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EVALUATION OF SHELTER VENTILATION BY MODEL TESTS- OPTION 1

GARD FINAL REPORT A1-51

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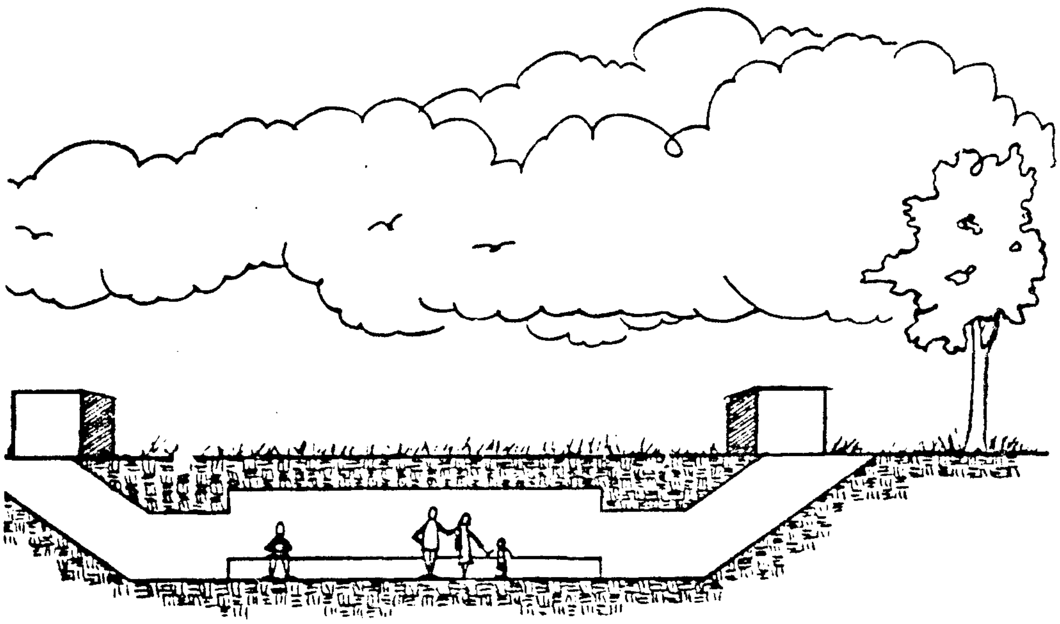

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PREPARED FOR:
FEDERAL EMERGENCY MANAGEMENT AGENCY
WASHINGTON, D.C. 20472

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FEMA WORK UNIT 1217I

MARCH 1983

PREPARED BY:

GARD, INC.
A SUBSIDIARY OF GATX
7449 NORTH NATCHEZ AVENUE
NILES, IL 60648
(312) 647-9000

84 01 26 053

GARD, INC.
DIVISION OF GATX CORPORATION
7449 North Natchez Avenue
Niles, Illinois 60648

DETACHABLE SUMMARY

EVALUATION OF SHELTER VENTILATION BY MODEL TESTS

OPTION 1 - BELOW GROUND SHELTERS

GARD FINAL REPORT A1-51

September, 1983

FEMA Work Unit 1217I

by

C. K. Krishnakumar
J. B. Koh
S. F. Fields
R. H. Henninger

for

Donald A. Bettge
FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, D.C. 20472

under Contract No. EMW-C-0633

INTRODUCTION

This study represents the second year's effort under a multi-year Shelter Ventilation Analysis Program. Its objectives were the following:

- o to estimate wind-induced ventilation flow rates (cfm) that could be achieved in a 100-man, below-ground blast shelter (Figure 1) using innovatively designed passive flow enhancement devices (FEDs) at the entrance and exit openings.
- o to prescribe guidelines for placement of the FEDs relative to the entrance and exit openings for optimum performance.
- o to evaluate the influence of FED design variables such as width and height on FED effectiveness.
- o to estimate the reduction of ventilation throughput due to an upstream flow obstruction such as a small building and to suggest guidelines for locating shelters sufficiently downstream of such obstacles.
- o to assess the ventilation throughput for a shelter with only two openings (one on each of two opposing walls) and to compare it with that for a shelter with four openings (one on each of all four walls).

The objectives stated above were achieved by performing scale model tests in a low-speed wind tunnel. A geometrically similar scale model of the blast shelter, fabricated to a length scale of 1:36 (model: full scale), was used in these tests (Figures 2a and 2b). Ventilation air flow rates through the model were determined for 4 different designs of FEDs (Figure 3) at various speeds and approach angles of the wind tunnel air stream. Model air volume flow rates were then translated to full-scale values using the appropriate volume rate scale.

METHOD OF TESTING

The method used for determining model air flow rates is a refinement of that used during the first year of this program. This method involves tracing the air flow with neutrally buoyant tracer bubbles and recording them at prescribed framing rates with motion photography as they pass through the wall openings. Velocities of a sufficiently large number of bubbles, normal to a wall opening are obtained by analyzing the movie films and then averaged to obtain the mean bubble flow velocity across the opening.

The new procedure involves replacing the leeward FEDs with a "tube and boxed FED" arrangement so that the air flow entering the model through the windward FEDs leaves through these tubes. Actual air volume flow rates through each tube (q_t) are then determined by measuring the axial velocities at the tube exit plane and translating them to volume flow rates using experimentally determined correlations. The axial velocities were measured with a Datametrics 800 VT hot-wire anemometer and the correlations of these readings with volume flow rates through the tube were obtained by a separate series of calibration tests. Model ventilation rates for the different approach wind conditions were then determined by multiplying values of the tube flow rates (q_t) by appropriate values of a "tube correction factor", as determined by comparative tracer bubble flow velocity measurements. (The tube correction factor is defined as the ratio of the ventilation rate with FEDs at all stairway openings to that with the "tube and boxed FED" arrangement at the leeward stairway openings.)

MODEL TESTS

The model tests consisted of four series of scale model tests in the wind tunnel, together with appropriate in-place calibration flow tests. In the first series of tests, four designs of FEDs were evaluated for their ventilation effectiveness. The most promising FED design was selected based on the results of these tests. In the second series of tests, shelter ventilation rates over the entire range of wind speeds and relative wind angles were determined for this particular design of FED. The third series of tests was run with a scale model of a rectangular shaped building as a flow obstruction at various distances upstream of a windward FED. Results of these tests were used to set guidelines to estimate the minimum clear distance required between a windward FED and an upstream obstruction to realize ventilation rates approaching those for the unobstructed flow. In the last series of tests, ventilation reductions due to a reduction in the number of wall openings and stairways from four to two were determined.

RESULTS AND CONCLUSIONS

The model tests established that ventilation of below-ground shelters can be greatly improved by appropriate utilization of FEDs. Based on the test results, guidelines were formulated for the number and area of entrance/exit openings, the geometry and size of FEDs and the placement of FEDs relative to the ground level openings. Shelter ventilation rates for the simple FED design, selected as the most promising in this study, are given in Figure 4. From these results, it appears that adequate ventilation (10 cfm per person) can be achieved in single-room, below-ground shelters over about two-thirds of the United States even at low wind speeds with properly located FEDs. The model tests further established that the ventilation effectiveness of FEDs can be seriously impaired by the presence of neighboring obstacles. Significant reductions in shelter ventilation rates are to be expected when the distance between the main windward FED and an upstream obstacle is less than six to seven hydraulic mean diameters (based on the frontal area of the obstacle facing the opening). It was also demonstrated that ventilation rates are considerably reduced (by about 40% for a relative wind angle of 15°) when the number of wall openings and stairways is reduced from four to two, the reductions being larger at larger values of the relative wind angle.

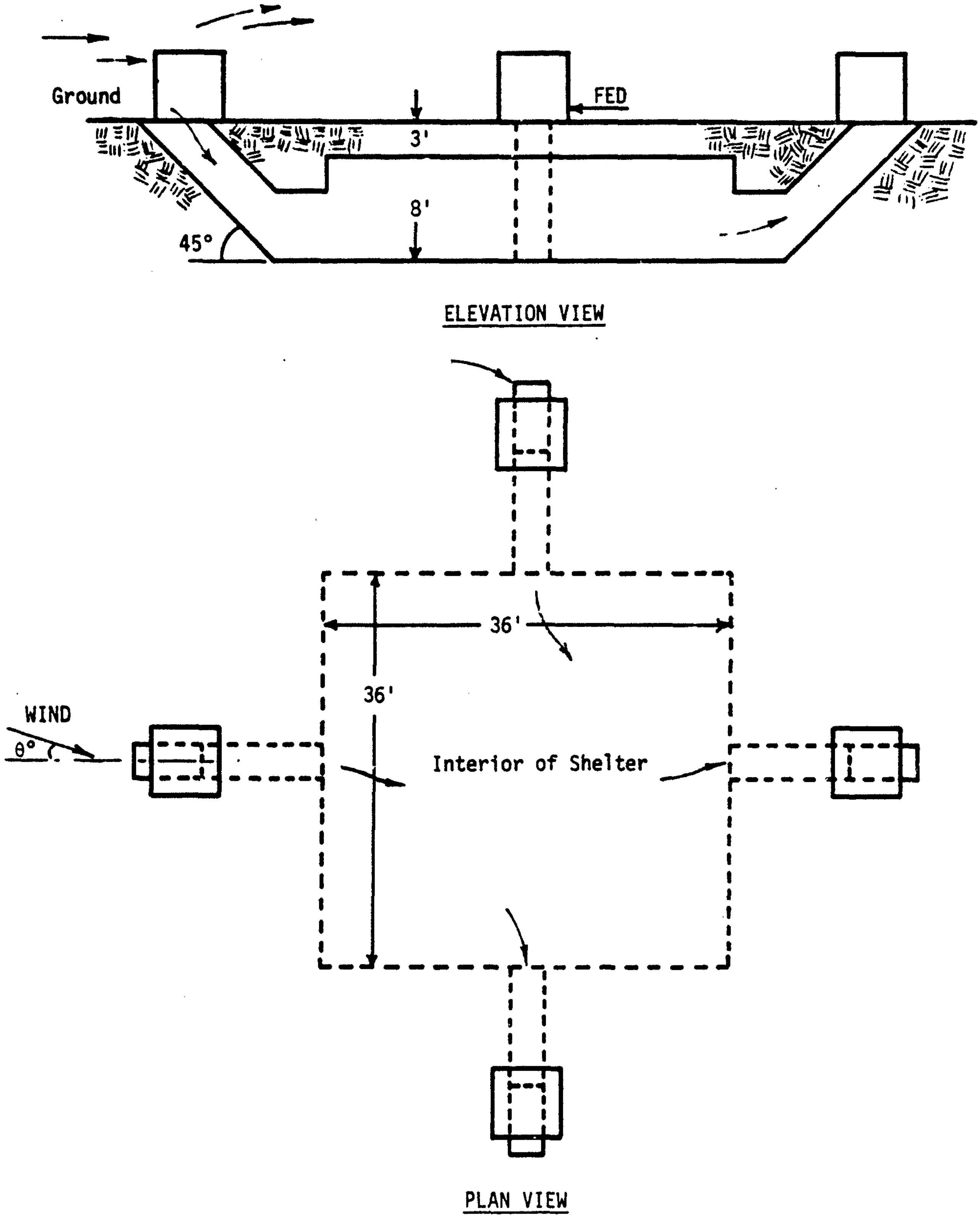

Figure 1 BELOW-GROUND SHELTER WITH FOUR FEDs

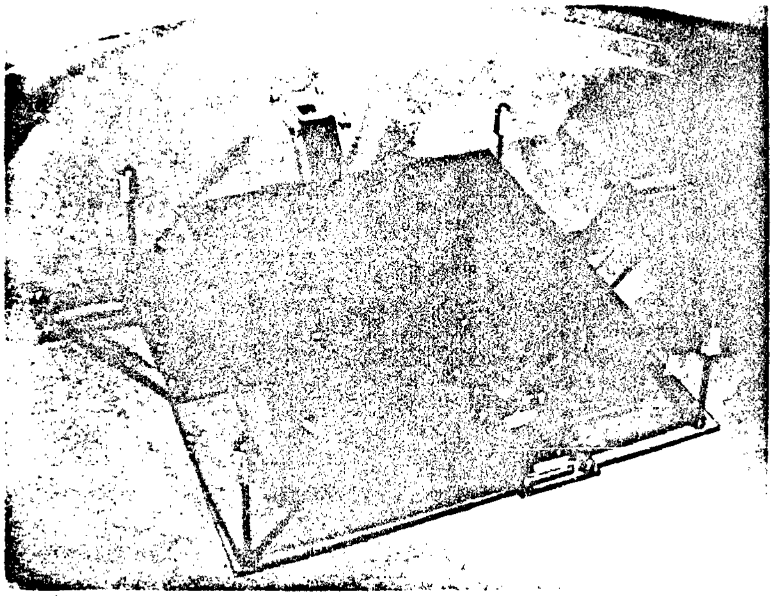

Figure 2a BELOW-GROUND SHELTER - VIEWED FROM ABOVE THE MODEL

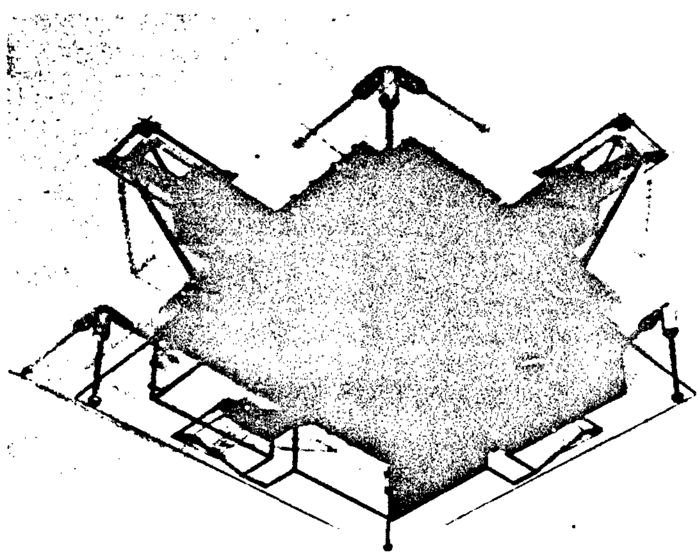

Figure 2b BELOW-GROUND SHELTER - VIEWED FROM BELOW THE MODEL

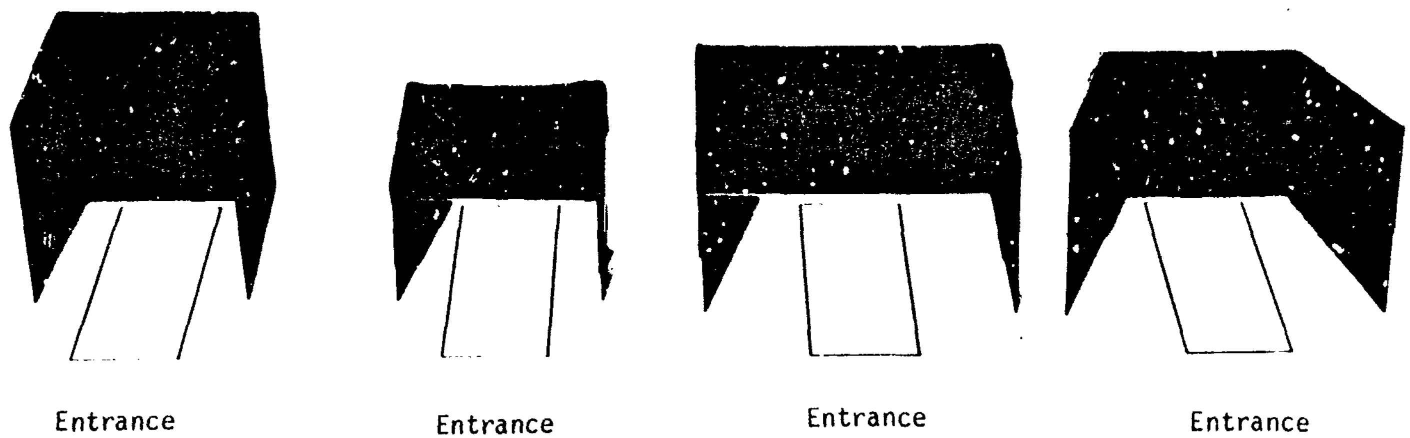

Figure 3 MODEL FEDs

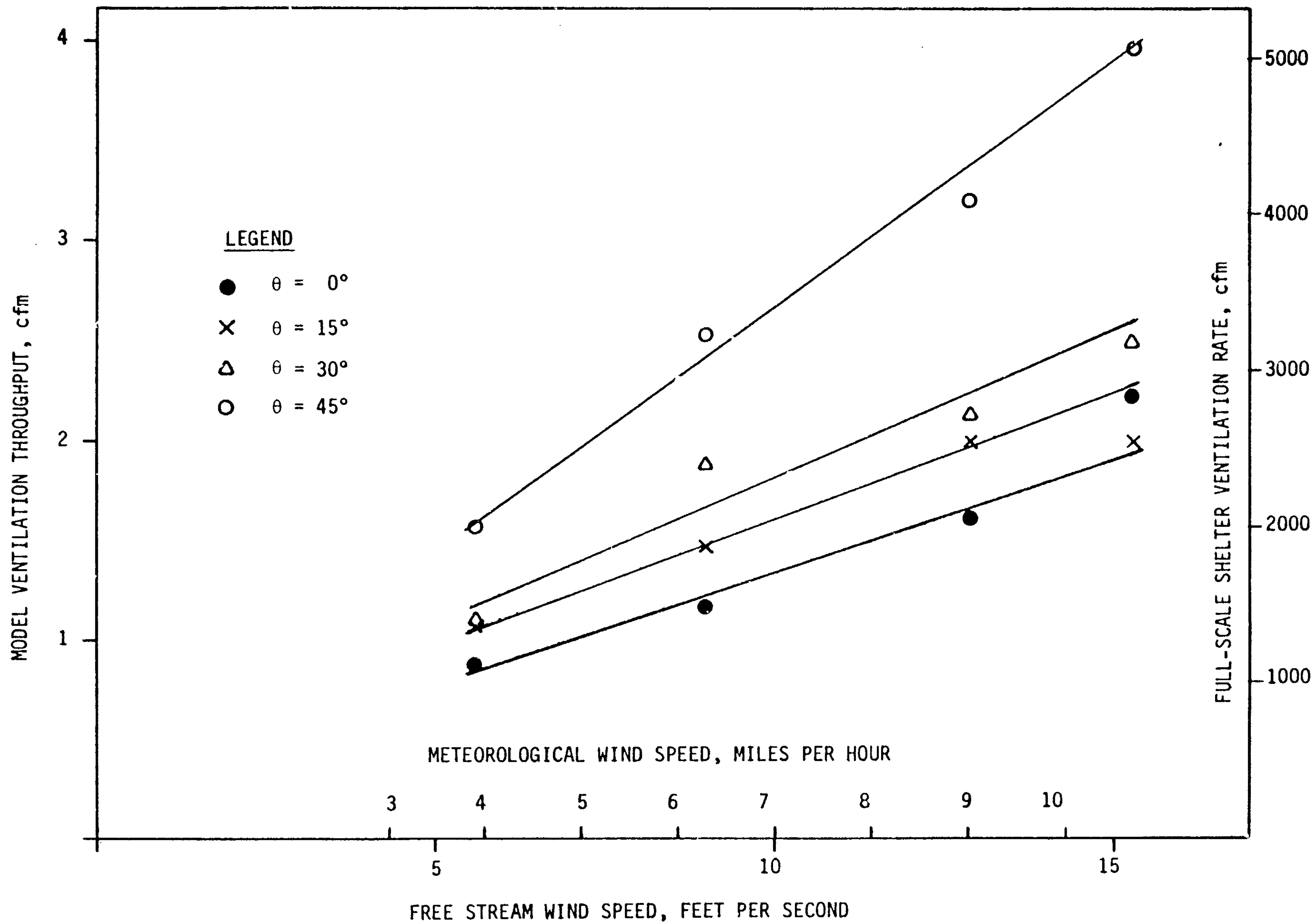

Figure 4 VENTILATION RATES FOR BELOW-GROUND SHELTER
(occupant density: 1 person per 10 square feet)

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Wind-induced ventilation rates that could be achieved in a 100-man below-ground shelter with simple designs of passive flow enhancement devices (FEDs) were estimated by scale model tests in a low-speed wind tunnel. Air volume flow rates through the model were determined by using bubble flow tracers and motion photography. Test results indicate that adequate ventilation can be achieved in the type of shelter considered by the use of FEDs even at relatively low wind speeds. The study also generated guidelines for the design of FEDs and their placement around stairway openings. In addition, —

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) estimates of reductions in ventilation rates due to an obstruction upstream of the windward FED and due to a decrease in the area of wall openings were made.

GARD, INC.
SUBSIDIARY OF GATX CORPORATION
7449 North Natchez Avenue
Niles, Illinois 60648

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PREFACE

GARD, INC. the research and development division of GATX, has prepared this report for the Federal Emergency Management Agency (FEMA). Mr. Donald Bettge of FEMA served as Project Officer during the entire program.

This report details the work done during the second year of a multi-year Shelter Ventilation Analysis Program. It describes the results of the experimental studies that were conducted to estimate the potential of wind-induced ventilation to ventilate a below-ground, blast shelter. Several simple designs of passive flow enhancement devices (FEDs) were concepted and their ventilation effectiveness evaluated. Decrease in ventilation rates due to reductions in area of wall openings and due to the presence of an obstruction upstream of the windward FED were also determined.

Individuals at GARD who participated in this program include:

R. H. Henninger - Project Engineer
Dr. S. F. Fields - Experimental Modeling
Dr. C. K. Krishnakumar - Experimental Modeling
J. B. Koh - Data Reduction

GARD wishes to thank Mr. Bettge and FEMA for the opportunity to have undertaken this study.

Respectfully submitted,

R. H. Henninger
R. H. Henninger, P.E.
Project Engineer

Approved by:

P. A. Saigh
P. A. Saigh, P.E.
Director, Government Programs

ABSTRACT

Wind-induced ventilation rates that could be achieved in a 100-man below-ground shelter with simple designs of passive flow enhancement devices (FEDs) were estimated by scale model tests in a low-speed wind tunnel. Air volume flow rates through the model were determined by using bubble flow tracers and motion photography. Test results indicate that adequate ventilation can be achieved in the type of shelter considered by the use of FEDs even at relatively low wind speeds. The study also generated guidelines for the design of FEDs and their placement around stairway openings. In addition, estimates of reductions in ventilation rates due to an obstruction upstream of the windward FED and due to a decrease in the area of wall openings were made.

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Section 1

INTRODUCTION

1.1 Background

In September of 1981, FEMA awarded a multi-year contract to GARD to carry out a Shelter Ventilation Analysis Program using scale model tests in a low-speed wind tunnel. The goal of this multi-year program is to analyze wind-induced ventilation in both below-ground and above-ground shelters under different wind conditions, to suggest guidelines for shelter design and to recommend expedient methods of enhancing ventilation throughput in those shelters. This report describes the study performed during the second year (Option 1) of this program.

During the first year of this program, the baseline wind-induced ventilation characteristics (air volume flow rate and distribution) for a single-room, upgraded, above-ground shelter were studied and established. Some preliminary tests were also conducted to evaluate the effectiveness of Flow Enhancement Devices (FEDs) placed near the entrance and exit openings of below-ground blast shelters in improving wind-induced ventilation. These tests strongly suggested the possibility of achieving acceptable levels of ventilation in below-ground shelters even at moderate wind speeds with properly designed FEDs. Results of the first year's work under the program have been published in the form of a project report (Ref. 1).

The second year of the program (Option 1) has been focused upon quantitatively estimating the ventilation enhancement associated with the application of several designs of FEDs to a below-ground blast shelter. Also as part of this study, a limited number of tests were conducted to estimate the influence of a neighboring upstream flow obstruction (namely, a small building) on the ventilation throughput of the shelter.

1.2 Objectives

The objectives of the second year study were the following:

- to estimate wind-induced ventilation flow rates (cfm) that could be achieved in a 100-man, below-ground blast shelter using flow enhancement devices (FEDs) at the entrance and exit openings.
- to set guidelines for placement of the FEDs relative to the entrance and exit openings for optimum performance.
- to evaluate the influence of FED design variables such as width and height on FED effectiveness.
- to estimate the reduction of ventilation throughput due to an upstream flow obstruction such as a small building and to suggest guidelines for locating shelters sufficiently downstream of such obstacles.
- to assess the ventilation throughput for a shelter with only two openings (one on each of two opposing walls) and to compare it with that for a shelter with four openings (one on each of all four walls).

1.3 Literature Review

During the last two decades several experimental studies (Ref. 2-5) were performed on full-scale, below-ground shelters to investigate their ventilation requirements. These studies indicated that adequate ventilation to control the thermal environment in below-ground shelters cannot be obtained from natural forces (wind and thermal effects) alone. Whitehill, et al. (Ref. 6) investigated the use of induced draft as a means of ventilating family-sized, below-ground shelters. In this study, a kerosene lantern was mounted at the base of an air exhaust stack and served as a light source and as a heat source to induce air flow through the shelter. The study concluded that ventilation rates of up to 3 cfm per occupant could be provided by this technique. Many studies relating to the design and performance of forced ventilating equipment for below-ground shelters have also been made in the past 15 to 20 years. These are briefly discussed in a recent FEMA study (Ref. 7).

In a series of wind tunnel model tests, Mattingly et al. (Ref. 8) investigated the role of bushes and trees in modifying the pressure distribution around residential buildings. They observed that the pressure distributions on both the windward and the leeward sides could be substantially altered by proper planting of the trees. White (Ref. 9) analyzed the influence of shrubs, hedges and trees on the flow field around single family homes using wind tunnel scale model studies. Comparisons of model results with full-scale data were also made in some cases.

Wind tunnel investigations were also made by Lee et al. (Ref. 10) to estimate wind pressure forces on a low-rise building which was part of a group of similar buildings. The influence of the building geometry, the spacing parameters which describe the array, the approach surface conditions and the wind direction on the pressure forces were analyzed. The study developed a graphical prediction method to estimate the surface pressure forces acting on a building which is situated within an array of similar low-rise buildings.

In summary, it may be concluded from available literature that (i) adequate ventilation to control the thermal environment in below-ground shelters cannot be obtained from natural ventilation alone and (ii) air flow patterns and pressure distributions at a given location can be strongly influenced by neighboring obstacles such as trees, buildings, etc. No previous data is available on the ventilation enhancement capabilities of passive devices such as the FEDs analyzed in the present work.

1.4 Approach Technique

The objectives stated in Section 1.2 were achieved by performing scale model tests in a low-speed wind tunnel.* A geometrically similar scale model of the blast shelter which was fabricated to a length scale of 1:36 (model: full scale) in the previous study was used in these tests. Ventilation air flow rates through the model were determined for 4 different designs of FEDs at various speeds and approach angles of the wind tunnel air stream. Model air volume flow rates were then translated to full-scale values using the appropriate volume rate scale. In order to determine the model air volume flow rates, a method similar to that used in GARD's previous study (Ref. 1) was used. Details of this method, which involve flow tracing and motion photography, are given in Section 2.2. From the results of these tests, the most promising FED design was selected and for that particular

* A description of the wind tunnel and a discussion of scaling considerations are given in GARD's previous study (Ref. 1).

design, the influence of its placement relative to the edges of the stairway openings was evaluated. Tests were also run with a scale model of a rectangular shaped building as a flow obstruction at various distances upstream of the main windward FED. Results of these tests were used to set guidelines to estimate the minimum clear distance required between a windward FED and an upstream obstruction so that ventilation rates approaching those for the unobstructed flow can be realized.

Section 2

MODEL TESTS

This task consisted of four series of scale model tests in the wind tunnel together with appropriate in-place calibration flow tests. These tests determined the wind-induced air volume flow rates through the model for a variety of approach wind conditions (free stream conditions in the wind tunnel) and for different values of FED design variables. The technique and procedure used in the tests and a description of the shelter model follow.

2.1 Shelter Geometry and Model Fabrication

The below-ground shelter model was the same as that used in the preliminary investigations conducted during the first year of the program. Figure 2.1 shows a schematic of the shelter with full scale dimensions. The shelter is intended for use by approximately 100 occupants. It has four stairways sloping at 45° to the ground surface which lead to centrally located door openings on each side wall. The roof of the full-scale shelter is three feet below the surface of the ground.

Figures 2.2 and 2.3 show photographs of the model. The model is fabricated to a length scale of 1:36 (model:full scale) from 3/16-inch thick, clear Plexiglas sheets. One of the side walls together with its stairway is detachable. This provides access to the interior of the model and facilitates placement of simulated occupants. The bottom surfaces of the ceilings of the shelter and its stairways are painted black for photographic recording of the tracer bubbles. During testing the model is suspended from a clear Plexiglas turn-table by four long bolts with countersunk heads at the top.

Figures 2.4 and 2.5 show the different designs of FEDs which were analyzed for their effectiveness (contribution to shelter ventilation). Each of these designs has three side walls and a roof with the fourth side open. (See Figure 2.6 for a typical layout of an FED around a stairway opening.)

Designs 1, 2 and 3 have the same length of side walls. Design 2 is shorter than the other two (full-scale height of ~ 4 feet compared to 6 feet

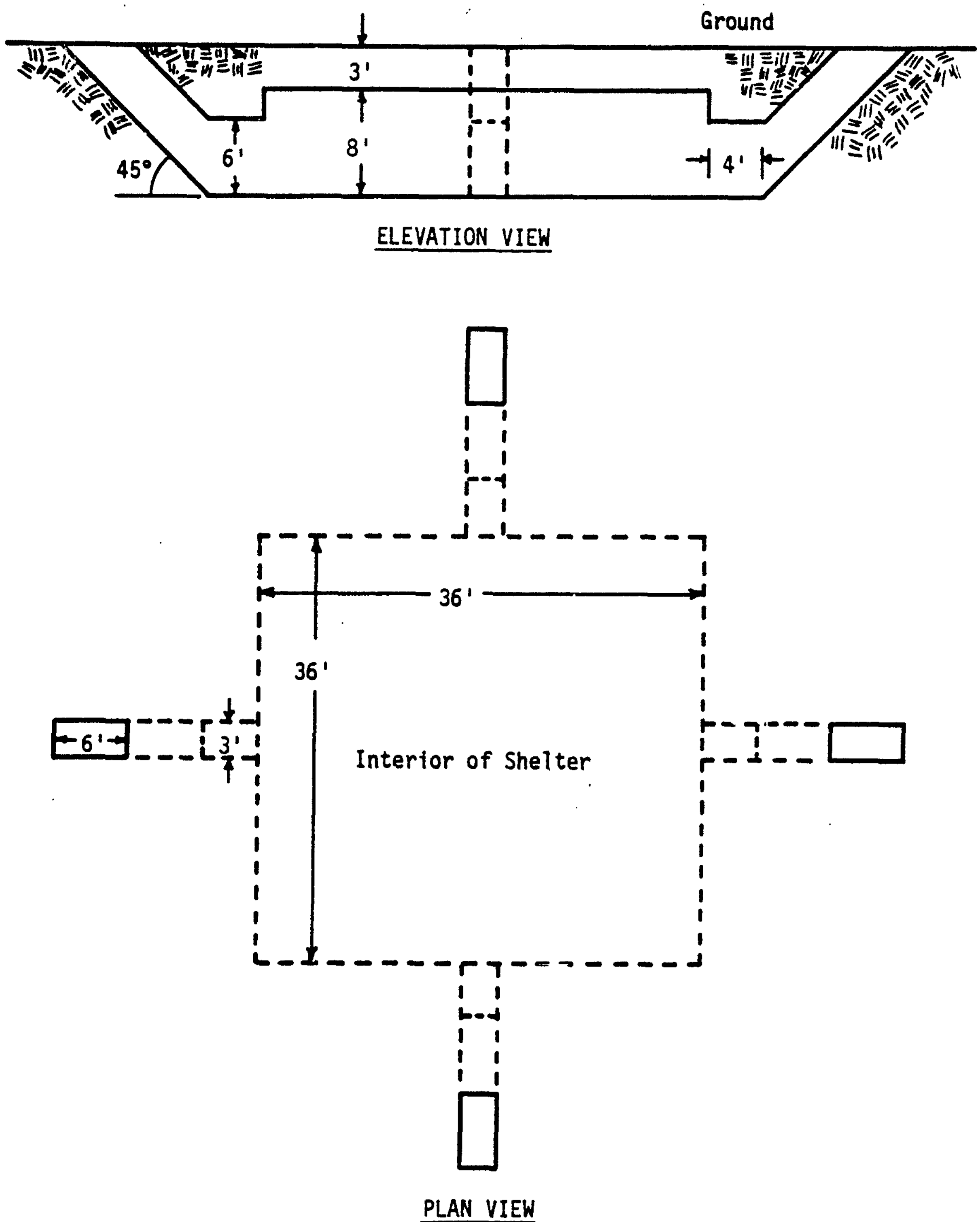


Figure 2.1 SCHEMATIC OF BELOW-GROUND SHELTER

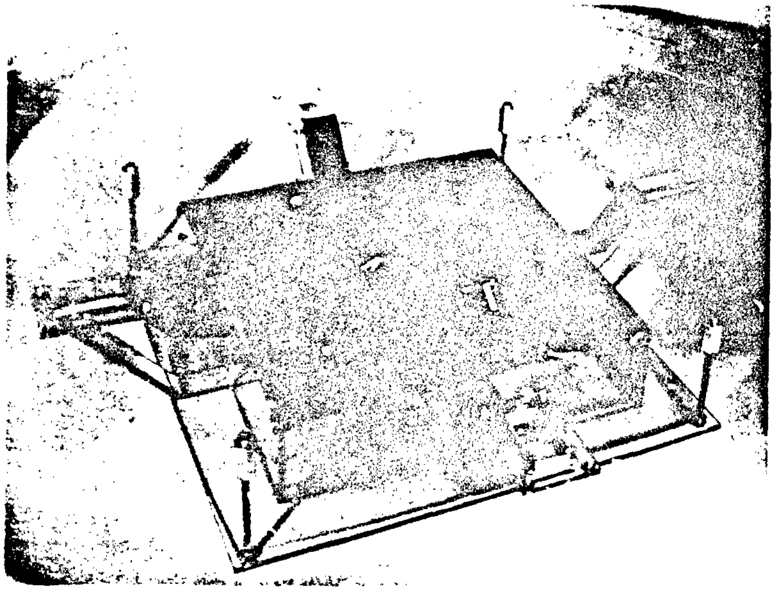


Figure 2.2 BELOWGROUND SHELTER - VIEWED FROM ABOVE THE MODEL

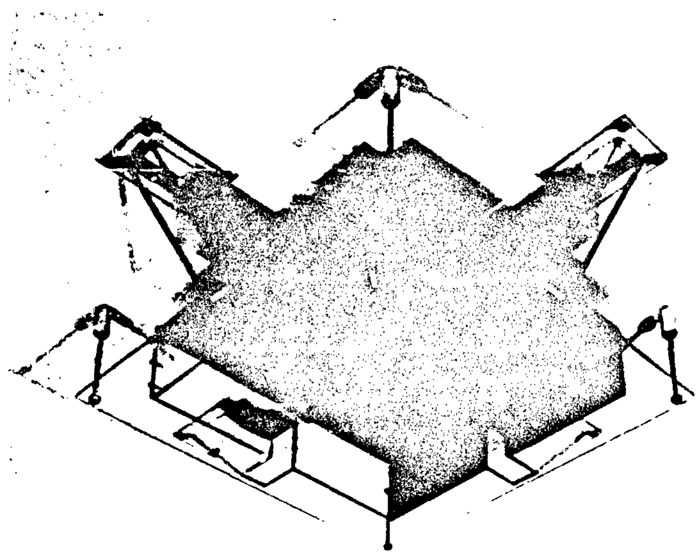


Figure 2.3 BELOWGROUND SHELTER - VIEWED FROM BELOW THE MODEL

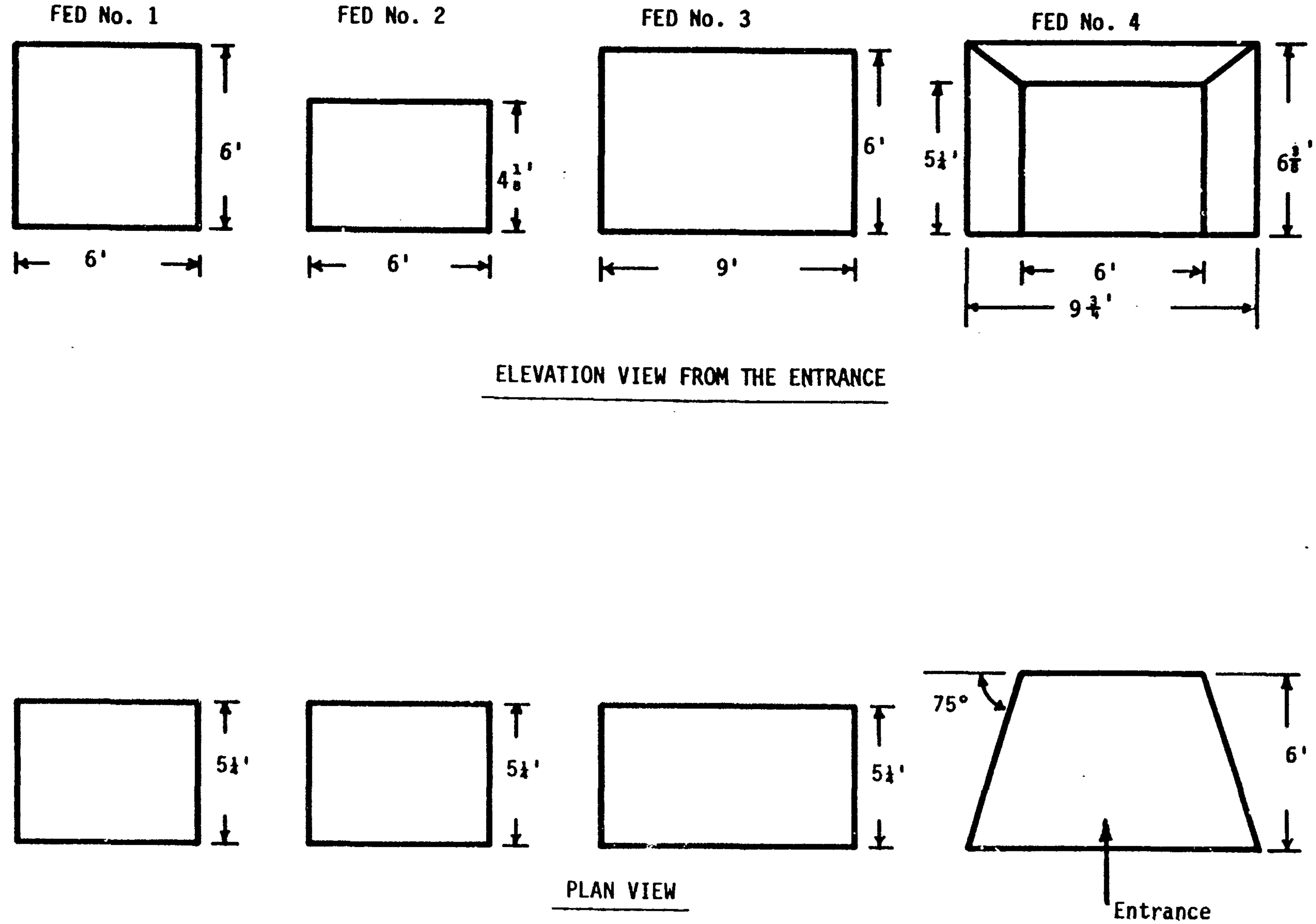


Figure 2.4 FLOW ENHANCEMENT DEVICES FOR BELOW-GROUND SHELTER

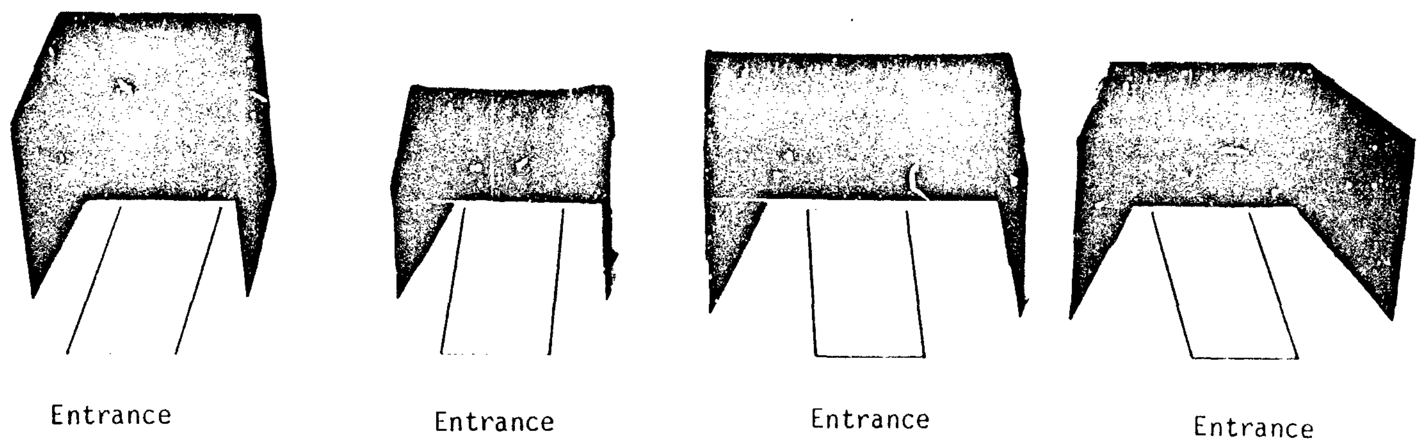
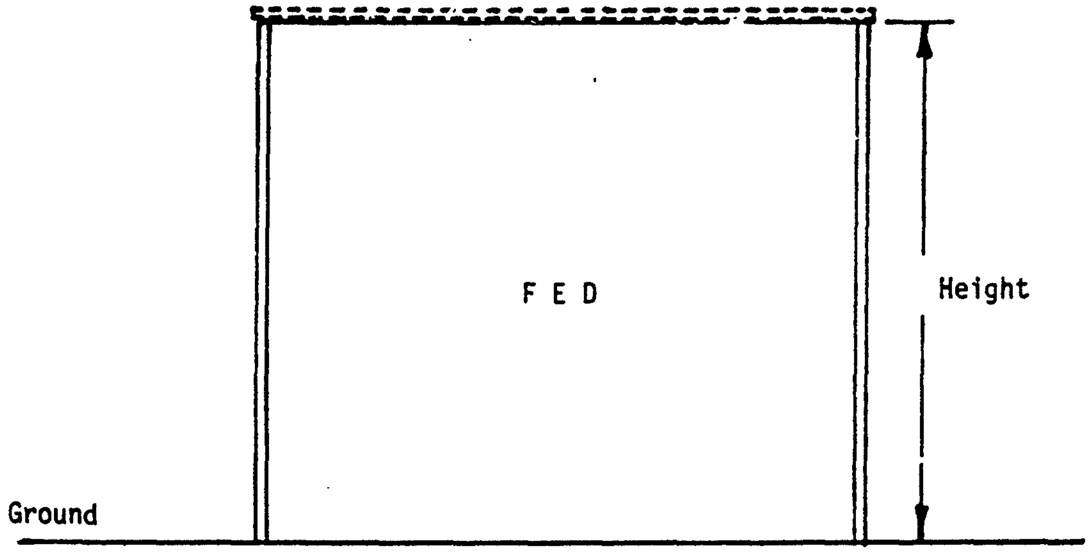
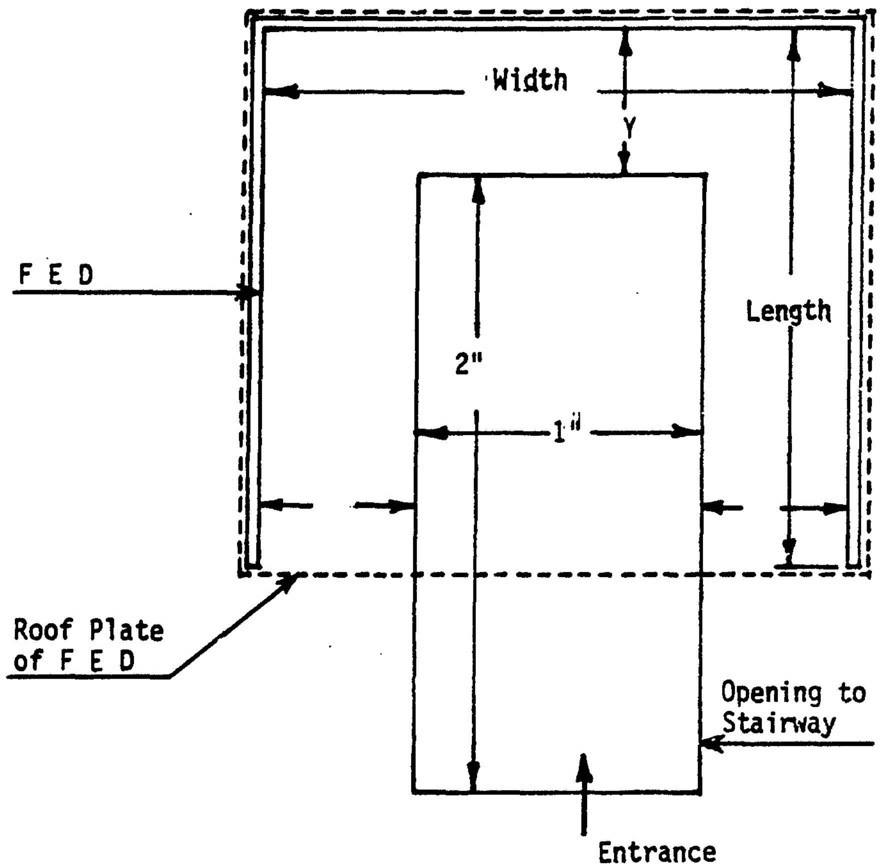


Figure 2.5 MODEL FEDs



ELEVATION VIEW



PLAN VIEW

Figure 2.6 TYPICAL FED LAYOUT AROUND A STAIRWAY OPENING for designs 1 and 3). Design 3 which spans three feet (full-scale dimension) on either side of the stairway openings is wider than designs 1 and 2 which span only 18 inches on either side of the openings. Design 4 has side walls and roof sloping at 15° as shown in Figure 2.6. Four FEDs of each design were fabricated from 1/16-inch thick sheet metal.

2.2 Method of Testing

The desired free stream air speeds in the tunnel are set by adjusting an A.C. frequency controller which regulates the rotational speed of the blower. By controlling the air flow through a counterjet manifold system located near the entrance section of the wind tunnel, a power-law velocity distribution having an exponent of 1/3 is obtained in the boundary layer of the approach wind. This corresponds to the velocity distribution on the earth's surface in city suburbs (Ref. 11). The boundary layer thickness in the wind tunnel for this distribution is approximately 12 inches. Desired values of the approach wind angle relative to the axes on the shelter model are set by suitably rotating the turn-table. (Figure 2.7 shows a typical setting of the turn-table.)

The method used for determining model air volume flow rates is a refinement of that described in Ref. 1. This method involves tracing the air flow with neutrally buoyant tracer bubbles and recording them at prescribed framing rates with motion photography as they pass through the wall openings. Velocities (V_B) of a sufficiently large number of bubbles (25 to 30), normal to a wall opening are obtained by analyzing the movie films and then averaged to obtain the mean bubble flow velocity across the opening. In the previous study, the average bubble velocity thus obtained was multiplied by the area of the opening and an experimentally determined "area coefficient" to obtain the air volume flow rate. In the present study, this procedure was replaced by the more accurate one described below.

The new procedure involves replacing the leeward FEDs with the "tube and boxed FED" arrangement shown in Figure 2.8, so that the air flow entering the model through the windward FEDs leaves through these tubes. Actual air volume flow rates through each tube (q_t) are then determined by measuring the axial velocities at the tube exit plane and translating them to volume flow rates using empirical correlations. The axial velocities are measured with a Datametrics 800 VT hot-wire anemometer using the setup

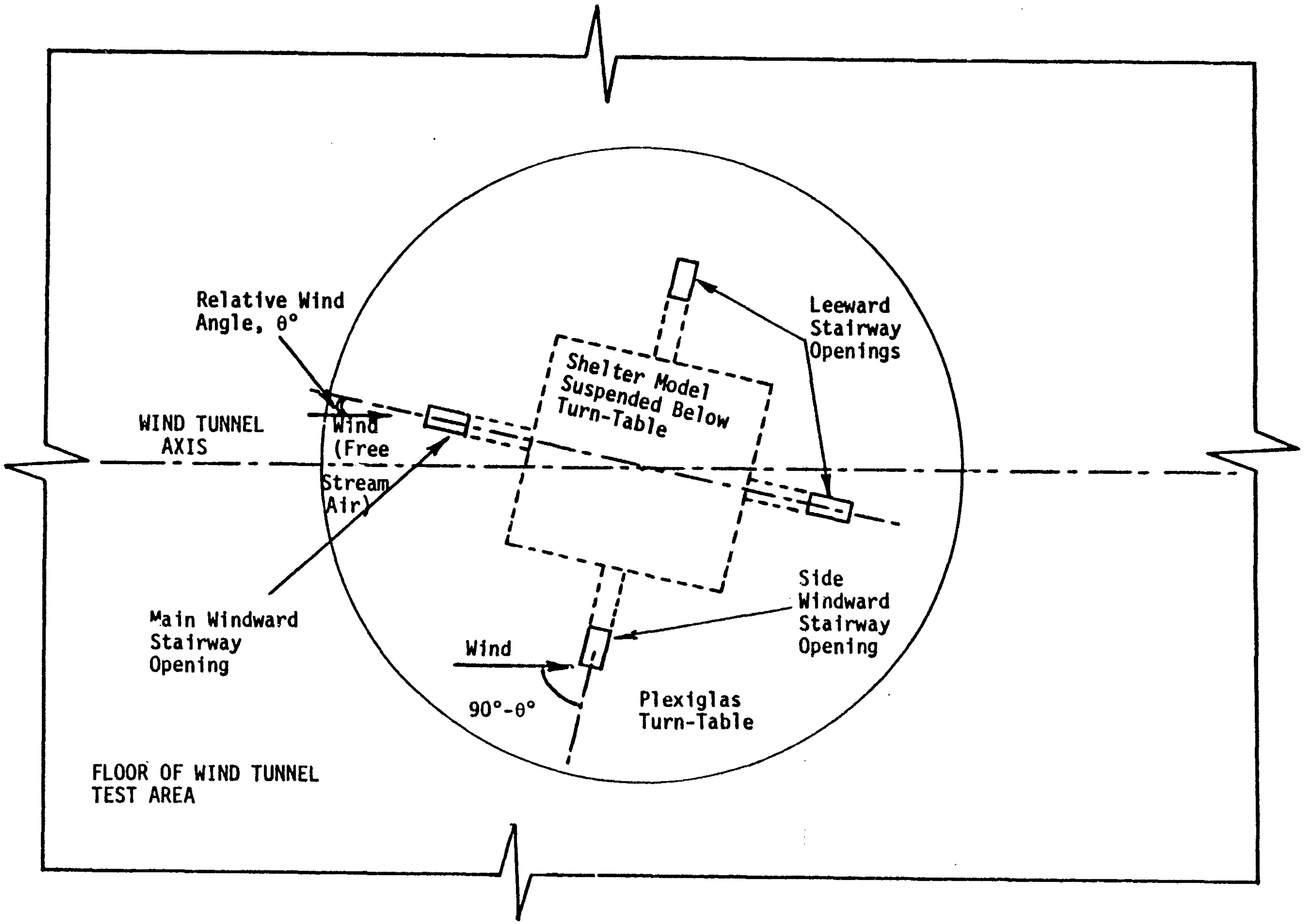


Figure 2.7 A TYPICAL TURN-TABLE SETTING

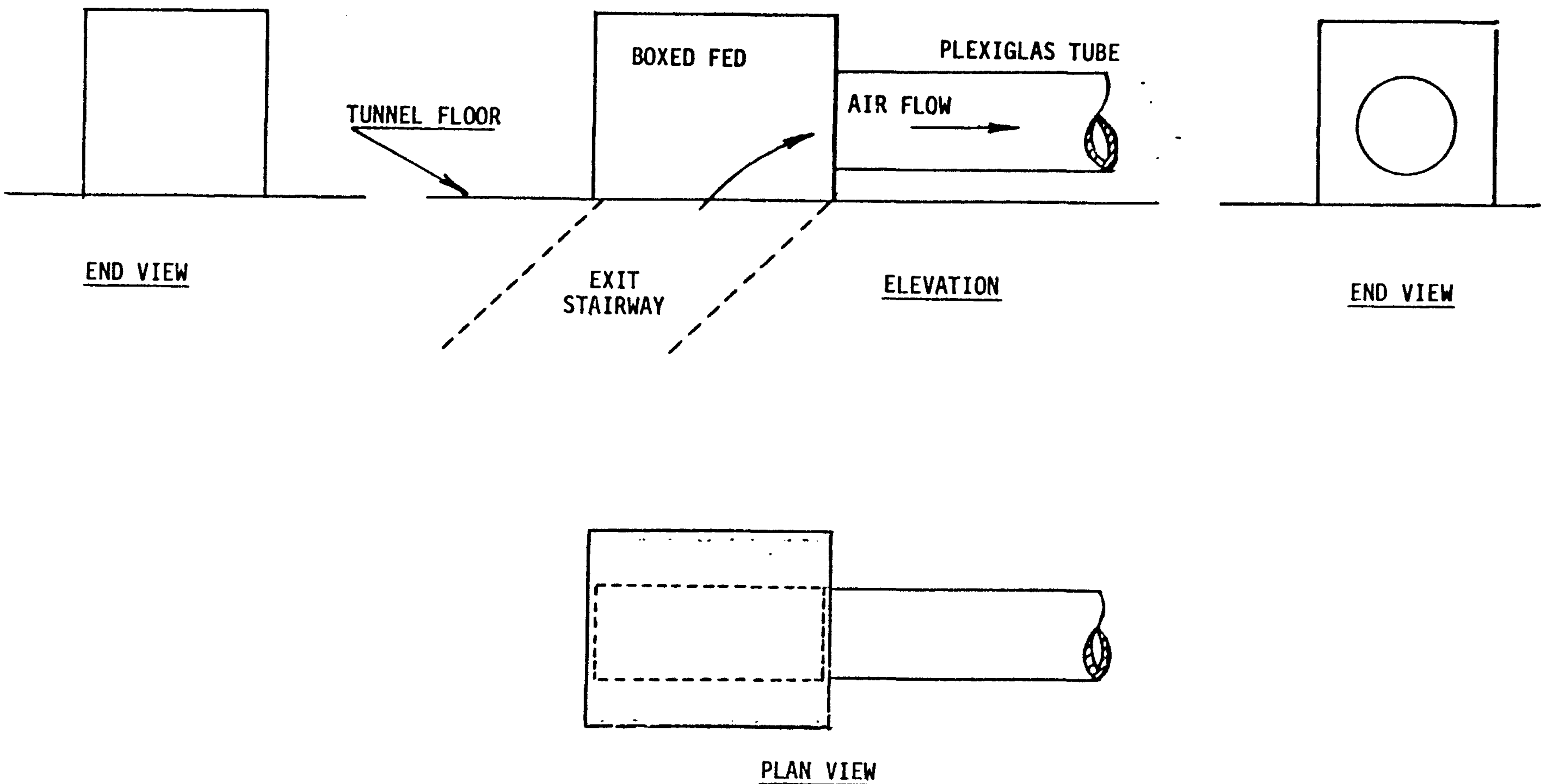


Figure 2.8 TUBE AND BOXED FED ARRANGEMENT

shown in Figure 2.9 and the correlations of these readings with volume flow rates through the tube are obtained by a separate series of calibration tests described in Appendix A.

Model ventilation rates for the different approach wind conditions are determined by multiplying values of the tube flow rates (q_t) by appropriate values of a "tube correction factor". The tube correction factor is defined as the ratio of the ventilation rate with FEDs at all stairway openings to that with the "tube and boxed FED" arrangement at the leeward stairway openings. To obtain values of the tube correction factor, tracer bubble flows are filmed again with the "tube and boxed FED" arrangement at the leeward openings and the corresponding values of average bubble flow velocities (V_b) through the windward wall openings determined. For a given wind condition, the ratio of the mean bubble flow velocity (V_B) through the main windward FED obtained with FEDs at all stairway openings to that obtained with the "tube and boxed FED" arrangement at the leeward openings is taken as the value of the tube correction factor.*

The equation for calculating the model ventilation rate can, therefore, be written as

$$\text{Model Ventilation Rate} = (q_{t,1} + q_{t,2}) * (V_B/V_b) \tag{1}$$

where $q_{t,1}$ and $q_{t,2}$ are the volume flow rates through the two leeward Plexiglass tubes, determined as functions of the anemometer reading from the calibration tests (Appendix A).

The steps involved in determining the model ventilation rate for a particular wind condition can be summarized as follows.

(i) With FEDs at the windward stairway openings and the "tube and boxed FED" arrangement at the leeward openings, measure the axial velocities at the exit planes of each of the tubes using the Datametrics hot-wire anemometer.

*This calculation assumes that the ratio of the bubble flow velocities (V_B/V_b) for each of the windward openings is the same. This may not be strictly true at relative wind angles other than 45°, the differences becoming more significant at smaller values of θ. However, for those wind conditions, the larger part of the ventilation air enters the model through the main windward FED and wall openings. Therefore, the error in the value of the model ventilation rate incurred by assuming the tube correction factor to be equal to the ratio (V_B/V_b) for the main windward wall opening will be insignificant.

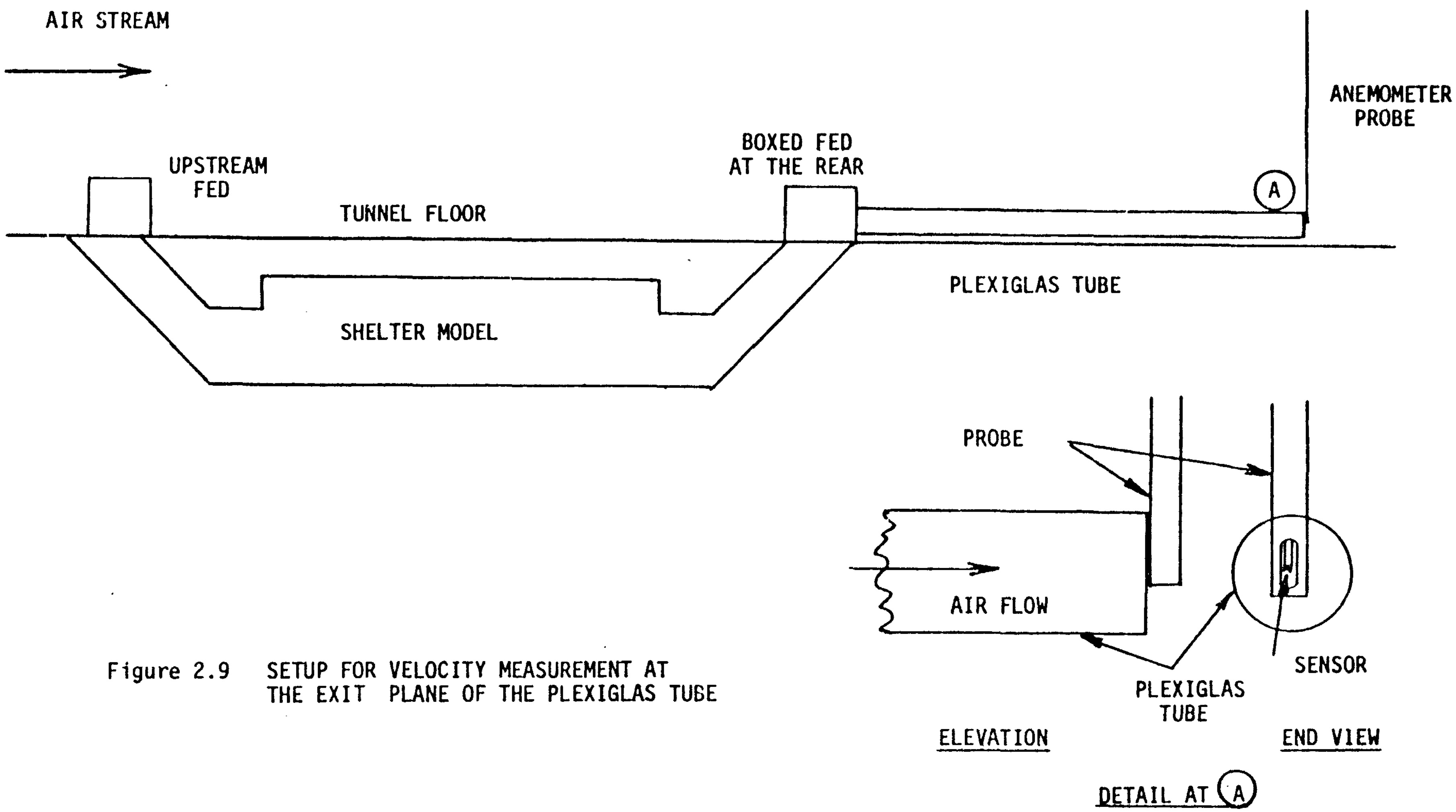


Figure 2.9 SETUP FOR VELOCITY MEASUREMENT AT THE EXIT PLANE OF THE PLEXIGLAS TUBE

(ii) From the anemometer readings and the results of the calibration tests explained in Appendix A, calculate the air volume flow rates $q_{t,1}$ and $q_{t,2}$ through the tubes.

(iii) With the "tube and boxed FED" arrangement at the leeward stairway openings, photographically record tracer bubble flow through the main windward wall opening and determine the mean bubble flow velocity V_b.

(iv) Replace the "tube and boxed FED" arrangement at the leeward stairway openings with FEDs; record tracer bubble flow and determine the mean bubble flow velocity V_B through the main windward wall opening.

(v) Calculate model ventilation rate using Equation 1 .

2.3 Test Series 1: Design Guidelines for FEDs

The objectives of this series of tests were to evaluate the influence of FED design variables on their effectiveness and to set guidelines for their design. These objectives were achieved by determining the contributions of the four FED designs described in Section 2.1 to the ventilation rate of the model sheter. (A typical model setup with FEDs at all four stairway openings is shown in Figure 2.10. Figure 2.11 is a photograph of the FED arrangement and a typical flow pattern around them.) The ventilation rates of the model shelter for the different free stream conditions were determined by following the steps laid out in the previous section. With each set of FEDs, tests were conducted over a free stream wind speed range of 5 fps to 15 fps at relative wind angles of 15° and 45°. In all the tests, FEDs were placed such that they spanned the same distance "X" on either side of the stairway opening (see Figure 2.6). The clearance "Y" was set at one-quarter of an inch (full scale: 9") for all the tests. (Preliminary tests from the first year study showed that the value of "Y" should be less than about one-half inch (full scale: 18") for maximum values of the ventilation rate.)

2.4 Results of Test Series 1

Table 2.1 gives results of these tests. Designs 1 and 4 show comparable

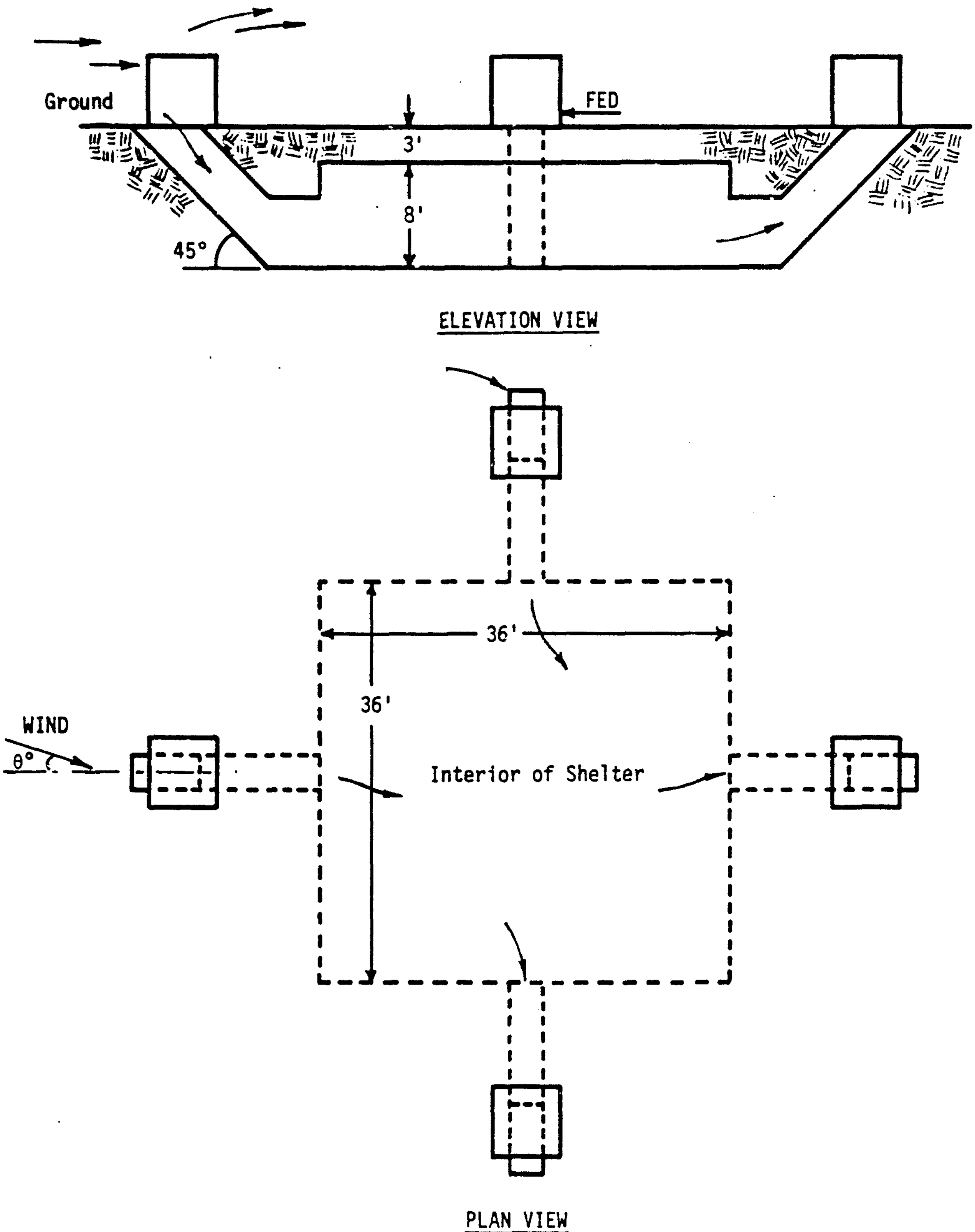


Figure 2.10 BELOW-GROUND SHELTER WITH FOUR FEDs

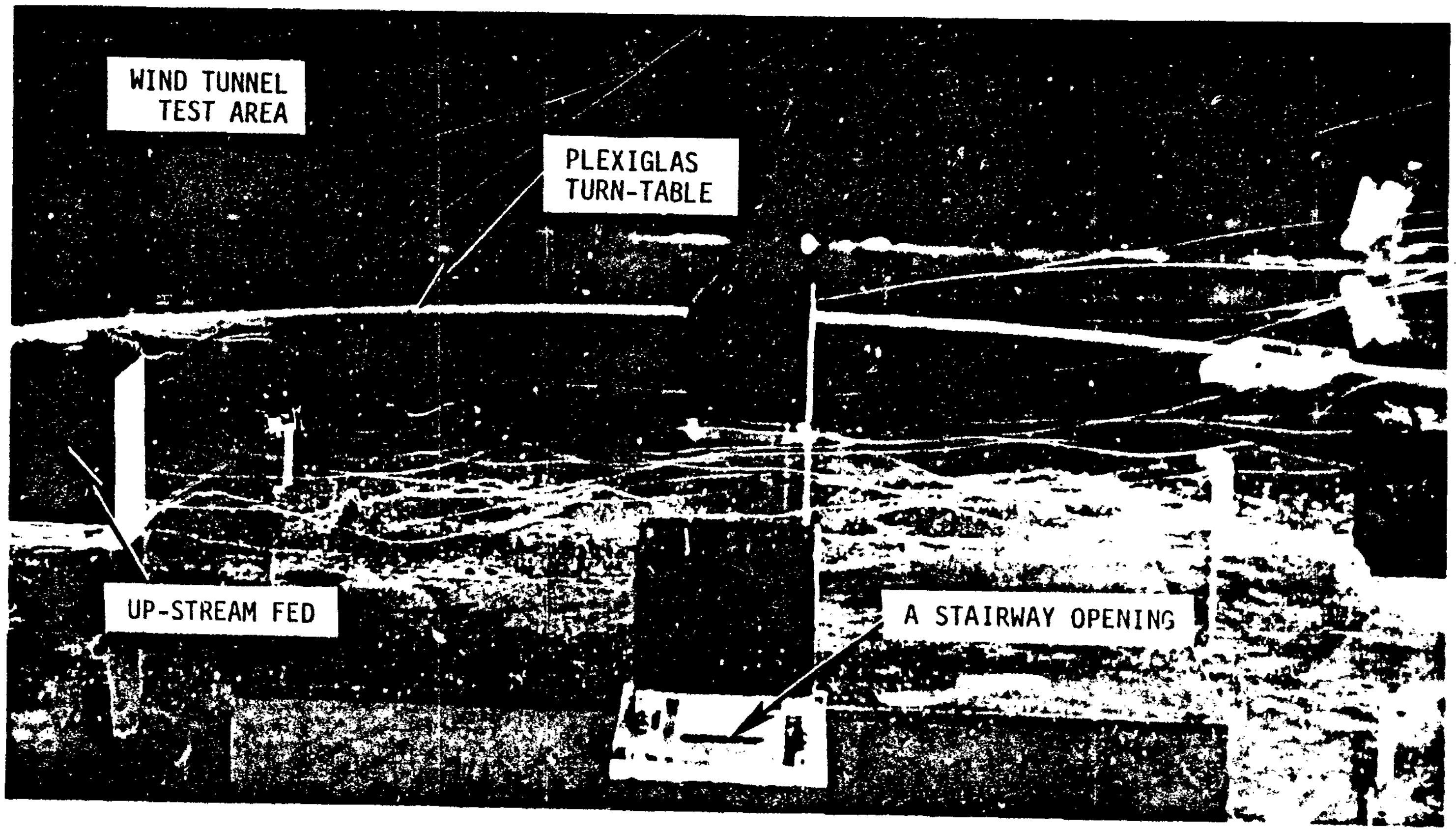


Figure 2.11 STREAM LINES PAST AN ARRANGEMENT OF FOUR FEDS
(Flow is from left to right)

Table 2.1 COMPARATIVE PERFORMANCE OF FED DESIGNS

Relative Wind Angle θ°	FED Design #	Normalized mean bubble flow velocity for main windward wall opening at free stream wind speeds of			
		5.5 fps	9.0 fps	12.9 fps	15.0 fps
15°	1	1.00	1.00	1.00	1.00
	2	0.84	0.87	0.91	-
	3	0.89	0.93	0.90	-
	4	0.99	1.00	1.02	1.00
45°	1	1.00	1.00	1.00	1.00
	4	1.18	1.18	1.12	1.12

performance whereas designs 2 and 3 are significantly less effective (see results for $\theta=15°$). At the lower wind speeds, design 2 is approximately 15% less effective due to its shorter height. Design 3 which has the same height as design 1, is tco wide for its side walls to create the most effective pressure zones at the stairway openings. Air volume flow rates with this design are about 10% less than for design 1 or 4 at low wind speeds. It can be concluded that, increasing the FED span much more than that of the stairway opening does not augment the ventilation throughput; it may even lead to a reduction in ventilation flow. On the other hand, increasing the height of the FED from about 4 feet to 6 feet (full-scale dimensions) increases the ventilation throughput significantly (by about 15%). FEDs less than 6 feet wide were not tested since these are not expected to be effective especially at larger values of the relative wind angle. Design 4, although it performed only as effectively as design 1 at a relative wind angle of 15°, was expected to perform better than all other designs including design 1, at larger values of the relative wind angle. This was substantiated by the results for the relative wind angle of 45°. However, considering the complexity of putting together expedient FEDs conforming to design 4 and the fact that the overall performance of design 1 is quite comparable to that of design 4, the simplier configuration of design 1 was chosen for use in all subsequent tests.

2.5 Test Series 2: Performance of FED Design 1

The object of this series of tests was to determine the ventilation throughput values with FED design 1 over the entire range of relative wind angles and wind speeds of interest. Since the model is symmetric with respect to both the longitudinal and lateral axes of the shelter, the relative wind angle was varied only in the range of 0° to 45°. Wind speeds (free stream speeds in the tunnel) were varied from 5.5 feet per second to 15 feet per second. Model ventilation flow rates were determined by first measuring the air flow rates through the leeward Plexiglas tubes with the Datametrics anemometer and then multiplying them by the tube correction factor as explained previously.

Table 2.2 shows the results of these tests. Also shown in the same table are model ventilation throughput values when the shelter was occupied

Table 2.2 VENTILATION AUGMENTATION BY FED DESIGN 1

Relative Wind Angle θ°	Test Series	Model cfm at free stream wind speeds of			
		5.5 fps	9.0 fps	12.9 fps	15.0 fps
0°	A	0.97	1.41	1.87	2.58
	B	1.12	1.62	2.15	2.97
	C	0.87	1.17	1.61	2.23
15°	A	0.87	1.36	1.79	2.15
	B	1.18	1.83	2.41	2.91
	C	1.06	1.47	2.01	2.02
30°	A	0.94	1.60	2.02	2.43
	B	1.12	1.91	2.40	2.89
	C	1.10	1.89	2.14	2.49
45°	A	1.02	1.71	2.40	2.83
	B	1.58	2.65	3.72	4.39
	C	1.56	2.53	3.21	3.95

Test Series A: Volume flow rate through leeward tubes $q_{t,1} + q_{t,2}$

Test Series B: Model ventilation rate, $[(q_{t,1}+q_{t,2}) \times V_B/V_b]$

Test Series C: Model ventilation rate when occupied at 1 person per 10 sq.ft.

at a density of 1 person per 10 square foot. To obtain these values, tests were run with simulated occupants inside the model (1-inch high, 3/8-inch diameter cylindrical blocks were used to simulate occupants in a sitting posture), and mean bubble flow velocities through the main inlet opening at the various wind velocities were determined. Ratios of model ventilation throughput values with occupants, to those without occupants, were obtained by taking the corresponding ratios of the mean bubble flow velocities through the main windward wall opening. Table 2.3 shows values of this ratio for the different free stream conditions. Model ventilation throughput values obtained without the occupants were then decremented by the corresponding values of this ratio to obtain ventilation rates with the occupants.

2.6 Results of Test Series 2

Figure 2.12 shows the graphical correlation of model ventilation throughput (occupant density: 1 person per 10 square feet) with approach wind speed. Projected values of ventilation throughput to the full-scale shelter are also shown in this figure. These values were obtained by scaling up the model throughput values by the volume rate scale (1:1296 model to full scale). Wind speeds indicated in the figure correspond to those at an altitude of 10 meters above the ground. (Metereological wind speeds are normally recorded at this altitude.)

Several important observations can be made from Figure 2.12.

- By providing FEDs at each stairway opening, ventilation rates of 10 CFM per person can be obtained in the below-ground shelter tested at all values of the relative wind angle even at relatively low wind speeds (less than 5 MPH).
- The lowest values of ventilation throughput are obtained for a head-on wind (θ=0°). At this orientation, only the upstream stairway acts as an inlet and the other three act as outlets. The area ratio of inlet to outlet openings is the smallest for this case. Consequently, the ventilation throughput values are also the lowest. For values of the relative wind angle not equal to zero, the distribution between inlet and outlet opening areas is more uniform and the ventilation

Table 2.3 VENTILATION REDUCTION DUE TO OCCUPANTS

Relative Wind Angle θ°	Ratio of model cfm with occupants to that without occupants at free stream wind speeds of			
	5.5 fps	9.0 fps	12.9 fps	15.0 fps
0°	0.78	0.73	0.75	0.75
15°	0.91	0.80	0.83	0.69
30°	0.98	0.99	0.89	0.86
45°	0.99	0.95	0.86	0.90

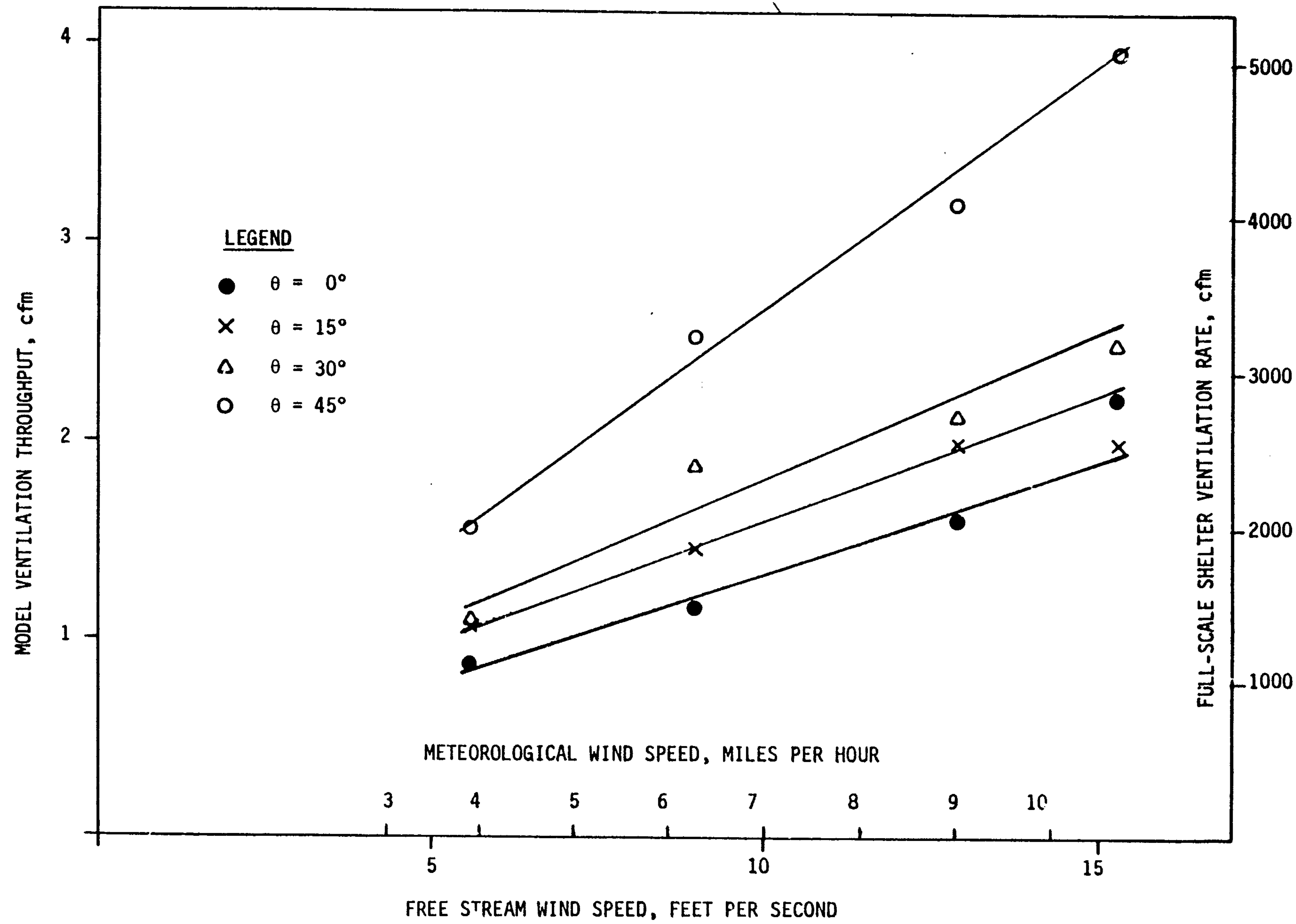


Figure 2.12 VENTILATION RATES FOR BELOW-GROUND SHELTER
(occupant density: 1 person per 10 square feet)

throughput values are correspondingly higher. At θ equal to 15°, there is very little net flow through the side windward stairway which has a relative wind angle of 75° (90°-θ). At θ equal to 30°, there is a definite, but small, net inflow through the side windward stairway that has a relative wind angle of 60° (90°-θ). Still the major part of the inflow is through the main windward stairway opening. At θ equal to 45°, equal distribution of inlet and outlet opening areas exists and the ventilation flow rates have their largest values.

- The relation between ventilation throughput and wind speed is basically linear at all values of relative wind angle.

- Reductions in ventilation throughput due to occupants vary from about 7% to 25%, with the larger reductions taking place at head-on or near head-on winds (Table 2.3).

2.7 Test Series 3: Effect of an Upstream Flow Obstruction

Tests under this series were performed with the object of determining guidelines for locating FEDs downstream of an obstacle so that the reductions in wind-induced shelter ventilation due to the obstacle become insignificant. In these tests, a scale model of a rectangular, single-story building (full-scale dimensions: 36 feet long x 24 feet wide x 13.5 feet high) was used as the obstacle with the 24 feet x 13.5 feet wall facing the shelter. The characteristic length dimension D_H of the obstacle was taken as its hydraulic mean diameter (which is equal to four times the face area divided by the perimeter). The obstacle model was placed a distance of 2 D_H upstream of the main windward FED. For this location of the obstacle, the ventilation throughput for the shelter model was determined for different free stream wind speeds. This was done by measuring the air flow through tubes attached to the leeward FEDs with the Datametrics anemometer and then correcting the measurements for the tube effects as explained earlier. The obstacle model was then moved further upstream to a distance of 6.25 D_H from the FED and the tests repeated. Tests were done for relative wind angles of 0° and 15° for each location of the obstacle.

2.8 Results of Test Series 3

Figure 2.13 and Table 2.4 show the reductions in ventilation throughput due to the upstream building model for the different free stream velocities. At the larger distance of 6.25 D_H (full-scale distance of approximately 110 feet) for the obstacle upstream of the FED, the airflow reductions due to it are small. They range from 5% to 15%. At the shorter distance of 2 D_H (full-scale distance of 36 feet), flow reductions are severe. They range from 30% to 40% of the ventilation rates without the obstacle. It is also clear that reductions in ventilation rates at θ equal to 15° are smaller than those for a head-on wind.

2.9 Test Series 4 - Ventilation Throughput with Two FEDs

Tests described in the previous sections established the wind-induced ventilation flow rates obtainable in the shelter with four symmetrically placed FEDs. Because of the symmetrical placement of FEDs with respect to the longitudinal and lateral axes of the shelter, reasonably good ventilation is realized at all values of the relative wind angle. The object of the present series of tests was to estimate the ventilation flow reductions at various wind speeds and angles when only two stairways were provided, one on each of two opposite walls.

In these tests, the same blast shelter model was used with the openings on two of the side walls sealed. Model ventilation throughput values were determined by measuring the air flow rates through the "boxed FED and tube" arrangement at the leeward opening with the Datametrics anemometer and then multiplying them with appropriate values of the tube correction factor as explained earlier. Tests were performed at relative wind angles of 0° and 15° for free stream wind speeds ranging from 5.5 fps to 15 fps.

2.10 Results of Test Series 4

Table 2.5 shows the results of these tests. For the head-on wind, the ventilation rates with two FEDs are approximately 70% of those with four FEDs (reductions of 30%). At θ equal to 15°, the ventilation rates average about 57% of those with four FEDs (reductions of 43%). It may be noted that, when four FEDs (and stairways) are provided, the contribution of the openings on

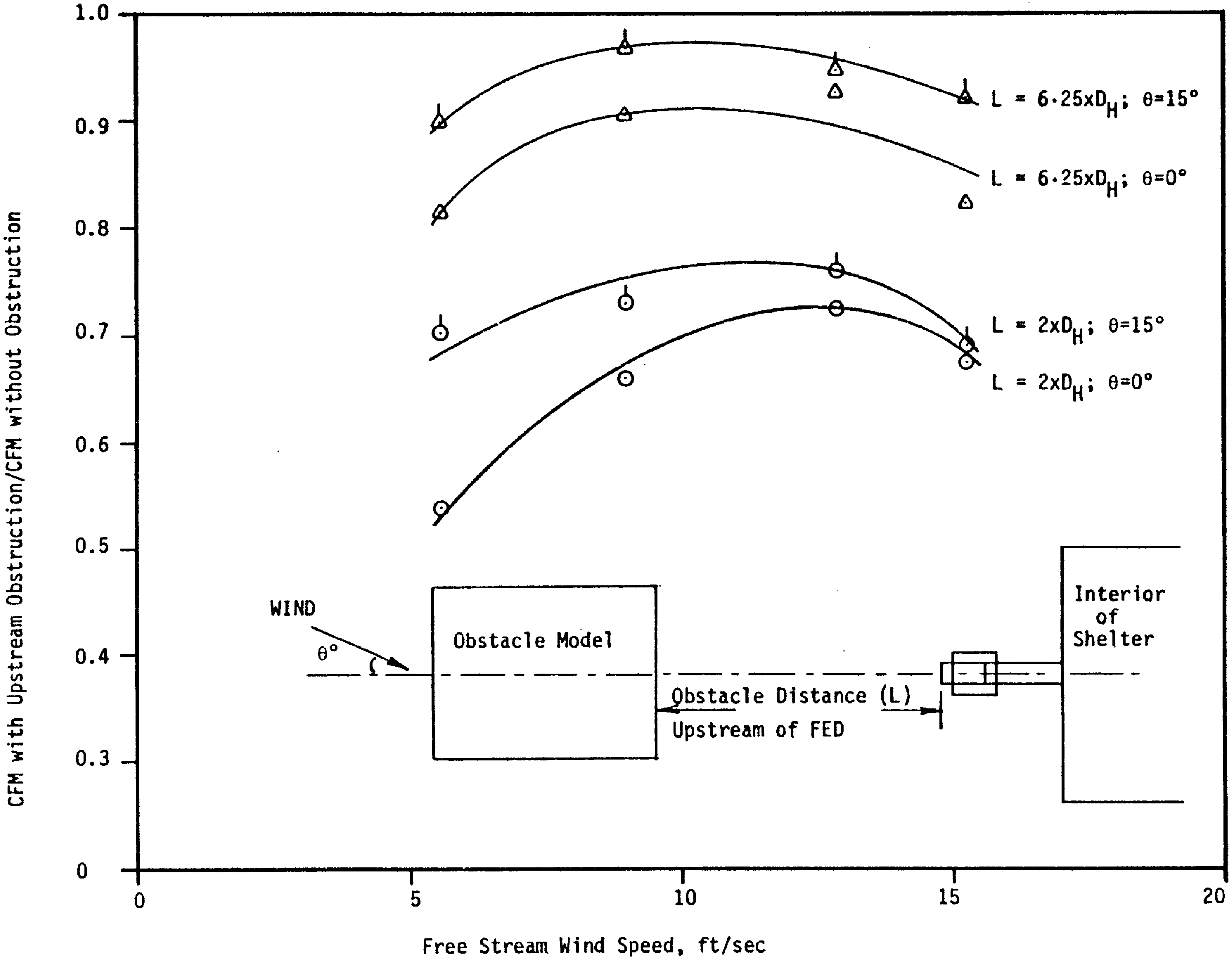


Figure 2.13 EFFECTS OF UPSTREAM OBSTRUCTION ON VENTILATION THROUGHPUT

Table 2.4 VENTILATION REDUCTIONS DUE TO AN UPSTREAM BUILDING

Relative Wind Angle θ°	Distance of Building Upstream of FED	Ratio of model cfm with obstruction to that without obstruction at free stream wind speeds of			
		5.5 fps	9.0 fps	12.9 fps	15.0 fps
0°	$2.0 \times D_H$	0.54	0.66	0.72	0.67
	$6.25 \times D_H$	0.82	0.91	0.93	0.82
15°	$2.0 \times D_H$	0.70	0.73	0.76	0.69
	$6.25 \times D_H$	0.90	0.97	0.95	0.92

Table 2.5 VENTILATION THROUGHPUT WITH TWO FEDS VS FOUR FEDS

Relative Wind Angle θ°	Ratio of model cfm with two FEDs to that with four FEDs at free stream wind speeds of			
	5.5 fps	9.0 fps	12.9 fps	15.0 fps
0°	0.70	0.70	0.72	0.63
15°	0.55	0.58	0.56	0.57

the side walls to the shelter ventilation rate is minimal at θ equal to $0°$. As θ is increased from $0°$ to $45°$, the fraction of the air flow entering and leaving through the side openings steadily increases and that passing through the main windward and leeward openings decreases. It is, therefore to be expected that the ratio of ventilation rate with two FEDs to that with four FEDs would steadily decrease as θ increases from $0°$ to $45°$.

Section 3

CONCLUSIONS AND RECOMMENDATIONS

The model tests have established that ventilation of below-ground shelters can be greatly improved by appropriate utilization of FEDs. Design 1 was found to be particularly impressive. It has a simple design and is effective at all values of the relative wind angle. The model tests also established that the ventilation effectiveness of FEDs can be seriously impaired by the presence of neighboring obstacles. Significant reductions in shelter ventilation rates should be expected when the distance between the main windward FED and an upstream obstacle is less than six to seven hydraulic mean diameters.

The following detailed observations and recommendations can be made on the basis of the test results and are suggested as guidelines to be used when designing for natural ventilation of key worker blast shelters:

1. Flow Enhancement Devices (FEDs)

   Below-ground key worker blast shelters with entrances/exits at grade level require the use of flow enhancement devices (FEDs) in order to achieve acceptable ventilation rates with natural wind forces. Proper application of FEDs at entrances/exits to capture the wind can create ventilation rates of 10 cfm/person even at low wind speeds, i.e., less than 5 mph.

2. Quantity and Location of Entrances/Exits

   For maximum ventilation effectiveness, a below-ground key worker blast shelter should have four (4) entrances/exits, one along each exterior wall connecting the occupied shelter area to the grade level opening. Entrances/exits should be symmetrically located with respect to the longitudinal and lateral axes of the shelter (Figure 2.10) to improve uniformity of air distribution inside the shelter.

3. Entrance/Exit Area

The total entrance and exit opening area strongly influences the ventilation effectiveness of a key worker shelter. It is recommended that a minimum total opening area of 6% of the shelter floor area be provided on the exterior walls.

4. Neighboring Flow Obstructions

When a key worker shelter is to be built in the vicinity of above-ground structures, a minimum distance of 6-7 hydraulic mean diameters must be provided between each of the grade level entrance/exit openings and the structure nearest it. The mean hydraulic diameter is four times the structure's frontal area facing the opening divided by the perimeter of the frontal area.

5. Size and Placement of FEDs

FEDs should be employed around each grade level entrance/exit opening and have the following characteristics:

a) The FEDs should be rectangular in shape with three side walls and a roof (Figure 2.5).
b) They should have a minimum height of six feet above grade level.
c) They should be placed around the perimeter (two sides and rear) of the grade level opening with each FED facing outward in a different direction (see Figure 2.10).
d) The side walls of the FEDs should extend forward to approximately 2/3 the length of the opening.
e) The width of an FED should be approximately two times that of the stairway opening and the FED should be placed symmetrically with respect to the longitudinal axis of the opening. The rear wall should be positioned not farther than about 12 inches to 18 inches from the back edge of the opening.

6. Construction of FEDs

The sidewalls and roof of the FEDs should be constructed (assembled) using solid materials that can withstand moderate wind gusts. Materials suitable for sidewall construction include sand bags, stones, bricks, cement blocks, wood, plastic film reinforced with bracing, etc. For roofs, plywood sheets, door panels, plastic films reinforced with bracing, etc., may be used. An array of sand bags may be placed over the roof to prevent it from being blown off by wind forces.

It is generally believed that wind-induced ventilation is not adequate to control the thermal environment in below-ground shelters (Ref. 7). This is true when flow enhancement devices are not used at the stairway openings. This observation is supported by past full-scale tests (Ref. 7) and by the present wind tunnel studies. However, the present study also shows that substantially higher wind-induced ventilation rates can be generated in below-ground shelters by the use of FEDs. Reference 12 (Figure 13 of Chapter 12) shows that a ventilation rate of 10 cfm/person will be sufficient to maintain an effective temperature of 82°F with 90% adequacy over about two-thirds of the United States. The present study indicates that ventilation rates of this magnitude can be achieved in single-room, below-ground shelters even at low wind speeds (less than 5 MPH) with properly located FEDs. Further, it is noted that the ventilation throughput increases linearly with wind speed at all values of the relative wind angle. It follows that locations in the country requiring ventilation rates larger than 10 cfm per person (Ref. 12) may still be adequately ventilated with FEDs if stronger winds prevail in those areas.

For a given wind condition, ventilation rates that can be achieved with FEDs in a below-ground shelter depend on the total area and distribution of the wall openings and possibly on the configurations of the stairway passages. A proper combination of these variables may eliminate or significantly reduce the forced ventilation requirements of even large multi-purpose, below-ground buildings. With these structures, the larger flexibility with respect to design variables should facilitate even more efficient FED designs.*

*With blast shelters, the design and construction of FEDs should be such as to facilitate assembly by the occupants in a relative short time, using only readily available materials. Only FED designs conforming to these guidelines were considered in the present study.

However, the influence of internal partitions on the ventilation throughput and more importantly on the air distribution in these buildings will have to be analyzed by additional tests. Practical ways of improving air distribution in these complex shaped buildings should also be investigated.

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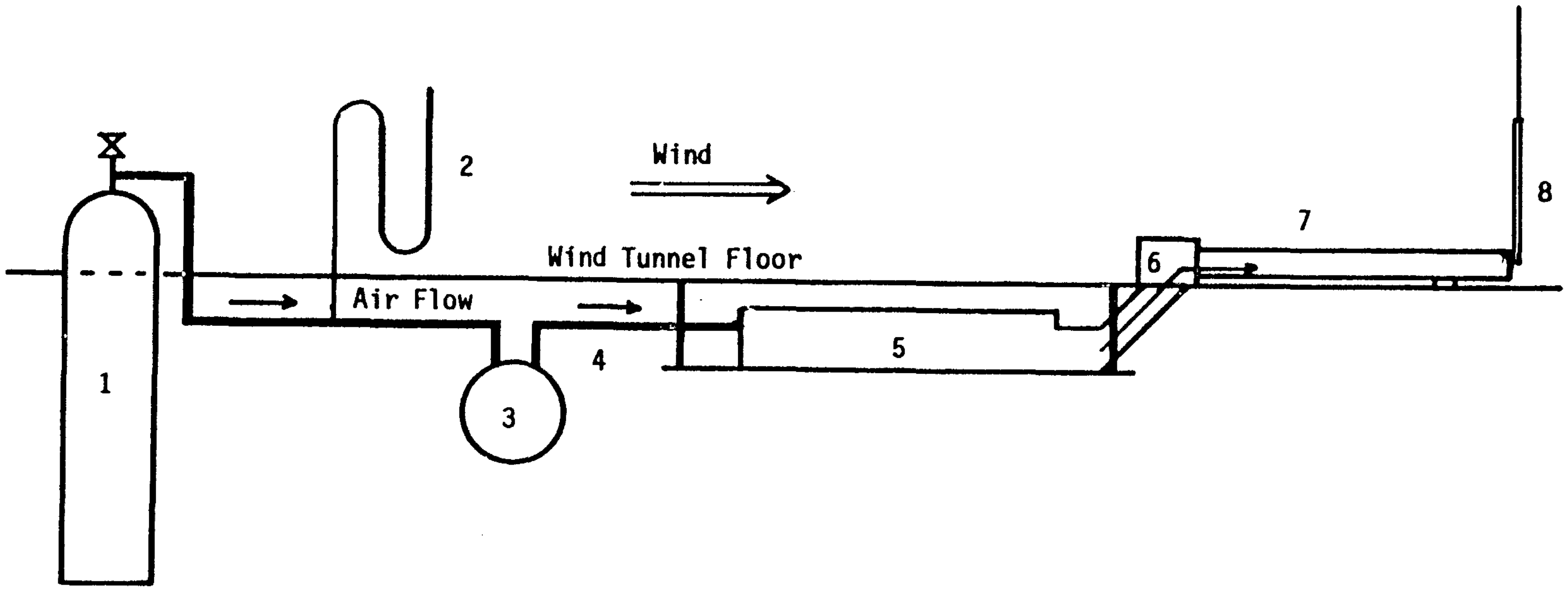
APPENDIX A

CALIBRATION FLOW TESTS

These tests were made to establish the correlation between the actual air volume flow rates through the model and the axial velocity measurements of the Datametrics hot-wire anemometer located at the exit planes of the one-inch diameter Plexiglas outlet tubes. (Figure A.1 shows a schematic of the calibration test setup.) A "boxed FED" with a one-inch diameter Plexiglas tube leading out of it was placed at one end of a leeward stairway opening. The remaining three stairway openings were sealed tight. The bottom edges of the "boxed FED" were taped to the turn-table to prevent air leakage. The anemometer probe was positioned at the exit plane of the Plexiglas tube with its sensor on the tube axis. The side wall on the windward side of the shelter model was then removed and replaced with a Plexiglas sheet having a half-inch opening. Air from a compressed air cylinder, flowing through a Sprague gas flow meter, was admitted into the shelter model at controlled rates through this opening. (Calibration of the gas flow meter itself was checked in a separate volume displacement calibration test in the range of 0.1 CFM to 1.3 CFM and found to be accurate to within ± 1%.) By regulating the air flow from the compressed air cylinder, the correlation between the anemometer reading and the actual volume flow rate of air through the model (given by the gas flow meter) was determined for the entire flow rate range of interest. The test was repeated for wind tunnel free stream speeds varying from about 5 fps to 15 fps. Following this, the turn-table was rotated to set another value of the relative wind angle and the tests repeated for relative wind angles of 0°, 15°, 30° and 45°. The following correlation was obtained over the entire range of free stream velocities tested, indicating that the reading of the anemometer was not significantly influenced by the external flow field in the range of velocities tested.

$$q_t = 1.475 \quad V_A^{0.751}$$

where q_t = volume flow rate through the Plexiglas tube, cfm
V_A = velocity reading of Datametrics anemometer recorded by the datalogger.



1. Compressed Air Cylinder
2. U-Tube Manometer
3. Sprague Wet Test-Gas Meter
4. ½" I.D. Tygon Tubing
5. Below-Ground Shelter Model with Three Stairways Blocked
6. FED Model with Openings to Stairway and to Plexiglas Tubing
7. 1" I.D. Plexiglas Tubing
8. Datametrics 800-VTP Hot-Wire Anemometer

Figure A.1 SETUP FOR IN-PLACE CALIBRATION OF HOT-WIRE ANEMOMETER

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Evaluation of Shelter Ventilation by Model Tests - Option 1
GARD Final Report AI-51
FEMA Contract No. EMW-C-0633, FEMA Work Unit 1217I
by C. K. Krishnakumar, J. B. Koh, S. F. Fields, R. H. Henninger
December 1983 (UNCLASSIFIED) pp 51

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by C. K. Krishnakumar, J. B. Koh, S. F. Fields, R. H. Henninger
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Wind-induced ventilation rates that could be achieved in a 100-man below-ground shelter with simple designs of passive flow enhancement devices (FEDs) were estimated by scale model tests in a low-speed wind tunnel. Air volume flow rates through the model were determined by using bubble flow tracers and motion photography. Test results indicate that adequate ventilation can be achieved in the type of shelter considered by the use of FEDs even at relatively low wind speeds. The study also generated guidelines for the design of FEDs and their placement around stairway openings. In addition, estimates of reductions in ventilation rates due to an obstruction upstream of the windward FED and due to a decrease in the area of wall openings were made.