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ERRORS IN MEASUREMENTS OF WIND SPEED AND DIRECTION MADE WITH TOWER- OR STACK-MOUNTED INSTRUMENTS

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ORA Project 06973

sponsored by:

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
PUBLIC HEALTH SERVICE
NIH GRANT NO. AP-00233-03
WASHINGTON, D.C.

administered through:

OFFICE OF RESEARCH ADMINISTRATION   ANN ARBOR

June 1966

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ABSTRACT

Towers and smokestacks affect wind flow so that wind sensors mounted on them do not indicate the true free-air flow. To determine the probable errors in measurements of wind speed and direction around such structures, quarter-scale models were tested in a large wind tunnel. Data on changes in wind speed and direction were obtained by using smoke, tiny wind wanes, and a scale model propeller anemometer. Most emphasis has been placed on a relatively open lattice-type tower, but a solid tower and a stack were also studied.

The results show that in the wake of lattice-type towers disturbance is moderate to severe, and that in the wake of solid towers and stacks there is extreme turbulence, with reversal of flow. Recommendations for locating wind sensors in the wind field relative to the supporting structure are given for each of the three structures studied. Guidelines are given regarding probable errors in measurements of wind speed and direction around different supporting structures.

1. INTRODUCTION

The usual method of measuring the speed and direction of the wind at several levels above the ground is to erect a tower and mount the sensors out from it on retractable booms. A rule of thumb often used by one of the authors is, "Locate the instruments into the prevailing wind, and out from the tower at a distance equal to, or greater than, the tower width at that height." This is expected to give fairly accurate observations of wind speed and direction for about 270 degrees of arc. Other meteorologists use different guidelines. A modest search of the literature in June 1965 revealed only one study that documented errors in wind speed and direction measurements caused by the tower itself: Moses and Daubek[6] determined the errors in speed and direction caused by an open tower when the wind sensor (a Bendix Aerovane) was mounted on a boom whose length was about half the width of the tower. They found that:

> The air flow on the lee side of the tower may be reduced to nearly one-half its true value for light winds and nearly 25 per cent for speeds of 10 to 14 mph. An increase in

measured wind speed exceeding 30 per cent occurred when the wind blowing toward the anemometer made an angle of 20 to 40 deg with respect to the sides of the tower adjacent to the anemometer..... The effect on direction appeared to be relatively smaller, with the greatest mean deviation of 11 deg.....

In view of such large errors in indicated wind speed about one tower, and of the paucity of information on errors caused by others, we decided to make a wind tunnel study of the wind flow pattern around one or more typical tower models and to attempt, from critical analysis of the results, to develop guidelines for the distance and direction at which sensors should be located to achieve a specified accuracy. A quarter-scale model of a typical guyed tower of uniform cross-section was chosen for the first tests.

In air pollution studies it is often suggested to the consulting meteorologist that he use an already built smokestack to support his wind instruments. To obtain some information on the pros and cons of such an installation, we decided to make some wind tunnel measurements of the flow around a quarter-scale model of a typical stack. The results of these tests are reported here.

After beginning this study, we learned that a similar wind tunnel study on a quarter-scale tower model, conducted by Hsi and Cermak, was nearing completion at Colorado State University. This study has been reported in detail[5], and a shorter technical article has been submitted for publication[2]. The findings reported for an open tower are very similar to ours.

Since completing our wind-tunnel tests with a simulated smokestack, we have learned of a report, "Estimation of the Effect of the 300-Meter Meteorological Mast Structure on the Wind-Gauge Readings," by a group of Russian scientists[1]. This report presents first a theoretical approach and then an experimental study of correction factors to be applied to wind observations made 7.5 meters out from a 2.4-meter diameter pipe mast (boom length $\sim$ 3D). This was not a model study but an in-place study, made at 225 meters on a 300-meter mast. They used six wind-speed sensors and two wind-direction sensors mounted on booms extending as much as 22 meters ($\approx$9D) from the mast. Since our data are limited to one wind speed and one Reynolds number, a direct comparison between the results of our smokestack study and their study is difficult. However, there is agreement in the general conclusions on arranging wind sensors on cylindrical masts or smokestacks.

2. EXPERIMENTAL STUDY

The study was performed in a low-speed return-duct tunnel at The University of Michigan, having a working section 5 1/2 feet high, 8 feet wide, and 30 feet long (Figure 1). The quarter-scale tower model measured 30 inches across each face and 62 inches high (Figure 2); it was an accurate reproduction of two sections of the 1050-foot WJBK-TV tower in Detroit, which measures approximately 10 feet across each face. The model, shown in Figure 2, incorporates the elevator guide rails, radio frequency ducting, and other details of the structure. Speed and direction tests were conducted at two heights above the tunnel floor; see sections I and II, Figure 2. To simulate the greatest possible density of elements in a tower of triangular cross-section, speed and direction tests were conducted with a solid model, each of the three faces being covered with cardboard (Figures 5b and 6c).

Glazed sewer pipe, 14 inches in diameter and extending from floor to ceiling, was used as a quarter-scale model of a stack 56 inches in diameter (Figures 5a and 6d).

The wind speed in the tunnel was kept essentially constant for all tests, the speed being recorded by a Gill propeller anemometer[4] (Figure 6, parts a through d) , connected to an Esterline Angus milliampere recorder.

Three different types of tests were performed.

2.1. <u>Smoke Tests</u>. Oil fog smoke was injected from one or more quarter-inch diameter outlets into the undisturbed air stream in front of the horizontally supported tower, and instantaneous photos of the smoke trail were made (Figures 3, 7, 8, and 9). The photographs were made with a 35-mm camera (Honeywell Pentax with 55-mm Takumar lens). The air stream was viewed through the plate glass windows which make up one wall of the tunnel.

2.2. <u>Flag Tests</u>. Flags mounted on a bar (Figures 4, 6b, and 6c) were moved to different locations in front of and behind the vertical tower or stack. Five-second time-exposure photographs were taken through windows in the ceiling of the tunnel to determine the flow and turbulence pattern (Figures 10 and 11). By using the film negatives and a projector, the pictures were transferred directly to the graphs of Figures 13 through 17. The flags were an adaptation of Sakagami's wind-direction sensors[7] and The University of Michigan flag sampler[3]. The top edge of each flag had a narrow strip of opaque white Scotch tape (Figures 4 and 6c) which contrasted well with the black Bristol board on the tunnel floor (Figures 10 and 11).

2.3. Anemometer Tests. A second propeller anemometer, wired to a second Esterline Angus recorder but with its propeller cut to 2 3/4 inches in diameter, was employed to simulate a quarter-scale model of the Aerovane propeller (Figure 6a). This was moved to selected locations about the tower and its readings compared with readings taken at the same locations when the tower was not in the tunnel. These data yielded the velocity ratios given in Figures 19 through 22. The locations were selected to correspond to those at which an Aerovane would be mounted on a retractable boom extending 1/2, 1, or 2 tower widths (1/2D, 1D, 2D) out from the tower. One limitation in the setup used was that the anemometer was fixed in a forward direction and therefore measured only the flow component parallel to the axis of the tunnel. For other wind directions the instrument response closely approximates the total speed multiplied by the cosine of the angle between the wind direction and the tunnel axis.[4] For an angle of 10° the response is 98% of true; for 20° it is 94% of true. In our recommendations we have considered errors in wind direction greater than 10 degrees to be unacceptable. Since the directional error of the propeller anemometer is only 2% or less for such angles the limitation mentioned above is of no real consequence.

Since the density of the tower structures is non-symmetrical (Figure 2) five different boom arrangements could be considered for the open tower. These are shown in Figure 5. Furthermore, the difference in tower density with height has been considered. Sections I and II (see Figure 2) each have a total frontal area $A = 10 \times 31 = 310$ in^2; the shadow area of Section I is $A_1 \sim 80$ in^2, and that of Section II is $A_2 \sim 140$ in^2. Hence the "shadow density" of Section I, $A_1/A \sim 80/310 \times 100\% \sim 26\%$, and that of Section II, $A_2/A \sim 140/310 \times 100\% \sim 45\%$.

To assure kinematic and dynamic similarities as well as possible, we applied criteria set forth by Hsi and Cermak[5]. The tower they used is very similar, in both structure and size, to the one used for this study. To determine whether difference in Reynolds number influences the wind distribution, Hsi and Cermak made velocity measurements for 10, 30, and 60 fps, and concluded that "the model wind data are not influenced by Reynolds number variation and are similar to the prototype wind-field." Hence our data for the open tower model should be valid at least for the wind-speed range of 10 to 60 fps (7 to 40 mph).

For the solid tower and the smokestack, the effect of scaling upon the wind-field depends upon the Reynolds number. For the quarter-scale model, the Reynolds number is 1/4 that of a full-sized tower. This fact makes generalization of the tests with the solid tower and smokestack more difficult. It should be mentioned, however, that the solid tower was chosen only as an extreme case of the open tower, where the shadow density = 100%.

3. CALIBRATION OF WIND TUNNEL

3.1. Wind-Direction Tests. The open tunnel flow was tested for laminar flow by means of flags. A pipe with the flags mounted on it was placed in traverses at distances of 0, 5, 10, and 15 feet (measured from the forward end of the working section of the tunnel), and at heights of primary concern (Sections I and II, Figures 1 and 2). Time-exposure photographs were taken through the windows in the ceiling of the tunnel.

Analysis of the photographs indicates that the flow in the tunnel is undisturbed throughout; that is, there was no indication of convergence or divergence of flow within the accuracy of the technique (probably ±3 degrees of axial flow).

3.2. Wind-Speed Tests. The wind-speed distribution in the "open tunnel" was tested for a given constant flow in the opening of the tunnel by use of the second propeller anemometer. The results are given in Table 1 and Figure 12. Figure 12 shows, the speed is slightly higher near the walls of the tunnel than in the center; moreover, the flow becomes somewhat more uniform farther downwind in the tunnel, in the area where most of tests were conducted. No significant difference of wind speed with height was found, at least not at the intermediate heights at which the experiments were run; see Table 2. The wind distribution in the open tunnel has been applied in evaluating the relative wind speed around each obstacle.

4. RESULTS

4.1. Smoke Tests. The pictures of the smoke flowing by the tower structure show that there are considerable disturbances in the flow pattern; see Figures 7 through 9. They indicate that Karman vortex streets are formed behind the pipes in the tower structure. Although some qualitative data could be obtained from the smoke pictures, no quantitative data for distances of 1/2D, 1D, and 2D from the tower could be obtained; therefore the smoke tests were quickly abandoned in favor of the flag and anemometer tests.

4.2. Wide-Direction Tests.

4.2.1. Tower. The wind-direction profiles analyzed from photographs taken in front of and behind the open tower are presented in Figures 13 through 15, and those for the solid tower in Figure 16.

The general findings for the open tower are as follows:

(1) Flow in front of the tower is laminar; flow in its wake is turbulent.

(2) The width of the turbulent wake behind the

tower is fairly constant, 1D to 1 1/2D, for distances of 1/2D to 6D downwind from the tower, and is about the same for Sections I and II and for the different orientations of the tower. See Figures 14 and 15.

(3) For distances up to 1D, the wake behind Section II is considerably more turbulent than that behind Section I; but at downwind distances greater than 2D there is little difference in the intensity of the turbulence.

(4) The turbulence is rather strong behind the center of the tower, even at distances of more than 4D.

The general findings for the solid tower are as follows:

(1) Upstream from the tower the flow is not turbulent, but measurements of the direction of flow are in error at least 1D ahead of the tower.

(2) Downstream from the tower the flow is extremely turbulent at all distances up to 6D, and for the full width of our observations (2D). At downstream distances up to 1/2D, the flow direction near the center of the wake is reversed. At downstream distances up to 2D, and for a width of at

least 1D, the indicated wind direction may be from any azimuth.

(3) All measurements of wind direction downstream from the tower were completely unreliable.

4.2.2. Stack. For a cylindrical obstacle the wind direction profile is dependent upon the Reynolds number, and the picture shown in Figure 17 cannot be generalized as well as could the results for the open tower.

The general findings for the stack are as follows:

(1) The flow in the wake of the stack is very turbulent.

(2) The turbulence reaches many stack diameters downwind.

(3) One sector of the wake has a negative direction.

(4) There are Karman vortex streets.

4.3. Wind-Speed Tests. The data obtained are summarized in Tables 3 through 13, and graphically represented in polar diagrams, Figures 19 through 21. Figure 18 shows the coordinate-systems used in the figures.

In the tables,

Column 1 "Ref. No." is a reference number.

Column 2 "Coordinates" give the relative location of the sensor; see Figure 18.

Column 3 "U" is measured wind speed (mph) corrected for change in basic flow.*

Column 4 "Flow Type" is a subjective evaluation of the flow stability made from the charts and/or observed during the runs.

LL stands for "very laminar"

L stands for "laminar"

T stands for "turbulent" ($\approx\pm0.3$ mph)

TT stands for "very turbulent" ($>\pm0.5$ mph).

Column 5 "Uo" is undisturbed flow (mph), read from wind speed distribution in the open tunnel; see Figure 12.

Column 6 "U/Uo" is relative wind speed, in percentages.

On the graphs U/Uo is plotted against wind direction for different arrangements

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*The wind-tunnel propeller was driven by a d-c motor whose speed changed by as much as 5% owing to fluctuating line voltage. By using a control anemometer near the forward end of the working section of the tunnel (see Figure 1) the indicated wind speeds were corrected.

of tower and boom, and for different lengths of the boom. In general, the results for flow types agree with those from the flag tests. Thus, e.g., in cases where TT or T is indicated, the flags are either rotating or fluctuating more than 20^{o}, and for LL the flags indicate steady flow.

4.3.1. Tower. A series of runs for all five cases, A-E (see Figure 18), was made at Section I (the less dense section) for 1/2D, 1D, 2D, 3D, and 4D; see Tables 3 through 7 and Figure 19, parts a through j.

At Section II, runs were made for cases A and E only; see Tables 8 and 9 and Figure 19, parts k through n. For the solid tower, cases A, B, and C are covered by one run, Table 10, Figure 20a; and cases D and E by one run, Table 11, Figure 20b.

The general findings for the open tower are as follows:

(1) In general, the density distribution in the tower structure influences the location of the wake, the angle occupied by the wake, the effect of the shading, and the location of maximum readings.

(2) The mentioned effects are more pronounced when shorter booms are used.

(3) There is no significant difference in the disturbing effect at Sections I and II. This might be because the height of the horizontal tower member of Section II (see Figure 2) is small compared to the length of the boom; hence the difference in structure density as seen by the sensor is less than the two density numbers would tend to indicate.

(4) At a boom length of 1D, the minimum wind speed varies significantly for the five cases.

The general findings for the solid tower are as follows:

(1) The distribution features for the solid tower are similar to those for the open tower, but the values of the ratio U/Uo are greatly accentuated.

(2) At distances up to 2D in the center of the wake, wind flow is reversed (U/Uo<0).

4.3.2. <u>Stack</u>. A series of runs for boom lengths of 1/2D, 1D, 2D, 3D, and 4D, as well as some for 6D, 8D, and 10D, were made for the cylindrical stack; see Tables 12 and 13, and Figure 21. These data are valid for the Reynolds number corresponding to a quarter-scale model exposed to a wind speed of about 8 mph, but no generalization for other Reynolds numbers is claimed.

The general findings for the stack are as follows:

(1) The sector occupied by the wake increases with decreasing boom length.

(2) The deviation of the velocity ratio U/Uo from 100% increases with decreasing boom length.

To determine the effect of mounting wind sensors near the top of a stack, observations were made in the wake of a stack not extending to the ceiling. Table 13 and Figure 22 present the velocity ratios U/Uo in a vertical plane through the center line of the stack.

The general findings for the area near the top of a stack are as follows:

(1) The influence of the top of the stack becomes negligible at levels ~3D below the top of the stack, at least for distances downwind up to 6D.

(2) The velocity ratio U/Uo improves rapidly (approaching 100%) as the observation level approaches and exceeds the top of the stack.

5. SUMMARY

The results of this study show that:

(1) There is a significant disturbance in the air flow pattern around and behind a structure, which is a complex function of tower structure and of sensor position.

(2) There is a sector in the wake of the tower in which the measured value of the component of the wind speed parallel to the undisturbed flow is lower than the true value, and the measurement of flow direction is in error.

(3) There are other sectors, most of them close to the wake-sector, in which the measured speed is larger than the true speed but the measured direction is not in serious error.

(4) There is a general correlation between the magnitude of fluctuations in wind direction and the decrease in wind speed.

Table 14 summarizes the limits of reasonable accuracy of observations as given by Figures 19 through 21. The recommendations given in the next section are based on this table.

6. RECOMMENDATIONS CONCERNING MOUNTING OF WIND SENSORS

6.1. Relatively Open Towers.*

(1) For measurements of wind speed that are accurate within $\pm 10\%$ of the true value, we recommend that the sensor be placed not less than 1D out from the tower, and located out from the corner into the wind of primary concern. Installation types A, B, and C are preferable to types D and E. Preferably locate sensors at heights of minimum tower density, above or below horizontal cross members. For this extension and location, measurements of speed are true within $\pm 10\%$ for a 310° sector of arc. If the boom is extended to 2D, the wind speed is accurate within $\pm 10\%$ for a 330° sector of arc. For these two arcs, measurements of wind direction are accurate within at least $\pm 10^{\circ}$, and probably within $\pm 5^{\circ}$.

(2) With a boom extension of 1D, observations of wind speeds accurate within $\pm 5\%$ of true can be obtained within only a 180° sector of arc. If the boom is extended to 2D, measurements of wind speed are accurate within $\pm 5\%$ for a 240° to 270° sector of arc.

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*For "Shadow densities" not exceeding 40 percent.

For these two arcs, measurements of wind direction are probably accurate within $\pm 5^{\circ}$.

(3) If wind measurements accurate within $\pm 5\%$ in speed and $\pm 5^{\circ}$ in direction are needed for the complete 360° of azimuth, we recommend that two sets of speed and direction sensors be used, placed 180° apart, located as in (1) above, and with a boom extension of not less than 1 1/2D.

(4) When a single wind sensor is to be used, a straight line passing from the sensor through the center of the tower should point in the direction of minimum concern.

(5) If circumstances preclude the use of the settings specified above, representative results can be calculated from the figures given for other boom lengths, tower structures, and/or tower orientations.

Most of these recommendations are diagrammatically shown in Figure 23.

6.2. Triangular Solid Towers.

(1) Preferably, solid towers should not be used for meteorological platforms.

(2) If only a solid tower is available, this study indicates* that, if a boom extending 2D is used, wind-speed measurements accurate within $\pm 10\%$ of true can be expected for an arc of about 240°. For this same arc measurements of wind direction are probably true within $\pm 5^{\circ}$.

6.3. <u>Circular</u> <u>Stacks</u>.

(1) Preferably, stacks should not be used as meteorological platforms.

(2) If a stack must be used, this study indicates* that by using a boom extension of 3D one can obtain wind speed measurements accurate within $\pm 10\%$ of the true value through an arc of about 180°, and wind direction measurements true within $\pm 5^{\circ}$ for an arc of about 300°; see Figure 24.

(3) If winds accurate within $\pm 10\%$ in speed and $\pm 5^{\circ}$ in direction are needed for the complete 360°

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*This study was performed with a Reynolds number of approximately 2.7×10^5 for the solid tower (L = side of tower); and 1.3×10^5 for the stack (L = diameter), corresponding to an average tunnel speed of 8 to 9 mph and quarter-scale models of supporting structures. We do not claim that the results are directly applicable to other wind speeds or other values of the Reynolds number.

of azimuth, we recommend using two sets of speed and direction sensors, 180° apart and located not less than 2D out from the stack.

(4) The accuracy of speed and direction measurements can be markedly improved by locating the top set of wind sensors 1/2D or higher above the stack.

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TABLE 1

Wind Speed Distribution in Open Tunnel.
(z = 15 inches)*

Ref. No.	Coordinate* (inches)		Uo (mph)	Ref. No.	Coordinate* (inches)		Uo (mph)
1	-60	-36	8.8	41	60	-36	8.85
2	"	-24	8.35	42	"	-24	8.6
3	"	-12	8.3	43	"	-12	8.5
4	"	0	8.2	44	"	0	8.55
5	"	12	8.3	45	"	12	8.6
6	"	24	8.5	46	"	24	8.85
7	"	36	9.0	47	"	36	9.15
11	-30	-36	8.8	51	90	-36	8.9
12	"	-24	8.4	52	"	-24	8.75
13	"	-12	8.3	53	"	-12	8.55
14	"	0	8.3	54	"	0	8.6
15	"	12	8.4	55	"	12	8.65
16	"	24	8.65	56	"	24	8.85
17	"	36	9.1	57	"	36	9.15
21	0	-36	8.8	61	120	-36	9.0
22	"	-24	8.55	62	"	-24	8.65
23	"	-12	8.3	63	"	-12	8.6
24	"	0	8.35	64	"	0	8.6
25	"	12	8.5	65	"	12	8.65
26	"	24	8.8	66	"	24	8.95
27	"	36	9.1	67	"	36	9.15
31	30	-36	8.8	81	180	-36	8.85
32	"	-24	8.6	82	"	-24	8.65
33	"	-12	8.45	83	"	-12	----
34	"	0	8.5	84	"	0	8.7
35	"	12	8.55	85	"	12	9.0
36	"	24	8.8	86	"	24	----
37	"	36	9.25	87	"	36	9.45

*x = along tunnel axis
y = across tunnel
z = height

TABLE 2

Comparison of Wind Speed in Open Tunnel at Two Levels.

Coordinates* x (inches)	Coordinates* y (inches)	Uo (mph) z = 15 (inches)	Uo (mph) z = 31 (inches)	$\lvert U_{o,15}-U_{o,31}\rvert$ (mph)
-30	-36	8.8	8.85	0.05
0	0	8.35	8.4	0.05
60	0	8.55	8.5	0.05
180	0	9.45	9.65	0.20

*x = along tunnel axis
y = across tunnel
z = height

TABLE 3

Wind Speed Distribution around Open Tower
At Section I, Case A.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow* Type	U_o (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.7	97
2	"	345	8.4	"	8.4	100
3	"	330	8.3	"	8.3	100
4	"	315	8.7	L	8.35	104
5	"	300	8.7	LL	8.5	102
6	"	285	9.0	"	8.45	107
7	"	270	9.0	"	8.4	107
8	"	255	9.1	"	8.45	108
9	"	240	9.1	"	8.45	108
10	"	225	9.1	"	8.45	108
11	"	210	9.4	L	8.4	112
12	"	195	9.15	LL	8.45	108
13	"	180	5.8	T	8.8	66
14	"	165	6.5	T	8.6	76
15	"	150	9.0	LL	8.5	106
16	"	135	9.15	"	8.4	108
17	"	120	9.2	"	8.45	109
18	"	105	9.1	"	8.45	108
19	"	090	9.1	"	8.45	108
20	"	075	9.0	"	8.45	107
21	"	060	8.7	"	8.4	104
22	"	045	8.7	L	8.35	104
23	"	030	8.6	LL	8.3	103
24	"	015	8.4	"	8.4	100
25	"	000	8.4	"	8.7	97
1	1D	360	8.5	LL	8.7	98
2	"	345	8.4	T	8.35	101
3	"	330	8.3	LL	8.25	101
4	"	315	8.75	"	8.5	103
5	"	300	8.8	"	8.7	101
6	"	285	9.1	"	8.8	104
7	"	270	9.2	"	8.75	105
8	"	255	9.5	"	8.8	108
9	"	240	9.1	"	8.75	104
10	"	225	9.3	"	8.65	107

TABLE 3 (concluded)

Wind Speed Distribution around Open Tower
At Section I, Case A.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow* Type	U_o (mph)	U/U_o (%)
11	1D	210	9.3	LL	8.55	108
12	"	195	9.2	"	8.65	106
13	"	180	6.1	T	8.8	69
14	"	165	6.4	TT	8.6	76
15	"	150	8.3	T	8.5	98
16	"	135	9.1	LL	8.5	107
17	"	120	9.3	"	8.75	107
18	"	105	9.5	"	8.8	108
19	"	090	9.2	"	8.75	105
20	"	075	9.1	"	8.8	104
21	"	060	8.8	"	8.7	101
22	"	045	8.75	"	8.5	103
23	"	030	8.6	"	8.3	103
24	"	015	8.4	"	8.35	101
25	"	000	8.5	T	8.7	98
1	2D	225	9.8	LL	9.3	106
2	"	210	9.6	L	8.8	109
3	"	195	9.7	L	9.3	104
4	"	180	6.4	T	8.8	73
5	"	165	8.7	T	8.55	102
6	"	150	9.4	LL	8.6	109
7	"	135	9.3	LL	8.9	104
1	4D					
2	"	180	6.6	T	9.0	73
3	"	165	9.5	LL	8.5	112
4	"	150	10.1	LL	9.2	110

*LL = very laminar
L = laminar
T = turbulent ($\approx \pm 0.3$mph)
TT = very turbulent ($> \pm 0.5$mph)

TABLE 4

Wind Speed Distribution Around Open Tower
At Section I, Case B.

Ref. No.	Coordinates r	θ	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.7	97
2	"	345	8.4	"	8.4	100
3	"	330	8.3	"	8.3	100
4	"	315	8.7	L	8.35	104
5	"	300	8.75	"	8.5	103
6	"	285	9.0	LL	8.45	107
7	"	270	8.9	"	8.4	106
8	"	255	8.9	"	8.45	105
9	"	240	9.2	"	8.45	109
10	"	225	9.2	"	8.45	109
11	"	210	9.25	L	8.4	107
12	"	195	9.2	LL	8.45	108
13	"	180	5.8	T	8.8	66
14	"	165	6.3	L	8.6	73
15	"	150	8.4	T	8.5	99
16	"	135	8.7	T	8.4	103
17	"	120	9.2	LL	8.45	109
18	"	105	8.9	"	8.45	105
19	"	090	9.1	"	8.45	107
20	"	075	9.0	"	8.45	107
21	"	060	8.75	"	8.4	104
22	"	045	8.7	L	8.35	104
23	"	030	8.6	LL	8.3	103
24	"	015	8.4	"	8.4	100
25	"	000	8.4	"	8.7	97
1	1D	360	8.5	LL	8.7	98
2	"	345	8.4	T	8.35	101
3	"	330	8.3	LL	8.25	101
4	"	315	8.75	"	8.45	103
5	"	300	8.8	"	8.7	101
6	"	285	9.1	"	8.8	104
7	"	270	9.2	"	8.75	105
8	"	255	9.5	"	8.8	108
9	"	240	9.3	"	8.75	106
10	"	225	9.3	"	8.65	107

TABLE 4 (concluded)

Wind Speed Distribution Around Open Tower
At Section I, Case B.

Ref. No.	Coordinates r	θ	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	9.15	LL	8.55	107
12	"	195	9.2	"	8.65	106
13	"	180	6.1	T	8.8	69
14	"	165	5.7	T	8.6	66
15	"	150	8.7	T	8.5	102
16	"	135	9.2	LL	8.5	108
17	"	120	9.3	"	8.75	106
18	"	105	9.5	"	8.8	108
19	"	090	9.1	"	8.75	104
20	"	075	9.1	"	8.8	104
21	"	060	8.8	"	8.7	101
22	"	045	8.75	"	8.5	103
23	"	030	8.6	"	8.3	103
24	"	015	8.4	T	8.35	101
25	"	000	8.5	LL	8.7	98
1	2D	225	9.8	LL	9.3	105
2	"	210	9.6	"	8.8	109
3	"	195	9.7	"	9.3	104
4	"	180	6.4	T	8.8	73
5	"	165	8.6	T	8.55	100
6	"	150	9.35	T	8.55	109
7	"	135	9.5	LL	8.9	107
1	4D	195				
2	"	180	6.6	T	9.0	73
3	"	165	8.7	T	8.7	100
4	"	150	9.4	LL	9.3	101

TABLE 5

Wind Speed Distribution Around Open Tower
At Section I, Case C.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/Uo (%)
1	1/2D	360	8.4	LL	8.7	97
2	"	345	8.4	"	8.4	100
3	"	330	8.2	"	8.3	99
4	"	315	8.7	L	8.35	104
5	"	300	8.7	LL	8.5	103
6	"	285	9.0	"	8.45	107
7	"	270	9.0	"	8.4	107
8	"	255	9.1	"	8.45	108
9	"	240	9.1	"	8.45	108
10	"	225	9.1	"	8.45	108
11	"	210	9.35	"	8.4	111
12	"	195	9.1	T	8.45	108
13	"	180	6.6	"	8.8	75
14	"	165	4.5	"	8.6	52
15	"	150	6.7	"	8.5	79
16	"	135	8.0	TT	8.4	95
17	"	120	9.25	L	8.4	110
18	"	105	9.0	LL	8.45	107
19	"	090	9.1	"	8.45	108
20	"	075	9.0	"	8.45	106
21	"	060	8.7	"	8.4	104
22	"	045	8.7	"	8.35	104
23	"	030	8.6	"	8.3	103
24	"	015	8.4	"	8.4	100
25	"	000	8.4	"	8.7	97
1	1D	360	8.5	LL	8.7	98
2	"	345	8.4	"	8.35	101
3	"	330	8.3	"	8.25	101
4	"	315	8.75	L	8.5	103
5	"	300	8.8	LL	8.7	101
6	"	285	9.1	L	8.8	104
7	"	270	9.2	LL	8.75	105
8	"	255	9.5	"	8.8	108
9	"	240	9.1	"	8.75	104
10	"	225	9.15	L	8.65	106

TABLE 5 (concluded)

Wind Speed Distribution Around Open Tower
At Section I, Case C.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	9.2	LL	8.55	107
12	"	195	9.1	"	8.65	105
13	"	180	7.1	T	8.8	81
14	"	165	7.6	"	8.6	89
15	"	150	8.4	"	8.5	99
16	"	135	9.3	L	8.5	109
17	"	120	9.25	LL	8.6	107
18	"	105	9.1	"	8.7	104
19	"	090	9.2	"	8.75	105
20	"	075	9.1	"	8.8	104
21	"	060	8.8	"	8.7	101
22	"	045	8.75	"	8.5	103
23	"	030	8.6	"	8.3	103
24	"	015	8.4	"	8.35	101
25	"	000	8.5	"	8.7	98
1	2D	225	9.55	LL	9.3	103
2	"	210	9.35	"	8.8	106
3	"	195	9.7	"	9.3	104
4	"	180	7.4	T	8.8	84
5	"	165	9.3	L	8.55	109
6	"	150	9.3	LL	8.6	108
7	"	135	9.5	"	8.9	107
2	4D	180	7.7	T	9.0	86
3	"	165	9.0	"	8.5	106
4	"	150	9.0	LL	9.15	108

TABLE 6

Wind Speed Distribution Around Open Tower
At Section I, Case D.

Ref. No.	Coordinates r	θ°	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.4	100
2	"	345	8.1	"	8.3	98
3	"	330	8.2	"	8.3	99
4	"	315	8.2	"	8.3	99
5	"	300	8.4	-	8.3	101
6	"	285	8.7	LL	8.35	104
7	"	270	8.85	"	8.35	106
8	"	255	9.1	"	8.35	109
9	"	240	9.2	L	8.35	110
10	"	225	7.8	T	8.35	93
11	"	210	8.4	"	8.4	100
12	"	195	5.95	"	8.5	69
13	"	180	6.0	"	8.6	70
14	"	165	8.6	LL	8.5	101
15	"	150	9.4	L	8.4	112
16	"	135	7.5	T	8.35	90
17	"	120	9.3	LL	8.35	111
18	"	105	9.1	"	8.35	109
19	"	090	8.85	"	8.35	106
20	"	075	8.7	"	8.35	104
21	"	060	8.4	"	8.3	101
22	"	045	8.2	L	8.3	99
23	"	030	8.2	LL	8.3	99
24	"	015	8.1	"	8.3	98
25	"	000	8.4	"	8.4	100
1	1D	360	8.6	LL	8.4	102
2	"	345	8.7	-	8.5	102
3	"	330	8.2	LL	8.3	99
4	"	315	8.4	-	8.35	101
5	"	300	8.5	LL	8.4	101
6	"	285	8.8	"	8.55	103
7	"	270	8.95	"	8.6	104
8	"	255	9.1	"	8.6	106
9	"	240	9.3	"	8.55	109
10	"	225	9.2	L	8.5	110

TABLE 6 (concluded)

Wind Speed Distribution Around Open Tower
At Section I, Case D.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	7.6	TT	8.45	90
12	"	195	6.5	"	8.5	72
13	"	180	6.2	"	8.6	72
14	"	165	9.0	L	8.5	106
15	"	150	7.7	TT	8.45	91
16	"	135	9.4	LL	8.5	111
17	"	120	9.4	"	8.55	110
18	"	105	9.1	"	8.35	108
19	"	090	8.95	"	8.6	104
20	"	075	8.8	"	8.55	103
21	"	060	8.5	"	8.4	101
22	"	045	8.4	-	8.35	101
23	"	030	8.3	-	8.25	101
24	"	015	8.75	-	8.5	103
25	"	000	8.6	-	8.4	102
1	2D	240				
2	"	225	9.6	LL	8.9	107
3	"	210	9.3	"	8.6	108
4	"	185	7.9	TT	8.5	93
5	"	170	7.1	"	8.7	92
6	"	165	7.6	"	8.5	90
7	"	150	9.4	LL	8.6	109
8	"	135	9.6	"	8.9	107
1	4D	195	9.3	LL	8.7	108
2	"	180	7.6	TT	8.9	86
3	"	165	9.2	LL	8.7	106

TABLE 7

Wind Speed Distribution Around Open Tower
At Section I, Case E.

Ref. No.	Coordinates r	θ°	U (mph)	Flow Type	Uo (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.4	100
2	"	345	8.1	"	8.3	98
3	"	330	8.7	"	8.4	104
4	"	315	8.2	L	8.3	99
5	"	300	8.4	"	8.3	101
6	"	285	8.7	LL	8.35	104
7	"	270	8.95	"	8.35	107
8	"	255	9.05	"	8.35	108
9	"	240	9.3	"	8.35	111
10	"	225	7.5	T	8.35	90
11	"	210	9.4	L	8.4	112
12	"	195	8.6	LL	8.5	101
13	"	180	3.5	T	8.6	41
14	"	165	8.6	LL	8.5	101
15	"	150	9.4	L	8.4	112
16	"	135	7.5	T	8.35	90
17	"	120	9.3	LL	8.35	111
18	"	105	9.05	"	8.35	108
19	"	090	8.95	"	8.35	107
20	"	075	8.7	"	8.35	104
21	"	060	8.4	L	8.3	101
22	"	045	8.2	"	8.3	99
23	"	030	8.7	LL	8.4	104
24	"	015	8.1	"	8.3	98
25	"	000	8.4	"	8.4	100
1	1D	360	8.6	LL	8.4	102
2	"	345	8.75	"	8.5	103
3	"	330	8.3	-	8.25	101
4	"	315	8.4	LL	8.35	101
5	"	300	8.5	"	8.4	101
6	"	285	8.75	"	8.55	102
7	"	270	9.0	"	8.6	104
8	"	255	9.1	"	8.6	106
9	"	240	9.4	"	8.55	110
10	"	225	9.4	"	8.5	111

TABLE 7 (concluded)

Wind Speed Distribution Around Open Tower At Section I, Case E.

Ref. No.	Coordinates r	θ^{o}	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	7.7	TT	8.45	91
12	"	195	9.0	L	8.5	106
13	"	180	3.6	TT	8.6	42
14	"	165	9.0	L	8.5	106
15	"	150	7.7	TT	8.45	91
16	"	135	9.4	LL	8.5	111
17	"	120	9.4	"	8.55	110
18	"	105	9.1	"	8.6	106
19	"	090	9.0	"	8.6	104
20	"	075	8.75	"	8.55	102
21	"	060	8.5	"	8.4	101
22	"	045	8.4	"	8.35	101
23	"	030	8.3	-	8.25	101
24	"	015	8.75	-	8.5	103
25	"	000	8.6	-	8.4	102
1	2D	240				
2	"	225	9.6	LL	8.9	107
3	"	210	9.4	"	8.6	109
4	"	195	7.6	T	8.5	90
5	"	180	4.5	T	8.7	52
6	"	165	7.6	T	8.5	90
7	"	150	9.4	LL	8.6	109
8	"	135	9.6	"	8.9	107
1	4D	195	9.2	LL	8.7	106
2	"	180	6.0	T	8.9	68
3	"	165	9.2	LL	8.7	106

TABLE 8

Wind Speed Distribution Around Open Tower
At Section II, Case A.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.7	97
2	"	345	8.4	-	8.4	100
3	"	330	8.35	LL	8.3	101
4	"	315	8.3	-	8.35	100
5	"	300	8.7	-	8.5	102
6	"	285	8.9	-	8.45	105
7	"	270	9.05	LL	8.4	108
8	"	255	9.1	"	8.45	107
9	"	240	9.25	"	8.45	109
10	"	225	9.45	"	8.45	111
11	"	210	9.3	L	8.4	111
12	"	195	8.6	TT	8.45	102
13	"	180	5.2	"	8.8	59
14	"	165	5.0	"	8.6	58
15	"	150	8.8	"	8.5	103
16	"	135	8.3	LL	8.4	99
17	"	120	8.35	"	8.45	99
18	"	105	9.1	"	8.45	108
19	"	090	9.1	"	8.45	108
20	"	075	9.0	"	8.45	107
21	"	060	8.7	"	8.4	104
22	"	045	8.7	L	8.35	104
23	"	030	8.6	LL	8.3	103
24	"	015	8.4	-	8.4	100
25	"	000	8.4	-	8.7	97
1	1D	360	8.5	LL	8.7	98
2	"	345	8.4	T	8.35	101
3	"	330	8.35	LL	8.25	101
4	"	315	8.4	"	8.3	101
5	"	300	8.85	"	8.4	105
6	"	285	9.2	"	8.6	107
7	"	270	9.15	"	8.75	104
8	"	255	9.3	"	8.8	105
9	"	240	9.45	"	8.75	108
10	"	225	9.5	"	8.65	110

TABLE 8 (concluded)

Wind Speed Distribution Around Open Tower
At Section II, Case A.

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	9.4	LL	8.55	110
12	"	195	9.2	T	8.45	109
13	"	180	6.05	TT	8.5	71
14	"	165	8.15	"	8.6	95
15	"	150	8.4	"	8.5	99
16	"	135	8.4	LL	8.3	101
17	"	120	8.35	"	8.25	101
18	"	105	9.5	"	8.8	108
19	"	090	9.2	"	8.75	105
20	"	075	9.1	-	8.8	104
21	"	060	8.8	-	8.7	101
22	"	045	8.75	-	8.5	103
23	"	030	8.6	-	8.3	103
24	"	015	8.4	-	8.35	101
25	"	000	8.5	-	8.7	98
2	2D	225	10.0	LL	9.3	107
3	"	210	9.6	"	8.8	109
4	"	195	9.5	"	8.55	111
5	"	180	7.15	TT	8.6	83
6	"	165	8.4	"	8.55	98
7	"	150	9.45	LL	8.6	110

TABLE 9

Wind Speed Distribution Around Open Tower
At Section II, Case E.

Ref. No.	Coordinates r	θ^{o}	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	360	8.4	LL	8.4	100
2	"	345	8.1	"	8.3	98
3	"	330	8.7	"	8.4	104
4	"	315	8.2	L	8.3	99
5	"	300	8.55	LL	8.3	103
6	"	285	8.8	"	8.35	105
7	"	270	9.0	"	8.35	106
8	"	255	9.25	"	8.35	111
9	"	240	9.1	"	8.35	109
10	"	225	7.0	TT	8.35	84
11	"	210	8.0	"	8.4	95
12	"	195	6.15	T	8.5	72
13	"	180	3.85	TT	8.6	45
14	"	165	6.15	T	8.5	72
15	"	150	8.0	"	8.4	95
16	"	135	7.0	TT	8.35	84
17	"	120	9.1	LL	8.35	109
18	"	105	9.25	"	8.35	111
19	"	090	9.0	"	8.35	106
20	"	075	8.8	"	8.35	105
21	"	060	8.55	"	8.3	103
22	"	045	8.2	L	8.3	99
23	"	030	8.7	LL	8.4	104
24	"	015	8.1	"	8.3	98
25	"	000	8.4	"	8.4	100
1	1D	360	8.6	LL	8.4	102
2	"	345	8.7	-	8.5	102
3	"	330	8.2	-	8.3	99
4	"	315	8.4	-	8.35	101
5	"	300	8.7	-	8.4	104
6	"	285	8.8	-	8.55	103
7	"	270	9.1	-	8.6	106
8	"	255	9.3	-	8.6	108
9	"	240	9.35	-	8.55	109
10	"	225	9.4	-	8.5	111

TABLE 9 (concluded)

Wind Speed Distribution Around Open Tower
At Section II, Case E.

Ref. No.	Coordinates r	θ^{o}	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	7.5	TT	8.45	89
12	"	195	7.9	"	8.5	91
13	"	180	4.7	"	8.7	55
14	"	165	7.9	"	8.5	91
15	"	150	7.5	"	8.45	89
16	"	135	9.4	-	8.5	111
17	"	120	9.35	-	8.55	109
18	"	105	9.3	-	8.6	108
19	"	090	9.1	-	8.6	106
20	"	075	8.8	-	8.55	103
21	"	060	8.7	-	8.4	104
22	"	045	8.4	-	8.35	101
23	"	030	8.2	-	8.3	99
24	"	015	8.7	-	8.5	102
25	"	000	8.6	-	8.4	102
1	2D	225	9.6	LL	8.9	108
2	"	210	9.45	"	8.6	111
3	"	195	7.7	TT	8.5	91
4	"	180	6.2	"	8.7	71
5	"	165	7.7	"	8.5	91
6	"	150	9.45	LL	8.6	111
1	4D	195	9.65	LL	8.65	111
2	"	180	7.1	TT	8.9	80
3	"	165	9.65	"	8.65	111

TABLE 10

Wind Speed Distribution Around Solid Tower
Case A (B,C).

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	000	---	--	---	---
2	"	015	---	--	---	---
3	"	030	7.1	LL	8.3	85
4	"	045	7.6	L	8.35	91
5	"	060	9.2	LL	8.4	109
6	"	075	9.5	T	8.35	114
7	"	090	9.65	"	8.4	115
8	"	105	10.15	L	8.45	120
9	"	120	11.7	"	8.45	138
10	"	135	13.1	T	8.45	155
11	"	150	13.2	"	8.45	157
12	"	165	8.9	TT	8.4	106
13	"	180	6.7	"	8.8	76
14	"	195	---	--	8.6	---
15	"	210	---	--	8.5	---
16	"	225	---	--	8.4	---
17	"	240	11.65	TT	8.4	136
18	"	255	12.3	L	8.45	146
19	"	270	11.3	LL	8.45	134
20	"	285	10.0	L	8.45	118
21	"	300	9.2	LL	8.4	109
22	"	315	7.6	L	8.35	91
23	"	330	7.1	LL	8.3	85
24	"	345	---	--	---	---
25	"	360	---	--	---	---
1	1D	360	8.45	LL	8.7	97
2	"	345	7.75	"	8.35	93
3	"	330	8.1	"	8.25	98
4	"	315	8.8	"	8.45	104
5	"	300	9.75	"	8.7	112
6	"	285	10.5	"	8.6	122
7	"	270	11.2	L	8.75	128
8	"	255	11.65	"	8.8	132
9	"	240	12.2	"	8.75	140
10	"	225	13.2	TT	8.65	155

TABLE 10 (concluded)

Wind Speed Distribution Around Solid Tower
Case A (B,C).

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	13.0	TT	8.55	152
12	"	195	13.15	T	8.45	156
13	"	180	7.15	TT	8.8	80
14	"	165	---	L	8.6	---
15	"	150	---	"	8.5	---
16	"	135	2.7	TT	8.5	32
17	"	120	13.15	T	8.6	153
18	"	105	11.8	L	8.7	136
19	"	090	11.2	"	9.3	121
20	"	075	10.0	"	8.8	113
21	"	060	9.75	"	8.7	112
22	"	045	8.8	LL	8.45	104
23	"	030	8.10	"	8.25	98
24	"	015	7.75	"	8.35	93
25	"	000	8.45	"	8.7	97
1	2D	210	11.8	T	8.8	134
2	"	195	11.7	--	8.55	136
3	"	180	8.6	TT	8.8	98
4	"	165	1.5	"	8.55	17
5	"	150	10.9	"	8.6	127
6	"	135	13.9	T	8.9	156
7	"	120	12.6	L	8.4	150

TABLE 11

Wind Speed Distribution Around Solid Tower
Case D (E).

Ref. No.	Coordinates r	θ^{o}	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	360	4.9	L	8.4	58
2	"	345	5.1	LL	8.3	62
3	"	330	9.2	"	8.4	109
4	"	315	6.1	"	8.3	73
5	"	300	8.3	"	8.35	99
6	"	285	11.2	"	8.35	134
7	"	270	13.1	T	8.35	157
8	"	255	8.45	TT	8.2	103
9	"	240	13.9	"	8.55	162
10	"	225	---	--	8.5	---
11	"	210	---	--	8.4	---
12	"	195	---	--	8.5	---
13	"	180	---	--	8.6	---
14	"	165	---	--	8.5	---
15	"	150	---	--	8.4	---
16	"	135	---	--	8.5	---
17	"	120	13.9	TT	8.55	162
18	"	105	8.45	"	8.2	103
19	"	090	13.1	L	8.35	157
20	"	075	11.2	"	8.35	134
21	"	060	8.3	"	8.35	99
22	"	045	6.1	"	8.3	73
23	"	030	9.2	"	8.4	109
24	"	015	5.1	"	8.3	62
25	"	000	4.9	"	8.4	58
1	1D	360	6.9	LL	8.4	82
2	"	345	7.35	"	8.3	89
3	"	330	9.75	"	8.7	112
4	"	315	8.3	"	8.35	99
5	"	300	9.2	"	8.4	109
6	"	285	11.0	L	8.55	128
7	"	270	12.0	"	8.6	140
8	"	255	13.8	T	8.6	161
9	"	240	14.4	"	9.25	156
10	"	225	0.8	TT	8.5	9

TABLE 11 (concluded)

Wind Speed Distribution Around Solid Tower
Case D (E).

Ref. No.	Coordinates r	θ^o	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
11	1D	210	---	--	8.45	---
12	"	195	---	--	8.5	---
13	"	180	---	--	8.6	---
14	"	165	---	--	8.5	---
15	"	150	---	--	8.45	---
16	"	135	0.8	TT	8.5	10
17	"	120	14.4	T	9.25	156
18	"	105	13.8	"	8.6	161
19	"	090	12.0	L	8.6	140
20	"	075	11.0	"	8.55	128
21	"	060	9.2	LL	8.4	109
22	"	045	8.3	"	8.35	99
23	"	030	9.75	"	8.7	112
24	"	015	7.35	"	8.3	89
25	"	000	6.9	"	8.4	82
1	2D	240	9.65	T	8.4	115
2	"	225	13.5	"	8.9	159
3	"	210	10.2	TT	8.6	116
4	"	195	4.2	"	8.5	49
5	"	180	0.9	"	8.7	10
6	"	165	4.2	"	8.5	49
7	"	150	10.2	"	8.6	116
8	"	135	13.5	T	8.9	159
9	"	120	9.65	"	8.4	115
1	4D	195	9.7	TT	8.7	112
2	"	180	5.9	"	8.9	66
3	"	165	9.7	"	8.7	112

TABLE 12

Wind Speed Distribution Around
Cylindrical Stack.
(Horizontal Distribution at height 15")

Ref. No.	Coordinates r	θ^{o}	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
1	1/2D	180	---	TT	8.6	---
2	"	165	---	"	8.6	---
3	"	150	0.0	"	8.4	0
4	"	135	7.6	"	8.4	90
5	"	120	11.7	L	8.35	140
6	"	105	11.1	"	8.3	134
7	"	090	10.2	LL	8.3	123
8	"	075	9.5	"	8.3	115
9	"	060	8.5	"	8.3	102
10	"	045	7.5	"	8.3	90
11	"	030	6.7	"	8.3	81
12	"	015	7.4	"	8.35	89
21	1D	180	---	TT	8.5	---
22	"	165	---	"	8.5	---
23	"	150	8.5	"	8.4	101
24	"	135	11.3	L	8.35	135
25	"	120	11.1	LL	8.3	134
26	"	105	10.7	"	8.3	129
27	"	090	9.8	"	8.5	118
28	"	075	9.1	L	8.3	110
29	"	060	8.5	"	8.3	102
30	"	045	7.9	"	8.3	95
31	"	030	7.5	"	8.3	90
32	"	015	7.4	"	8.35	89
33	"	000	7.5	"	8.4	89
41	2D	180	0.5	TT	8.6	≈5
42	"	165	5.4	"	8.5	64
43	"	150	9.8	T	8.45	116
44	"	135	10.1	L	8.4	120
45	"	120	10.0	LL	8.45	118
46	"	105	10.2	"	8.5	120
47	"	090	9.5	"	8.5	112
48	"	075	9.1	"	8.4	108
49	"	060	8.7	"	8.35	104
50	"	045	8.5	"	8.3	102
51	"	030	8.1	"	8.3	98
52	"	015	8.0	"	8.35	96
53	"	000	8.0	"	8.4	95

TABLE 12 (concluded)

Wind Speed Distribution Around Cylindrical Stack. (Horizontal Distribution at height 15")

Ref. No.	Coordinates r	θ°	U (mph)	Flow Type	U_o (mph)	U/U_o (%)
61	3D	180	4.0	TT	8.65	46
62	"	165	7.2	T	8.5	85
63	"	150	9.4	L	8.5	111
64	"	135	9.7	LL	8.55	113
65	"	120	9.8	"	8.7	113
66	"	105	8.8	"	8.8	116
67	"	090	9.7	"	8.8	110
68	"	075	9.3	"	8.7	107
69	"	060	8.9	"	8.55	104
70	"	045	8.7	"	8.35	104
71	"	030	8.4	"	8.25	102
72	"	015	8.1	"	8.3	98
73	"	000	8.3	"	8.35	99
74	4D	180	5.0	T	8.7	57
75	"	165	8.0	"	8.5	94
76	"	150	9.4	L	8.55	110
77	"	135	9.7	"	8.75	111
78	"	120	9.8	LL	9.0	109
79	"	105	10.4	"	9.1	114
80	"	090	9.8	"	9.1	108
81	"	075	9.6	"	9.05	106
82	"	060	9.0	"	8.9	101
83	"	045	8.9	"	8.5	105
84	"	030	8.5	"	8.2	104
85	"	015	8.1	"	8.2	99
86	"	000	8.3	"	8.3	100
88	6D	180	6.4	T	8.7	74
89	"	165	9.0	"	8.55	105
90	"	150	9.4	LL	8.8	107
91	8D	180	6.5	T	8.7	75
92	"	165	9.5	L	8.6	110
93	"	150	9.9	LL	9.2	108
94	10D	180	6.9	T	8.8	78

TABLE 13

Wind Speed Distribution in a Vertical Plane
Behind the Center of a Cylindrical Stack.

Ref. No.	Coordinates* x	z	U/U_o (%)	Ref. No.	Coordinates* x	z	U/U_o (%)
1	1/4D	-1/2D	112	29	1/4D	2D	---
2	1/2D	"	107	30	1/2D	"	---
3	1D	"	99	31	1D	"	---
4	2D	"	97	32	2D	"	0
5	4D	"	101	33	3D	"	53
				34	4D	"	73
6	1/4D	0D	50	35	5D	"	83
7	1/2D	"	55	36	6D	"	93
8	1D	"	76				
9	2D	"	88	37	1/4D	21/2D	---
10	4D	"	95	38	1/2D	"	---
				39	1D	"	---
11	1/4D	1/2D	--	40	2D	"	3
12	1/2D	"	--	41	3D	"	35
13	1D	"	32	42	4D	"	57
14	2D	"	71	43	5D	"	76
15	4D	"	93	44	6D	"	88
16	1/4D	1D	--	45	1/2D	∞	---
17	1/2D	"	--	46	1D	"	---
18	1D	"	∿3	47	2D	"	0
19	2D	"	45	48	3D	"	35
20	4D	"	88	49	4D	"	57
				50	5D	"	76
21	1/4D	11/2D	--	51	6D	"	76
22	1/2D	"	--				
23	1D	"	--				
24	2D	"	33				
25	3D	"	70				
26	4D	"	76				
27	5D	"	99				
28	6D	"	100				

*x = "boom length" or distance downwind from stack.
z = distance down from top of stack, in units of D (= diameter of stack).

TABLE 14

Summary of Findings from an Analysis of Figures 19 through 21.

Case	Boom Extension	Operation angle (deg) for wind speed accuracy of:		Extremes of Velocity Ratio U/U_o (%)	
		±10%	±5%	Maximum	Minimum
(a) Open Tower, Section I					
A	1D	325	180	110	68
	2D	340	270	109	73
B	1D	325	180	109	63
	2D	340	270	109	71
C	1D	340	200	109	81
	2D	345	270	109	84
D	1D	240	190	111	70
	2D	330	250	109	72
E	1D	230	200	112	42
	2D	330	260	109	52
Section II					
A	1D	340	200	109	71
	2D	345	240	112	82
E	1D	220	180	111	55
	2D	280	240	112	71
(b) Solid Tower					
A	1D	110	000	159	00
E	1D	000	000	160	00
	2D	250	~210	159	10
(c) Stack	1D	000	000	146	00
	2D	160	130	120	~5
	3D	180	130	116	46
	4D	190	160	113	57

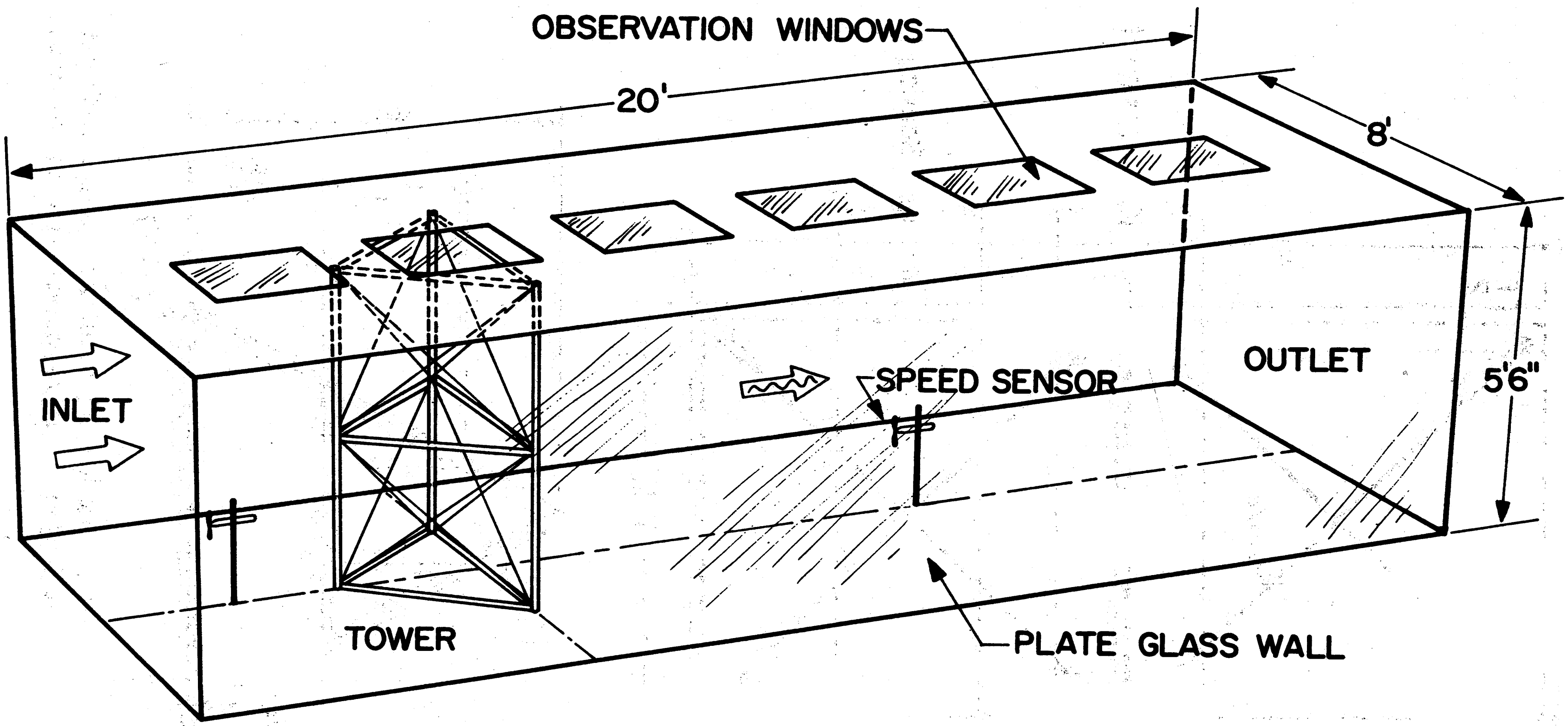


Figure 1. Working section of low speed wind tunnel.

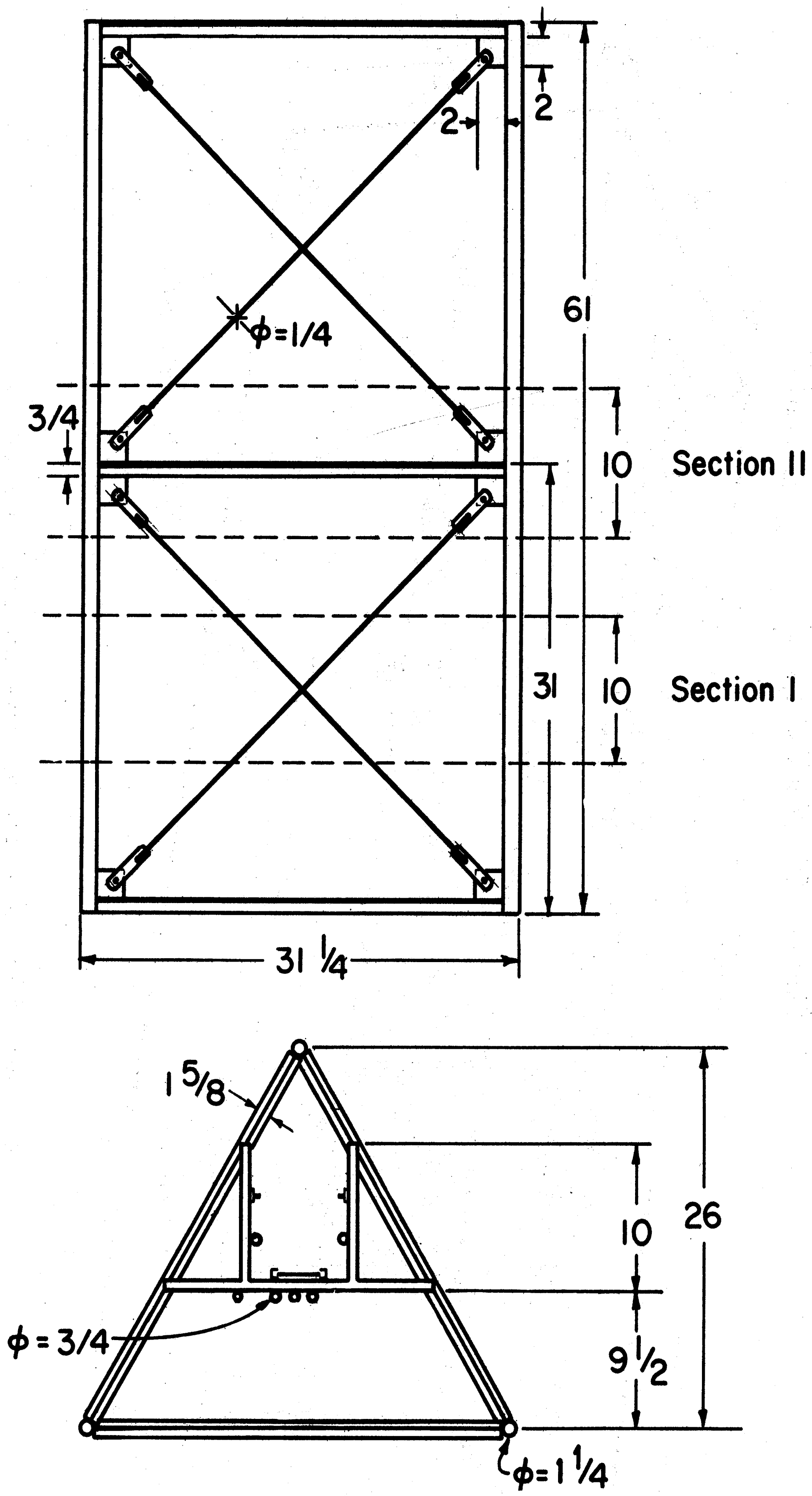


Figure 2. Scale model of WJBK-TV tower, Detroit, Michigan. (Dimensions are in inches.)

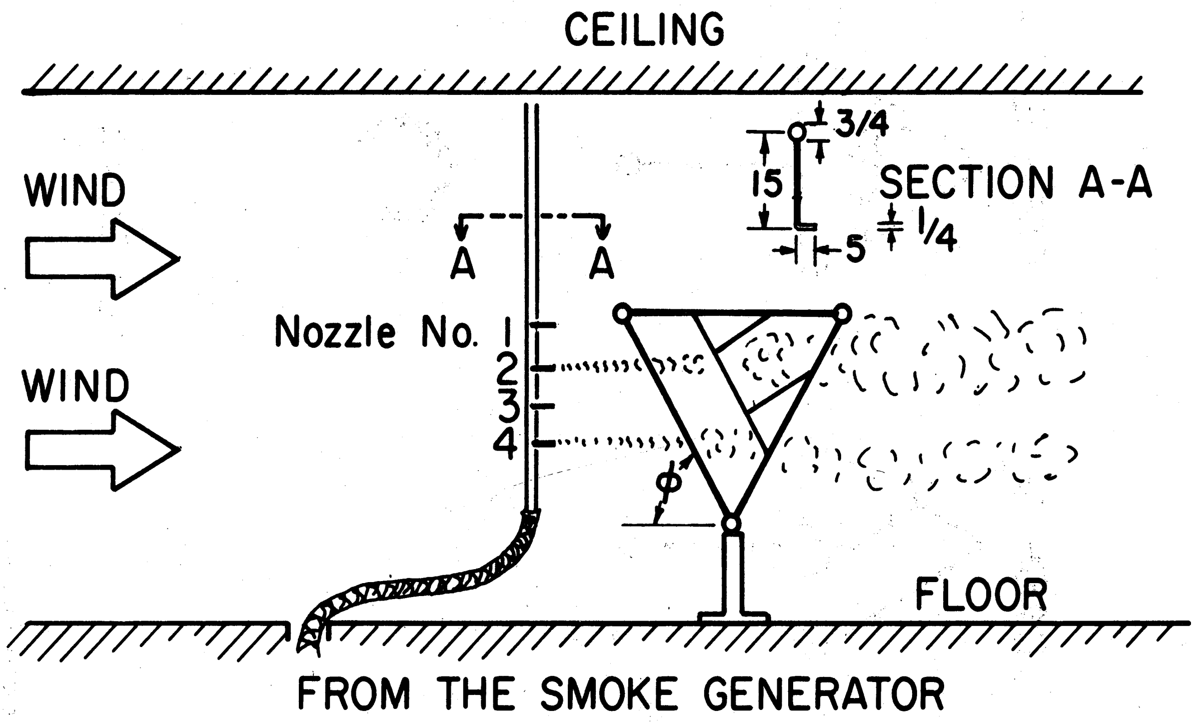


Figure 3. Arrangement for smoke tests. (Dimensions are in inches.)

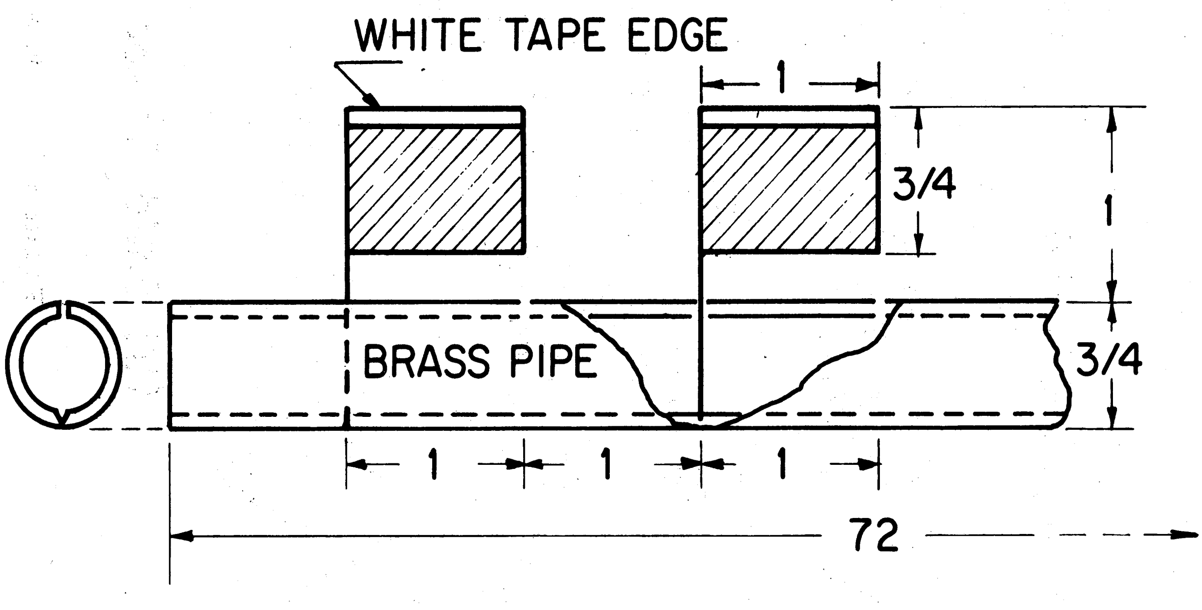


Figure 4. Flag arrangement on bar. (Dimensions are in inches.)

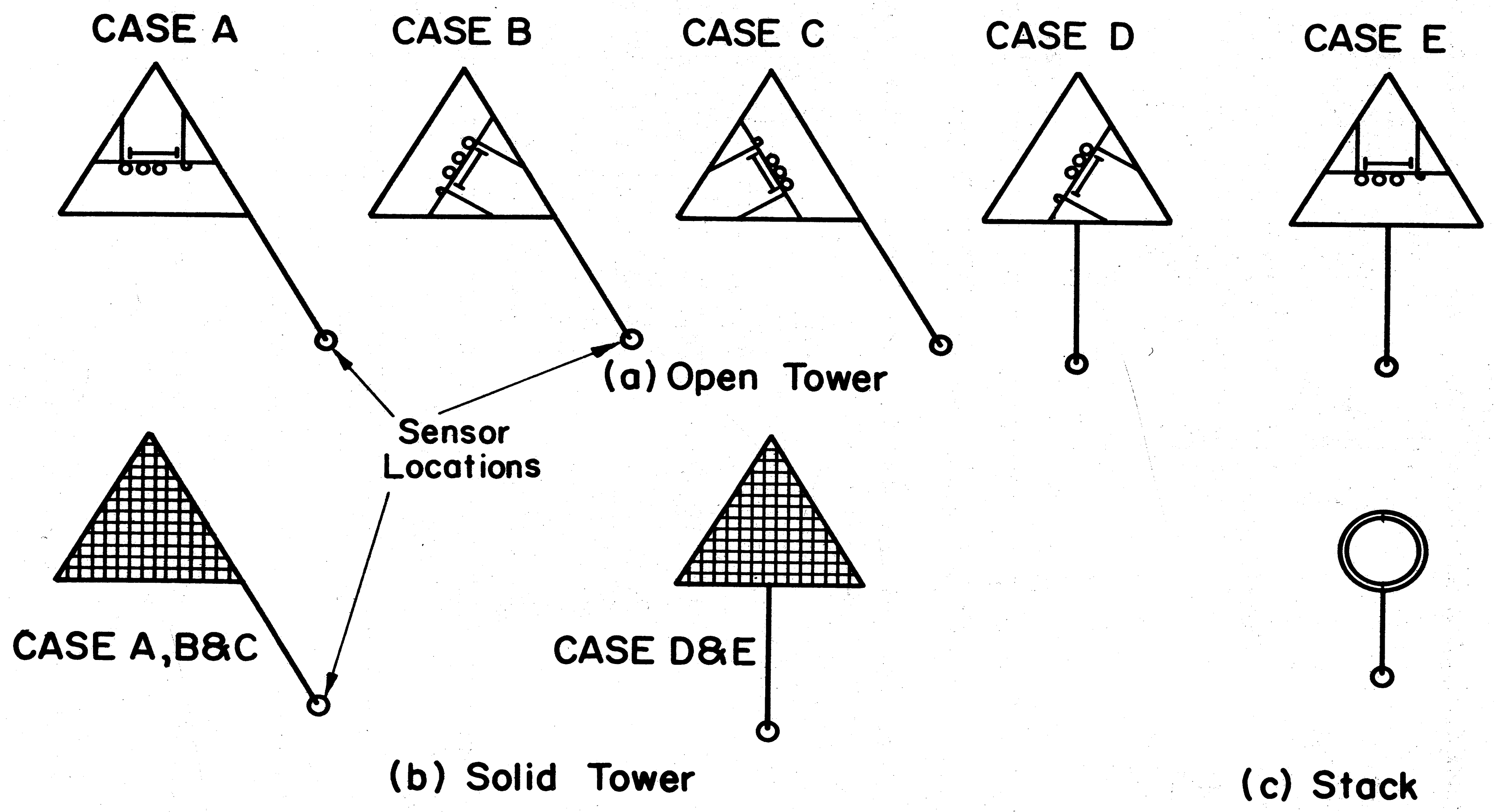
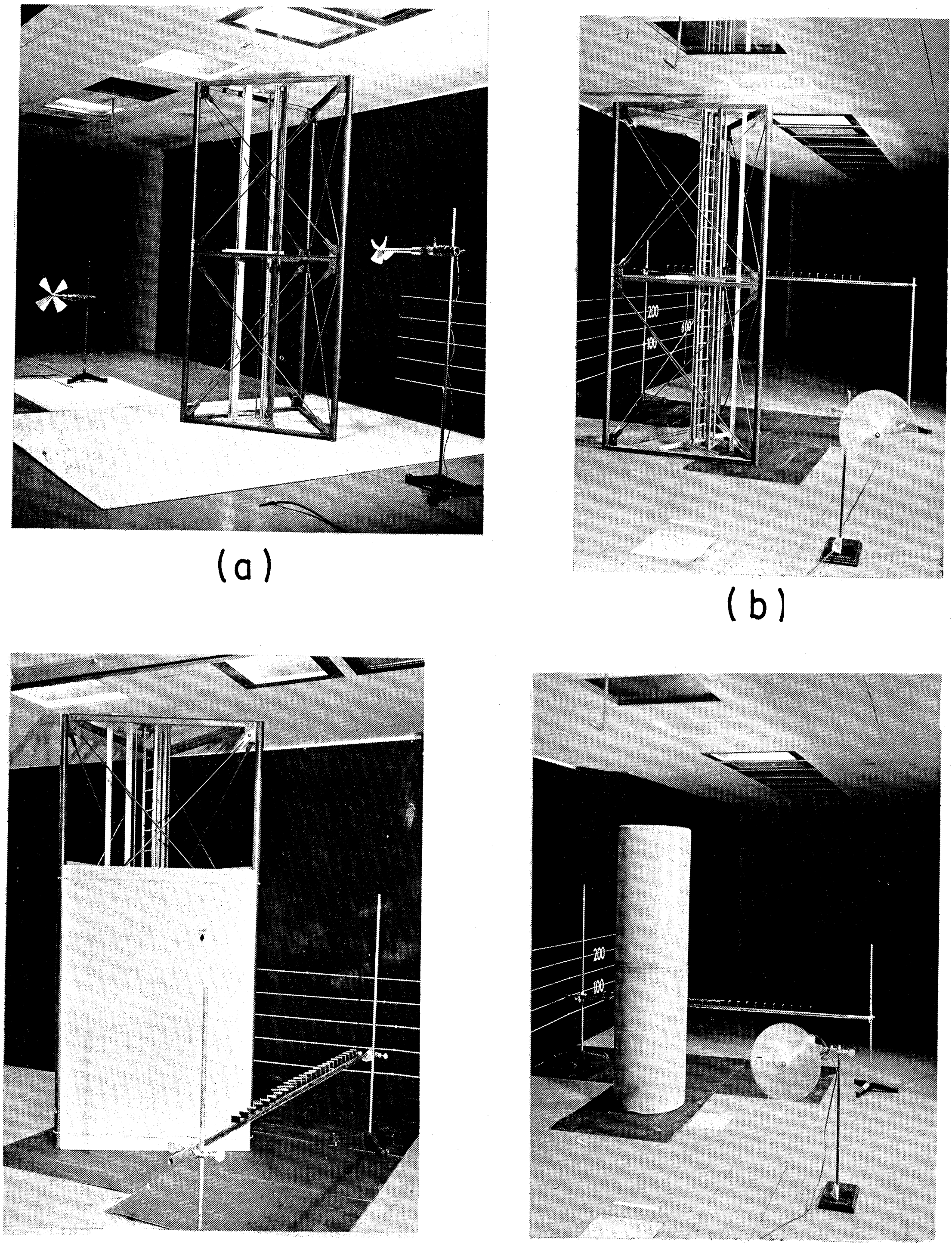


Figure 5. Boom and sensor locations.



(a) (b) (c) (d)

Figure 6. Photographs of tower, stack, anemometers and flags in tunnel.

(a) Open tower arranged for wind speed tests.

(b) Open tower arranged for wind direction tests; flags at Section II, above floor.

(c) Solid tower arranged for wind direction tests. (Note reversal of flags in wake of tower.)

(d) Stack (shortened) arranged for wind direction tests. (Note oscillation of flags in wake of stack.)

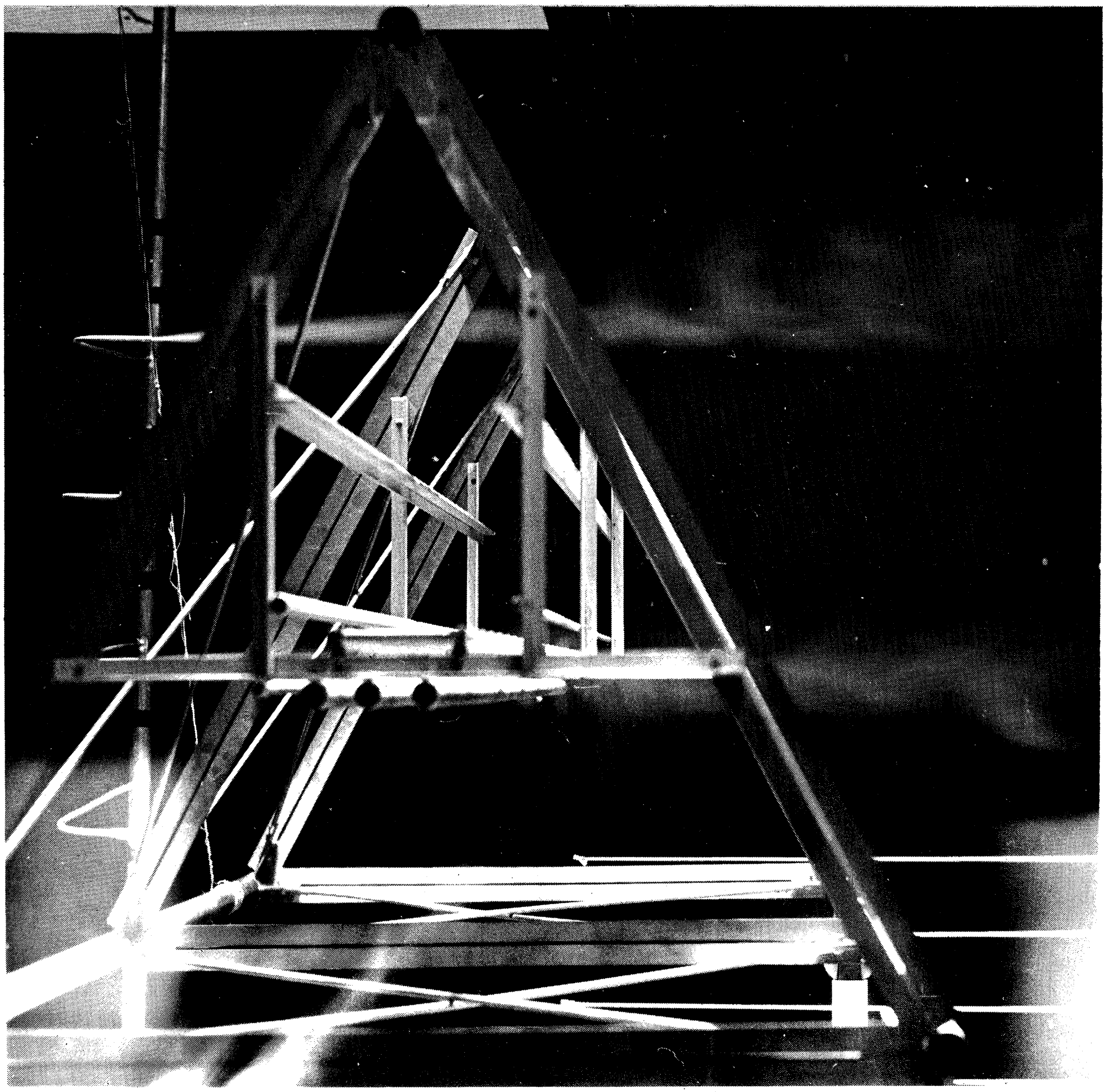


Figure 7. Photograph of Smoke Tests.

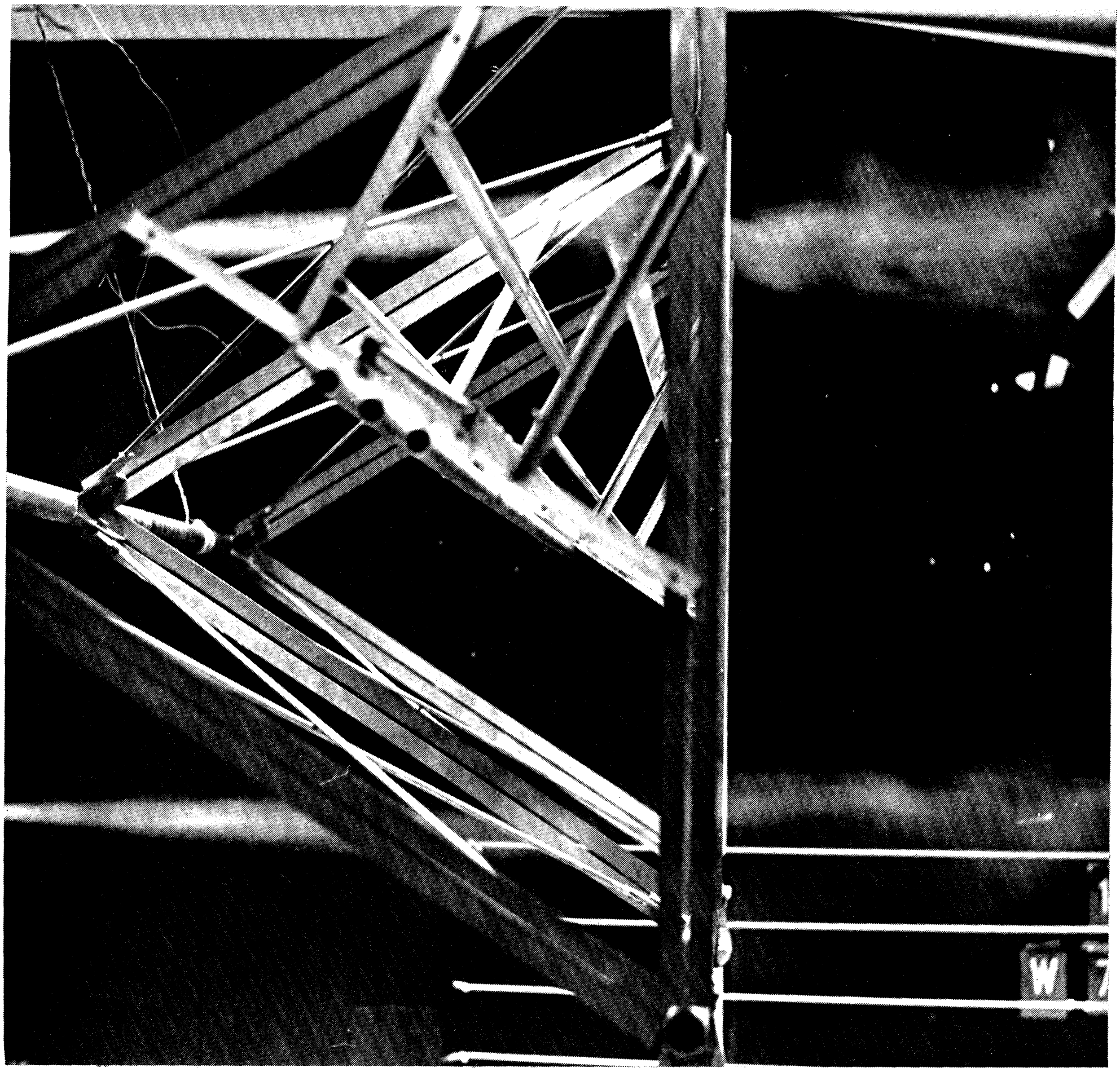


Figure 8. Photograph of Smoke Tests.

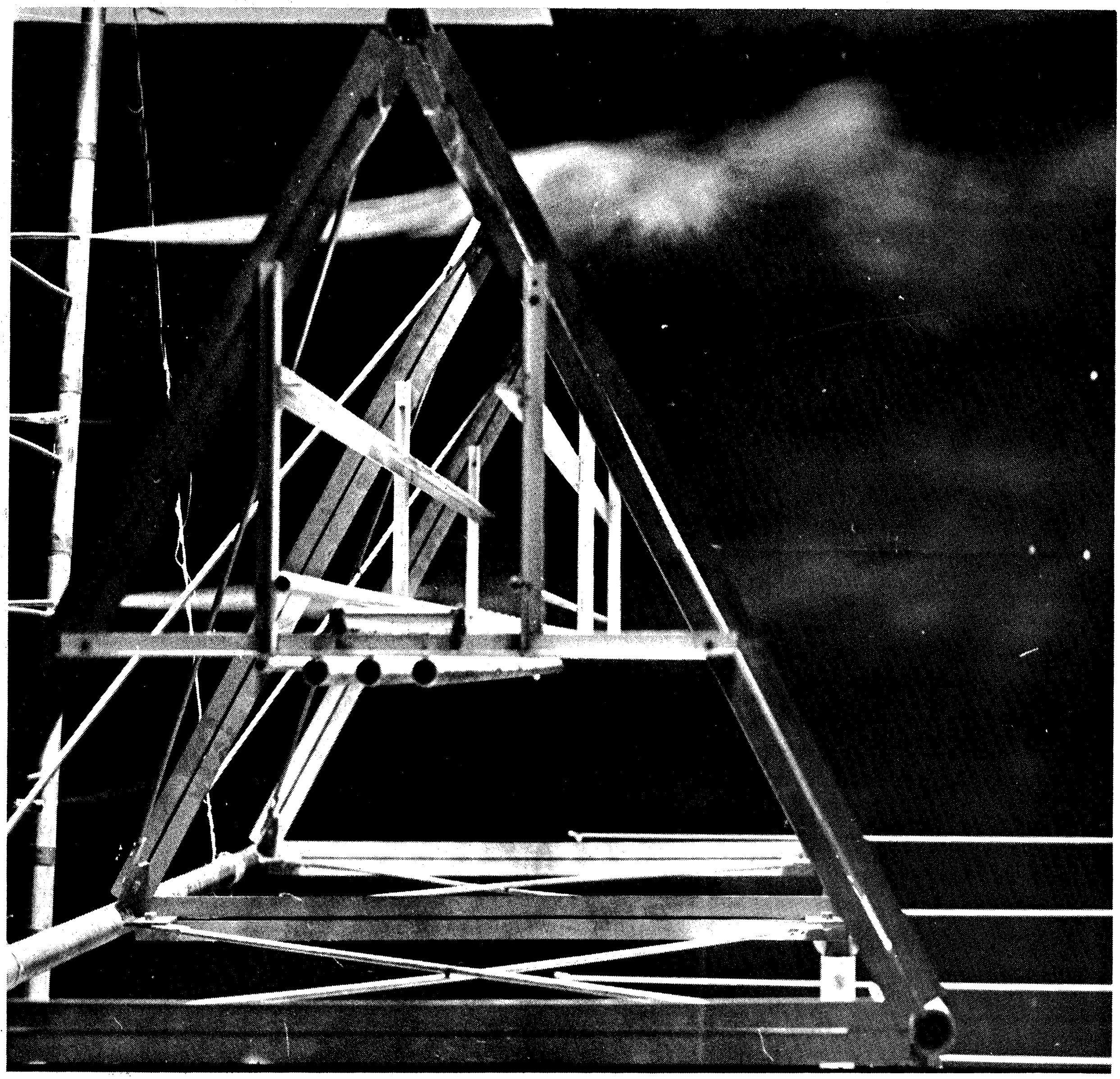


Figure 9. Photograph of Smoke Tests.

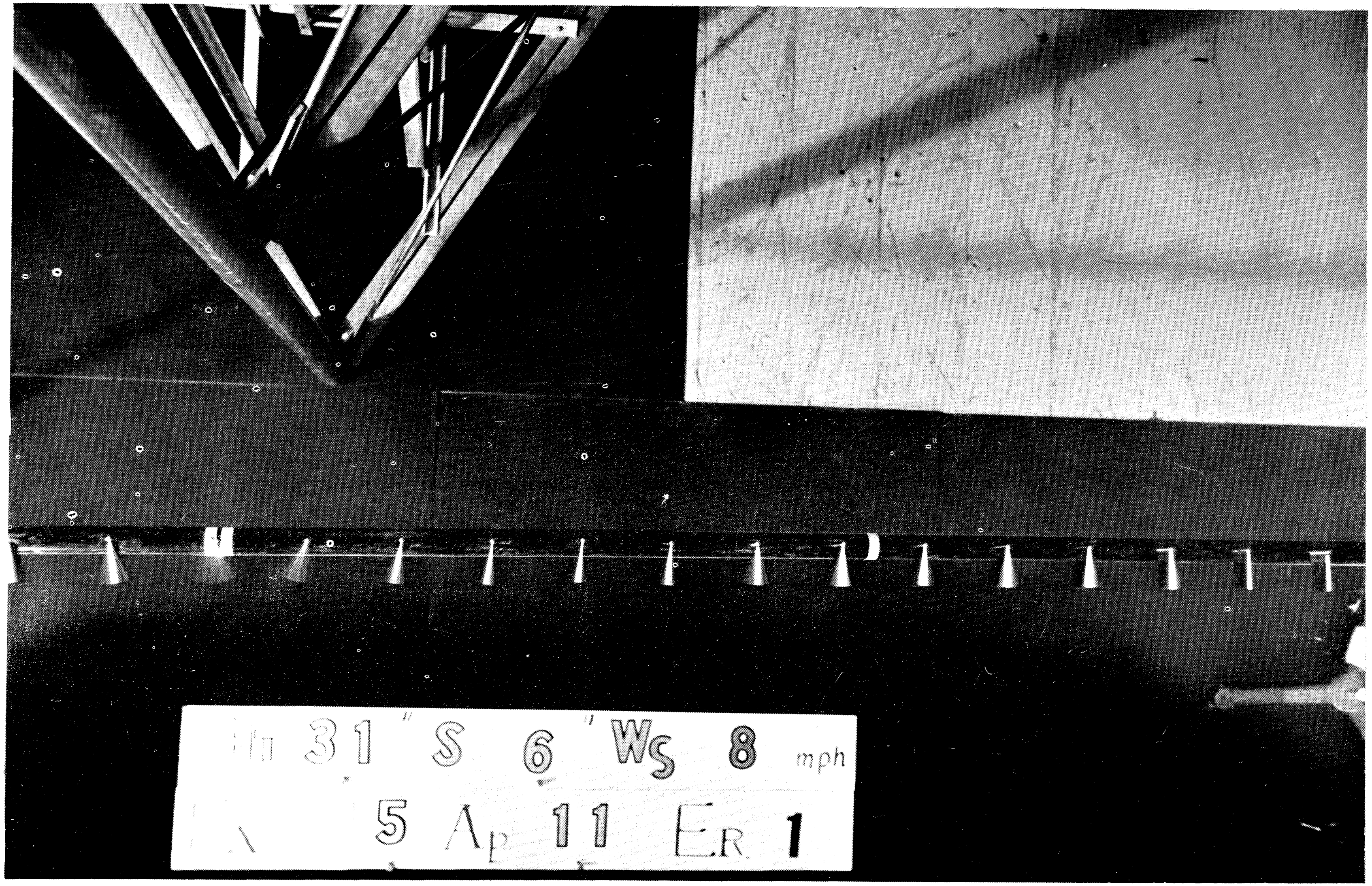
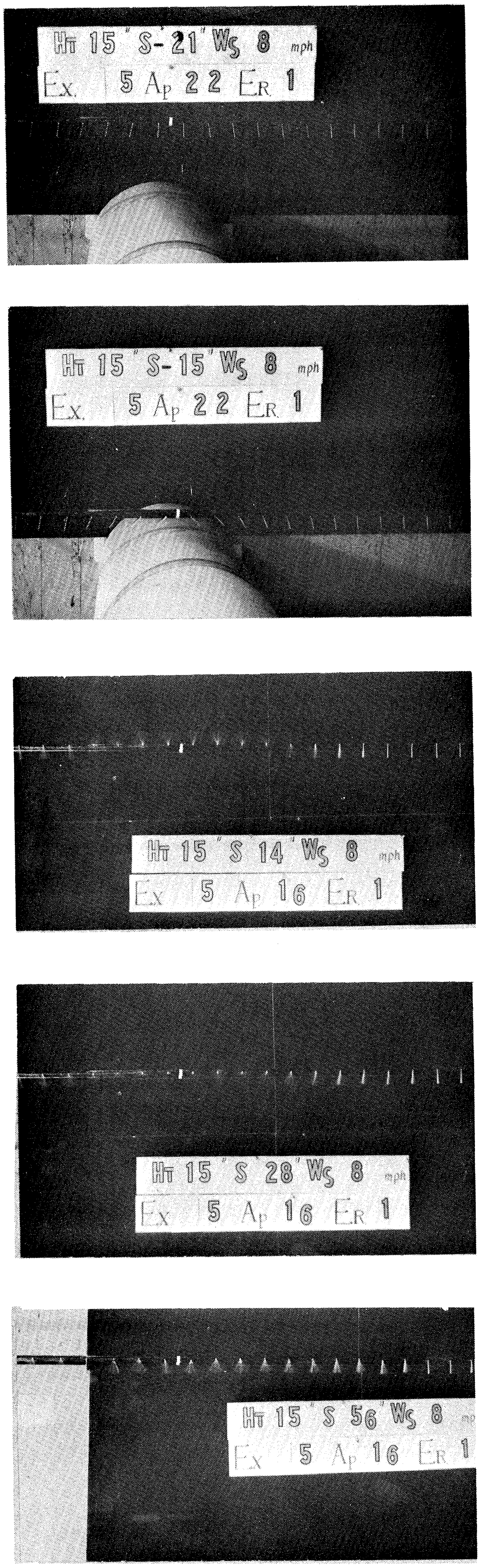


Figure 10. Flag tests (wind direction tests) around the open tower.



(a)

(b)

(c)

(d)

(e)

Figure 11. Flag tests (wind direction tests) around the stack. Flags located 21" ahead of zero line in (a), or 7" = -0.5D ahead of stack; 15" ahead of zero line in (b), or 1" = 0.1D ahead of stack; 14" back of zero line = 1D at (c); 28" = 2D at (d); 56" = 4D at (e).

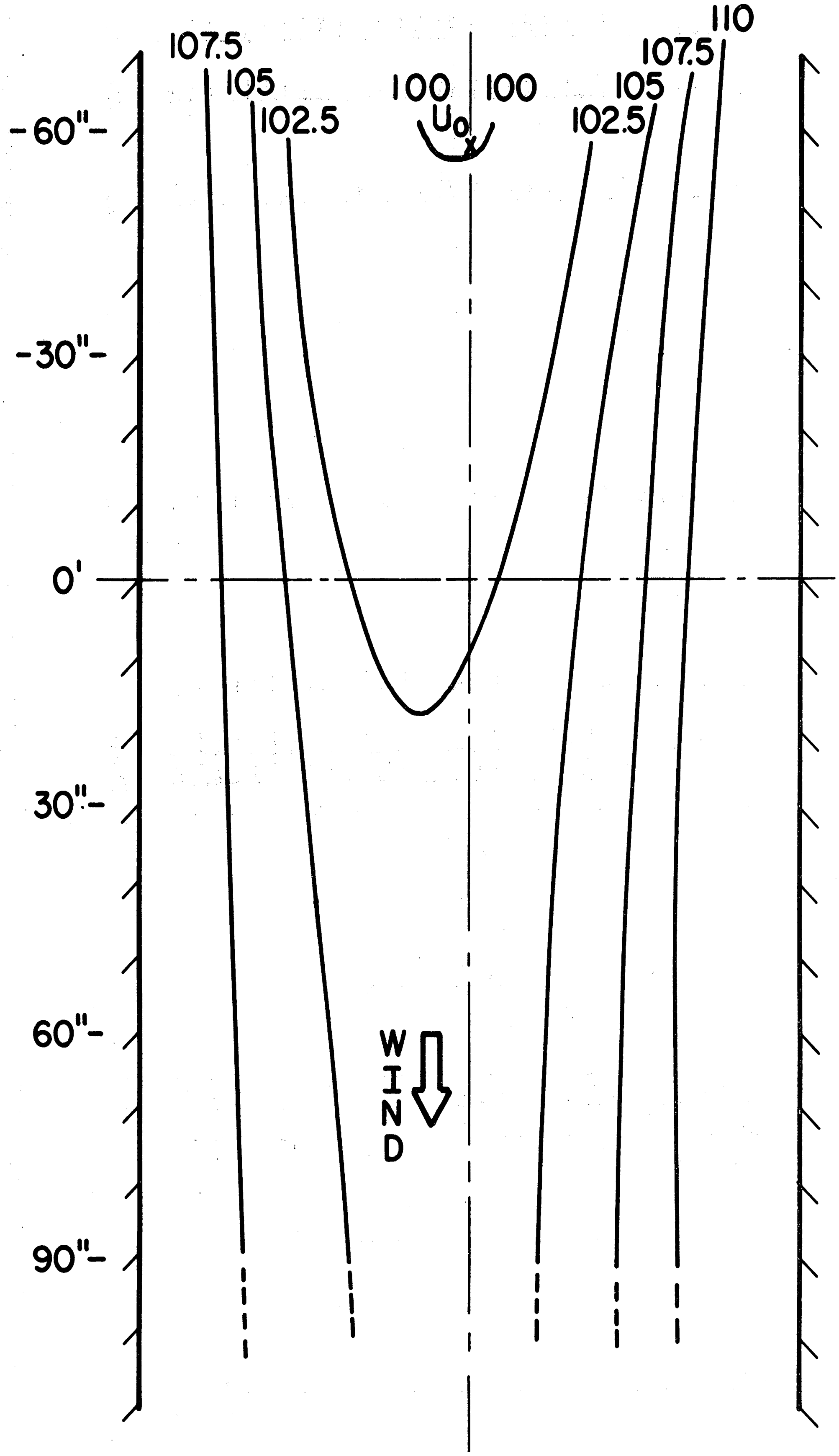


Figure 12. Wind speed distribution in open tunnel. (Units of U/Uo are in percent.)

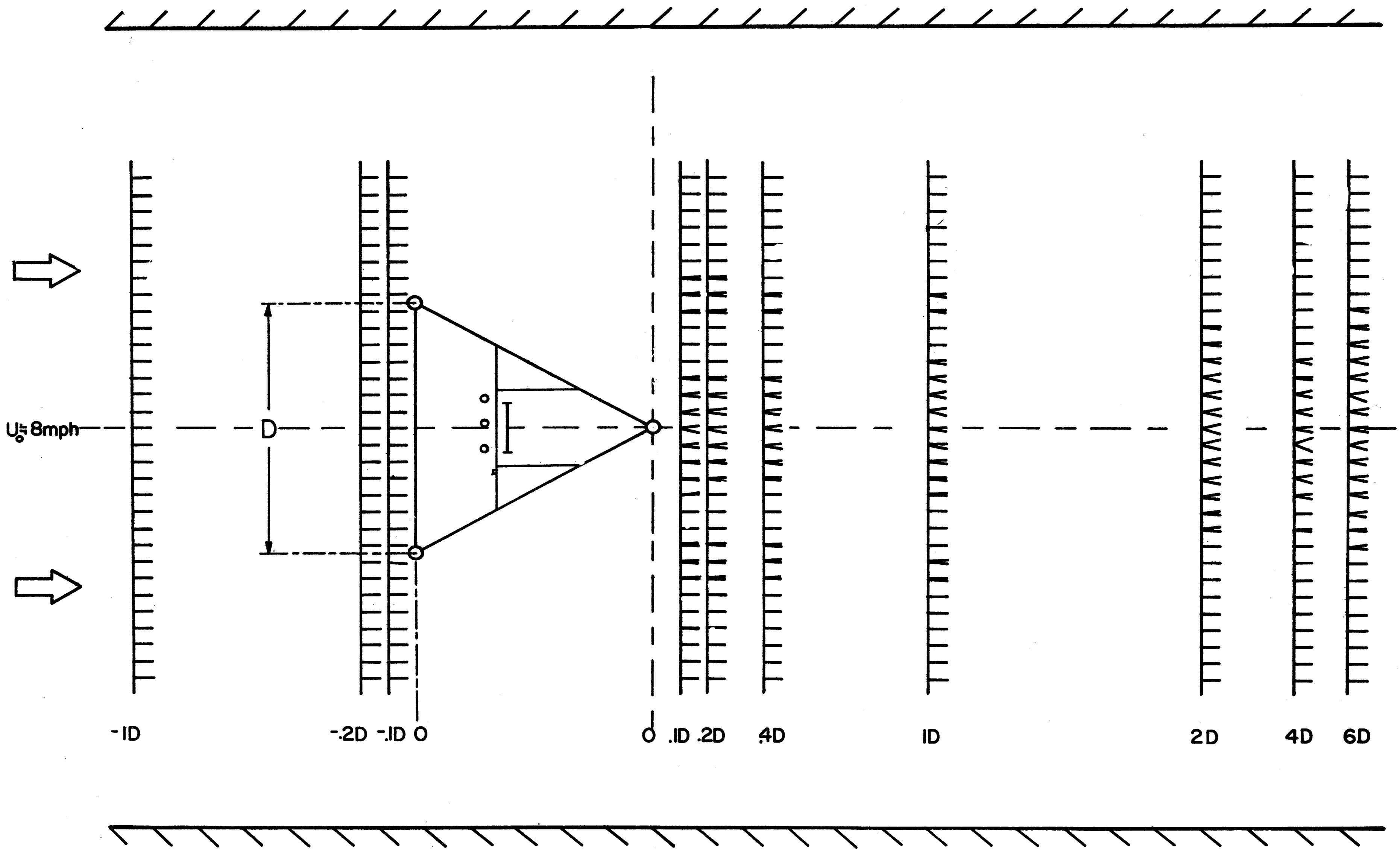


Figure 13. Wind direction profile around open tower, Section I.

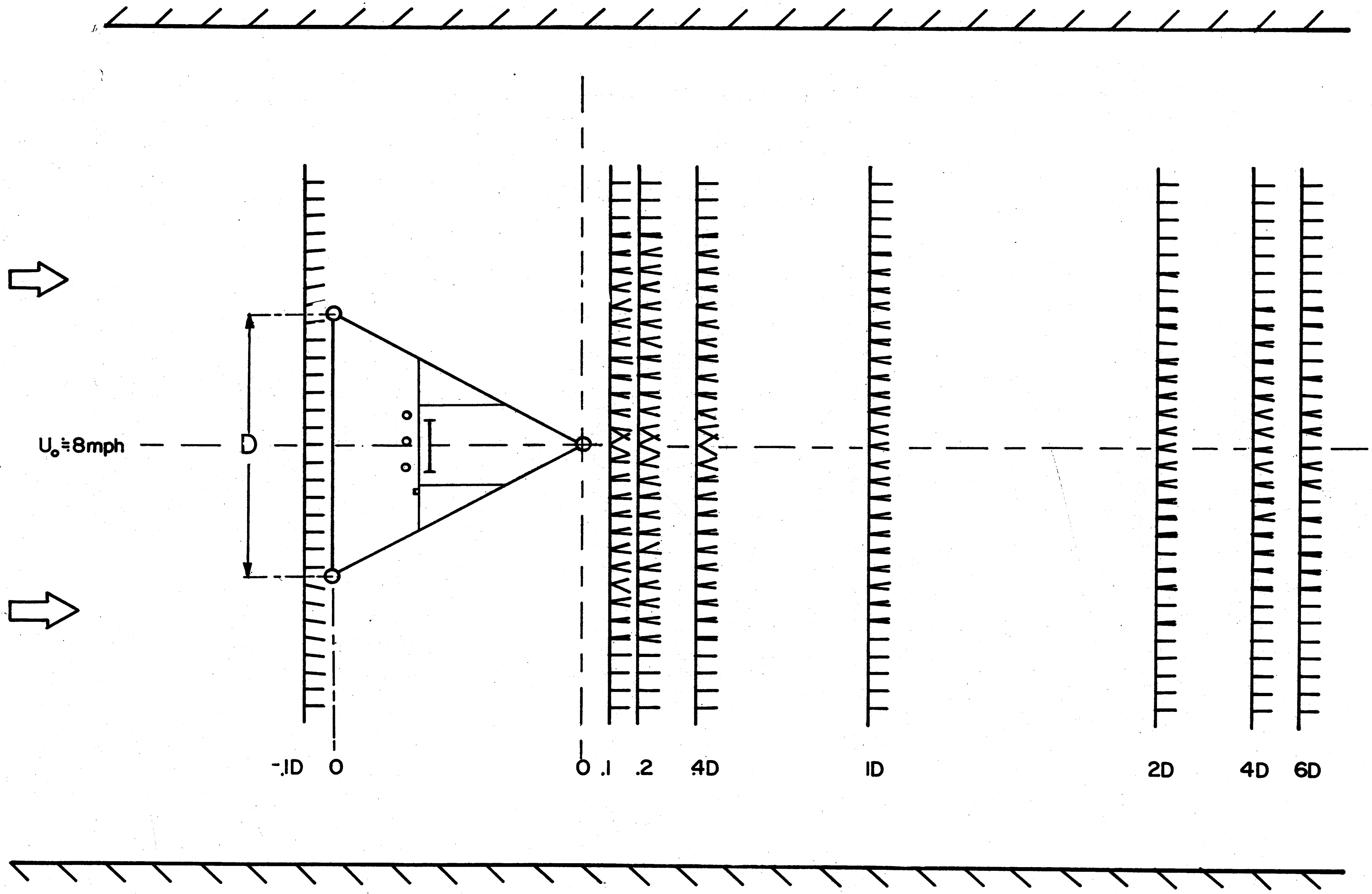


Figure 14. Wind direction profile around open tower, Section II.

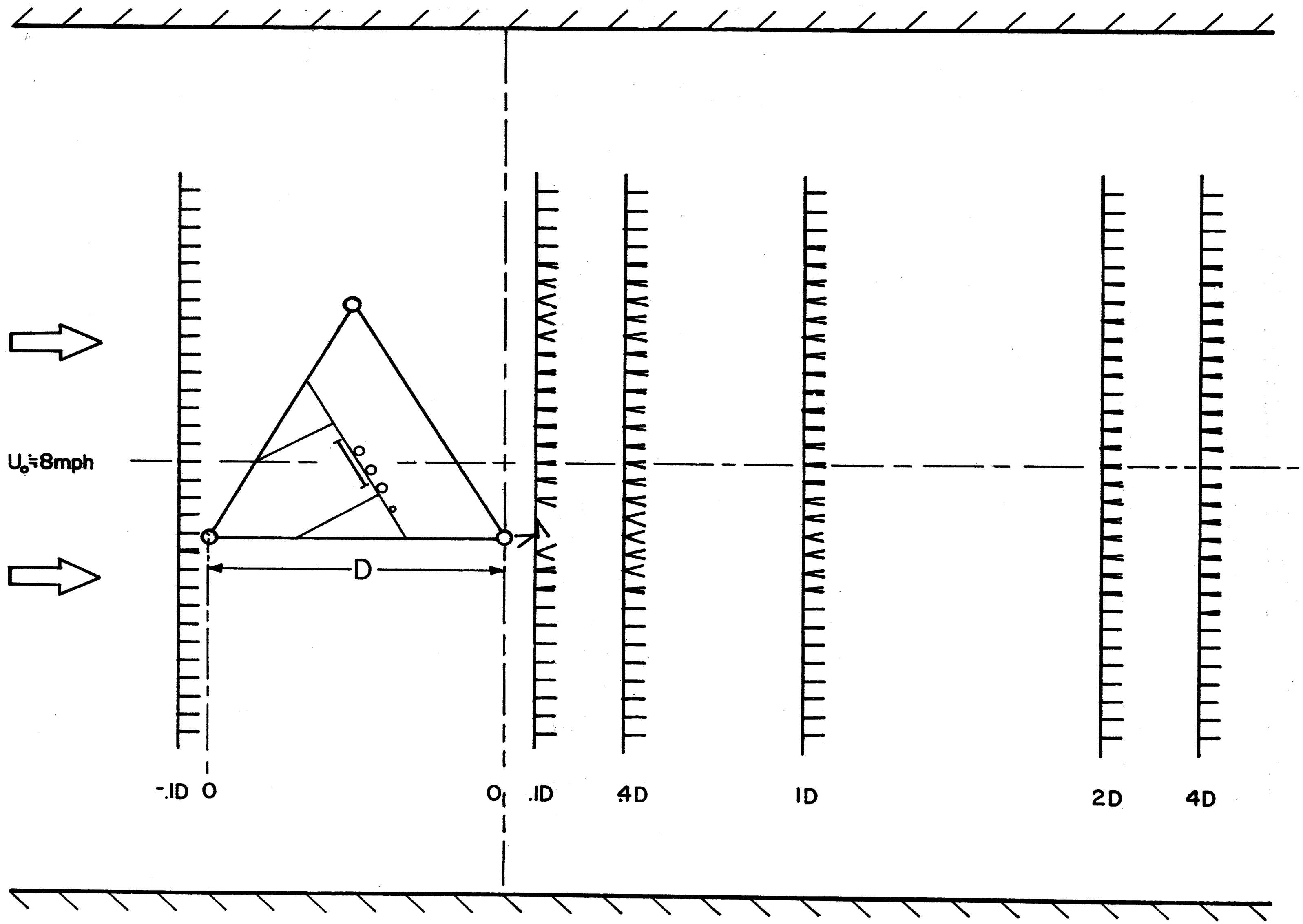


Figure 15. Wind direction profile around open tower, Section II.

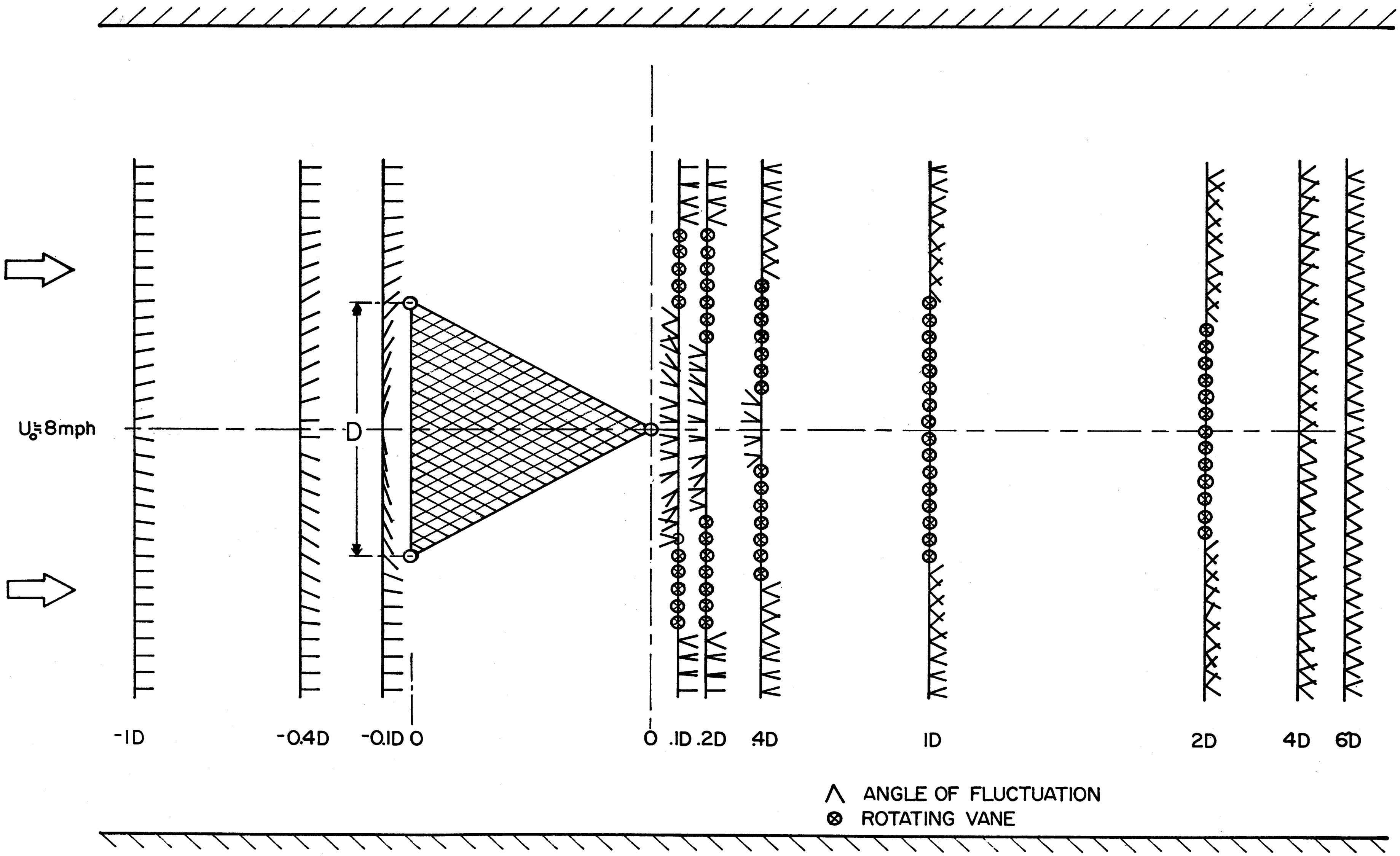


Figure 16. Wind direction profile around solid tower.

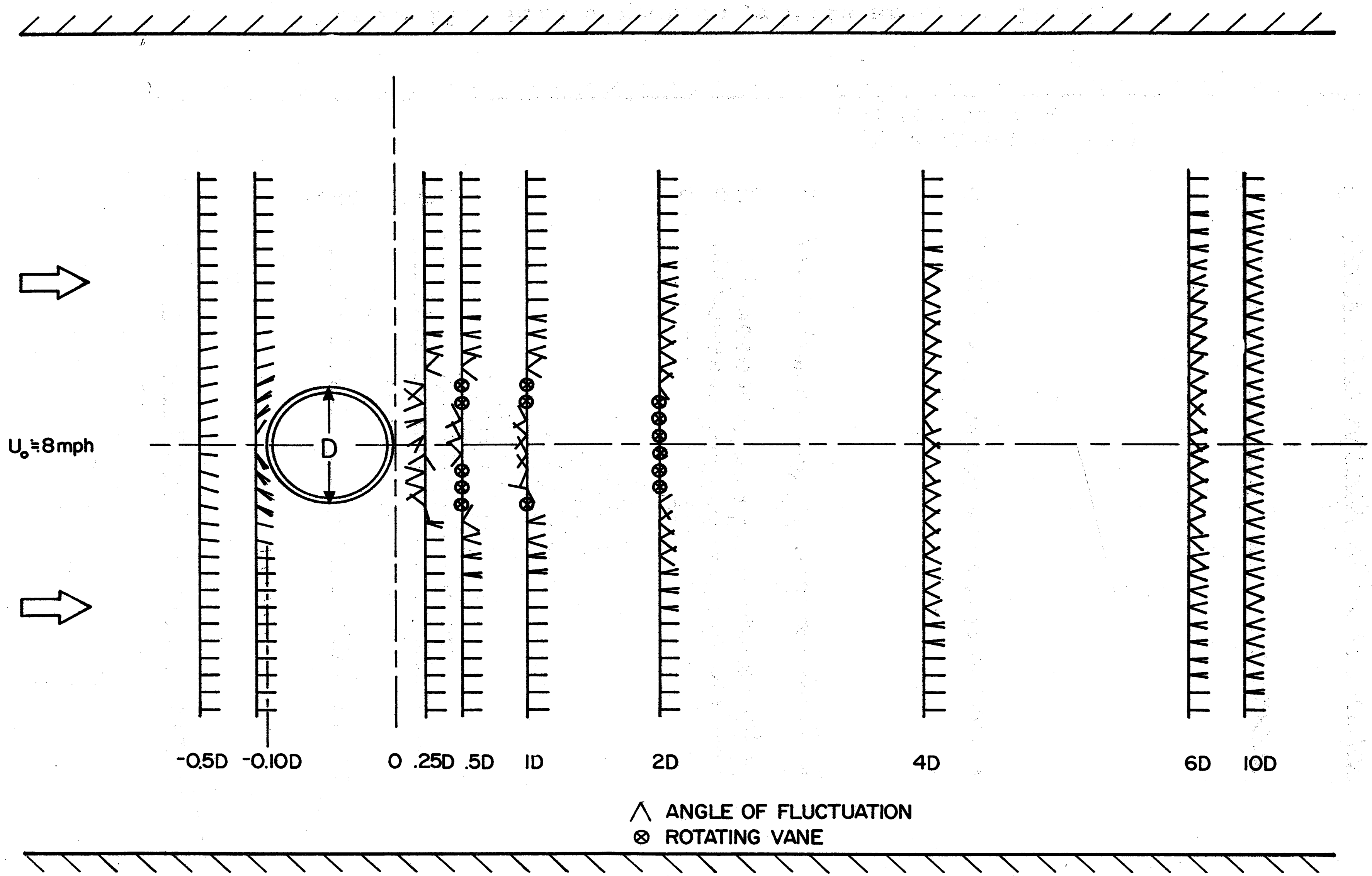


Figure 17. Wind direction profile around cylindrical stack.

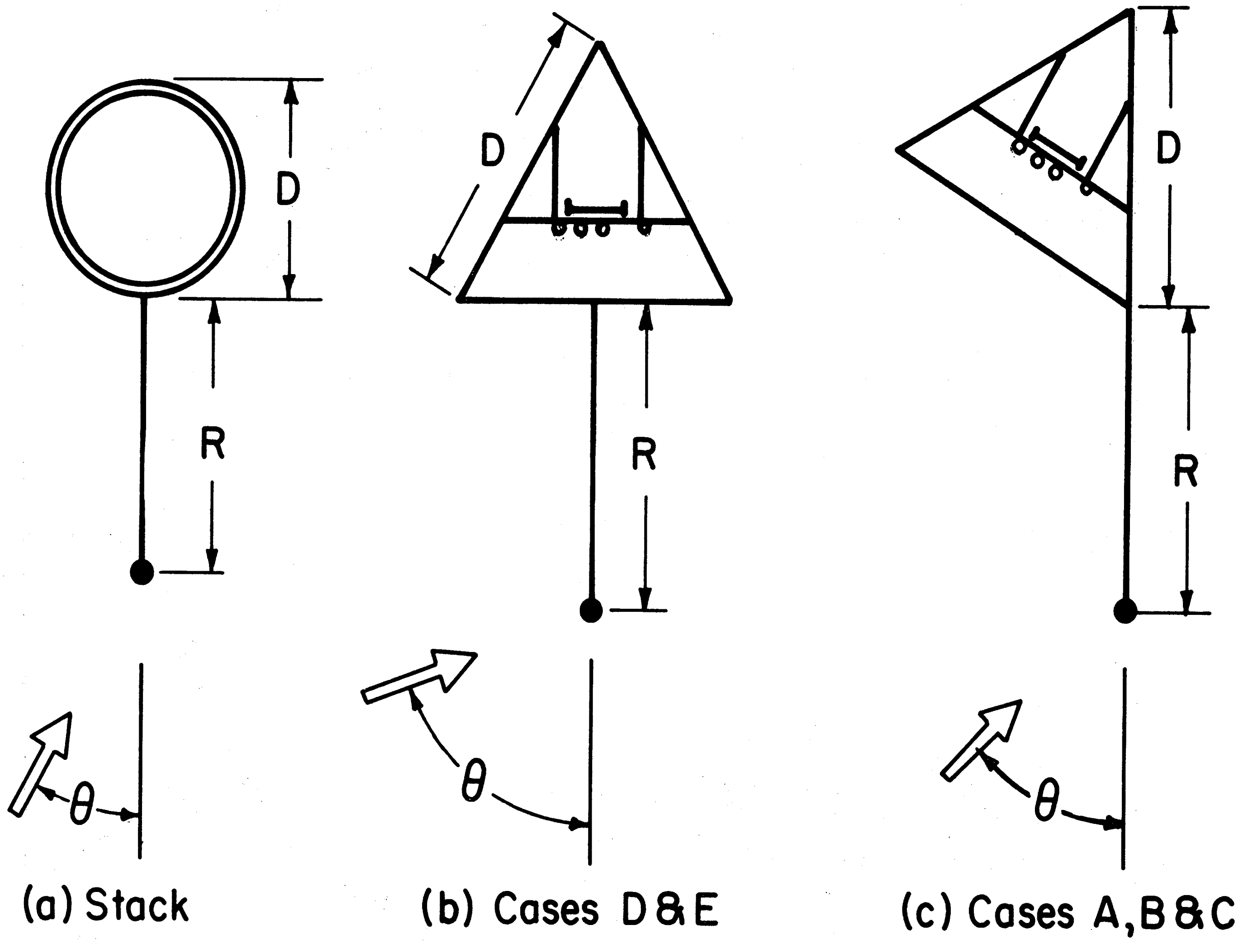
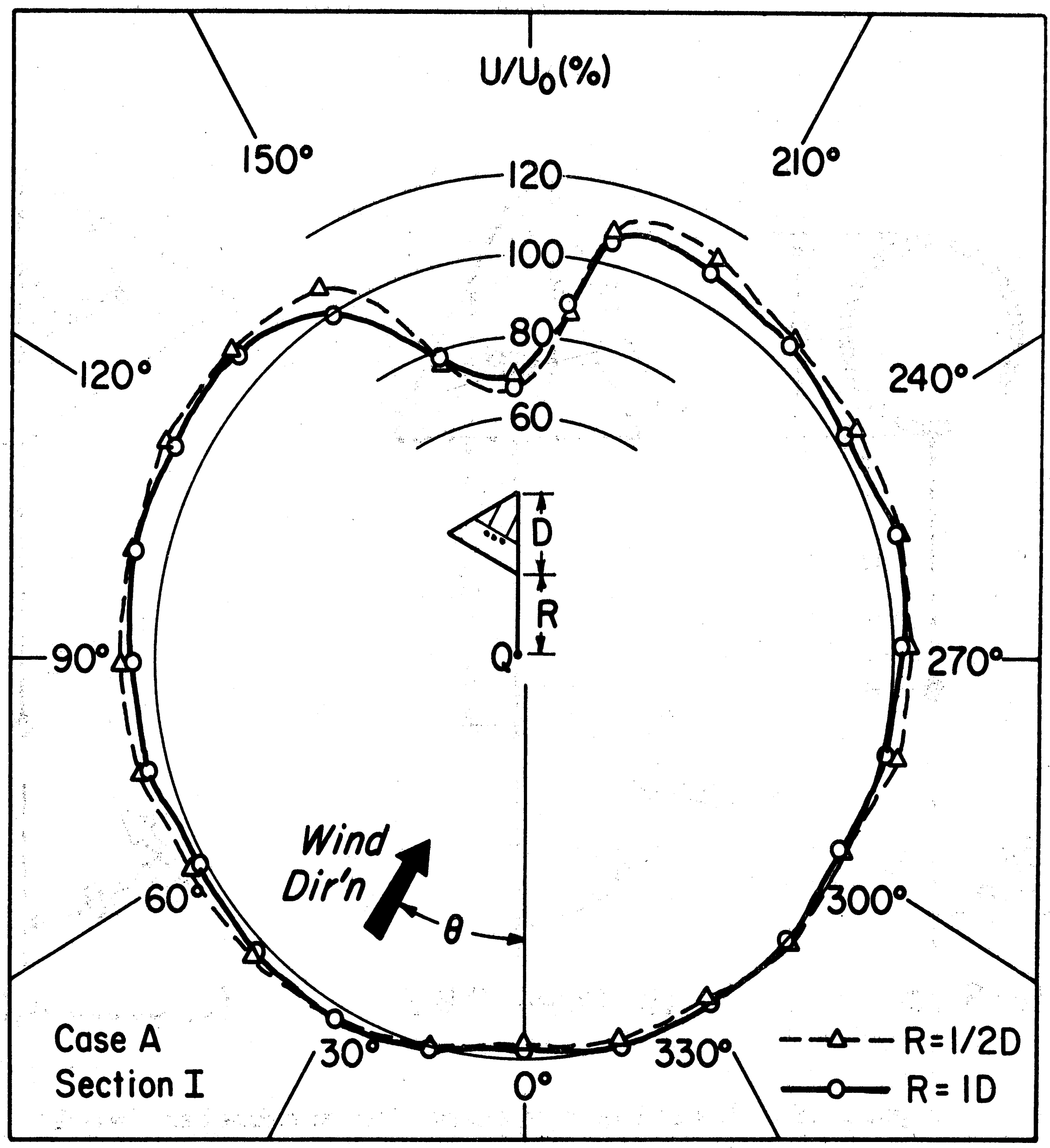
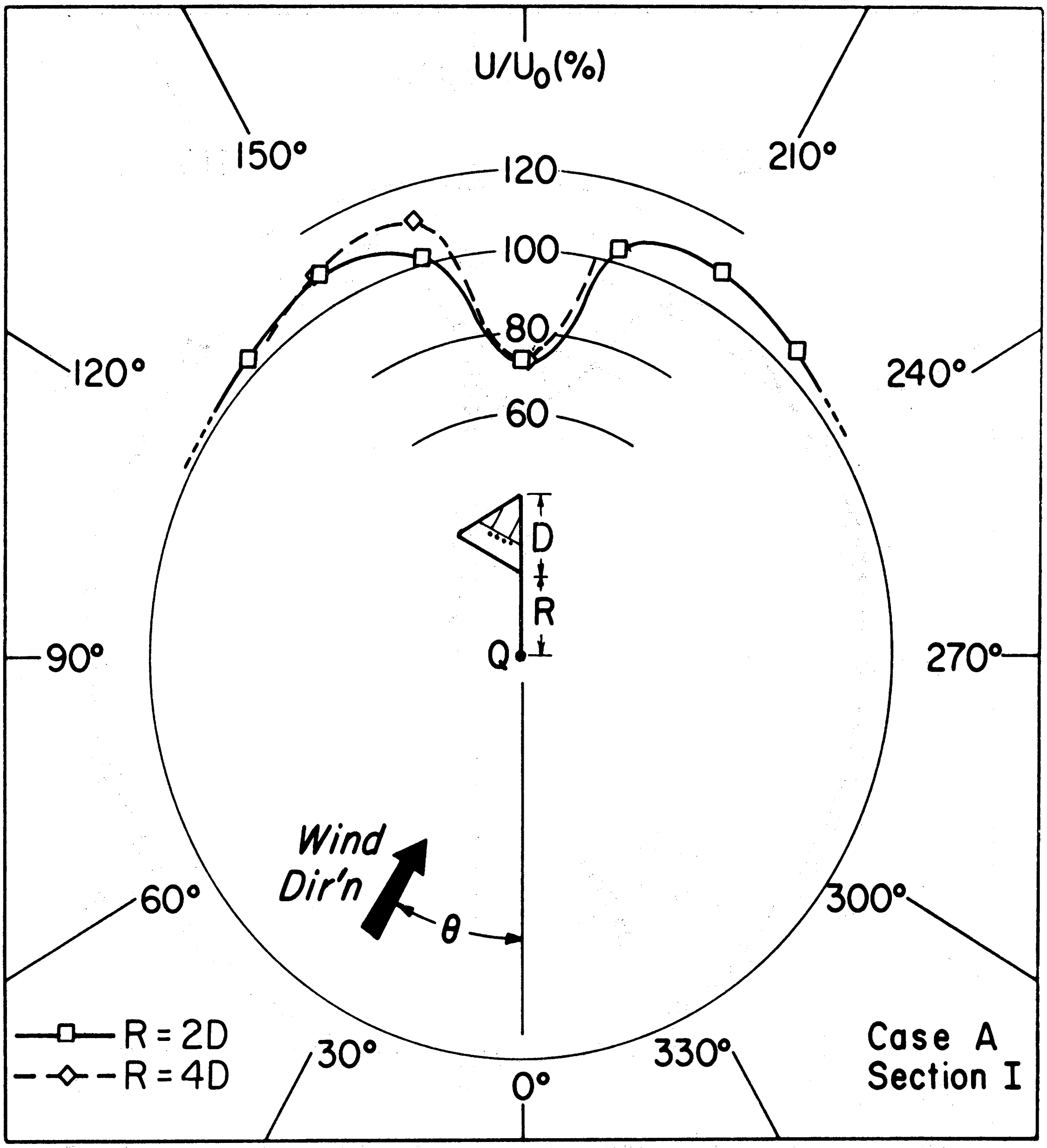


Figure 18. Coordinate systems for anemometer (wind speed) tests.

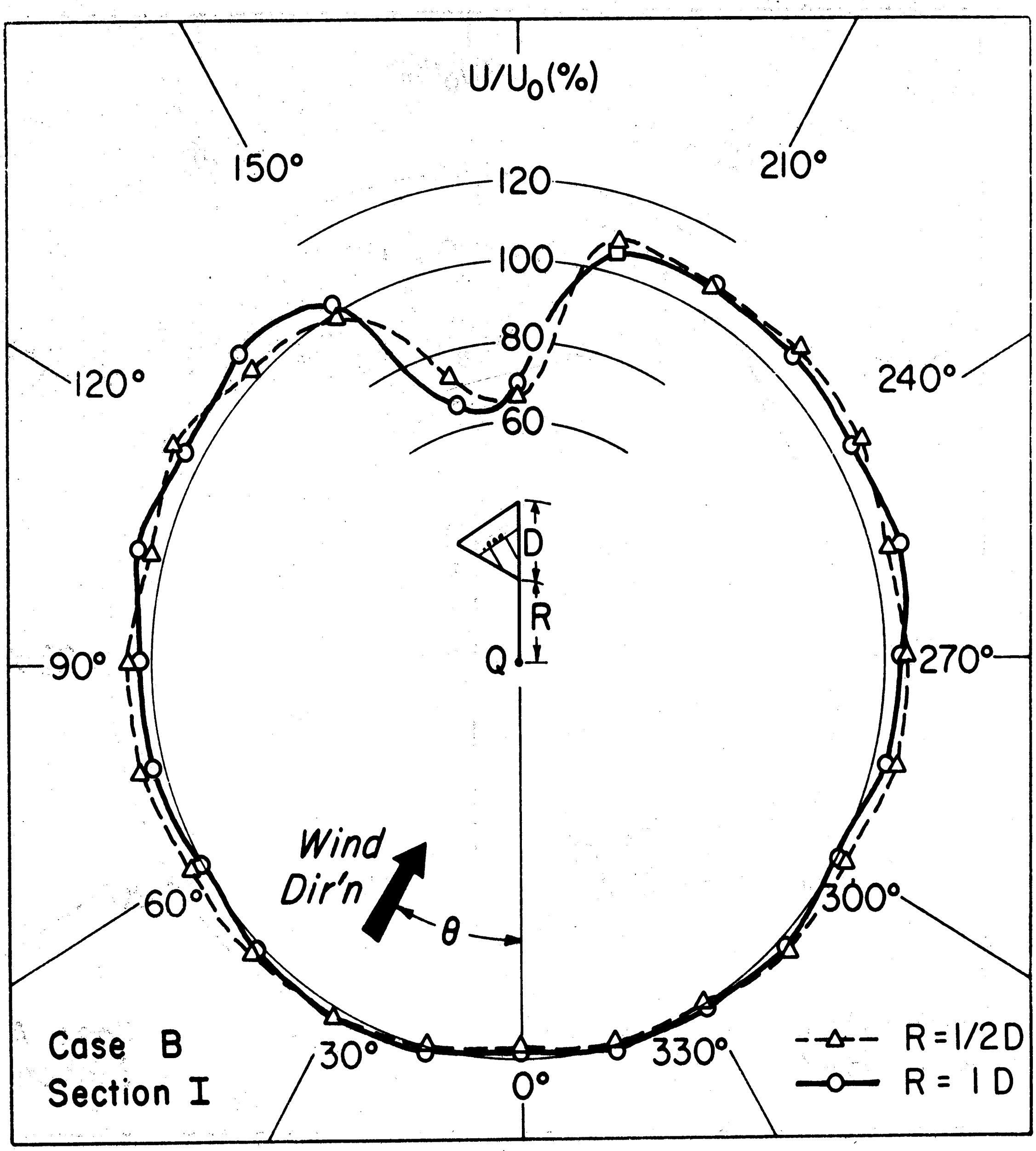


(a)

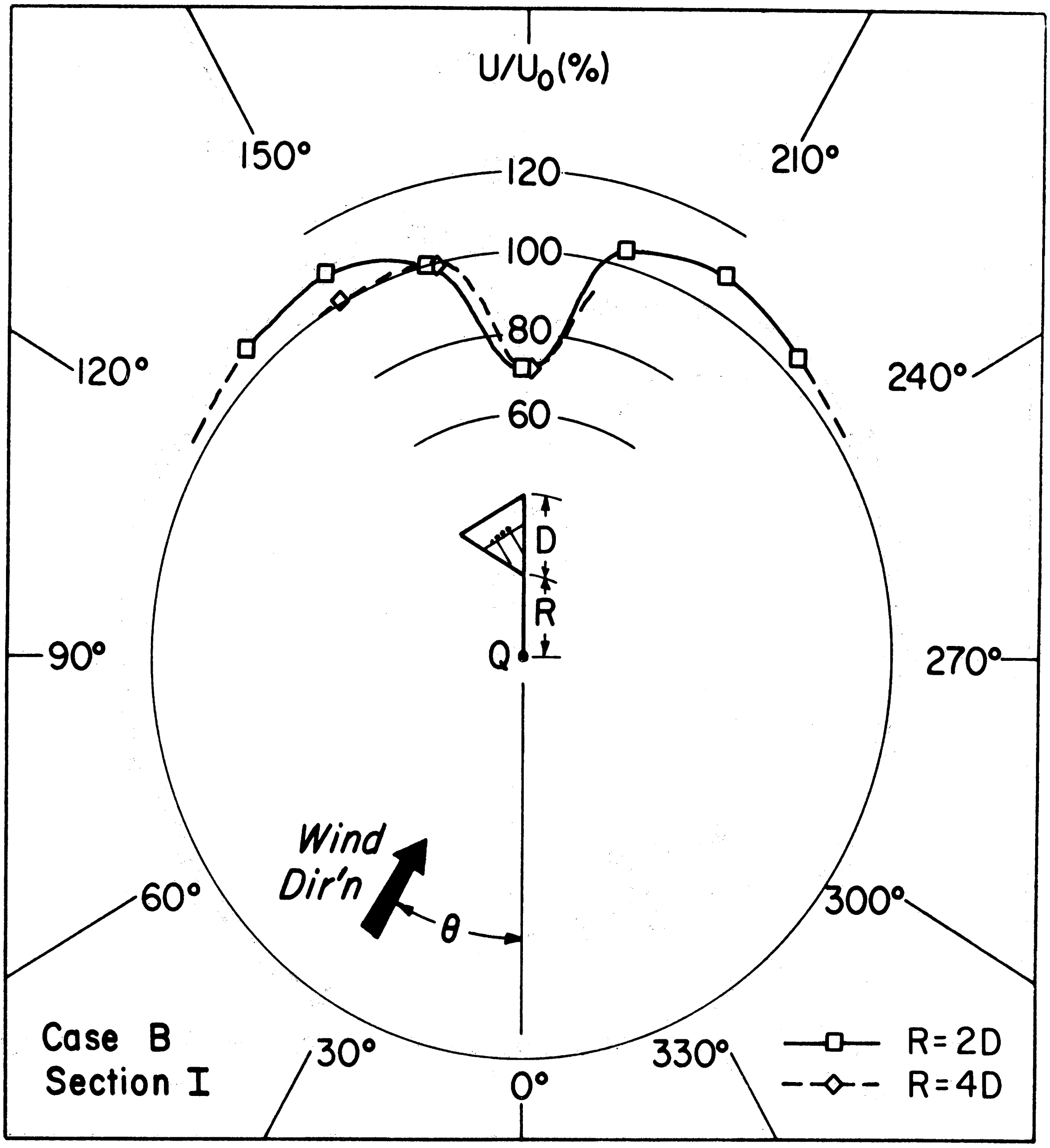
Figure 19. Wind speed profile at sensor, Q, located a distance R from open tower structure, for winds from 360° of arc.



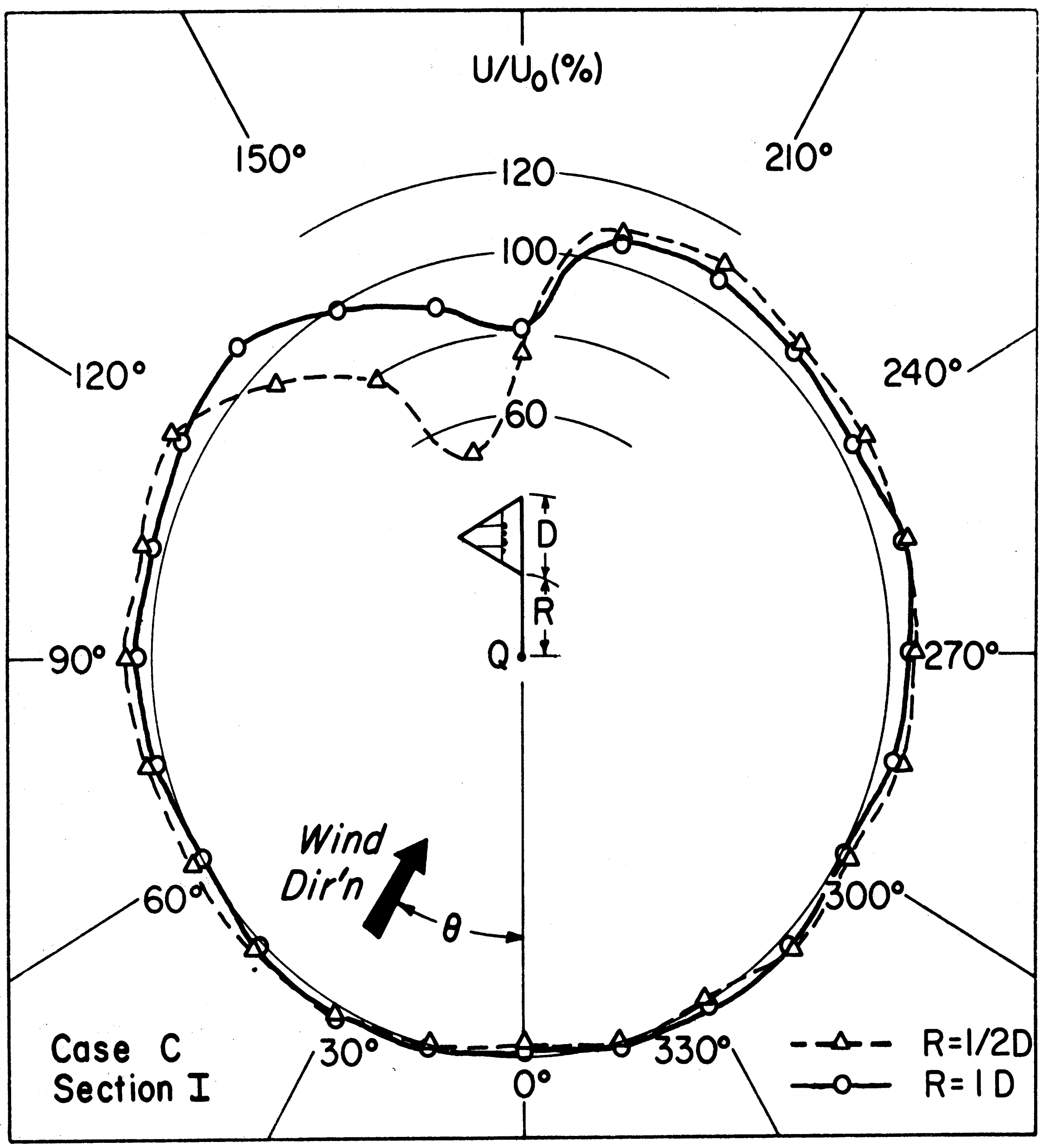
(b)
Figure 19. (Continued)



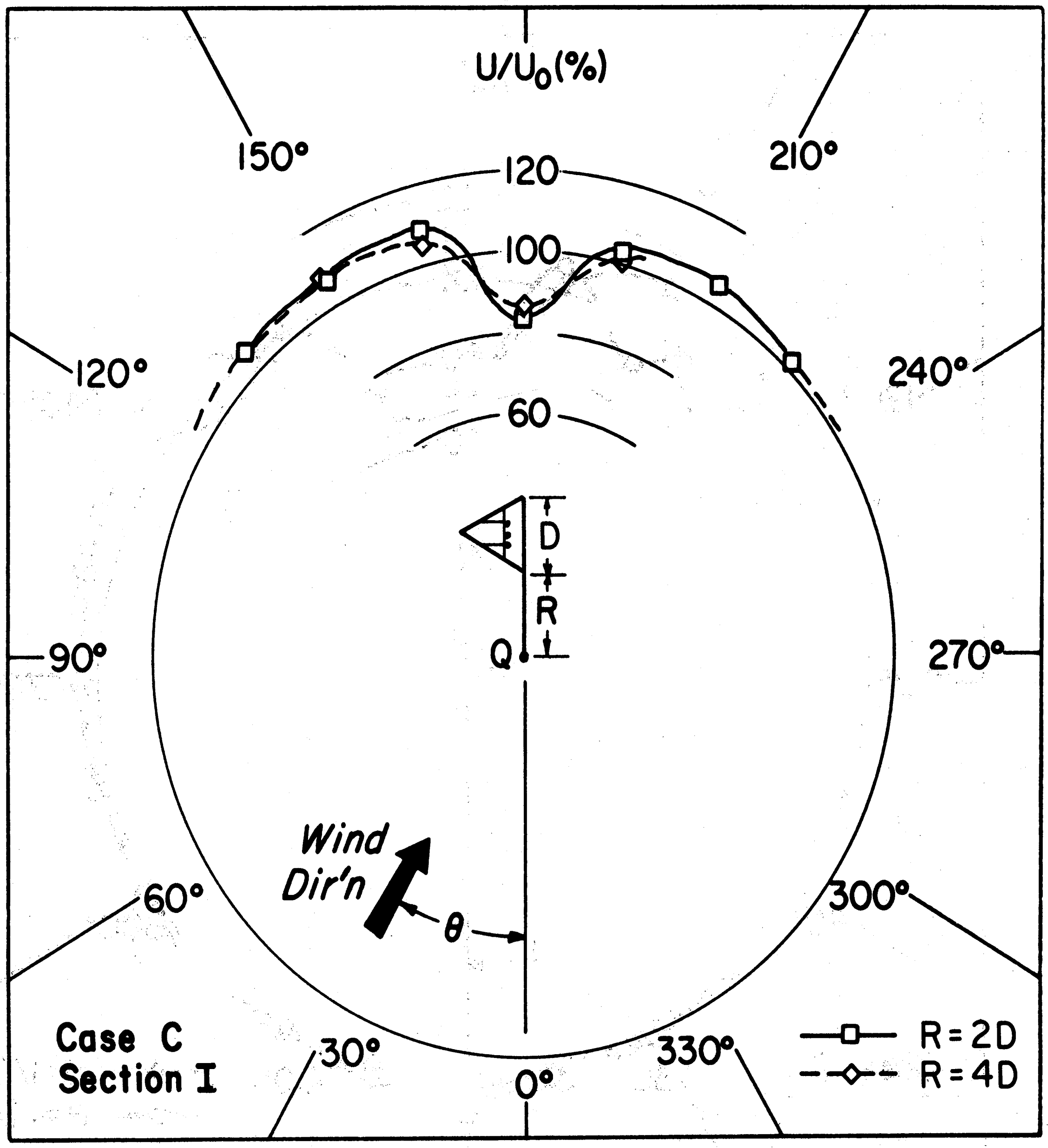
(c)
Figure 19. (Continued)



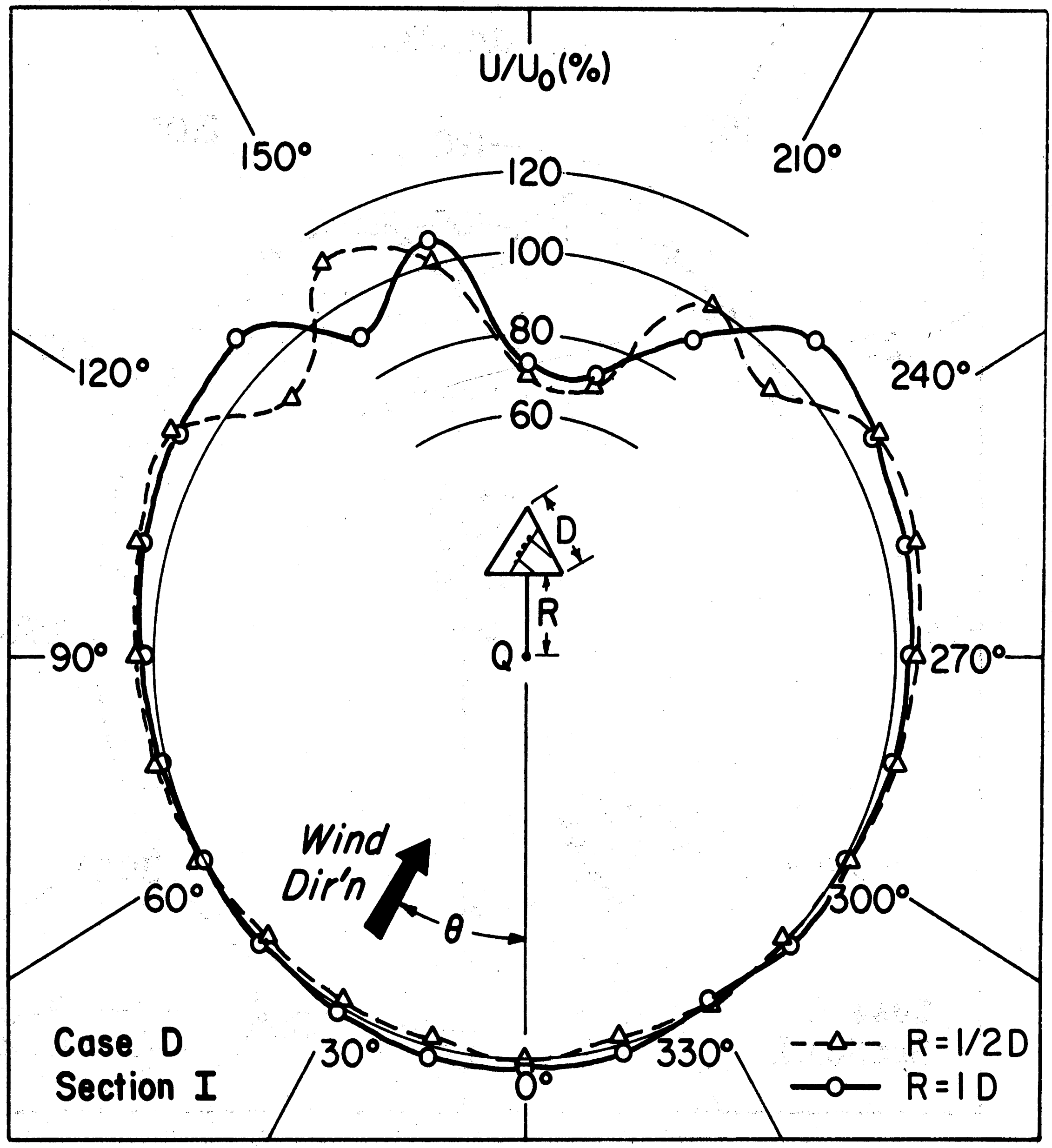
(d)
Figure 19. (Continued)



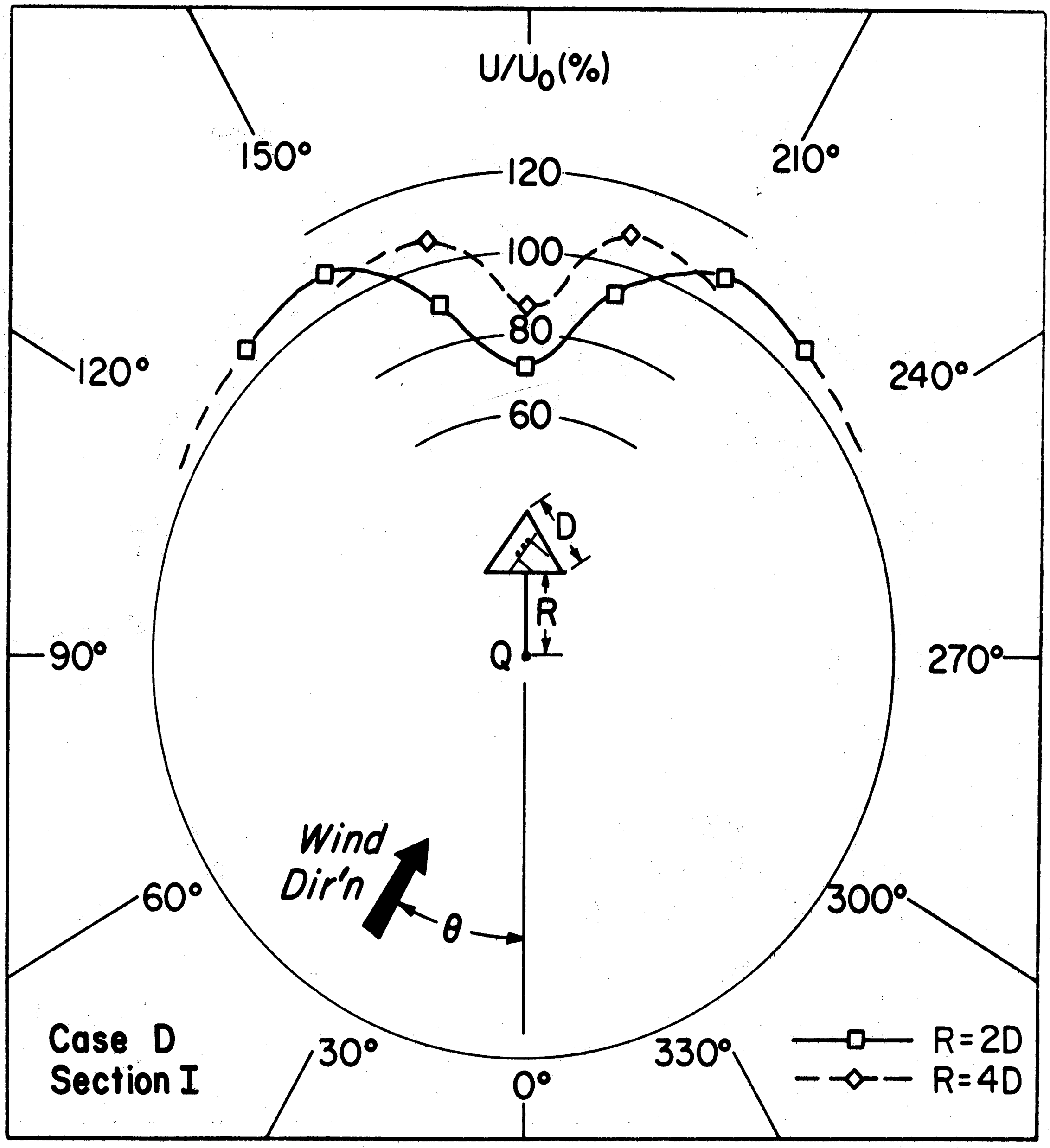
(e)
Figure 19. (Continued)



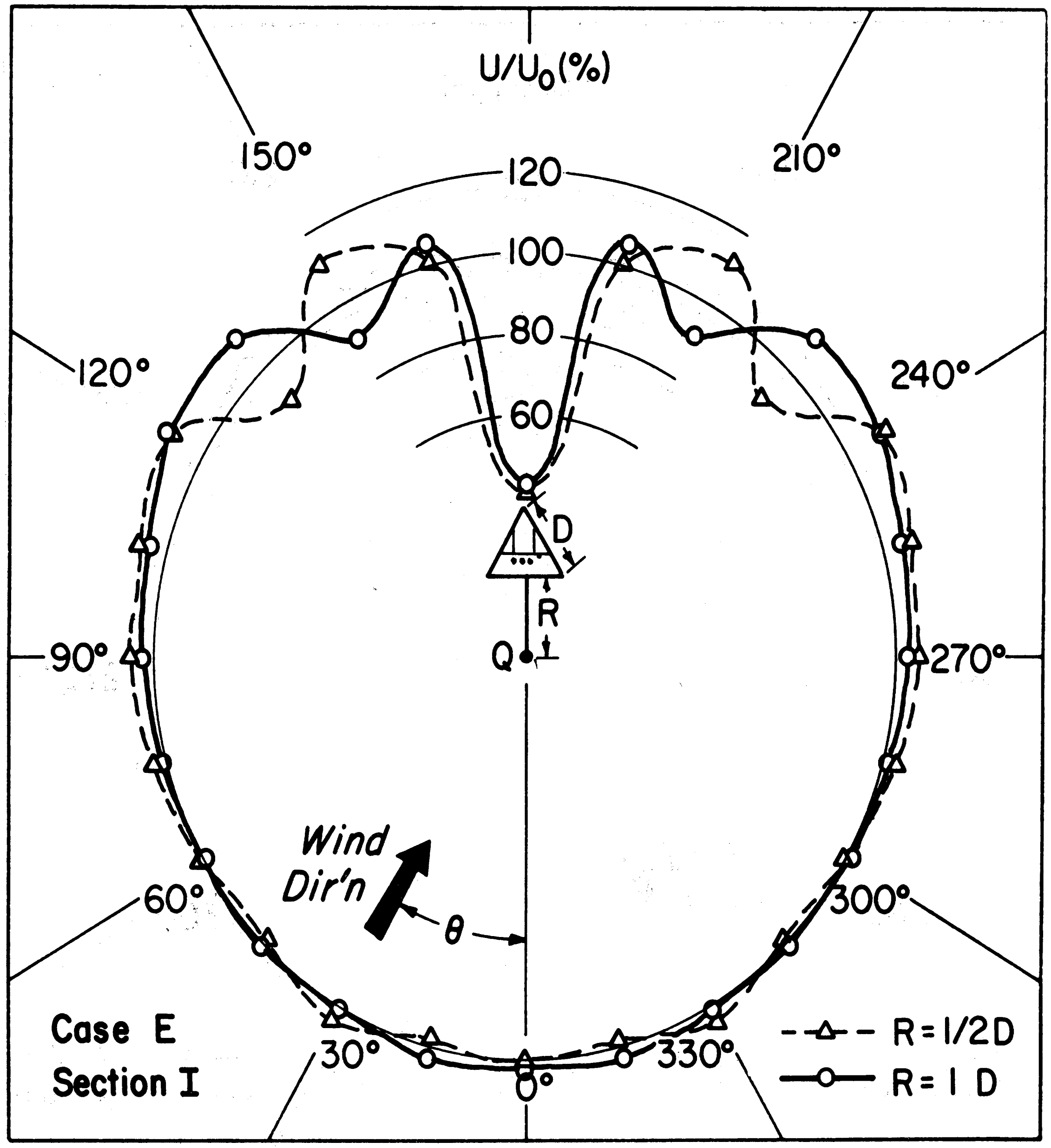
(f)
Figure 19. (Continued)



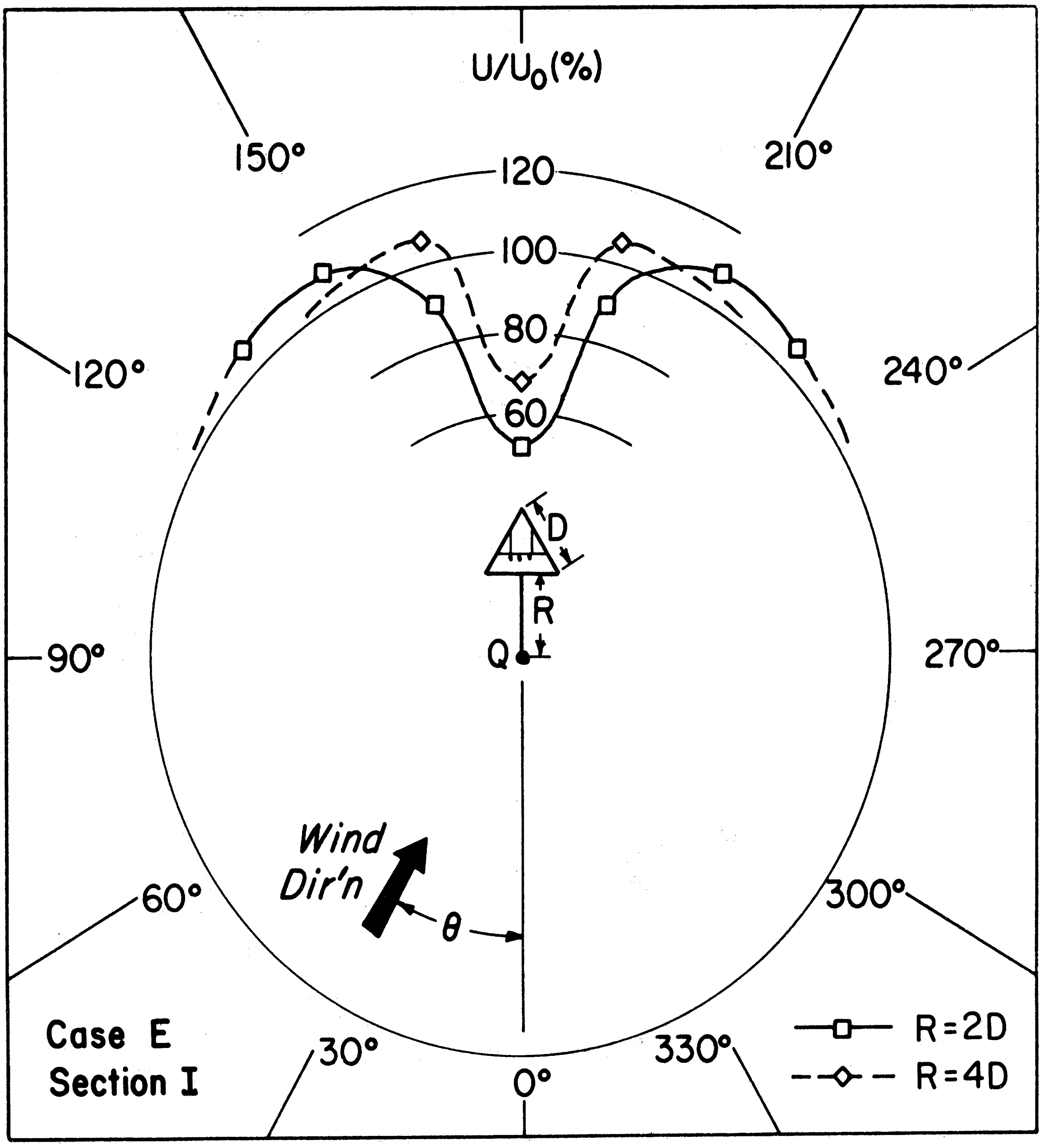
(g)
Figure 19. (Continued)



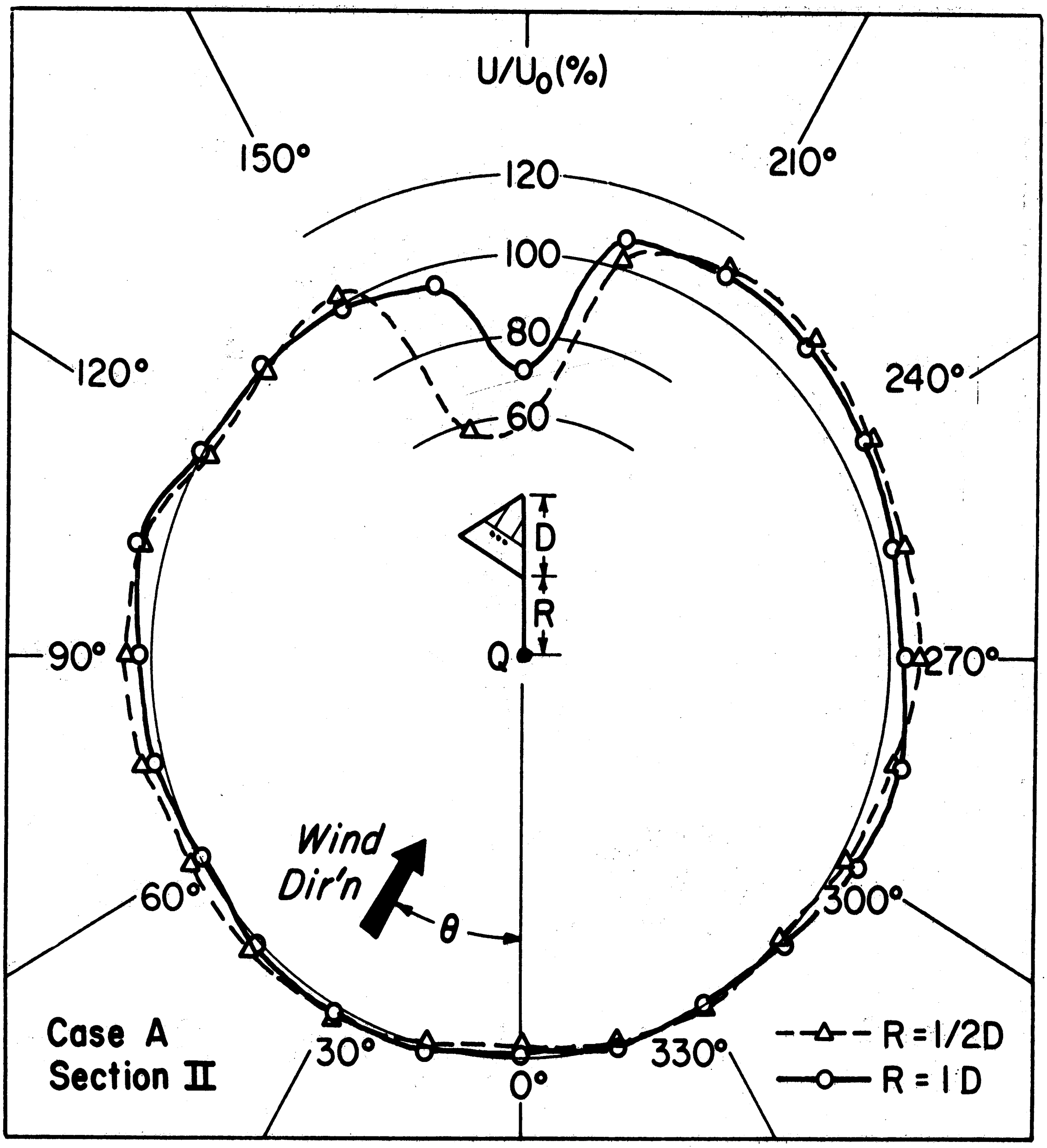
(h)
Figure 19. (Continued)



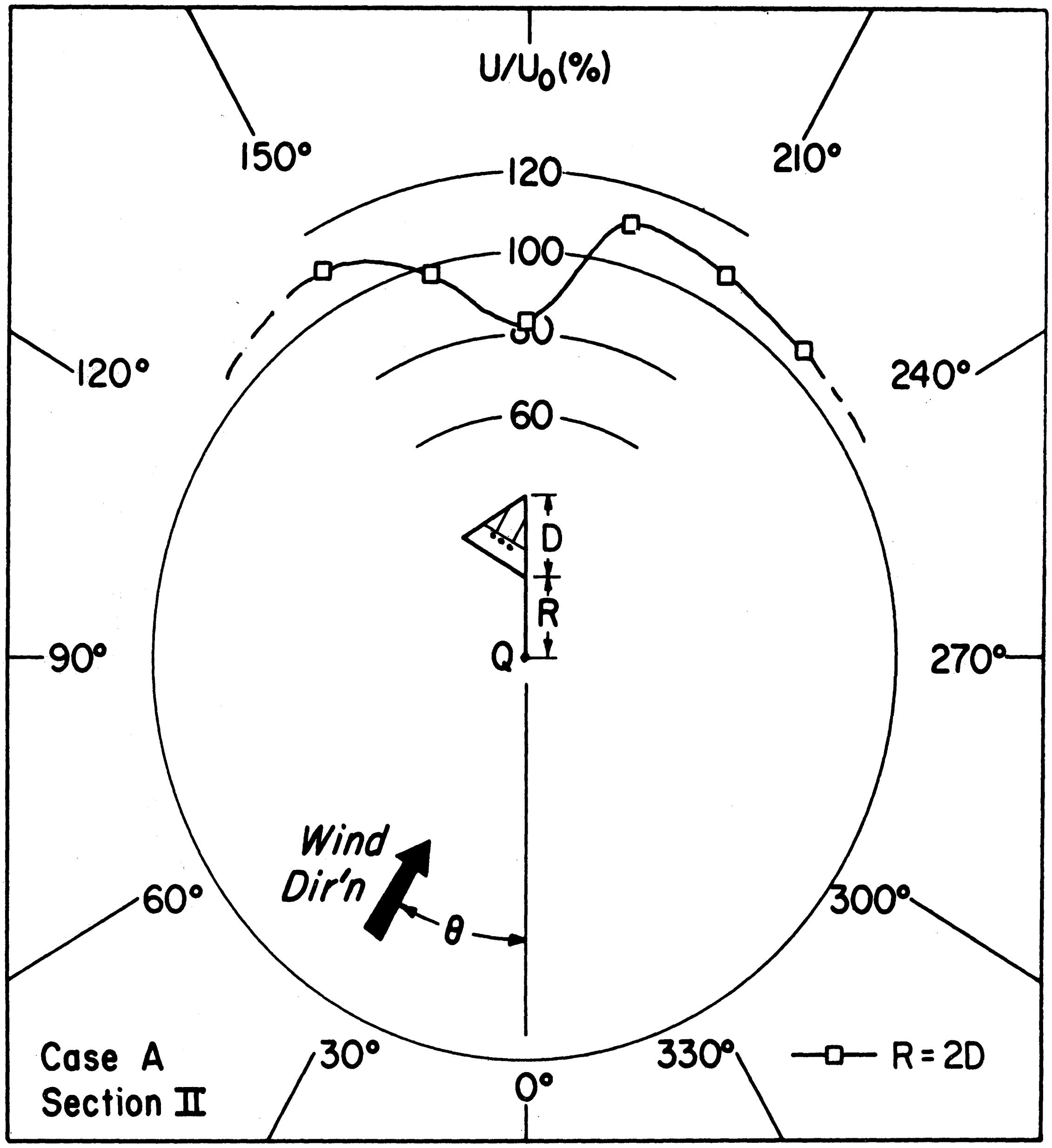
(i)
Figure 19. (Continued)



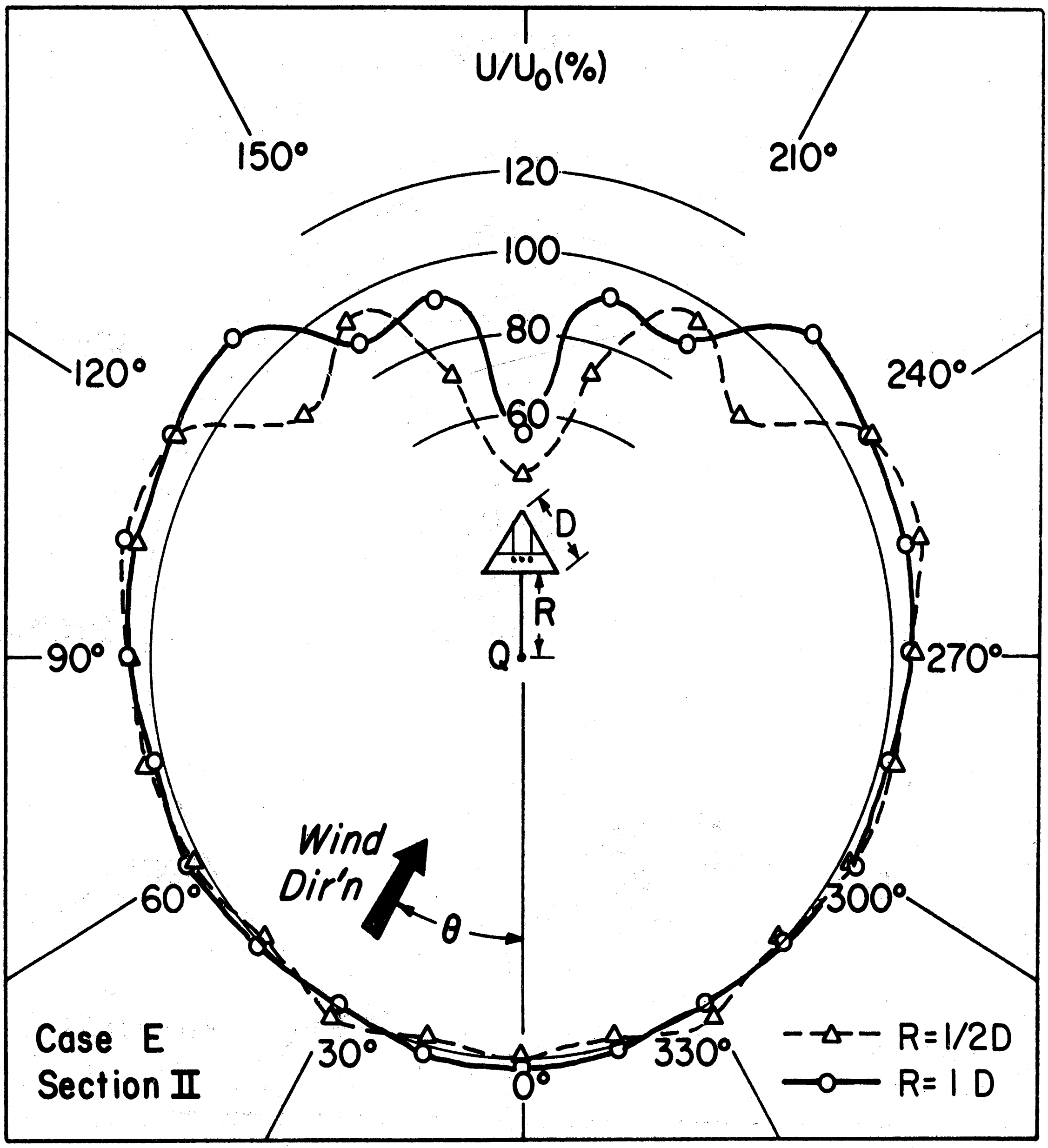
(j)
Figure 19. Continued



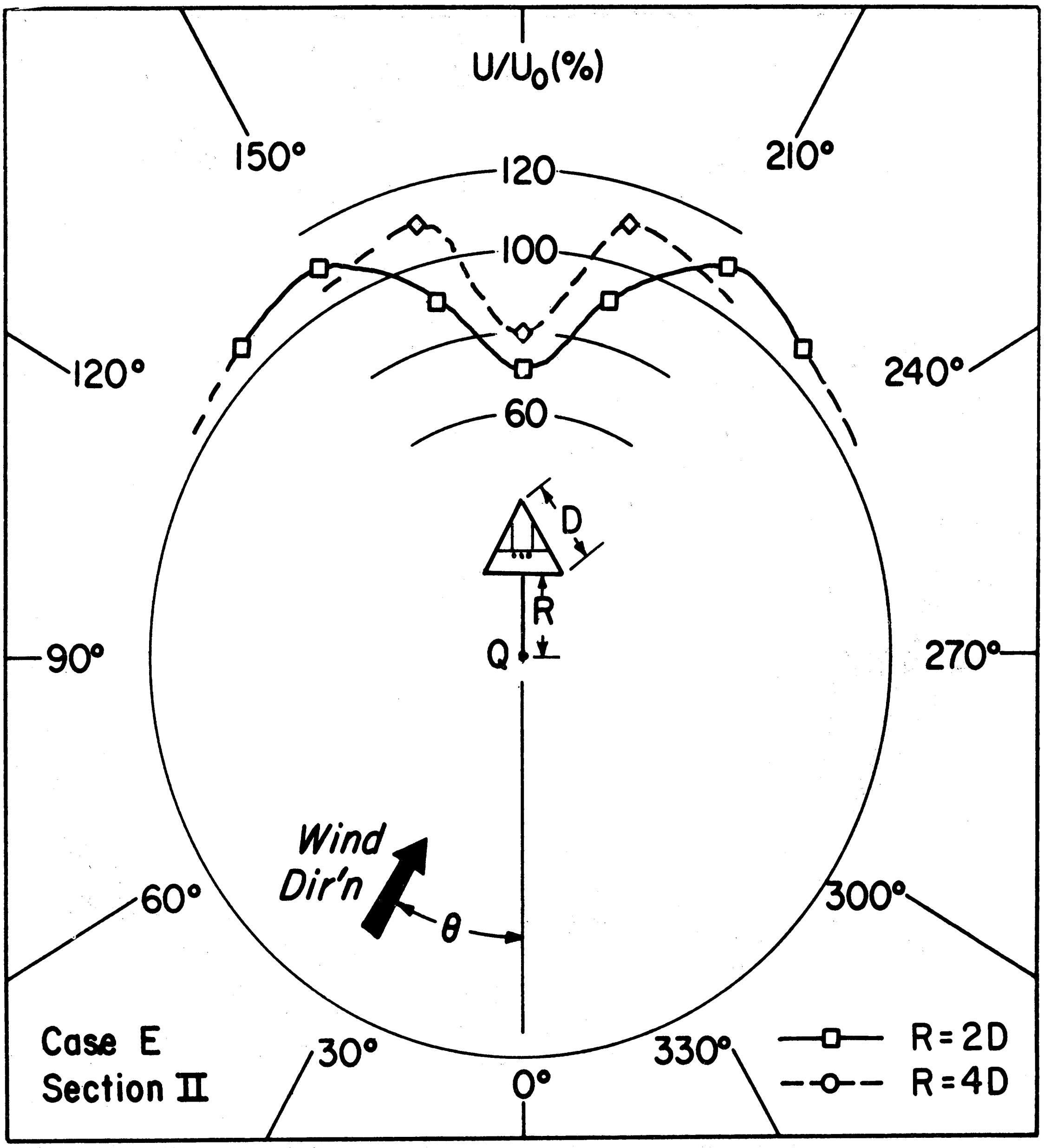
(k)
Figure 19. (Continued)



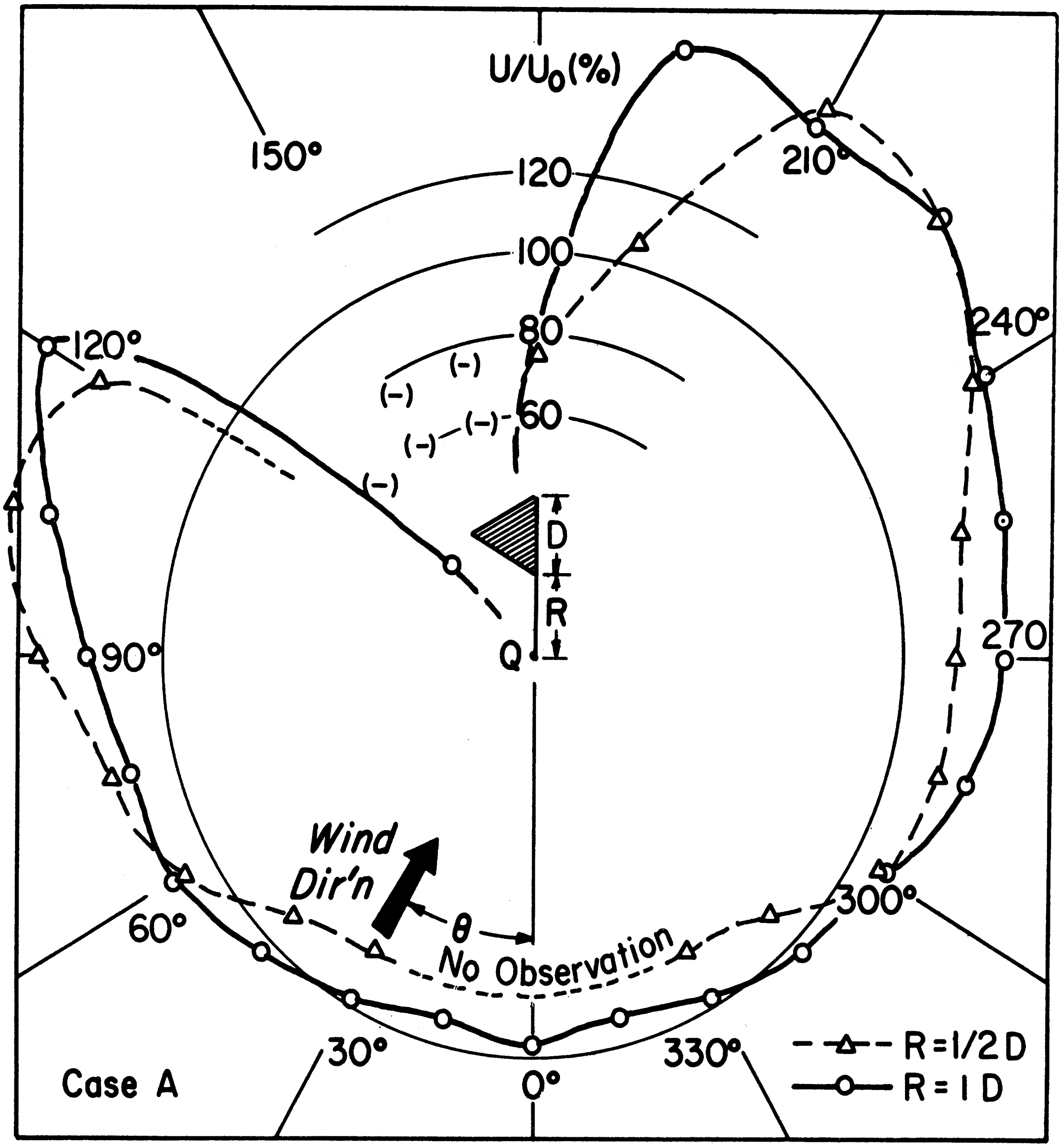
(1)
Figure 19. (Continued)



(m)
Figure 19. (Continued)

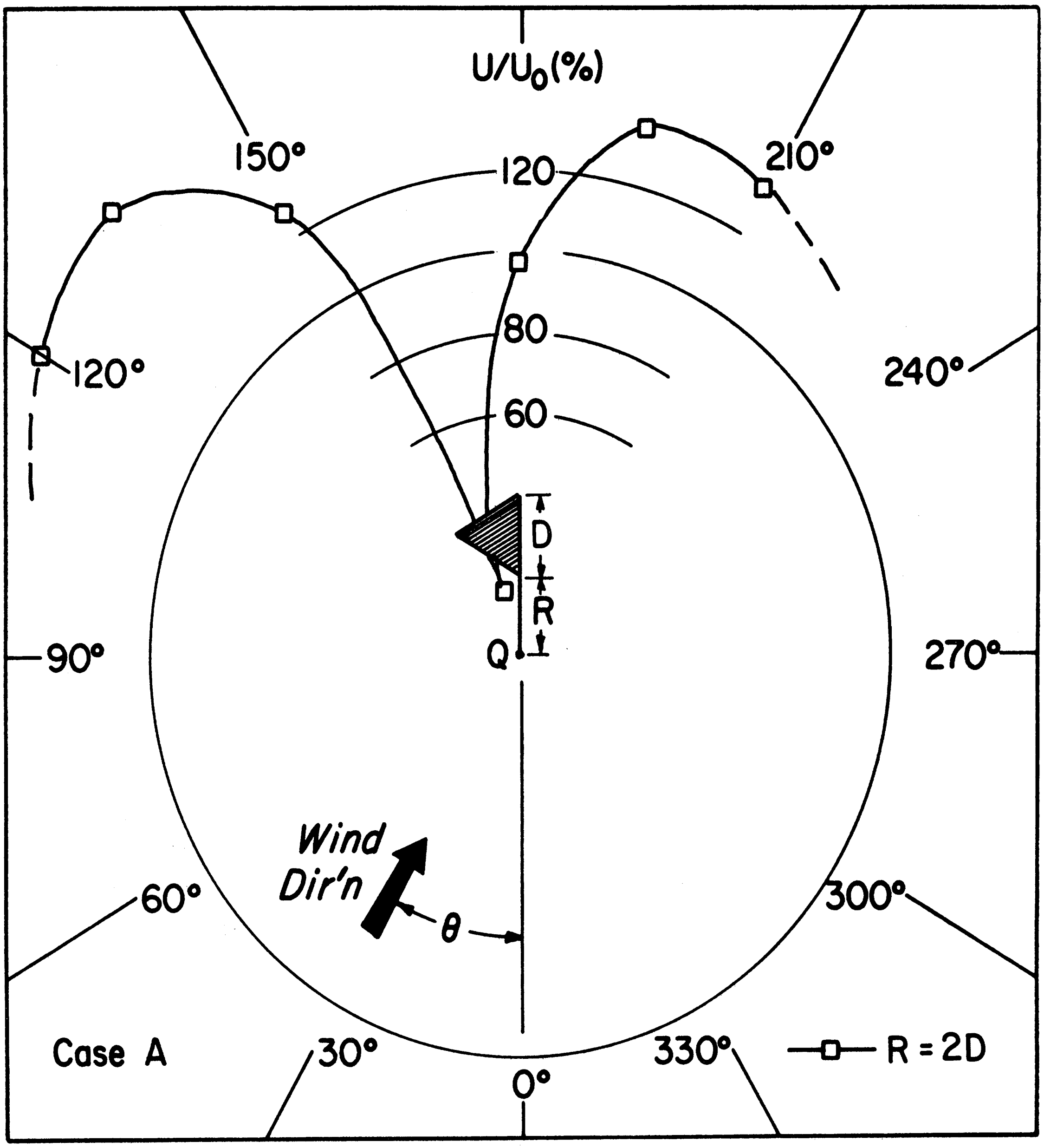


(n)
Figure 19. (Concluded)

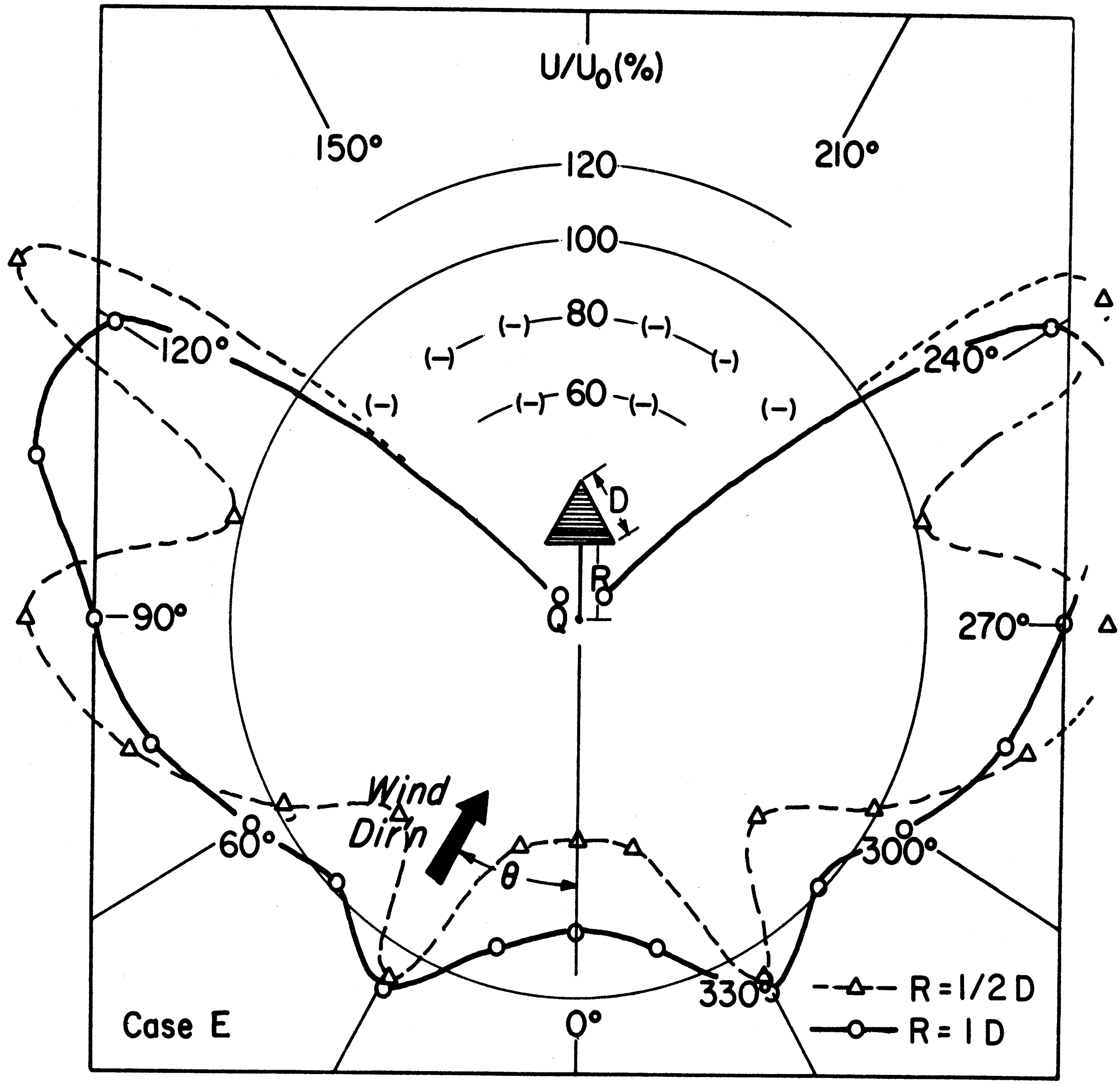


(a)

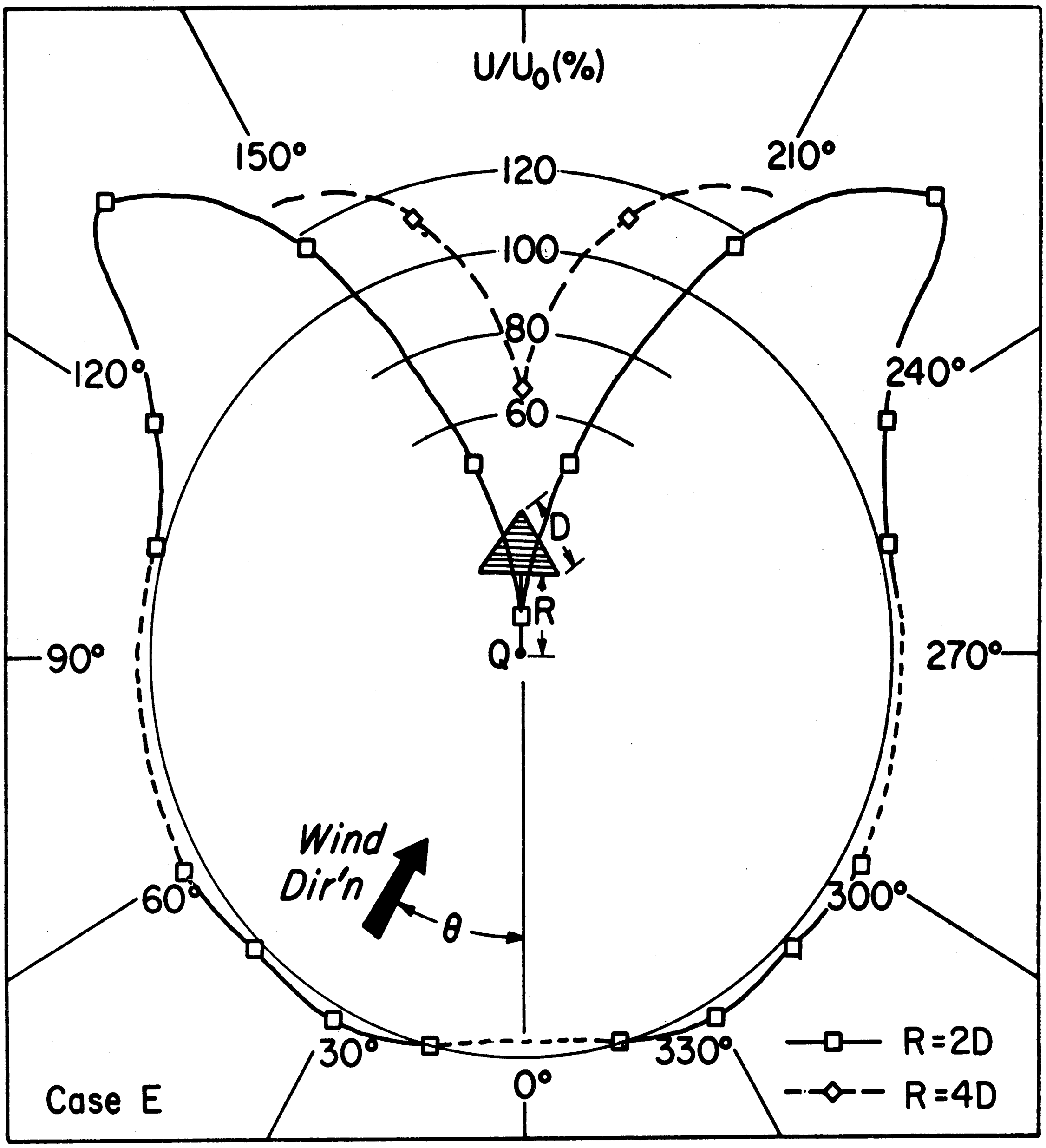
Figure 20. Same as Figure 19, but for solid tower.



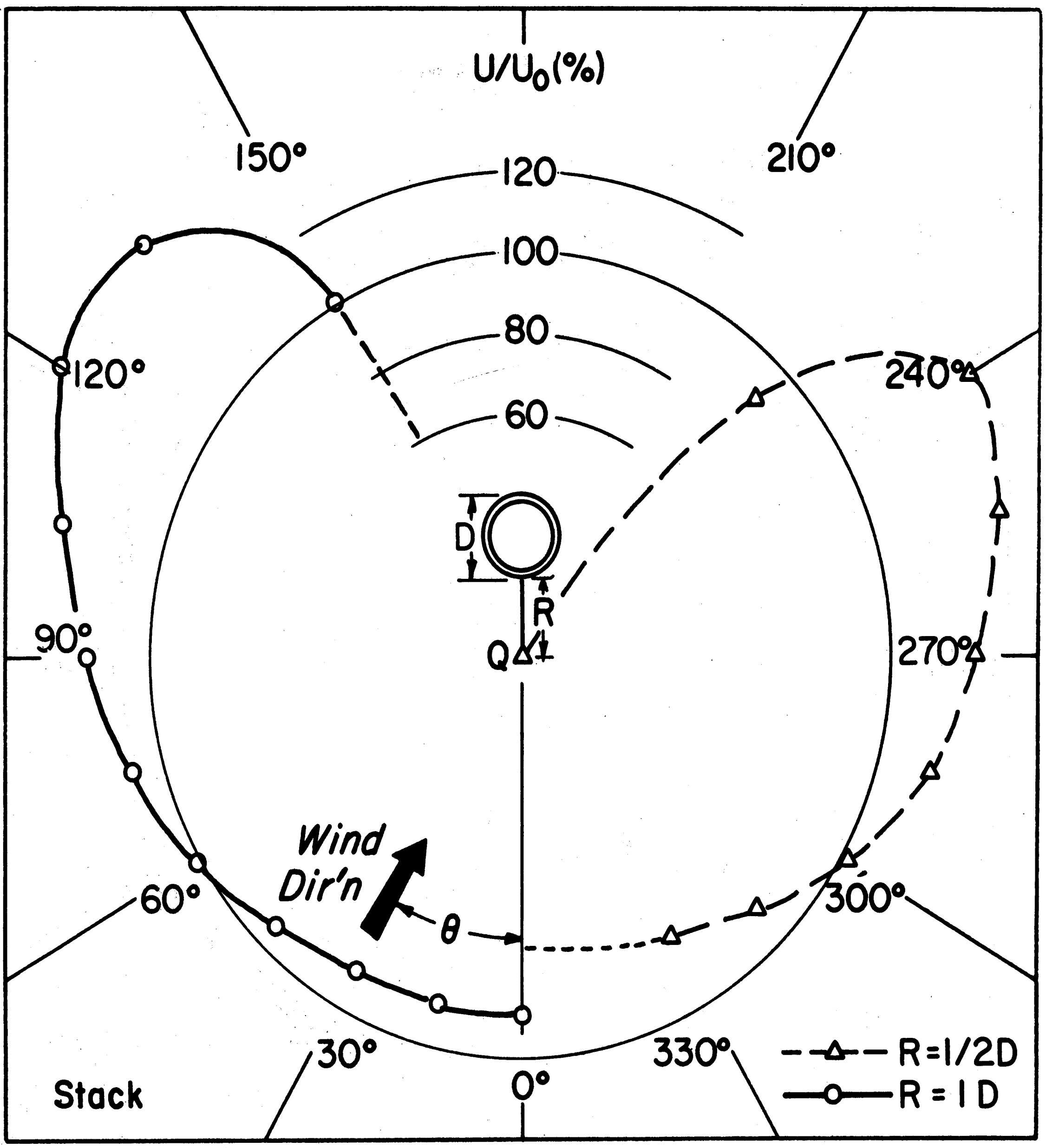
(b)
Figure 20. (Continued)



(c)
Figure 20. (Continued)

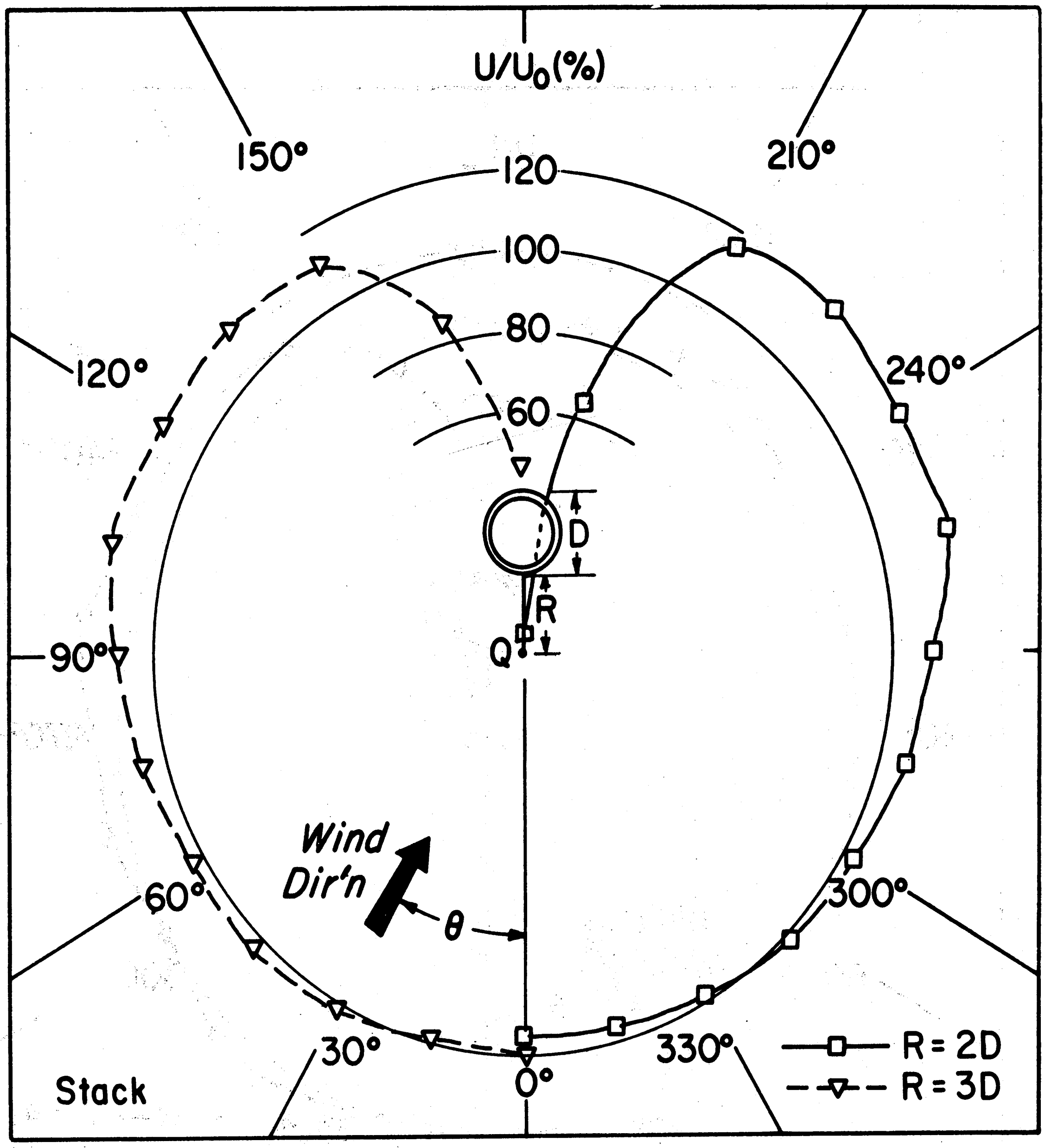


(d)
Figure 20. (Concluded)



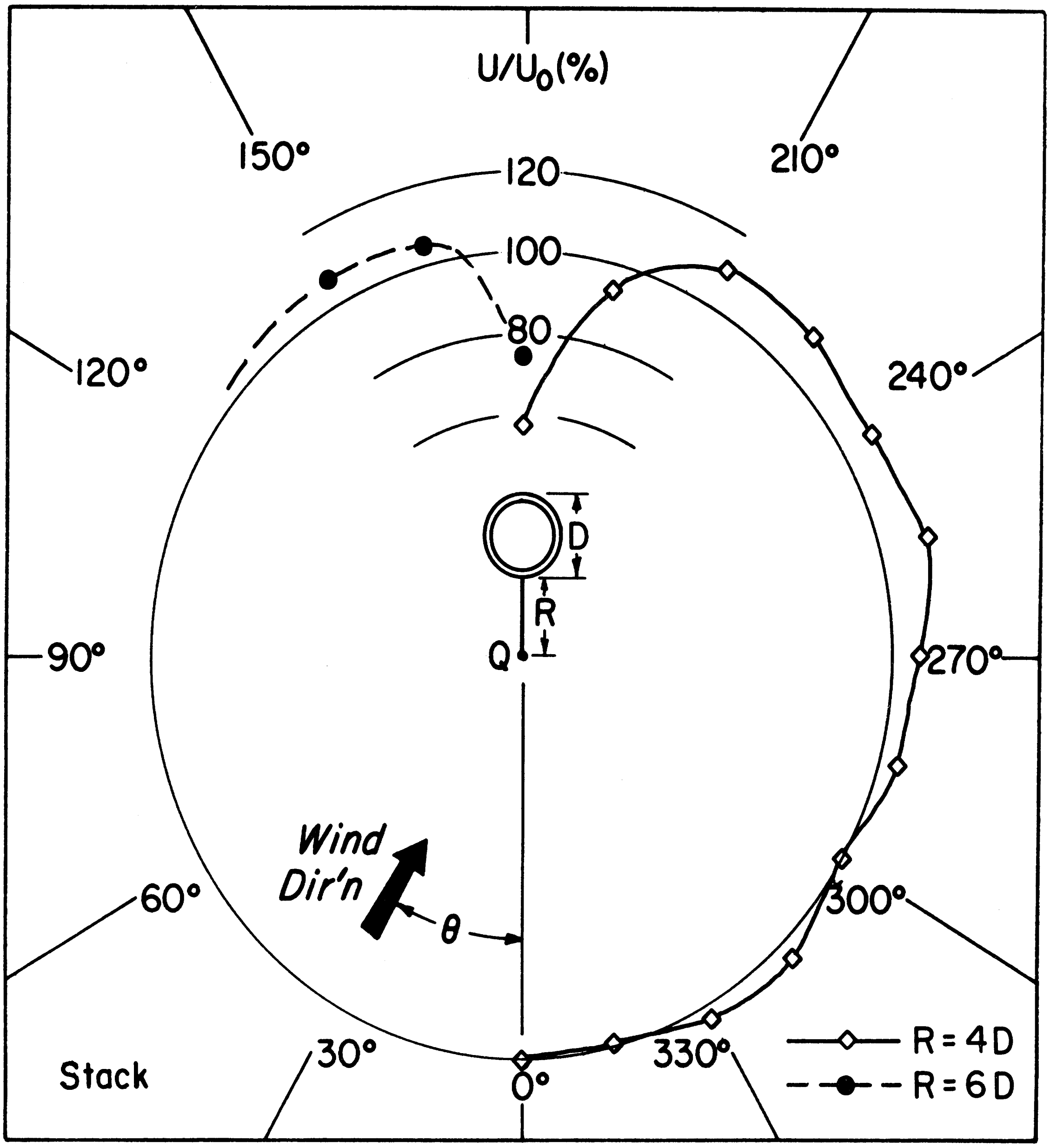
(a)

Figure 21. Same as Figure 19, but for stack.



(b)

Figure 21. (Continued)



(c)
Figure 21. (Concluded)

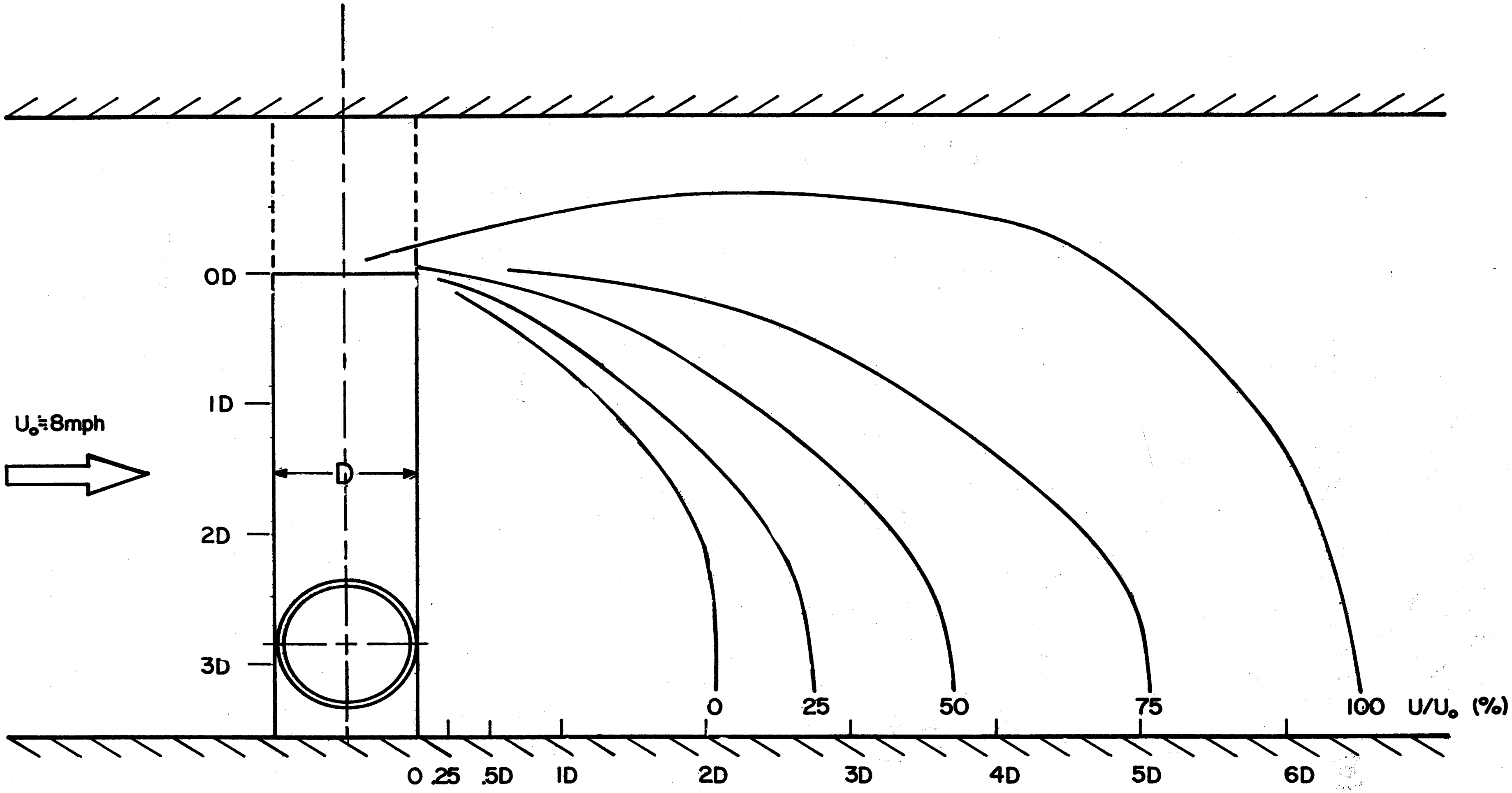
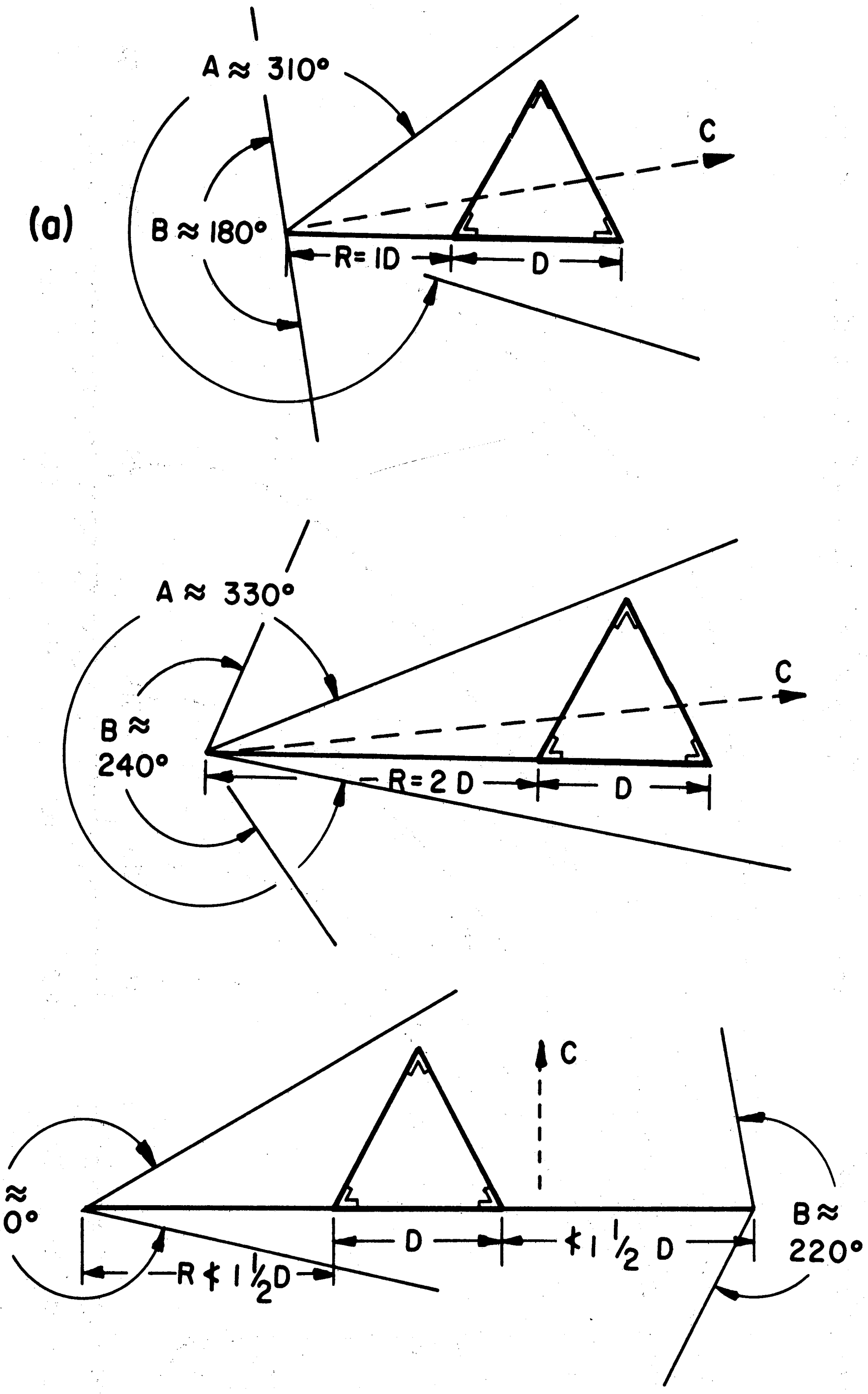


Figure 22. Wind speed profiles in a vertical plane behind the center of a cylindrical stack.

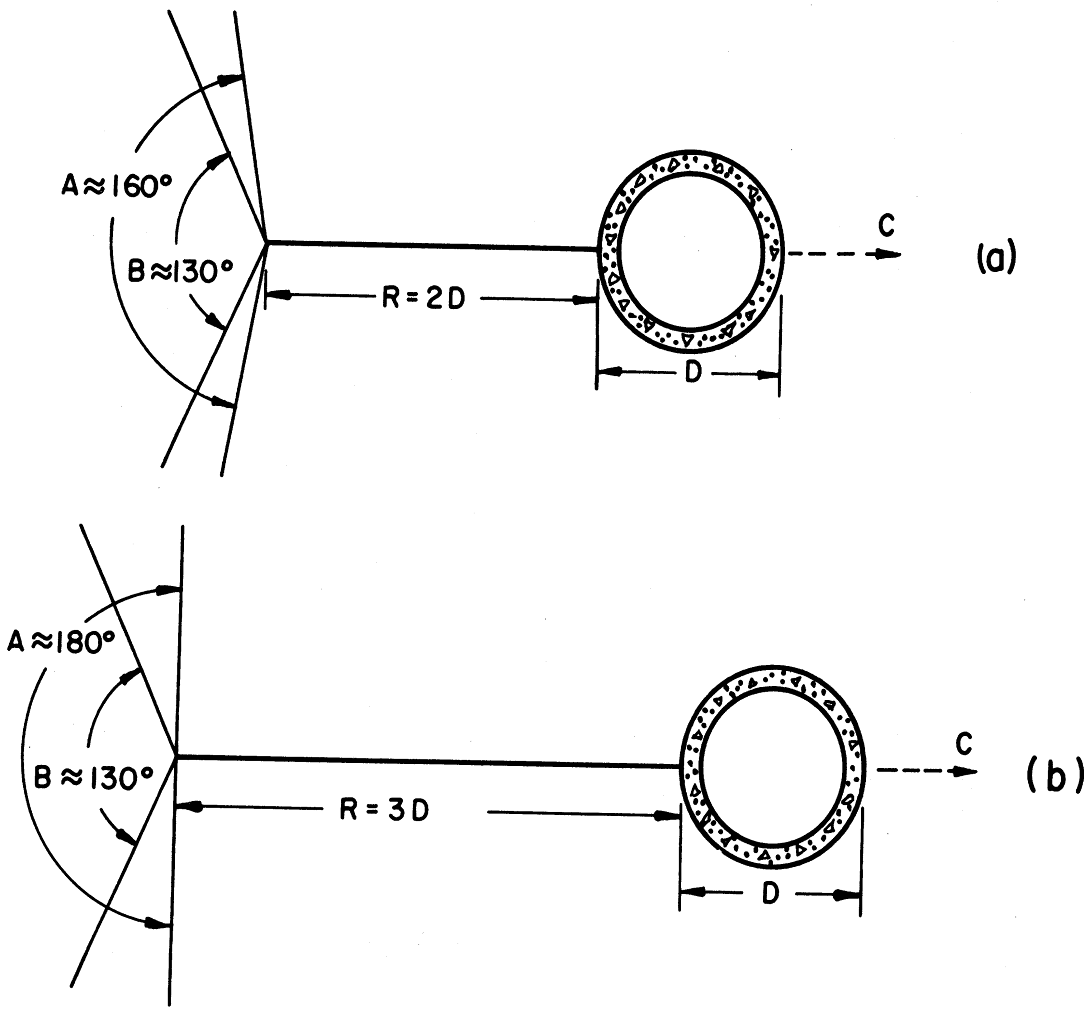


A: Speed true within ± 10% Direction true within ± 10°

B: Speed true within ± 5% Direction true within ± 5°

C: Arrow points: 1. toward wind direction of minimum concern, or 2. toward wind direction of lowest frequency.

Figure 23. Recommendations concerning mounting of wind sensors on a relatively open tower ("shadow densities" not exceeding 40 percent).



A: Speed true within ± 10%
Direction true within ± 5°

B: Speed true within ± 5%
Direction true within ± 5°

C: Arrow points: 1. toward wind direction of minimum concern,
or
2. toward wind direction of lowest frequency.

Figure 24. Recommendations concerning mounting of wind sensors on circular stacks.