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NASA TM X-73548

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(NASA-TM-X-73548) WIND TUNNEL MEASUREMENTS OF THE TOWER SHADOW ON MODELS OF THE ERDA/NASA 100 KW WIND TURBINE TOWER (NASA) 37 p HC A03/MF A01 CSCL 10B

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WIND TUNNEL MEASUREMENTS OF THE TOWER SHADOW ON MODELS OF THE ERDA/NASA 100 KW WIND TURBINE TOWER

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November 1976

1. Report No. NASA TM X-73548	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle WIND TUNNEL MEASUREMENTS OF THE TOWER SHADOW ON MODELS OF THE ERDA/NASA 100 KW WIND TURBINE TOWER		5. Report Date
		6. Performing Organization Code
7. Author(s) Joseph M. Savino and Lee H. Wagner		8. Performing Organization Report No. E-8984
		10. Work Unit No.
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Detailed wind speed profile measurements were made in the wake of a 1/25 scale and a 1/48 scale tower models to determine the magnitude of the speed reduction (the tower shadow). The 1/25 scale tower modeled closely the actual wind turbine including the service stairway and the equipment elevator rails on one face. The 1/48 scale model was made of all tubular members. Measurements were made on the 1/25 scale model with and without the stairway and elevator rails, and on the 1/48 all tube model without stairs and rails. The test results show that the stairs and rails were a major source of wind flow blockage. The all tubular 1/48 scale tower was found to offer less resistance to the wind than the 1/25 scale model that contained a large number of square sections. Shadow photos are included to show the extent of the blockage offered to the wind from various directions.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Energy	Solar	Unclassified - unlimited
Wind	Electric power generation	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

WIND TUNNEL MEASUREMENTS OF THE TOWER SHADOW ON MODELS OF THE ERDA/NASA 100 kW WIND TURBINE TOWER

by Joseph M. Savino and Lee H. Wagner

INTRODUCTION

The ERDA/NASA 100 kW Wind Turbine (referred to as the Mod-0) Figure 1, is a two-bladed propeller-type in which the rotor is designed to always operate on the downwind side of the support tower (Ref. 1). During operation, each blade must pass through the wake of the tower where the wind speeds are always lower than the surrounding unobstructed free wind stream. Some of the early Mod-0 test results showed that the blade root stresses were about 60% higher than the expected design values. This finding led to an investigation to determine the magnitude of the wind speed reduction caused by the tower. The purpose of this report is to present the results of tests that were conducted on models of the Mod-0 tower in a wind tunnel.

E-8984

DESCRIPTION OF APPARATUS

The Mod-0 wind turbine tower, shown in Figure 2, consisted of the basic tower structure, with a service personnel stairway situated on the inside, and a pair of I beams (for an equipment elevator) on one face. The basic tower structure uses 8-inch pipe for the four legs, channels for the horizontal members, back-to-back angles for the diagonals with gusset-plate attachments.

Two tower models were tested, a 1/25 and a 1/48 scale model, figure 3. The 1/48-scale model was made of all tubular members without gusset-plate joints. In the 1/25 scale model, square bars were used to simulate the horizontal channel members and the diagonal angle members of the Mod-0 tower. The stairs were simulated by using small diameter wires for the stair treads, and thin metal plates for the stair strings. The hand rails were not modeled. The stairway model for the 1/25-scale model was extended only up the lower four sections of the tower.

Figure 4 shows the 1/48 scale model (with the model stairway installed) and the wind speed measuring equipment as installed in the wind tunnel. The pitot tube, used to measure the local wind speeds, was installed on a system of motor-driven carriages. One carriage was used to position the pitot tube at any desired vertical position, and the other slowly moved the probe horizontally across the tower wake to make a continuous measurement of the wind speed distribution. The total pressure sensed by the pitot tube was referenced to a static pressure as measured by a tap on the wind tunnel wall. The velocity head (total minus static pressure) was sensed by a differential pressure gage of the strain gage type. It was found by actual measurement that the static pressure dis-

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tribution was uniform in the plane behind the tower where the measurements were made.

All wind speed measurements were at the single free stream value of 100 mph, ambient air temperatures, and near atmospheric pressure. Profiles were taken at a variety of elevations for wind approach angles to a reference face of the tower (the face with the I-beams was used as the reference face) of 0°, 10°, 25°, 35°, 40°, and 45°, Figure 5. The majority of profiles were made downwind of the third and fourth sections of the tower above the ground because the tower shadow effect had the greatest impact on the outer 50% of the blade length. In addition, all four upper sections were similar in construction except for their solidity so that only a limited number of profiles would be needed behind the upper two sections to determine their complete wake profile characteristics.

As in all model testing, the applicability of the tunnel test results to the full-scale tower arose. When the Mod-0 is operating in wind speeds from 10 to 40 mph, the Reynolds numbers based on the diameters and widths of the tower members, wind speeds, and ambient air properties are in the range where the drag coefficients of the members are constant, i.e., independent of the Reynolds Number. The same was true for Reynolds Number of the tower model members. This means that when the drag coefficients of the model members and the tower members are the same, then the wind speed profiles in the wake are similar. On this basis, it was concluded that the test results measured with a model tower are applicable to the full-size tower.

TEST RESULTS AND DISCUSSION

Some typical dimensionless wind speed profiles are shown in Figure 6 that were measured in the wake of the models of the Mod-0 tower, with and without the stairway and the equipment elevator rails on one face. These profiles were selected to illustrate some of the most serious tower blockage effects and some of the more favorable ones. The wind speeds and the lateral position were made dimensionless by the free stream wind speed V_o and the wake width Δ, respectively. In Figure 7 are plotted the average wind speeds and the minimum wind speeds at various elevations behind sections 3, 4, 5, and 6 of the tower models. The averages were calculated by integrating the individual horizontal wind profiles. The minimums are the lowest value measured in each profile.

When the profiles shown in Figure 6(a) through (f) are compared (a) with (b), (c) with (d), and (e) with (f) and when Figure 7(a) is compared with 7(b) the effect of removing the stairs and rails from the 1/25 scale models is clearly evident. That effect is that there is a sizeable increase in both the average and minimum wind speeds. This characteristic was noted in all the wind speed profiles that were measured after the stairs and rails were removed. One prominent feature of the profiles behind the tower with the stairs and rails was the wide and deep depression (Figure 7(a), (c), (e)) which existed over most of the tower height above section 2. The effect of this depression was that whenever a blade passed behind the tower, it was exposed for a brief moment to winds that were much lower than the average wind speed in the wake. These low speeds caused a sudden reduction in the angle of attack on the blade, which in turn caused a sudden reduction of both the thrust force and torque on the blade. Such load reduction impulses can be the source of blade and tower vibrations if these components are not properly tuned.

Figures 6(i) through (m) are profiles measured behind the bare 1/48 scale tower (without stairs and rails). When these are compared to those profiles behind the bare 1/25 scale tower, it is seen that the profiles are quite similar, but, the wind flow through the all tubular 1/48 model is higher by about 5% than through the 1/25 model. This latter fact is also evident when Figure 7(c) is compared with Figure 7(b).

Figure 7 summarizes all the measured wind speed profile data.

The data in Figure 7(a) are for the 1/25 scale tower with the stairs and rails. The greater blockage and the unsymmetrical nature of the blockage resulted in lower average and minimum wind speeds and greater scatter. This scatter reflects the fact the wind flow resistance of the tower is not uniform with elevation or the azimuthal position around it. A comparison of Figure 7(b) with 7(c) shows that both the average and minimum wind speeds are higher and less scattered for the all tubular 1/48 scale model and that the average wind flow through the 1/48 scale tower is nearly constant within about a ±6% for all heights and wind approach angles. The largest decreases are seen to occur behind the horizontal members.

In Figure 8 is shown a select number of shadow photographs to give a visual indication of the amount of blockage offered by the tower models with and without the stairs and elevator rails and from various angles of view. These shadow-photographs along with the profiles of Figure 6 show that two primary factors contribute to a large local wind speed reduction: the size of the obstruction(s) directly upstream and the number of obstructions that are directly in line with the wind direction or nearly so. This is most evident when comparing the shadow-photographs of the bare 1/25 model with those of the model with stairs and rails for all wind approach angles. In Figure 8(h) for example, the windward and leeward legs of the tower are almost in line, thereby causing the greatest wind speed reduction directly behind those legs where the horizontal and diagonals intersect to form a joint.

CONCLUSIONS AND RECOMMENDATIONS

The results of these tests show that:

1. The presence of the stairs and elevator rails caused some very large reductions (up to 100%) in the wind speed in the wake of the tower, when compared to the basic bare tower without the stairs and rails. For example, the local average wind speeds behind the 1/25 model with stairs and rails ranged from about 60% to 77% of free stream value whereas when the stairs and rails are removed, the local averages increased to a range between 72% and 85%. The minimums also increased from a range of 0 to 45% to a range of 45 to 70%.

2. Towers constructed from all tubular members offer less resistance to the wind than those made with some noncircular members. The average speed thru the upper four sections of the all tubular 1/48-scale model was about 85% versus 80% for the 1/25-scale model. The minimum value also increased for the all-tubular tower.

3. The average wind speed in the wake of the bare towers is very nearly independent of the direction that the wind approaches the tower and independent of the elevation. The exception is at those elevations behind the horizontal members where the average is about 5% lower.

4. The local wind speed reductions at any point or region in the wake of a tower is largely determined by the size of the members and number of members that are in line with the wind and directly upwind. In other words, the wind speed reductions increase as the blockage (the solidity) upstream increases. In the wakes of bare towers, the lowest wind speeds occur behind the joints where the vertical, horizontal, and diagonal members converge, and when these joints are in line with the wind (a wind direction at 45° to a typical face).

From the above tests it was learned that the following features should be considered in tower design to increase the wind flow through the tower (reduce tower shadow):

1. Use all tubular members.
2. Reduce the size and number of members to the minimum needed to meet the other tower design requirement, that is, reduce the tower shadow to a minimum.
3. Avoid the use of gussett plates at the joints.
4. Reduce the number of members that can line up with the wind to a minimum.
5. Reduce the number of members that meet to form a joint to a minimum.

REFERENCE

1. Richard L. Puthoff: Fabrication and Assembly of the ERDA/NASA 100-kilowatt Experimental Wind Turbine. NASA TM X-3390, 1976.

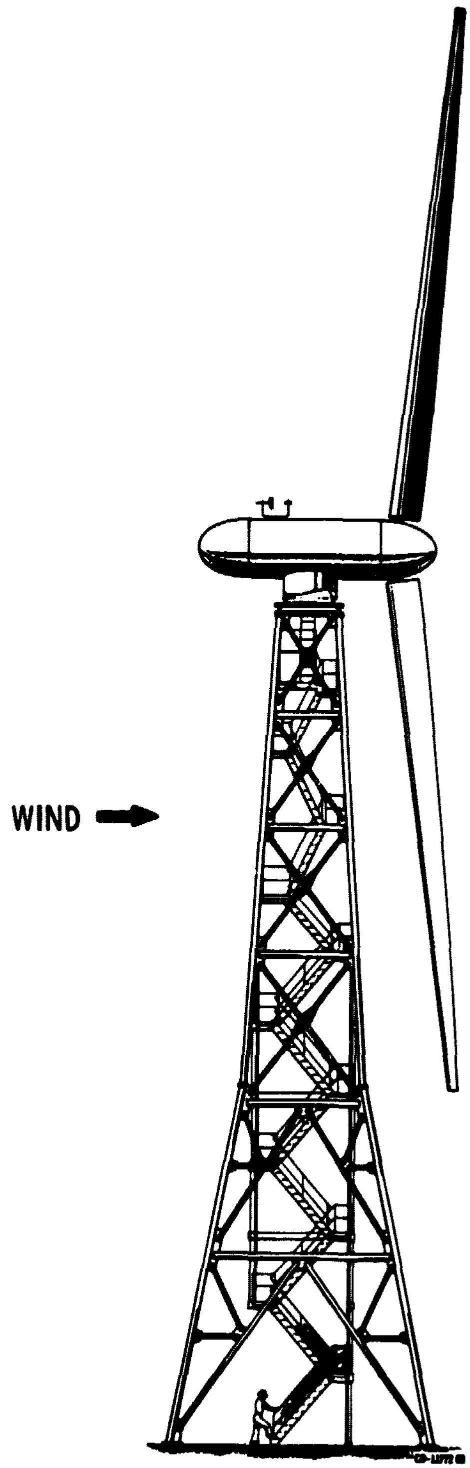

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Figure 1. - The ERDA/NASA 100 KW EXPERIMENTAL WIND TURBINE

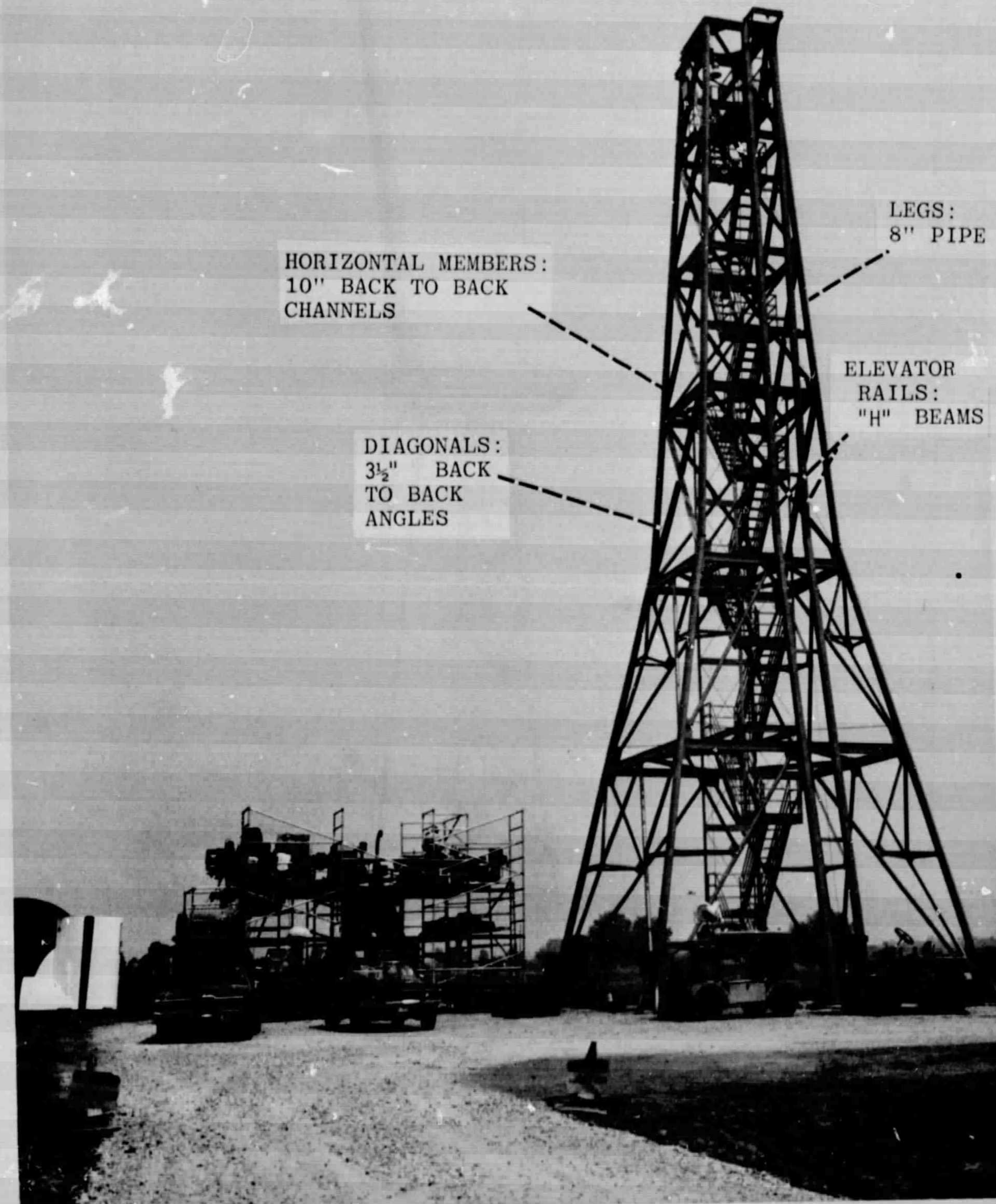


FIGURE 2. - ORIGINAL MOD-O TOWER WITH SERVICE STAIRS AND EQUIPMENT RAILS

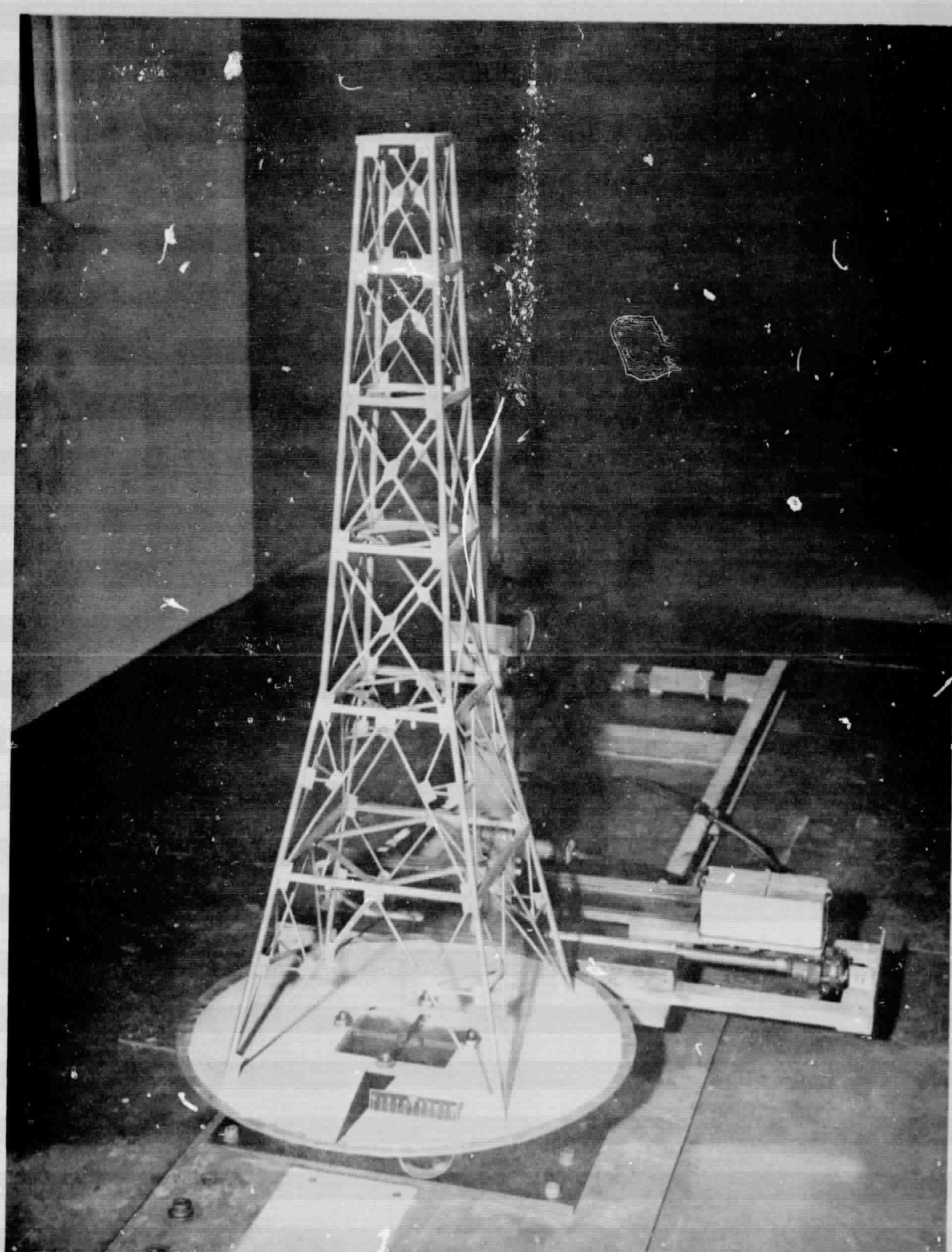


FIGURE 3A. - 1/25 SCALE MODEL OF MOD-0 TOWER - BARE

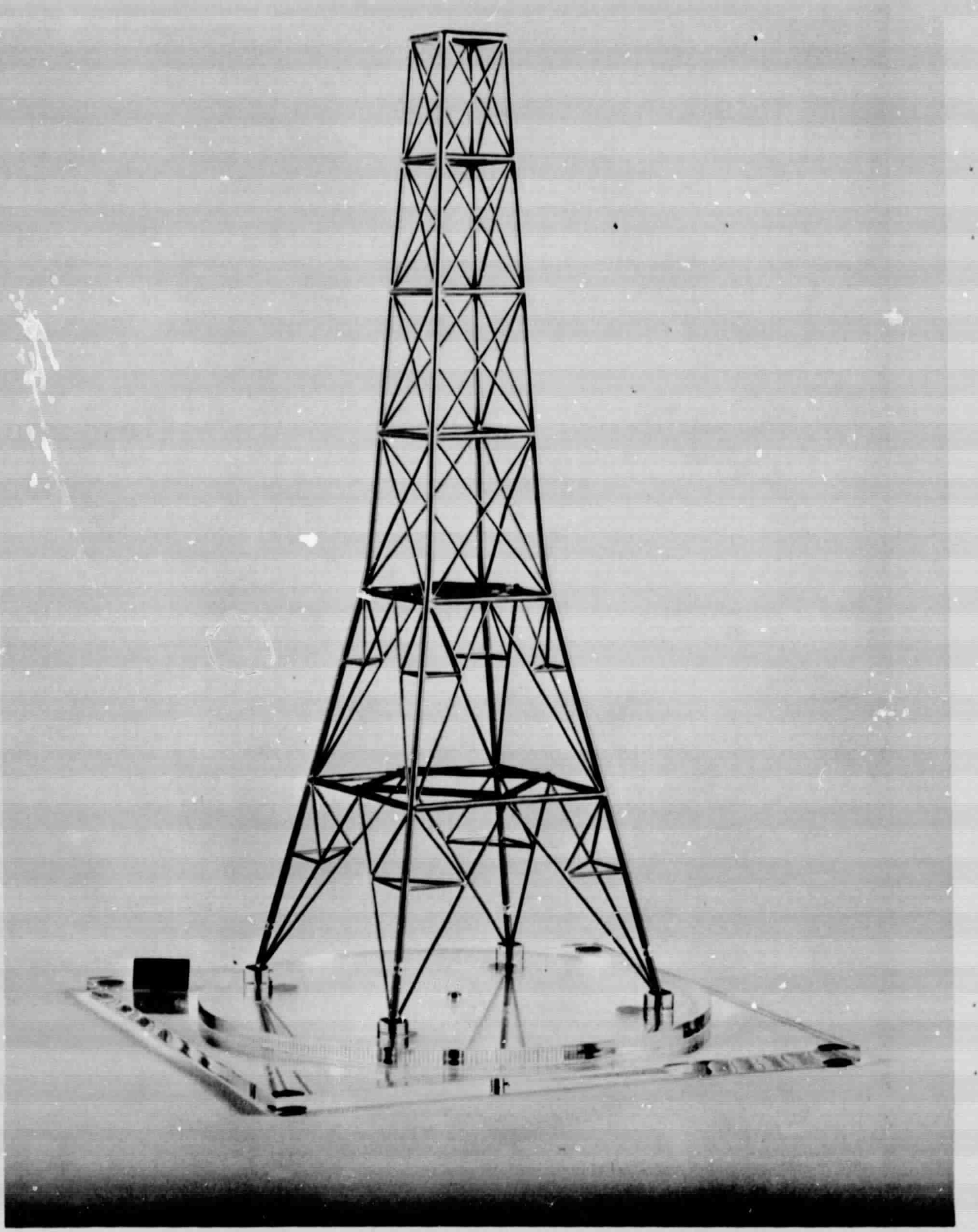


FIGURE 3B. - 1/48 SCALE ALL TUBULAR TOWER MODEL

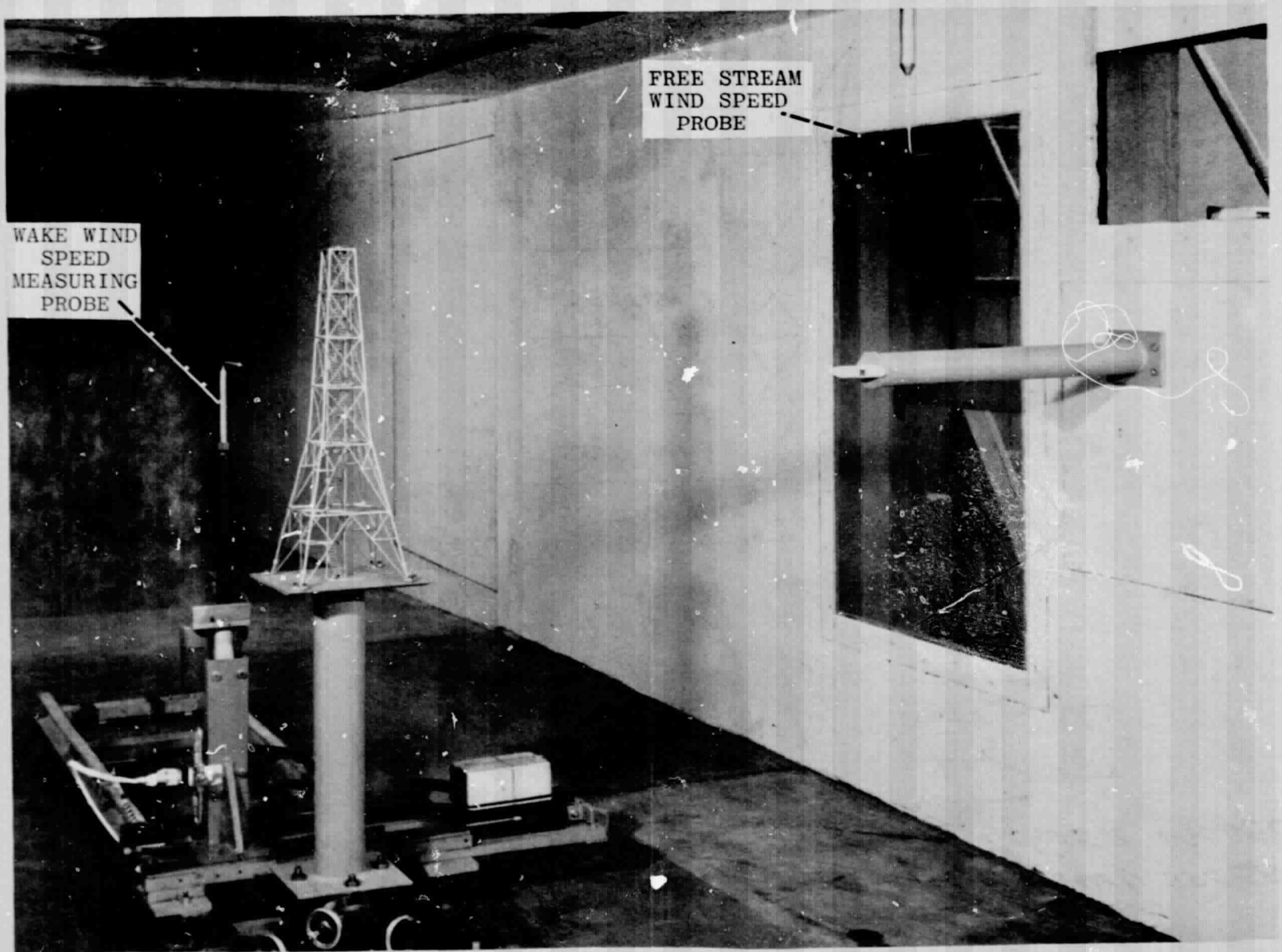


FIGURE 4. - 1/48 SCALE MODEL (WITH A MODEL STAIR) MOUNTED IN THE WIND TUNNEL AND WIND SPEED MEASURING

FIG 5 WIND TUNNEL SET UP FOR WIND SPEED MEASUREMENTS IN THE WAKE OF TOWER MODELS

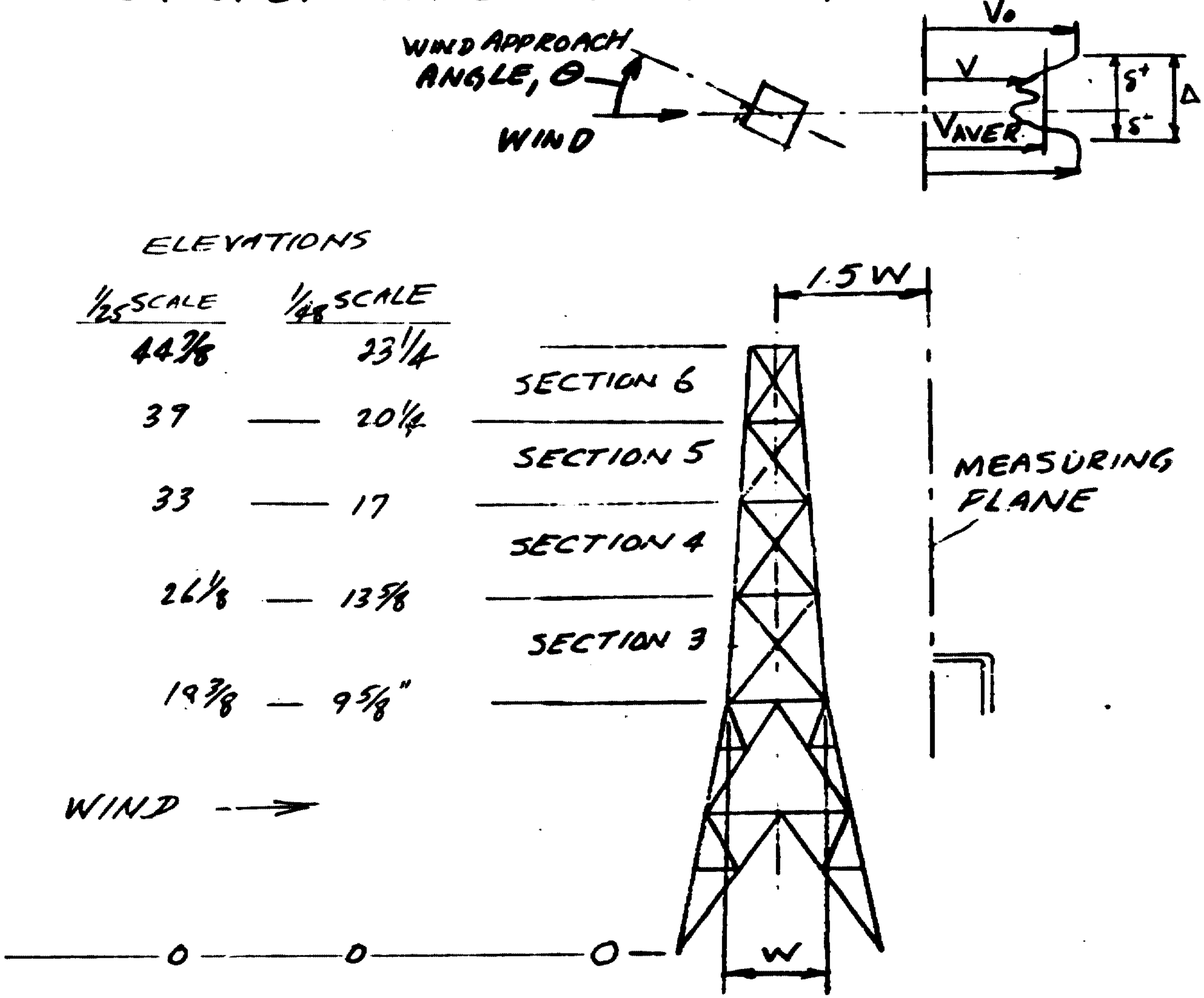
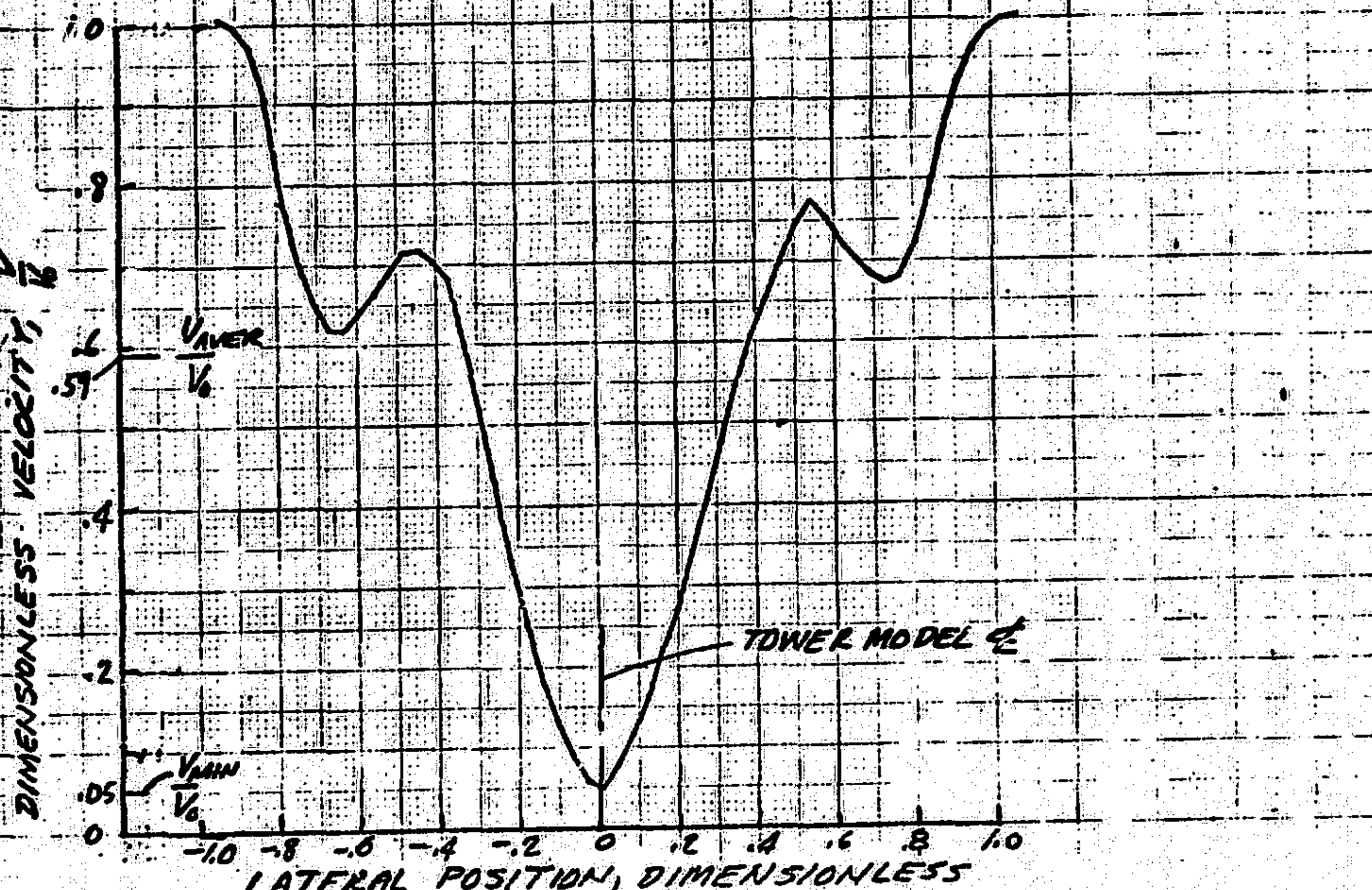


FIGURE 6 DIMENSIONLESS WIND SPEED PROFILES IN THE WAKE OF 1/25 & 1/48 SCALE TOWER MODELS



(a) WIND APPROACH ANGLE = 35°
ELEVATION = 20½ INCHES

WITH STAIRS & ELEVATOR RAILS
1/25 SCALE

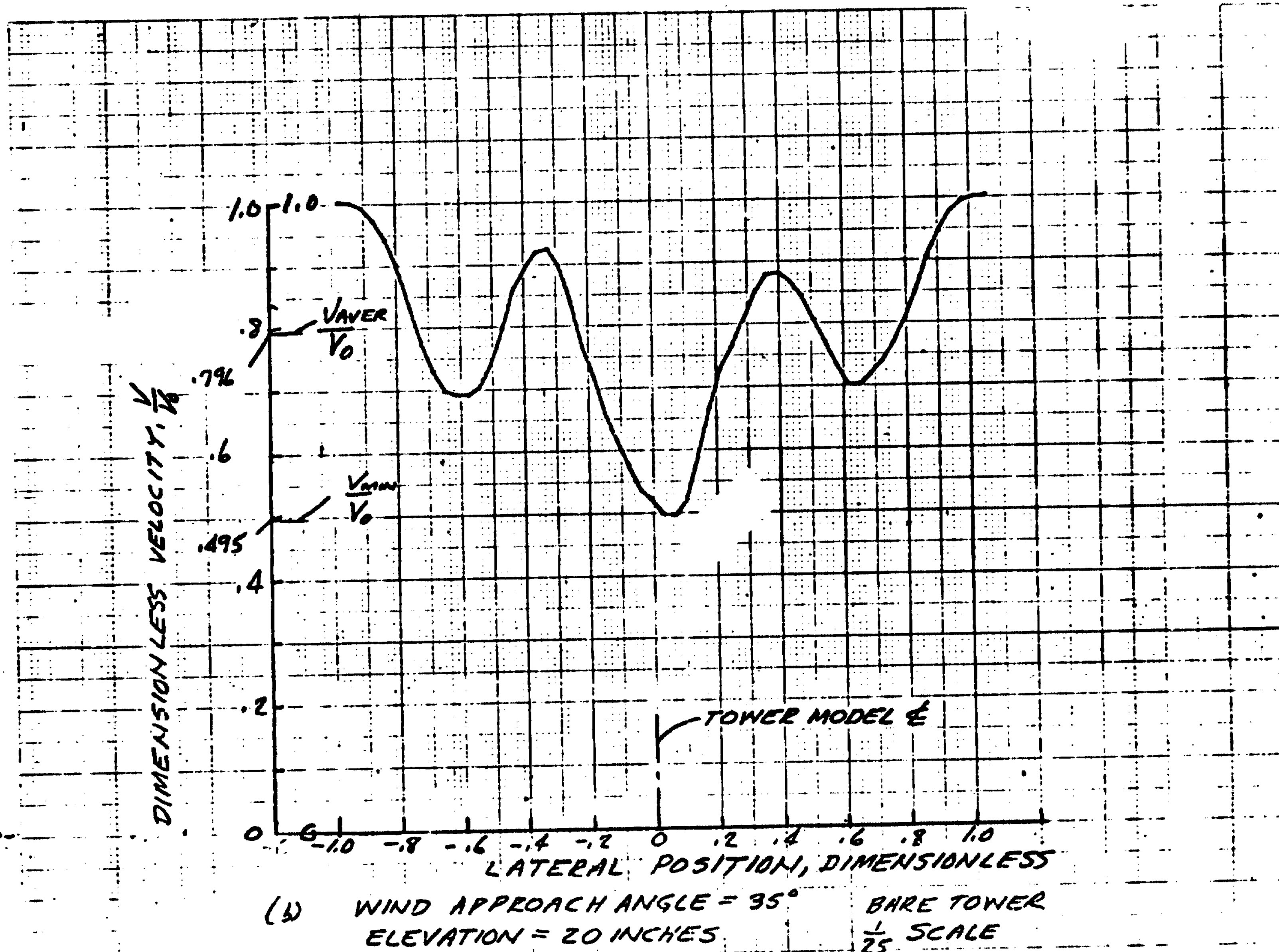

1.0
1.0
.8
$\frac{V_{AVER}}{V_0}$
.796
.6
$\frac{V_{MIN}}{V_0}$
.495
.4
.2
0
DIMENSIONLESS VELOCITY, $\frac{V}{V_0}$
TOWER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION, DIMENSIONLESS
(b) WIND APPROACH ANGLE = 35°
ELEVATION = 20 INCHES
BARE TOWER
$\frac{1}{25}$ SCALE

Fig. 6

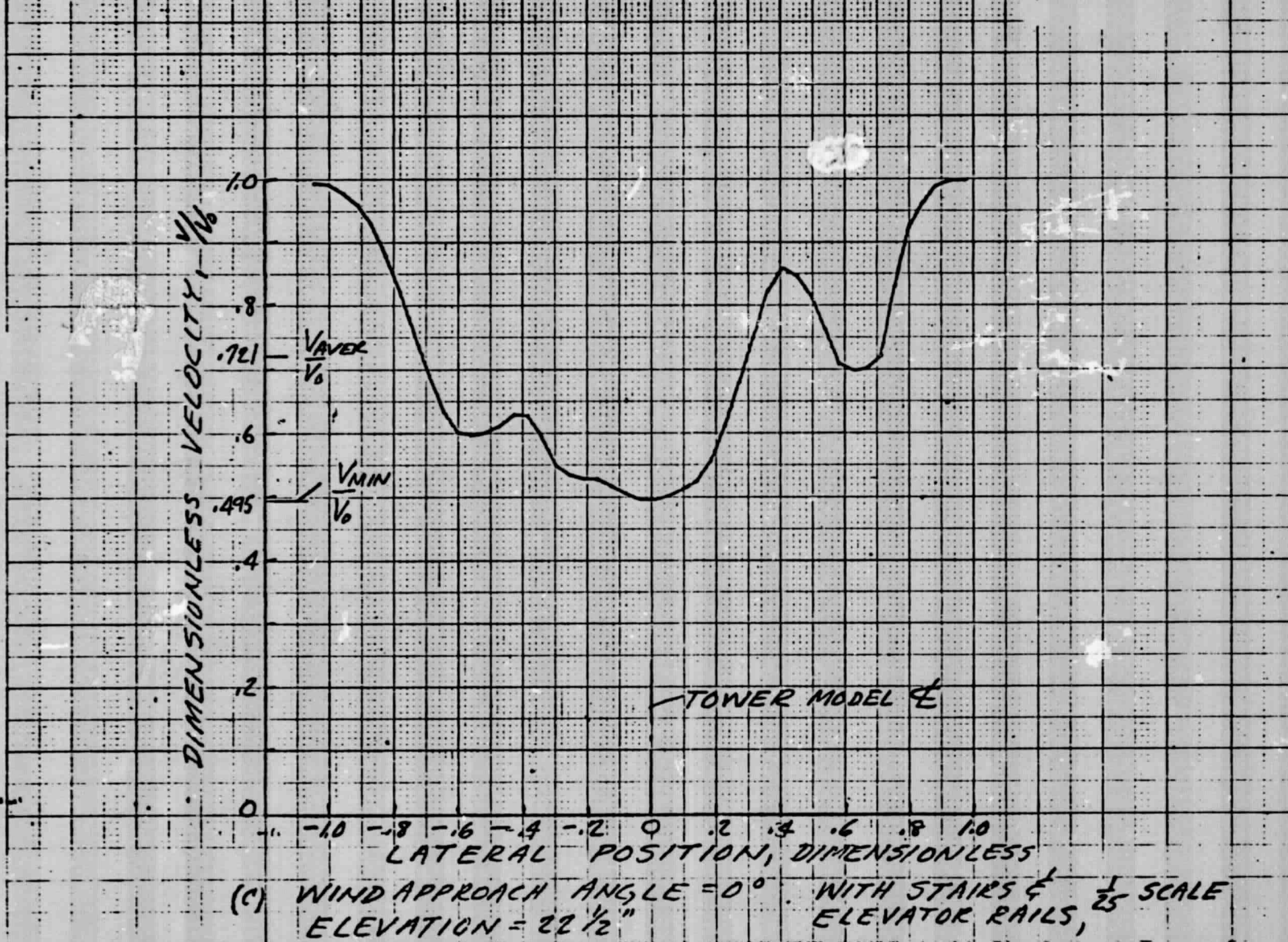
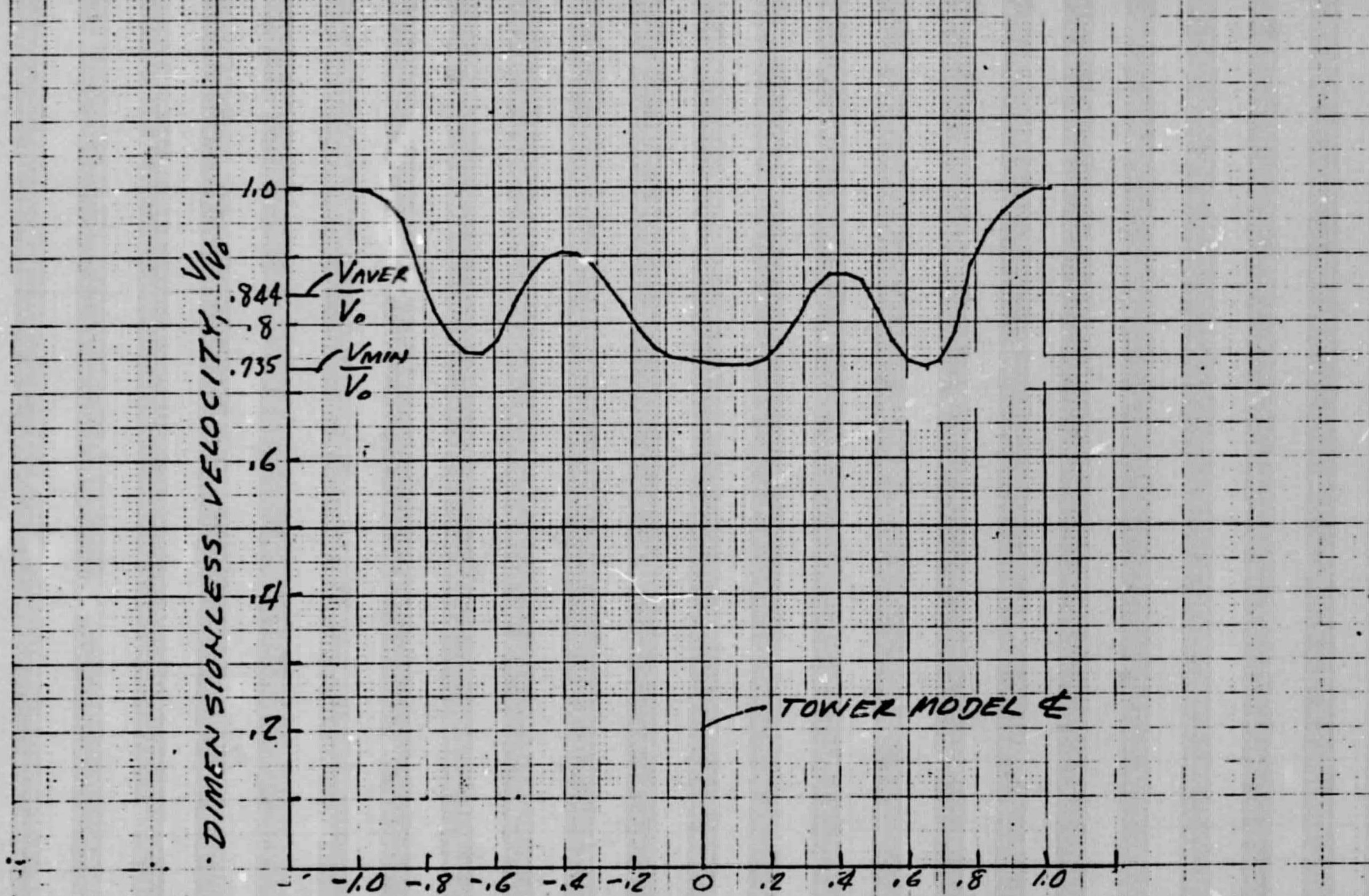
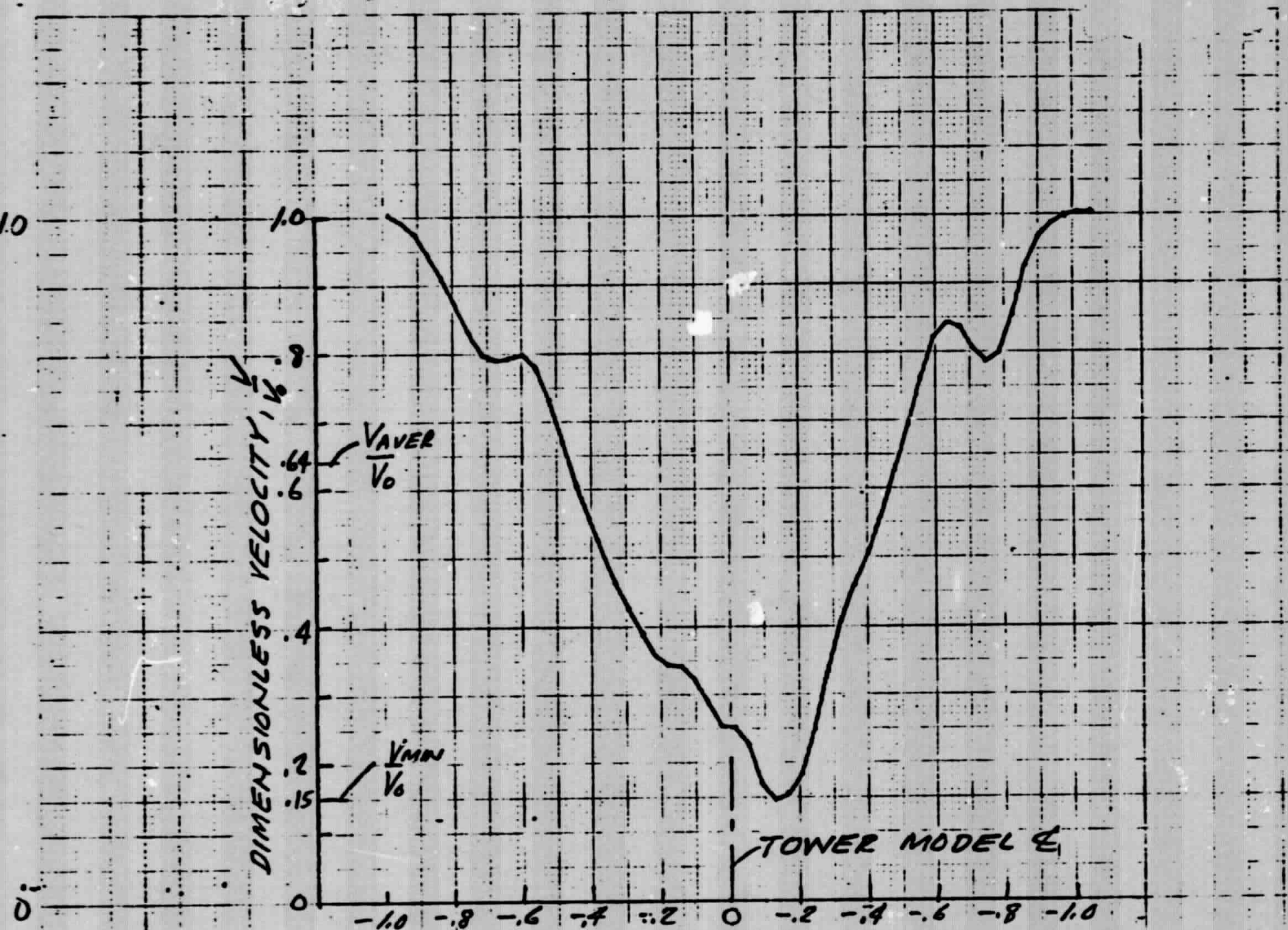

DIMENSIONLESS VELOCITY, V/V₀
1.0
.8
.721
V_AVER / V₀
.6
V_MIN / V₀
.495
.4
.2
0
TOWER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION, DIMENSIONLESS
(C) WIND APPROACH ANGLE = 0° WITH STAIRS & ELEVATOR RAILS, 1/25 SCALE
ELEVATION = 22 1/2"

Fig. 6



(d) WIND APPROACH ANGLE = 0 BARE TOWER, 1/25 SCALE
ELEVATION = 22½ INCHES

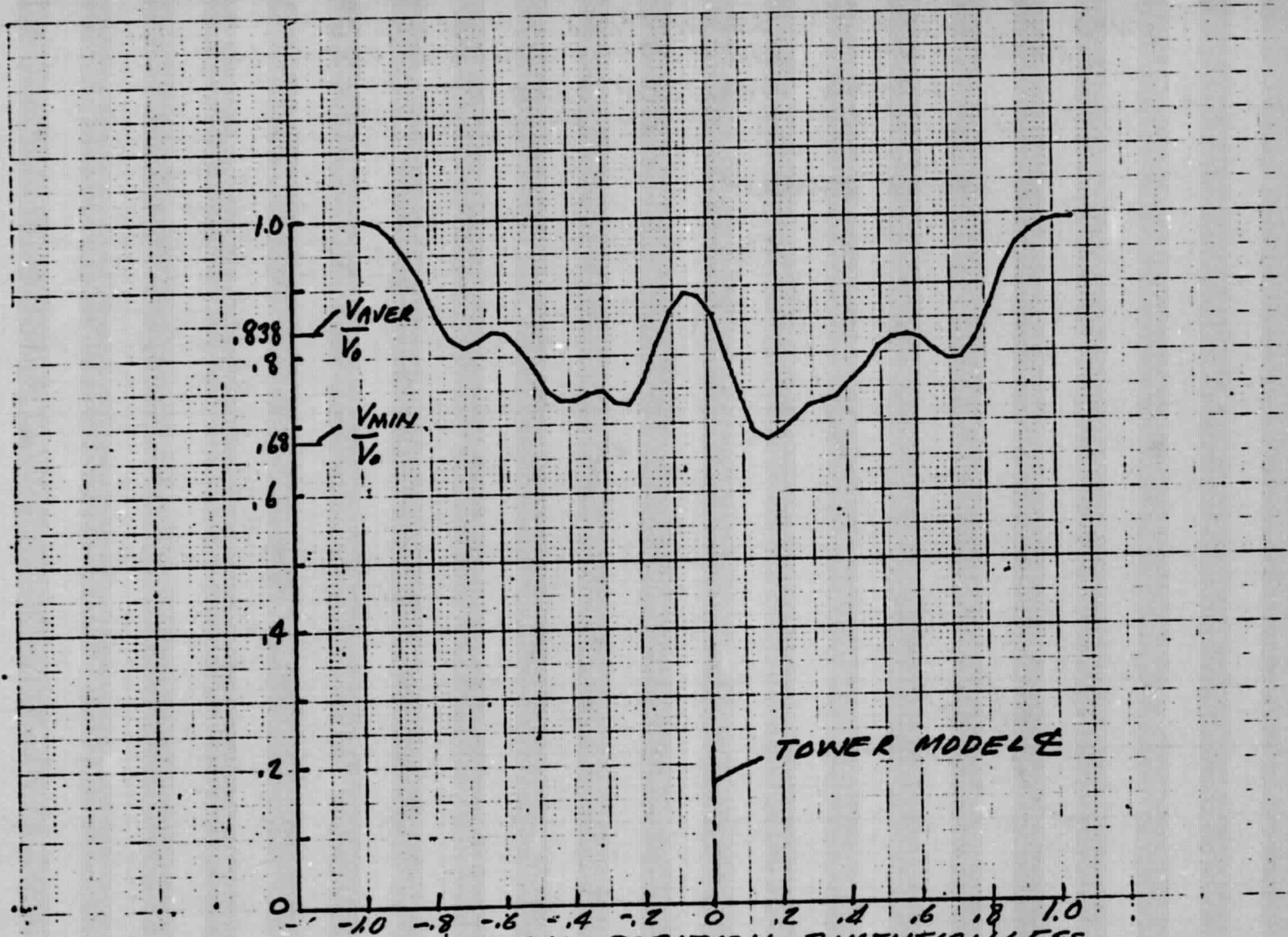
Fig. 6



(e) WIND APPROACH ANGLE = 35°
ELEVATION = 22½ INCHES

WITH STAIRS & ELEVATOR RAILS
$\frac{1}{25}$ SCALE

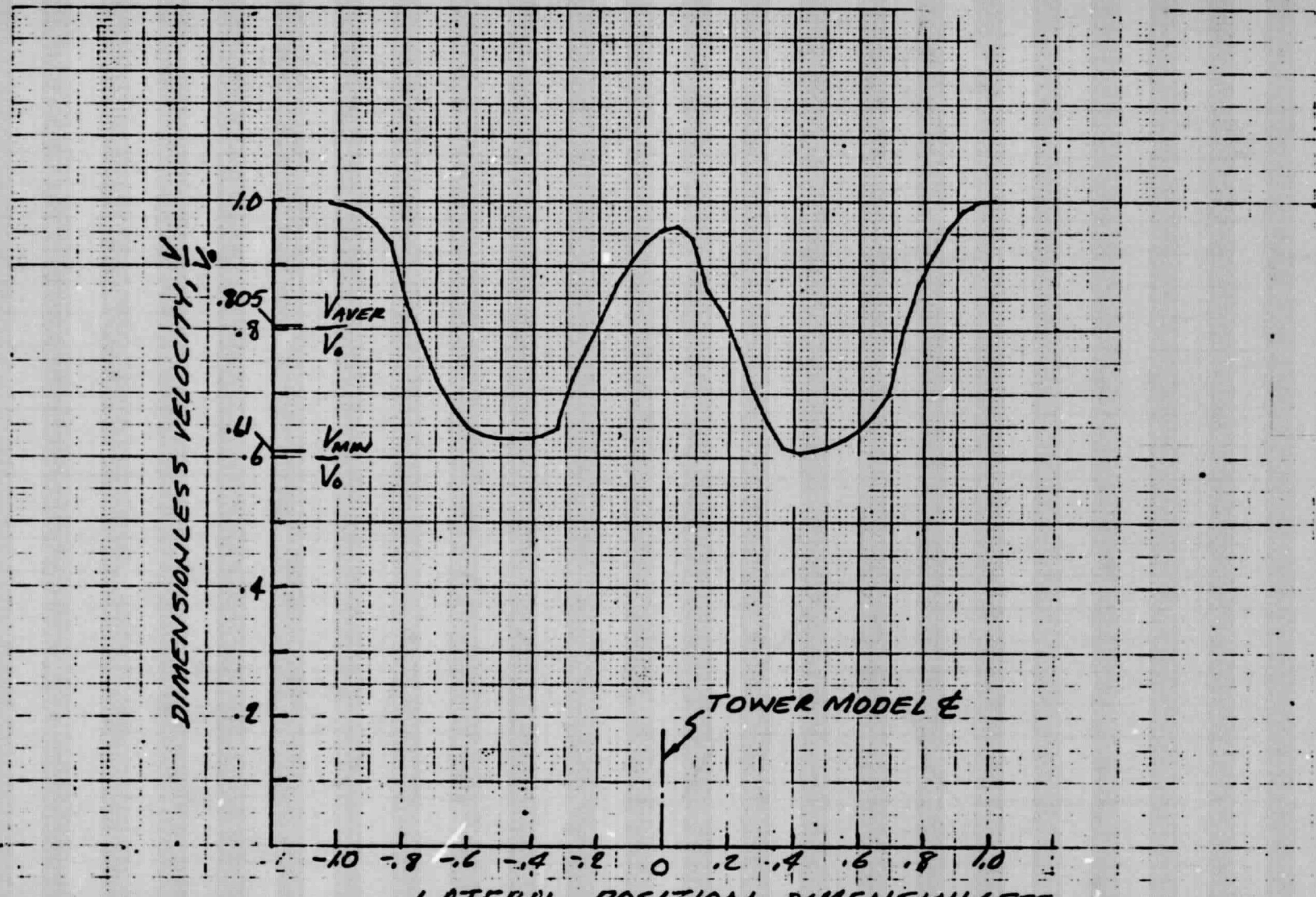
Fig. 6



(f) WIND APPROACH ANGLE = 35°
ELEVATION = 22½ INCHES

BARE TOWER
1/25 SCALE

Fig. 6



(g) WIND APPROACH ANGLE = 0° BARE TOWER
ELEVATION = 21 INCHES

Fig. 6

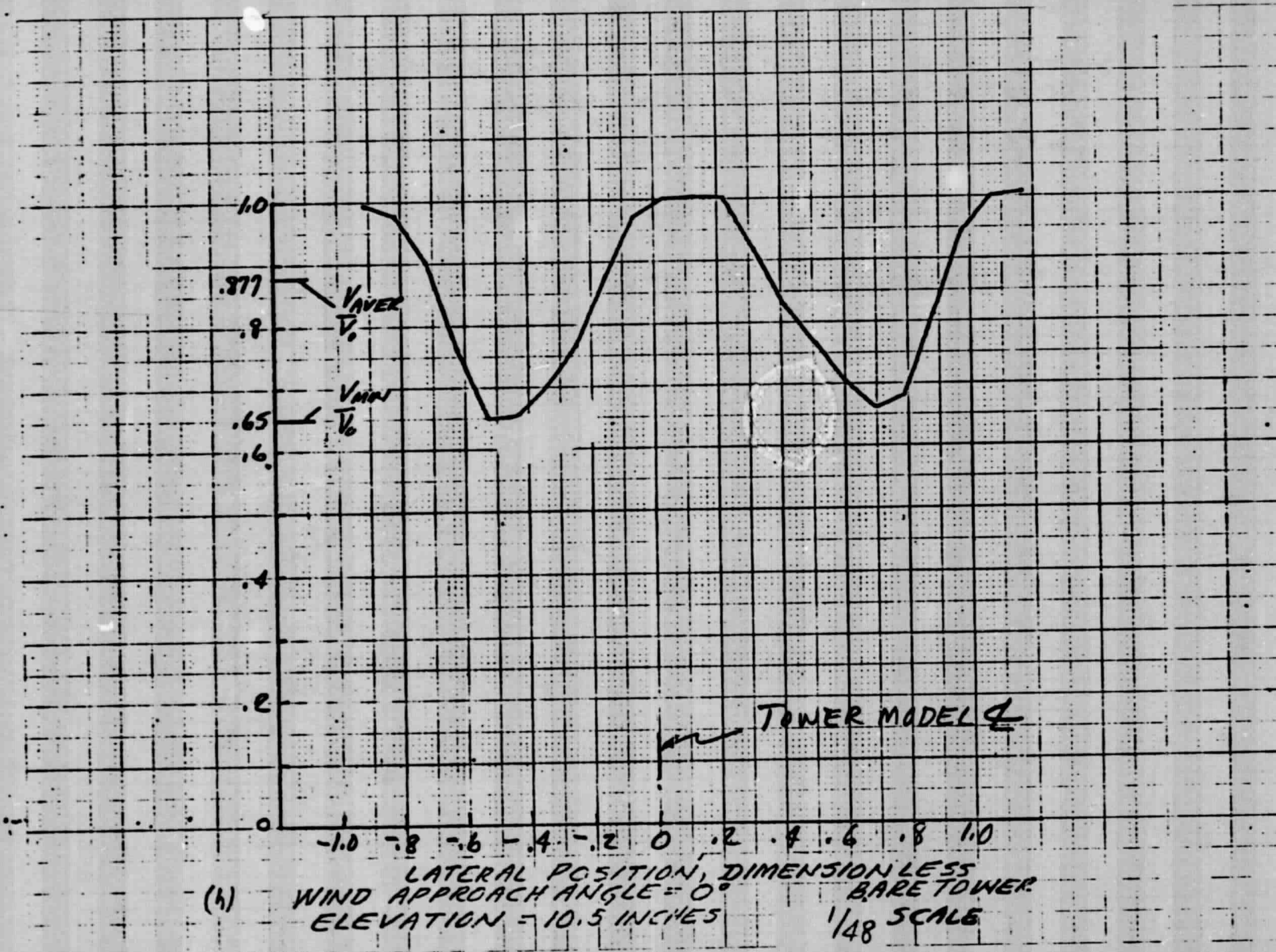

1.0
.877
.8
.65
.6
.4
.2
0
VAVER / V0
VMIN / V0
TOWER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION, DIMENSIONLESS
(h) WIND APPROACH ANGLE = 0°
ELEVATION = 10.5 INCHES
BARE TOWER
1/48 SCALE

Fig. 6

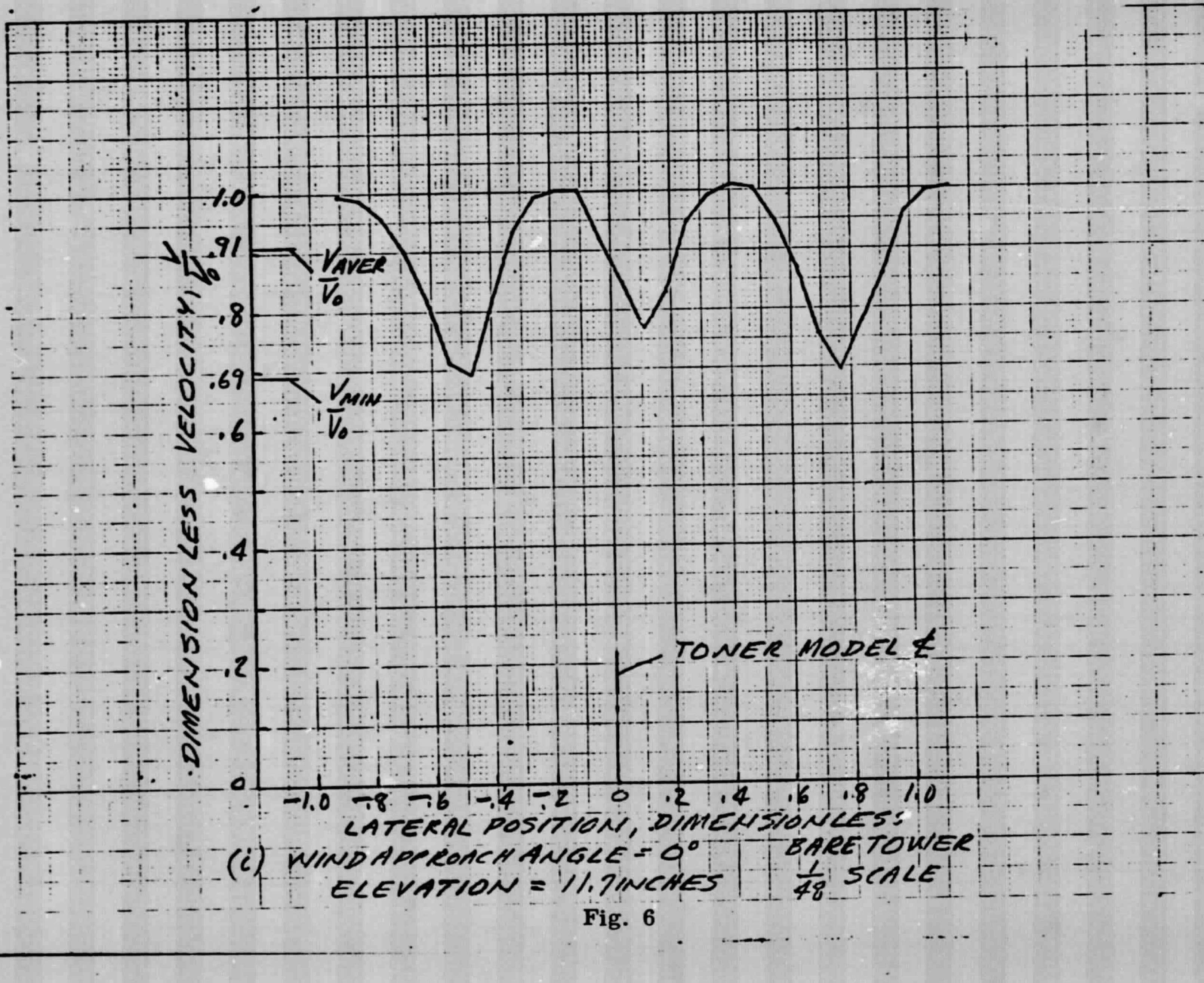

DIMENSIONLESS VELOCITY, V/V0
1.0
.91
.8
.69
.6
.4
.2
0
VAVER/V0
VMIN/V0
TONER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION, DIMENSIONLESS
(i) WIND APPROACH ANGLE = 0°
ELEVATION = 11.7 INCHES
BARE TOWER
1/48 SCALE

Fig. 6

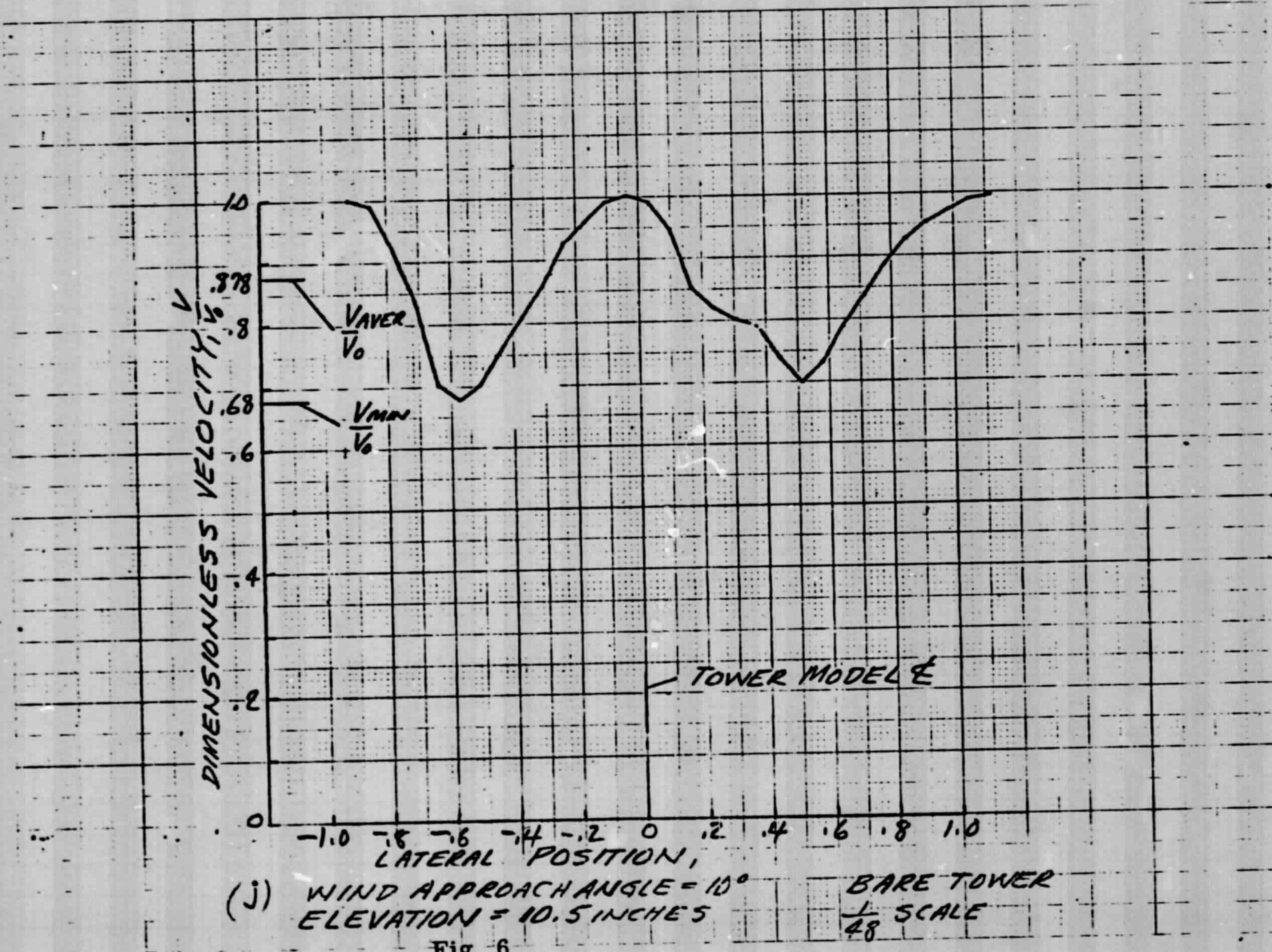
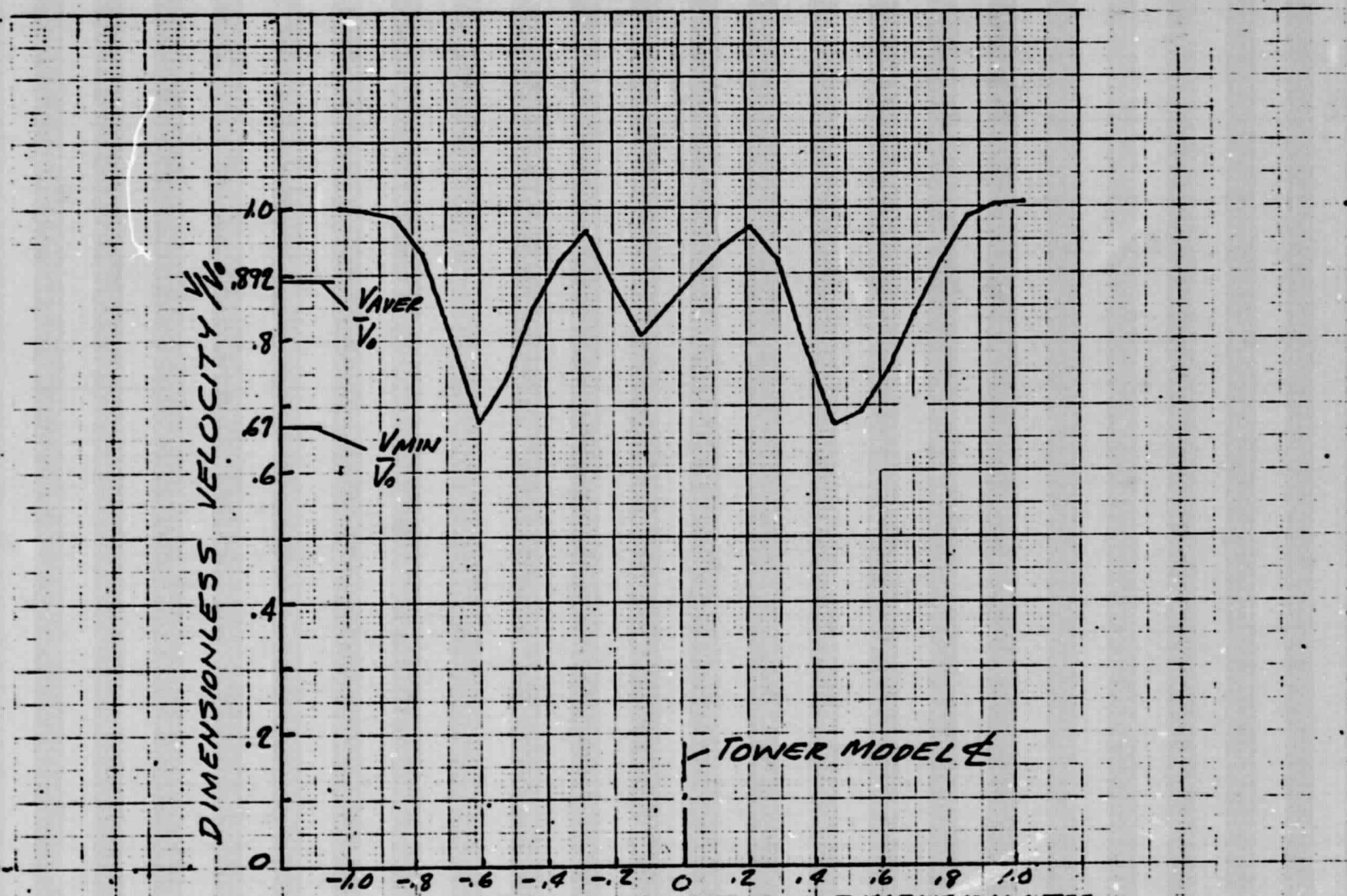

1.0
.878
.8
.68
.6
.4
.2
0
V_{AVER}/V_0
V_{MIN}/V_0
DIMENSIONLESS VELOCITY, V/V_0
TOWER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION,
(j) WIND APPROACH ANGLE = 10°
ELEVATION = 10.5 INCHES
BARE TOWER
1/48 SCALE

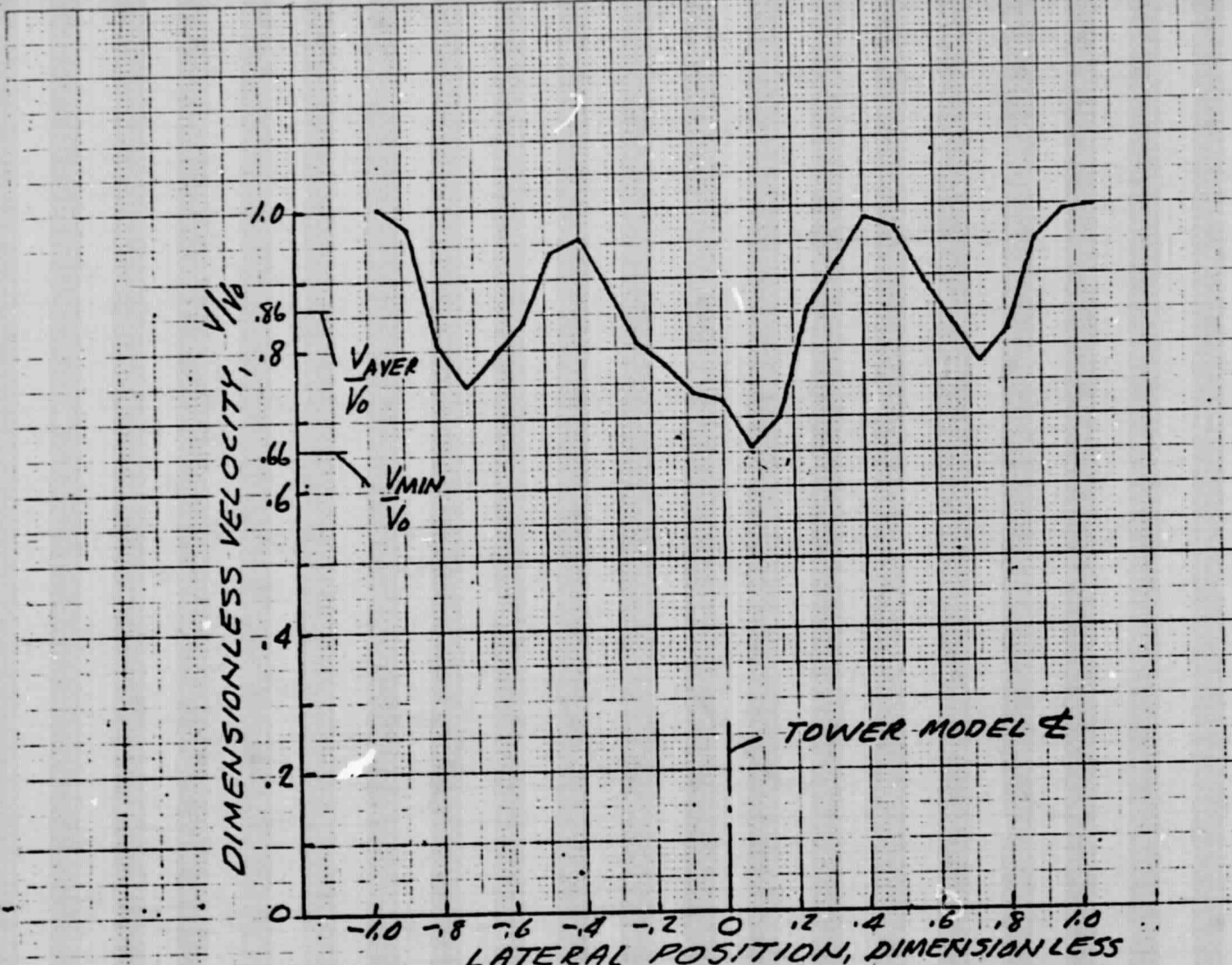
Fig. 6



(K) WIND APPROACH ANGLE = 10°
ELEVATION = 11.75 INCHES

BARE TOWER
1/48 SCALE

Fig. 6



(2) WIND APPROACH ANGLE = 35° BARE TOWER,
ELEVATION = 10.5 INCHES 1/48 SCALE

Fig. 6

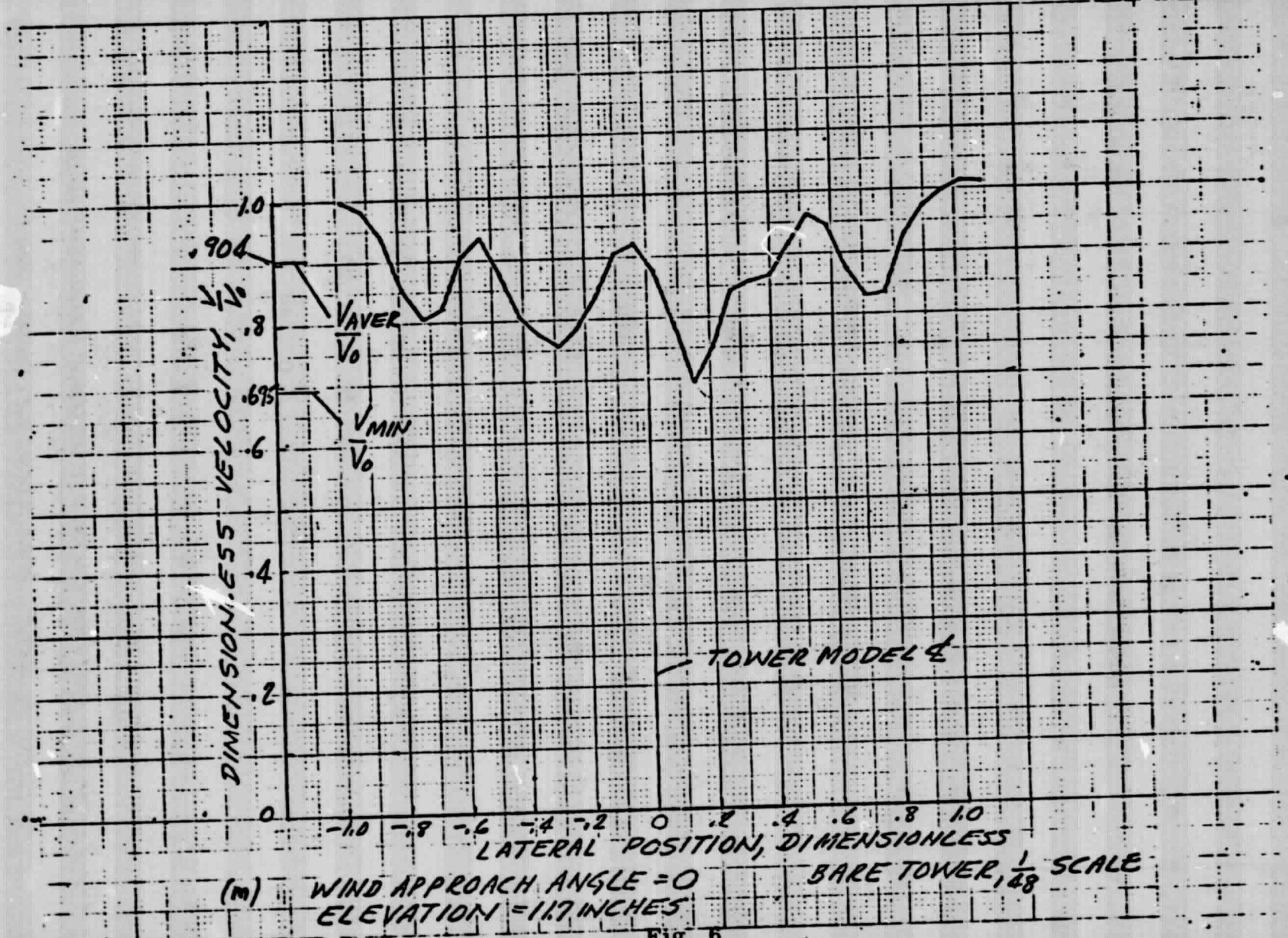

1.0
.904
.8
.695
.6
.4
.2
0
$\frac{V_{AVER}}{V_0}$
$\frac{V_{MIN}}{V_0}$
DIMENSIONLESS VELOCITY, V/V_0
TOWER MODEL ℄
-1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0
LATERAL POSITION, DIMENSIONLESS
(m) WIND APPROACH ANGLE = 0
ELEVATION = 11.7 INCHES
BARE TOWER, $\frac{1}{48}$ SCALE

Fig. 6

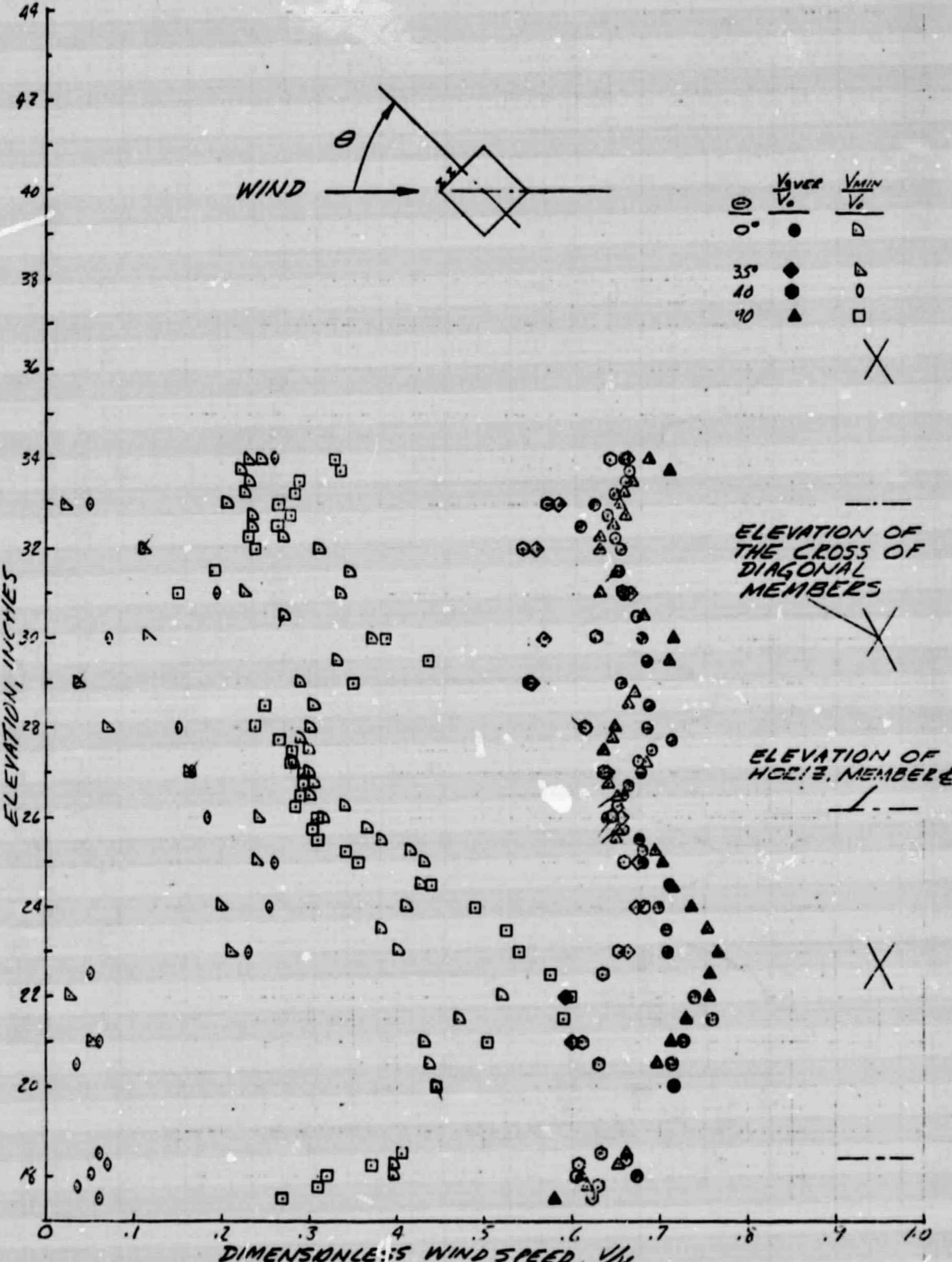
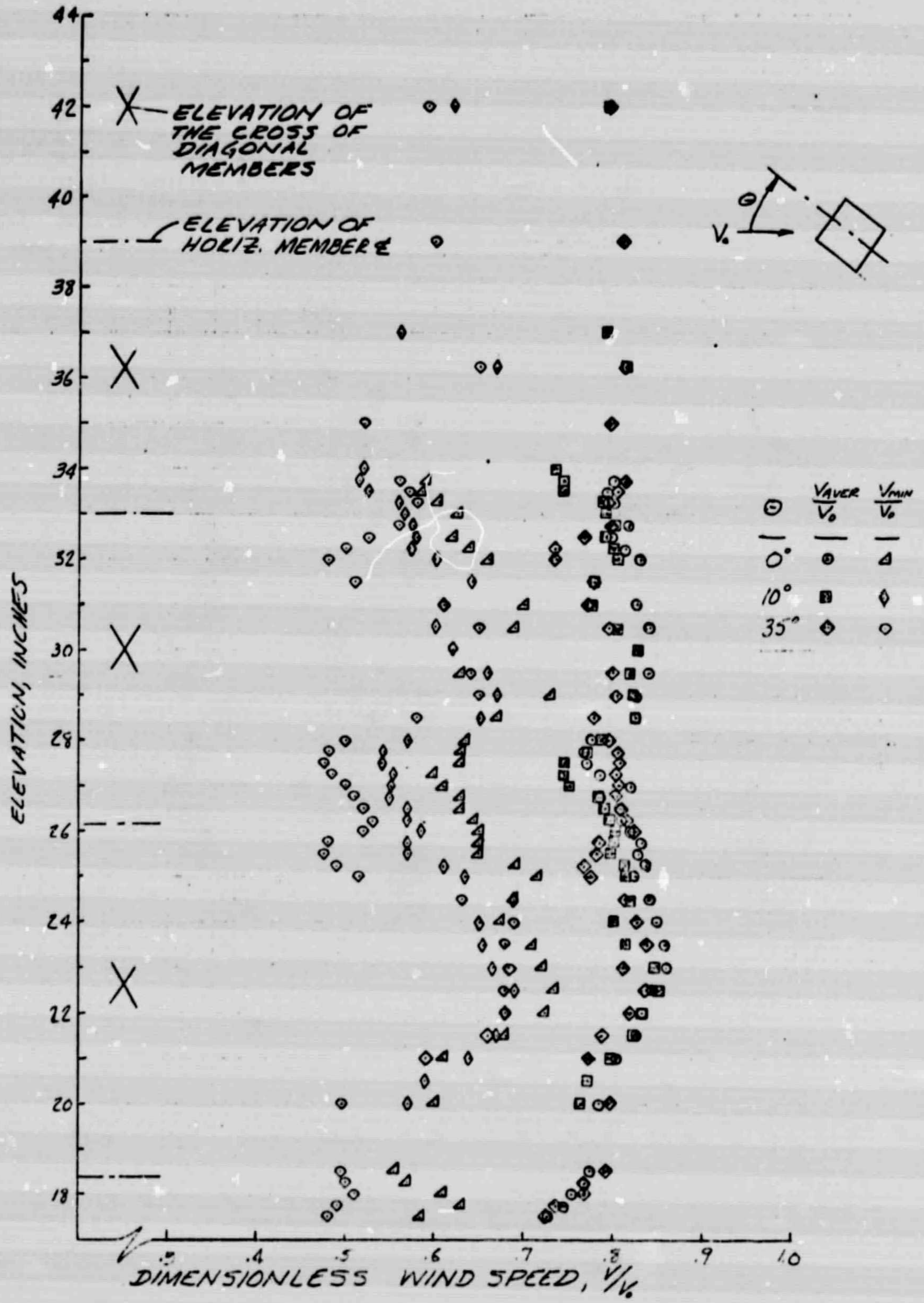


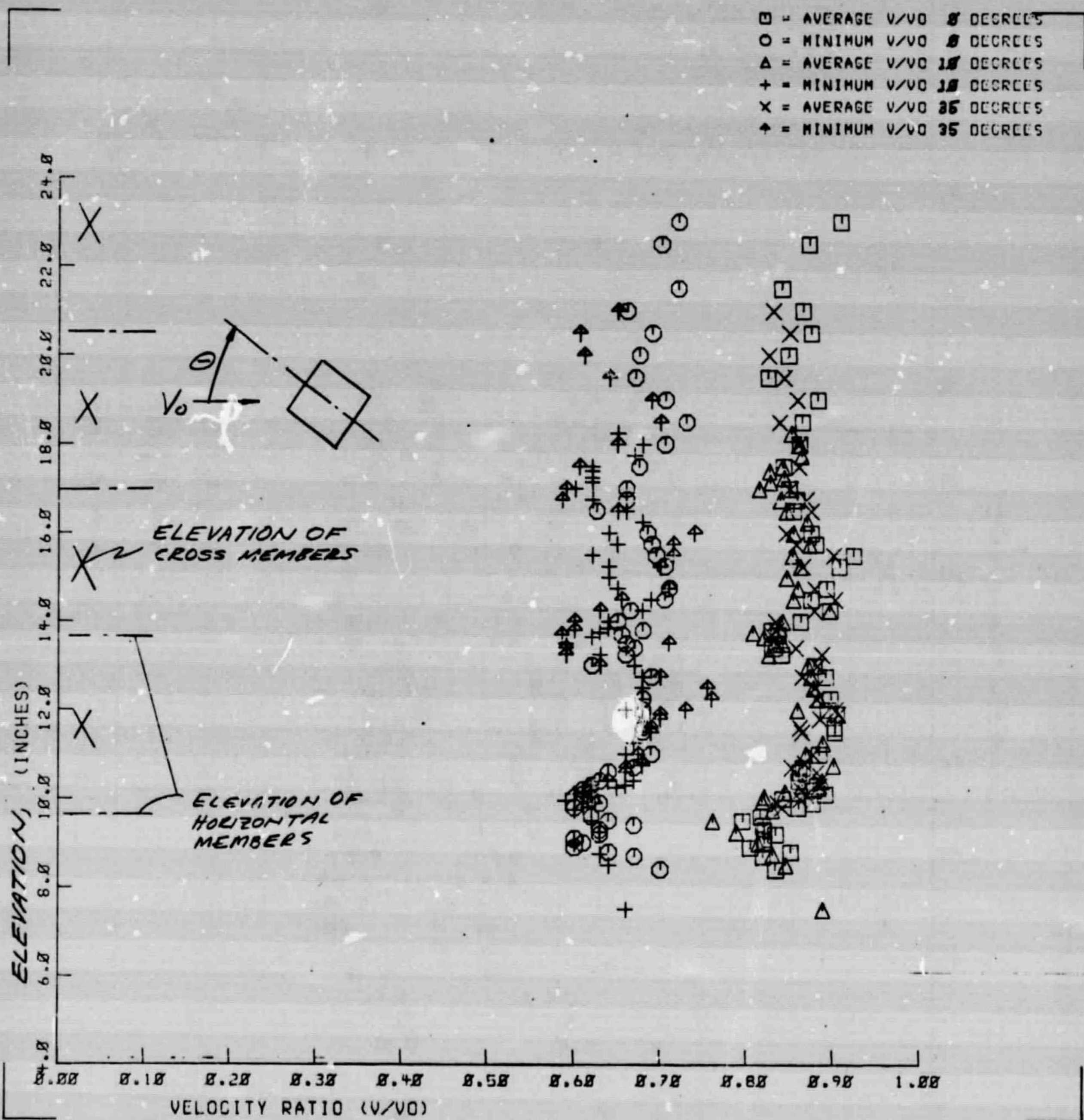
FIG. 7 VERTICAL DISTRIBUTION OF THE AVERAGE & MINIMUM WIND SPEEDS IN THE WAKE OF THE MOD-0 TOWER MODEL

(a) $\frac{1}{25}$ SCALE WITH STAIRS & ELEVATOR RAILS



VERTICAL DISTRIBUTION OF THE AVERAGE & MINIMUM WIND SPEEDS IN THE WAKE OF THE MOD-0 TOWER MODEL
(b) $\frac{1}{25}$ SCALE MODEL - BARE (WITHOUT STAIRS & ELEVATOR RAILS)

Fig. 7



(c) $\frac{1}{48}$ SCALE MODEL - BARE (WITHOUT STAIRS & ELEVATOR RAILS), ALL TUBE MEMBERS, NO GUSSET PLATES

Fig. 7

FIGURE 8. - SHADOW PHOTOS 1/25 SCALE MOD-0 TOWER. (A) WITH STAIRS AND ELEVATOR RAILS. WIND APPROACH ANGLE = 0°

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OF POOR QUALITY

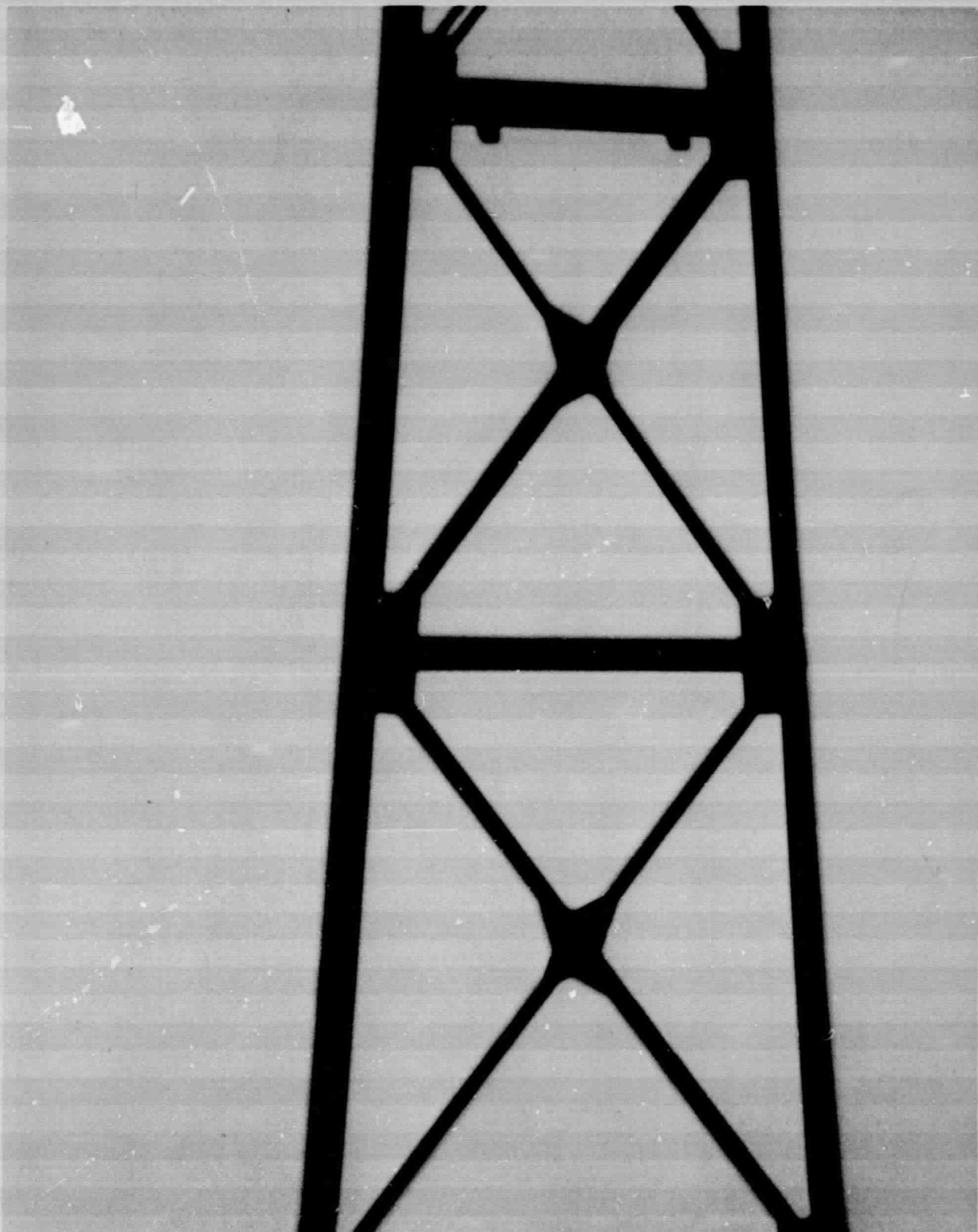

Fig. 8 (B) BARE TOWER. WIND APPROACH ANGLE = 0^{0}

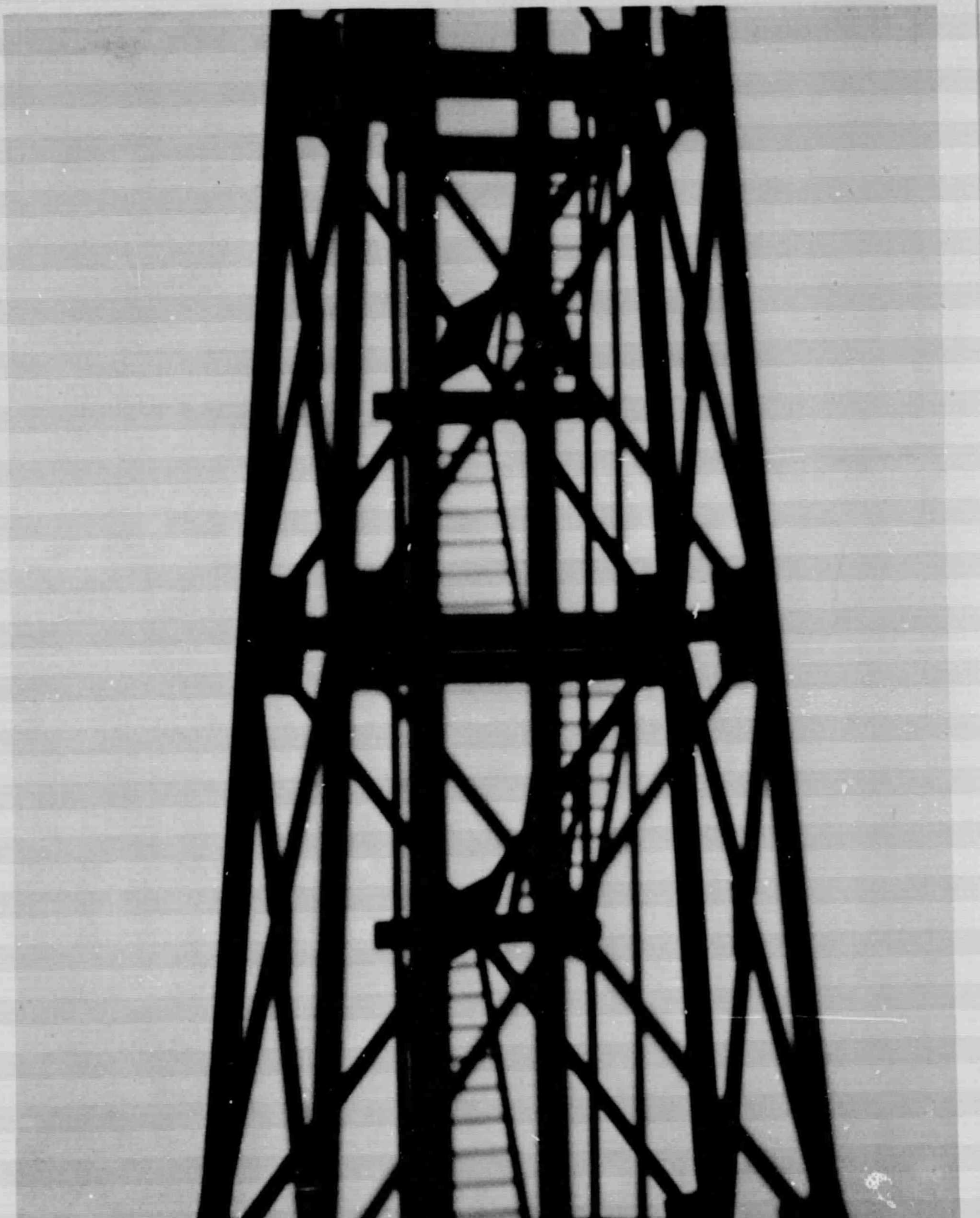

Fig. 8 (c) WITH STAIRS AND ELEVATOR RAILS. WIND APPROACH ANGLE = 10^{0}

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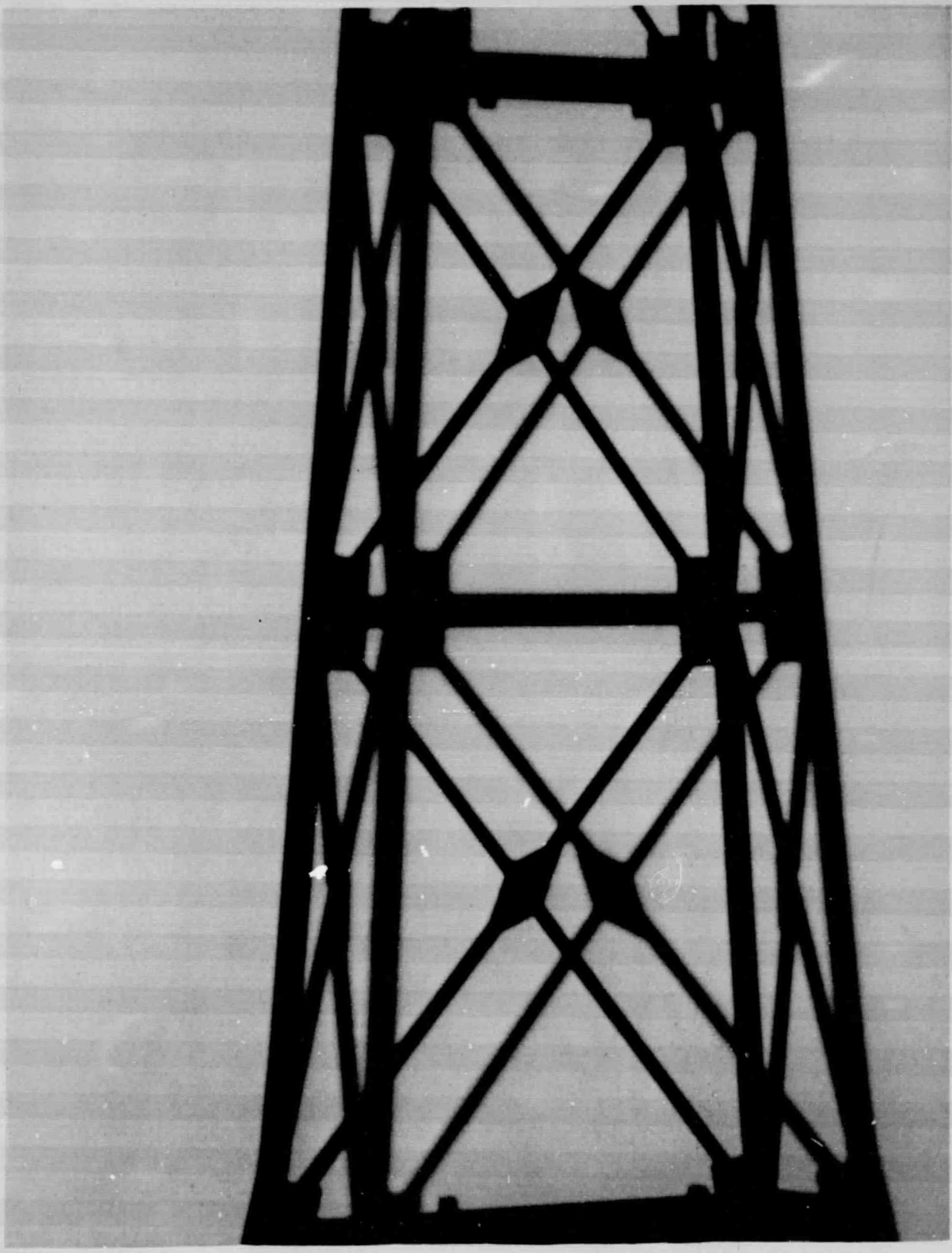

Fig. 8 (D) BARE TOWER WIND APPROACH ANGLE = 10°

Fig. 8 (E) WITH STAIRS AND ELEVATOR RAILS. WIND APPROACH ANGLE = 35°

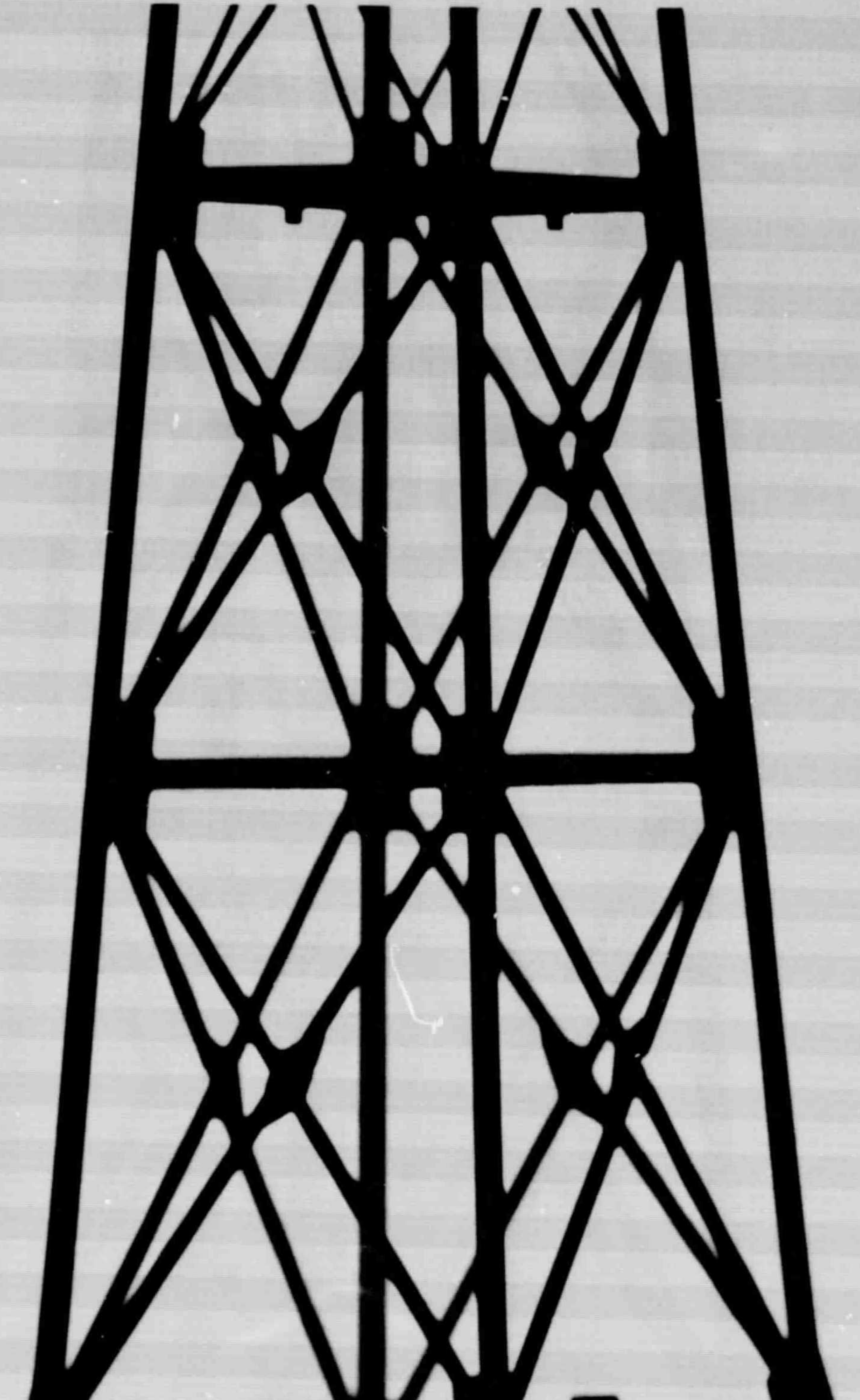

Fig. 8 (f) BARE TOWER. WIND APPROACH ANGLE = 35^0

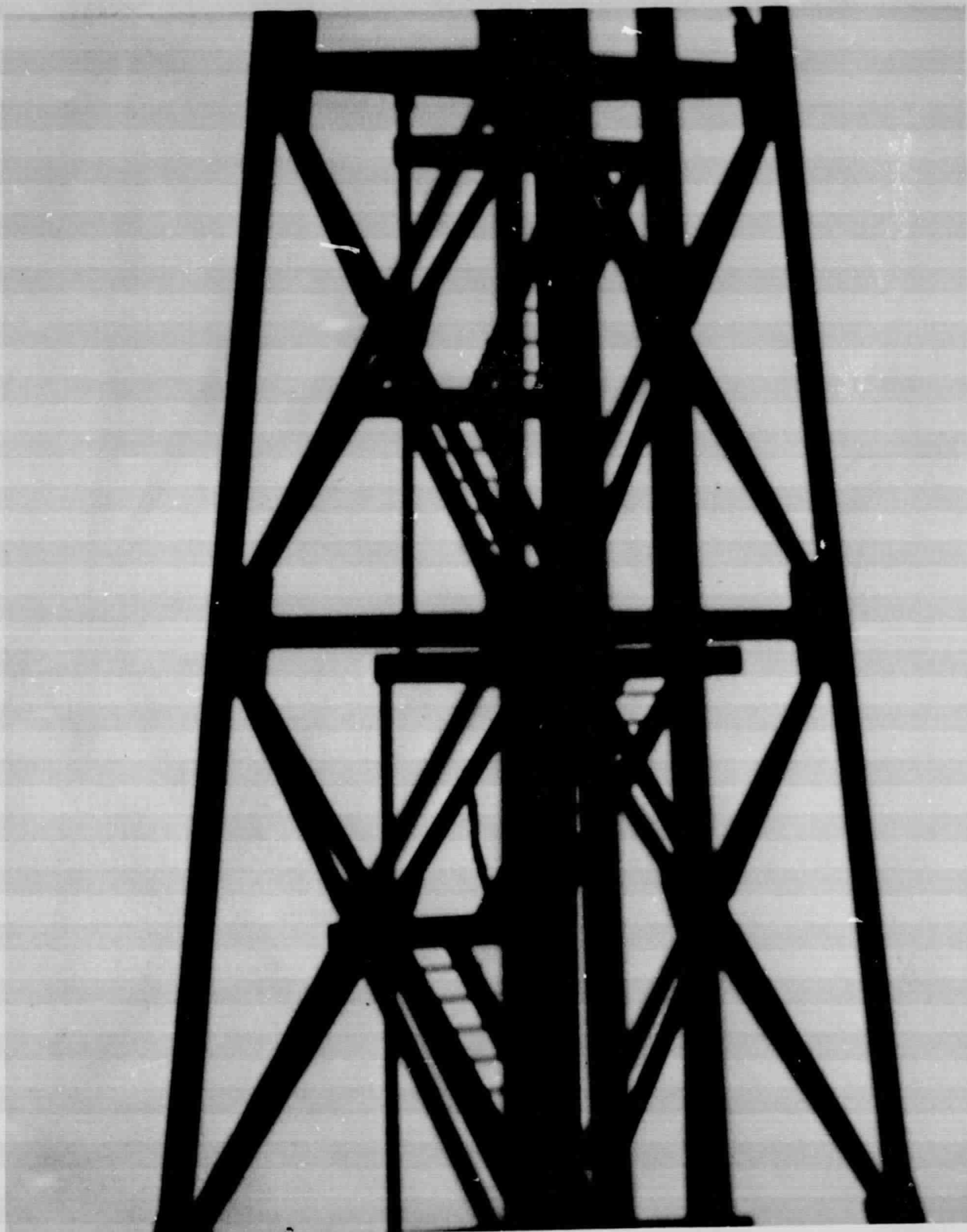

Fig. 8(G) WITH STAIRS AND ELEVATOR RAILS. WIND APPROACH ANGLE = 40^{0}

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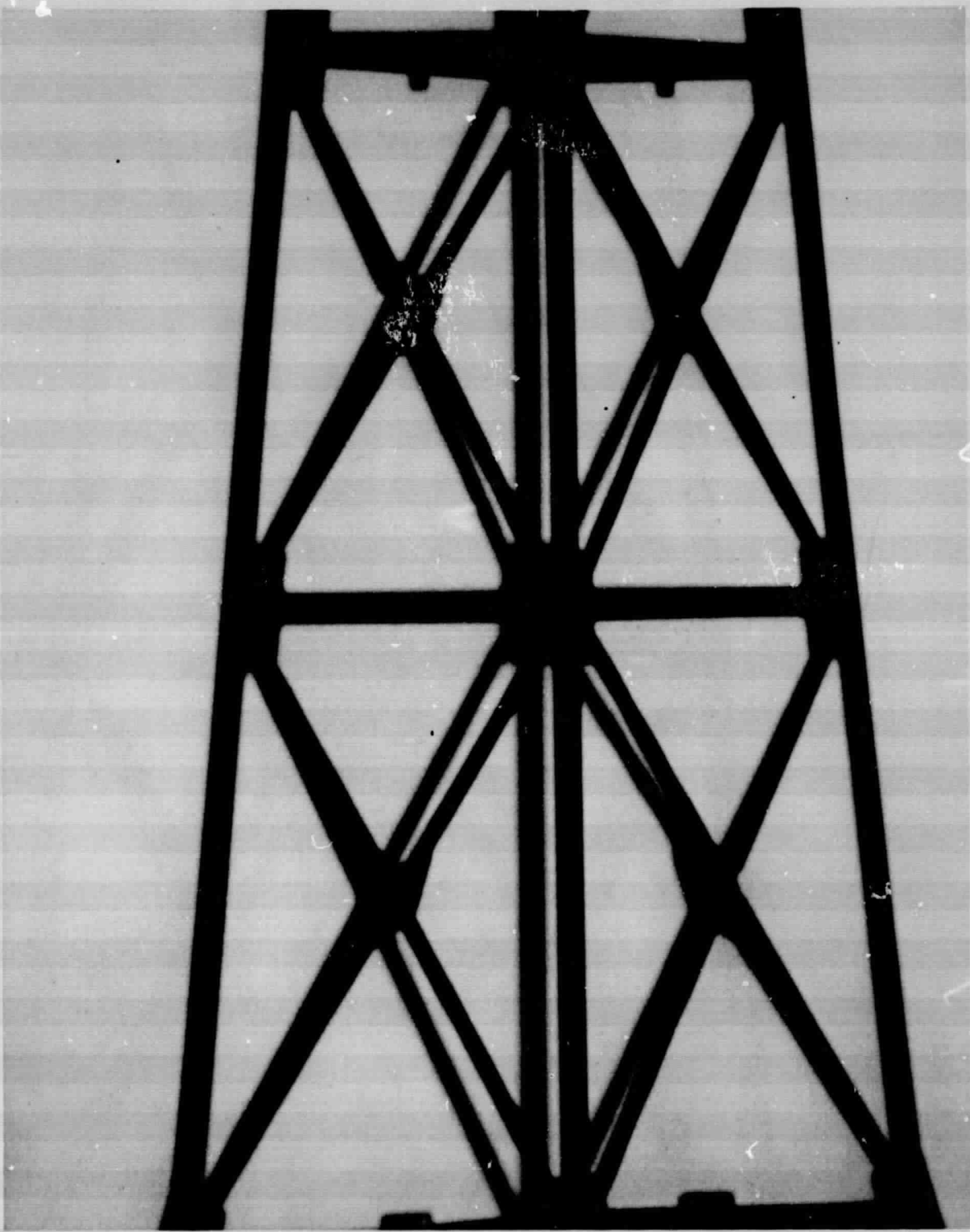

Fig. 8 (H) BARE TOWER. WIND APPROACH ANGLE = 40°

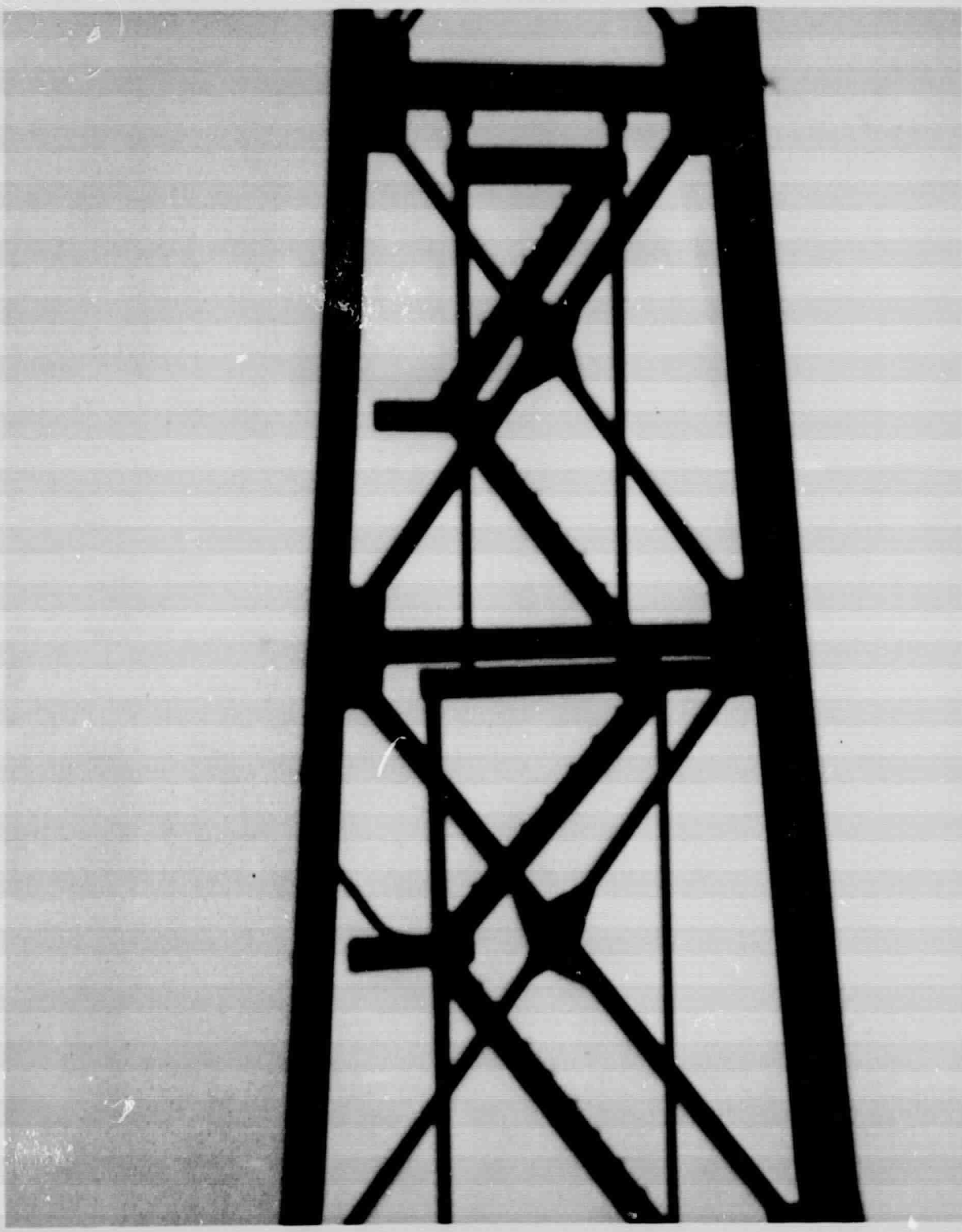

Fig. 8 (i) WITH STAIRS AND ELEVATOR RAILS. WIND APPROACH ANGLE = 90^{0}