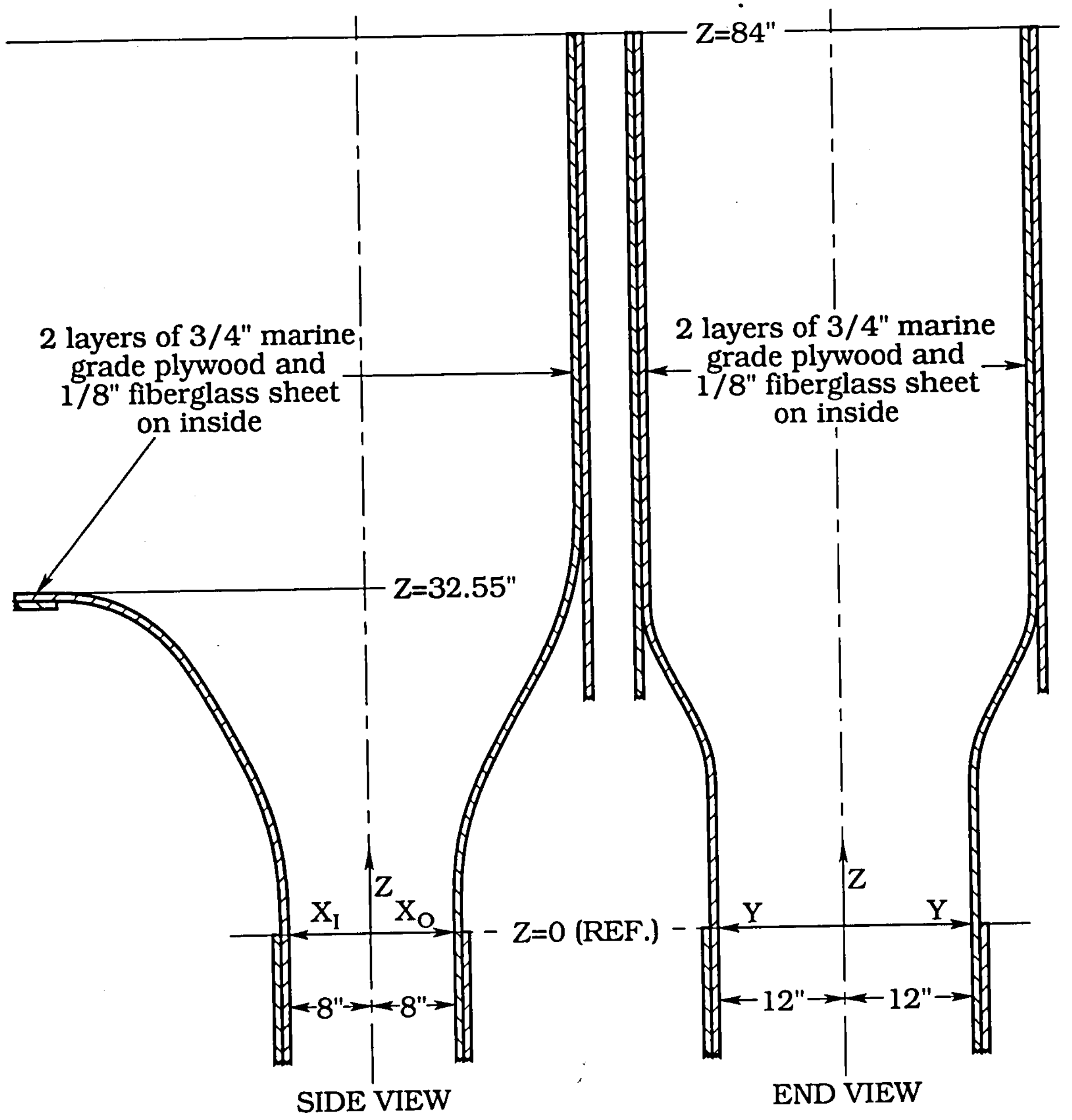
(a) Isometric view showing relative locations of tunnel components

Figure 1. - Langley 16- By 24-Inch Water Tunnel.



(b) Internal (flow path) geometry of tunnel

Figure 1.- Continued.



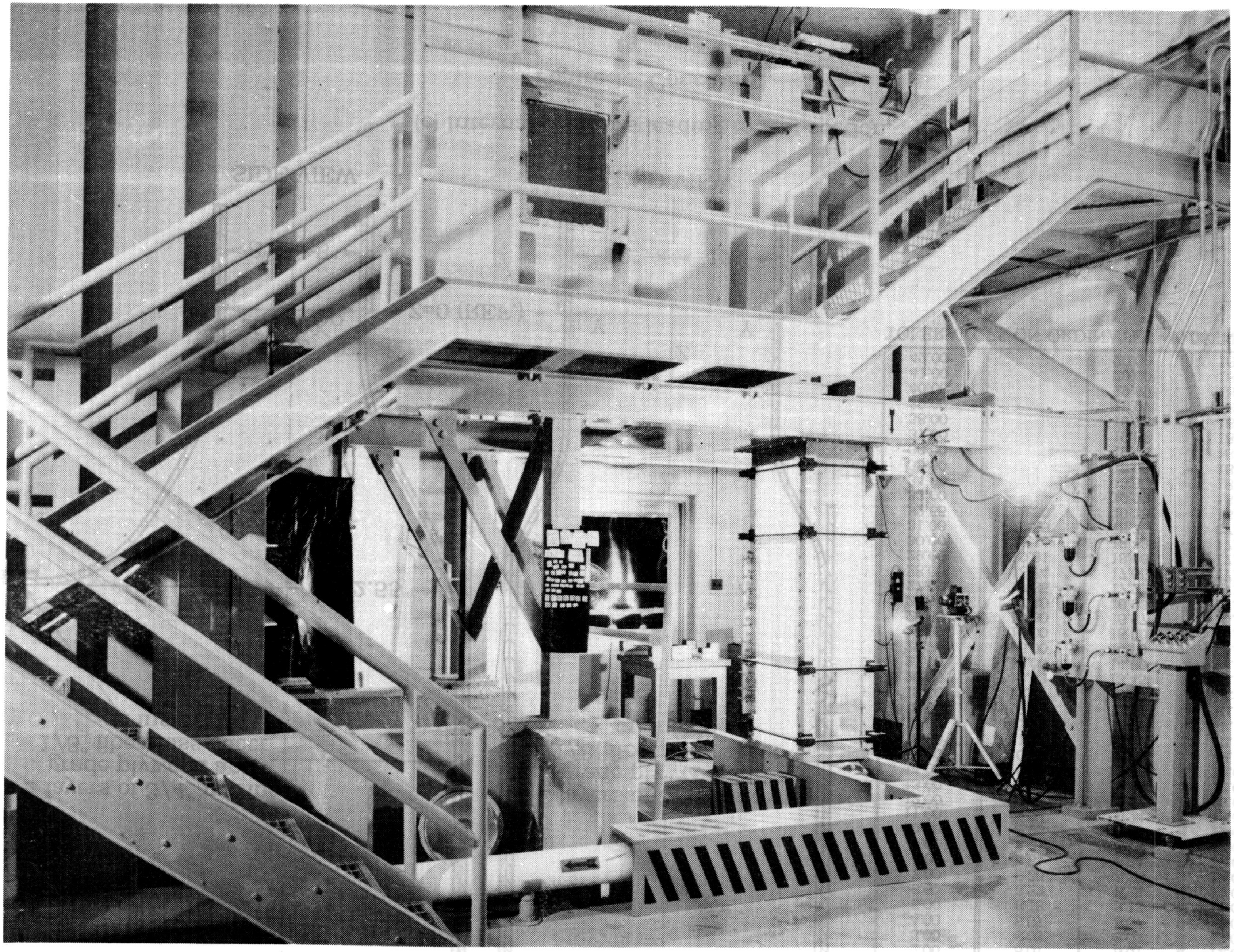
NOZZLE ORDINATES (INCHES)

Z	X_I	X_O	Y
0.00	8.00	8.00	12.00
1.00	8.00	8.00	12.00
2.00	8.01	8.01	12.00
3.00	8.03	8.03	12.00
4.00	8.07	8.07	12.00
5.00	8.13	8.13	12.00
6.00	8.22	8.22	12.00
7.00	8.35	8.35	12.00
8.00	8.51	8.51	12.00
9.00	8.71	8.71	12.00
10.00	8.95	8.95	12.00
11.00	9.24	9.24	12.00
12.00	9.57	9.57	12.00
13.00	9.94	9.94	12.01
14.00	10.35	10.35	12.04
15.00	10.79	10.79	12.12
16.00	11.27	11.27	12.27
17.00	11.78	11.78	12.51
18.00	12.31	12.31	12.83
19.00	12.87	12.87	13.24
20.00	13.43	13.43	13.72
21.00	14.00	14.00	14.26
22.74	15.00	14.99	15.27
24.39	16.00	15.89	16.19
25.88	17.00	16.67	16.90
26.41	17.40	16.93	17.12
27.00	17.85	17.21	17.33
28.00	18.74	17.65	17.61
29.00	19.81	18.06	17.81
30.00	21.14	18.43	17.93
31.00	22.86	18.76	17.98
32.55	29.50	19.18	18.00
33.00		19.29	18.00
34.00		19.50	18.00
35.00		19.65	18.00
36.00		19.78	18.00
37.00		19.87	18.00
38.00		19.93	18.00
39.00		19.97	18.00
40.00		19.99	18.00
41.00		20.00	18.00
42.00		20.00	18.00

TOLERANCES ON ORDINATES ± 0.06 INCH

(c) Internal contours leading to test section.

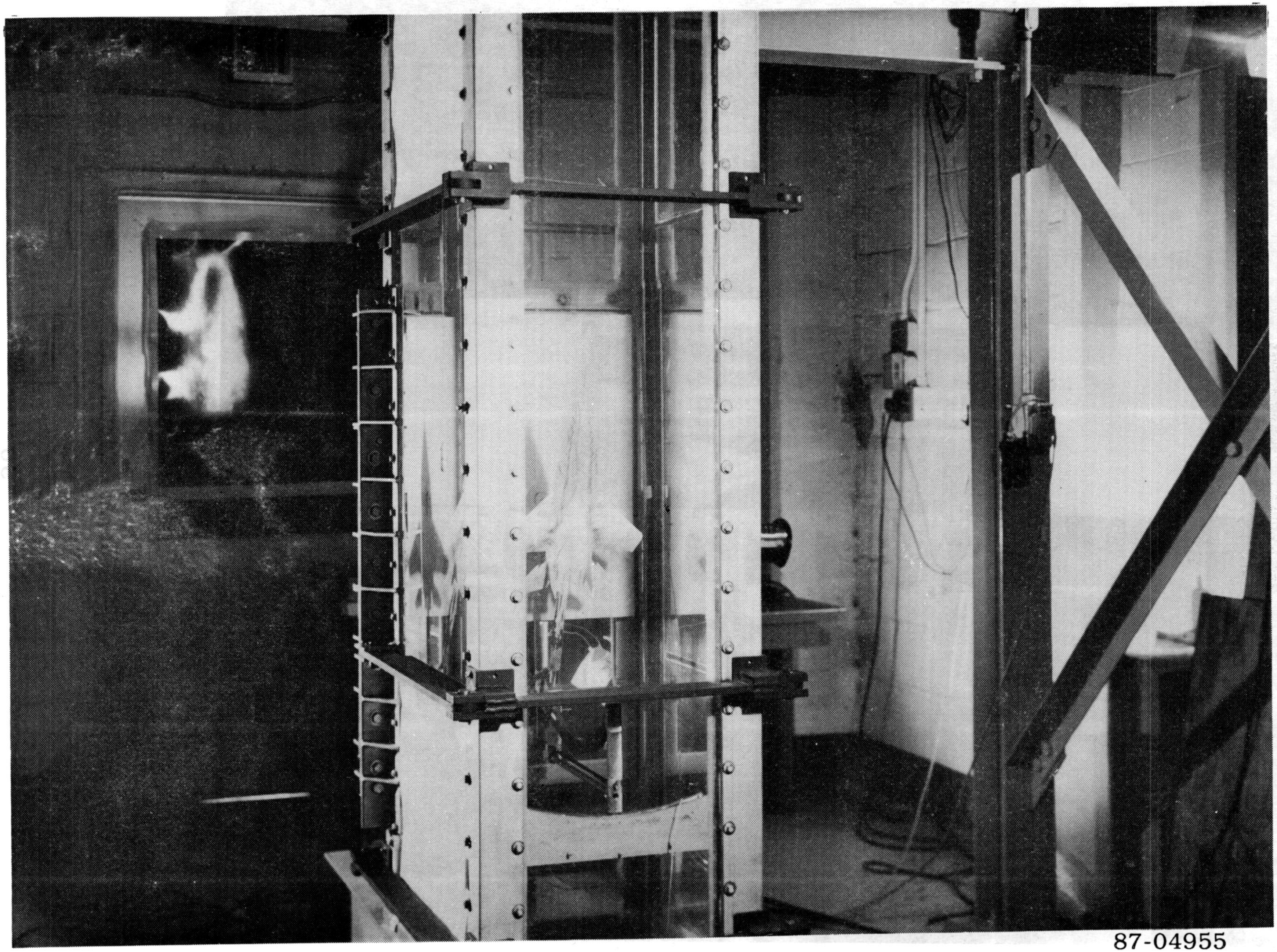
Figure 1.- Concluded.



L-87-3479

(a) Overall view of tunnel.

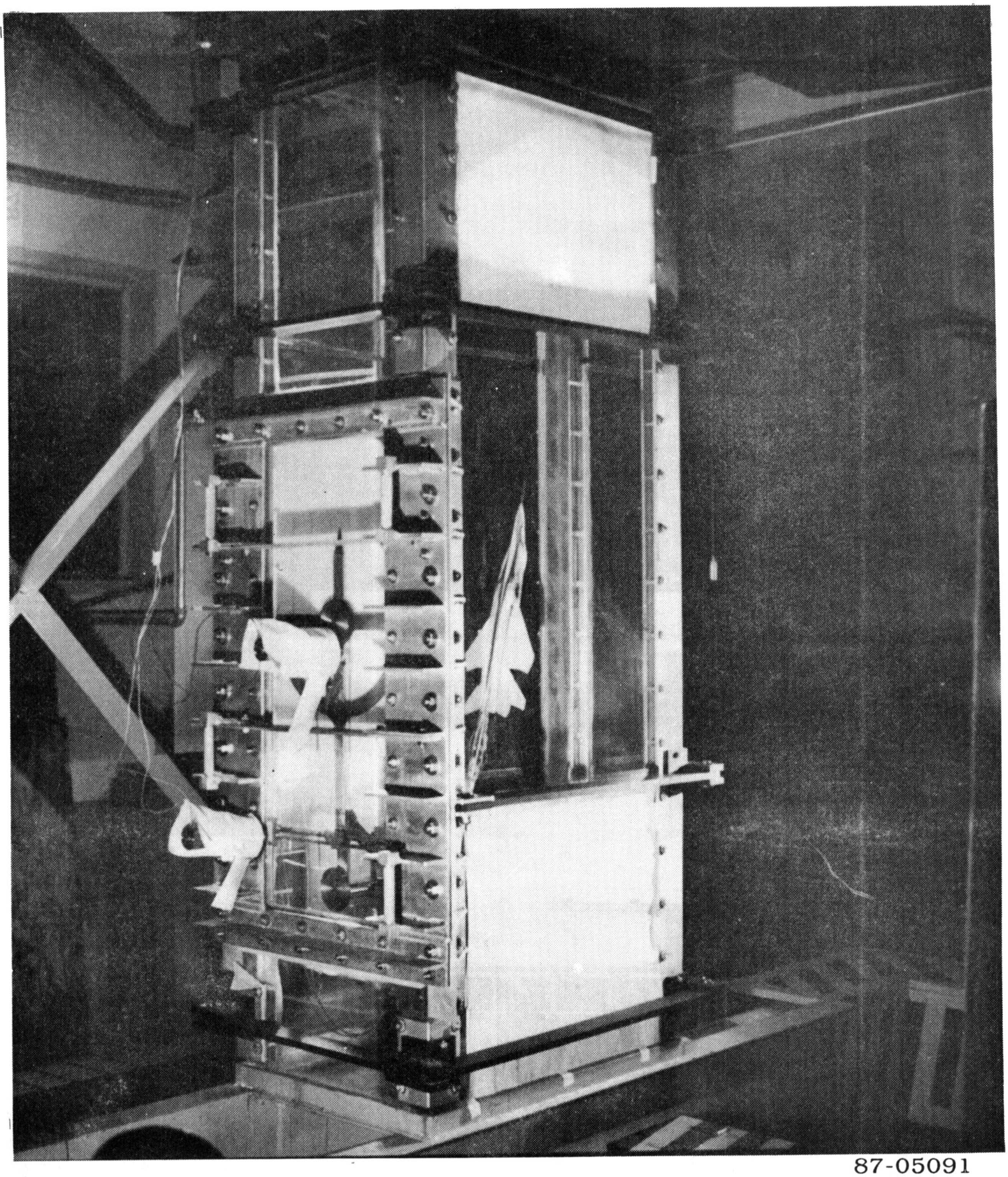
Figure 2. - Photographs of the Langley 16- By 24-Inch Water Tunnel.



87-04955

(b) Close-up view of "front face", (West wall) of test section.

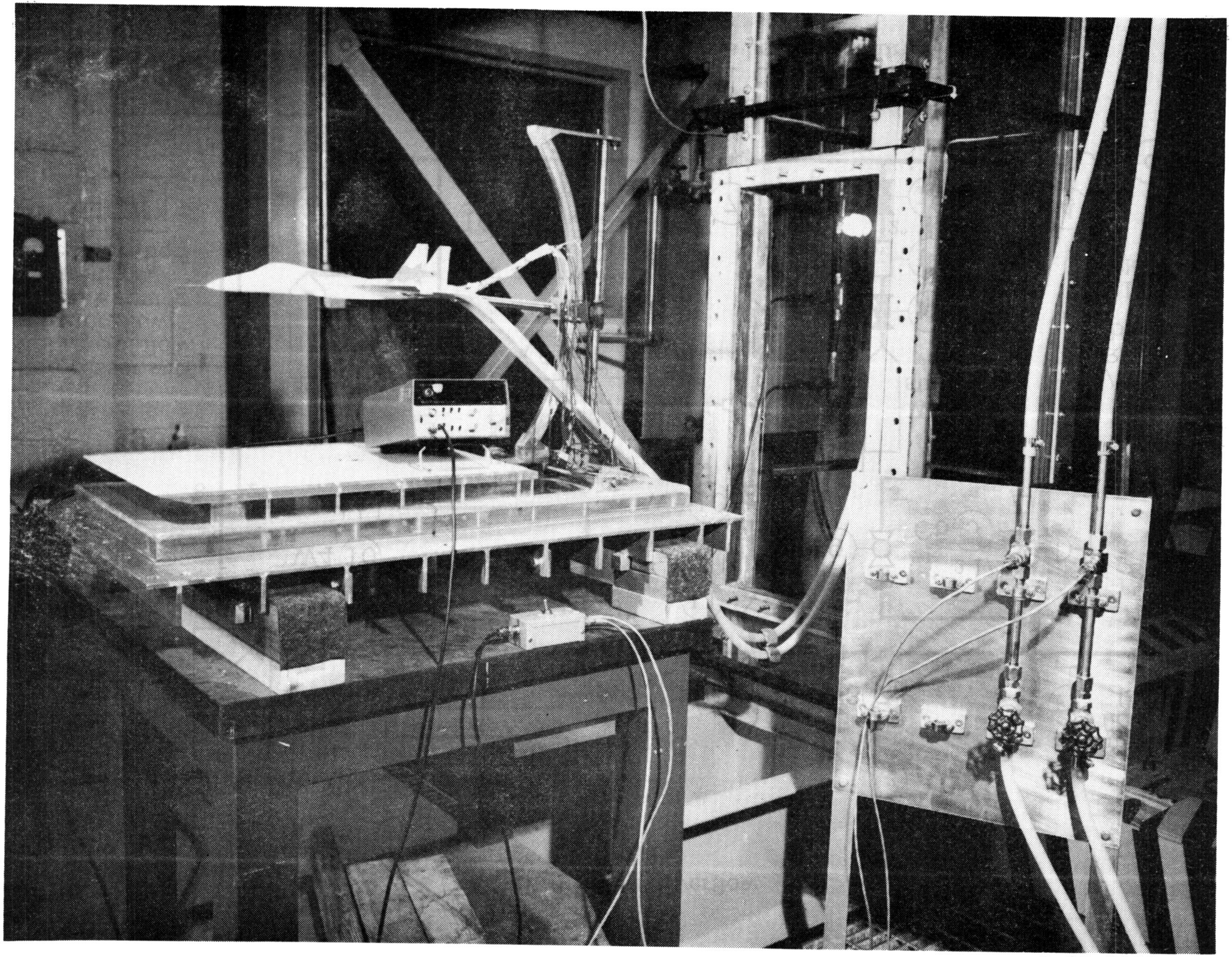
Figure 2. - Continued.



87-05091

(c) Close-up view of "rear face" (East wall) of test section.

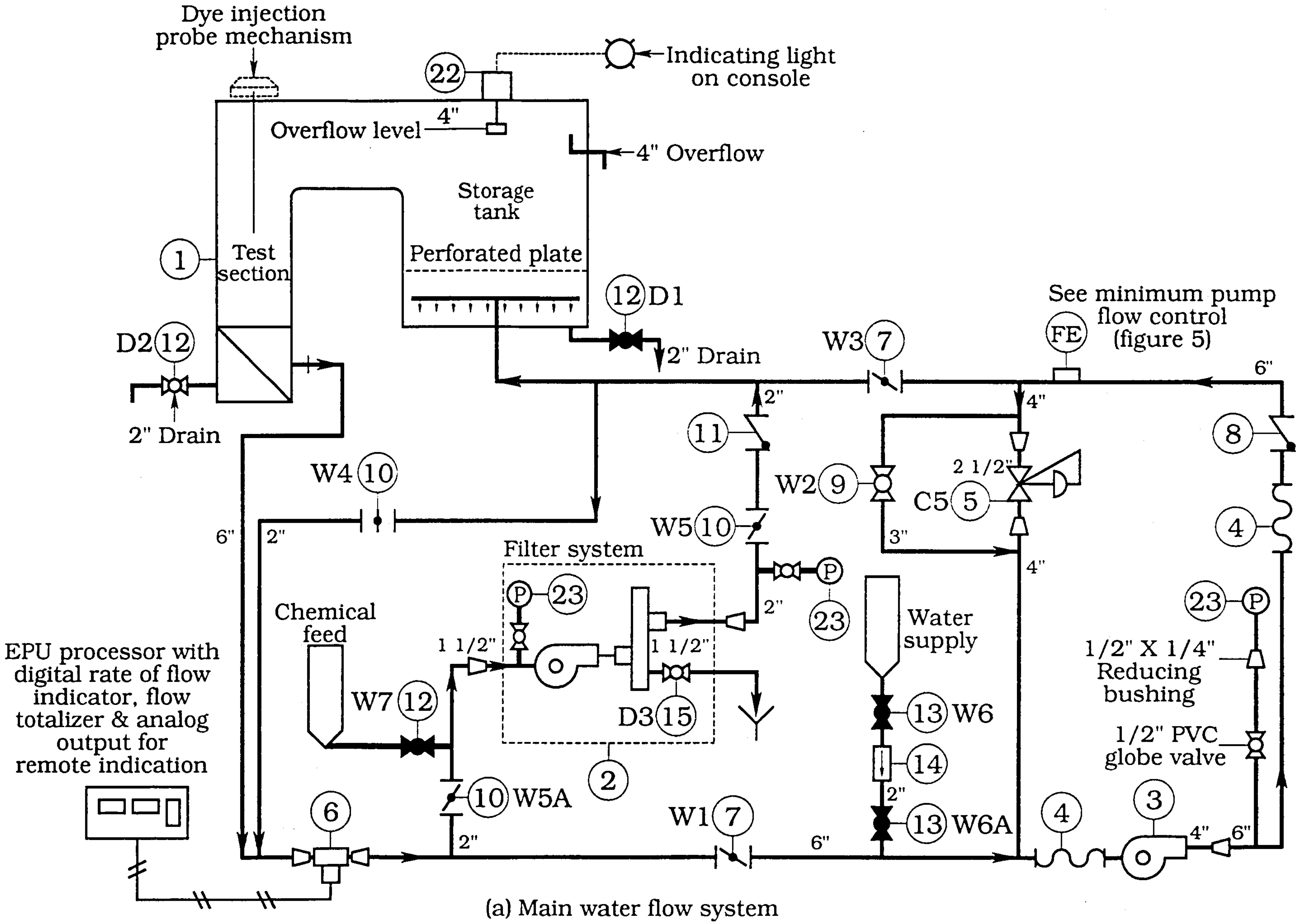
Figure 2. - Continued.



L-88-3121

(d) View showing access door removed and F-15 model installed on AOA/AOS mechanism.

Figure 2. - Concluded.



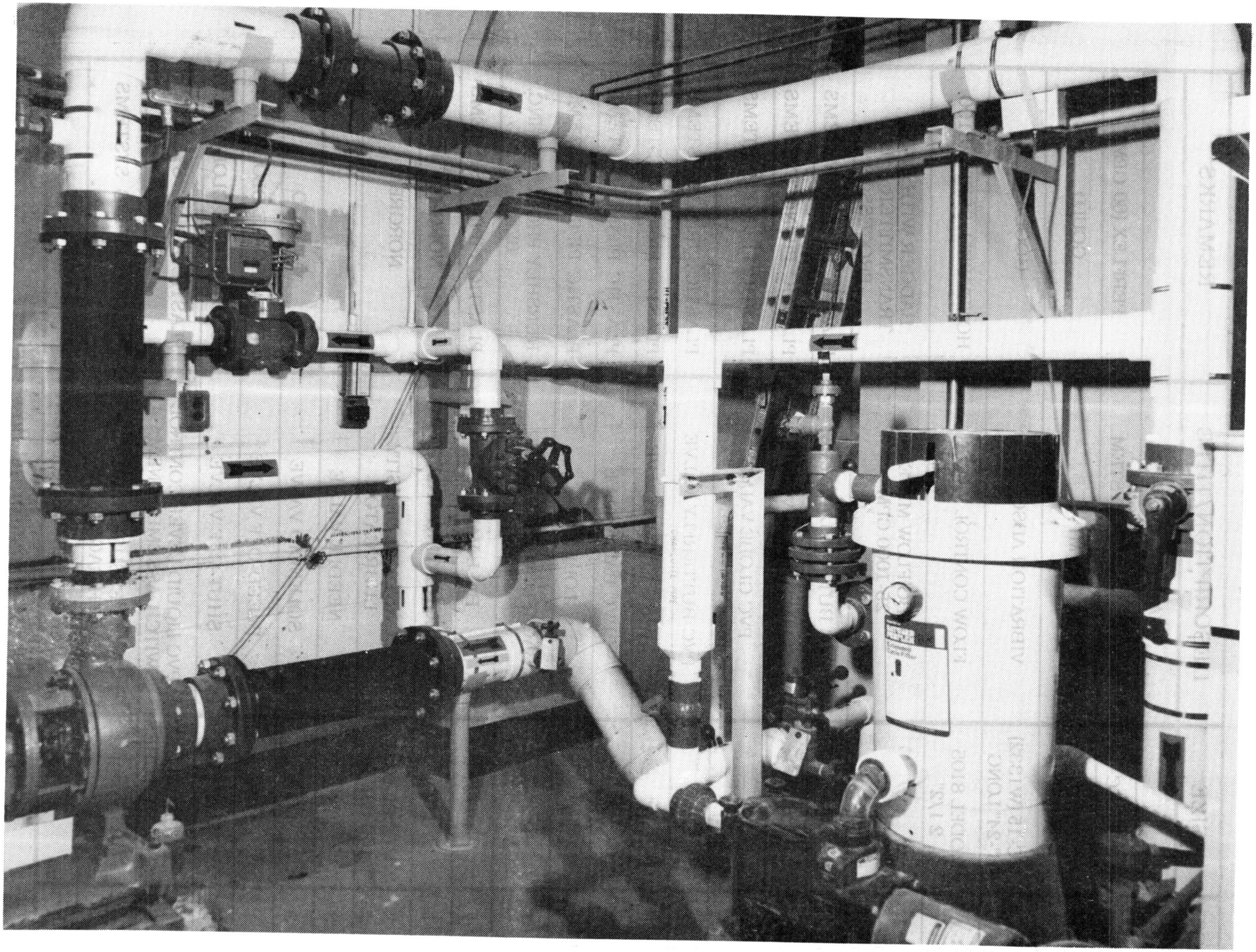
(a) Main water flow system

Figure 3.- Water tunnel flow diagram. Circled numbers refer to item number in parts list. See figure 3(b).

PARTS LIST				
ITEM	QTY	SIZE	DESCRIPTION/TITLE	REMARKS
1	1		WATER TUNNEL	
2	1	MODEL EC-65	WATER FILTER SYSTEM	PERFLEX (60 GPM)
3	1	MODEL 3196 4 X 6-10	PUMP	GOULD
4	2	VFC-15 (W1332) 6"-24" LONG	VIBRATION ABSORBER	GOODALL
5	1	MODEL 8105 2 1/2"	FLOW CONTROL VALVE	HONEYWELL SERIES 8100
6	1	4"	TURBO FLOW METER 25-1000 GPM	BADGER WITH EPT-2 TRANSMITTER & EPU PROCESSOR
7	2	6"	PVC BUTTERFLY VALVE	PLASTIC PIPING SYSTEMS
8	1	6"	SWING CHECK VALVE	PLASTIC PIPING SYSTEMS
9	1	3"	PVC GLOBE VALVE (NON-SLAM)	PLASTIC PIPING SYSTEMS
10	4	2"	PVC BUTTERFLY VALVE	PLASTIC PIPING SYSTEMS
11	1	2"	SWING CHECK VALVE	PLASTIC PIPING SYSTEMS
12	2	2"	PVC BALL VALVE	PLASTIC PIPING SYSTEMS
13	2	2"	GLOBE VALVE	PLASTIC PIPING SYSTEMS
14	1	2"	BACKFLOW PREVENTER	HERSHEY PRODUCTS, INC. BEECO
15	1	1 1/2"	BALL VALVE	PLASTIC PIPING SYSTEMS
16	1	1/2"	REGULATING VALVE	NORGREN
17	3	MODEL L02-400-03L-AU	CONSTANT DENSITY LUBRICATOR	NORGREN
18	3	1/4"	NEEDLE VALVE	
19	3	1/4"	SOLENOID VALVE	ASCO
20	1	1/2"	BLEED-OFF VALVE	125 LB. BRONZE GLOBE VALVE
21	2	1/2"	SHUT-OFF VALVE	125 LB. BRONZE GLOBE VALVE
22	1	2 NORMALLY OPEN SWITCHES	PVC LIQUID LEVEL CONTROL SWITCH ASSEMBLY NEMA 4	PLASTIC PIPING SYSTEMS
23	4	0-100 PSI	PRESSURE GAGE WITH GAGE GUARD	PLASTIC PIPING SYSTEMS
24	1		A0A MECHANISM EQUIPMENT	

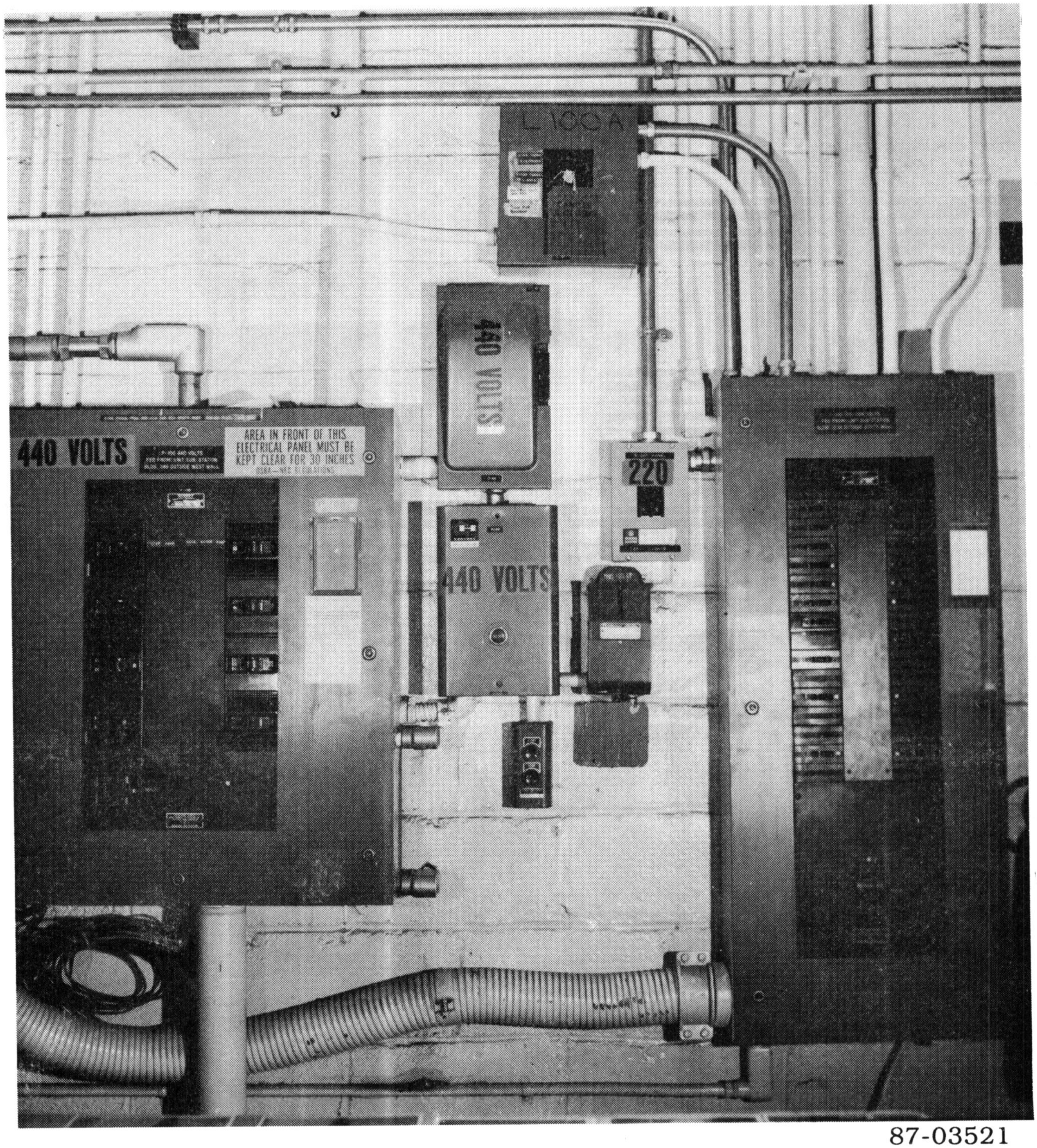
(b) Parts list for water tunnel flow system.

Figure 3.- Concluded.


87-03474

(a) Main water flow pump and piping.

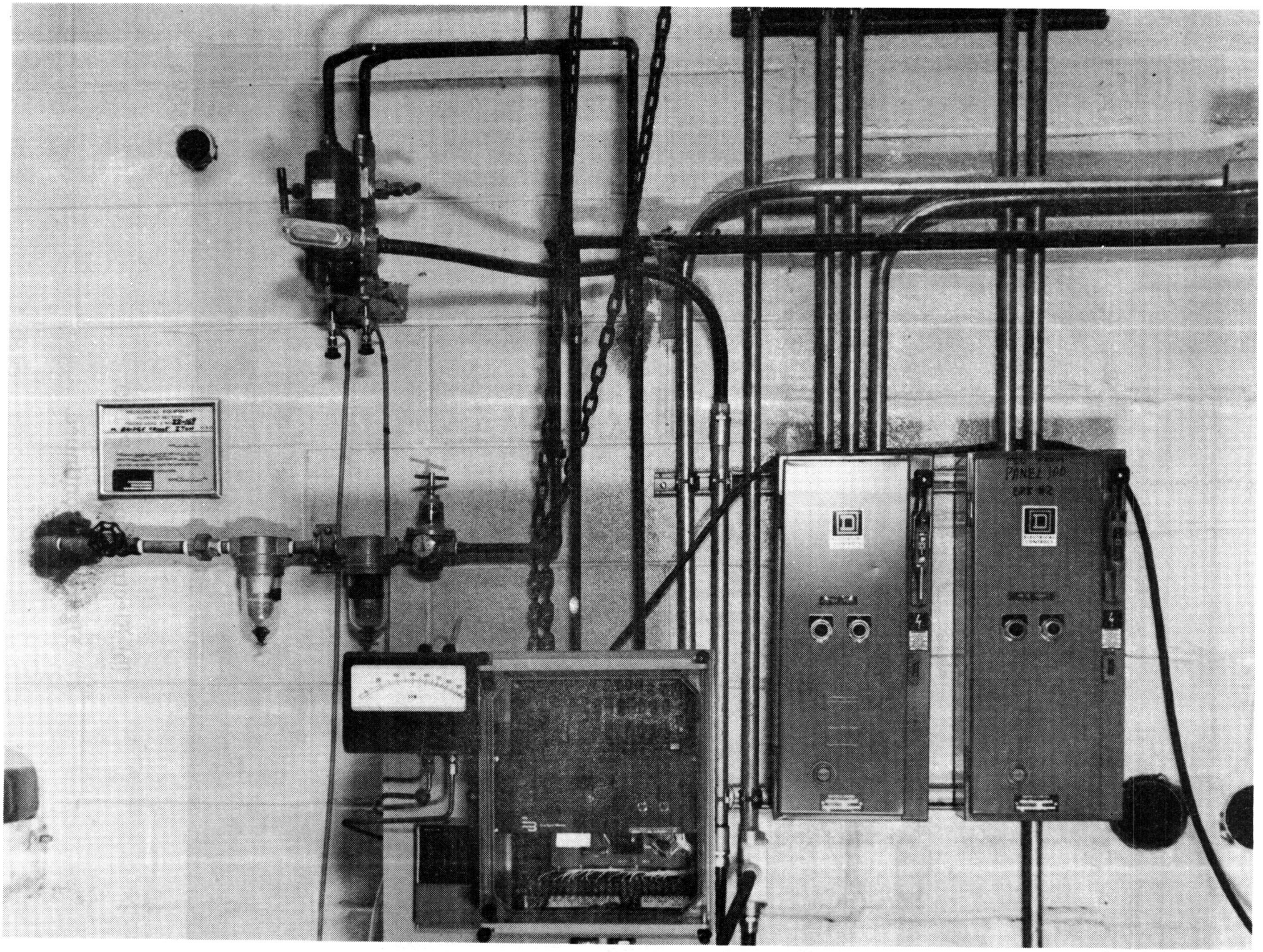
Figure 4. - Photographs of the main water flow pump equipment.



87-03521

(b) Electrical panel P-100.

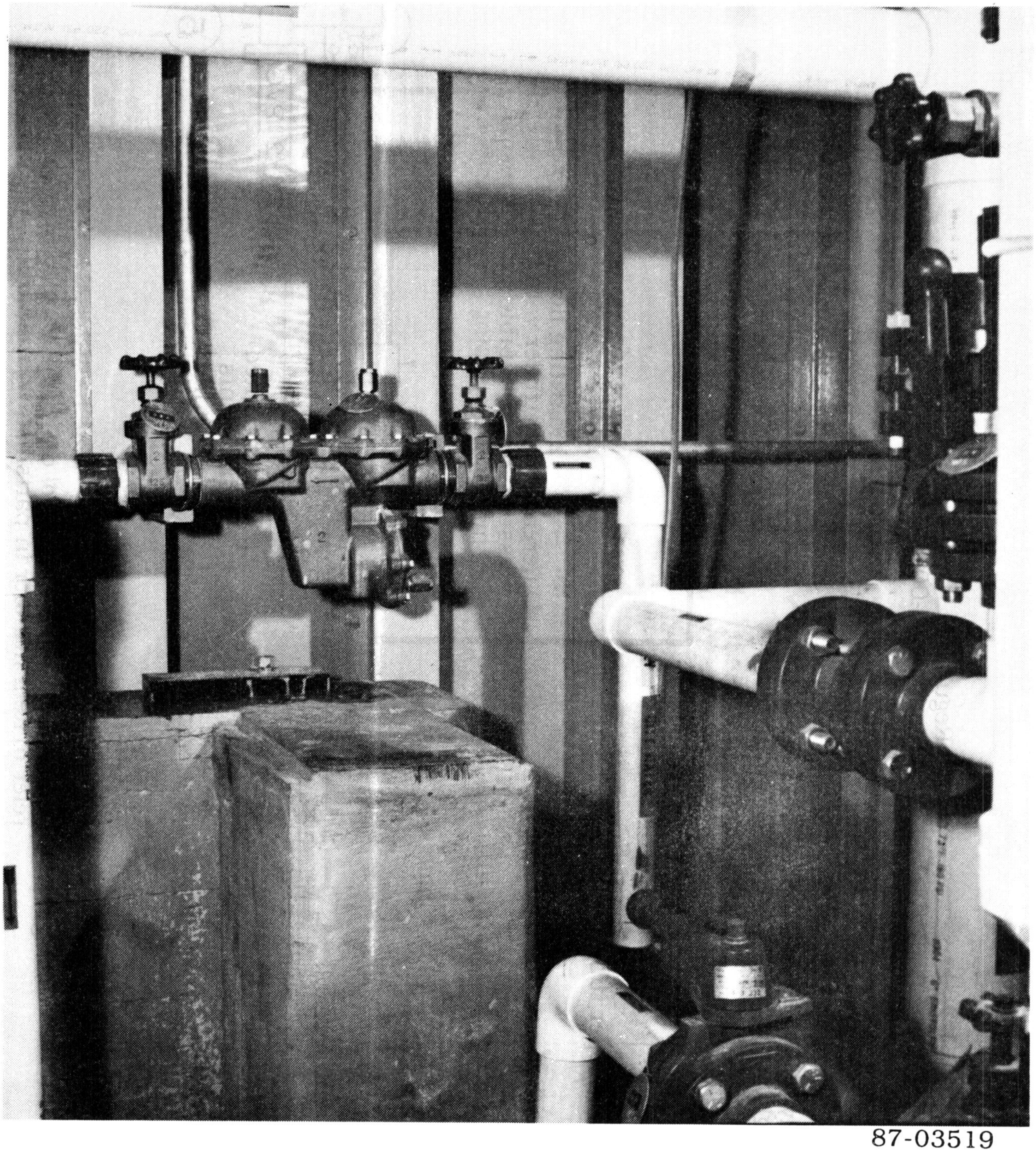
Figure 4. - Continued.



87-03472

(c) Minimum flow meter, and controller; and, Badger test section flow processor.

Figure 4. - Continued.


87-03519

(d) 2 inch main water supply line incorporating back flow preventer ⑭ on figure 3(a), and shut-off valves W6 and W6A.

Figure 4. - Concluded.

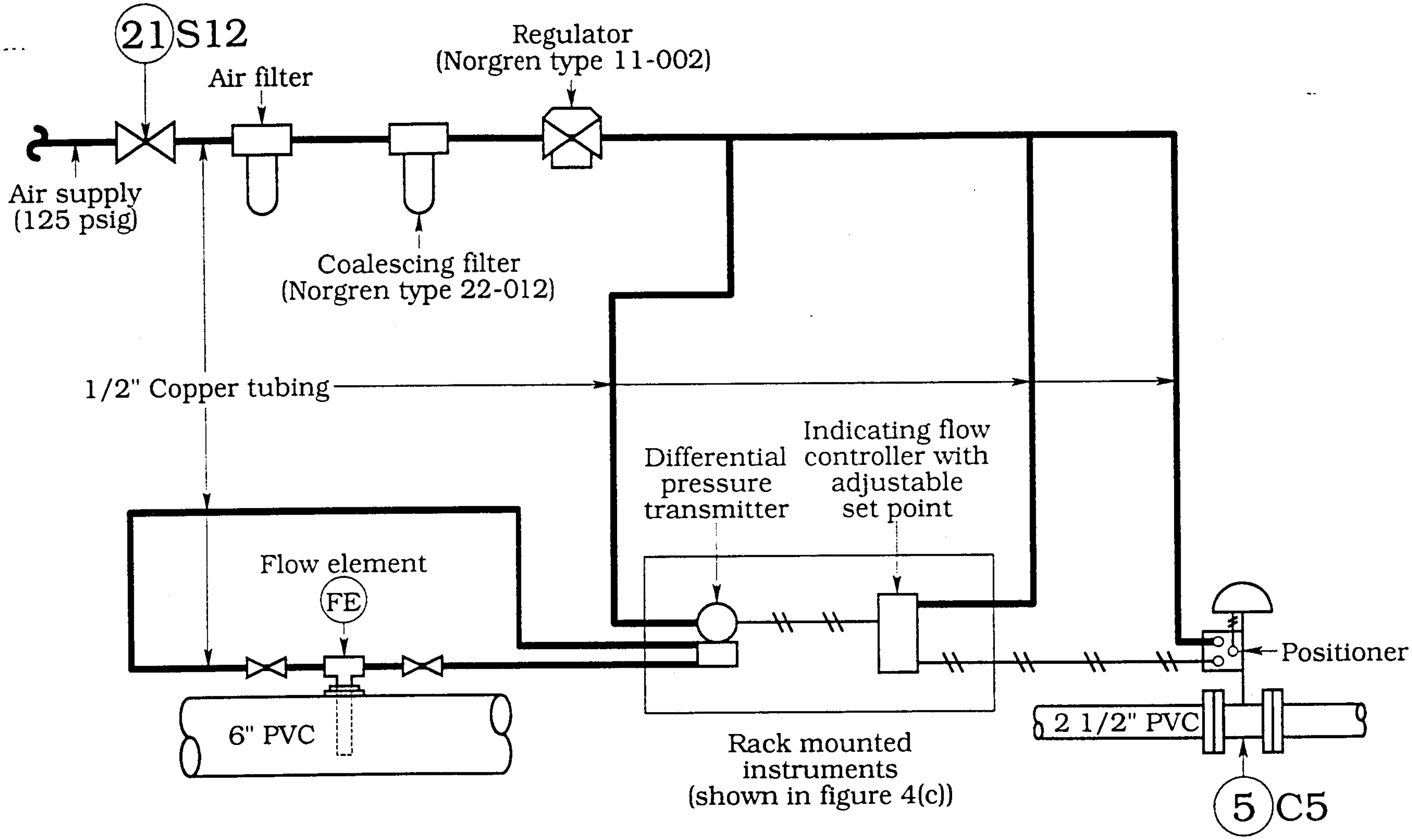
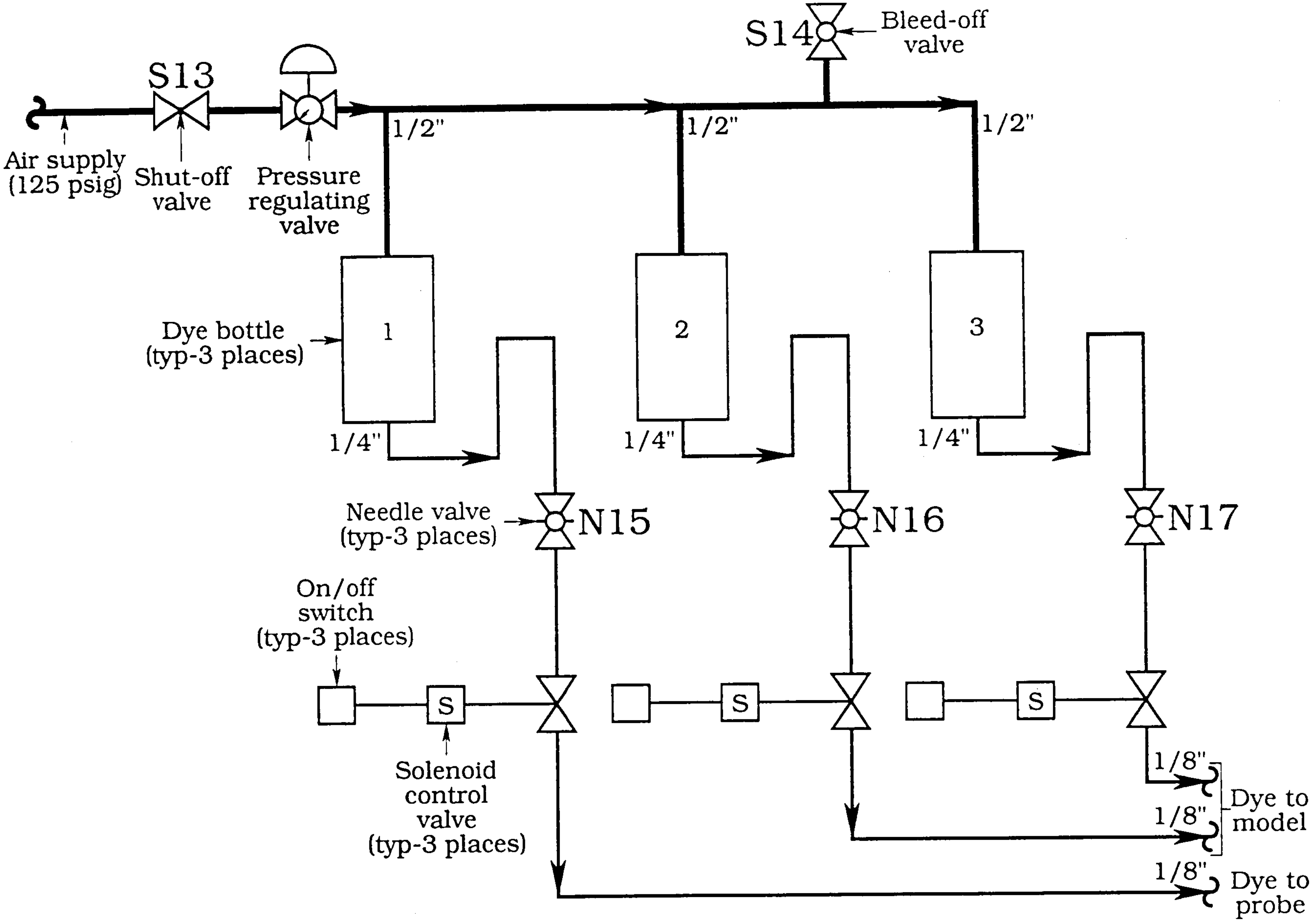
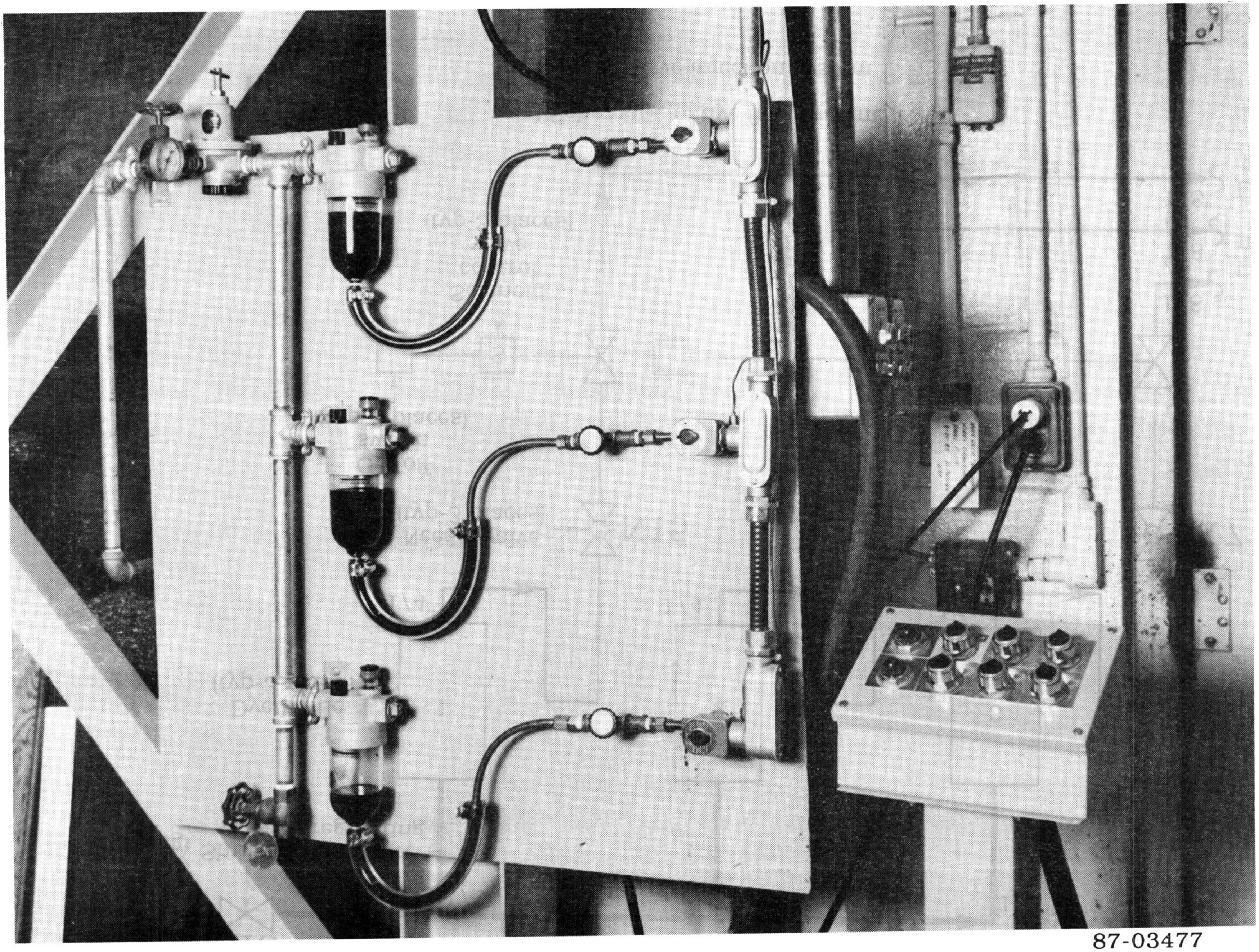


Figure 5.- Minimum pump flow control diagram. Circled numbers refer to item number in parts list, figure 3(b).



(a) Schematic of dye flow system

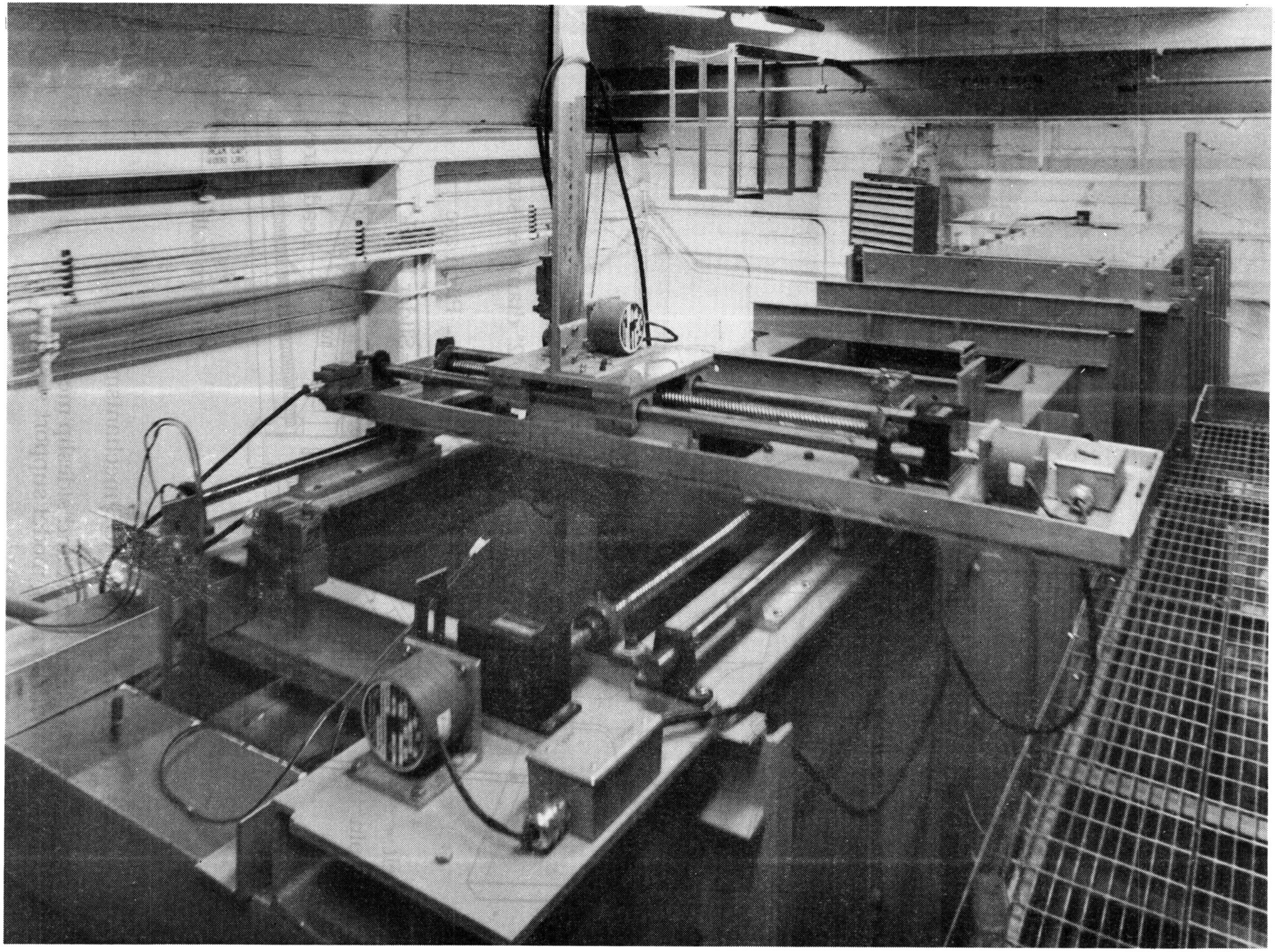
Figure 6.- Dye injection system



87-03477

(b) Photograph of dye reservoirs and dye flow/traversing probe control console.

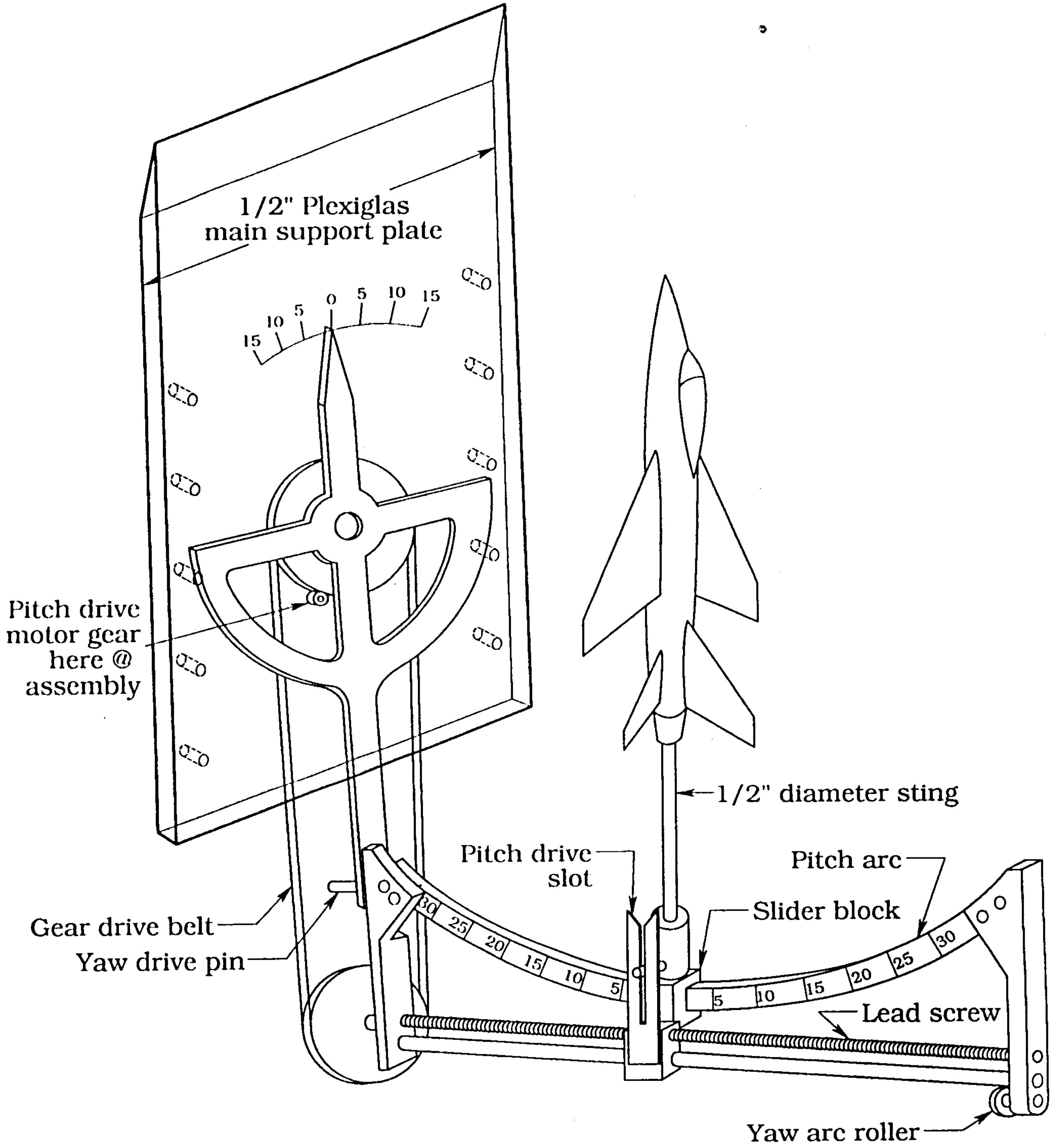
Figure 6. - Continued.



87-03480

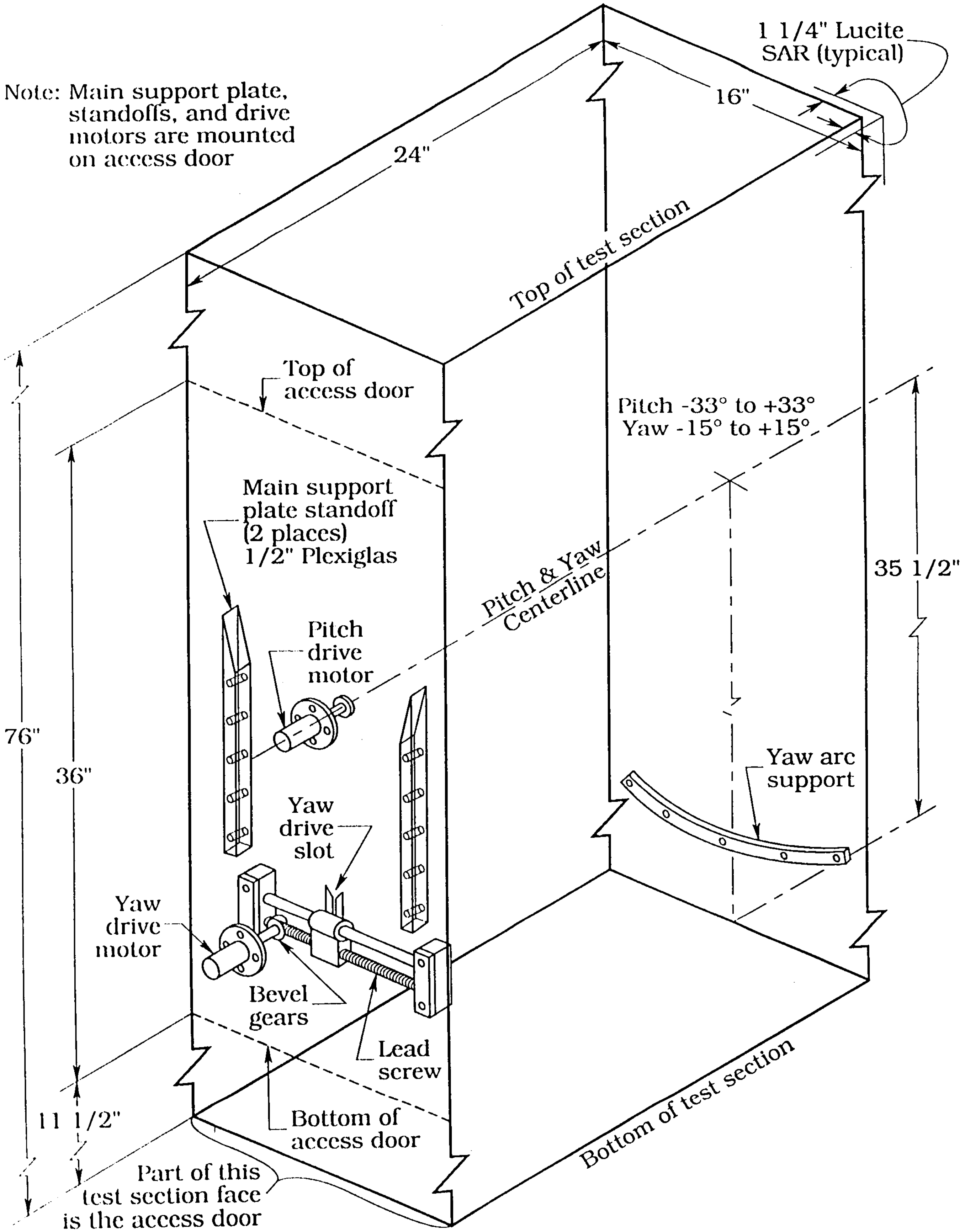
(c) Remote controlled actuator system for overhead probe.

Figure 6. - Concluded.



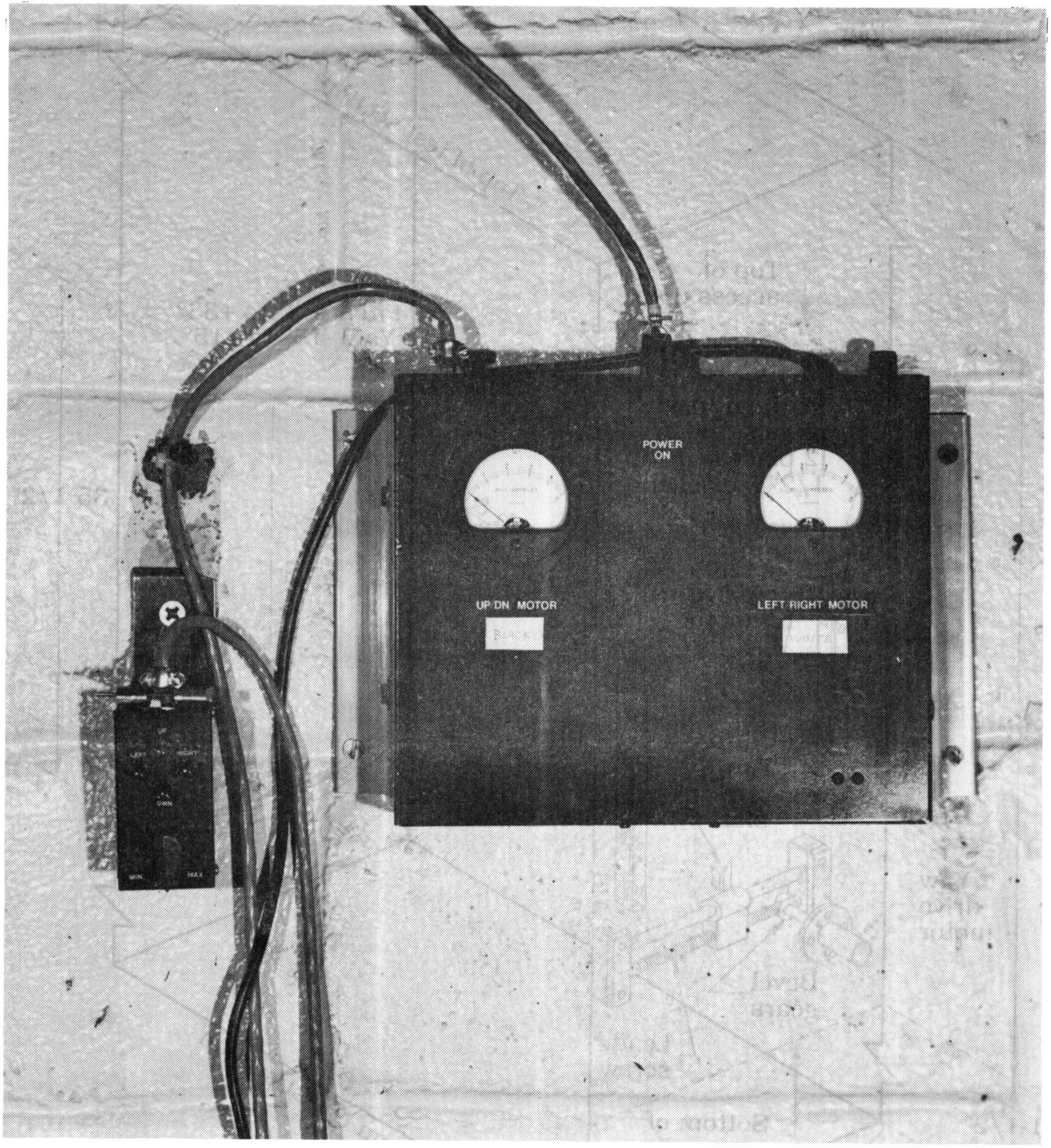
(a) Sketch of AOA/AOS mechanism

Figure 7.- Angle-of attack and sideslip mechanism, incorporating model support system.



(b) View of test section showing AOA/access door interconnections

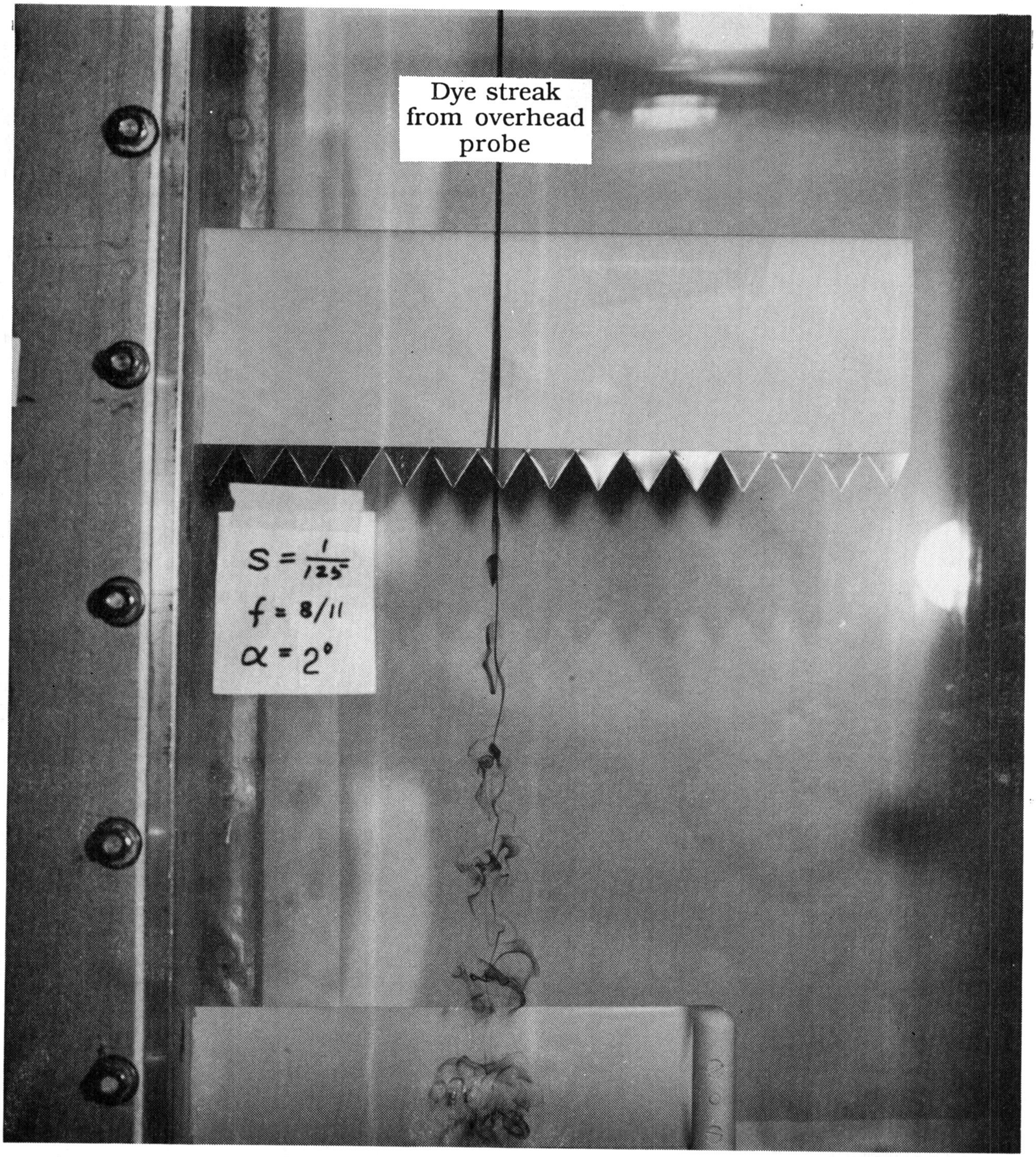
Figure 7. - Continued.



87-03522

(c) Photograph of hand-held AOA/AOS controller, and power supply, located on South wall of Room 100, Bldg. 1234.

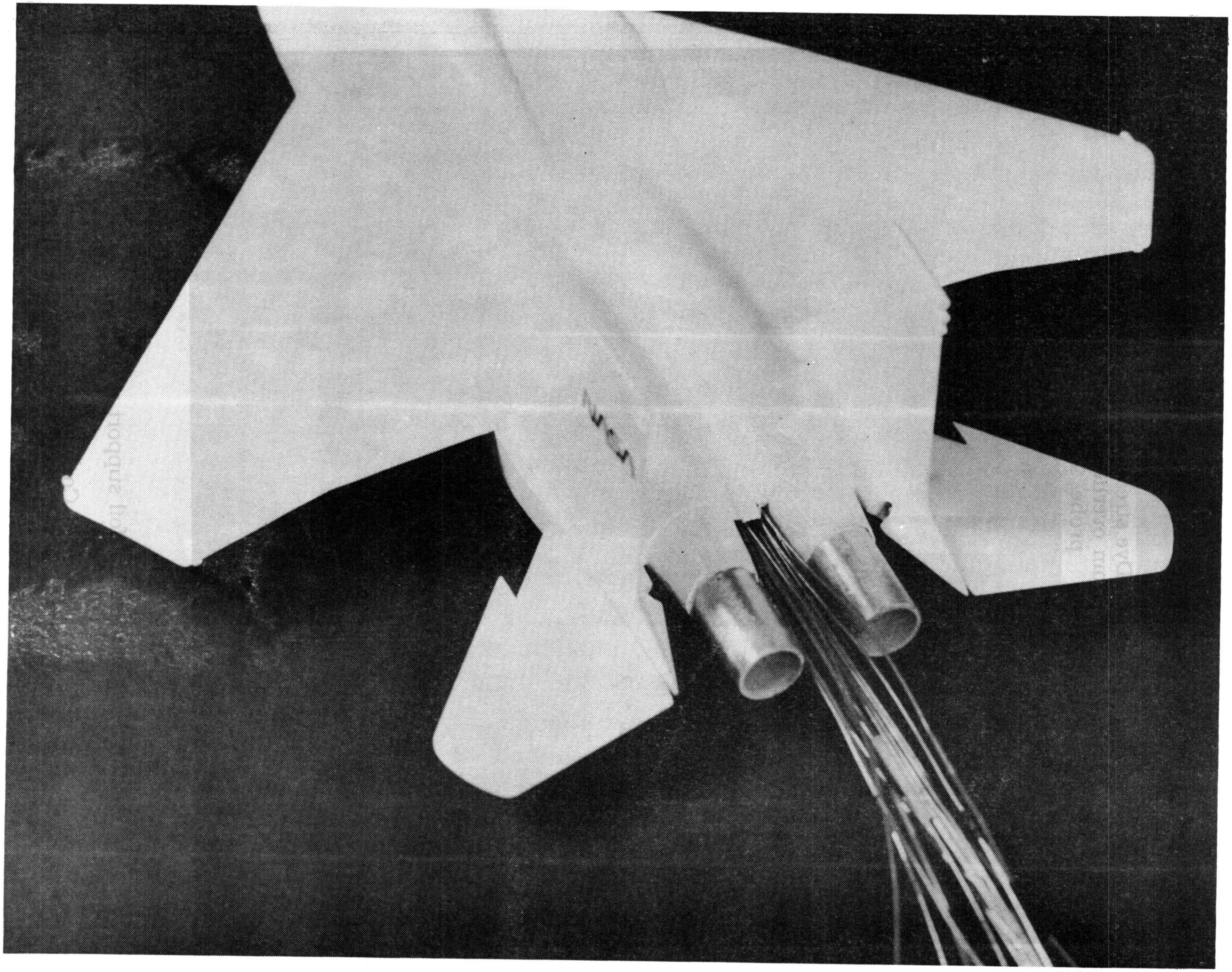
Figure 7. - Continued.



87-03387

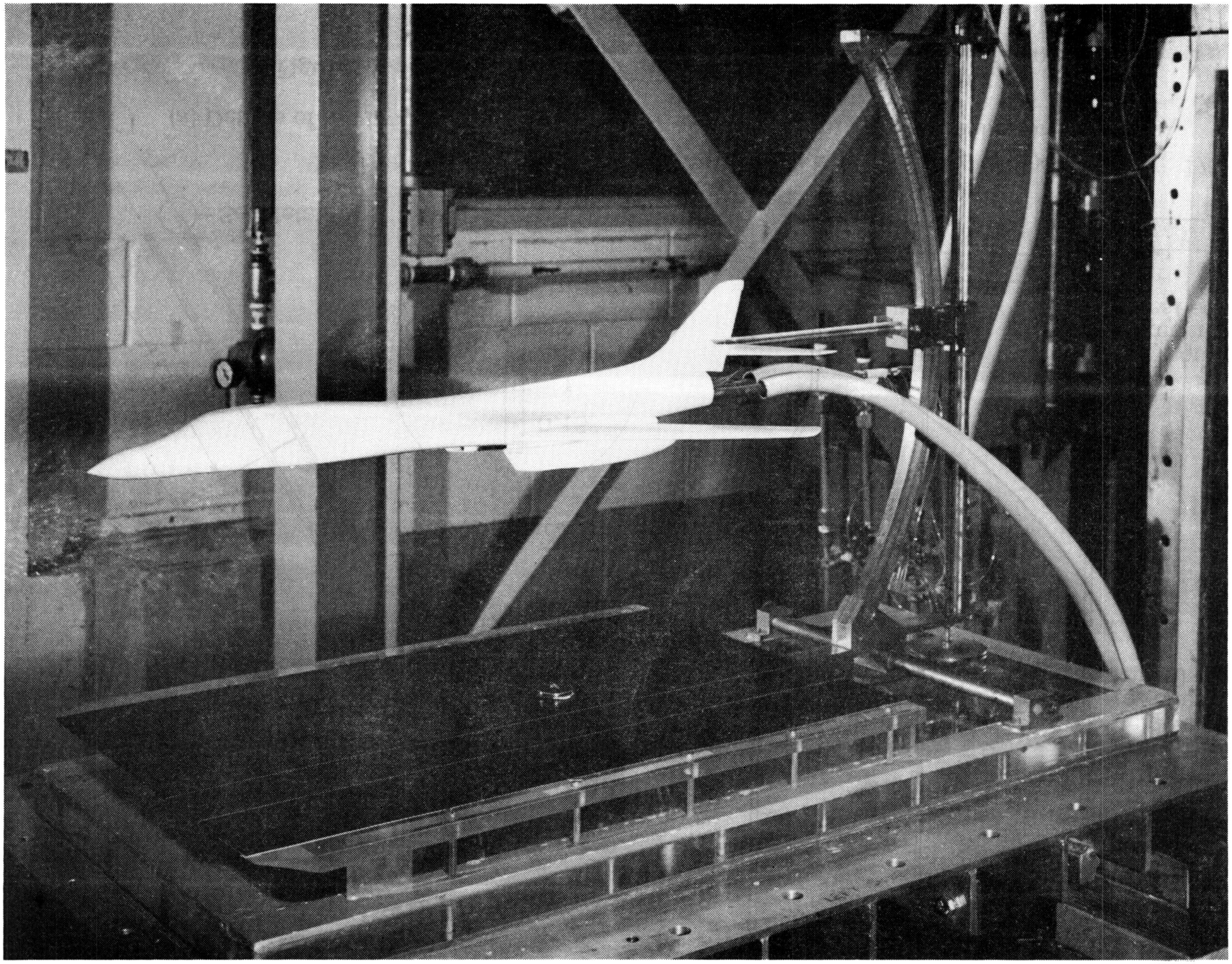
(d) Sting-mounted airfoil support plate assembly.

Figure 7. - Concluded.



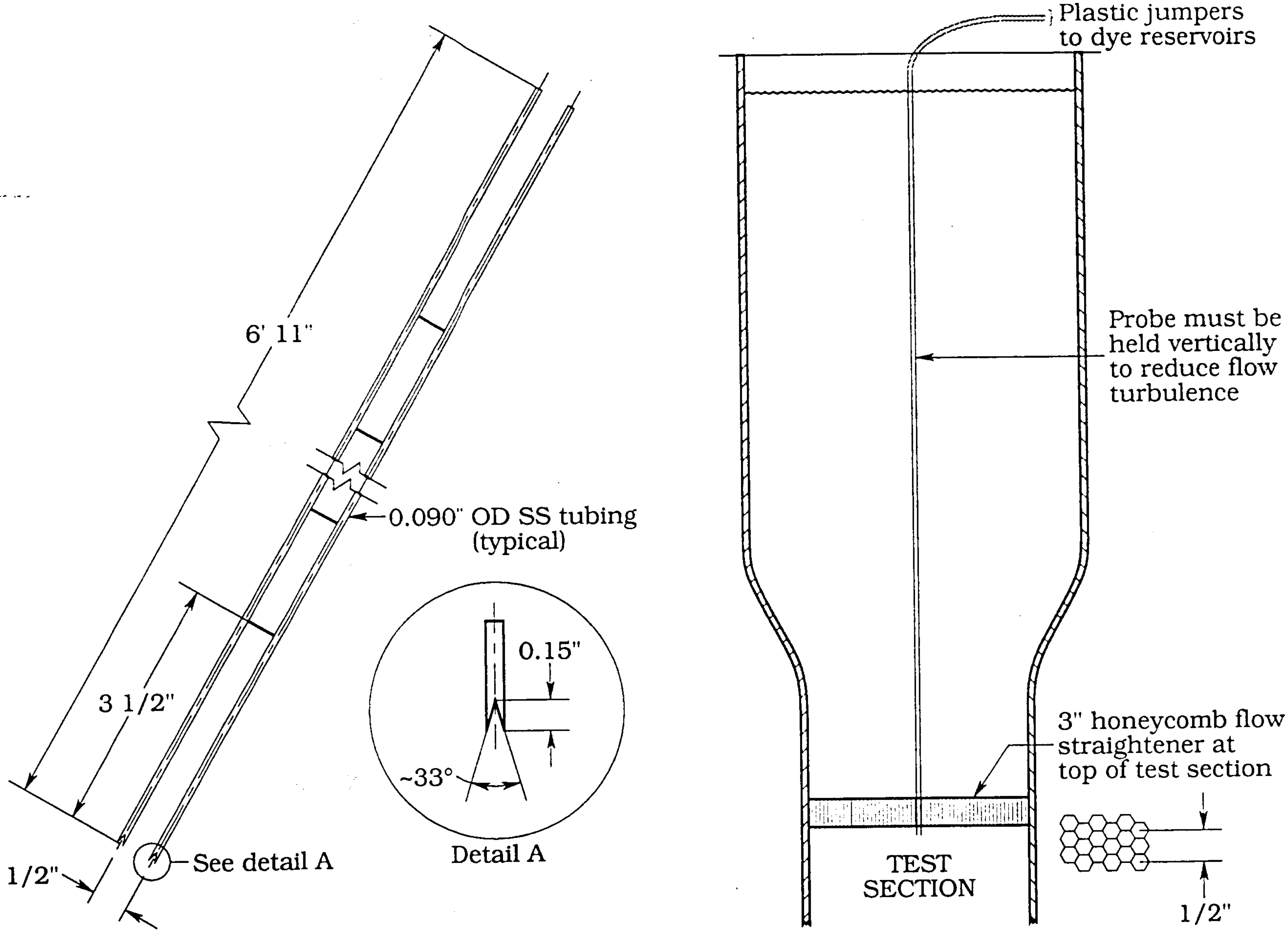
ECN 24138

Figure 8. - Photograph of 1/48 scale F-15 model showing inlet flow discharge tubes and dye orifice tubes.



L-88-8990

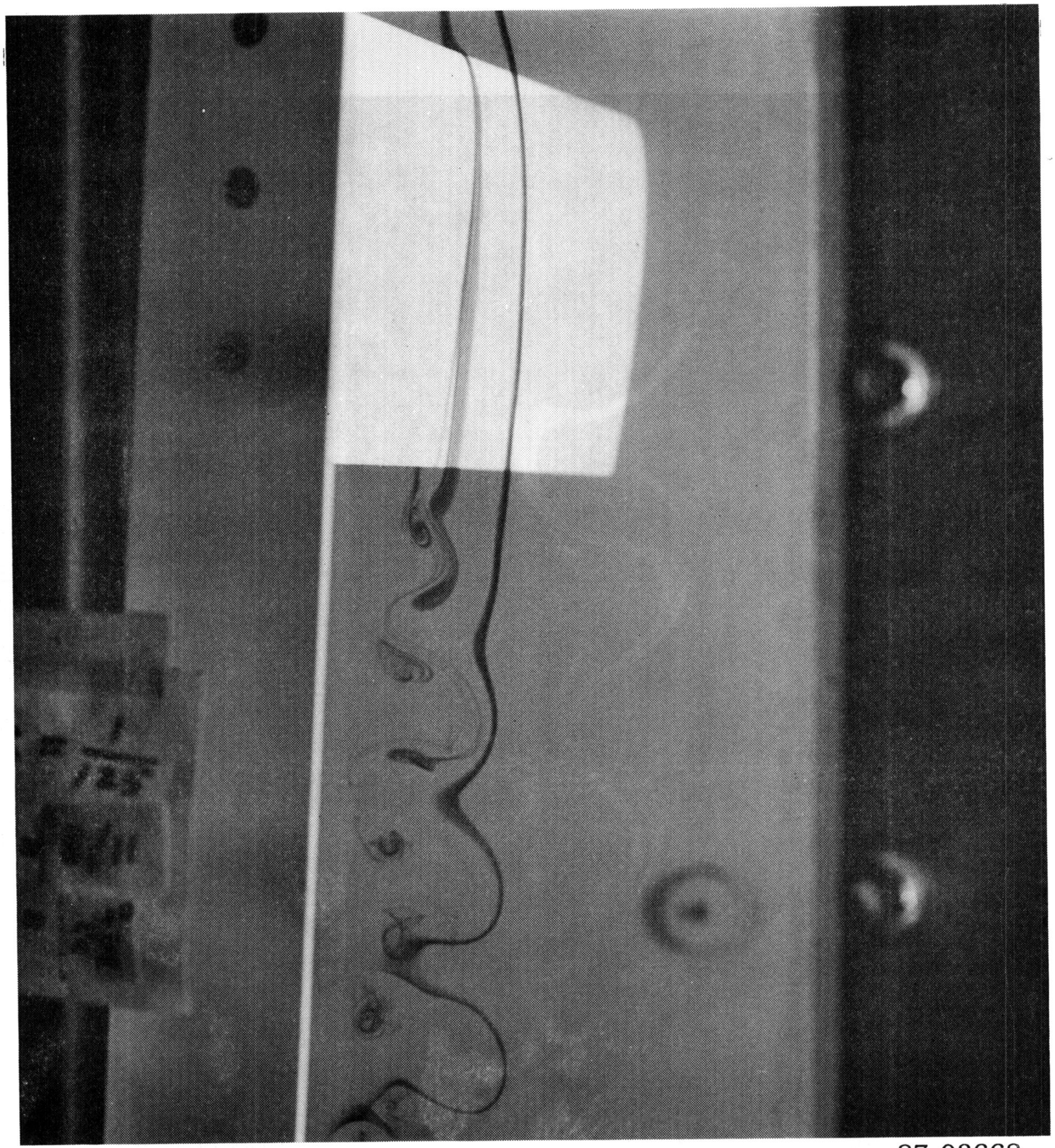
Figure 9. - Photograph of 1/72 scale B-1B model modified to simulate two exhaust nozzle flows in left hand nacelle with faired over inlets.



(a) Details of the twin probe

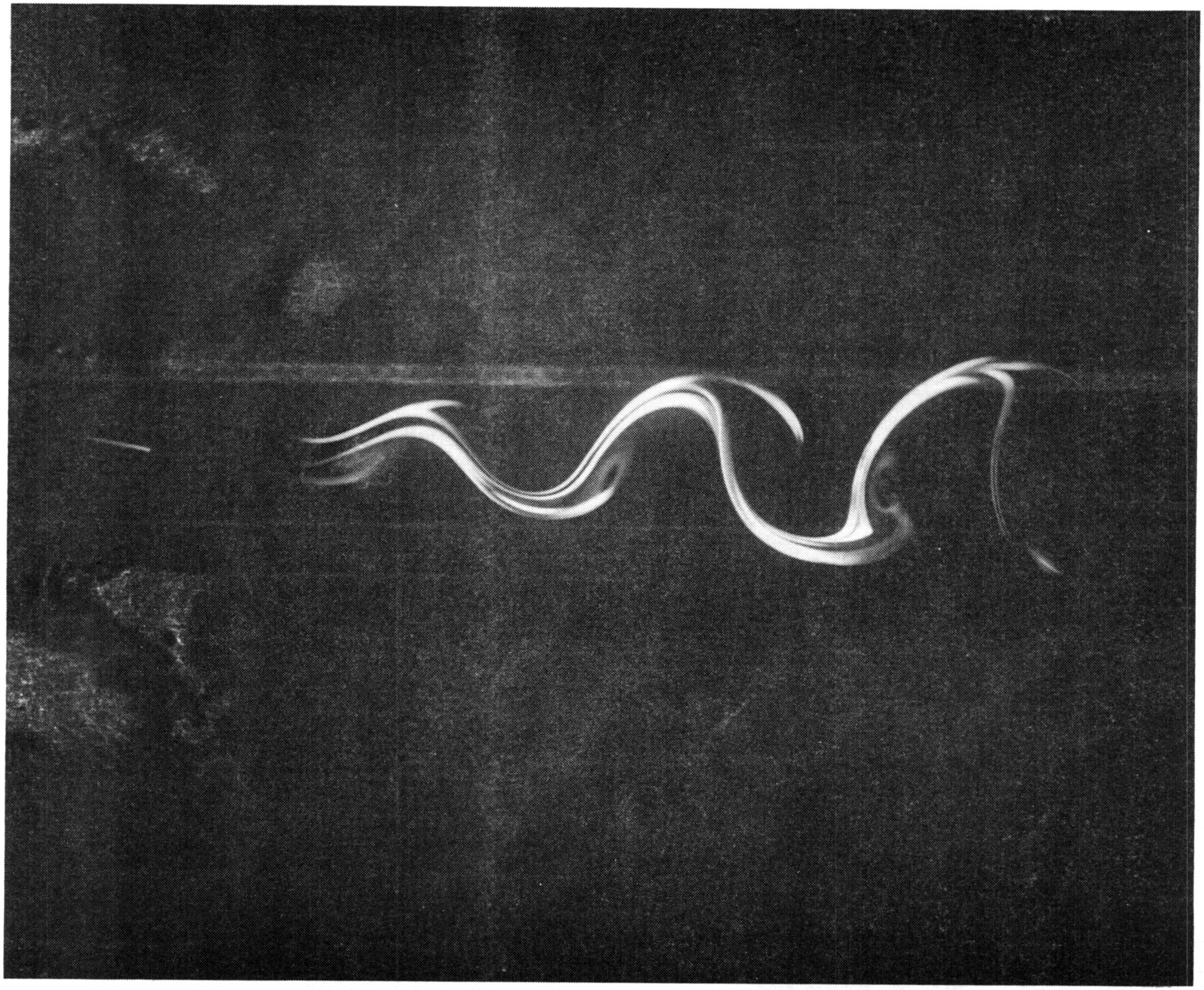
(b) Probe installation

Figure 10.- Sketches of the twin probe fixture used in conjuction with the flow straightener at the top of the test section.



87-03668

Figure 11. - Photograph of the flow over an airfoil with Gurney flap, visualized using an overhead, twin-probe fixture.



87-10952

Figure 12. - Laminar wake behind a wing at low Reynolds number, visualized using a laser light sheet.

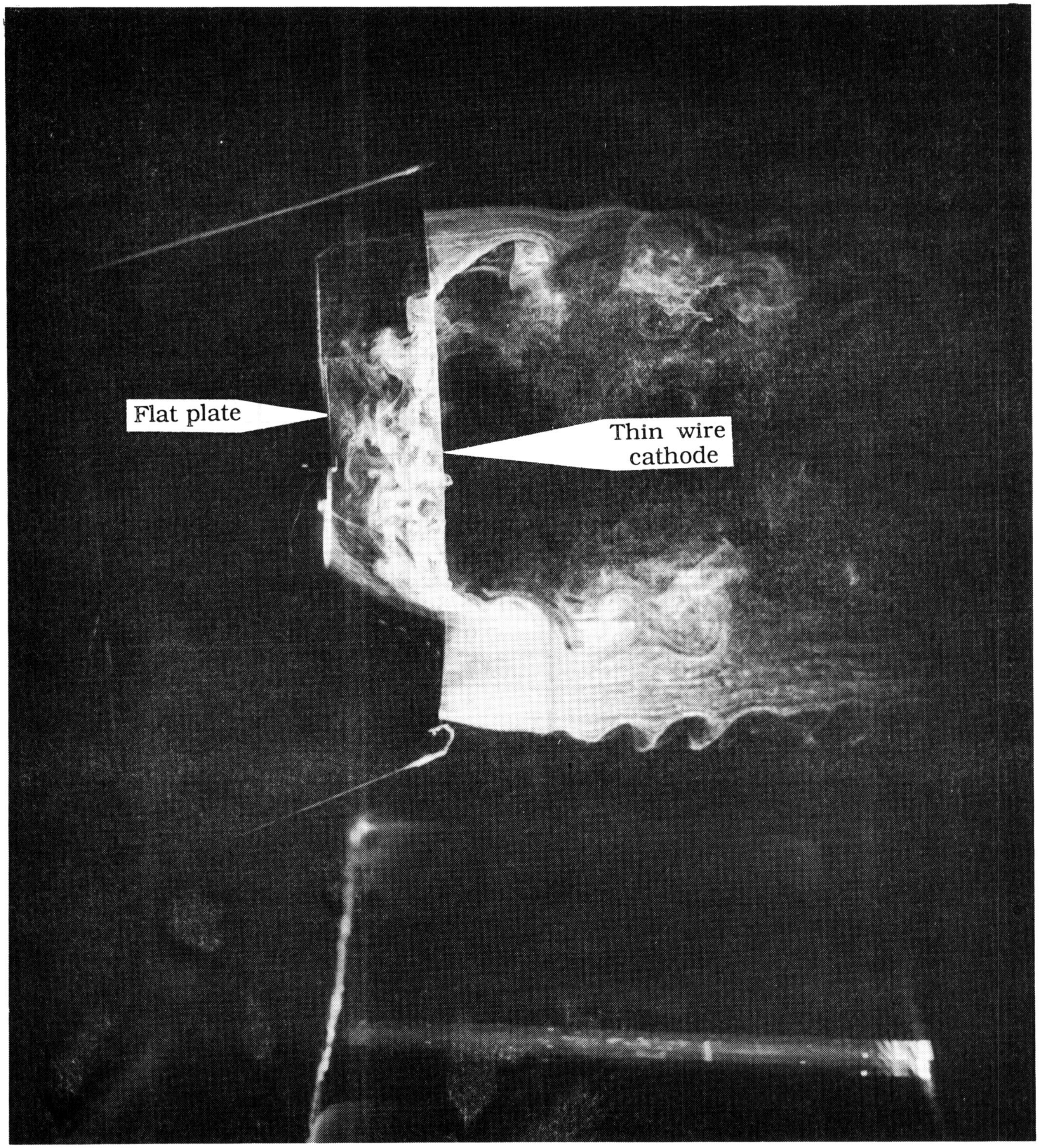
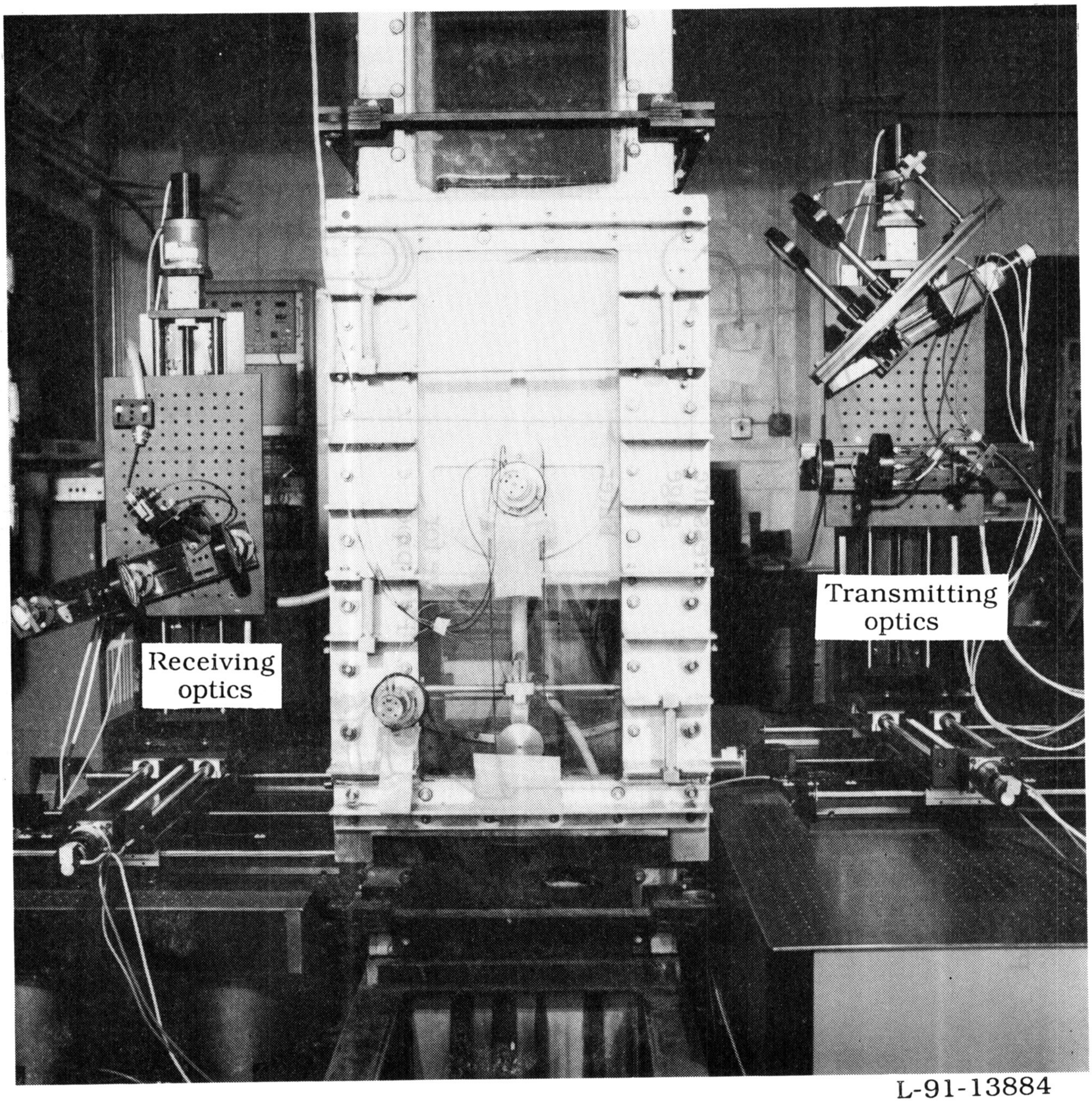


Figure 13. - Hydrogen bubble flow visualization technique used to show flow behind a flat plate.

HASSELBLAD FOCUSING DISTANCES WITH CLOSE UP LENSES					
Basic Lens	Focal length of added close up lenses (m)	Distances (inches)		Magnification	
		Near	Far	Near	Far
80 mm	+0.5	17 1/4	24 3/4	0.28	0.16
80 mm	+1.0	22 1/4	44	0.20	0.08
80 mm	+2.0	27 1/4	84	0.16	0.04
80 mm	+0.5, +1.0	14 1/2	18 3/16	0.38	0.25
80 mm	+0.5, +2.0	16	21	0.33	0.20
80 mm	+1.0, +2.0	19 1/2"	31 1/8	0.24	0.12
80 mm	+0.5, +1.0, +2.0	13 7/8"	16 5/8	0.40	0.28
150 mm	+0.5	21 5/8	26 1/4	0.49	0.30
150 mm	+1.0	29	45	0.31	0.15
150 mm	+2.0	37	80	0.23	0.075
150 mm	+0.5, +1.0	18	20 1/8	0.68	0.48
150 mm	+0.5, +2.0	19 13/16	22 5/8	0.59	0.38
150 mm	+1.0, +2.0	24 5/8	32 7/8	0.41	0.24
150 mm	+0.5, +1.0, +2.0	17	18 3/8	0.77	0.54

Note: It is suggested that, when combining close up lenses, the most powerful lens (i.e., shortest focal length) be placed nearest the camera lens for best picture quality.

Figure 14.- Focus distances and magnification factors for the 80 mm and 150 mm lenses.



L-91-13884

Figure 15. - Laser fluoresence anemometer installed at the Langley 16- By 24-Inch Water Tunnel.

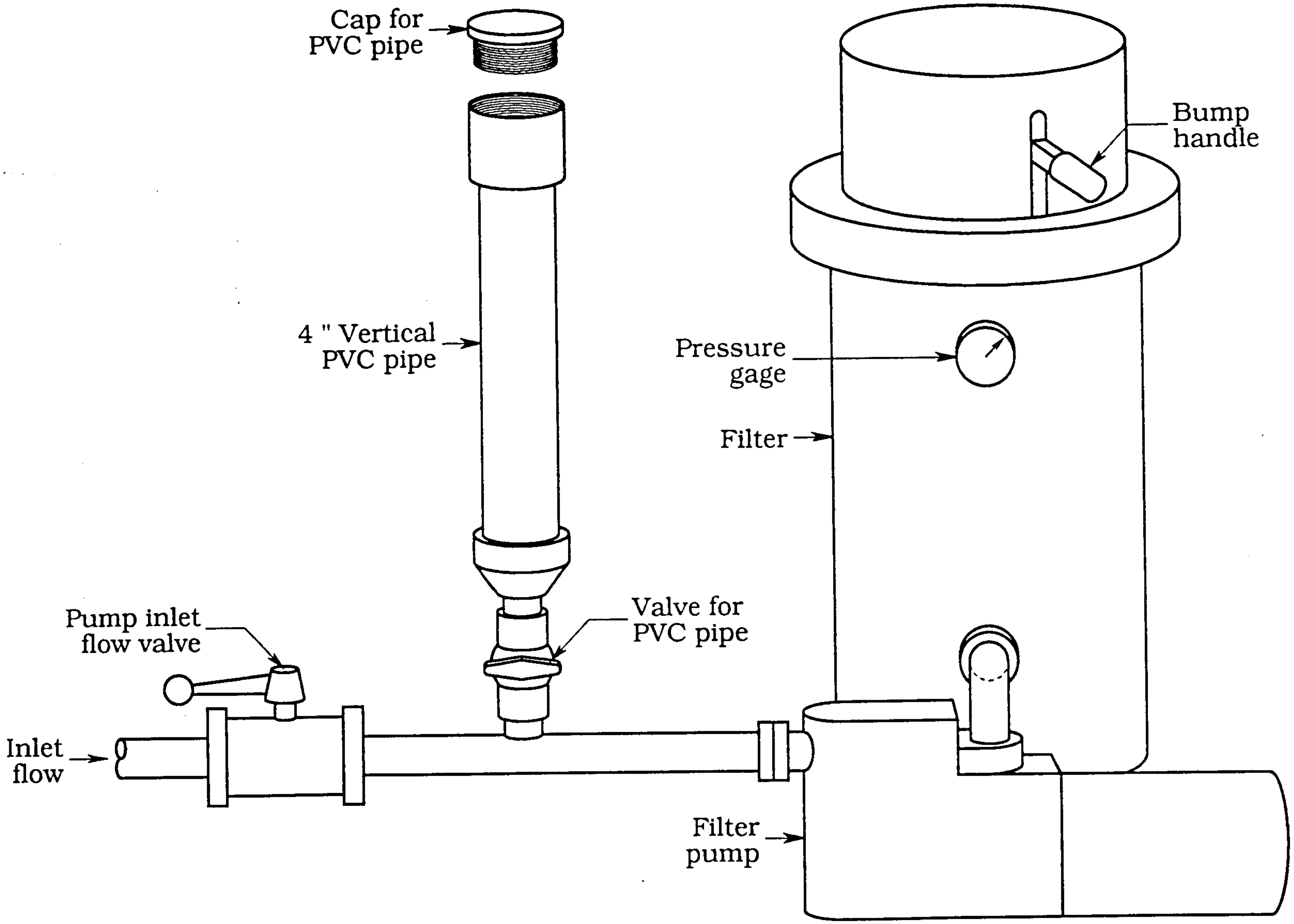
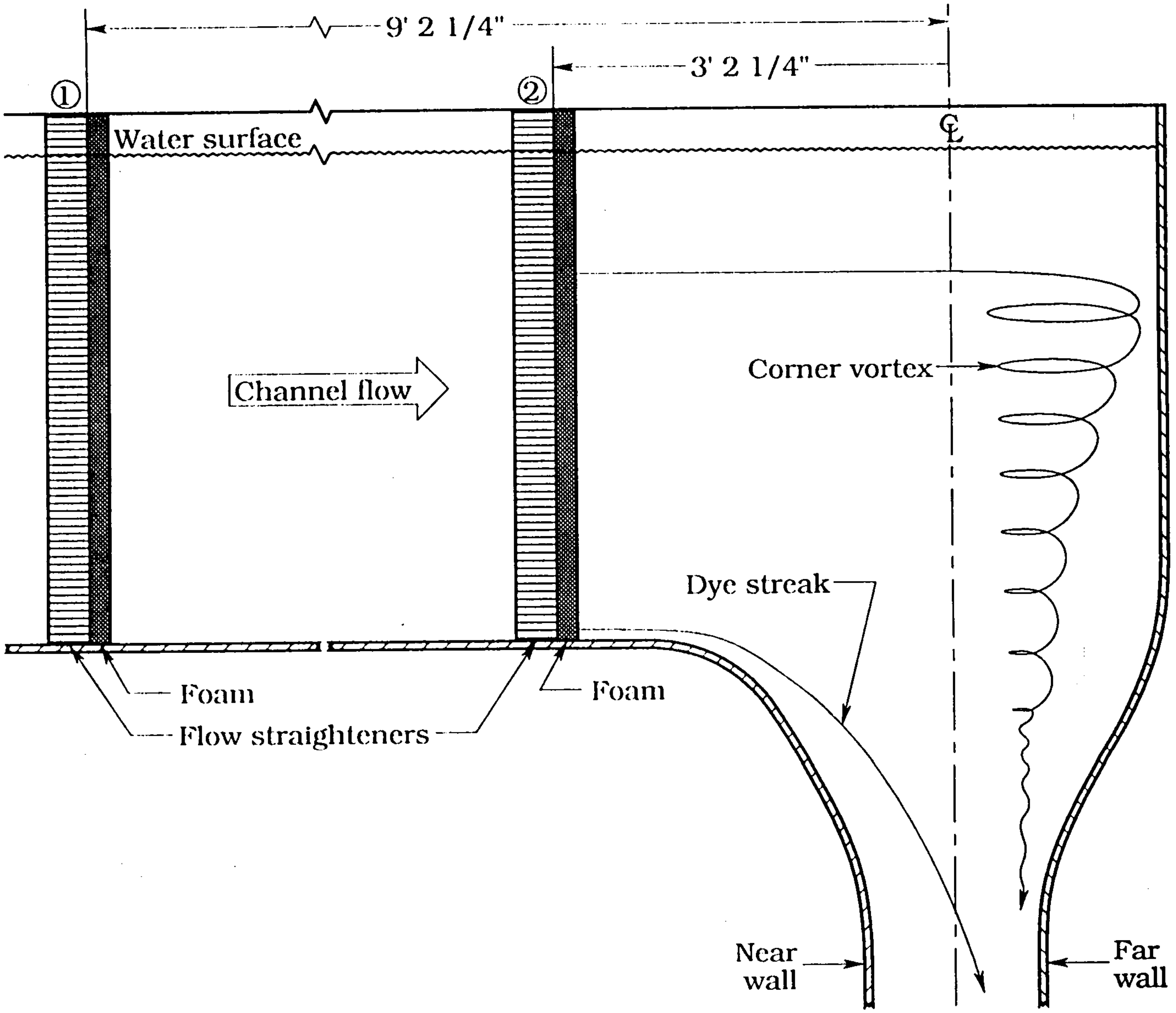
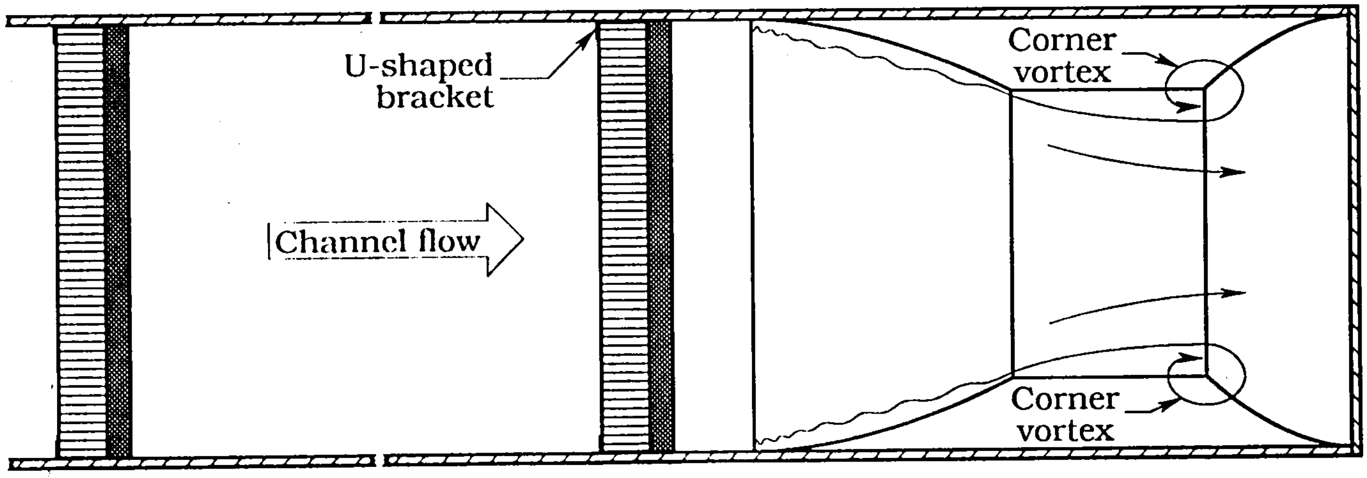


Figure 16.- Sketch of 4" PVC pipe and plumbing used to recharge filter media (see also figure 4(a)).

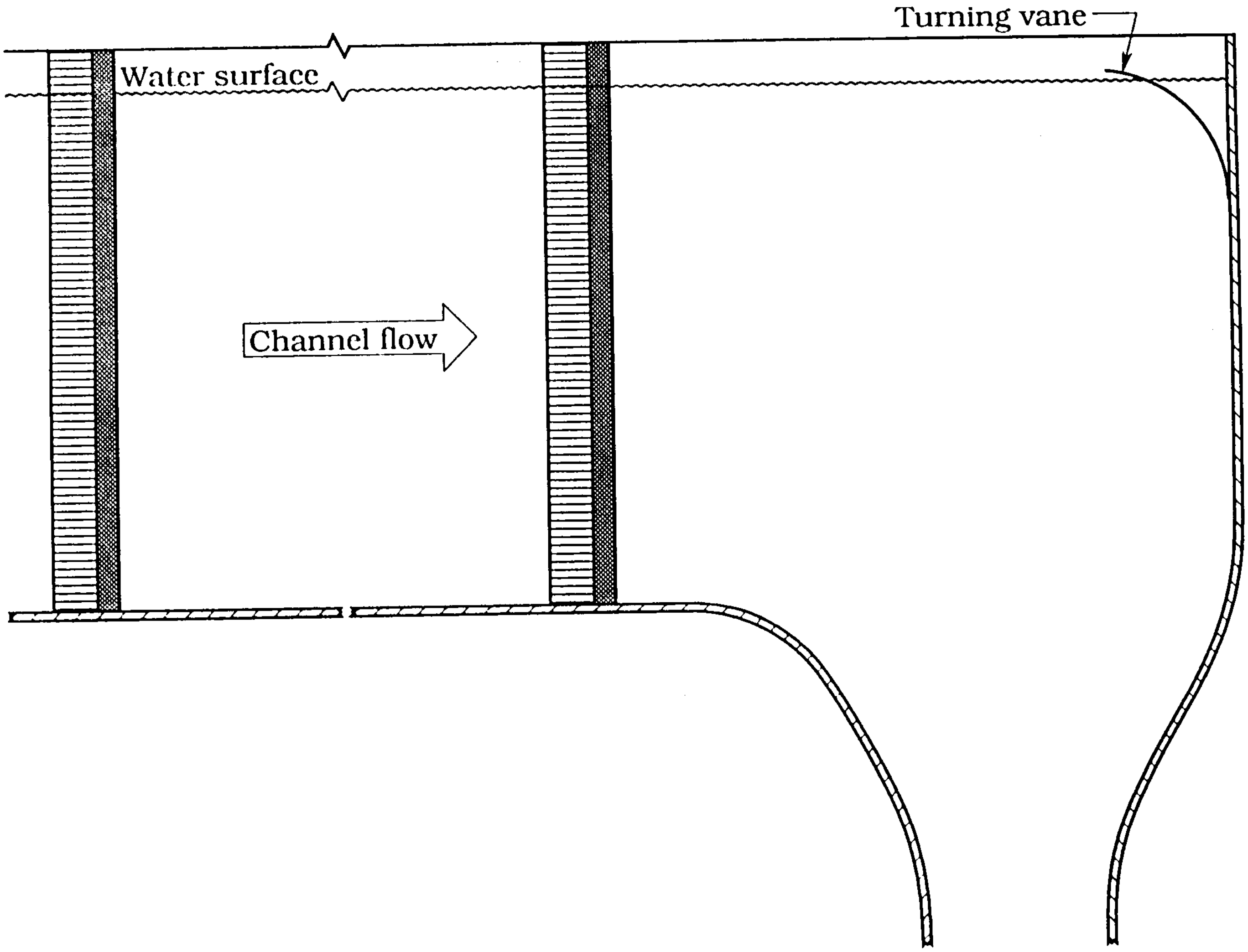


(a) View in pitch plane

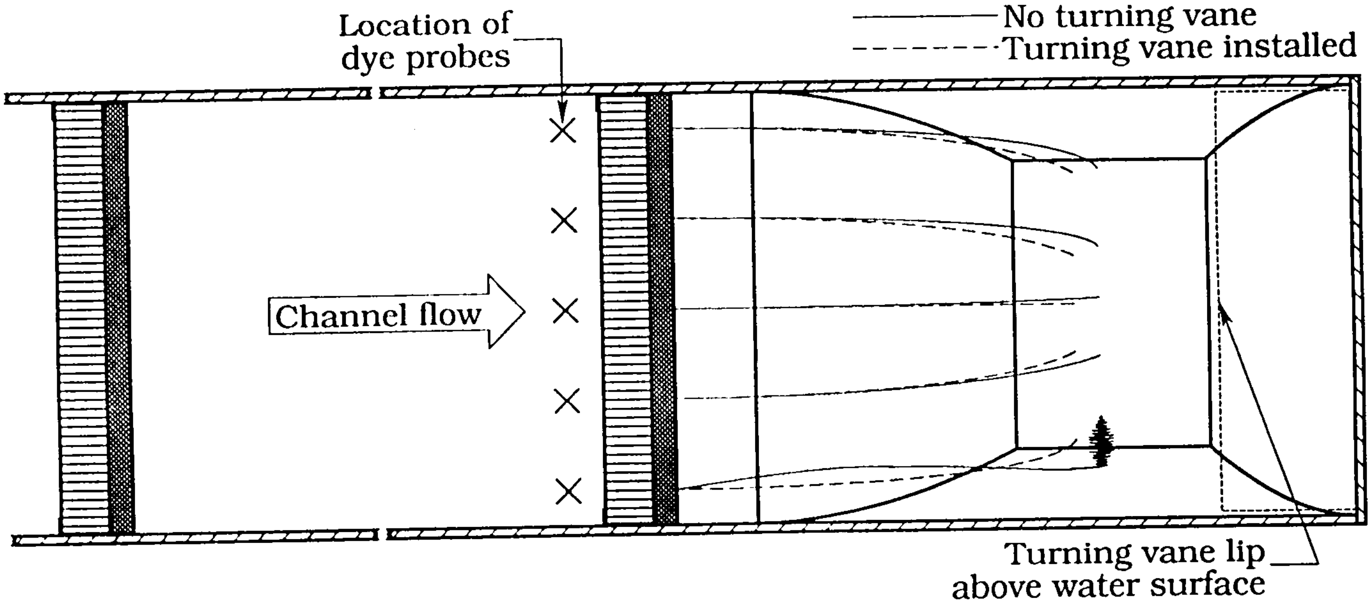


(b) Top view looking down on test section

Figure 17.- Contraction section corner vortices.



(a) Turning vane installation, side view



(b) Streakline path modification due to turning vane, top view

Figure 18.- Turning vane for flow path modification.

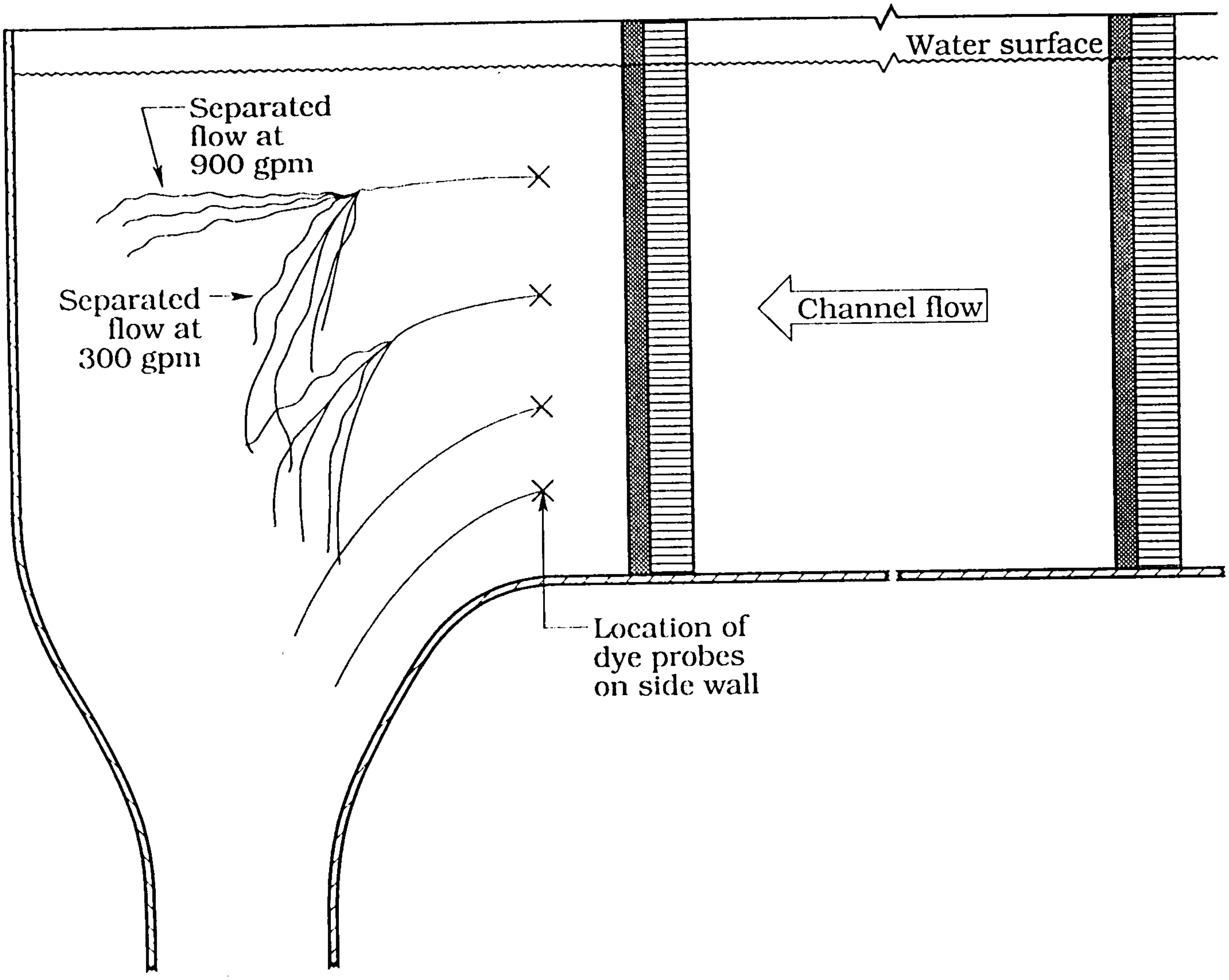
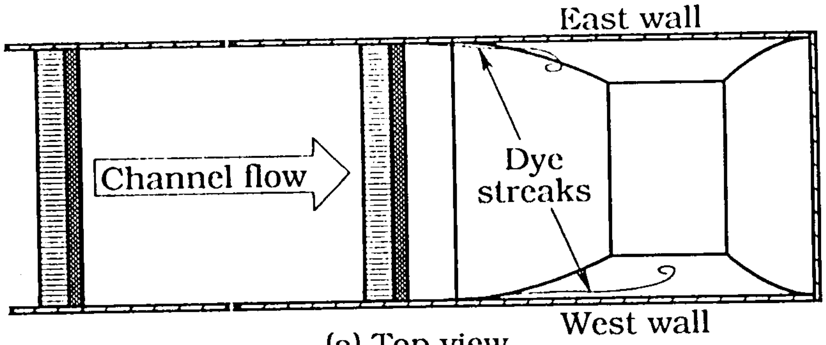
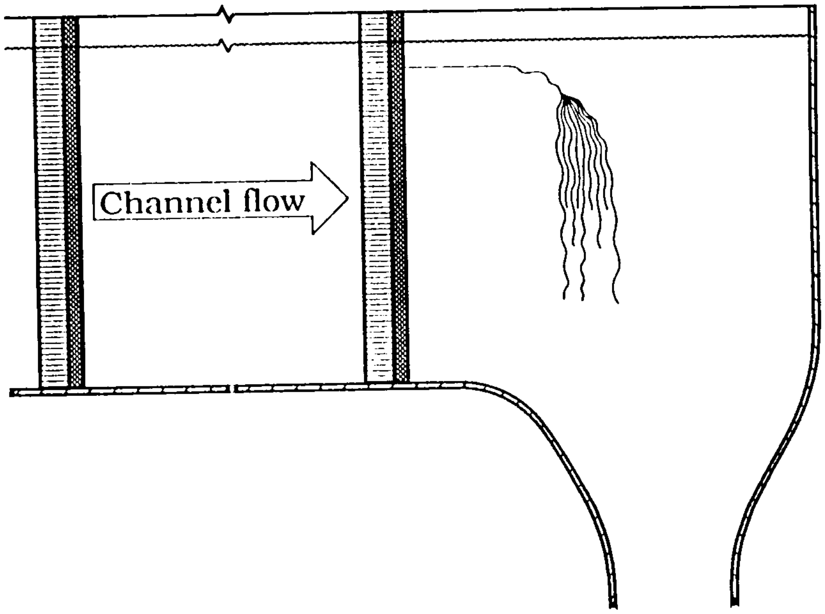


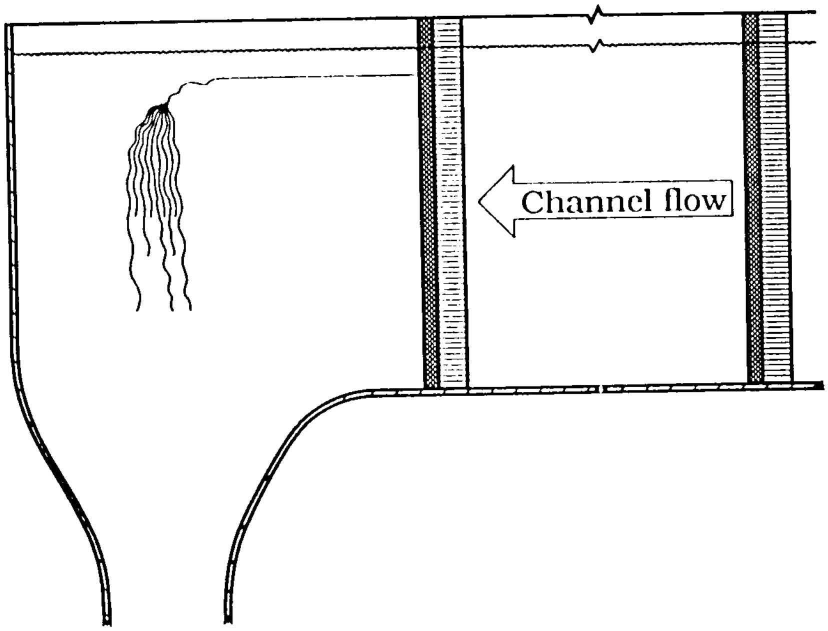
Figure 19.- Side wall flow separation.



(a) Top view



(b) Dye streak on east wall



(c) Dye streak on west wall

Figure 20.- Side wall separation locations after surface smoothing.

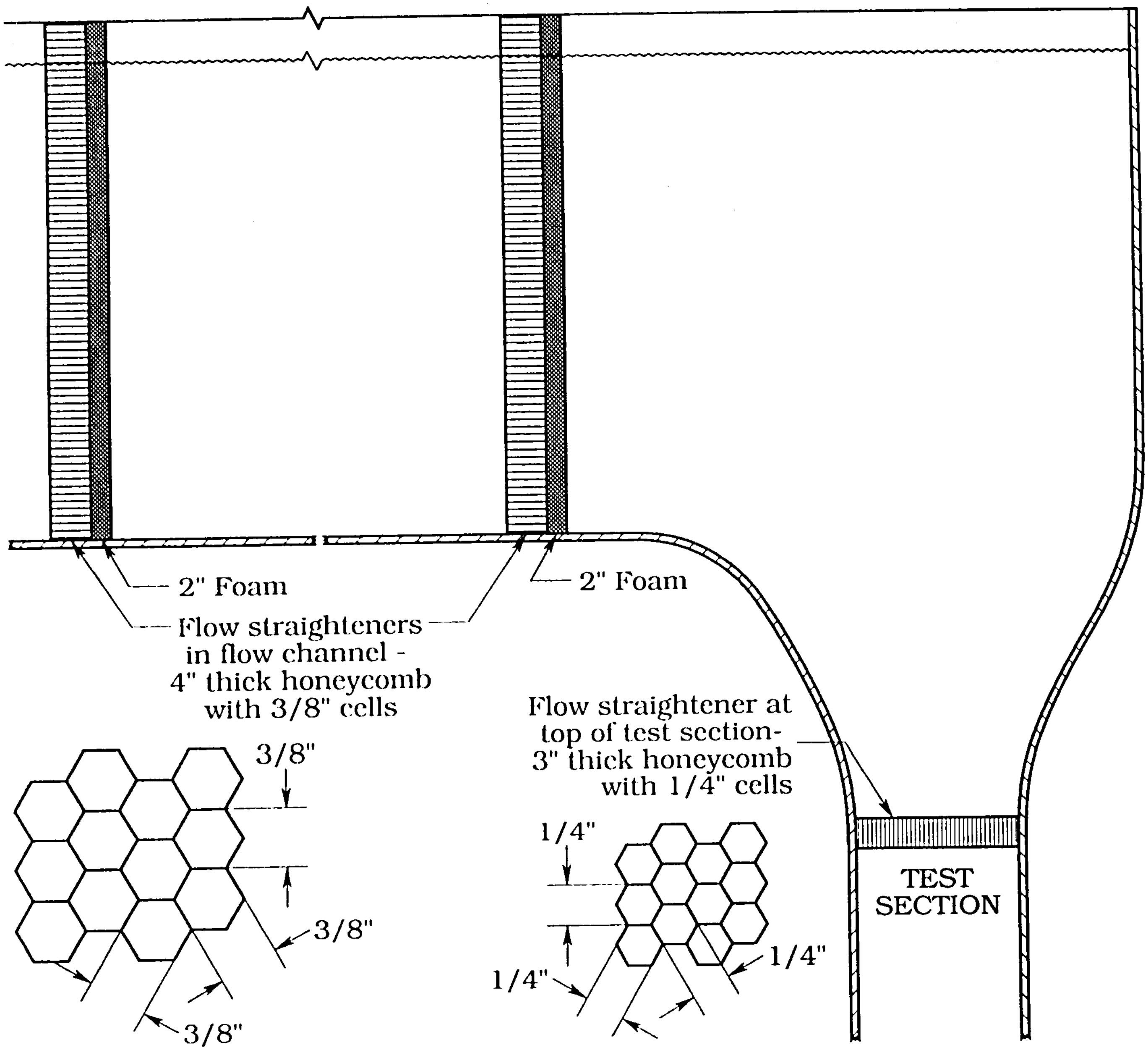
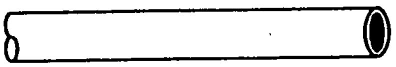
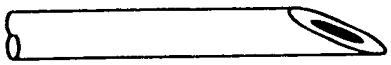


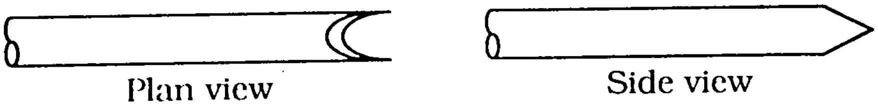
Figure 21.- Honeycomb in flow channel and above test section.



(a) Standard tip



(b) Hypodermic tip



(c) Vee tip

Figure 22. - Dye probe tip shapes.

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13. ABSTRACT *(Maximum 200 words)*

The Langley 16- By 24-Inch Water Tunnel, located in Building 1234 at the Langley Research Center, Hampton, Virginia is described in detail, along with all the supporting equipment used in its operation as a flow visualization test facility. These include the laser and incandescent lighting systems; and the photographic, video, and laser fluorescence anemometer systems used to make permanent records of the test results. This facility is a closed return water tunnel capable of test section velocities from 0 to 0.75 feet per second with flow through the 16- by 24-inch test section in a downward (vertical) direction. The velocity normally used for testing is 0.25 feet per second where the most uniform flow occurs, and is slow enough to easily observe flow phenomena such as vortex flow with the unaided eye.

This report also gives an overview of the operational characteristics, procedures, and capabilities of the water tunnel to potential users of the facility so they may determine if the facility meets their needs for a planned investigation.

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