

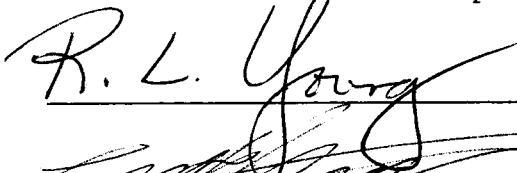
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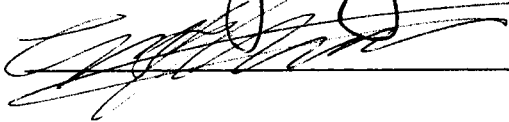
I am submitting herewith a thesis written by Amir H. Sheikholeslami entitled "Design of a Hot-Film Probe Calibrator, Calibration of UTSI Water Tunnel, and Flow Visualization Study of Secondary Flow in a Laminar Corner." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.



Frank G. Collins, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:



Vice Chancellor
Graduate Studies and Research

DESIGN OF A HOT-FILM PROBE CALIBRATOR, CALIBRATION
OF UTSI WATER TUNNEL, AND FLOW VISUALIZATION
STUDY OF SECONDARY FLOW IN A LAMINAR CORNER

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Amir H. Sheikholeslami

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ACKNOWLEDGMENT

The author wishes to express his appreciation for the assistance and guidance of Mr. Jim Goodman in the setting-up and operation of the DISA anemometer system used in this study.

ABSTRACT

The purpose of this study was the experimental investigation of secondary flow in a 90° corner for laminar flow in the test section of The University of Tennessee Space Institute (UTSI) water tunnel. A hot-film calibrator for velocities from 0.2 to 20 in/sec was designed and used to calibrate a TSI Model 1210-20W cylindrical quartz coated hot-film water probe. The hot-film probe was placed upstream of the test section and speed and turbulence level in the tunnel were measured.

Flow visualization techniques such as hydrogen bubbles and dye injection were used to search for the embedded vortices in the corner model. The major finding of this investigation was that, within the limitation of detection techniques employed, no vortices were found.

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CHAPTER I

INTRODUCTION

The first part of this study was the design of a hot-film calibrator for velocities from 0.2 to 20 in/sec. In the case of liquids, calibration is rather difficult. The probe must be located in a flow whose velocity is accurately known at all points. Several methods of calibration and equipment for hot-film probes in water were considered. One group of procedures consists of inserting the probe at specific points in a fully developed velocity profile, such as that found in a free jet. A second group of calibration procedures makes use of stagnant water, through which the probes are displaced at known velocities. This second method was selected for this investigation.

A TSI Model 1210-20W cylindrical quartz coated hot-film water probe was calibrated in a towing tank calibrator for low velocities, using a DISA constant temperature anemometer system. The bridge output was then linearized. The hot-film probe was placed upstream of the test section of the UTSI water tunnel. Speed and turbulence level in the tunnel were measured.

The second part of this study involved experimental search for secondary flow in a 90° corner at slow speeds

(laminar flow). Flow visualization techniques such as hydrogen bubbles and dye injection were used to locate the embedded vortices for laminar flow. Previous investigations had failed to visually locate the vortices. However, indirect evidence had indicated the presence of vortices which rotate oppositely to those for turbulent flow. Experimental work has been almost entirely confined to investigations of the turbulent layer. The work described here is mainly concerned with the laminar boundary layer in the incompressible flow with zero pressure gradient.

CHAPTER II

CALIBRATION METHOD

There are many ways to calibrate hot-film probes. The choice of the method depends on the measuring problem and on the desired degree of accuracy. The methods which were considered are: rotating tank, free jet, and towing tank. A brief description of each method will be given.

Rotating water tank: The water tank is caused to rotate on its axis. The water begins to move, increasing in velocity until after some time the entire quantity of water will be stable, behaving exactly like a rotating solid. The velocity is constant on concentric cylinders, increasing linearly from the axis. The velocity is then known at all points in the liquid. The disadvantages of this method are the creation of waves in the tank when the probe is inserted in the water and the wake of the probe which the probe passes through on successive cycles. This method is suited for a velocity range from 1.50 to 7.0 ft/sec.

Free jet: The principle of calibration in a free jet is the use of a small diameter orifice in a large tank with the water level kept at a certain constant height above the orifice. The flow velocity in the jet can be found from Bernoulli's equation. The drawback of

this method of calibration is that it can only be used to advantage for velocities greater than about 7.0 ft/sec and the need to know accurately the nozzle discharge coefficient.

Towing tank: Calibration in a towing tank consists of towing the probe in static water at known velocities. This method is reliable and accurate for low velocity calibration, it allows easy linearization, the relative probe-to-water velocity can be measured with great accuracy, the waves that are formed do not affect the results as they may in the rotating water tank method, and calibration can be performed in a short period of time.

Because of the low velocity range of interest, the last method of calibration in a towing tank was selected.

CHAPTER III

CALIBRATOR

A calibrator was designed and constructed to calibrate hot-film probes. The principle of the calibration is by towing the probe in static water. Speeds from 0.2 to 20 in/sec can be measured.

A towing tank of circular cross-section has on its top a pair of parallel solid steel shafts on which a probe supporting truck travels back and forth. The water is static and the truck velocity can be accurately determined.

The towing tank, as shown in Figures 1 and 2, consists of a 7-foot, 2-inches long PCV pipe which is $4\frac{1}{2}$ inches in diameter. A $\frac{1}{4}$ -inch wide opening which runs the length of the tank was cut on top of the pipe. At one end of the tank there is a 2×3 -inch opening for ease of installation and removal of the probe. The tank is supported by 4 carefully aligned 1-inch thick Plexiglas supports which form the framework of the calibrator.

The probe support truck, shown in Figure 3, is built of aluminum and has 2 linear ball bearing supports on each side. The 2 ball bearings are of the type LMD3 manufactured by Winferd M. Berg, Inc., of New York. The probe support is mounted in the middle of the truck.

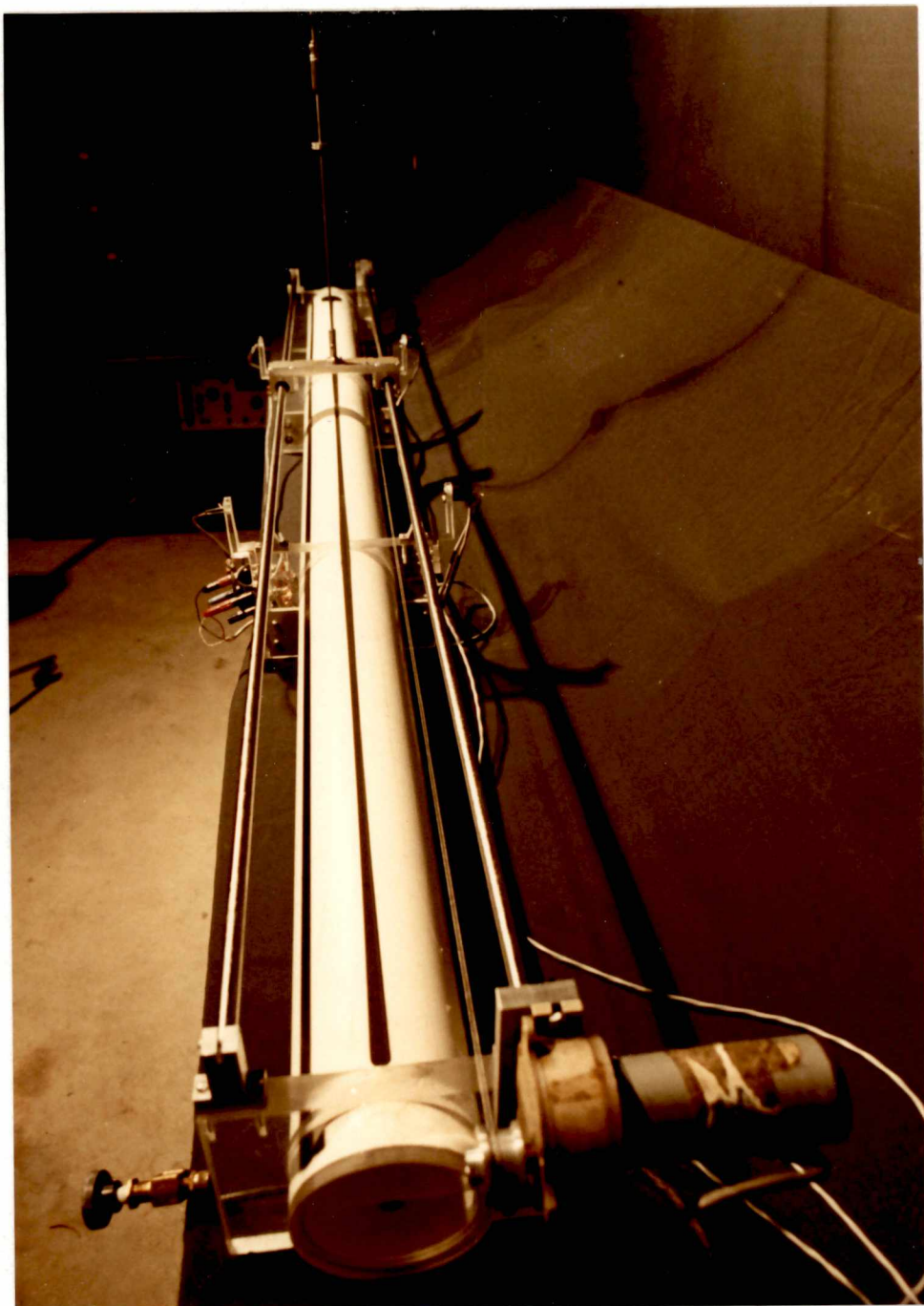


Figure 1. Towing Tank.

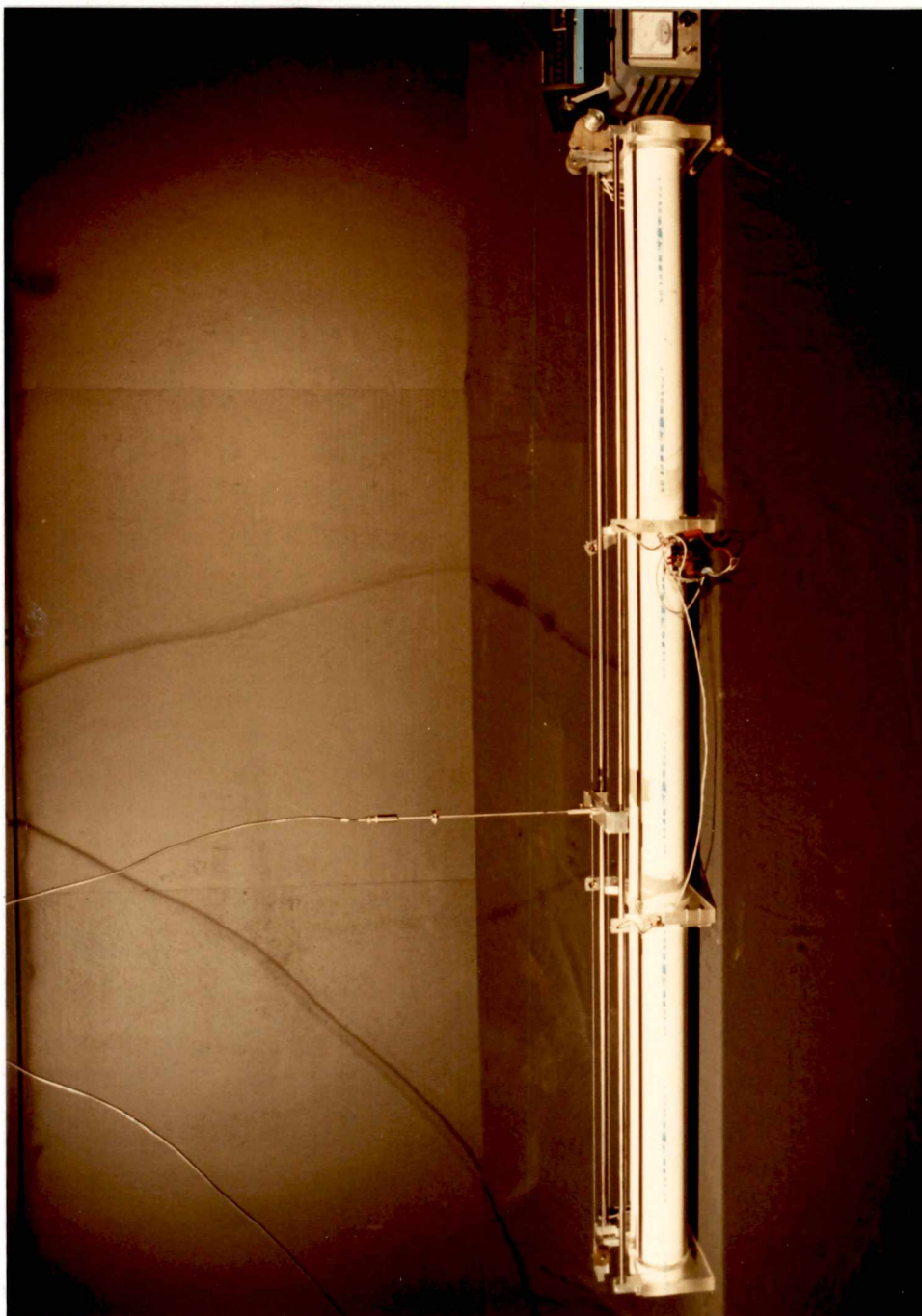


Figure 2. Calibrator.

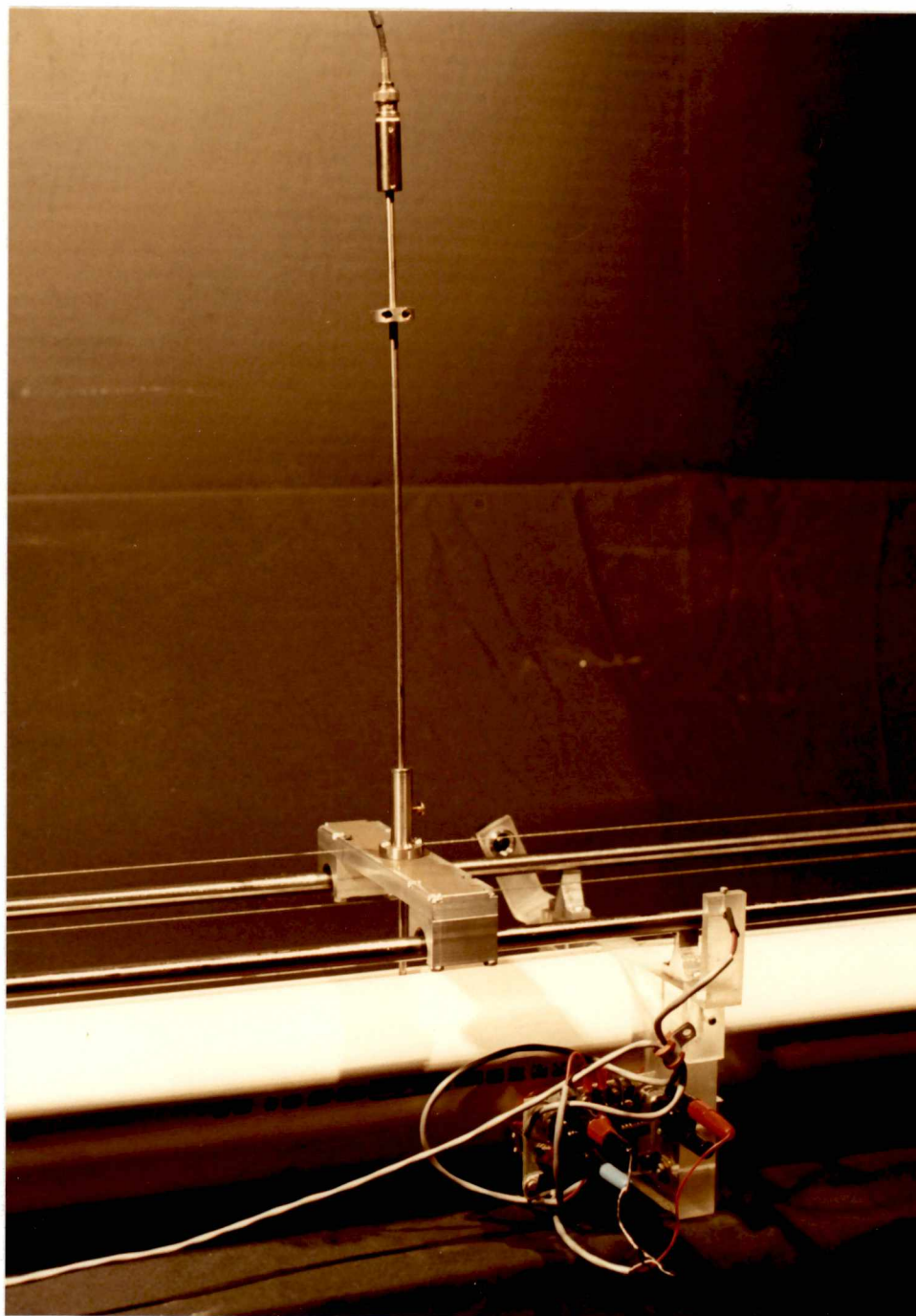


Figure 3. Probe Support Truck.

It has a lock screw which is used to adjust the height of the probe in the vertical plane.

The shafts are made out of solid steel and are 7 feet long. The shaft diameter ($\frac{1}{2}$ inch) was selected so that the rolling load caused no noticeable bending between the supports which are placed at 27-7/8-inch intervals. The shaft supports are fastened to the top of the tank supports. Shims are used under the shaft supports to allow accurate alignment of the shafts.

The truck is moved by means of a Motomatic E-500 DC motor (10:1) mounted at one end of the tank. The DC controller permits its speed to be set to any desired value between 0 and 500 RPM with an accuracy of $\pm 5\%$. The truck is driven by a steel cable passing over a set of $1\frac{1}{4}$ -inch diameter pulleys. Cable tension can be adjusted by means of the tension pulley at the opposite end of the tank from the DC motor. Two limit switches at each end of the tank stop the motor when the truck reaches its end position.

The truck is automatically and electronically timed between the 2 middle tank supports which are separated from each other by a distance of 27-7/8 inches. With these values, the speed is calculated. Attached to their respective holders, 2 Sylvania ECG Optical Transducers and 2 2.5-volt light bulbs are mounted on top of the 2

middle tank supports. The triggering circuit is mounted to the side of one of the tank supports (see Figure 4). A Data Precision Counter Model No. 5740 was used to measure the time the truck takes to travel between the 2 middle supports.

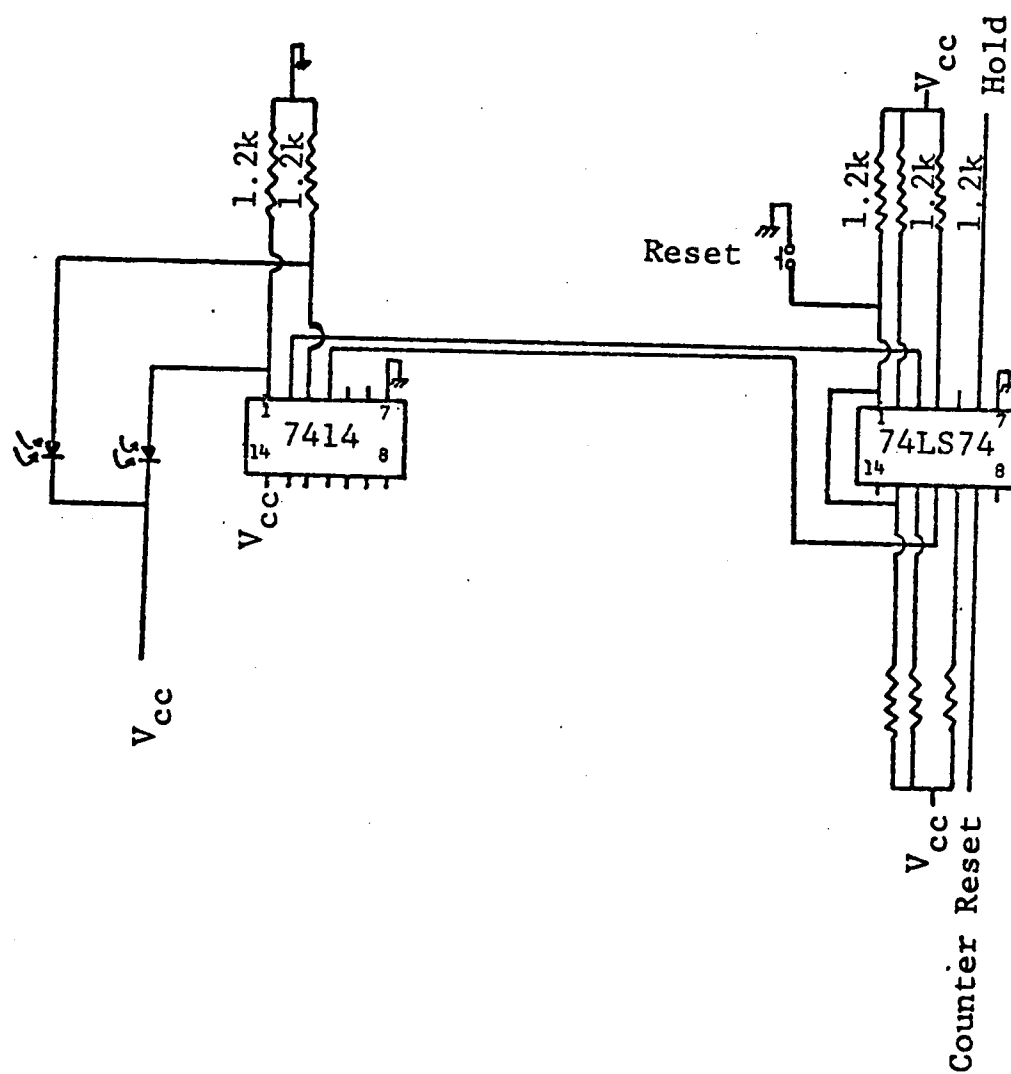


Figure 4. Triggering Circuit.

CHAPTER IV

CALIBRATION AND LINEARIZATION

A TSI Model 1210-20W standard straight probe (as shown in Figure 5) with cylindrical quartz coated hot-film sensor was calibrated in a towing tank for use in the UTSI water tunnel facilities. The towing tank calibrator was filled with tap water and was left standing to deaerate in the open-top tank for approximately 72 hours so that its temperature and pressure could come to equilibrium with the ambient conditions.

An overheat ratio of 1.045 was chosen to reduce the influence of free convection from the probe, which is the main factor setting the lower limit of the velocity at which a probe can be accurately operated. The lifetime of the probe is also improved by using this relatively low overheat ratio instead of the commonly-used values of from 1.1 to 1.5 .

The probe was mounted on the supporting truck. The speed of the truck was measured and adjusted until the desired speed was obtained. The probe was then lowered into the water, the electric motor was turned on and the corresponding voltage for the probe was recorded from the voltmeter. A typical calibration curve is shown in Figure 6. This work was performed with the following

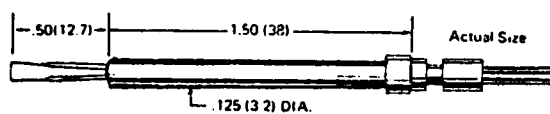
MODEL 1210 STANDARD STRAIGHT PROBE

Figure 5. Hot-film Probe.

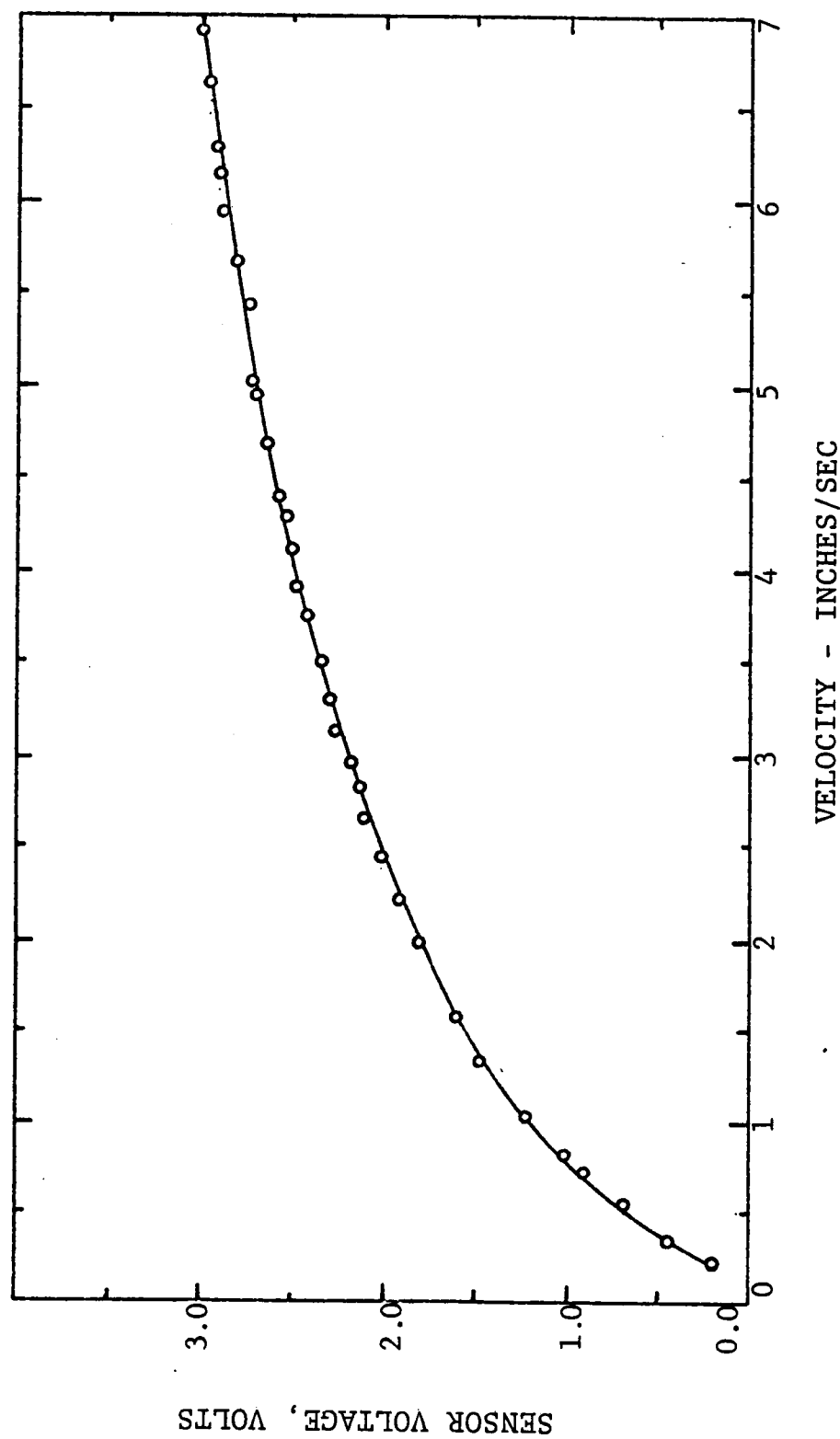


Figure 6. Calibration Curve.

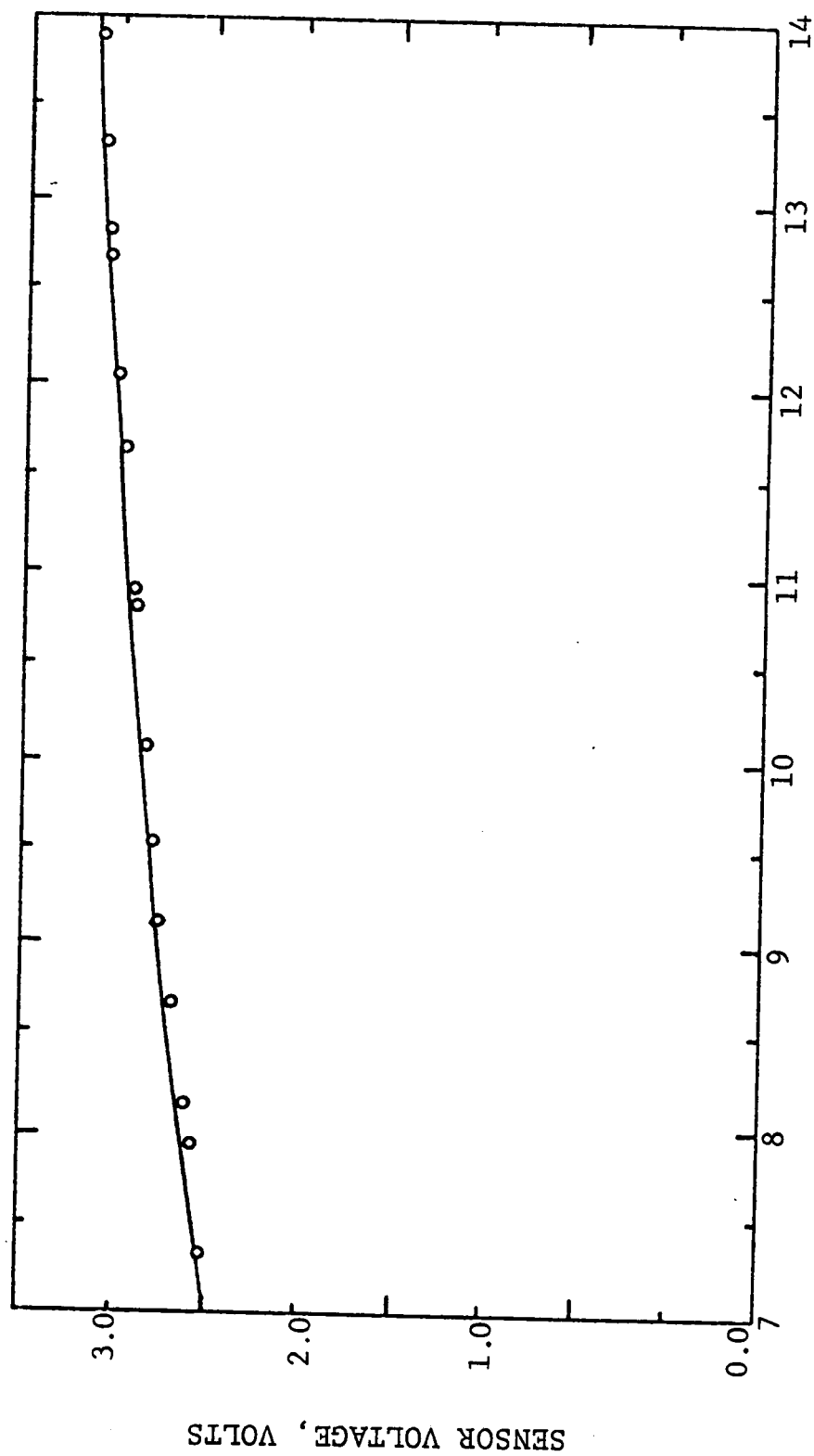


Figure 6. (Continued)

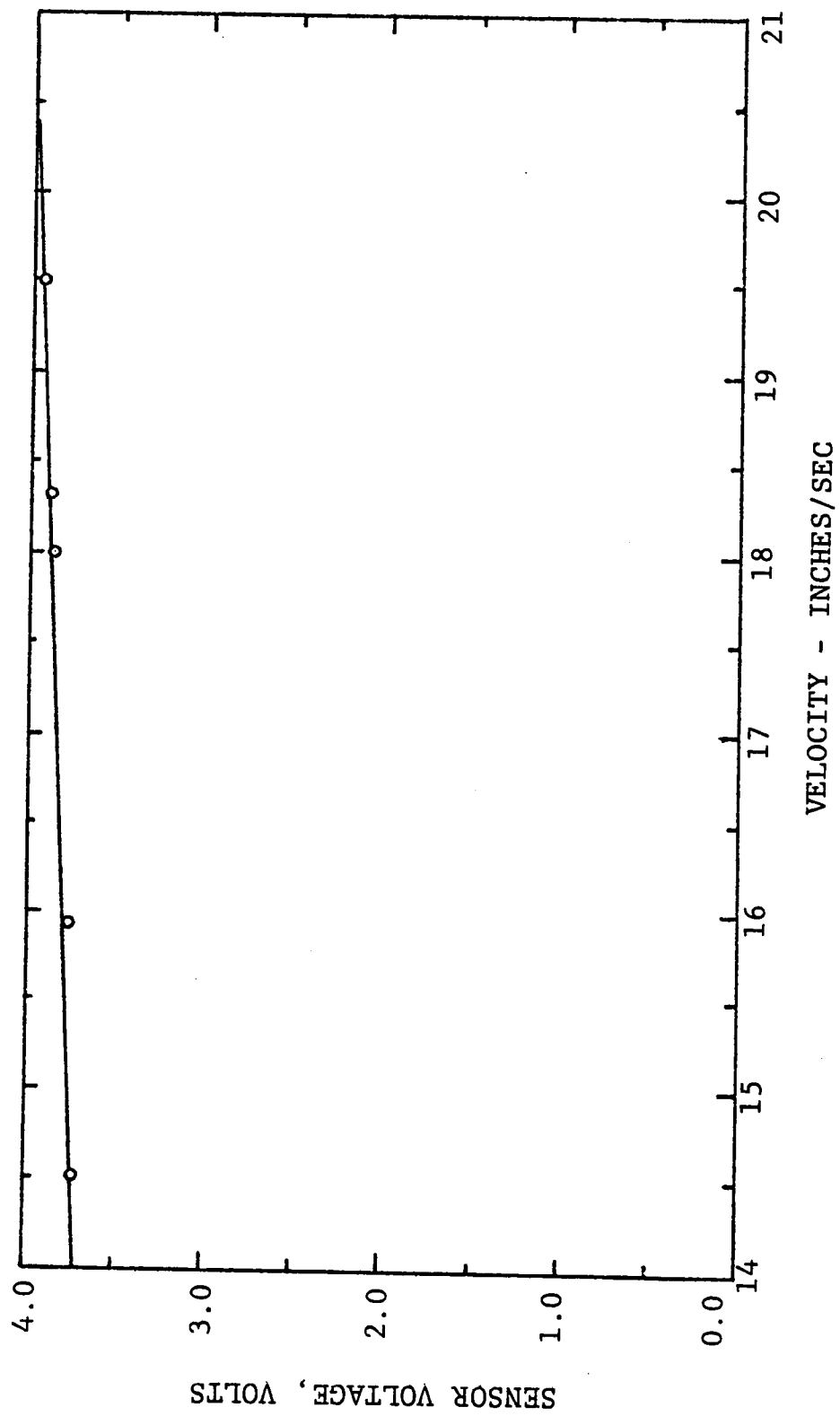


Figure 6. (Continued)

DISA anemometry setup: 55D01 Anemometer, 55D10 Linearizer, 55D25 Power Booster, and a standard DISA probe cable.

A Power Law, also called the Hot-wire Equation, is often used to approximate the nonlinear calibration curve. It is written in the form:

$$E^2 = A + BV^n, \quad (1)$$

where V is the fluid velocity, and A and B are nearly constant. The overheat ratio is defined as T_H/T_C , where the fluid temperature and the operating temperatures are T_C and T_H , respectively.

In equation (1) A is set equal to E_0^2 where E_0 is the measured voltage output at zero flow speed. Brunn, Reference [1], has shown that it is possible to express the Nonlinear Hot-wire Calibration Law in the form

$$E^2 - E_0^2 = kV^n, \quad (2)$$

where n and k are functions of velocity V . In practice, k and n must be assumed to be constant.

Nagib [2] has shown that it is better to write equation (2) as

$$E^2 - a^2 E_0^2 = kV^n, \quad (3)$$

where $a = 0.9$ for hot-wire measurements in air over the range of velocities from 10 to 100 ft/sec and

$a \approx 0$ for measurements with cylindrical hot-film fibers in water over the velocity from 0.05 to 2 ft/sec. Hence, $a = 0$ was chosen.

One method of calculating the exponent n is the use of 2 points, 1 and 2, on the calibration curve $E = f(V)$ and assume n and k to be constant between 1 and 2:

$$E_1^2 - E_O^2 = kV_1^n \quad , \quad (4)$$

$$E_2^2 - E_O^2 = kV_2^n \quad . \quad (5)$$

Then, by subtracting equation (5) from (4) and taking the logarithm of both sides, n can be calculated from the equation

$$n = \frac{\ln(E_1^2 - E_O^2) - \ln(E_2^2 - E_O^2)}{\ln V_1 - \ln V_2} \quad . \quad (6)$$

The values of n for 7 different velocities were calculated and are given in Table 1. The value of k was determined by substituting the known velocity of interest and the corresponding values of n and E from Table 1 into equation (3). The linearized result was obtained when the value of the exponent n was set at 0.235 on the linearizer (Figure 7), as recommended by Nagib [2].

The linearized measurements drifted too much during the calibration process because the

TABLE 1
CALIBRATION CONSTANT

Velocity (In/Sec)	Output E (Volts)	$V_2 - V_1$	Exponent n [Eq. (6)]
0.00	4.98	--	--
1.00	6.88	--	--
2.00	7.65	2.00	0.58
3.00	8.20	2.00	0.57
4.00	8.56	2.00	0.45
5.00	8.84	2.00	0.38
6.00	9.02	2.00	0.30
7.00	9.16	--	--

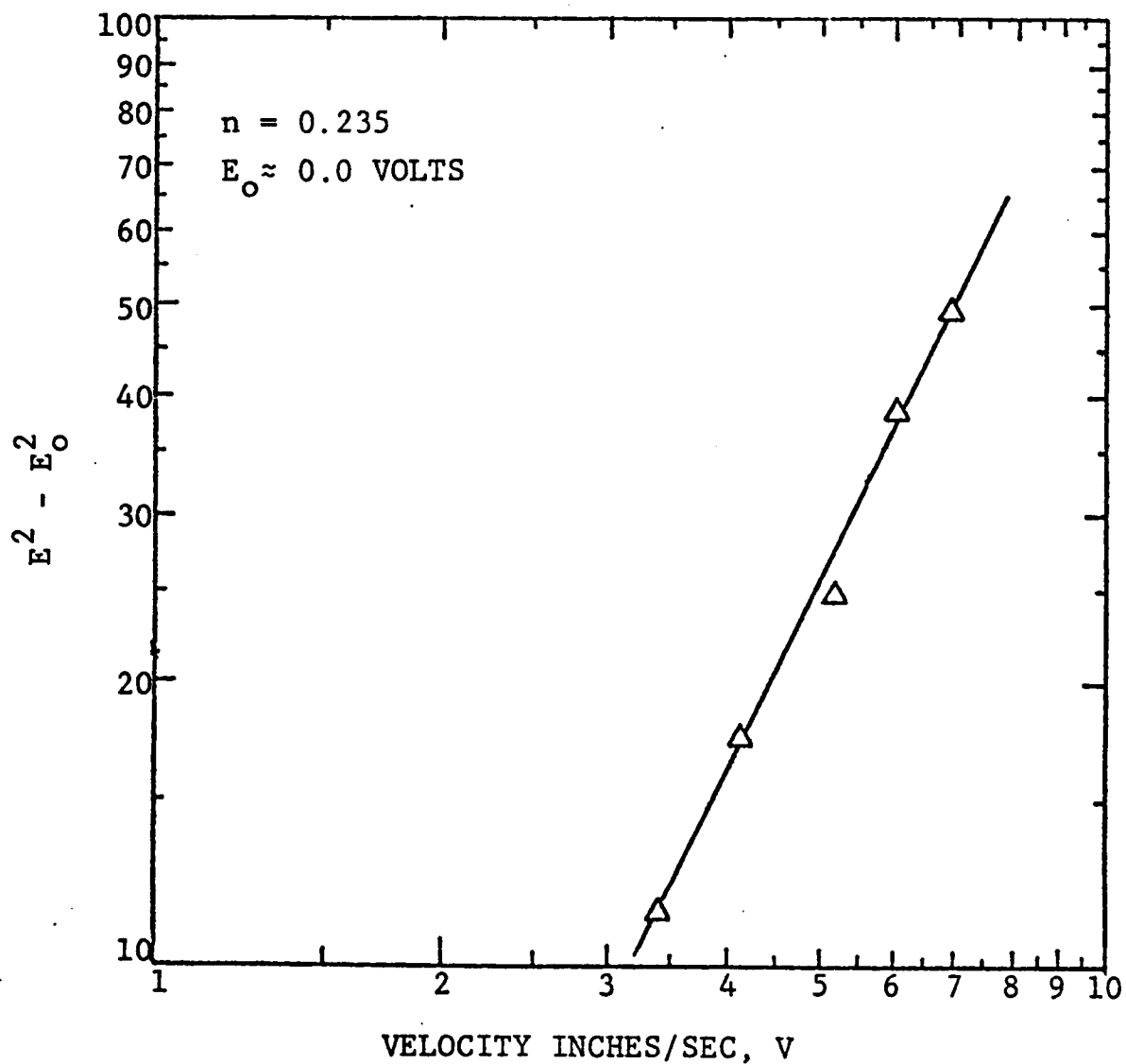


Figure 7. Linearized Output.

temperature compensation circuit of the linearizer had to be reset after every measurement. Tan-Atichat, Nagib and Pluister [2] also found that the drift encountered in hot-film anemometry in water remains appreciable. The drift in the output was only encountered for the linearized output. Several calibrations were made without using the linearizer and there was no evidence of the kind of drift which was seen in the linearized output. It was decided to use the nonlinearized output of the bridge for calibration.

CHAPTER V

WATER TUNNEL

A diagram of the water tunnel is shown in Figure 8. The tunnel has a closed circuit and a closed test section. The test section is inside a light-tight building, whose inside walls are painted black for photographic purposes. The water volume is about 2,100 gallons.

The test section is constructed of $\frac{1}{2}$ -inch thick Plexiglas. Its cross-section is 12 $\times$ 18 inches, and it is 59 inches long. The test section walls are diverged to account for the growth of the boundary layer at a free-stream speed of 6 in/sec. The flow in the test section can be viewed from the four sides of the test section.

The tunnel is powered by a 10-inch diameter 2-bladed propeller which is connected to a 1-horsepower motor. The motor is connected to a continuously variable speed transmission which allows the test section speed to be varied from 1 in/sec to greater than 1 ft/sec.

The stilling chamber is 61 inches in diameter and is 112 inches long. It contains four stainless steel screens and two aluminum honeycombs. This configuration of the stilling chamber keeps the Reynolds number in the chamber to less than 40. The turbulence level in the test section was designed to be 0.1%.

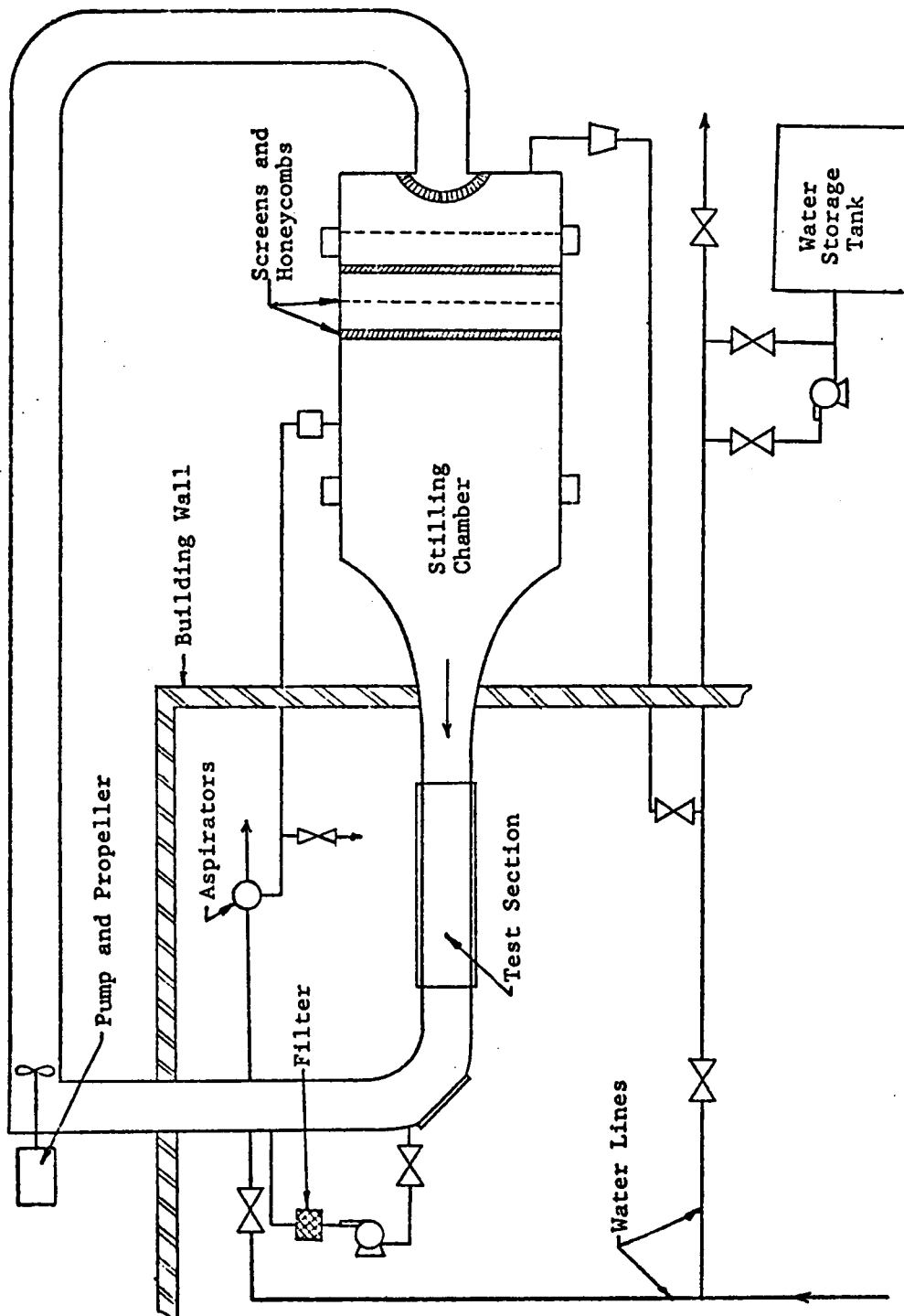


Figure 8. Diagram of UTSI Water Tunnel Facility.

The nozzle has a bell mouth that continuously changes from a circular shape to a rectangular shape. It has a contraction ratio of 13.5 and the boundary layer thickness remains constant along its surface.

There is a 4,000-gallon underground storage tank to store the water during cold nights. The water is conditioned with sodium sulphate (2% by weight) to increase its electrical conductivity and 0.1% sodium dichromate to inhibit corrosion.

A small portion of the main flow is bypassed through a woven polypropylene cartridge filter to filter the water to 10 micron. A process glass pipe is on top of the stilling chamber and is pumped by aspirator pumps to degas the water. The glass pipe also allows the water in the test section to be overpressured by 2 psi which increases the quality of the hydrogen bubble flow visualization.

The tunnel is operated from a master control panel inside the building. All of the valves are solenoid operated.

CHAPTER VI

WATER TUNNEL CALIBRATION

The counter on the master control panel of the water tunnel was calibrated using a TSI 1210-20W hot-film probe. The probe was mounted on an 18-inch long TSI Probe Support Model 1150-18 for water. It was then placed 6 inches upstream of the test section. The probe was positioned so that it was exactly in the center of the tunnel wall.

The hot-film probe was calibrated right before it was placed in the tunnel (Figure 9). The tunnel was then filled with water. Several runs were made and the corresponding readings of the anemometer output voltage and the counter were recorded. The water was then drained and the hot-film probe was recalibrated (Figure 9).

Since the probe could not be calibrated at the same exact temperature as that of the water in the tunnel, several attempts were made to remove the temperature effect from the calibration. The water in the calibrator tank was at a temperature of 67°F. A thermocouple, which was located just below the hot-film probe upstream of the test section, showed the temperature of the water in the tunnel to be about 60°F.

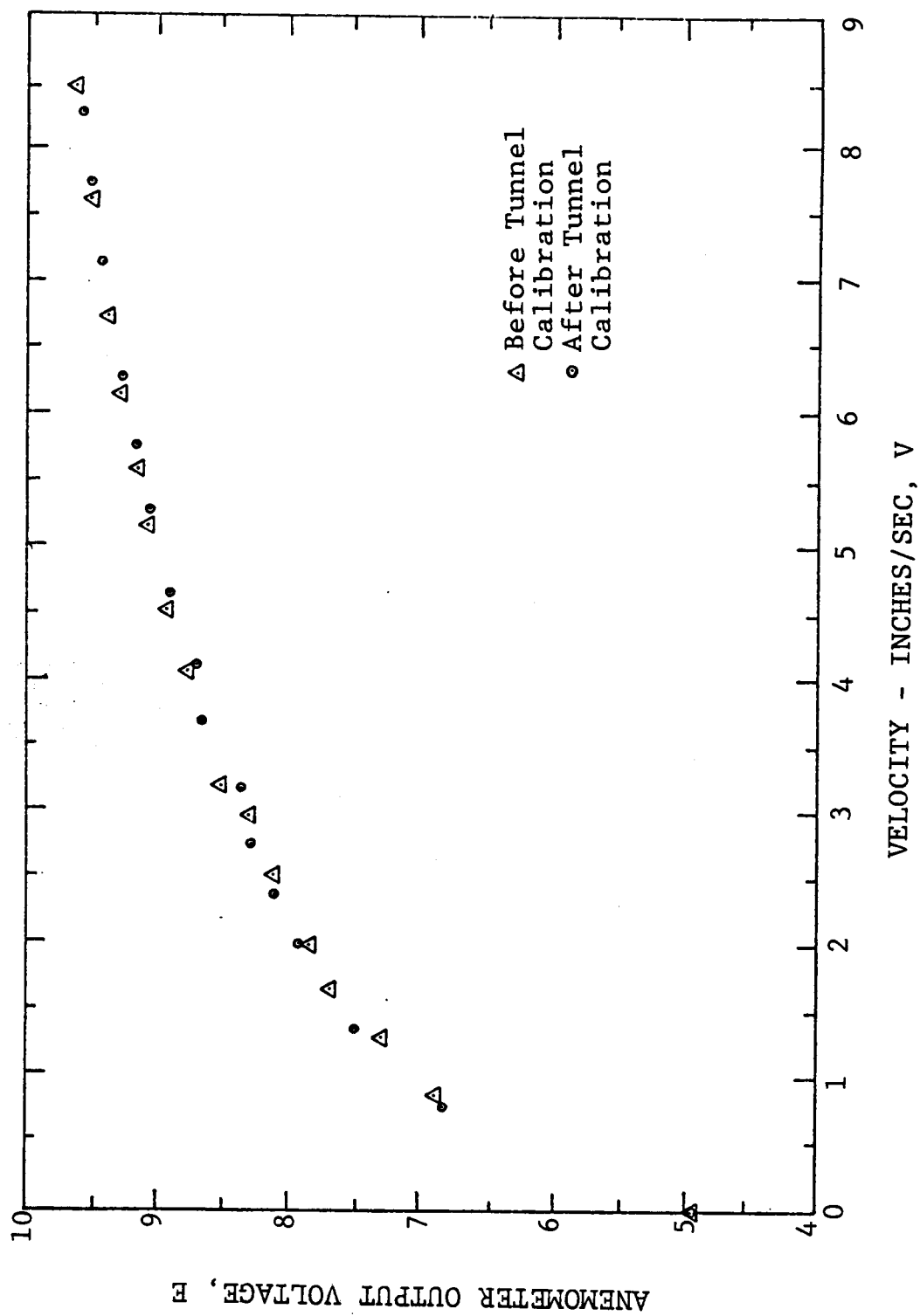


Figure 9. Hot-film Calibration Curve.

The first technique attempted to compensate for the change in water temperature consisted of changing the bridge resistance which controls the overheat ratio to maintain a constant overheat ratio at all temperatures. A second scheme of compensation consisted of maintaining the overheat resistance difference, $R_H - R_C$ constant, where R_H and R_C are the operating resistance and the cold resistance, respectively. The last method involved adjusting the anemometer resistance at a known velocity to yield the same bridge output as that during the hot-film calibration.

There was almost no difference between the first two methods when the operating resistance was calculated. The value of cold resistance, R_C , changed between 5.22 and 5.26 ohms during the several attempts which were made to calibrate the tunnel. When R_C is multiplied by the overheat ratio of 1.045 an operating resistance of 5.45 to 5.50 ohms is calculated by the first method. When the overheat resistance was kept constant, in this case $R_H - R_C = 0.24$ ohms, it also gave a calculated operating resistance of 5.46 to 5.50, which is almost the same value of operating resistance as the one calculated from the first method. The last method of temperature compensation was not used because the only accurately known velocity in the tunnel is at zero flow. This method works best when the maximum or the average velocity is known.

The major problem which was encountered during calibration was that of keeping moisture out of the connection between the probe and the probe support. At first, only the O-ring which is supplied with the probe was used. The resulting velocities, which are shown in Figure 10, were of the order of half as much of the predicted values given by the equation

$$V = 0.0647C - 6.424 \quad , \quad (7)$$

where V and C are velocity and counter, respectively. Equation (7) is a least square method for calculating the flow velocity in the tunnel which was obtained during previous experimental work which estimated the tunnel speed from the estimated speed of hydrogen bubbles. The connection was checked and moisture was found in it. It was assumed that this was the reason for the inaccurate results.

In the subsequent attempt, vacuum grease was applied around the O-ring and the probe was reinstalled in the tunnel. Five different runs were made, with results as shown in Figure 11. They are closer to the values calculated from equation (7) than the ones shown in Figure 10.

To make even a better seal, the vacuum grease was removed and RTV was applied instead. The RTV

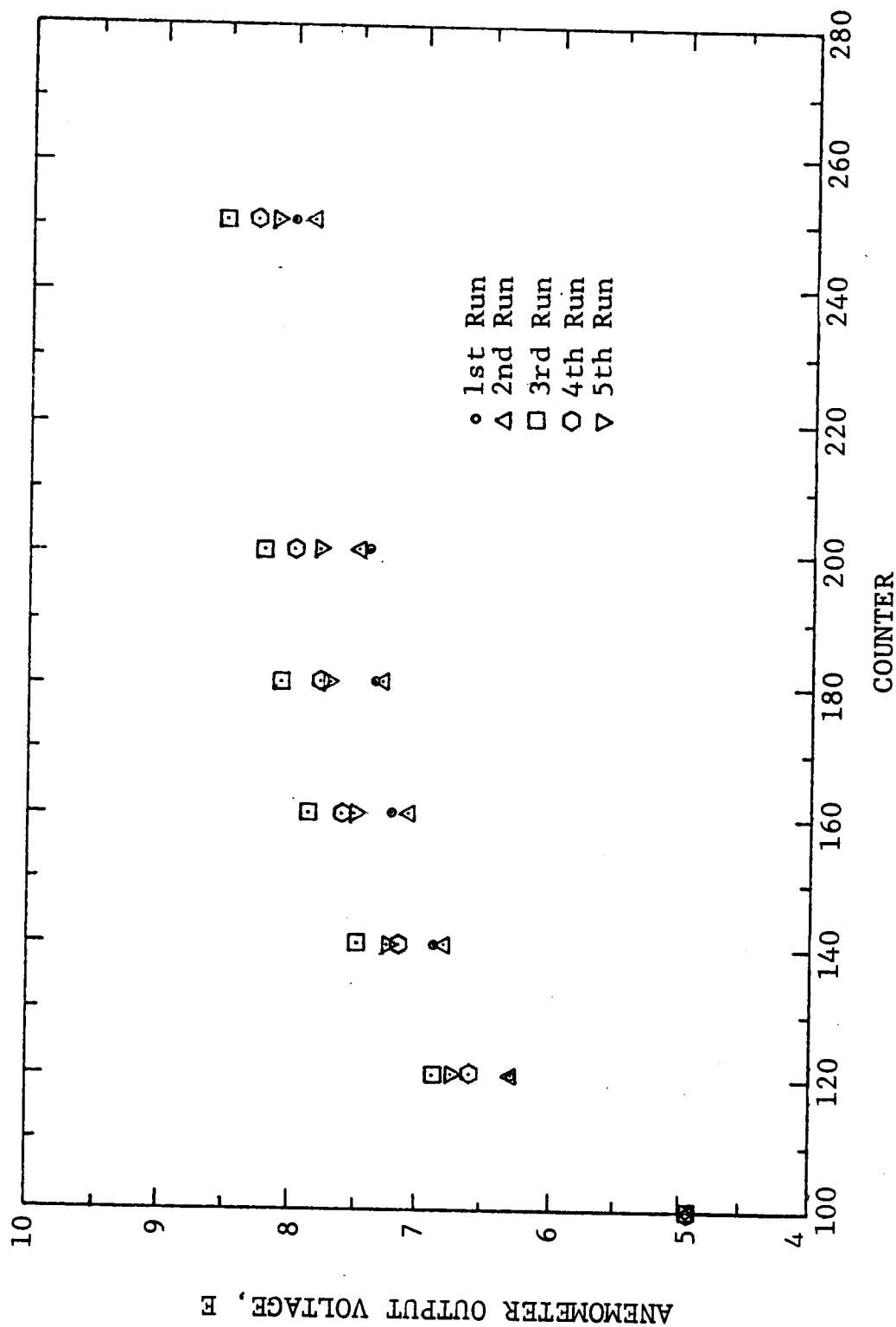


Figure 10. Tunnel Calibration Curve, Using Only the O-Ring on the Probe Connection.

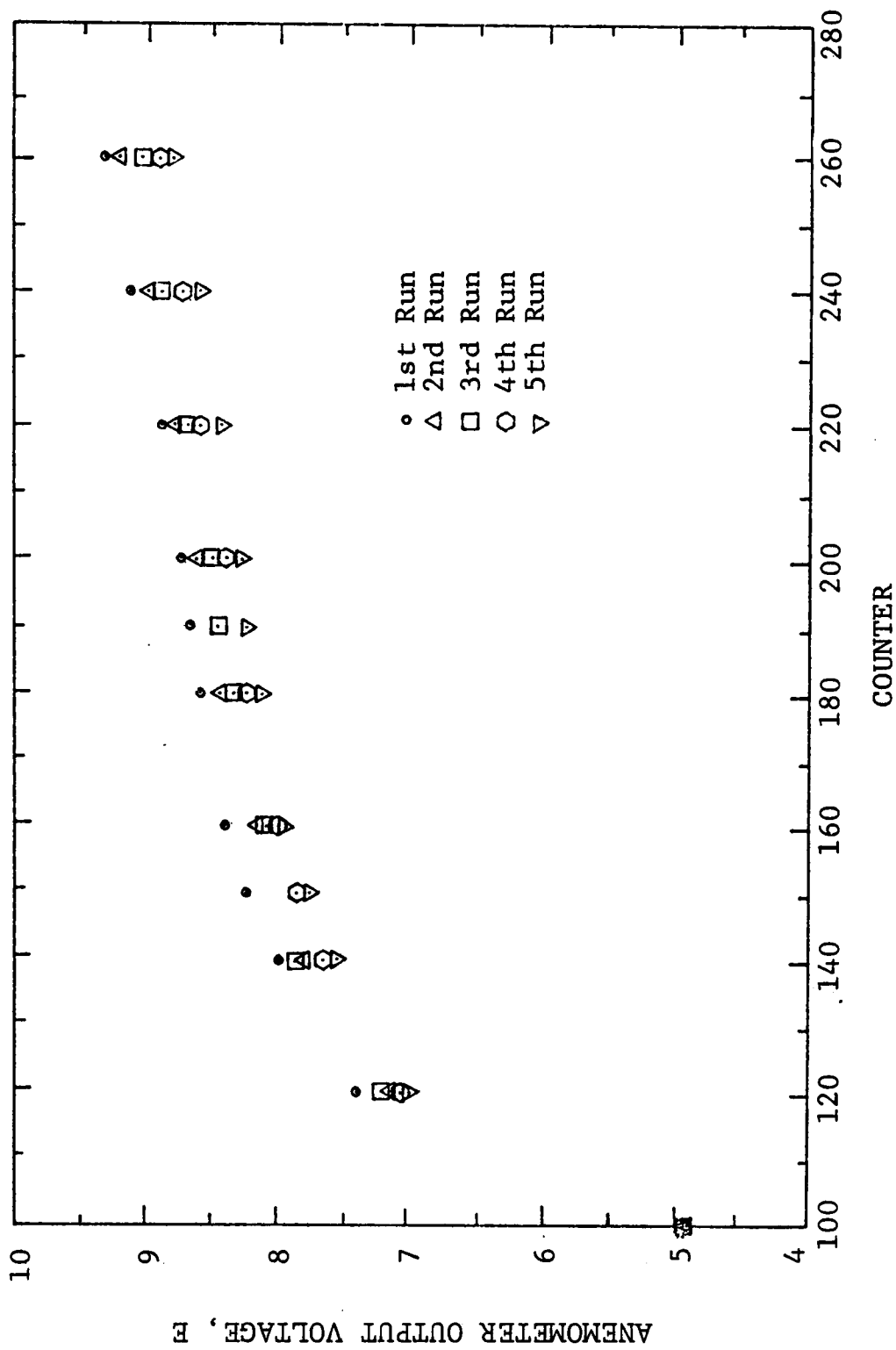


Figure 11. Tunnel Calibration Curve, Using Vacuum Grease on the Probe Connection.

was let dry for about one hour. Then the tunnel was filled with water and seven runs were made. The results (Figure 12) are more like the predicted values as given by equation (7).

In conclusion, it can be said that it is very important to keep the moisture out of the probe-to-probe support connection. Also, the calibration curve for before and after the runs are within acceptable limits for hot-film sensors.

The turbulence in the tunnel was measured using an HP 3400A true RMS voltmeter. The turbulence level was measured as less than 0.1% (Figure 13). The tunnel velocity profile for 3 different flow velocities was recorded (Figure 14). The probe was moved to 6 different locations in the flow field and the anemometer voltage output was recorded at distances of 2, 4, 6, $6\frac{1}{2}$, 7, $7\frac{5}{8}$, and 8 inches from the center of the test section. The flow velocity vs. counter reading and equation (7) are shown in Figure 15.

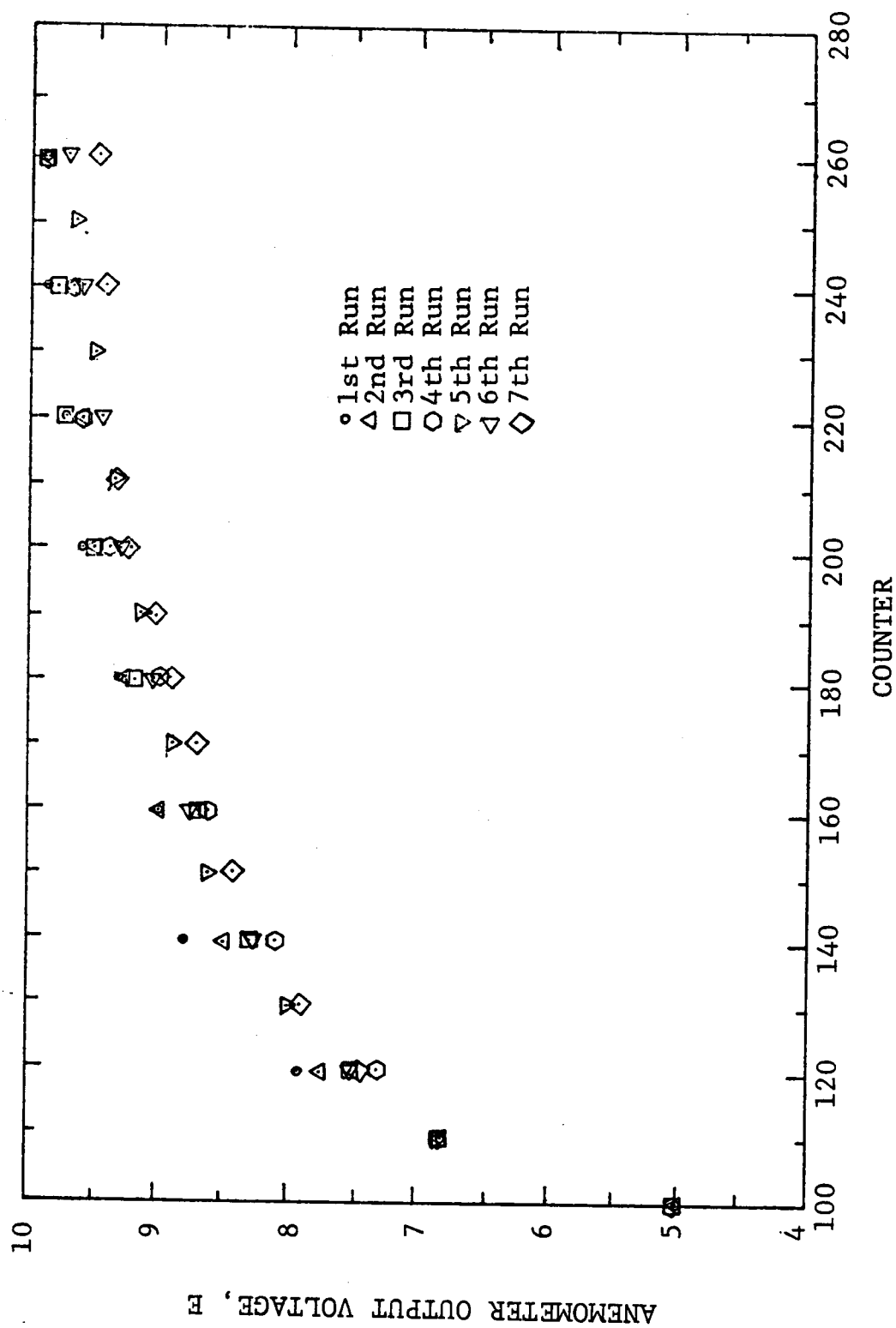


Figure 12. Tunnel Calibration Curve, Using RTV on the Probe Connection.

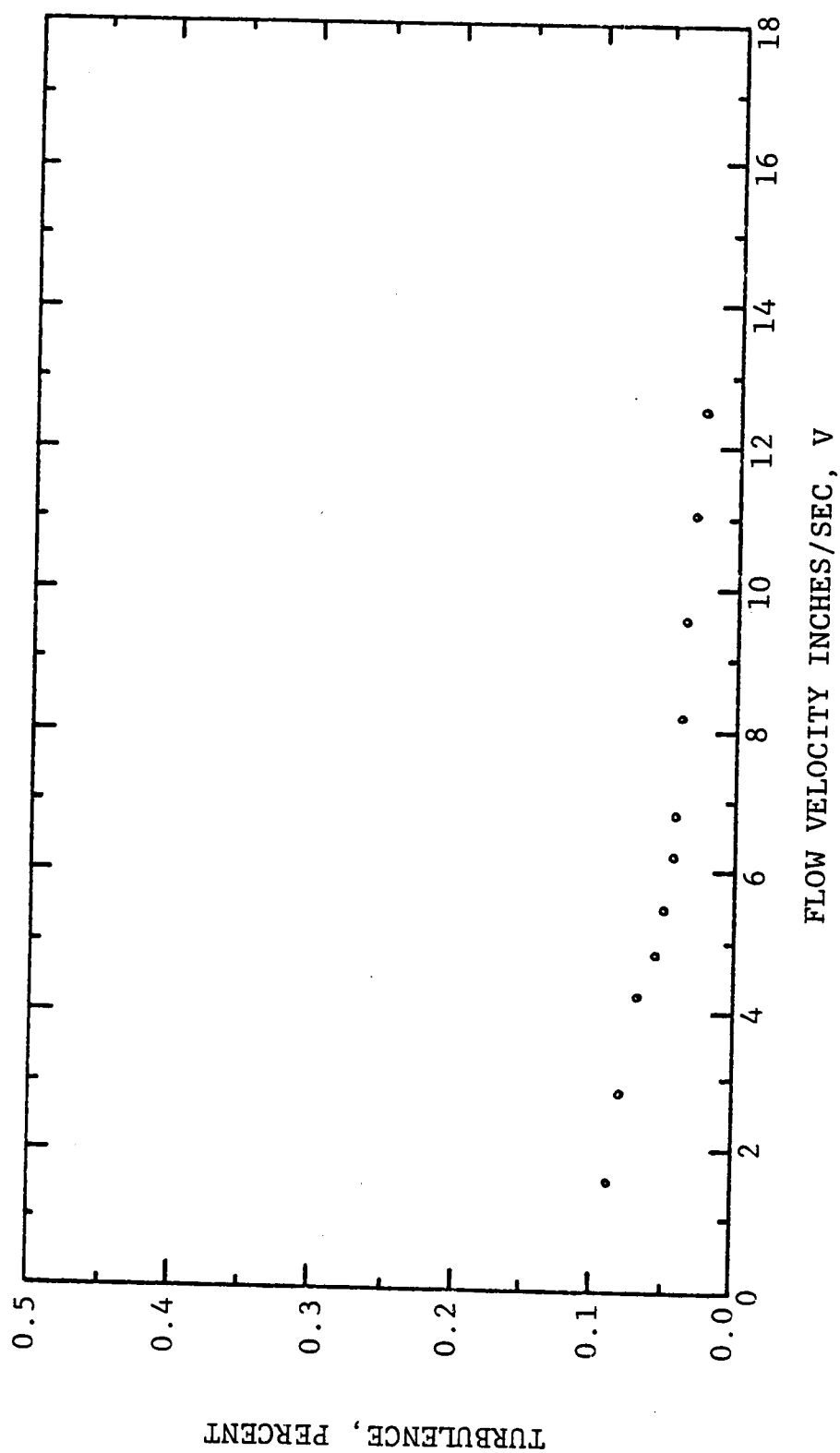


Figure 13. Turbulence Measurements.

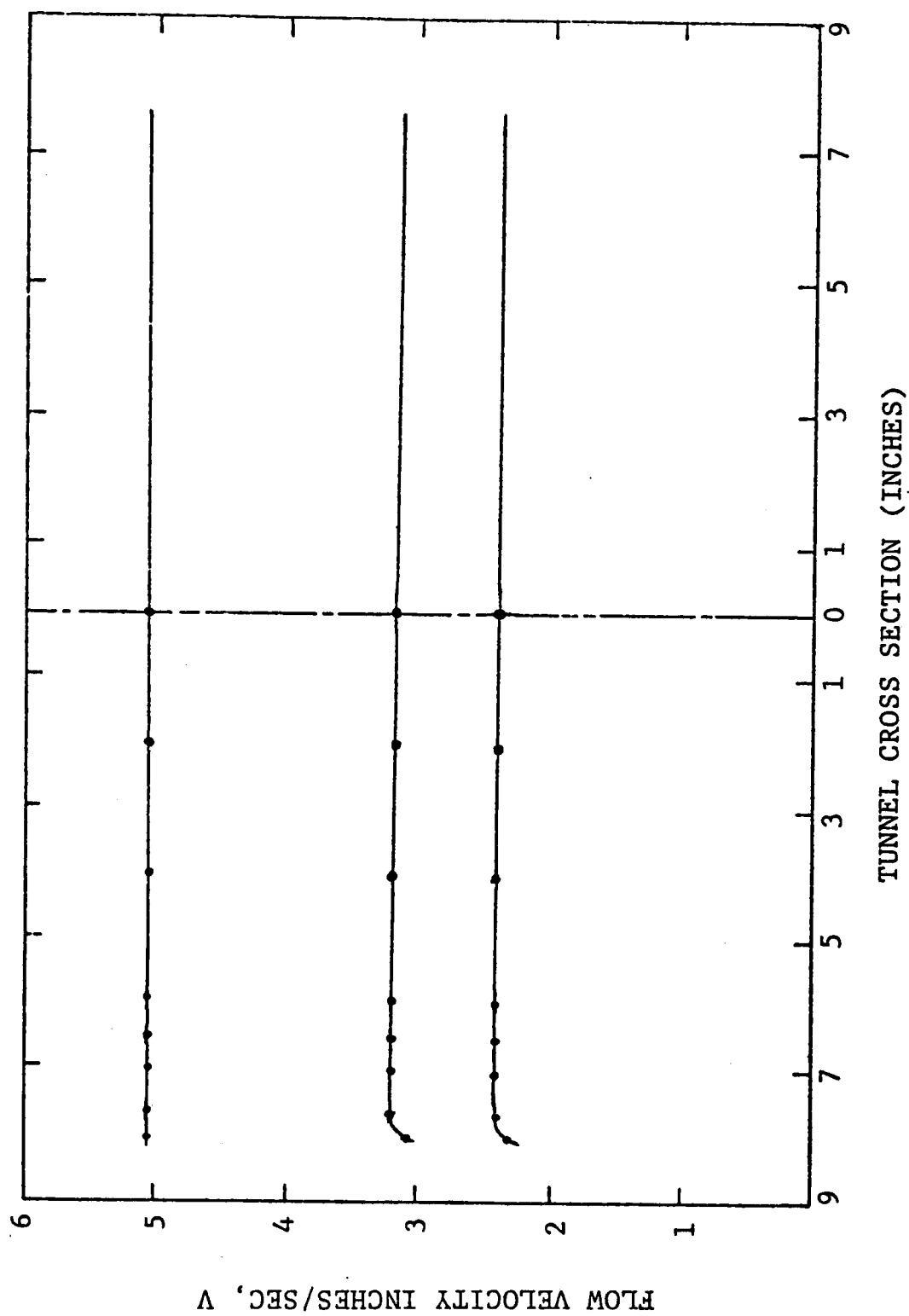


Figure 14. Tunnel Velocity Profile.

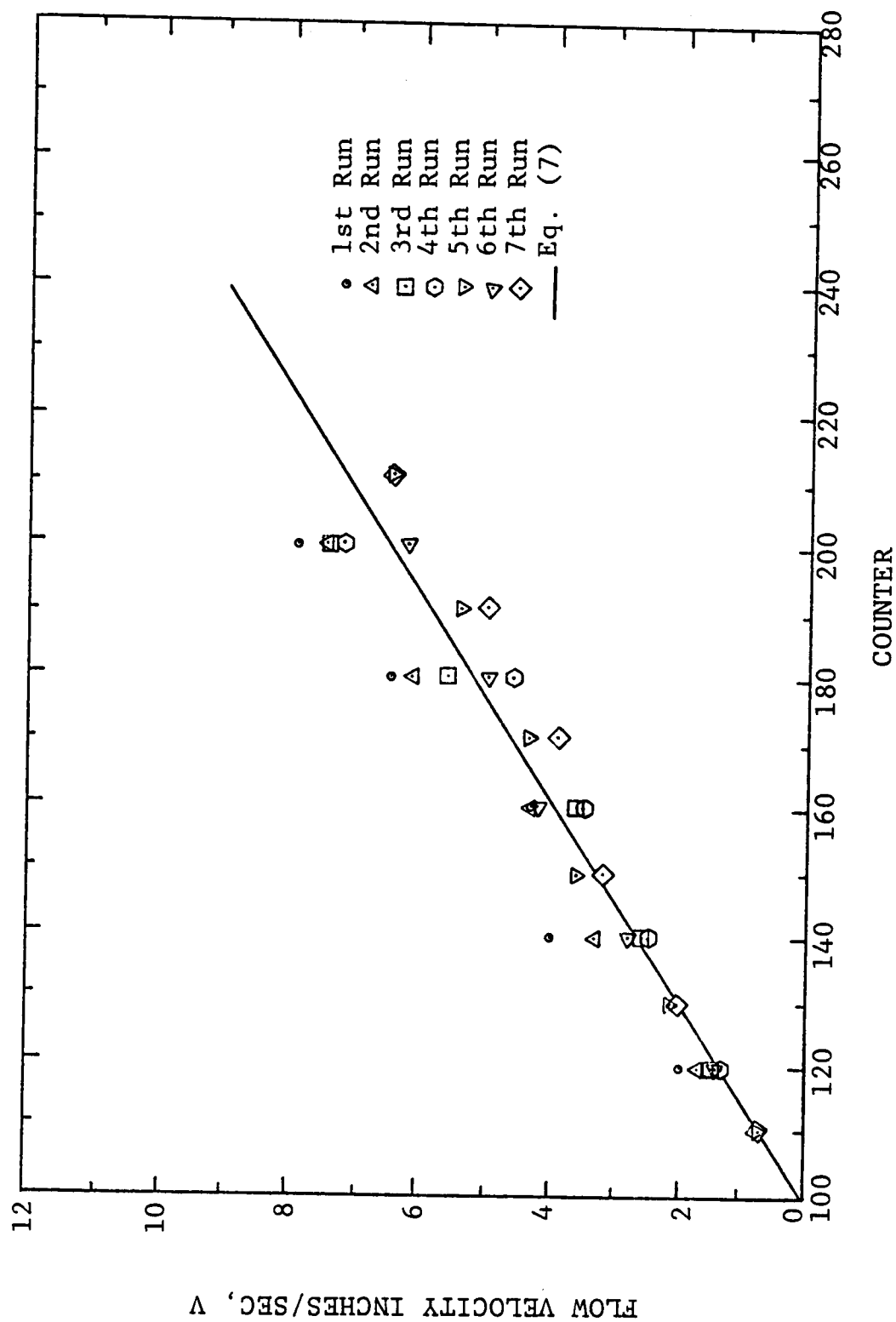


Figure 15. The Final Calibration Curve for the Tunnel.

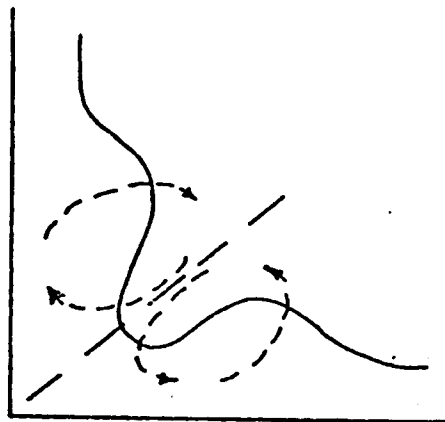
CHAPTER VII

CORNER FLOW

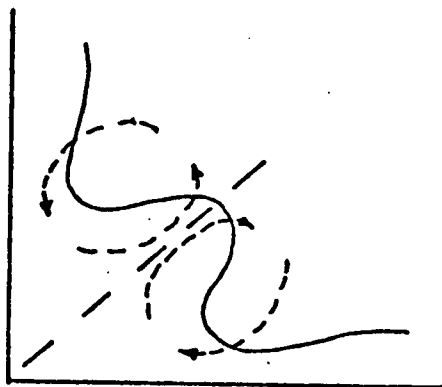
The streamwise flow along a corner formed by the intersection of two semi-infinite plates is related to the flow in the wing-body junction, wing-fin assemblies and the walls of a wind tunnel. The flow field in a corner is three-dimensional due to the viscous interaction of the boundary layers that develop on the two plates forming the corner.

Experimental evidence indicates the presence of secondary flows in the corner for both laminar and turbulent flow, although the mechanism for their creation is thought to be quite different. For turbulent flow, secondary motion in a corner is created by gradients of Reynolds stresses which lead to forces in the secondary flow plane which induce secondary velocities. For laminar flow, the secondary motion is thought either to be associated with the progressive changes in the form of the velocity profiles as the flow proceeds downstream or the result of a localized instability in the corner where the velocity profiles have points of inflection.

Figure 16(a) shows the secondary motion and associated isotach (line of constant velocity) for turbulent flow. Because the early theories involved the



(a) Turbulent Flow



(b) Laminar Flow

Figure 16. Secondary Motion in a Corner.

turbulent structure of the flow, it was thought that secondary motions did not occur for laminar flow.

The hot-wire measurements of Zamir and Young [3], however, showed its presence but in a rotational sense opposite to that of turbulent flow (Figure 16(b)). They concluded the presence of secondary motion from the shape of the isotachs. Transition to turbulent flow began at $Re_x = 6 \times 10^4$ and turbulent spots appeared at $Re_x = 2 \times 10^5$. They speculated that the secondary motions that were observed could have been the result of a flow instability that occurs before transition takes place. Therefore, experimental work at lower Reynolds numbers was required.

CHAPTER VIII

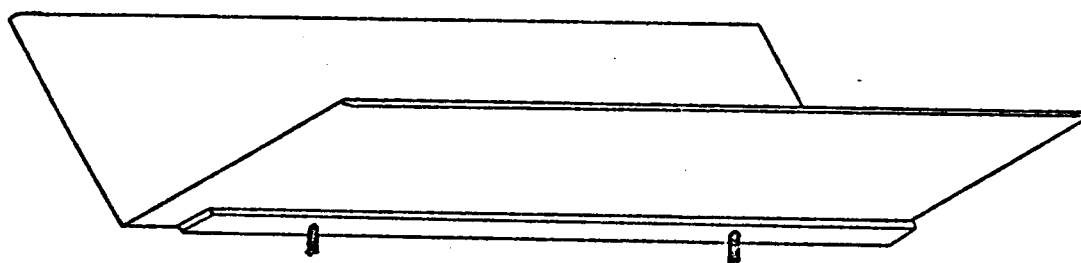
CORNER FLOW MODEL

The experimental setup consisted of two flat plates bolted onto an angle iron to form a right-angled corner. The leading edge was given an approximately elliptical shape with a ratio of major to minor axes of eight. The 2 plates formed a sharp corner at the joint (Figure 17).

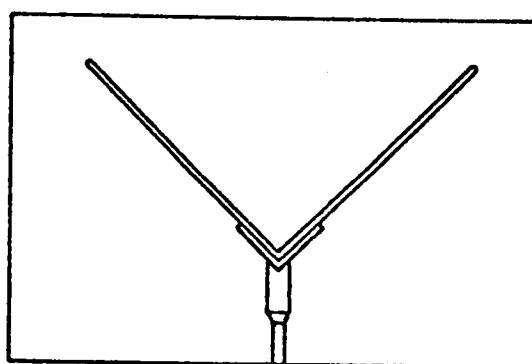
The model was made from $\frac{1}{4}$ -inch thick plates of Plexiglas and aluminum. Both materials are used in the as-delivered state and the surfaces were not ground. The model, which is shown in Figure 17, is 9.75 inches wide by 48 inches long. As shown in Figure 18, 46 pressure measuring orifices (0.040-inch inside diameter) were placed in the aluminum side.

The model was placed in the center of the water tunnel test section and was supported on two linear motion feedthroughs which are attached to the lower wall of the test section. The linear motion feedthroughs were used to align the model so that no streamwise pressure gradient would exist in the corner.

Hydrogen bubble generator wires were placed on the leading edge of the corner. The wires were positioned at 1-inch intervals horizontally, as shown in Figure 19.



(a) Isometric View



(b) End View Mounted in Tunnel

Figure 17. Corner Flow Model.

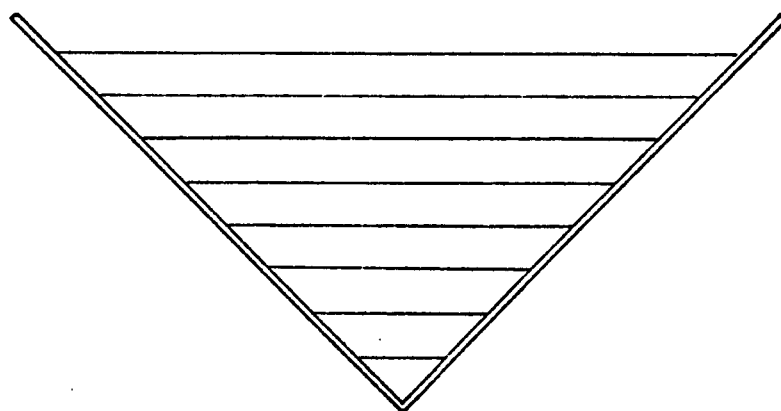


Figure 19. Horizontal Hydrogen Bubble Generator Wires.

The vertically positioned wires, which were also positioned at 1-inch intervals, are shown in Figure 20.

Three hypodermic needles were placed into the aluminum side for dye injection. The needles were located $8\frac{1}{2}$ inches from the leading edge of the corner and at distances of 0.10, 0.20 and 0.30 inches from the corner (Figure 18).

At a free stream speed of $1/3$ ft/sec, the boundary layer of a 48-inch long flat plate is about 0.7-inch thick. Therefore, the model has a minimum lateral extent of about 14 boundary layer thicknesses which is sufficient to eliminate edge effects.

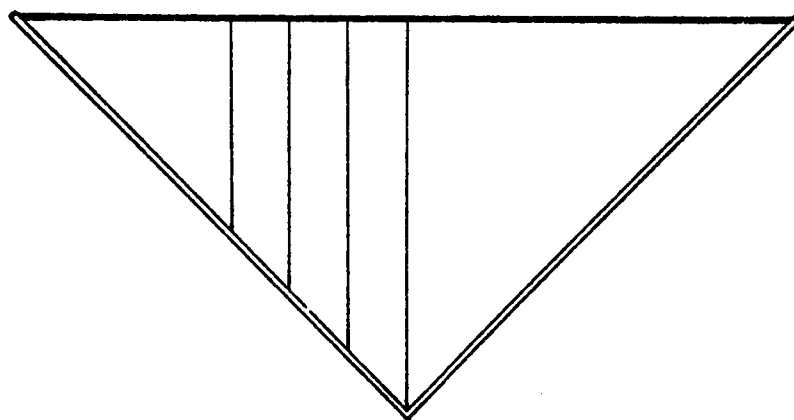


Figure 20. Vertical Hydrogen Bubble Generator Wires.

CHAPTER IX

RESULTS OF CORNER FLOW TESTS

The corner flow experiments were performed at a free stream velocity of 3.0 in/sec. This speed corresponds to a Reynolds number per foot of 2.0×10^4 . Zamir and Young [3] found that transition from laminar to turbulent flow began at a length Reynolds number of 6×10^4 . Therefore, the flow stayed laminar over the entire length of the model.

Hydrogen bubbles were generated from a 0.001-inch diameter monel wire. The sheets of bubbles proved too difficult to illuminate in the corner. Then the wire was corrugated by passing it through a pair of gears. The bubbles generated by the wire then came together and were released at the downstream peaks of the corrugations forming streaklines from these points. The streaklines were easier to photograph because of the increased number of bubbles. The hydrogen bubbles were generated with 50 to 100 volts between the wire and model and about 200 milliamps of current between the electrodes.

The manner in which the free stream flow proceeded over the model leading edge was visually examined by placing an 18-inch long monel wire oriented perpendicular to the corner bisection at a distance of $5\frac{1}{2}$ inches

upstream of the model and by injecting dye from a hypodermic needle which was placed at a distance of 3 inches from the model and oriented along the model axis. Both the hydrogen bubbles and the dye streaks (which were emitted with the tube at various distances above and below the model axis) indicated that the flow was uniform before the model and then it passed smoothly over the model, without separation or skewing, when the model was properly aligned with the tunnel flow.

The wires were placed horizontally at 1-inch intervals on the leading edge of the corner. The bubbles were illuminated from the side with 2 quartz lamps (3400K bulbs). They were photographed, using Kodak tri-x pan film with a motorized Canon A-1 camera. The pictures were taken in the shutter priority AE mode at a shutter speed of 1/90 sec. It was difficult to photograph the bubble sheets in the blackened corner. The wires were placed at both 1-inch and $\frac{1}{4}$ -inch intervals vertically on the leading edge of the corner. In this case it was difficult to get sufficient light in the darkened corner to illuminate the bubbles. The bubbles could be seen for about 20 inches into the corner and then they were absorbed into the water. The wires were replaced after each run.

To better examine the flow in the corner, dye streaks were used. The dye consisted of a mixture of milk, alcohol, and food coloring. The dye was ejected from the pressure measuring orifices which were $5\frac{1}{2}$, $12\frac{1}{2}$ and $22\frac{1}{2}$ inches from the leading edge and $\frac{1}{2}$, 1.12, 1.75 and 4.75 inches from the centerline of the corner. Dye was also emitted from the 3 hypodermic needles which were embedded in the aluminum plate at $8\frac{1}{2}$ inches from the leading edge and 0.1, 0.2 and 0.3 inches from the centerline of the corner. The dye was fed by a regulated pressurized air line. It was emitted at a speed sufficient that the streaks did not become unstable due to their own flow.

The dye streaks could be seen along the entire length of the model. Red, green and yellow colored dyes were tried and it was found that the yellow dye gave the best result for photography. Kodak ASA 400 color film was used to photograph the streaks with the camera set at a shutter priority AE mode speed of 1/60 sec.

Figure 21 shows the hydrogen bubble streaklines that are generated by the first and third horizontal wires. The second and fifth hydrogen bubble streaklines are shown in Figure 22. Figure 23 shows the fourth and sixth hydrogen bubble streaklines. Figure 24 shows the fifth, seventh and eighth hydrogen bubble streaklines.



Figure 21. Hydrogen Bubble Streaklines from Wires One and Three.

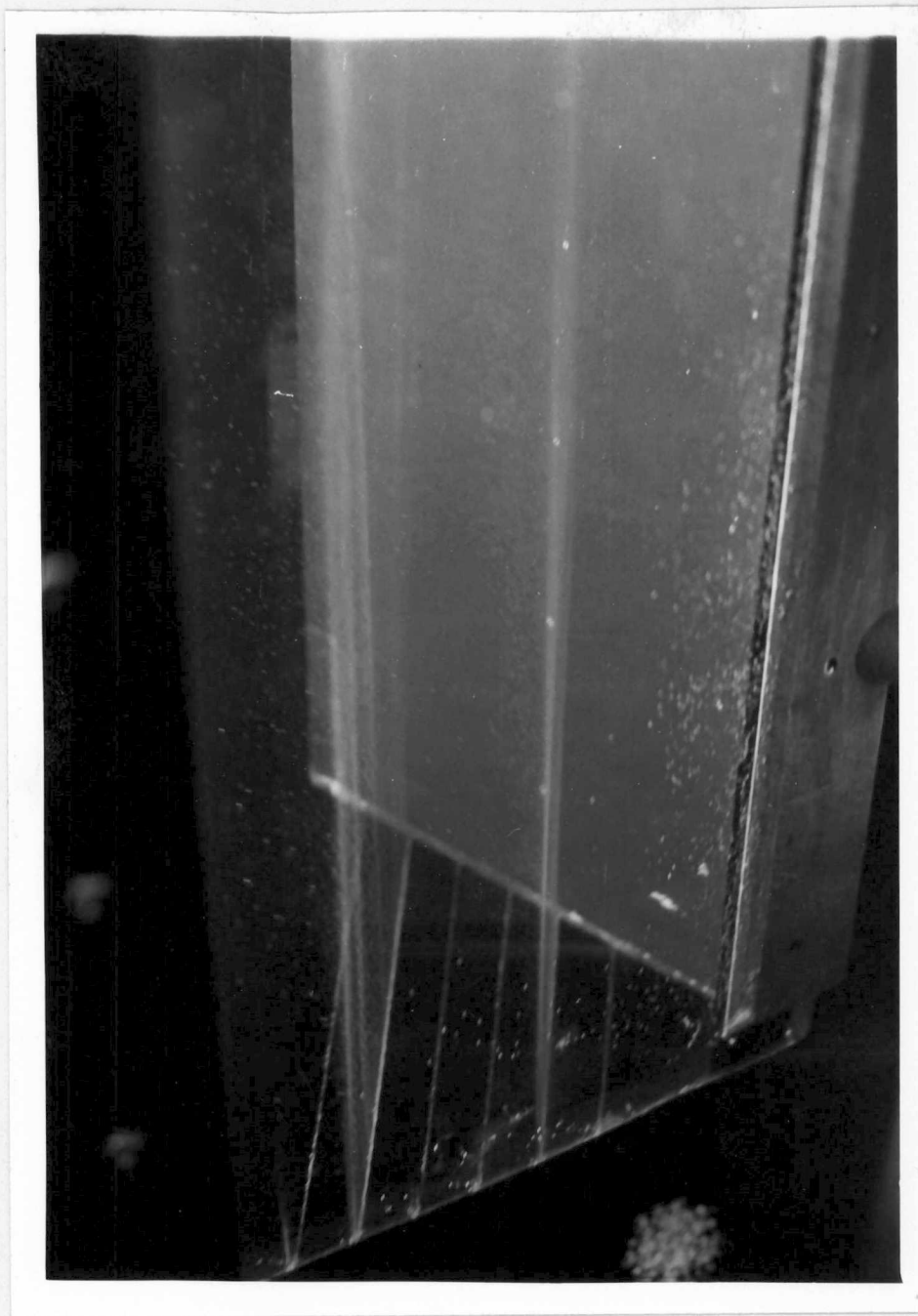


Figure 22. Hydrogen Bubble Streaklines from Wires Two and Five.



Figure 23. Hydrogen Bubble Streaklines from Wires Four and Six.

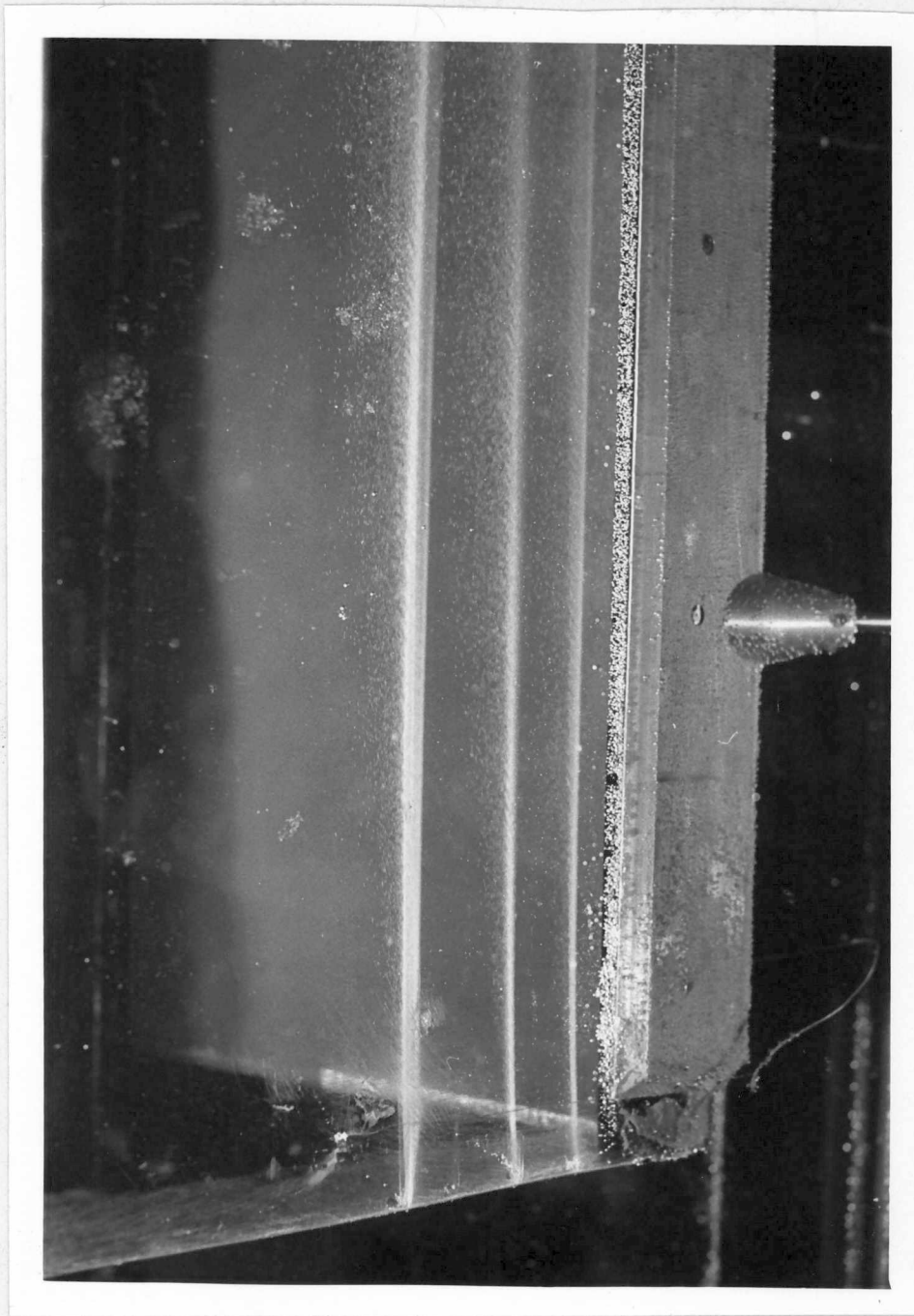


Figure 24. Hydrogen Bubble Streaklines from Wires Five, Seven and Eight.

Figure 25 shows the vertical hydrogen bubble streaklines. It can be observed from Figures 21 through 25 that there is no indication of secondary motion in the corner.

Figures 26 through 29 show the dye streaklines. Figure 26 shows the streakline being ejected from the orifice which is at 1.75 inches from the corner center. Figures 27, 28 and 29 show the dye streaklines emitted from the 0.5, 0.3 and 0.1-inch orifices from the corner center. From these photographs it can be observed that none of the streaklines examined showed any indication of the presence of secondary motion in the entire length of the model. These results indicate that secondary motion does not exist in a laminar corner, contrary to the measurements of Zamir [3].

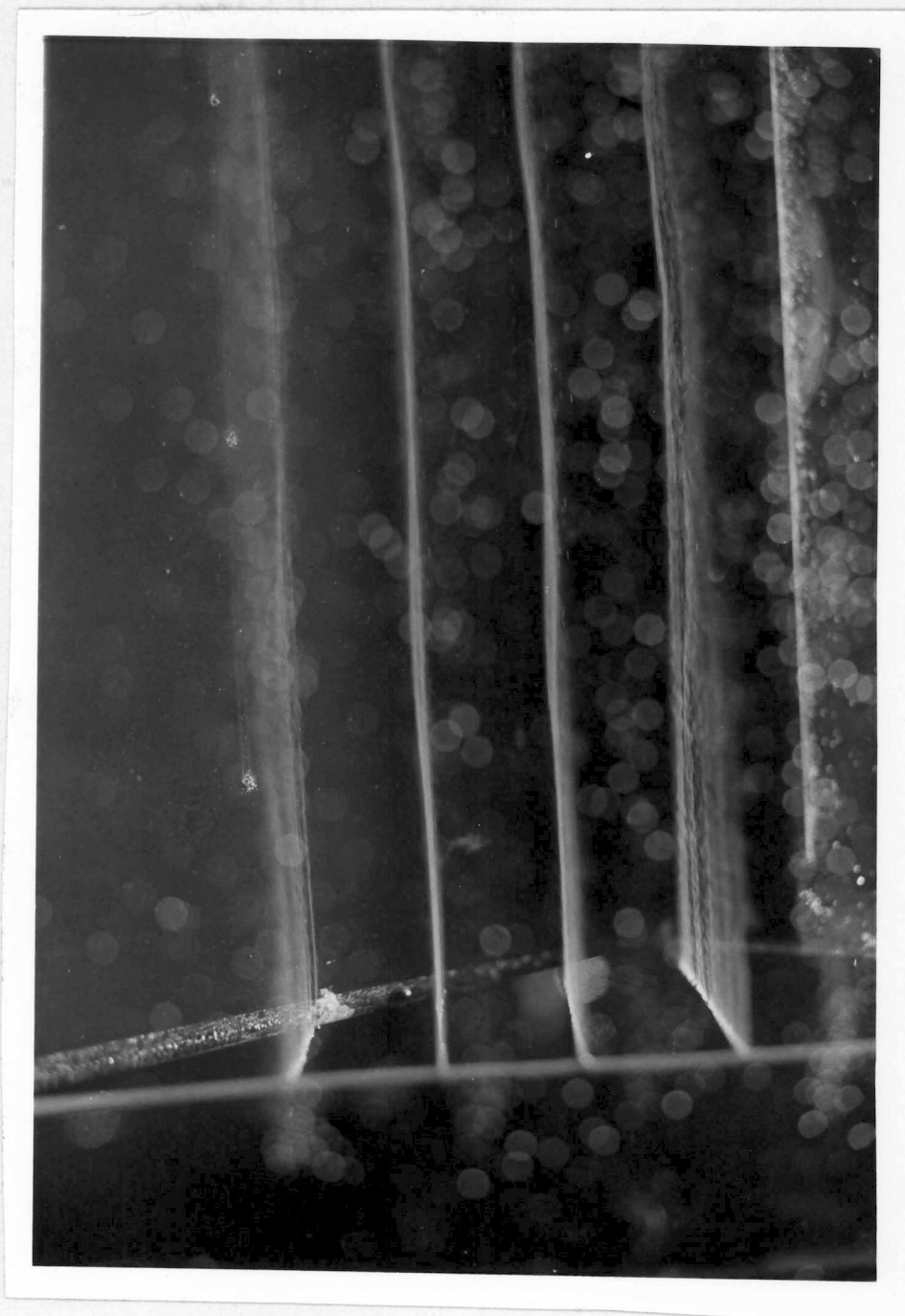


Figure 25. Vertical Hydrogen Bubble Streaklines.



Figure 26. Dye Streaklines Orifice 1.75 Inches from Corner Center.

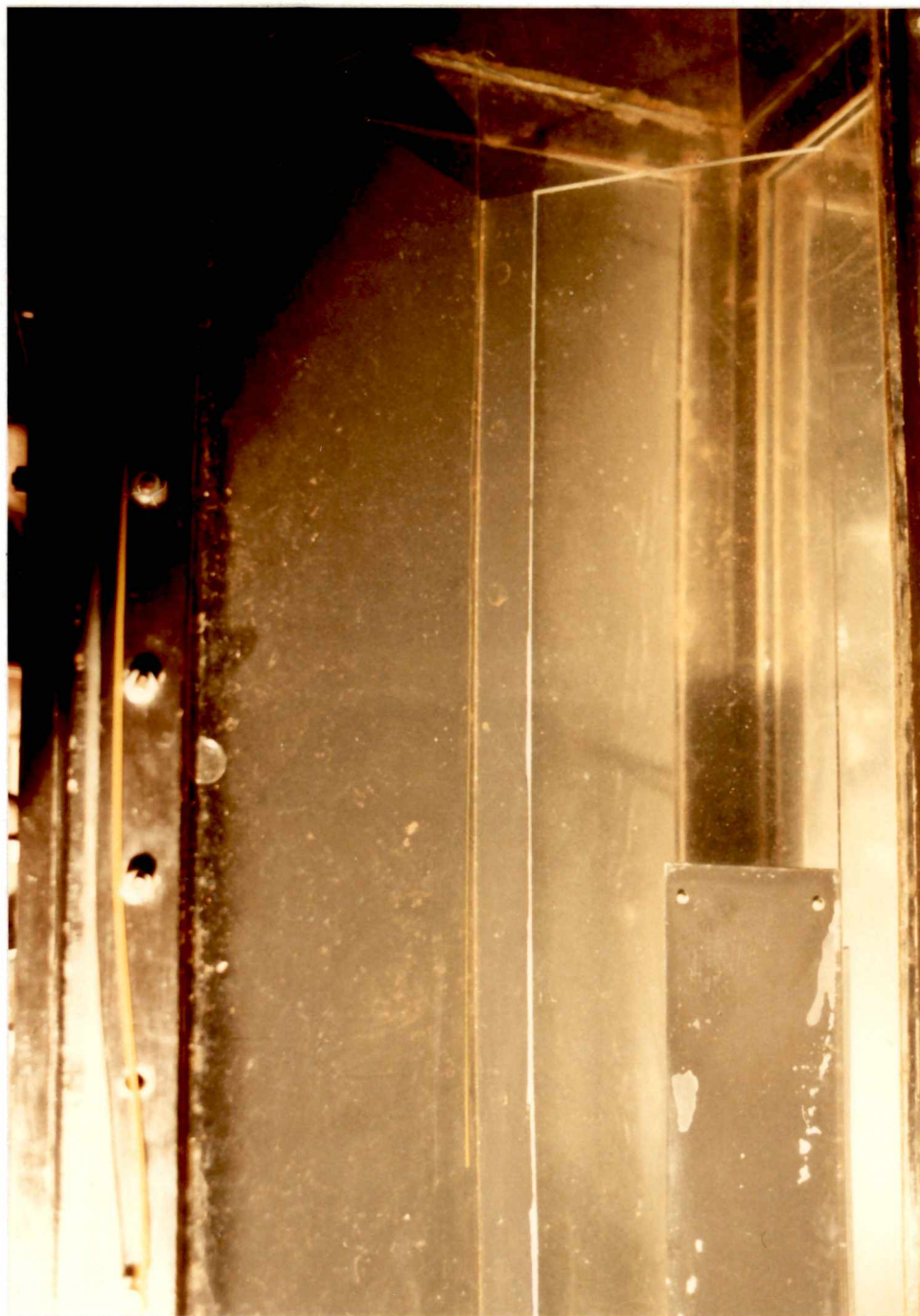


Figure 27. Dye Streakline Orifice 0.5 Inch from Corner Center.

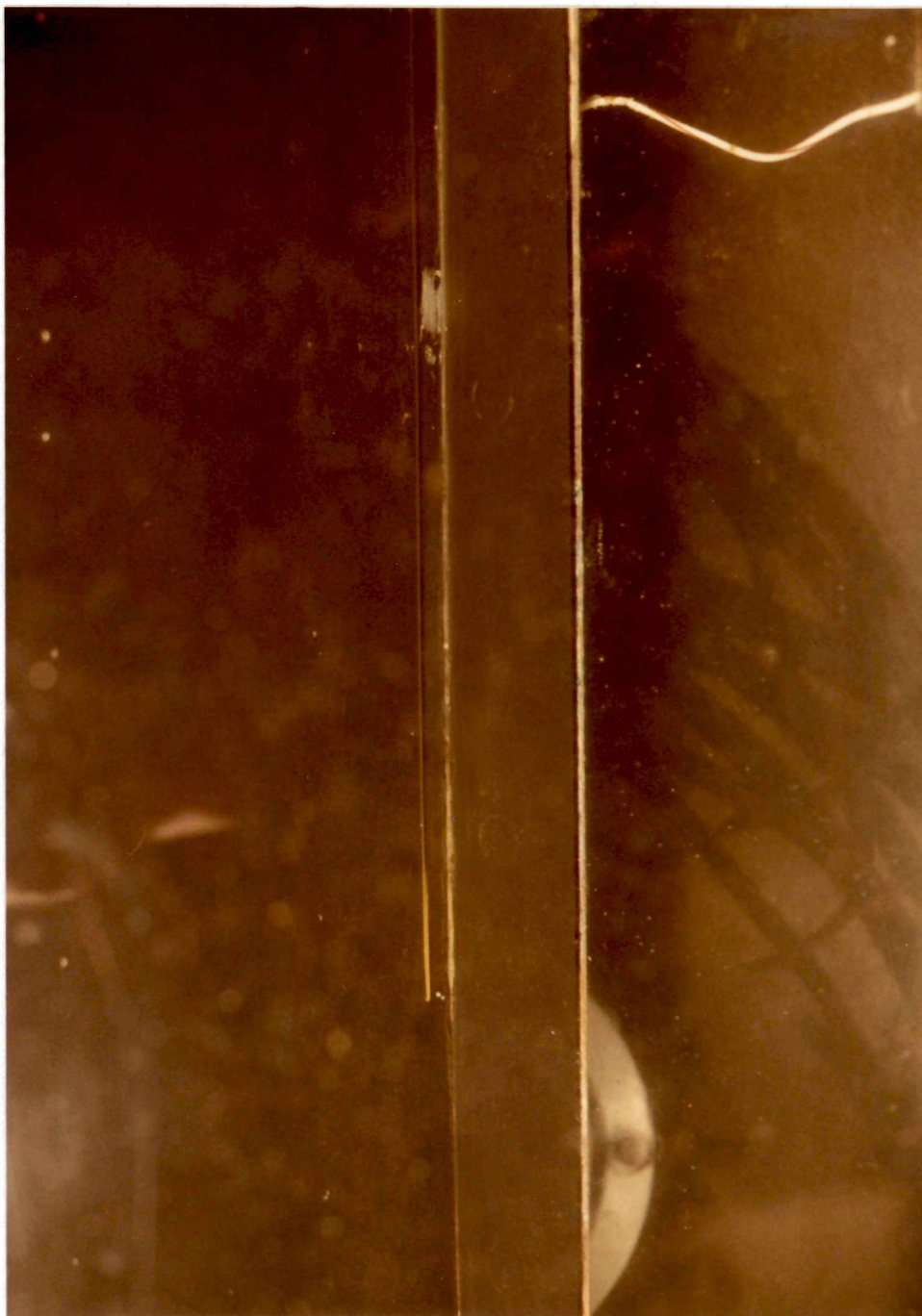


Figure 28. Dye Streakline Orifice 0.3 Inch from Corner Center.

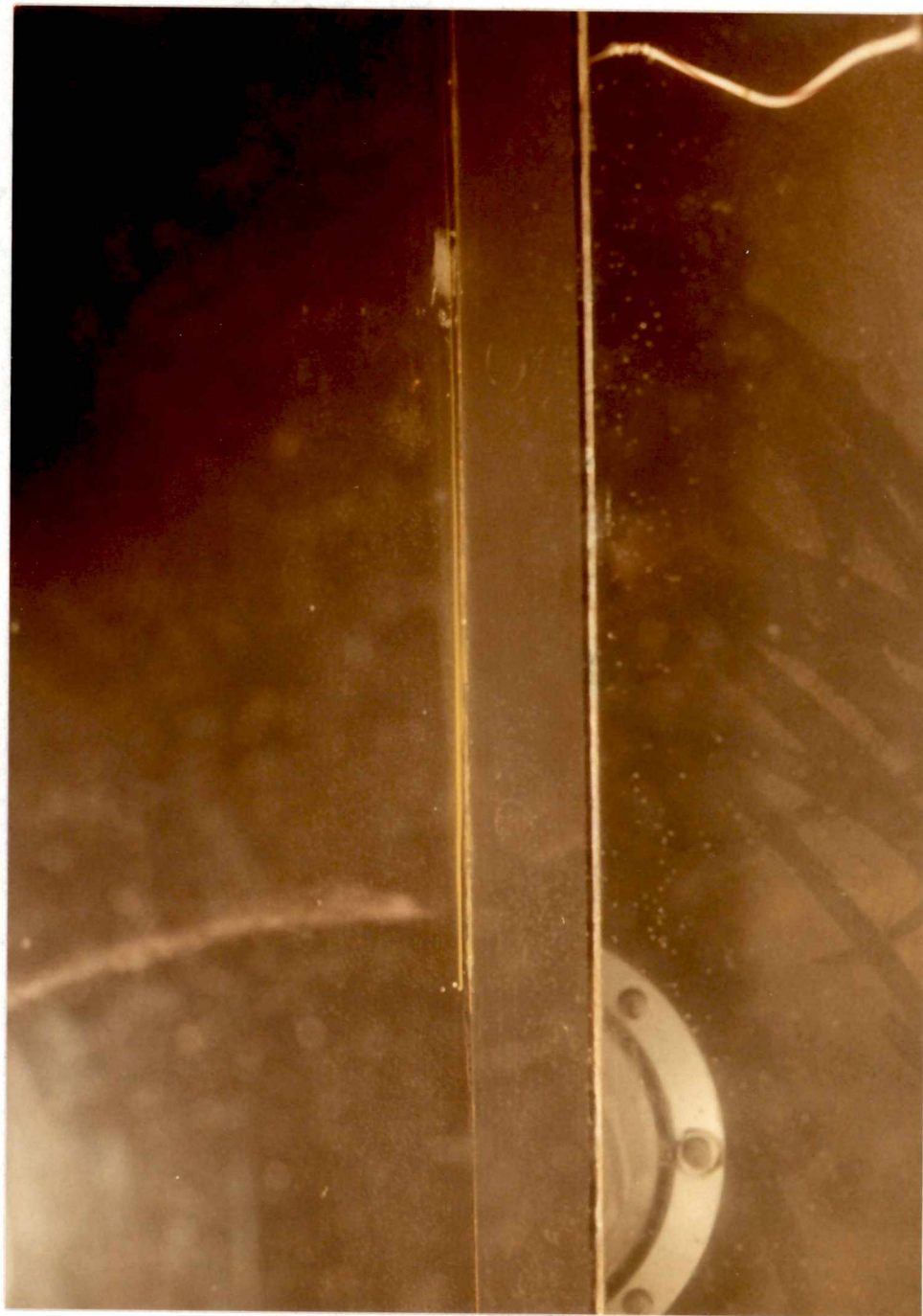


Figure 29. Dye Streakline Orifice 0.1 Inch from Corner Center.

CHAPTER X

CONCLUSION

A satisfactory calibrator for calibrating hot-film probes for use in water over the velocity range of 0.2 to 20 in/sec was designed and constructed. This unit satisfactorily calibrated the probe and worked without any problems. The calibrated probe was then used to measure the flow in the water tunnel. It was found that it was very important to have a good seal in the probe-to-probe support connection to keep moisture out. Small amounts of moisture led to completely erroneous velocity measurement. The turbulence level which was measured was within the predicted values for the water tunnel and the velocity profiles were straight.

The flow visualization techniques of hydrogen bubbles and dye injection were used to examine the laminar flow in a corner. Within the limitation of the detection techniques employed, no vortices or secondary motions were found to exist for the laminar corner flow.

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