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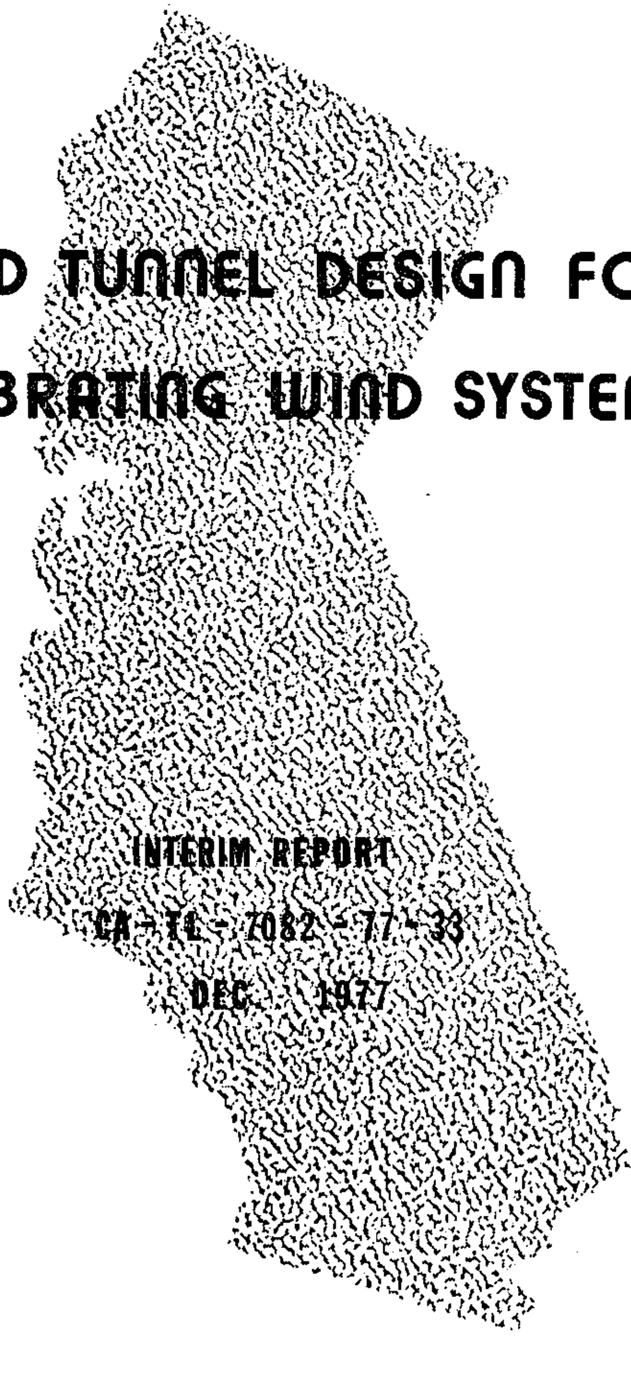
TRANSPORTATION LABORATORY

RESEARCH REPORT

WIND TUNNEL DESIGN FOR CALIBRATING WIND SYSTEMS



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DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

December 1977

TL No. 657082

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this interim research report titled:

WIND TUNNEL DESIGN FOR
CALIBRATING WIND SYSTEMS

Study made by .... Enviro-Chemical Branch

Under the Supervision of .... Earl C. Shirley, P. E.
and
Carl R. Sundquist, P. E.

Principal Investigator .... Andrew J. Ranzieri, P. E.

Co-Investigator .... Kenneth O. Pinkerman, P. E.

Report Prepared by .... Donald L. Poelstra, P. E.
and
Kenneth O. Pinkerman, P. E.

Very truly yours,

GEORGE A. HILL
Chief, Office of Transportation Laboratory

DLP/AJR:bjs
Attachment

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Also special acknowledgement is given to Wesley E. Faist of the Engineering, Administration, and Services Branch for his efforts and cooperation in housing and installing the wind tunnel at the Transportation Laboratory. The assistance of Orvis D. Box in preparation of this report is appreciated.

INTRODUCTION

The assessment of the impact of transportation systems on the air environment requires the quantitative prediction of pollutant concentrations. To estimate concentrations of air pollutants requires knowledge of a large number of variables, a major variable being wind speed. All air quality models presently used by Caltrans are sensitive to wind speed(1,2,3,4,8). Generally, the lower the wind speed, the higher the pollutant concentrations. In order to have air quality models predict with a high degree of accuracy, it is necessary to reduce the uncertainty of the input variables. In many of Caltrans' air quality studies, mechanical weather stations are used to supplement the existing historical meteorological data sources and to provide information on the micro-meteorology of a specific study area. These stations give wind speed, wind direction, and temperature information.

In order to add credibility to monitored field data and the results from the analyses of these data, it is necessary to have instruments that are accurately calibrated. The most common and widely used method for calibrating meteorological systems is in a wind tunnel. Another possible use of wind tunnels is to predict air quality for special plume dispersion studies. By using similarity theory in conjunction with the wind tunnel, air flows around and over various types of obstructions consistent with certain land uses and highway structures can be simulated. These air flows and their characteristics can be used in air quality models to predict pollutant concentrations for complex terrain areas.

This report discusses the basic design and construction of a wind tunnel system including the description and function of each section. The tunnel was designed to make maximum use of an existing wind tunnel previously used by the Transportation

Laboratory to test traffic cones under windy conditions (winds in excess of 40 mph). Although crude in its design, certain portions of the system were salvaged and utilized to minimize costs. The modifications to the existing tunnel and the design of the sections that were added to provide a wind tunnel with acceptable air flow characteristics are discussed.

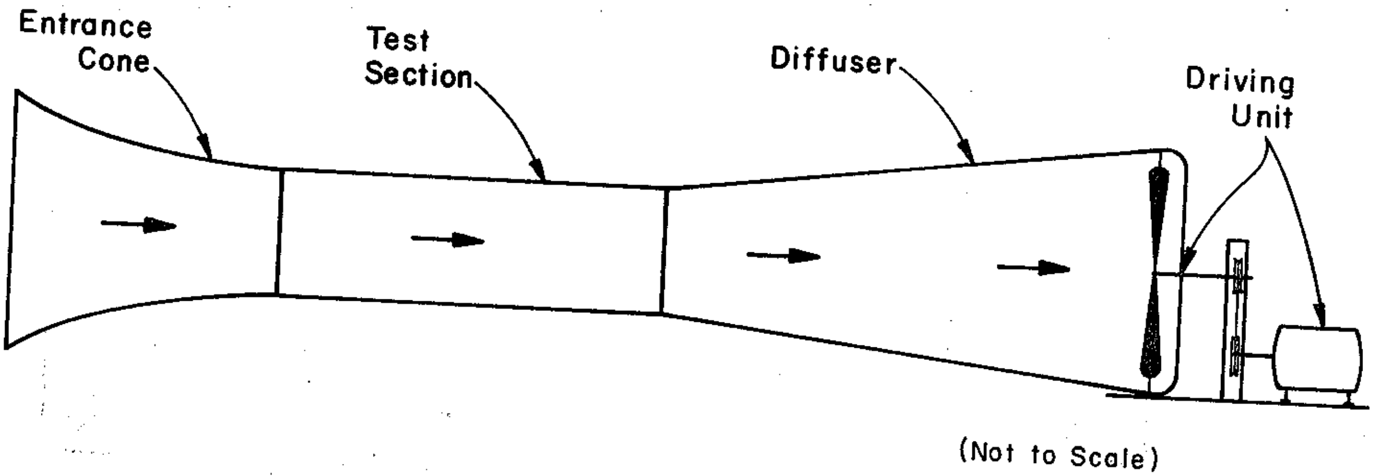
The wind tunnel described in this report has been used to calibrate mechanical weather stations for the past year and a half. These instruments should be calibrated at least once a year when they are in service. Caltrans has approximately 100 mechanical weather stations.

WIND TUNNEL CONCEPTS

There are two basic approaches to wind tunnel configuration. They are open-circuit tunnels and closed-circuit tunnels. The open-circuit tunnel has no guided return of the air (see figure 1). After the air leaves the system, it is not recirculated unless the system is completely enclosed in a room or building, in which case the air circulates by devious paths back to the intake. In most open-circuit systems however, the tunnel either draws or exhausts directly to the atmosphere. Except for the induction-type high-speed tunnel and a few special-purpose tunnels, the open-circuit arrangement is rarely employed, largely due to its dependence on weather conditions. The closed-circuit or "return-flow" tunnel has, as the last name implies, a continuous path of air (see Figure 2).

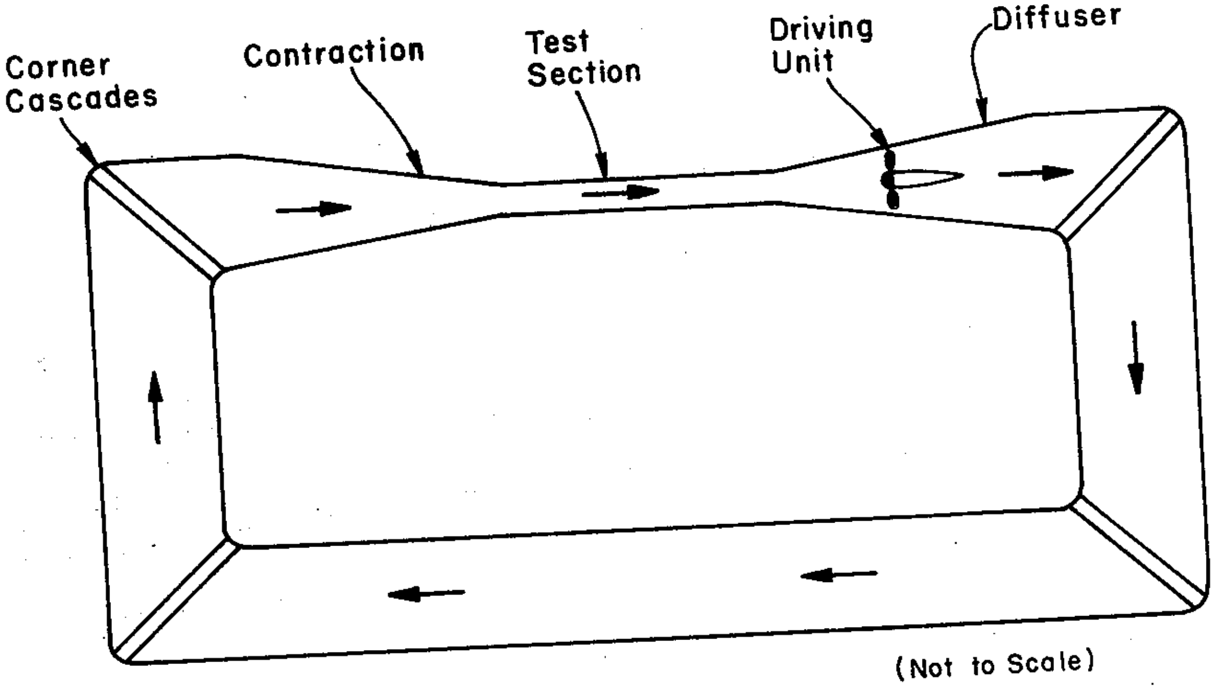
The design used by the Transportation Laboratory was based on the open-circuit system because of space and facilities available. All open-circuit wind tunnels have four basic components as shown in Figure 1. Each is described in detail below.

<u>The Entrance Cone or Contraction</u> - This section is located upstream of the testing area. In this section the air is accelerated approximately from rest at the entrance to the conditions required at the testing section. The Entrance Cone may contain or be preceded by screens or other devices to help reduce turbulence and produce a uniform airstream. (See Figure 3.)



OPEN-CIRCUIT WIND TUNNEL SYSTEM
ELEVATION VIEW

Figure 1



CLOSED-CIRCUIT WIND TUNNEL SYSTEM
PLAN VIEW

Figure 2

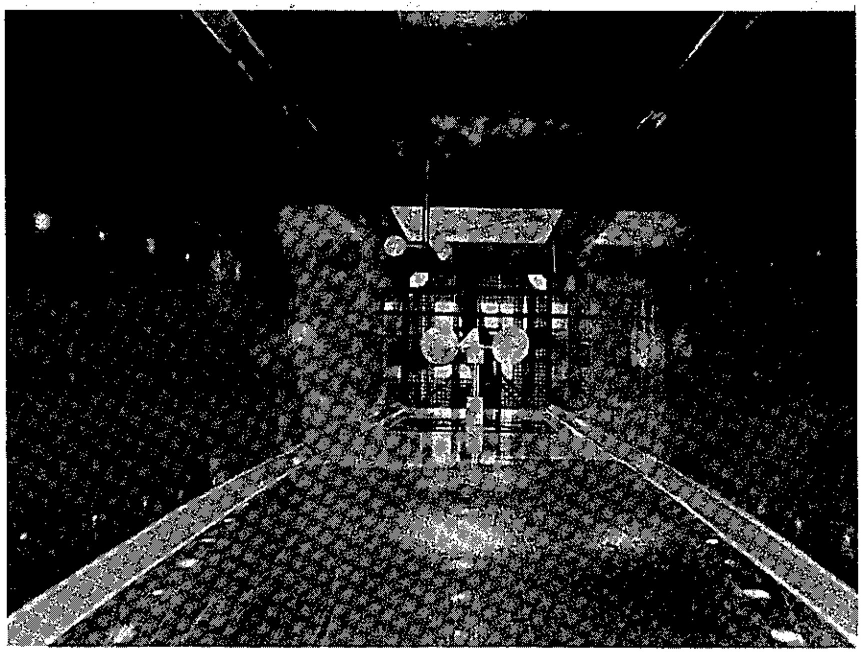


Figure 3

View of interior of wind tunnel looking through the entrance cone to the test section with anemometer in place for testing.

The Test Section - This section is where the instrument to be calibrated is placed and the required observations are made. In a closed-throat tunnel, this section is bounded by rigid walls. (See Figure 4.)

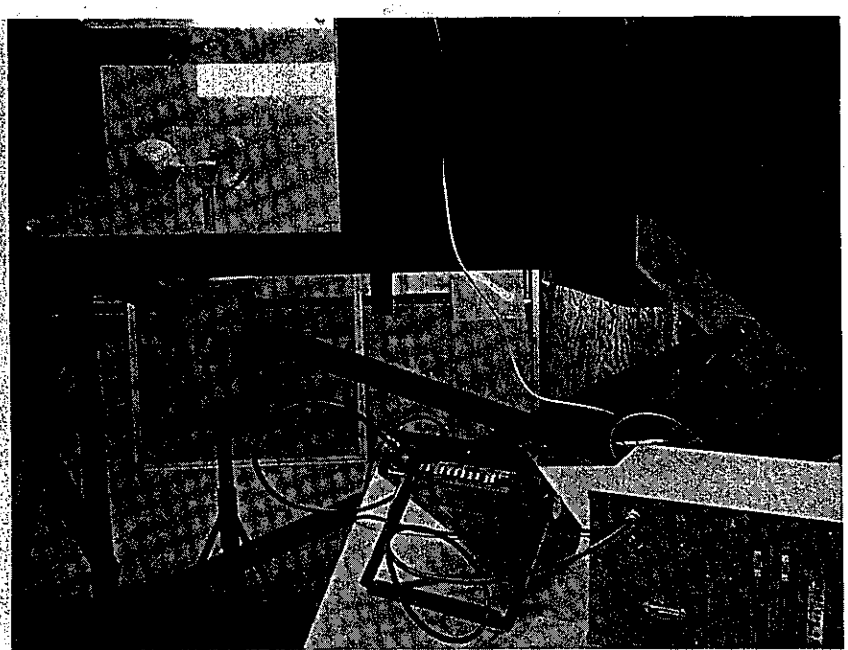


Figure 4

View of test section from outside with anemometer in place. Voltage meter and manometer in foreground are used to check calibration.

The Diffuser - This section converts the kinetic energy of the air-stream back into pressure energy as efficiently as possible to minimize air flow separation and upstream turbulence.

The Driving Unit - The fourth component is the driving unit, which is necessary to maintain the flow. In low speed systems this is usually done by means of a fan or propeller. (See Figure 5.)

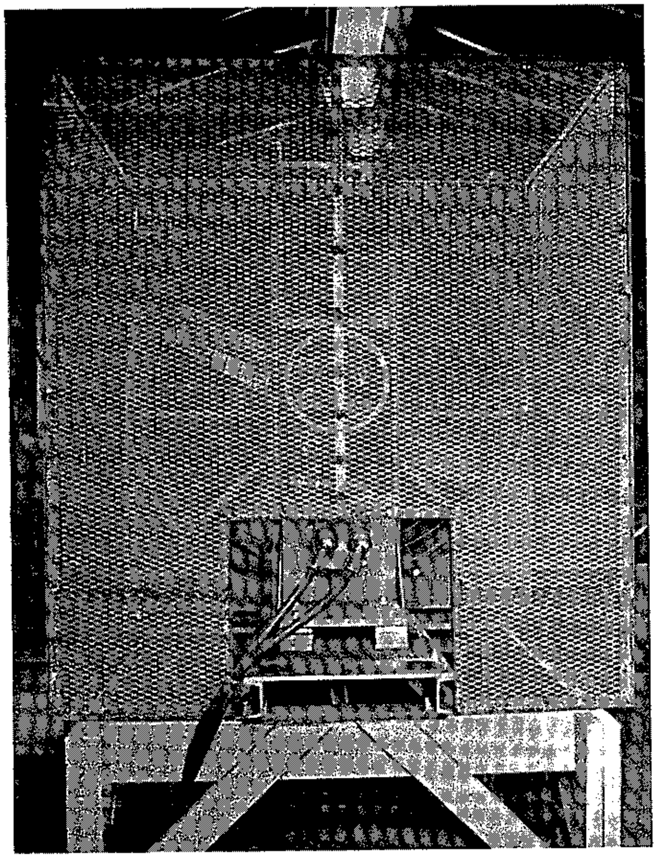


Figure 5

Fan used as driving unit for air flow through wind tunnel.

WIND TUNNEL DESIGN

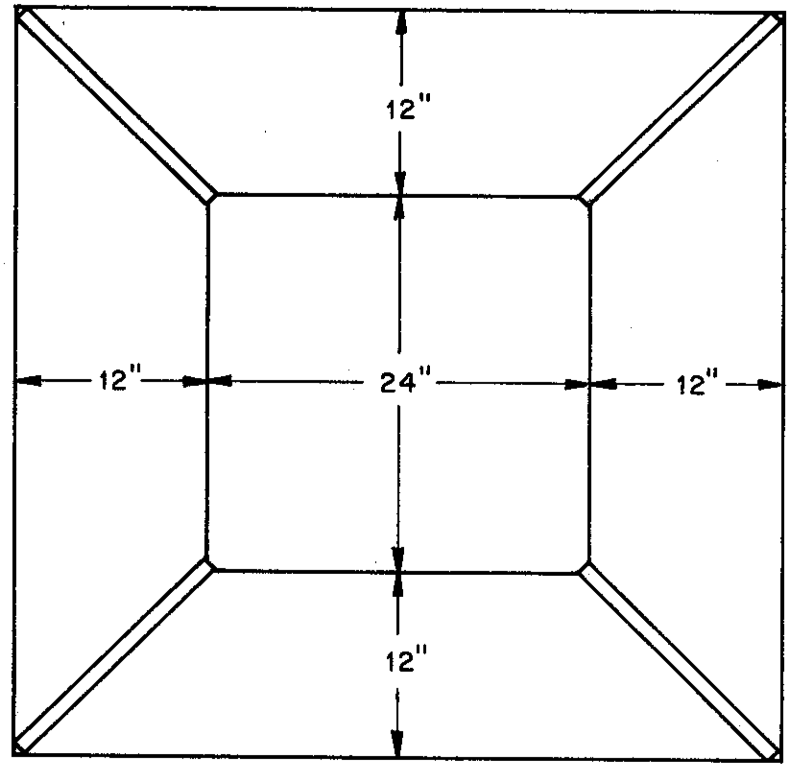
This discussion describes the design of modifications required to make the existing wind tunnel capable of calibrating wind systems. The design approach used was based on references (5) and (6). The two sections of the existing tunnel which were redesigned are the contraction (entrance cone) and the test section (working section). The old driving unit was replaced with a new one that could provide air flows as low as 5 mph.

Contraction

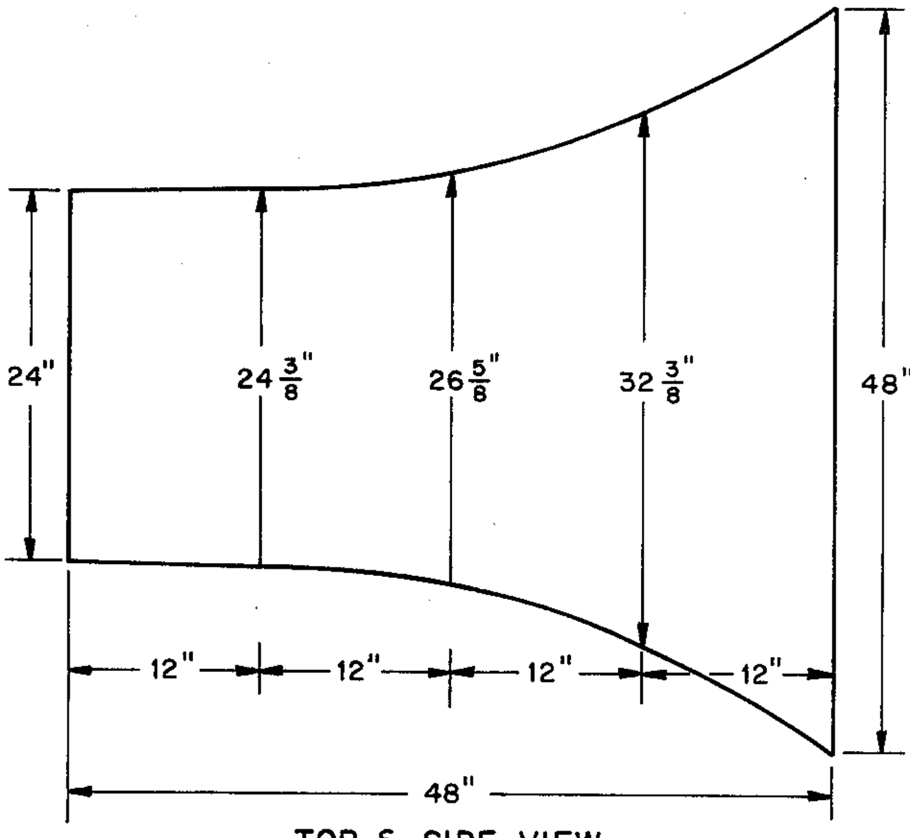
The purpose of the contraction section is to reduce spatial irregularities in the velocity distribution across the working section(5). In addition the contraction enhances the performance of inlet screens as they reduce eddy turbulence to very small scale especially at low Reynolds Number. Ideally a contraction should produce a uniform velocity distribution at exit (the working section), should have velocity gradients which are positive everywhere along its wall (or insufficiently negative to cause separation of the boundary layer), and should be of reasonably short length(5). See Figures 1 and 3.

The majority of existing wind tunnels have a contraction ratio of about 4 to maintain a well streamlined flow field. The contraction ratio is defined as the cross-sectional area of the entrance divided by the cross-sectional area of the test section.

Because of the limited space to house the wind tunnel and the low velocities required for calibration, a 4 to 1 contraction ratio was used in the design. It is recommended(6) that the length of the contraction be equal to about 1.5 diameters of the testing chamber diameter. Since the testing chamber is a 2 ft x 2 ft square section, an equivalent diameter was calculated. This equivalent diameter was 2.3 ft. This called for a length of contraction of about 3.5 ft. In order to construct a smooth warp section, the length of the contraction



END VIEW
Figure 6



TOP & SIDE VIEW
Figure 6A

was made to be 4 ft. The contraction is curved sharply at first and then gradually as the test section is approached. Figures 6 and 6A show the plan for the contraction with all pertinent dimensions.

Test Section

The length of the test section was based on the recommendation that the length be approximately 3 times the diameter. The cross-sectional area of the throat of the testing section was predetermined by the dimensions of the existing diffuser section. The equivalent diameter is 2.3 ft. The ideal total length would have been about 7 ft, however, because of space and construction materials used, the length of the working section was made to be 6 feet. An important consideration was given to minimizing the boundary effects on the air flow. To achieve this all 90° corners were rounded and all sides of the tunnel sections were varnished to maintain a uniform air flow through the system. Screens were also placed at the opening and behind the working section to reduce localized turbulence and provide a uniform flow field. Turbulence introduced by a screen is isotropic and this improves the performance of the contraction. Size of the screen mesh was determined by the pressure drop coefficient.

The pressure drop coefficient K is defined by the equation

$$K = \frac{P_1 - P_2}{1/2\ \rho v^2} \qquad (1)$$

Where P_1 and P_2 are the pressures upstream and downstream of the screen respectively, ρ is the air density, and v is the velocity.

Where a screen is to be used for reducing the nonuniformity of a steady flow, it is recommended(5) that the pressure drop coefficient be on the order of 2.0. A #20 mesh screen has a pressure drop coefficient(5) of 2.0 at standard atmospheric conditions and a velocity of 30 ft/sec. Since stainless steel is the strongest of wire meshes, #20 stainless steel wire mesh was selected. As a safety feature, the screen at the opening helps keep out any foreign material that might damage the instruments. The screen behind the working section helps keep any instrument or parts of instruments that become detached from being damaged by the fan.

A check was made to determine if laminar or turbulent flow existed in the test section for the minimum wind speed of 5 mph. The flow regime was determined using the Reynolds Number for a non-circular section:

$$R = \frac{V(4R_n)}{\nu} \tag{2}$$

Where R = Reynolds Number
V = velocity
R_n = hydraulic radius, area of flow divided by wetted perimeter
ν = kinematic viscosity

This equation gives satisfactory results for turbulent flow but, if used for laminar flow, large errors are introduced(5). If the Reynolds Number is less than about 1600, the flow is laminar; however if it is greater than about 4000, it is said to be turbulent. In light of the above foregoing discussion, equation (2) is used to calculate the order of magnitude of the Reynolds Number to determine the flow regime.

The calculated Reynolds Number in this case, is about 1.0×10^5 or about 2-1/2 times the order of magnitude of the lower limit of turbulent flow. It is reasonable to assume that for the minimum wind speeds the flow will be turbulent (small scale) and a uniform wind flow field will exist away from the boundary layer effects. Details of the Reynolds Number calculation is given in Appendix A.

Diffuser

The diffuser used for this wind tunnel was from an existing wind tunnel. It is recommended that whole angles of divergence from 5 to 7 degrees be used for the diffuser section(5,6).

The existing diffuser section has a whole angle of 14 degrees plus or minus and goes from a cross-sectional area of 4 ft^2 to approximately 14 ft^2. Comparing these figures with those in reference 5, page 56, indicates that the efficiency of 0.8 is achieved. The efficiency No. is defined by the equation

$$N_D = \frac{P_2 - P_1}{1/2\ \rho v_1^2 - 1/2\ \rho v_2^2} \qquad (3)$$

Where P_1 and P_2 are the pressures at the beginning and end of the diffuser respectively. V_1 and V_2 are the velocities, and ρ is the air density.

Because of the lower wind speeds required to calibrate wind systems for air quality predictions, the possibility of air flow separation in the diffuser section will be minimal. Therefore, since this is an open system, the whole angle of 14° with an efficiency of 0.80 was accepted as adequate.

Driving Unit

The driving unit consists of three main parts: (1) The Fan or Propeller Assembly, (2) The Hydraulic Motor, and (3) The Hydraulic Power Unit.

The Fan Assembly utilized is actually part of the driving unit from the wind tunnel used for traffic cone testing. The old driving unit was capable of only one fixed speed and consisted of a 10 hp-3 phase 220 volt motor capable of 1200 RPM, plus the Fan Assembly. The fan has four fixed-pitch blades and was joined to the motor by a shaft, V-belts and pulleys. This, of course was not suitable for use in the calibration of wind instruments. A unit with a variable speed control was required. Analysis of the requirements for speed and control resulted in the purchase of a Hydraulic Motor (Vickers #MFB-20-V-10) which is of axial piston, fixed displacement, variable horsepower, in-line design.

The Hydraulic Power Unit is comprised of a Vickers #PVB-15 hydraulic pump driven by a 15 HP, 1800 RPM, 208 Volt AC, 3 phase, 60 cycle, open drip-proof Baldor Electric Motor. The pump is of axial piston, variable displacement, in-line design. Displacement is varied by means of a pressure compensator which accurately controls the output rpm of the hydraulic motor and is operated remotely from both the power unit and the hydraulic motor. The hydraulic power unit also includes a filler-breather-strainer, an oil level site gauge a 25 micron oil filter, a 2000 psi pressure relief valve, and an electric motor starter, all mounted and plumbed on a 45 gallon oil reservoir.

The complete driving unit described above is continuously variable from 100 rpm to 1000 rpm and has a maximum capability of 780 in.-lbs torque. This is equivalent to approximately 1 1/4 H.P. at 100 rpm and 13 H.P. at 1000 rpm.

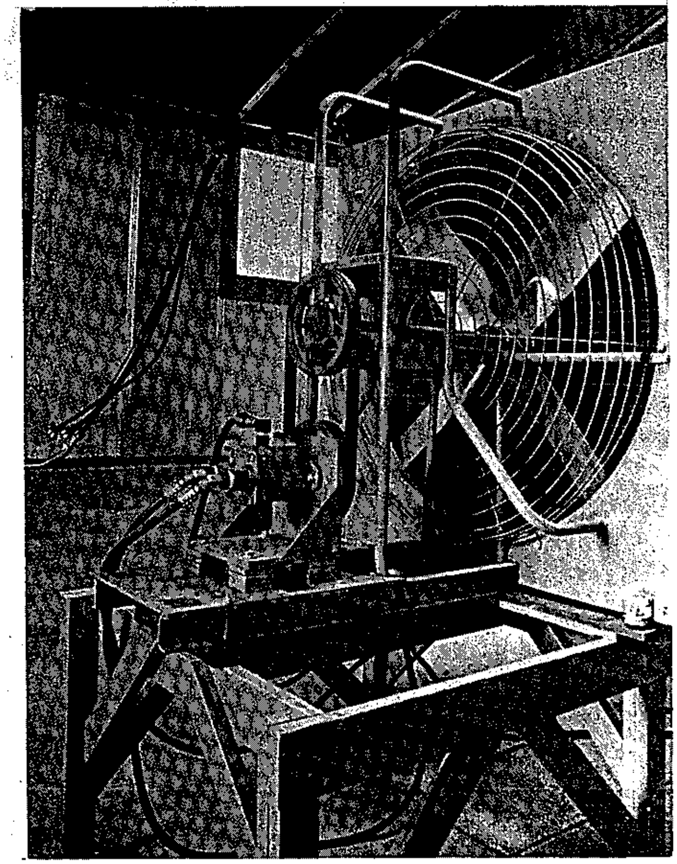


Figure 7

The driving unit for the wind tunnel. Unit consists of the propeller assembly, hydraulic motor, and hydraulic power unit which includes a 15 hp electric motor.

WIND TUNNEL
PERFORMANCE CHECK

One of the first checks conducted with the wind tunnel was to run the various types of wind instruments used by Caltrans in the Test Section. Plexiglass inserts, approximately 1 1/2 x 2 foot were installed in the middle of the Test Section on all sides. Several interchangeable inserts were made for the bottom side of the Test Section. Holes were made in several of these inserts to facilitate the installation of the various wind instruments in the wind tunnel.

No problems were encountered in running these instruments until an anemometer bivane was installed. When the anemometer bivane was installed and the air velocity increased, there was a definite vertical motion in the movement of its tail. This indicated that a vortex was created by the fan which was not broken up by the screen between the diffuser and the test section. This problem was solved by placing a "straightener" section between the diffuser and the test section. The straightener section consisted of 36 four inch square grids approximately 1 ft deep made of 1/8 inch aluminum. This along with the screen behind the test section breaks up the vortex effect caused by the fan and makes the flow linear through the test section. The next step in checking out the wind tunnel was to run wind speed profiles through the test section from the middle of all the sides. The equipment used were two inclined manometers and two Pitot tubes. The reference manometer used was a Meriam Model 40G010. Its range is from 0 to .5 inches of water pressure and the calibration accuracy is ± .01 of an inch water pressure. Another manometer, a Dwyer Series 100 AV Durablock manometer Model #125-AV, was purchased especially for use with the wind tunnel. The range is 0-1.0 inches of water and the calibration accuracy is ± .005 of an inch of water pressure (see Figure 8). One of the Pitot tubes used was model PAC-8-KL which has a 1/8" stem diameter and is 8 inches long. It is made of a high temperature alloy and is used strictly as a reference for both profiling and calibration of wind instruments. The other is a Model PCC-24-KL which also has a stem diameter of 1/8" but is 24 inches long. It is also made of high temperature alloy, and was used only for profiling the wind tunnel. The wind tunnel was profiled with the 24 inch probe from both sides of the test section using the 8 inch probe in the top as the reference. Then the reference probe was mounted in the west side and the tunnel profiled from the top and bottom. Each side was profiled at 5 different velocities, from approximately 5.5 mph to about 28.5 mph. According to a reference(7) a carefully made and accurately leveled manometer can retain its accuracy at velocities as low as 600 ft/min (approximately 6.8 mph), however, we found it to be quite accurate even at 5.5 mph. Readings were taken on the normal axis of each side of the test section at 1/2, 1, 2, 3, 6, 9, 12, 15, 18, 22, and 23 inches. After these data were taken, all the readings in the center were normalized and the others adjusted accordingly.

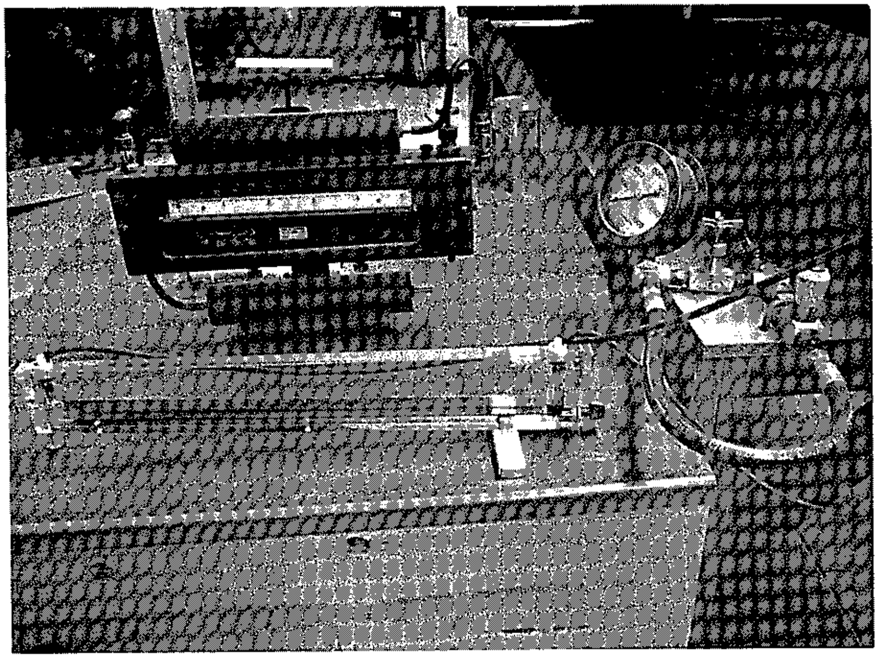


Figure 8

Manometer used for calibrating wind tunnel.

After normalizing the data for each point, all the readings an equal distance from each side were grouped. For instance, 22 inches from the west side was the same position as 2 inches from the east side. Therefore, summing the readings at the same distance from the sides, there were 8 readings for each velocity. These readings vary from 1 to 10 inches from the sides. Only 4 readings were taken at 1/2 inch from the side and at the center (the Pitot tube would only reach 23 inches across the section and there is duplication at the center). The average was then taken for each of these groups after eliminating the high and low readings (see Appendix A, figures 10-15 and Table 1-3). The diagram in Figure 10 is a plot of the information obtained. As shown by the diagram and data, the wind tunnel does have a very uniform profile especially at low velocities. In fact, even at high velocities there is very little boundary layer effect more than two inches from the side. As for turbulence, there was little noticed except 1/2 inch from the side, which accounts for the wide variety in the readings at that position. For all the other positions, the manometer remained very stable.

Another problem encountered with the system was with the driving unit. The unit would not maintain a steady velocity. It was determined that the problem was in the warming up of the hydraulic fluid. Once the fluid was completely warmed up, the wind tunnel would maintain a fairly constant velocity. This problem could be eliminated by using some type of heating element to maintain the hydraulic fluid at a constant temperature. Another solution is to start running the wind tunnel about 1/2 to 1 hour before using, thereby giving the fluid time to warm up. This has become a part of our standard calibration procedure.

An additional difficulty encountered during the performance check was the inability to use the Pitot tube as a reference for speeds of less than 5 mph. This is a problem because the majority of the wind speeds recorded in field measurements are between 0 and 5 mph. To solve this problem, a reference cup anemometer with a threshold velocity of approximately 1/2 mph was installed (see Figure 9). Placement was slightly forward of the plexiglassed area of the working section and far enough away from the sides to eliminate boundary layer effects. The cups are connected by a shaft to a chopper which chops the beam from a self-contained light emitting diode. A photo detector then counts the light pulses and converts the count into frequency. The frequency is then converted by a signal conditioner into an analog voltage which is directly related to speed.

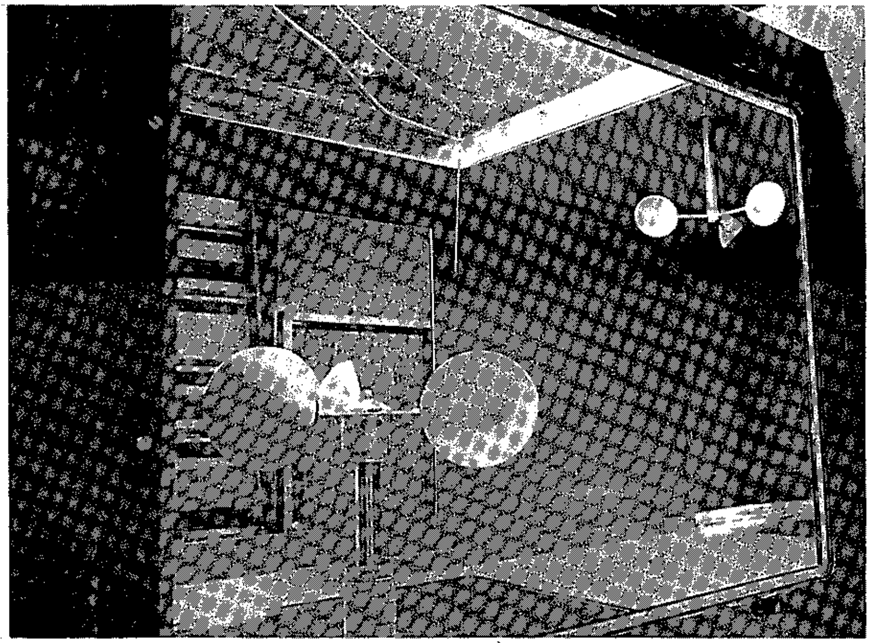
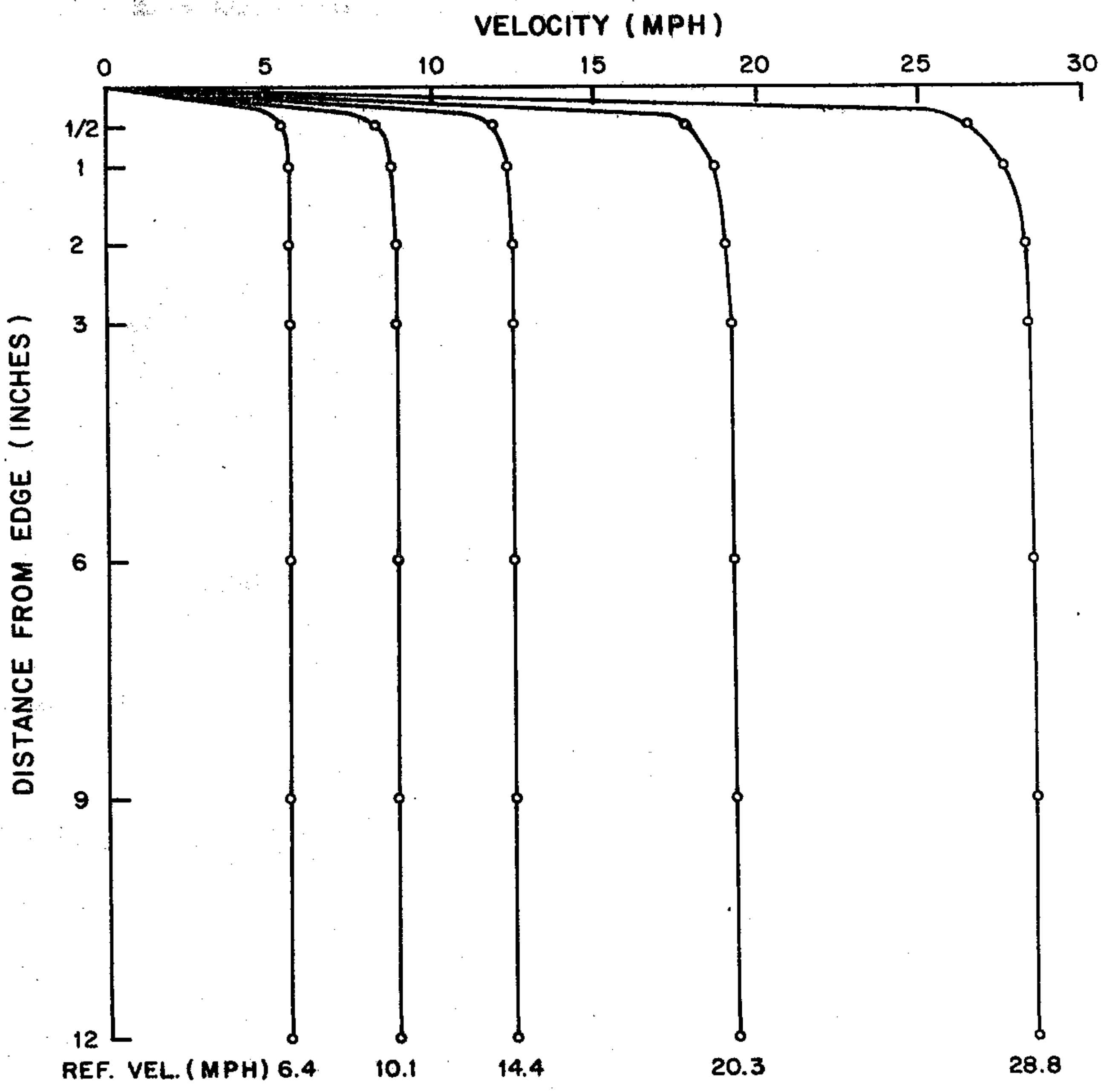


Figure 9

Cup anemometers shown in place for calibrating the wind tunnel for low velocities (less than 5 mph).



NORMALIZED VELOCITY PROFILES

Figure 10

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APPENDIX A

Calculation of Reynolds Number in Working Section

Cross-section properties: (2 ft x 2 ft)

Area = $4\ ft^2$

Wetted Perimeter = 8 ft

$$R_n = \frac{A}{P} = \frac{4}{8} = 0.50\ ft$$

Wind Speed = 5 mph = 7.34 ft/sec

Kinematic viscosity at 59° F and 29.92" Hg

$$\nu = 1.57 \times 10^{-4}\ ft^2/sec$$

$$R = \frac{7.34\ (4)\ 0.5}{1.57 \times 10^{-4}} = 9.35 \times 10^4 \simeq 1.0 \times \underline{\underline{10^5}}$$

R >>4000, therefore flow is turbulent.

Table #1

Distance from Side (in.)	Top	Bottom	West	East	Average	Adjusted Average*	Adjusted Average* in mph
		Side					
Reference manometer @ .02 inches of water.							
1/2"	.014	.014	.012	.014	.014	.014	5.4
1"	.014 .015	.015 .015	.012 .014	.014 .016	.014	.015	5.6
2"	.015 .015	.015 .015	.014 .014	.014 .015	.015	.015	5.6
3"	.015 .015	.015 .015	.015 .014	.015 .015	.015	.015	5.6
6"	.015 .015	.015 .015	.015 .014	.015 .015	.015	.015	5.6
9"	.015 .015	.015 .015	.015 .015	.015 .015	.015	.015	5.6
12"	.015	.015	.015	.015	.015	.015	5.6
Reference manometer @ .05 inches of water.							
1/2"	.029	.036	.032	.034	.033	.033	8.3
1"	.036 .032	.038 .037	.036 .037	.037 .037	.036	.037	8.8
2"	.037 .035	.038 .037	.038 .039	.038 .038	.038	.038	8.9
3"	.037 .035	.038 .038	.038 .039	.038 .038	.038	.038	8.9
6"	.037 .037	.038 .038	.038 .039	.038 .038	.038	.038	8.9
9"	.038 .037	.038 .038	.038 .039	.038 .038	.038	.038	8.9
12"	.038	.038	.038	.038	.038	.038	8.9

*Average obtained by eliminating the highest and lowest readings.

Table 2

Distance from Side (in.)	Top	Side Bottom	West	East	Average	Adjusted Average*	Adjusted Average* in mph
Reference manometer @ 0.1 inches of water							
1/2"	.064	.071	.065	.074	.069	.068	11.9
1"	.070 .071	.075 .072	.074 .072	.071 .076	.073	.073	12.3
2"	.074 .074	.075 .071	.076 .075	.075 .076	.075	.075	12.5
3"	.074 .075	.075 .073	.076 .075	.075 .077	.075	.075	12.5
6"	.075 .075	.075 .074	.076 .075	.075 .075	.075	.075	12.5
9"	.075 .075	.075 .074	.076 .075	.075 .075	.075	.075	12.5
12"	.075	.075	.075	.075	.075	.075	12.5
Reference manometer @ 0.2 inches of water							
1/2"	.150	.160	.135	.152	.149	.151	17.7
1"	.170 .164	.176 .174	.165 .155	.164 .177	.168	.169	18.7
2"	.177 .177	.179 .178	.176 .173	.166 .179	.176	.177	19.1
3"	.180 .178	.179 .179	.179 .178	.179 .179	.179	.179	19.25
6"	.180 .178	.180 .180	.179 .178	.180 .180	.179	.179	19.25
9"	.180 .180	.181 .180	.180 .179	.179 .181	.180	.180	19.3
12"	.180	.180	.180	.180	.180	.180	19.3

*Average obtained by eliminating the highest and lowest readings.

Table 3

Distance from Side (in.)	Side Top	Bottom	West	East	Average	Adjusted Average*	Adjusted Average* in mph
Reference manometer @ 0.4 inches of water.							
1/2"	.342	.342	.343	.342	.342	.342	26.6
1"	.365 .366	.374 .372	.345 .370	.370 .365	.366	.368	27.6
2"	.383 .385	.385 .383	.370 .380	.382 .383	.381	.383	28.2
3"	.389 .386	.385 .385	.385 .387	.390 .386	.387	.386	28.3
6"	.392 .391	.389 .388	.390 .390	.393 .389	.390	.390	28.4
9"	.391 .392	.390 .391	.393 .393	.393 .390	.392	.392	28.5
12"	.393	.393	.393	.393	.393	.393	28.5

*Average obtained by eliminating the highest and lowest readings.

CORRECTED DATA-REFERENCE MANOMETER AT .02 INCHES OF WATER

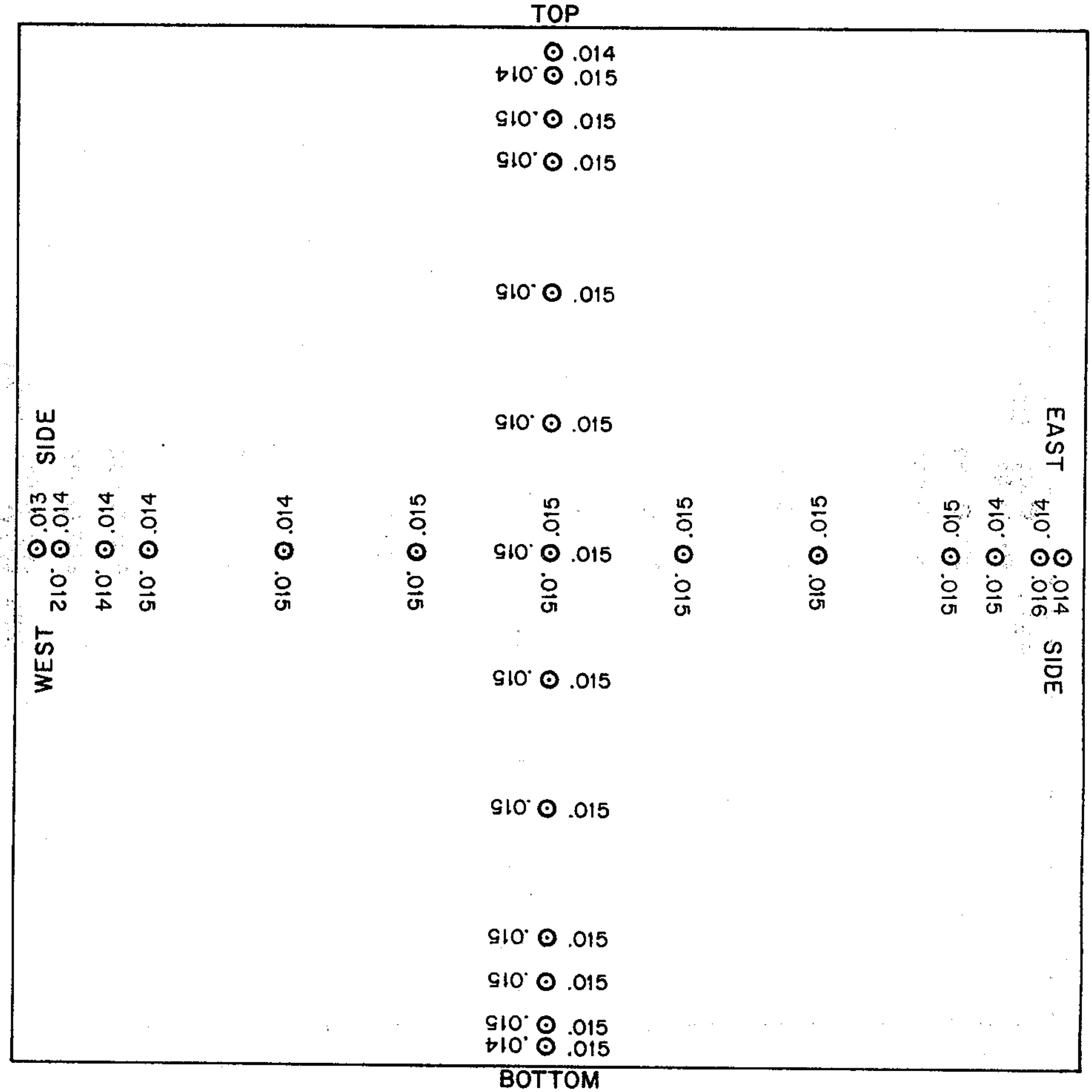

Figure 11

CORRECTED DATA-REFERENCE MANOMETER
AT .05 INCHES OF WATER

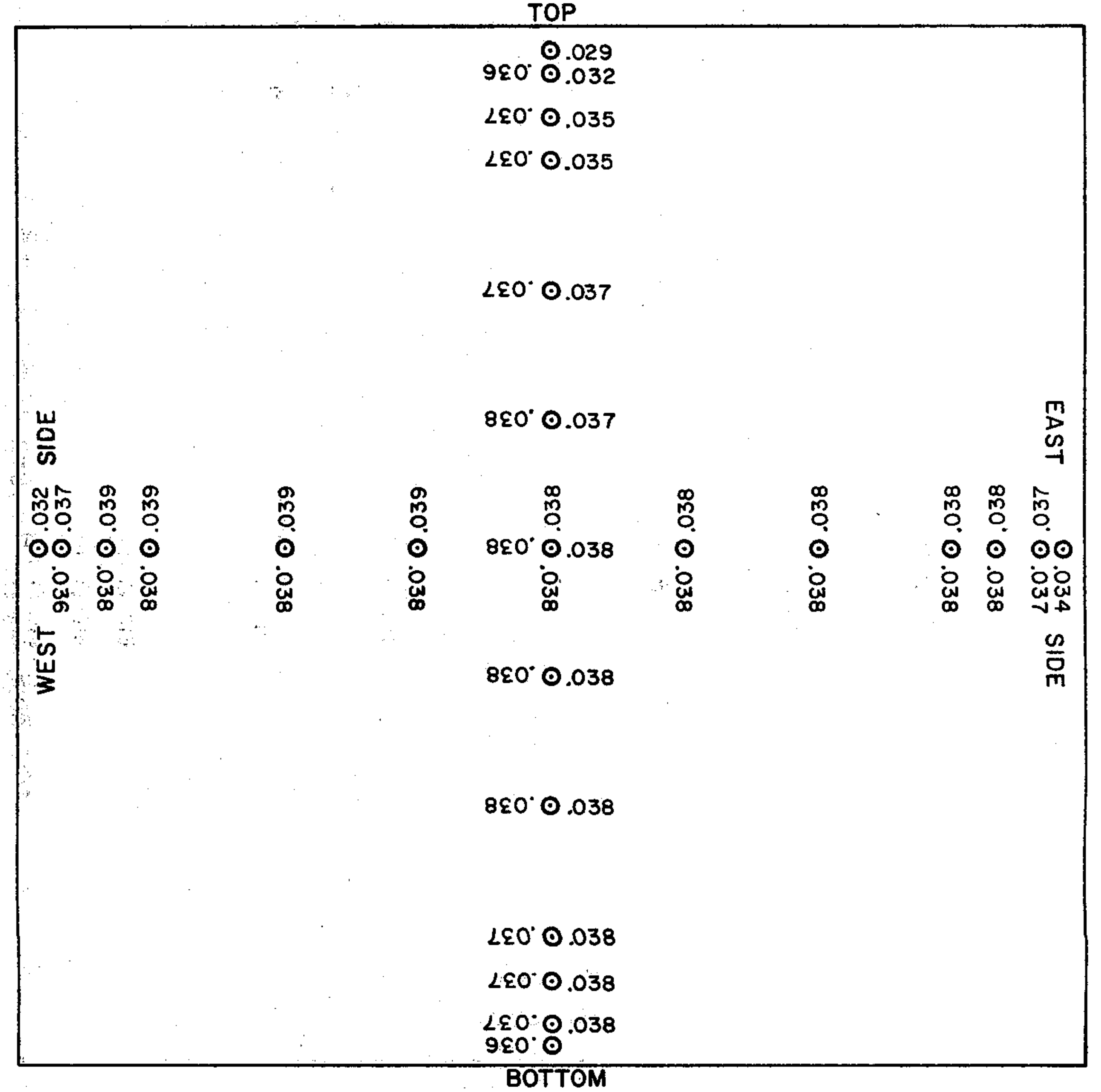

Figure 12

CORRECTED DATA–REFERENCE MANOMETER AT 0.1 INCHES OF WATER

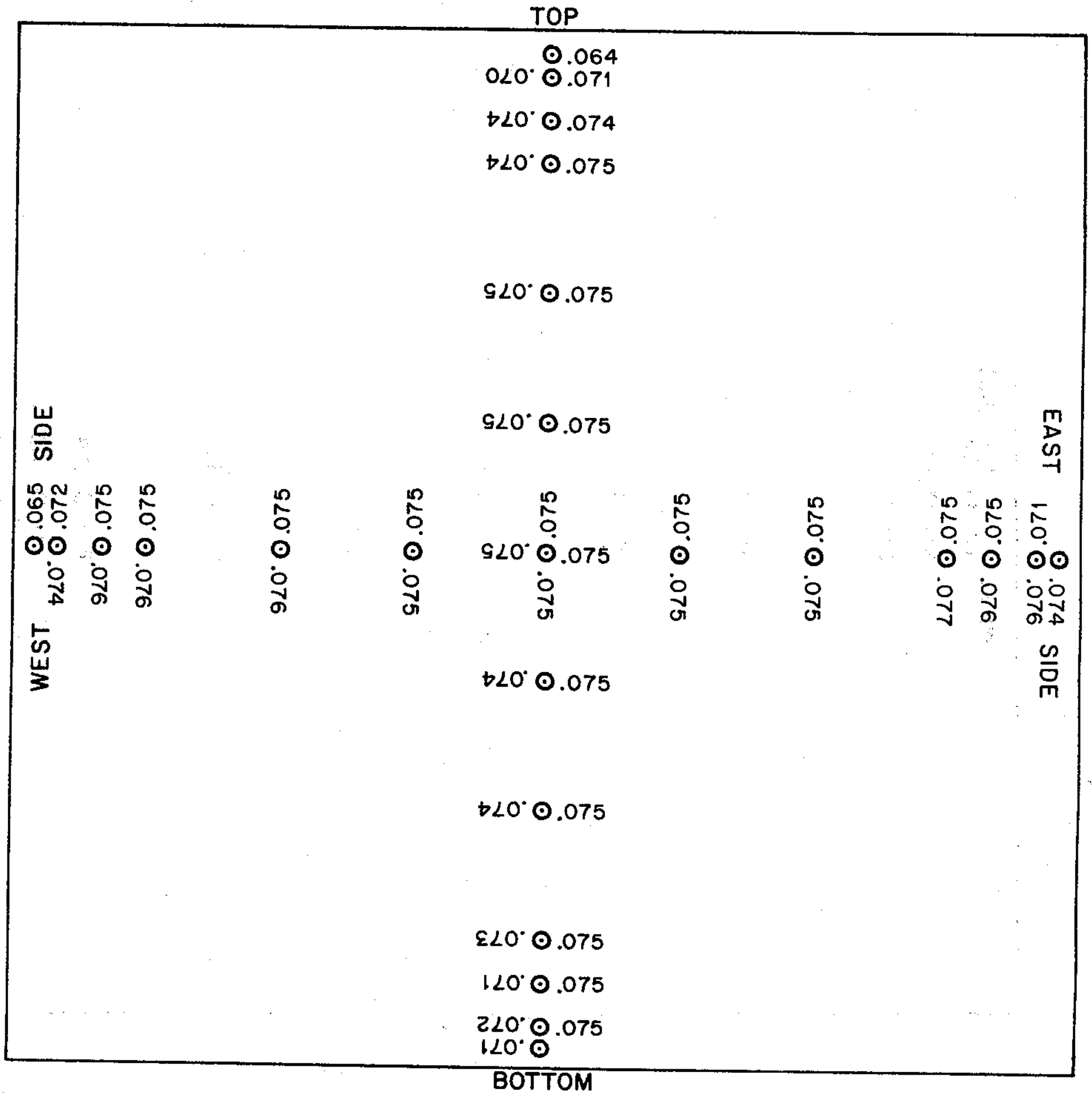

Figure 13

CORRECTED DATA-REFERENCE MANOMETER
AT 0.2 INCHES OF WATER

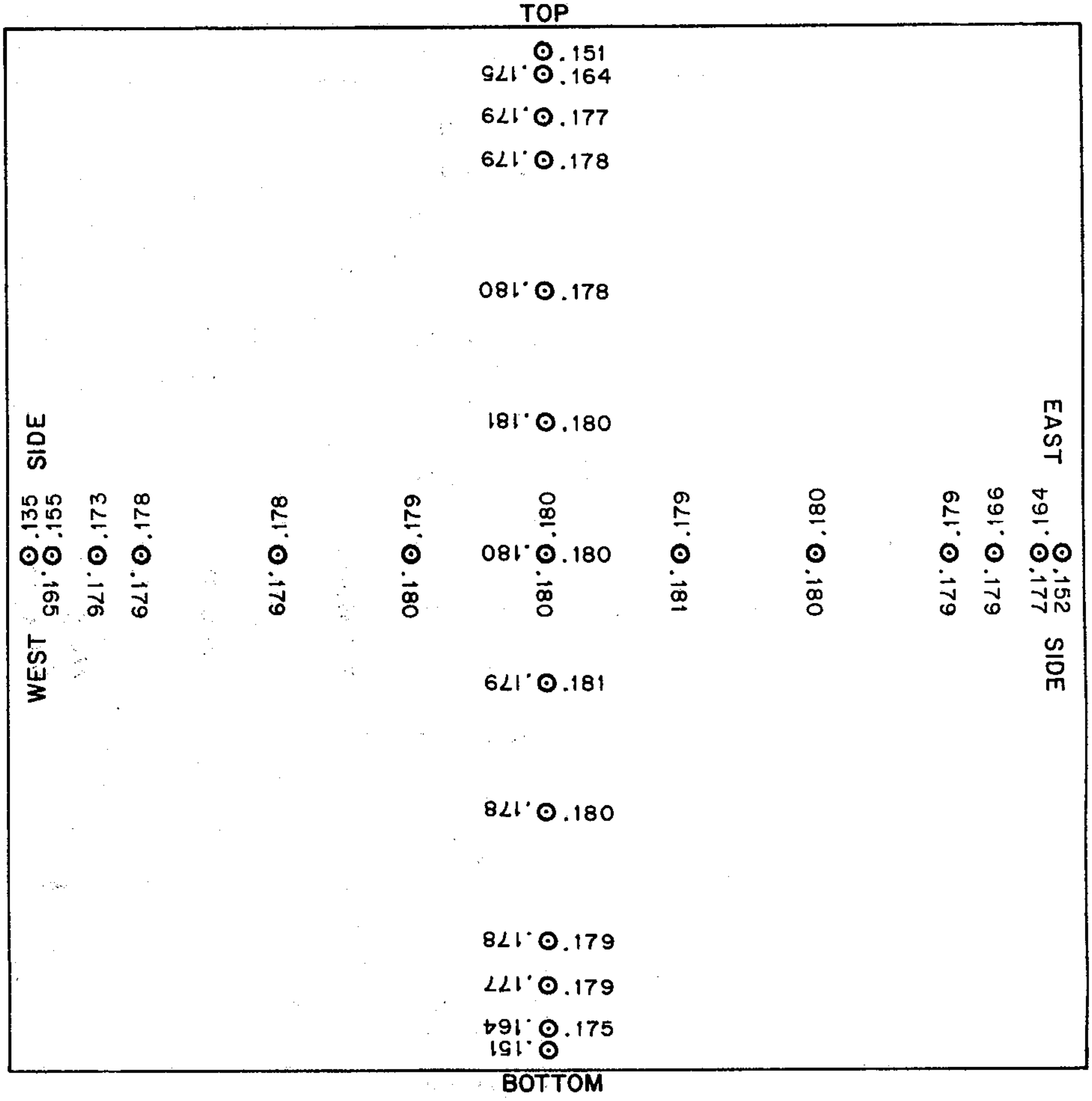

Figure 14

CORRECTED DATA-REFERENCE MANOMETER AT 0.4 INCHES OF WATER

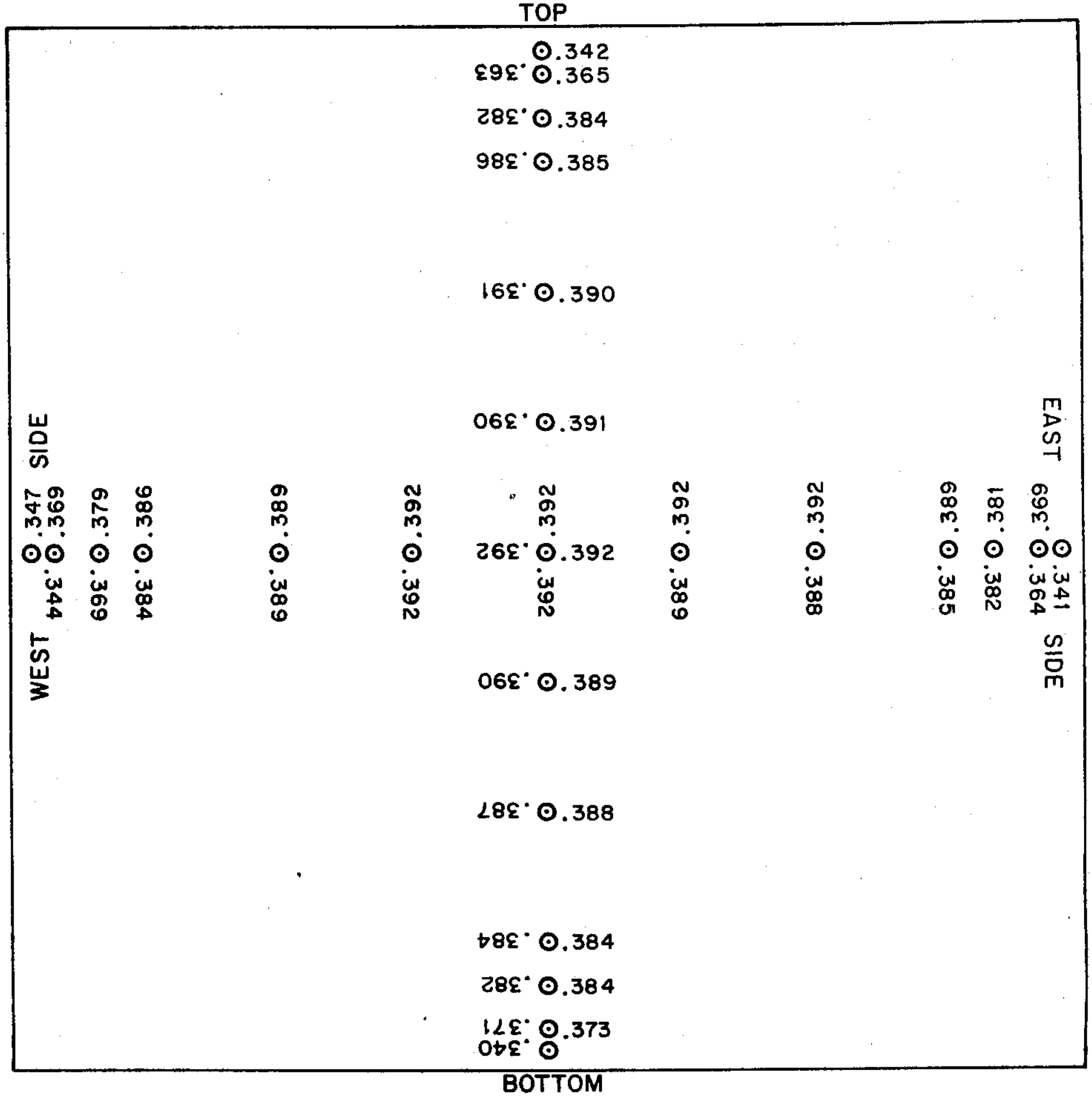

Figure 15