WIND AND AIR-POLLUTION-CONTROL STUDY OF YERBA BUENA CENTER

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ABSTRACT

Measurements were made on a model of the proposed Yerba Buena Center in the Colorado State University Environmental Wind Tunnel to obtain wind speed and direction and air-quality information. Hot-wire anemometer measurements provided mean wind speed, peak wind speed, and turbulence-intensity data at pedestrian level points throughout the Center for south, west, and northwest winds. Air quality was sampled by measuring concentrations of Krypton-85 tracer gas at locations throughout the model. The tracer gas was released from the garage exhaust stacks at two stack/approach-speed ratios for the three wind directions. Diffusion from the eight exhaust stacks was studied for three stack combinations: 1) 6 tall stacks, 2) 2 short stacks, 3) two short stacks extended to the height of the tall stacks.

Flow visualization was accomplished using smoke formed from titanium tetrachloride. Color motion pictures were made for smoke release from street level for all streets in and on the circumference of the Center and release from the exhaust stacks for the three wind directions and one wind speed. Motion pictures of the air flow for the west wind under stably stratified (inversion) conditions, were also obtained.

Implementation of the recommended measures to reduce wind speed and automobile exhausts in the Center made as a result of the model study will produce an environment in the Center which will be comfortable for a large percentage of the time -- 98% of the time at most locations.

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PURPOSE AND OBJECTIVES OF INVESTIGATION

The purpose of this investigation is to provide quantitative and qualitative information on winds in the Yerba Buena Center which can be used during the planning and design phases to help optimize the environment which will be created within the Center. By means of a small scale model subjected to winds in an environmental wind tunnel, the effects of geometrical modifications of the building complex upon local wind speed, gustiness and air-pollution potentials were determined by direct measurement and observation. This information in the form of numerical data and motion pictures of smoke to visualize the overall wind patterns together with data on natural winds over San Francisco is structured to help in attainment of the following objectives:

1. Optimize the level of human comfort outside of buildings within the Center by minimizing the speed and gusts of winds interacting with pedestrians in plazas, galleries and walkways.
2. Develop geometrical features of skylights to achieve their intended function without introduction of adverse wind effects.
3. Locate parking-garage exhaust stacks to minimize automobile exhaust intake into air-conditioning systems of neighboring buildings.
4. Locate air-conditioning intakes to help minimize the intake of air pollutants for prevailing wind directions.

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c	Time-mean concentration
K_c	Mean concentration coefficient = $\frac{c\,\overline{U}_{ref}\,L^2}{Q}$
L	Characteristic length of the model (average building height)
Q	Pollutant (tracer) release rate
RMS	Root-mean-square
$\overline{U}$	Local time-mean velocity
$\overline{U}_{ref}$	Reference mean velocity (measured at Federal Building anemometer)
$\overline{U}_g$	Gradient wind speed
U_{max}	Peak local wind speed
$\sqrt{\overline{u'^2}}$	Root-mean-square of the velocity flucutations
$\sqrt{\overline{u'^2}}/U$	Turbulence intensity
V_{stack}	Velocity of stack effluent
ν	Kinematic viscosity

I. INTRODUCTION

The interaction between winds and structures of an urban development such as the Yerba Buena Center site shown in the Frontispiece is extremely complex. Because of this complexity and the variability of meteorological characteristics for natural winds, architects, engineers and city planners are unable to determine the effect of proposed structures on local wind environment during planning and design with the information normally available. This situation often results in adverse wind conditions being created for pedestrians and unfavorable circulation of air pollutants being realized when the structures are finally constructed. At this stage of development remedial measures are usually either very costly to implement or no possible solutions may be available.

Fortunately, wind-tunnel facilities (1,2)* and capabilities for simulating natural winds (3,4) have been developed during the past decade which permit modelling of winds in cities (5). Mean wind speeds, gust intensities and pollutant concentrations can be accurately measured for a wide range of meteorological conditions which are characteristic for a particular site when buildings are modelled to a scale of 1:500 (one foot in the model equals 500 feet in the city) or larger. A distinct advantage of measuring winds directly in a small scale model is that numerous configurations and modifications of the proposed development can be investigated for environmental effects before the cost of actual construction has been realized. When tall buildings and/or buildings with large glass windows are involved, the same

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*Number refers to entry in LIST OF REFERENCES.

modelling procedure can be used to determine forces on the buildings. Wind pressures measured in the laboratory on model buildings can be used to design the building frame and external cladding as well as aid in the selection of glass lights. Investigations of air-pollutant circulation and wind pressure on glass lights of the Children's Hospital, Washington, D.C. (6) and wind pressure on cladding of the Standard Oil (Indiana) Building (7) are examples of recent wind-engineering studies performed on small-scale models.

II. SIMULATION OF FLOW

In order that the wind-tunnel test results correspond to those expected in the field, the air flow around the model should be similar to the prototype flow. The conditions for such a similarity are usually found in the equations of motion for a given flow. Cermak et al. (8), Halitsky (9), Cermak and Arya (4) and many others have discussed a variety of modeling problems and their similarity requirements. It is generally agreed that, in the case of a neutral* atmosphere, dynamic similarity can be achieved if the model satisfies the following criteria:

(1) Geometrical similarity,

(2) Reynolds number $\frac{\bar{U}L}{\nu}$ similarity,

(3) Boundary-condition similarity.

Geometrical similarity requires that all the components of the surrounding structures and topography be scaled in the same proportion as components of the proposed buildings. The actual maximum scale possible is usually limited by width of the wind-tunnel test section. The Environmental Wind Tunnel has a cross section of 12 ft x 8 ft. In order to avoid interference by walls of the wind tunnel, the model should occupy no more than the center 10 ft of the tunnel floor. The maximum dimension of the Center and surrounding buildings to be represented is about 2200 ft in extent; thus, a scale of 1:220 satisfies the space requirement. A scale of 1:240 (1" = 20') was, however, found to be more convenient for model construction. The Yerba Buena Center consists of buildings varying in height. The highest building, the

*No temperature stratification.

Market Street tower (400 ft high) was scaled to 18 inches. The blockage presented by the model at the scale used was considerably reduced when the wind-tunnel roof was raised to produce zero pressure gradient over the model. The adjustment of the wind-tunnel cross section ensures that flow is not distorted in the simulation.

For a sharp-edged structure, Reynolds number equality is not essential and the flow patterns are similar if a critical lower limit of the Reynolds number is exceeded. The drag coefficient for a sharp-edged body becomes a constant above a Reynolds number of about 3×10^3. Also according to Golden (10), as quoted by Halitsky, the diffusion patterns around sharp-edged structures are invariant for Reynolds numbers greater than 11,000. As both the model and prototype are placed in air flow, this diffusion critical Reynolds number corresponds to $\overline{U}L = 2\ ft^2/sec$. The proposed Yerba Buena Center buildings extend to 400 ft vertically, therefore, the Reynolds numbers in the prototype would be above the critical if the wind speed is greater than 1/200 ft/sec which is nearly always true. The wind-tunnel air speeds used are about 10 ft/sec and 15 ft/sec so that the Reynolds number in the wind tunnel is also greater than the critical. Thus both the model and the prototype are in the class of flows which are independent of Reynolds number and the fact that the model Reynolds number is approximately 100 times less than the prototype value does not invalidate the flow similarity.

Boundary-condition similarity requires that the approach flows be similar in the model and prototype. Mean velocity and turbulence profiles in the approach flow were generated which have characteristics typical of an urban atmosphere. The urban geometry up to 1/2 mile upwind from the Center was modeled in the wind tunnel by placing street blocks in the same orientation found in the prototype. Buildings on these blocks were not replicas of the actual buildings but represented statistical averages of actual building heights in the area.

In view of the preceding discussion and past experience, it can be said with confidence that the flow over the proposed Yerba Buena Center in its location was portrayed in the model and that the results can be used for design purposes on the full-scale development.

III. MODEL AND WIND-TUNNEL FACILITIES

Model

Two models of Yerba Buena Center were constructed in the Fluid Dynamics and Diffusion Laboratory. The first model (Fig. 1) of the center proper, based on Master-Plan Drawings of April, 1971, was constructed from "Lucite" plastic according to the original proposal. In most of the proposed structures, only the exterior features of aerodynamic importance were modeled. Some components, like multi-level elevated garage, spiral ramps etc., were fabricated to provide floor by floor detail in order to study the dispersal patterns of automobile exhaust. All the adjoining structures, whose detailed measurements were available, were made of styrofoam. However, the city details up to half a mile upwind from the Yerba Buena Center were constructed from 2 1/4 in. x 3 1/2 in. x 7 1/2 in. bricks with the help of an aerial photograph of the site. All these features were erected to a scale of 1:240. The revised plan (February, 1972) was modeled entirely by use of styrofoam blocks as shown in Fig. 2. A plan view of the Center showing the heights of all buildings is shown in Fig. 3. The skylight over Howard Street and the 44 ft level plazas and bridges are constructed of 1/8 in. -thick transparent plastic sheet in order to allow for measurements of wind underneath the skylight. Photographs showing the skylight configuration are given in Fig. 4. The proposed trees in various plazas shown in Fig. 3 are modeled to ensure the same aerodynamic characteristics as are typical of natural trees. Figure 5 shows the sketch of a typical tree.

Wind Tunnel

The model of Yerba Buena Center was mounted on a 10 ft diameter turntable on which a number of adjacent structures were also included. Such an arrangement permits exposure of the model to winds from various directions. The experimental work on the model was accomplished in the Environmental Wind Tunnel of the Fluid Dynamics and Diffusion Laboratory at Colorado State University shown in Fig. 6. Its large 12 ft wide test section can accommodate large models like that of the Yerba Buena Center. The Environmental Wind Tunnel is an open-circuit type and its blower can be driven by two different motors depending upon the application involved. For air-pollution studies, in which a radioactive tracer is used, the smaller motor is employed. For this application air is discharged out of the building through an opening in the wall. For larger wind speeds up to 60 ft/sec a 150 H.P. motor can be used. The air speed is set by varying the fan-blade pitch. The wind-tunnel ceiling can be adjusted such that static pressure remains constant as wind passes over the model. The large entrance is provided with honeycomb straighteners and a pair of screens to eliminate any large-scale disturbances produced in the wind-tunnel room.

The placement of the model in the wind tunnel is shown schematically in Fig. 7. At the entrance section, a grid of cardboard tubes of 2 1/2 in. diameter and varying lengths in five layers, were placed to stimulate the boundary layer growth. The tubes are followed by 10 ft length of randomized roughness scaled to produce effects similar to those produced by the city complex. The wind then passes over the model of Yerba Buena Center and the upwind structures of the city which cover a 19 ft length of the wind-tunnel floor. The wind-tunnel roof shown curved in the sketch, is adjusted experimentally to minimize the blocking effect of the model.

Wind measurement - The air velocity in the wind tunnel was monitored by a pitot-static tube of standard design, 1/8 in. in diameter. The two pressure ports of the tube were connected to an electronic differential pressure transducer (Transonic, equibar type 120) to read the dynamic pressure. This pressure is converted to wind velocity by evaluating local density from local temperature and barometric pressure measurements.

The measurements of wind velocity and gustiness over the model were made with a hot-wire anemometer. As wind discomfort is caused mainly by the resultant horizontal wind components, the measurements are made with a hot-wire which was mounted vertically in the wind tunnel. The hot-wire sensor used in this study was mainly 0.0005 in. in diameter tungsten wire mounted on a Disa probe holder. A constant temperature hot-wire anemometer designed at Colorado State University was used to operate the probe. The mean value of the anemometer output was measured by an integrating type Hewlett-Packard digital voltmeter. The RMS of the fluctuating signal of the anemometer was read on a Disa Type 55D RMS voltmeter. The peak gust speeds were picked from a digital recording of the anemometer output.

Flow Visualization

The complex flows around the buildings were visualized by introducing white smoke either from a small source at ground level or from the garage exhaust stacks.

Motion pictures were taken of the smoke patterns, mainly from the top through a window in the roof of the tunnel. A Bolex H16 Reflex camera was used with both a 10 mm and a 25 mm lens. Kodak 7242 EF, a high-speed, indoor Ektachrome, was used and was exposed and forced developed for an ASA speed of 500. Lighting was provided by 650 watt quartz-iodine Colortran lamps, 1000 watt incandescent Mole-Ricardson units and high-intensity carbon-arc "Trouper" lamps made by Strong.

A few words about the motion picture are appropriate. The purpose of the pictures is to enable the viewer to quickly visualize the airflow around the model. To photograph the smoke high-intensity lights must be positioned around the model and film exposure calculated. Because the smoke will disperse rapidly in the turbulent airflow the exposure must be increased to get good pictures of the smoke. But this will over-expose areas where the smoke is more dense. Accordingly, the photographer must rely upon his judgment and experience in choosing the exposure to give the best picture of the phenomenon under study and may take several sequences at different exposures when it is felt desirable to show the whole range of airflow. Without apology, this will result in some footage being over- or under-exposed. With this in mind, the varying quality of the films may be more understandable.

Color film is used because it yields the best information and is also more realistic for the viewer.

Titanium tetrachloride is used to produce the smoke. It is a colorless liquid which reacts strongly in moist air to form a dense white cloud of titanium dioxide and hydrochloric acid. Because of the reaction of the titanium tetrachloride with the moisture in the air the smoke is warm and will tend to rise. This gives an excellent simulation of smoke from a stack, but only in the area immediately surrounding a smoke source on the ground will the smoke give a faithful representation of surface conditions. Also, the smoke particles have large surface areas and may absorb heat from the necessary photographic lamps. Hence, the viewer should be cautious in evaluating smoke visualization pictures taken from above when the source is on the surface.

Air quality sampling - The main source of pollution considered in this study is the exhaust from the underground parking garage. Three combinations of these sources were investigated --

(1) 6 tall stacks in the arena and central plaza,

(2) 2 short stacks in the central plaza,

(3) 2 short stacks extended to the height of the six tall stacks (64 ft).

Krypton-85 was used for the tracer gas and was introduced into the model system through a flow meter. The Krypton-85 has a half life of 10.6 years so there is no appreciable decay during a diffusion experiment. The radioactive gas was procured from Oak Ridge National Laboratories. With both safety and economy in mind the gas was diluted about a million times with air before use. This also assures that the tracer will have properties very similar to those of air. The tracer gas entered the tunnel at the ambient temperature, hence the plume has neutral buoyancy. Radiation counting was done with cylindrically jacketed Geiger-Mueller (G.M.) tubes. Calibration of the source gas and G.M. tubes was done by comparing a source of known strength (Thallium-204 reference standard) to a known volume of source gas.

For each pollution source the quality of air at various air conditioning intakes around the buildings and at pedestrian level was determined by sampling the tracer gas-air mixture and measuring the concentration of Kr-85 in the mixture. The details of the sampling system are sketched in Fig. 8. Samples were drawn from the wind tunnel through 1/8 in.-I.D. flexible tubing and collected in glass bottles by displacement over water. This arrangement enabled 25 samples to be obtained at the same time for one release and thus conserved the radioactive Kr-85. In order to collect the samples, negative gauge pressure is created in the reservoir and the ball valve is opened. The suction then draws the gas sample into the bottle. Each sample was transferred individually from the glass bottle to the cylindrical jacket around the G.M. tube by pressurizing the reservoir and forcing water back into the bottle. Kr-85 concentration was counted using a Nuclear-Chicago Ultrascaler. After counting, the G.M. tube jacket was filled with water to flush the gas sample out through an exhaust line. The G.M. tube is then ready to receive the next sample.

When the Nuclear Chicago Ultrascalar counts N counts there is a 97% probability that the true count lies within the range $N \pm \sqrt{N}$,(11). That is, the percent error in the diffusion measurements is given as $1/\sqrt{N} \times 100$ or less (to 97% certainty). For typical high counts near $N = 3000$ the error is less than 1.8% and for near background counts of $N = 50$ the error is less than 14%. A count of approximately 400 was the average for all measurements. Thus the average error is less than approximately 5%.

IV. NATURAL WINDS

Winds on the average flow from a westerly direction in San Francisco which are persistent in the warm clear months, namely, May to August. However, the strong winds tend to flow from the south during rainy periods (from October to April) in addition to west and northwest directions. The topographic features of the San Francisco Bay area and other characteristics of its climate distort the flow patterns in the lower levels. This distortion is such that, according to the U.S. Department of Commerce Climatological Summary (12) there are found differences of climate, not only in the Bay area, but also within the city. Such a situation requires that a wind reference station be as close to the Yerba Buena Center as possible.

Fortunately, the Federal Office Building at 50 Fulton Street (see Fig. 9) offers a position which is in an area where winds are representative of those at the Center. All the information on winds in the proposed center should thus be referred to the mean wind speed at the Federal Office Building. A model of the Federal Office Building was placed in the wind tunnel for each wind direction studied and the reference wind established for this purpose. The reference wind and its relationship to winds over the Center are shown in Figs. 14, 15 and 16 for south, west and northwest winds respectively. Appendix B tabulates the mean and extreme winds recorded at the Federal Office Building over the past several years (12) as well as a frequency distribution for hourly mean winds.

V. TEST RESULTS AND DISCUSSION

Model Data and Their Interpretation

The following data on the wind flow in the Yerba Buena Center model were obtained to meet the objectives of this study.

1. Motion pictures of flow at various places in the Center made visible by introduction of smoke.
2. Characteristics of flow approaching the center.
3. Characteristics of surface winds generated by the structures.
4. Air-quality measurements.
5. Evaluation of various proposed layout schemes.
6. Motion picture of simulated inversion flow from the west.

These data pertain only to the final master plan of Yerba Buena Center. The wind study of the first plan was described in a preliminary report by the authors and is not included here. The data are reported in non-dimensional form for easy application to the field situations. Mean and peak wind speeds are reported as a fraction of the reference wind value. The RMS of the fluctuating wind speed is expressed as a percentage of the mean wind speed at the place of observation. Air-quality data are normalized using the reference wind speed, the pollutant discharge rate, and a length significant to diffusion.

Flow Visualization

Two series of tests were conducted to visualize the detailed pattern of flow in the center for winds blowing from the south, west, and northwest directions. One series records the dispersal of pollutants from individual exhaust stacks and the other illustrates the general pattern of flow throughout the Center. A total of 3000 ft of 16 mm color motion pictures was produced to record the tests.

Examination of the motion pictures reveals that in general the plazas are quiet for winds from the northwest (Reel 3, run 20J). The reason is that the Yerba Buena Center interior is shielded by towers on the northwest side. It is also flanked by tall structures on the northeast and southwest sides. The smoke indicates disturbed flow near the surface as it tends to move in various directions. The tendency to remain near the ground indicates low wind speeds. The plazas do show definite wind directions for winds from the south and west (Reel 2, run 6J and Reel 3, run 13J). For both these wind directions active winds are generated by tall buildings on Fourth Street. Thus strong winds are predicted at the elevated sidewalks along the Apparel Mart. Strong winds are also very noticeable through observations of smoke in the Market Street Plaza and on walkways between the office tower on Mission Street and the Market Street Plaza (once again, Reel 2, run 6J and Reel 3, run 13J). The swirling, vortex motion at the corners of the Market Street Tower is of prime significance for south and west winds. The Sports Arena Plaza is relatively quiet for south and west winds.

Dispersal of smoke issuing from individual stacks shows a variety of patterns (Reel 5). For the northwest wind the smoke tends to rise and stay aloft and is removed by sporadic wind activity (Run 21J). South winds, especially those at the intersection of Howard Street and the Sports Arena and Central Plazas, cause the effluent from tall stacks to descend to pedestrian level (Run 7J). This tendency for the effluent to flow toward the ground indicates a higher concentration probability for the south wind than for the other wind directions. Releases of smoke through stacks in the Central Plaza for winds from the west also descend to pedestrian level (Run 23J). Figures 10 and 11 illustrate the stack effluent dispersal in the Sports Arena and Central Plazas.

A stably stratified atmosphere was simulated for the west wind by placing 2200 lbs of dry ice at the entrance to the wind-tunnel test section. The west wind was studied because it is the most common wind direction during inversion conditions (13). Figures 12 and 13 show two vertical temperature distributions under the stably stratified condition. The inversion simulated in the wind tunnel was ground based, thus pollutants exhausted into the atmosphere are trapped very near the ground. The actual situation is much less severe because the inversions are usually elevated above ground level.

Quantitative measurements of both wind speeds and the quality of air to be reported later in this section will be seen to confirm the visual observations. The record of wind movement through the urban area contained in the motion pictures should help the Architects evaluate the wind motion and avoid serious air-pollution or human-comfort problems.

Approach-Flow Characteristics

It was pointed out in a previous section that an important part of the simulation technique is the boundary condition similarity. The mean velocity profiles in the flow approaching the model and its turbulence characteristics should be similar to those in the prototype. In general, however, such information for the prototype is not available. Therefore, the safest procedure is that the approach flow should be conditioned by modeling topographic features upwind from the model. There is also a need to thicken the boundary layer by introducing a porous step at the leading edge of the wind-tunnel test section. Such a practice produces the mean velocity and turbulence profiles shown in Figs. 14, 15, and 16. The turbulence intensity of 30% to 40% near the surface is typical of those observed in cities. Figure 17 shows the model geometry in the vicinity of the locations where the vertical profiles were measured.

The mean velocity characteristics are usually found by expressing the mean velocity as a power of the height above the ground

$$\bar{U} \propto z^{\alpha}.$$

Log-log plots of the mean velocity distributions are shown in Figs. 18, 19, and 20. The west wind passes over an area well built up with tall structures and results in an $\alpha = 0.63$. The south wind flows over relatively low buildings yielding a power index $\alpha = 0.44$. A meaningful power-law relation does not exist for the northwest wind at the location measured because of the surrounding high buildings. These data indicate strong influence of local buildings on vertical distribution of wind in a city complex.

Ground-Level Wind Data and Their Interpretation

The "winds" in a built-up urban complex are strongly transient in nature. Sudden and brief increases in wind speeds and wind directions (called gusts) are followed by a relatively mild wind. Such unsteady conditions are usually described by a mean wind speed $\bar{U}$, a root-mean-square of the fluctuations of wind about the mean $\sqrt{\overline{u'^2}}$ and finally by the peak wind speeds U_{max} expected at a given position.

As mentioned earlier, wind-speed information will be useful only if it is related to wind measured at a reference point in the vicinity of the center. All the wind speeds (the mean and the peak) are reported as ratios to the mean wind speed $\overline{U}_{ref}$ at the Federal Office Building where the wind instruments are mounted 80 ft above ground level.

South Wind (Figure 21)

There are few tall structures upwind of the Center for a south wind. As a result, winds in the Center are generally higher for the south wind than for the other directions studied. The mean wind speed ranges from a high of $\overline{U}/\overline{U}_{ref} = 1.43$ at the center of the northeast face of the office tower to a low of 0.20 under the skylight in the Sports Arena plaza. The peak wind speed is also a minimum ($0.44\ \overline{U}_{ref}$) under the skylight, this time in the central plaza. The peak speed is a maximum ($2.30\ \overline{U}_{ref}$) at the north corner of the arena.

Turbulence levels in the complex are generally between 30% and 40%. The minimum value of 19% is found at the west corner of the office tower building. The most turbulent location is on the roof of the hotel at the west corner of the swimming pool.

Of prime interest is a jet rounding the west corner of the office tower. Turbulence in the high speed region of the jet is of the order of 20% but ranges from 37% to 49% in the strong shear region at the edge of the jet.

Under the skylight air motion is rather quiet. The greatest peak normalized velocity is only 0.50 and the greatest mean normalized velocity measured is 0.20. Turbulence is also relatively low at approximately 25%. The Central and Sports Arena plazas are also generally quiet.

Strong winds were measured at the corner of Howard and Third Streets and also near the Mission Street garage air intake.

West Wind (Figure 22)

The extremes in the normalized mean wind speed for the west wind were 0.33 at the corner of the administration offices in the Sports Arena plaza and 2.54 at the north corner of the office tower.

The peak wind minimum (1.07) was found under the skylight in the Sports Arena plaza. The normalized peak wind also reached its maximum of 4.38 at the north corner of the office tower.

The turbulence intensity varied from 14% near the trees southeast of the theater to 71% at the corner of the administration offices in the Sports Arena plaza. Turbulence intensities were generally, as for the south wind, between 30% and 40%.

There are strong winds on the bridges crossing Mission Street and on the Apparel Mart walkway. Once again there is a stong jet at the base of the office tower.

The Arena plaza has generally low winds but fairly high turbulence, except near the skylight where the turbulence also is low. Wind speeds are slightly higher in the Central Plaza.

Northwest Wind (Figure 23)

Winds in the Center are quite calm when the wind is from the northwest. The normalized mean wind speed varies from 0.18 on the walkway near the south corner of the Apparel Mart to 1.03 on both the bridge over Mission Street and the walkway near the office building on Mission Street and near Third Street. The normalized peak wind extremes are 0.68 under the skylight in the Arena plaza and 2.61 at the north corner of the office tower. All of these values are from 40% to 60% of their counterparts for the west wind.

Turbulence levels for the northwest wind are generally higher than for the other two winds. Typical values are from 40% to 50%. Values range from 37% on the walkway on the southwest side of the Sports Arena near the skylight to 62% under the skylight near the shops in the hotel. (At this point the mean velocity is very low so the wind fluctuations also remain small.)

The Sports Arena and Central plazas are very quiet. Wind speeds are low compared to the other two directions.

The office tower induces a strong wind at its base. Also, there is a strong backflow along the walkway between the Market Street plaza and the Mission Street office building. These are the only areas where strong winds were encountered for a northwest wind.

Skylight Testing

Measurements were made at a few points around the skylight with the skylight in place and also with the skylight removed for south and northwest winds. The results of mean velocity and turbulence intensity measurements are shown in Figs. 24 and 25. It can be seen that the presence of the skylight is generally beneficial from a pedestrian comfort standpoint. At nearly all points the winds were either unchanged or reduced by addition of the skylight.

Summary of Winds in the Center

For a given gradient wind speed the south wind poses the greatest problem of strong winds at ground level in the Center. (Note that the south wind speeds are normalized with a velocity of 4.97 ft/sec whereas the west and northwest winds are normalized with the considerably lower speed of 2.72 ft/sec for the same gradient wind speed of 15 ft/sec.) The northwest wind causes the least disturbance.

For all wind directions the office tower building causes strong winds at street level. The maximum speed, either for the mean or peak wind, was recorded at the tower base for all three wind directions.

The flow under the skylight is generally calm and mild for all wind directions. Winds in the galleria are at acceptable low levels excepting in the general area adjacent to the Apparel Mart for a west wind.

It is possible to relate the velocity data to pedestrian comfort. Following the guidelines suggested by Australian researchers (15), peak winds below 35 mph should not cause noticeable pedestrian discomfort. To ensure that a satisfactory wind condition occurs for a high percentage of the time, a limiting value of $U_{max}/\bar{U}_{ref}$ must be specified. If this ratio is set at a value of 3, a wind speed of 11.7 mph at the Federal Office Building will correspond to a wind of 35 mph in the Center. Using a frequency-wind speed distribution for one-hour averages over a one-year period provided by the U. S. Weather Service personnel at the Federal Office Building (see Appendix B), the 11.7 mph wind will be exceeded only 18% of the time during a year. In regions where $U_{max}/\bar{U}_{ref} = 2$ local winds will exceed 35 mph only 2% of the time over a period of one year.

Defining human comfort is obviously very difficult and subjective. It is certainly not a function of the wind gust speed alone but of temperature, humidity, suspended dirt particles and duration of exposures. However, using current guidelines, only the few areas at the corners of high buildings in the Center entrance to plazas from Howard and Mission Streets and an area southwest of the Apparel Mart should present an uncomfortable wind environment more than 18% of the time.

Air-Quality Data

The concentration measurements of the effluent released from the stacks are made separately for application to strong and average wind conditions to account for the change in the ratio of approach wind speed to exit speed of stack effluent. This ratio controls the behaviour of the plumes. The proposed stack exhaust velocity is about 30 ft/sec and strong and average winds in San Francisco correspond to about 50 ft/sec and 12 ft/sec respectively. Thus diffusion of Krypton-85 tracer gas was, in general, observed at the following speed ratios:

$$\text{Strong winds:} \quad \frac{\overline{V}_{stack}}{\overline{U}_{approach}} \approx 0.6$$

$$\text{Average winds:} \quad \frac{\overline{V}_{stack}}{\overline{U}_{approach}} \approx 2.4 \ .$$

All diffusion testing was done at one wind-tunnel speed (or gradient wind speed). The mass-flow rate through each stack of the Kr-85 tracer was also constant for all tests. The stack/approach speed ratio was changed by changing the stack outlet diameter. The outlet diameter was 1/16 in. for the average wind case and 1/8 in. for the strong winds case. Appendix C shows calculations of the outlet diameters required to give the desired velocity ratios.

The pollution sources were studied in three groups separately, viz.,

1. 2 short stacks (15 ft),
2. 2 short stacks extended to the height of the 6 tall stacks,
3. 6 tall stacks (64 ft).

The mass-flow rate of tracer gas was the same through all the stacks for all of the tests. Figure 26 is a schematic of the three stack configurations. The data were collected for three wind directions, i.e., south, west, and northwest. In all, fourteen sets of concentration data were obtained. (Data for the average south wind with the 2 short stacks were not obtained since this wind occurs infrequently.) The concentrations are observed at the proposed intake points around structures, other places around structures where the plume was found to hit the building, and at pedestrian level.

All the concentrations are represented in non-dimensional form as a concentration coefficient K_c for easy application to the prototype. A useful form for K_c is

$$K_c = \frac{c\, \overline{U}_{ref}\, L^2}{Q}$$

where c is the concentration (say mg/ft^3), Q the rate of release of pollutant (mg/sec), $\overline{U}_{ref}$ the mean wind speed at a reference point (Federal Building) and L is a length significant to the diffusion phenomenon (in this case it is chosen to be 320 ft for the prototype -- the average height of nearby tall buildings). The values of K_c calculated from the observed concentrations (with L = 320/240 ft) are displayed in Figures 27 through 40. Shown on each figure are approximate lines of constant concentration. These contour lines depict the general diffusion patterns quite conveniently. It should be noted however, that the isoconcentration lines were drawn through data points established at ground level, roof level, and intermediate levels.

An examination of these figures reveals the areas of highest pollutant concentration. The position of such areas relative to the source indicate the direction in which the plumes travel. It will be noticed that concentration coefficients are higher for strong winds than those for average winds. Also a comparison of data in Figures 27, 28 and 29 for short stacks with those in Figures 32, 33 and 34 for the same stacks extended to 64 ft shows the decreases in the level of pollution possible by raising the stack height. For example, the maximum K_c observed for short stacks during south winds (Fig. 27) is in the Central Plaza and has a value of 25.3. The coefficient is reduced to 9.65 by raising the stacks. This change also produces a smaller area of high concentration. The direction of the plume matches, in general, with the motion observed in the motion picture.

Application

The data can be utilized to examine the possible hazard situations expected in the operation of the Yerba Buena Center. The Architects provided the following data and stated some problems as follows:

Source data:

Total Exhaust 1500 cu ft/hr/car

CO_2 11.4% by volume

CO 3.0% by volume

Hydrocarbons 460 ppm/car

Hexane 69.1 grams/hr/car

Hazard situations:

1. Pollutant levels at the Plaza adjacent to the 2 low-level (+60) exhaust stacks.

   The worst possible situation would be afternoon garage exiting after a Sports Arena event. This produces the peak pollutant production while people would be congregated below the low stacks. The maximum number of cars operating at this peak is estimated at 480 cars, with the exhaust of 120 cars coming from the pair of low stacks.

   The worst typical day-time situation would be produced by late afternoon exiting from the garage, unrelated to the Sports Arena. The maximum number of cars operating in this situation is estimated at 100 with the exhaust of 25 cars coming from the pair of stacks.

2. Pollutant levels in the Sports Arena due to the proximity of the intakes to exhaust shafts.

   The worst possible situation would be late afternoon garage exiting while the Sports Arena was occupied. This is similar to the above situation, with the exhaust of 12.5 cars coming from each stack.

Let us evaluate the first possibility for 2 low-level stacks as an example of how the concentration coefficients K_c are to be used. The exhaust due to 120 cars (released through these stacks) is

$$1500\ ft^3/hr/car \times 120\ cars = 180{,}000\ ft^3/hr$$

$$Q = \begin{cases} CO_2: & 11.4 \times 180{,}000 = 2.05 \times 10^6 \% ft^3/hr \\ CO: & 3 \times 180{,}000 = 5.4 \times 10^5 \% \ ft^3/hr \\ \text{Hydrocarbons:} & 460 \times 180{,}000 = 8.28 \times 10^7 ppm \ ft^3/hr \\ \text{Hexane:} & 69.1 \times 120 = 8.3 \times 10^3 \ gm/hr \end{cases}$$

The dispersal could be worst during "light variable" conditions which are indicated to occur so often (14). In the afternoon this condition prevails during November through February. Such conditions may not have any fixed direction for air flow over San Francisco. Thus, the "light variable" condition should be evaluated for the various wind directions studied in the tunnel.

Let U_{ref} = 5 miles/hr

= 26,400 ft/hr.

Now

$$C = K_c \left[\frac{Q}{U_{ref} \ L^2}\right]$$

Hence

$$C = \begin{cases} CO_2: & K_c\left[\dfrac{2.05 \times 10^6 \% \ ft^3/hr}{26{,}400 \ ft/hr \ (320)^2 \ ft^2}\right] \\ CO: & K_c\left[\dfrac{5.4 \times 10^5 \% \ ft^3/hr}{26{,}400 \ ft/hr \ (320)^2 \ ft^2}\right] \\ HC: & K_c\left[\dfrac{8.28 \times 10^7 ppm \ ft^3/hr}{26{,}400 \ ft/hr \ (320)^2 \ ft^2}\right] \\ \text{Hexane:} & K_c\left[\dfrac{8.3 \times 10^3 gm/hr}{26{,}400 \ ft/hr \ (320)^2 \ ft^2}\right] \end{cases}$$

or

$$C = \begin{cases} CO_2: & 7.6K_c \text{ ppm} \\ CO: & 2.0K_c \text{ ppm} \\ HC: & 0.031K_c \text{ ppm} \\ \text{Hexane}: & 0.11K_c \text{ mgm/m}^3 \,. \end{cases}$$

The maximum concentrations, for emission from the short stacks only, are:

For south wind: $(K_c)_{max}$ = 25.3 (near the short stack in the Central Plaza)

$$C_{max} = \begin{cases} CO_2: & 192 \text{ ppm} \\ CO: & 50.6 \text{ ppm} \\ HC: & 0.78 \text{ ppm} \\ \text{Hexane}: & 2.78 \text{ mg/m}_1^3 \end{cases}$$

For west wind: $(K_c)_{max}$ = 7.45 (at the south corner of the Central Plaza)

$$C_{max} = \begin{cases} CO_2: & 56.6 \text{ ppm} \\ CO: & 14.9 \text{ ppm} \\ HC: & 0.23 \text{ ppm} \\ \text{Hexane}: & 0.82 \text{ mg/m}_1^3 \end{cases}$$

For the northwest wind: $(K_c)_{max}$ = 9.52 (near the west corner of of the Apparel Mart)

$$C_{max} = \begin{cases} CO_2: & 72.4 \text{ ppm} \\ CO: & 19.0 \text{ ppm} \\ HC: & 0.30 \text{ ppm} \\ \text{Hexane}: & 1.05 \text{ mg/m}^3 \,. \end{cases}$$

Concentrations at any other point in the center where K_c was measured can be calculated in the same manner. It should be emphasized that these calculated concentrations are for exhaust from the two short stacks only. The total concentration would be the sum of the concentrations from the six tall stacks, the two short stacks (values calculated in the foregoing example) and also the background concentrations that exist, even with no exhaust from the stacks.

RECOMMENDATIONS

The staff of the Fluid Dynamics and Diffusion Laboratory in consultation with the Architects have concluded that several courses of action, some of which have been implemented while the study was in progress, are possible for improvement of the local environment within the Yerba Buena Center. The following recommendations are based on wind data and air-pollutant concentration data obtained by measurements over the 1:240 scale model:

(1) Eliminate the open space beneath the Market Street Tower.

(2) Add more dense tree configurations at entrances to various plazas from Howard and Mission Streets and particularly at the entrance to the Market Street Plaza opposite the Market Street Tower.

(3) Add horizontal cantilevered surfaces extending about 20 ft out from the Market Street Tower at an elevation of about 20 ft above street level in an effort to minimize winds near the base of this building.

(4) The skylight over Howard Street should be no higher than the roof of the adjacent building to the southwest if wind disturbances near the Sports Arena and in the galleria are to be minimized.

(5) To provide adequate dispersion of automobile exhausts in the Plazas at all times, the two short stacks in the Central Plaza should be raised to the level of the other six stacks.

(6) When future additions or modifications to the Yerba Buena Center are considered the flow-visualization motion pictures

should be consulted to obtain some indication of the wind modifications which may result.

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APPENDIX A

CONTENT OF THE FLOW VISUALIZATION MOTION PICTURES

Reel 1 - Original Model

Wind Direction	Vol.	Run No.	Description
W	15 fps	1A	Various shots - Tufts - high speed
W	1.5	2A	Various shots - Tufts - low speed
W	1.5	3B	Half Garage
W	15	4B	Half Garage - Low Skylight
W	15	5B	No Garage - No Skylight
W	15	6C	No Garage - Inclined Skylight high speed
W	1.5	7C	No Garage - Inclined Skylight low speed
W	1.5	8D	Mkt. St. Twr. - Mkt. St. Closure
NW	1.5	9D	Mkt. St. Twr.
NW	3	10D	Mkt. St. Twr. - with Eyebrow
NW	6	11D	Mkt. St. Twr. - with Eyebrow
NW	6	12D	Mkt. St. Twr. - Eyebrow + Closure
NW	6	13E	Mkt. St. Twr. moved - Eyebrow
NW	6	14E	Mkt. St. Twr. moved - Eyebrow + closure
NW	3	15E	Mkt. St. Twr. moved - Eyebrow + closure
W	3	16E	Mkt. St. Twr. moved - Closure
W	3	17E	Mkt. St. Twr. moved
W	3	18E	Mkt. St. Twr. moved - Eyebrow
W	3	19E	Mkt. St. Twr. moved - Traces along Mkt. St.

Reel 2 - Modified Model - South Wind

1J	Source - 4th St. (A series of shots of source in successive positions along street)
2J	Source - Folsom Street
3J	Source - Howard Street
4J	Source - Mission Street
5J	Source - Market Street
6J	Source - Plazas

Reel 3 - Modified Model - West Wind

8J	Source - 4th Street
9J	Source - Folsom Street
10J	Source - Howard Street
11J	Source - Mission Street
12J	Source - Market Street
13J	Source - Plazas
24K	Inversion Study

Reel 4 - Modified Model - Northwest Wind

Wind Direction	Vol.	Run No.	Description
		15J	Source - 4th Street
		16J	Source - Folsom Street
		17J	Source - Howard Street
		18J	Source - Mission Street
		19J	Source - Market Street
		20J	Source - Plazas

Reel 5 - Modified Model - Stacks

7J	South wind - stacks
7A-J	South wind - low stacks raised
14J	West wind - stacks
23J	West wind - low stacks raised
21J	Northwest wind - stacks

APPENDIX B

MEANS AND EXTREMES OF WIND AT FEDERAL OFFICE BUILDING -- REFERENCE 12

MONTH Record	MEAN WIND (MPH) 28 yrs	PRE-VAILING DIRECTION 28 yrs	FASTEST MILE (MPH) 34 yrs	DIRECTION 34 yrs	YEAR
J	6.7	N	47	SE	1965
F	7.5	W	47	SW	1938
M	8.5	W	44	S	1948
A	9.5	W	38	W	1965+
M	10.4	W	38	W	1965+
J	10.9	W	40	W	1965+
J	11.2	W	38	W	1939
A	10.5	W	34	W	1966+
S	9.1	W	32	W	1956+
O	7.6	W	43	SE	1950
N	6.3	W	41	S	1953
D	6.5	N	45	SE	1965
Year	8.7	W	47	SE	1965+

FREQUENCY DISTRIBUTION OF HOURLY MEAN WIND SPEED FOR A ONE-YEAR PERIOD*

$\bar{U}$ (MPH)	F (Occurrences/Yr)
1	270
2	485
3	560
4	600
5	740
6	740
7	765
8	735
9	675
10	595
11	525
12	420
13	355
14	310
15	270
16	235
17	265
18	90
19	45
20	30
21+	10

+ also on earlier years

* Data from Federal Building, 50 Fulton Street, San Francisco, for 1966.

APPENDIX C

STACK OUTLET-DIAMETER CALCULATIONS

To conserve Krypton-85 and still ensure sufficient concentration for accurate measurement a flow rate through the 6 tall stacks of $Q = 2000\ cm^3/min$ was chosen.

Six 1/8 in. I.D. stack outlets have a cross-section area

$$A = 6\pi(\frac{1}{16})^2\ in^2 = 0.475\ cm^2.$$

Then the average velocity at the outlet is

$$\overline{V}_{stack} = \frac{Q}{A} = 2.30\ ft/sec$$

This corresponds to a velocity ratio of approximately

$$\frac{V_{stack}}{U_{approach}} \approx 0.6\ ,\ \text{the strong winds case.}$$

A velocity ratio of 2.4 is obtained by halving the outlet diameter.

When tracer gas was released from the two short stacks Q was reduced to $666\ cm^3/min$ to keep the stack velocity constant. All the stacks were connected by a large diameter manifold to guarantee the flow rate would be the same out of each stack.

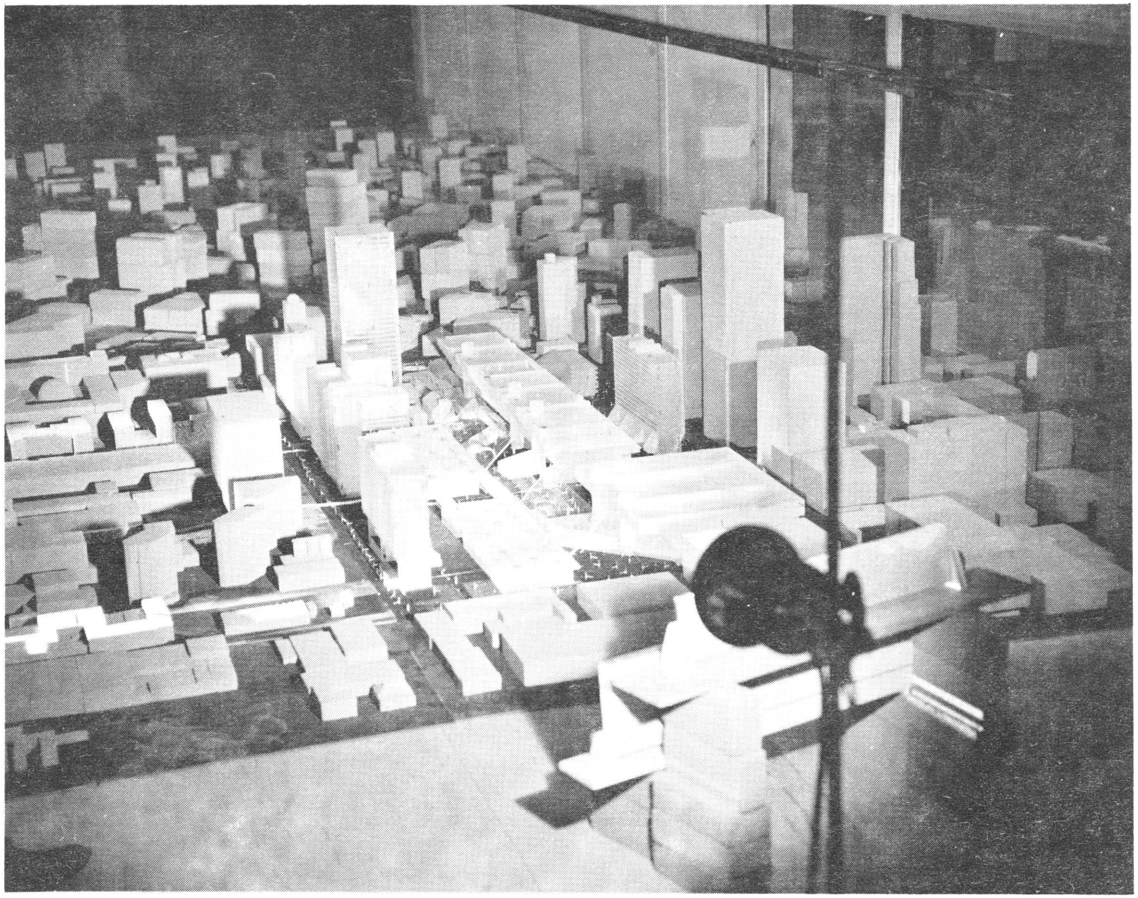


Fig. 1 Aerodynamic model of the first version of the Yerba Buena Center facing a northwest wind.

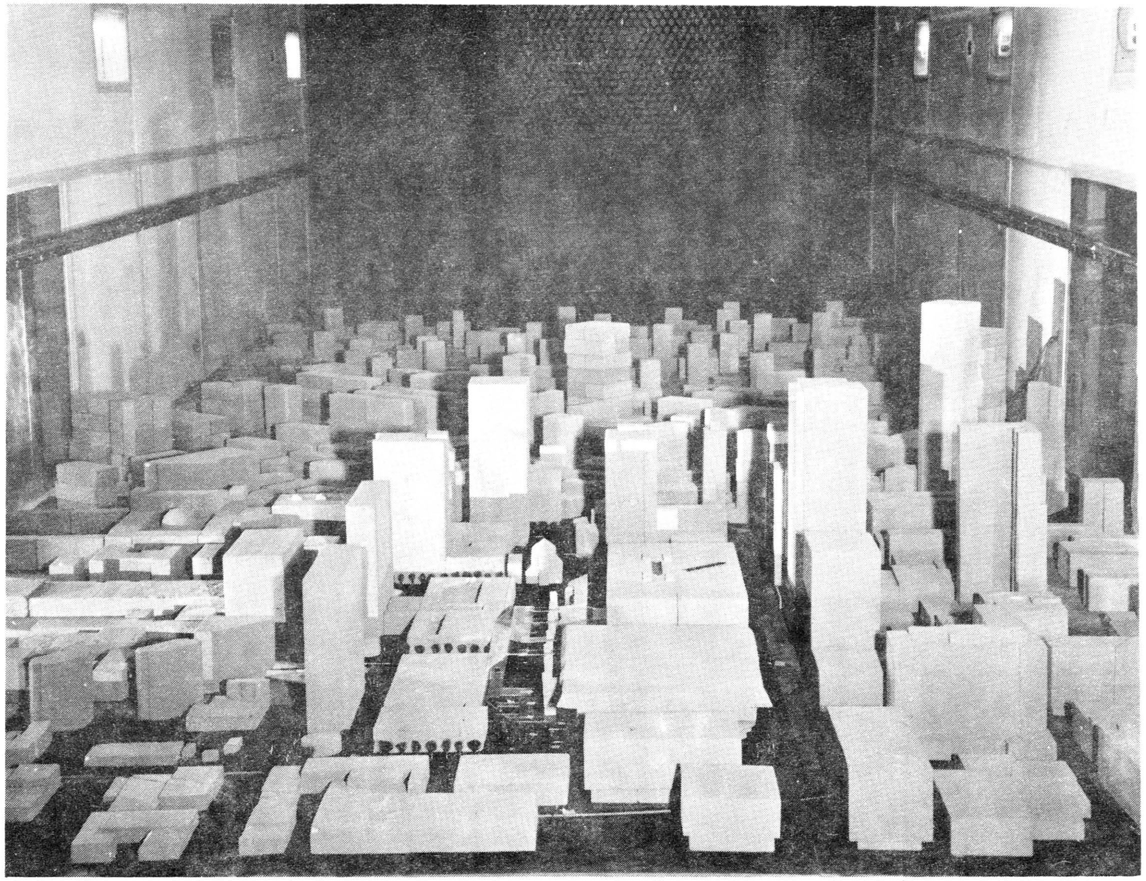


Fig. 2 Aerodynamic model based on the final master plan of the Yerba Buena Center facing a northwesterly wind.

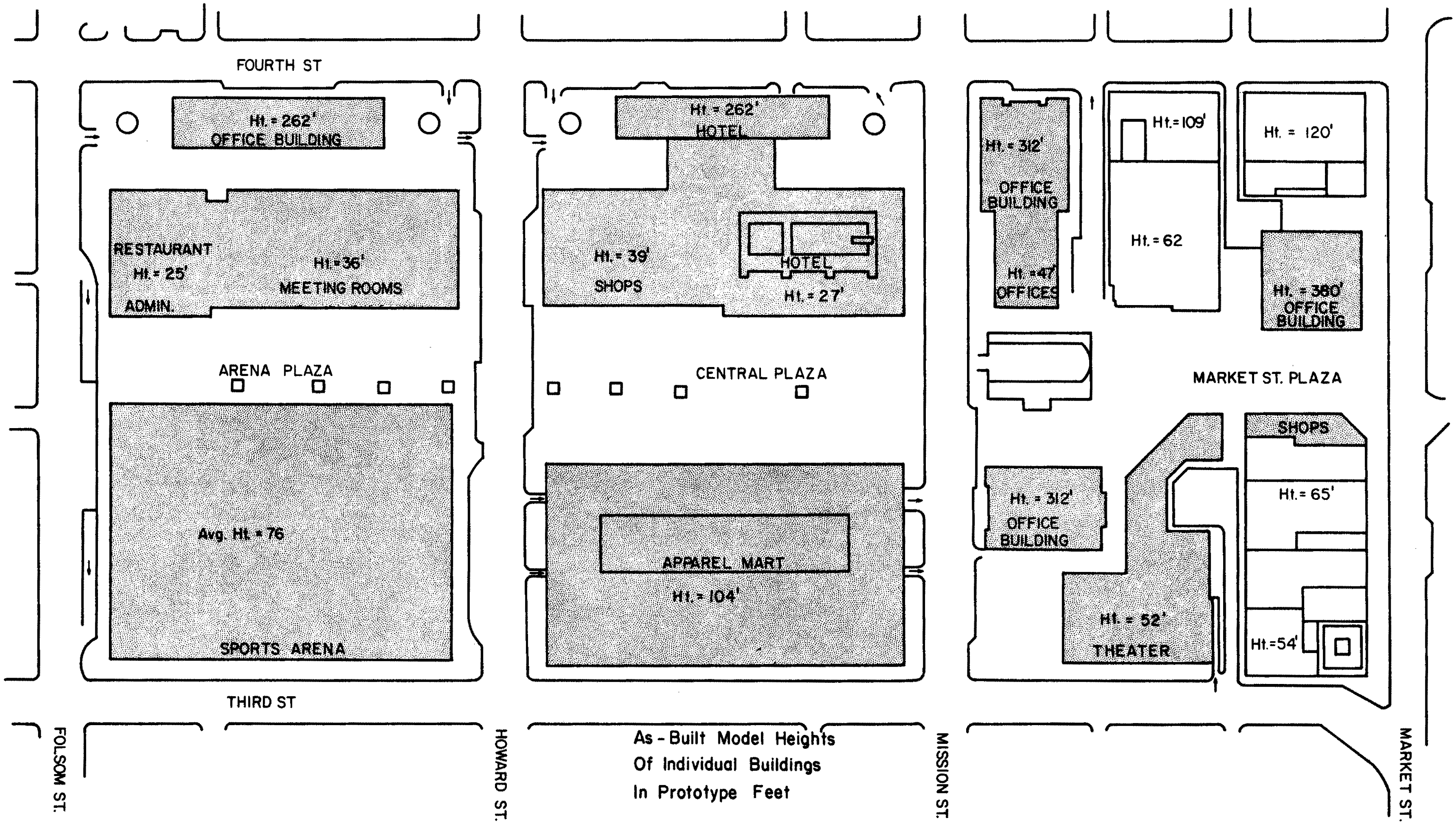
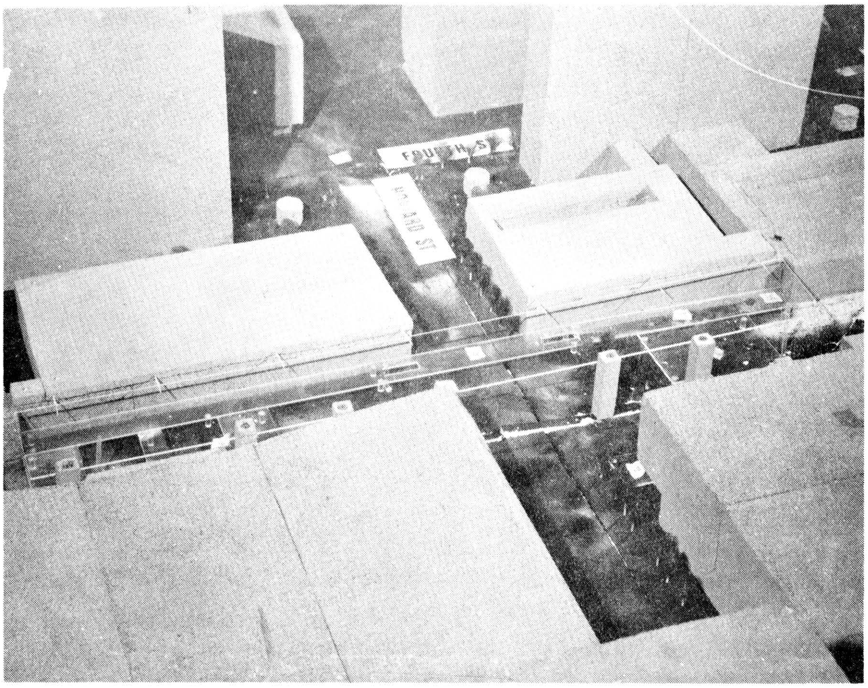


Fig. 3 Plan view of the Yerba Buena Center model. Heights of buildings are given in feet.



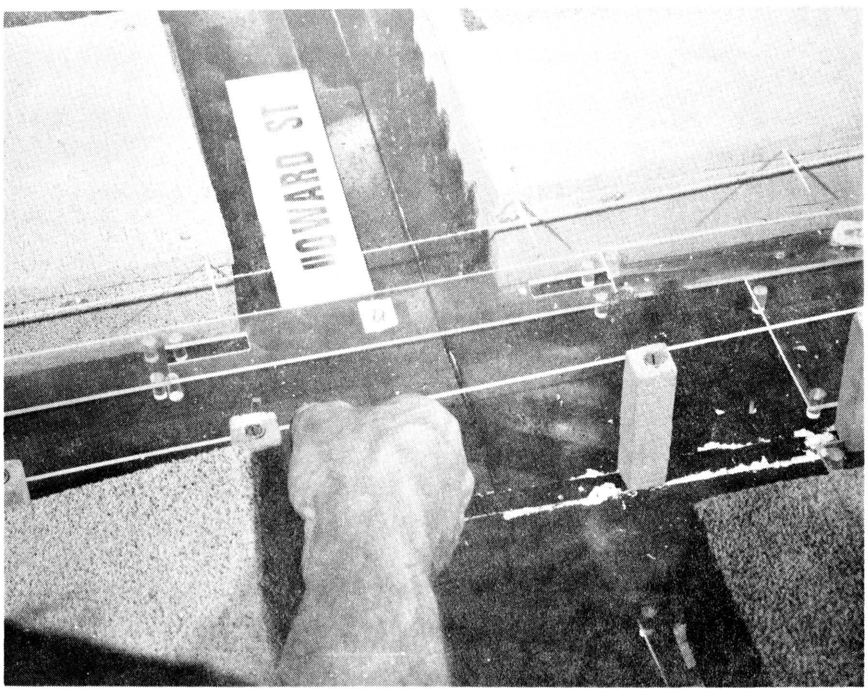


Fig. 4 Photographs showing the skylight location and configuration.

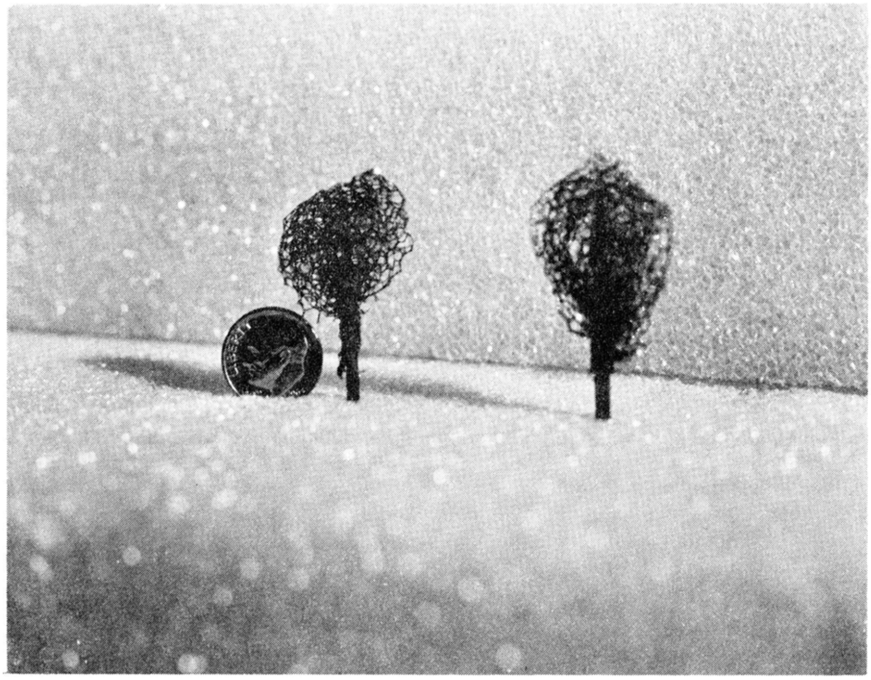


Fig. 5a Model trees used in the wind tunnel testing.

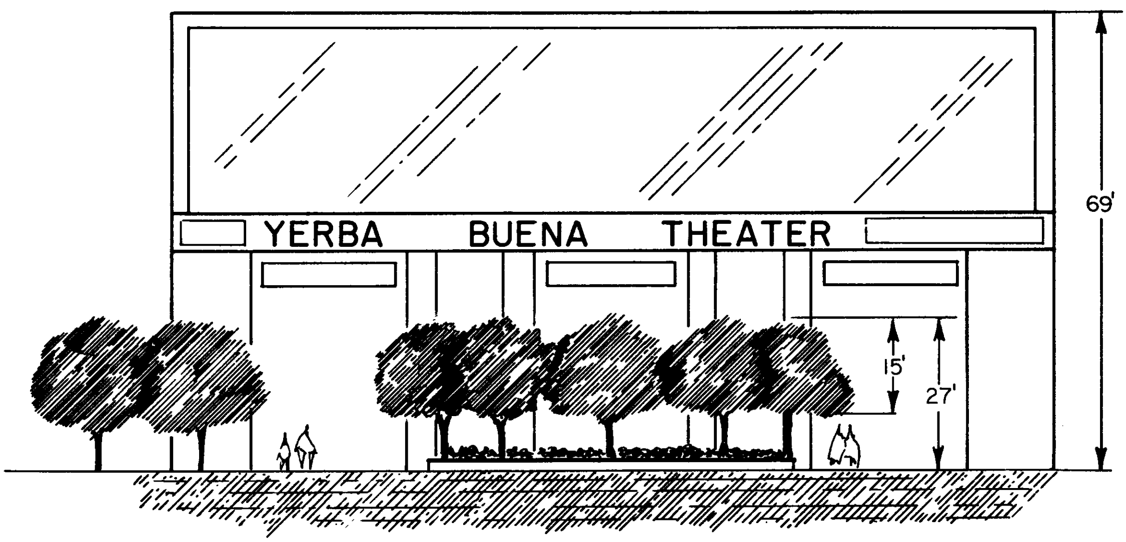


Fig. 5b Schematic showing the size and shape of typical trees.

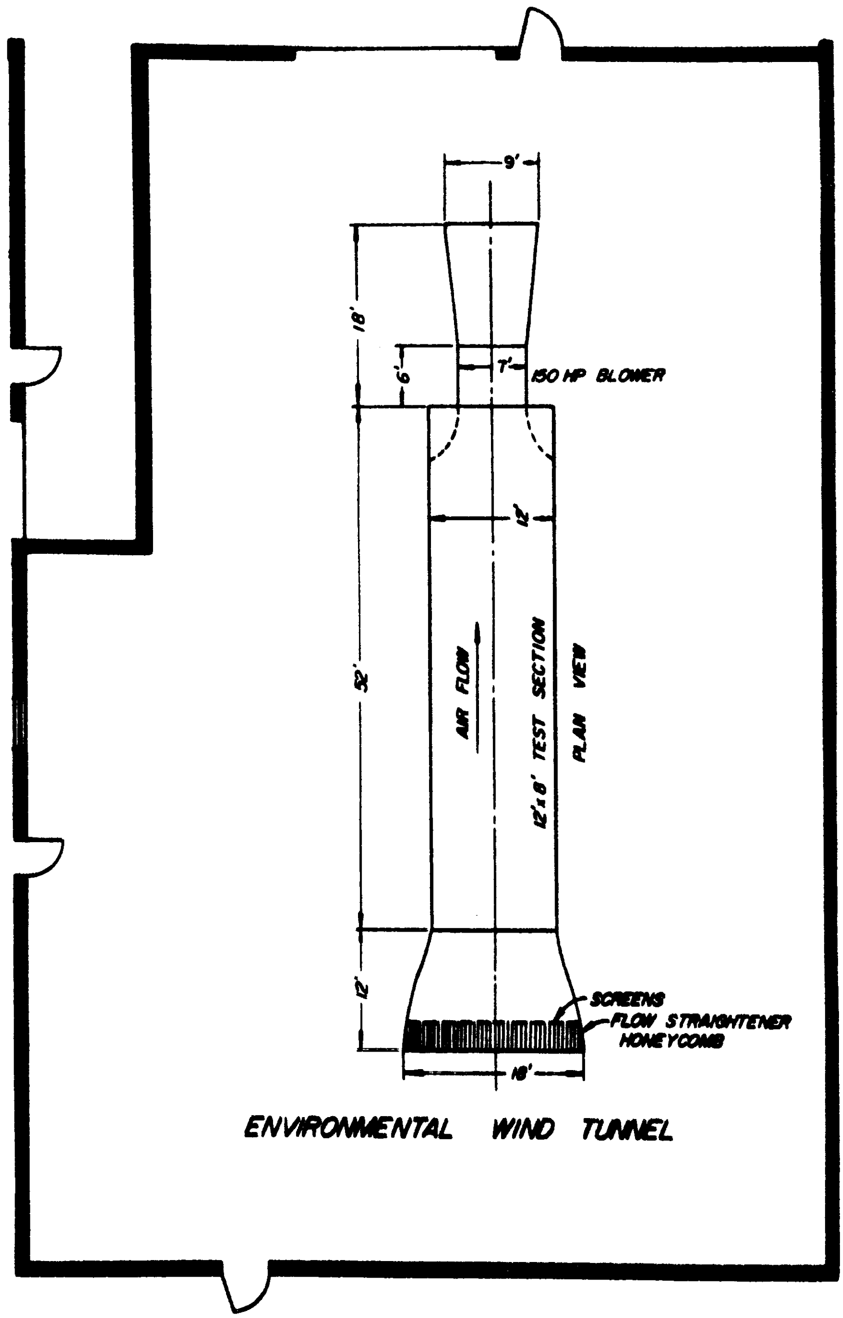


Fig. 6 Plan view of environmental wind tunnel facility.

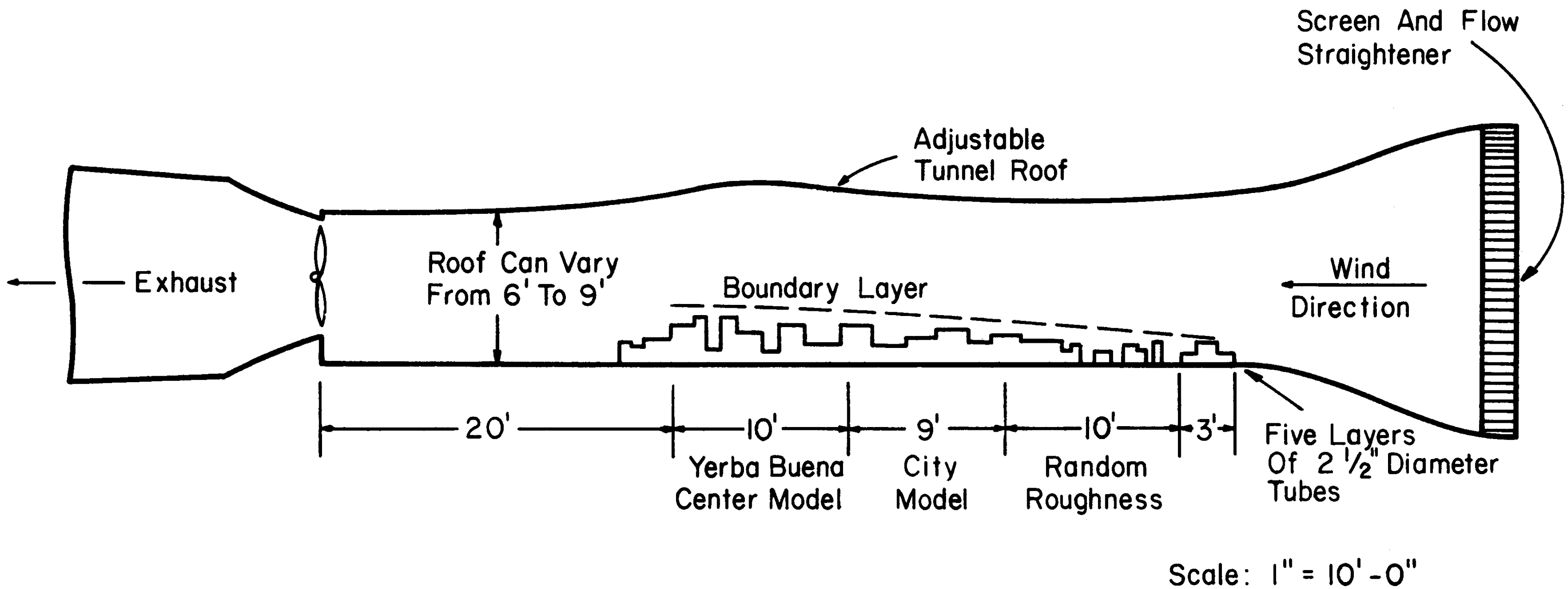


Fig. 7 Schematic of the CSU Environmental Wind Tunnel showing the model location and upwind roughness conditions.

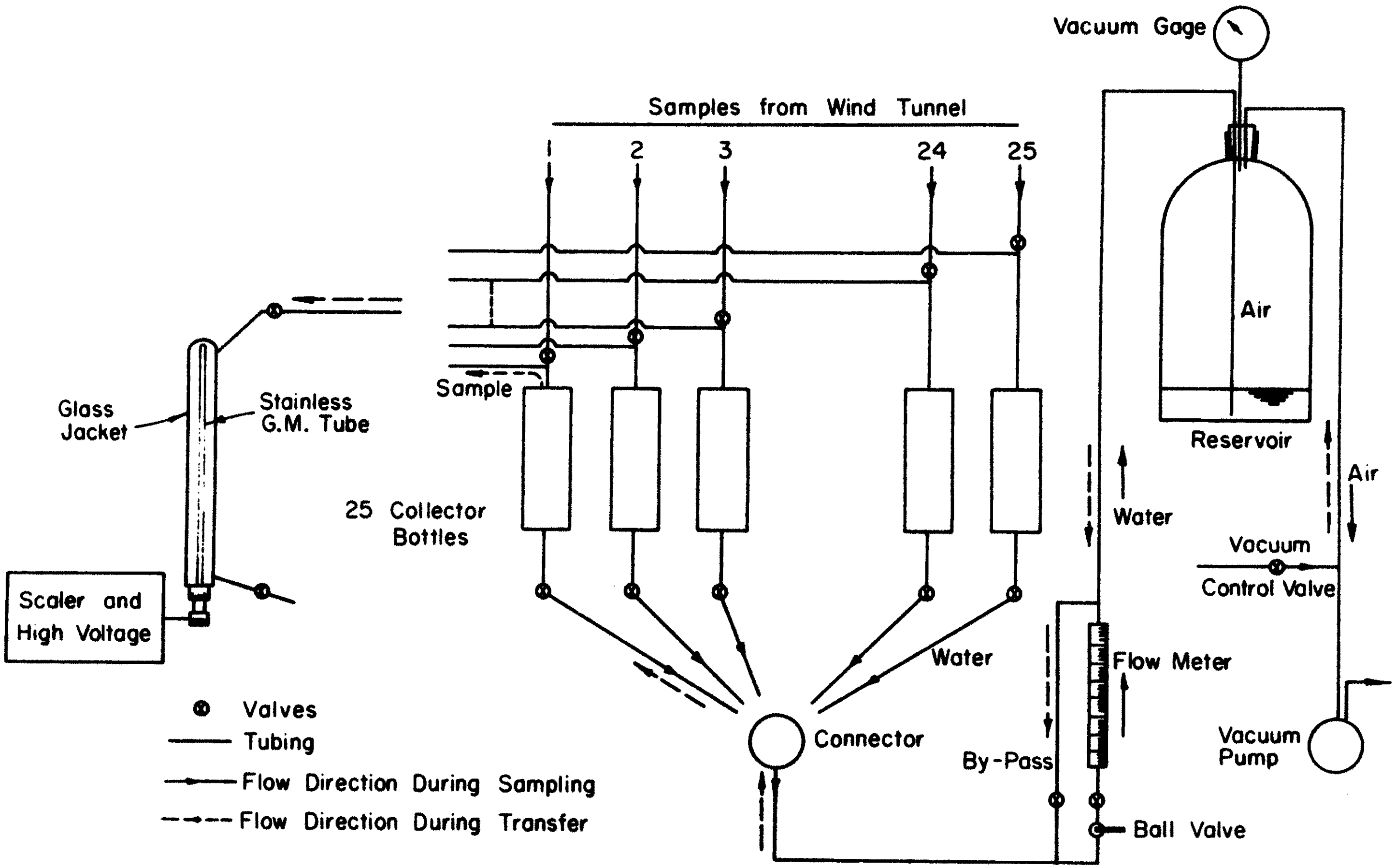


Fig. 8 Diffusion sampling and detection system.

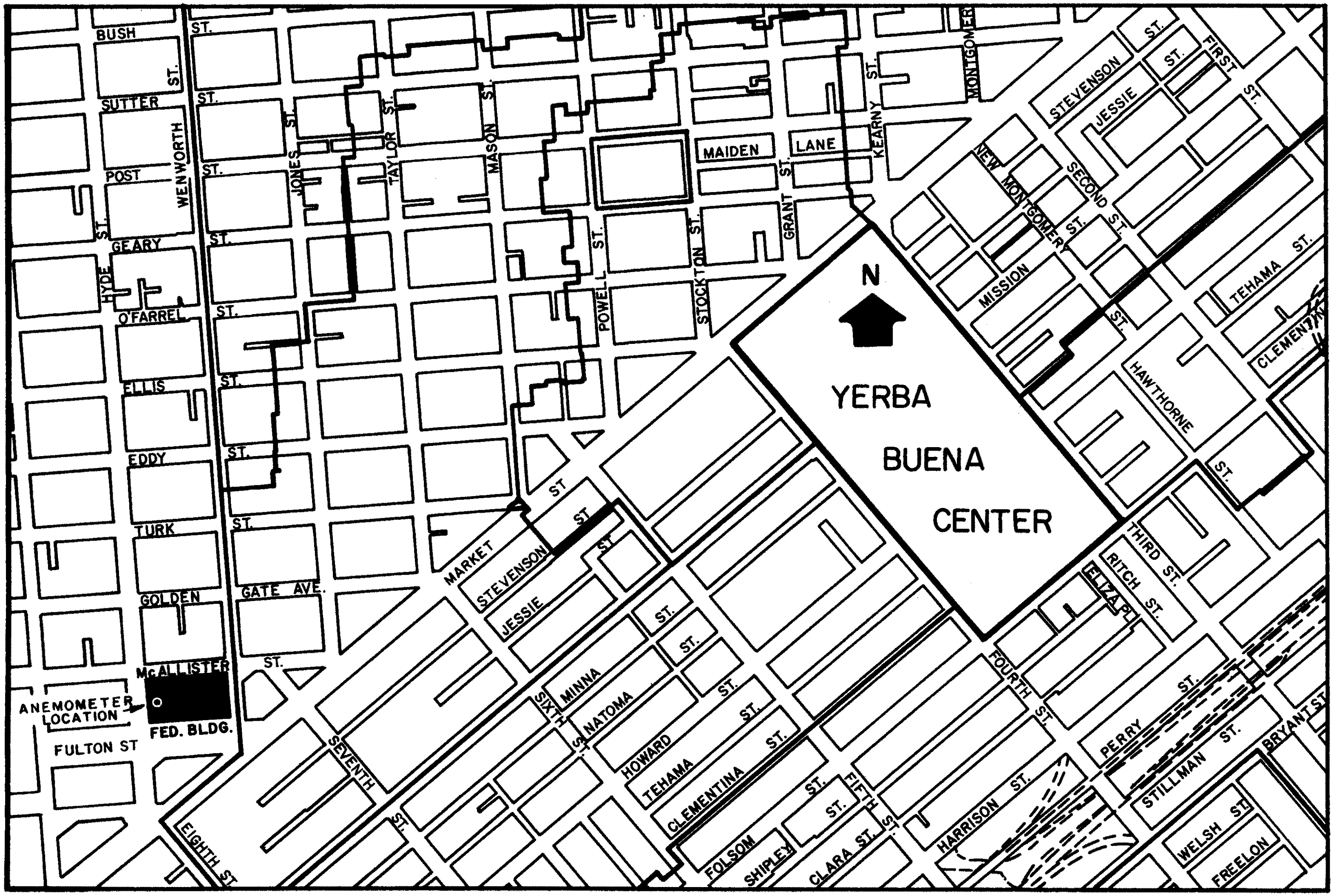


Fig. 9 Position of Federal Office Building in relation to Yerba Buena Center.

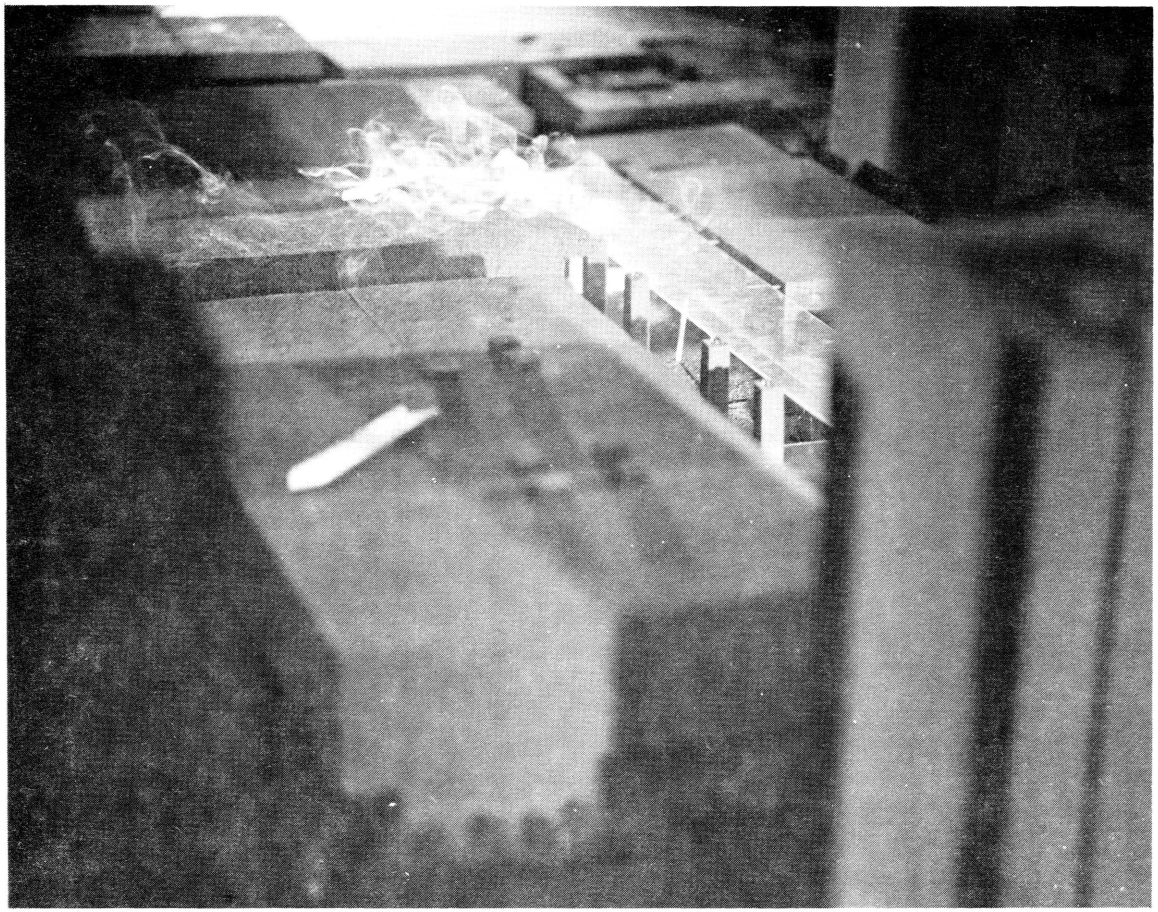


Fig. 10 An example of the diffusion pattern from stacks in the Sports Arena Plaza.

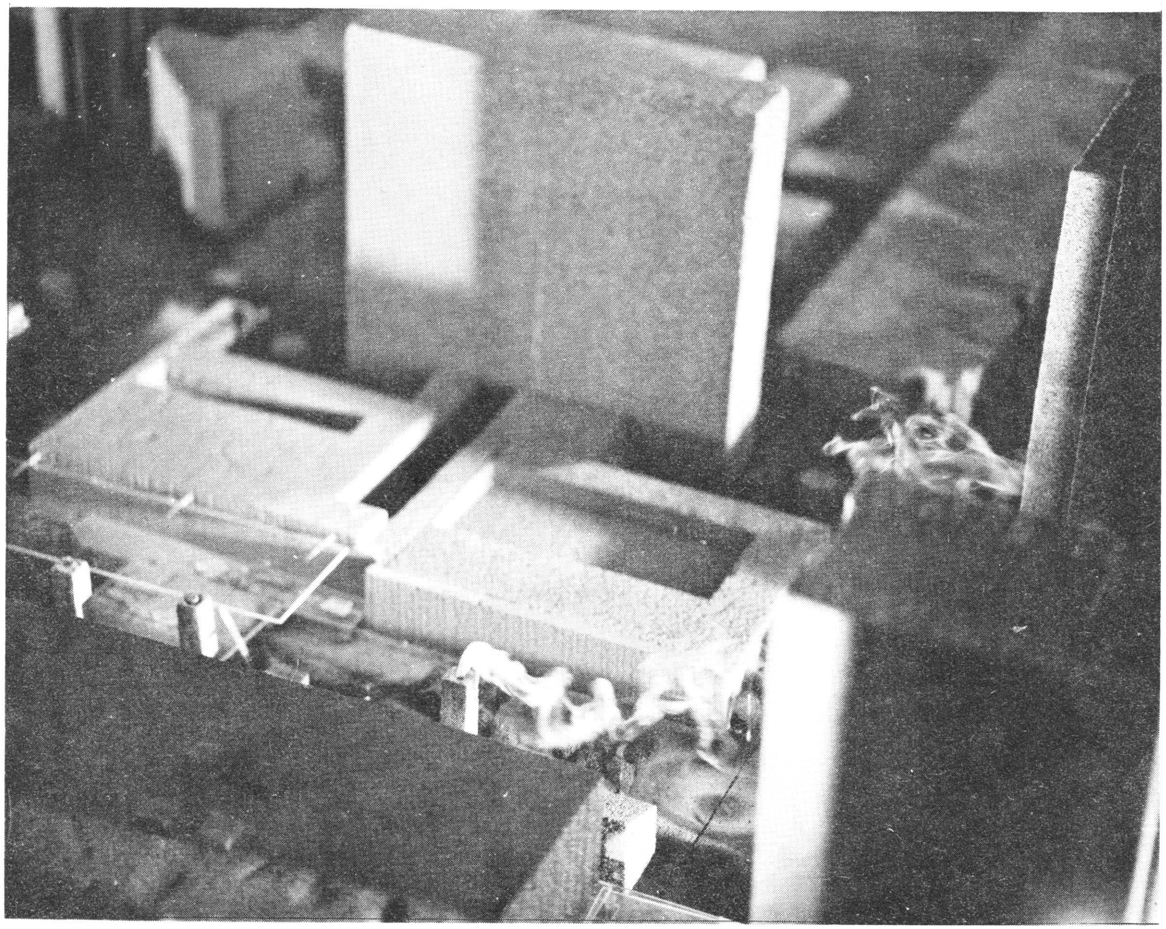


Fig. 11 An example of the diffusion pattern from stacks in the Central Plaza.

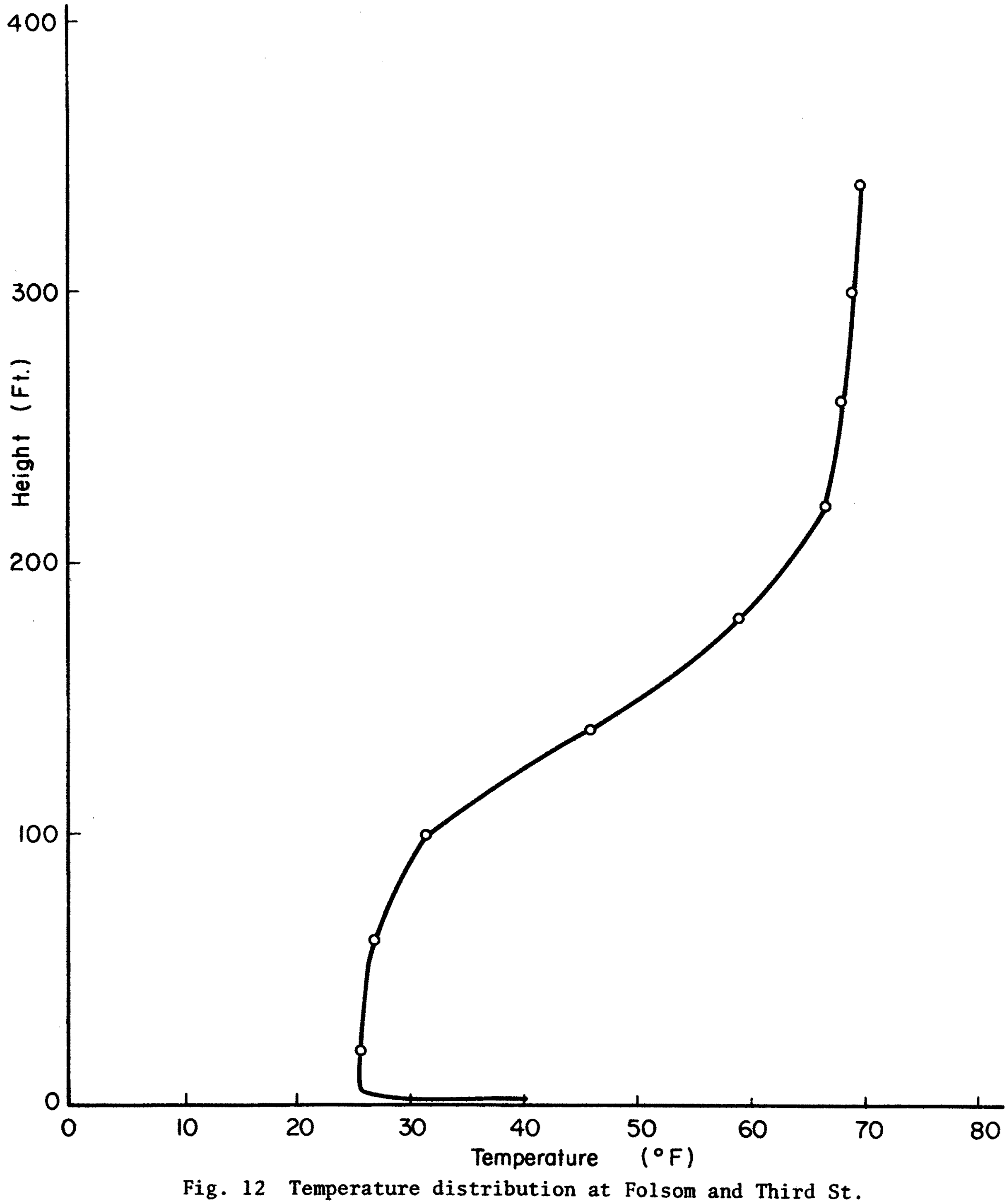


Fig. 12 Temperature distribution at Folsom and Third St. crossing during inversion test (west wind).

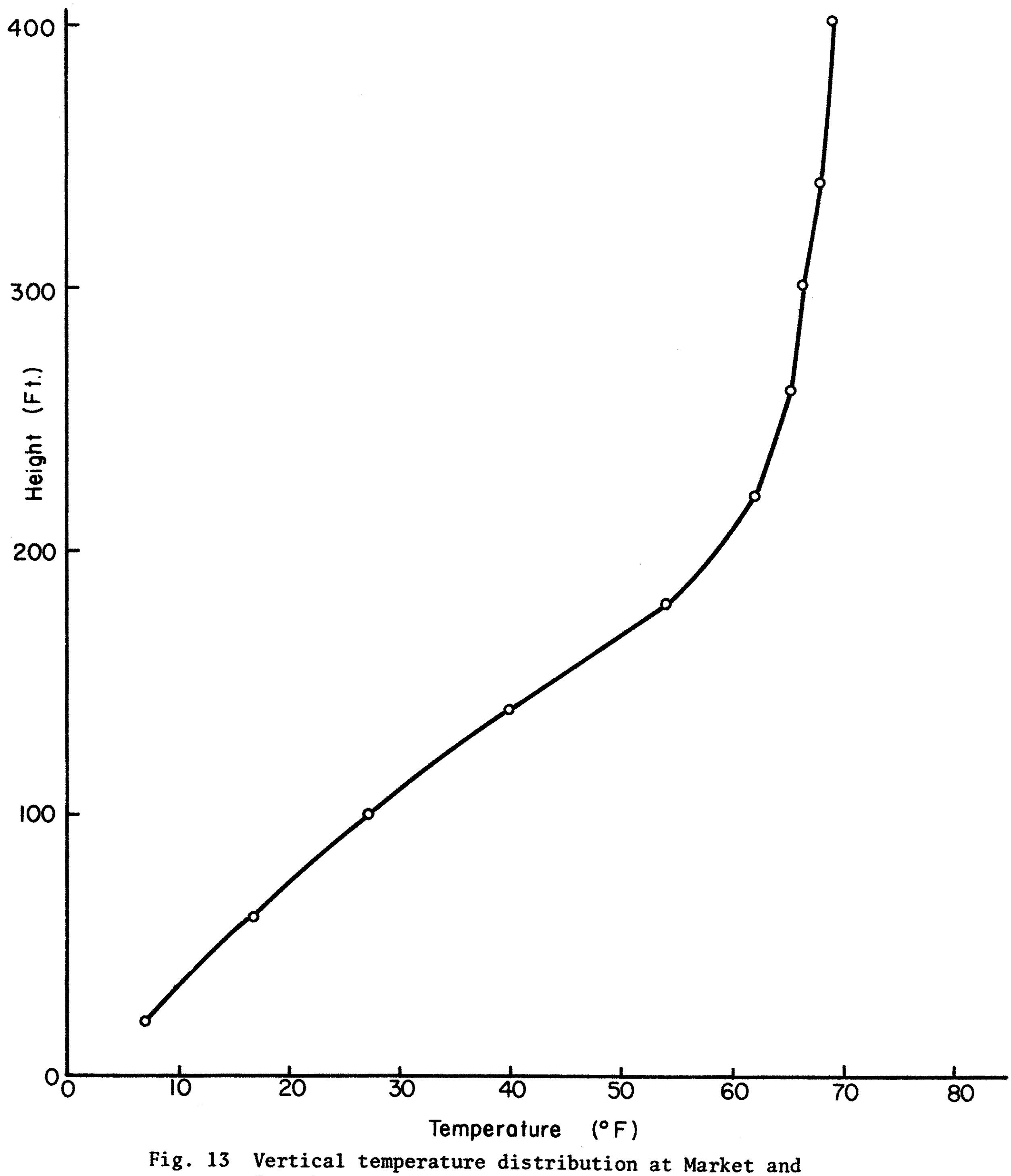


Fig. 13 Vertical temperature distribution at Market and Fourth St. crossing during inversion testing (west wind).

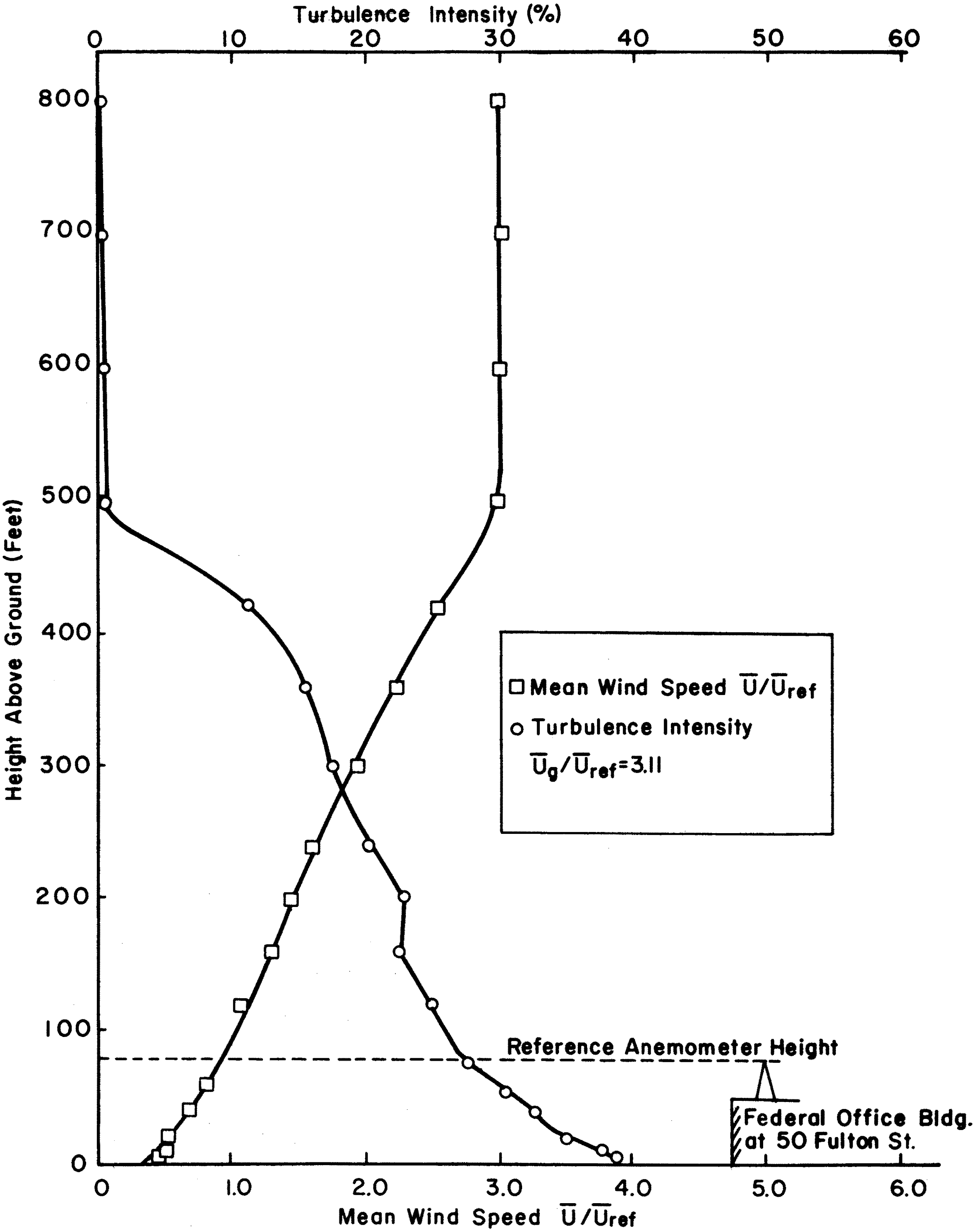


Fig. 14 South wind vertical profiles of mean wind speed and turbulence intensity. Location is at the corner of Folsom and Fifth Sts. $\overline{U}_g$ = 15 ft/sec.

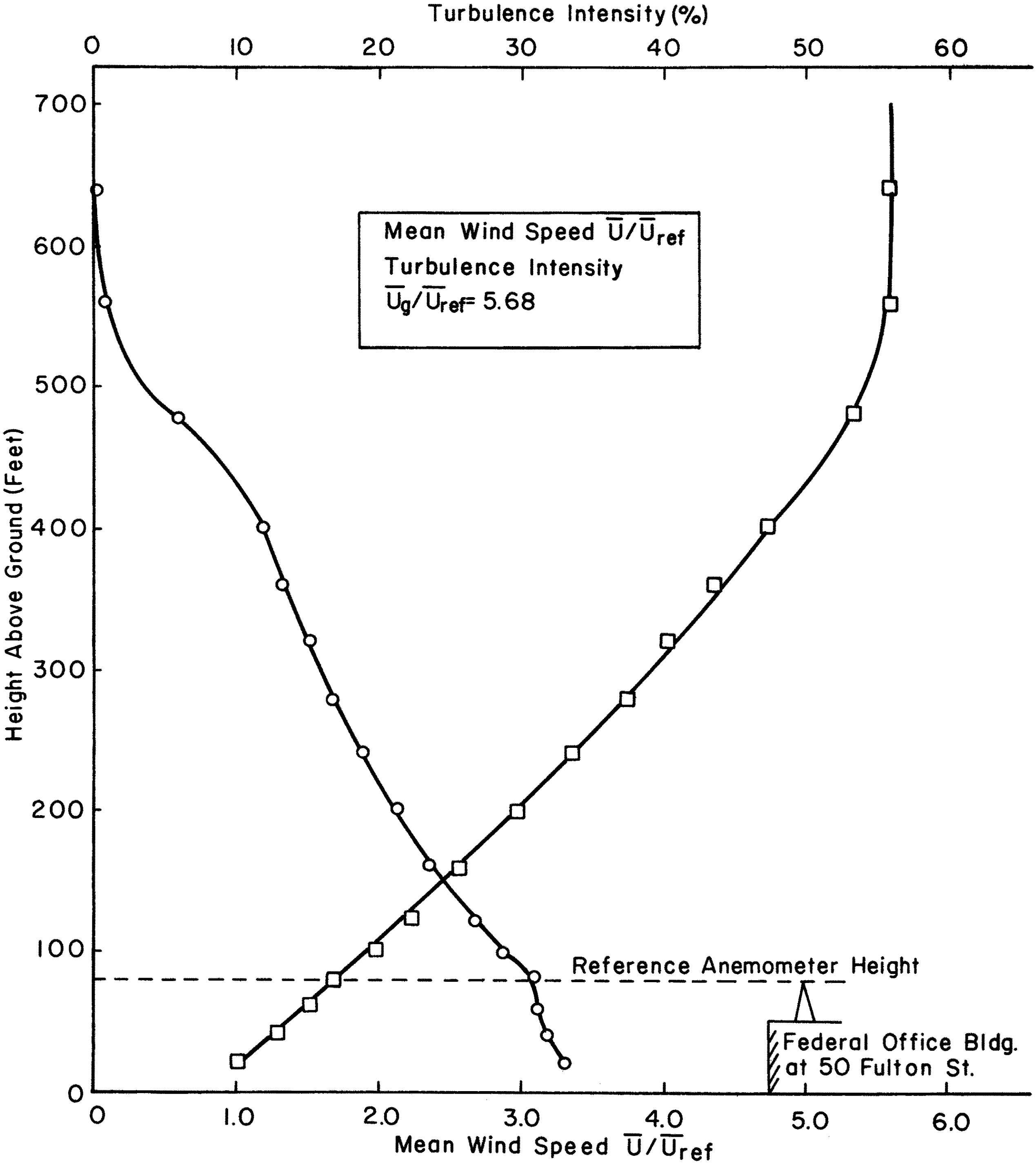


Fig. 15 West wind vertical profile of mean wind speed and turbulence intensity. Location is at the corner of Market and Fourth Sts. $\overline{U}_g$ = 15 ft/sec.

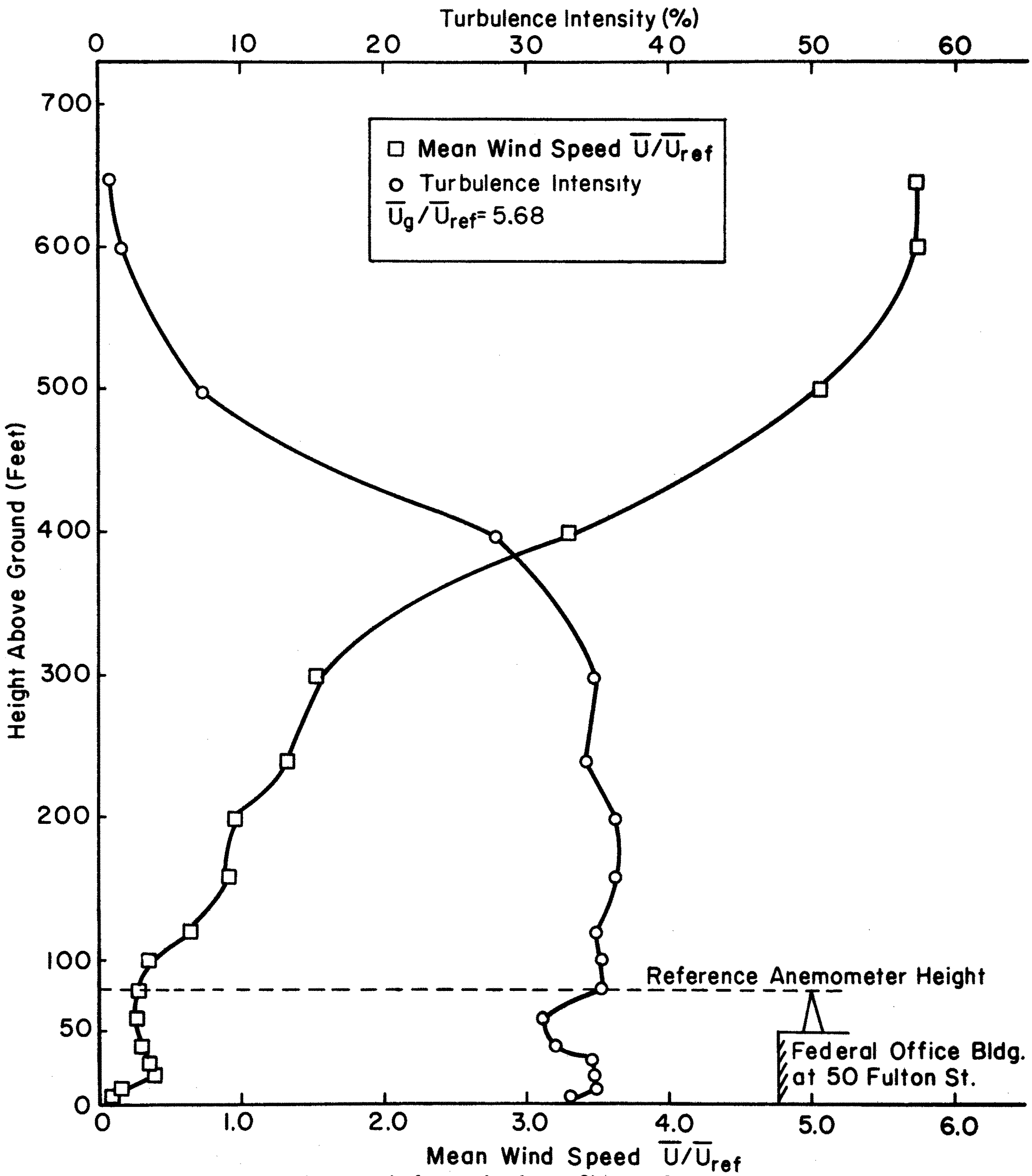


Fig. 16 Northwest wind vertical profiles of mean wind speed and turbulence intensity. Location is on Stockton between Post and Geary Sts. $\overline{U}_g$ = 15 ft/sec.

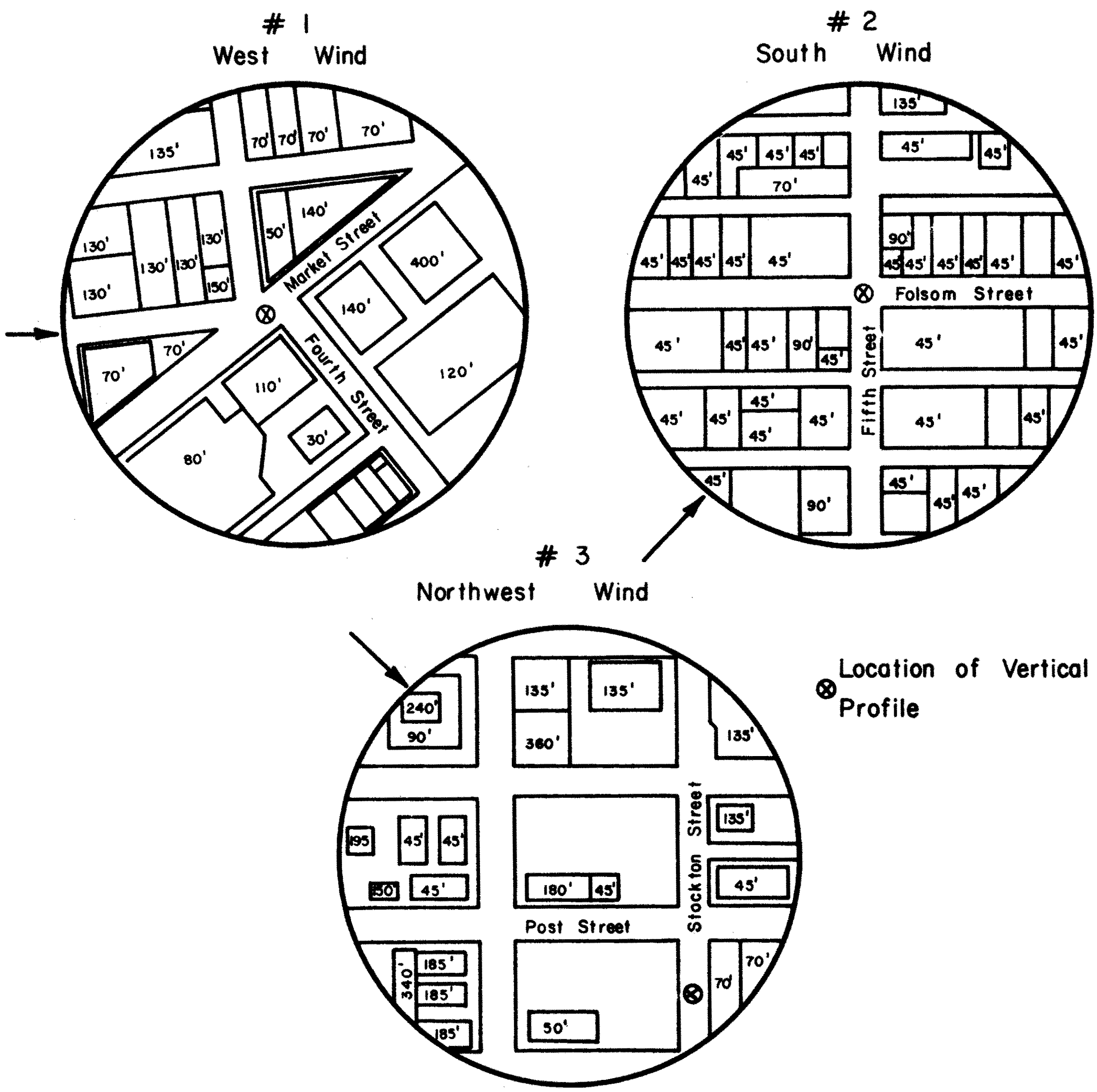


Fig. 17 Plan views of the three areas where vertical mean velocity and turbulence intensity profiles were measured. Building heights are given in feet.

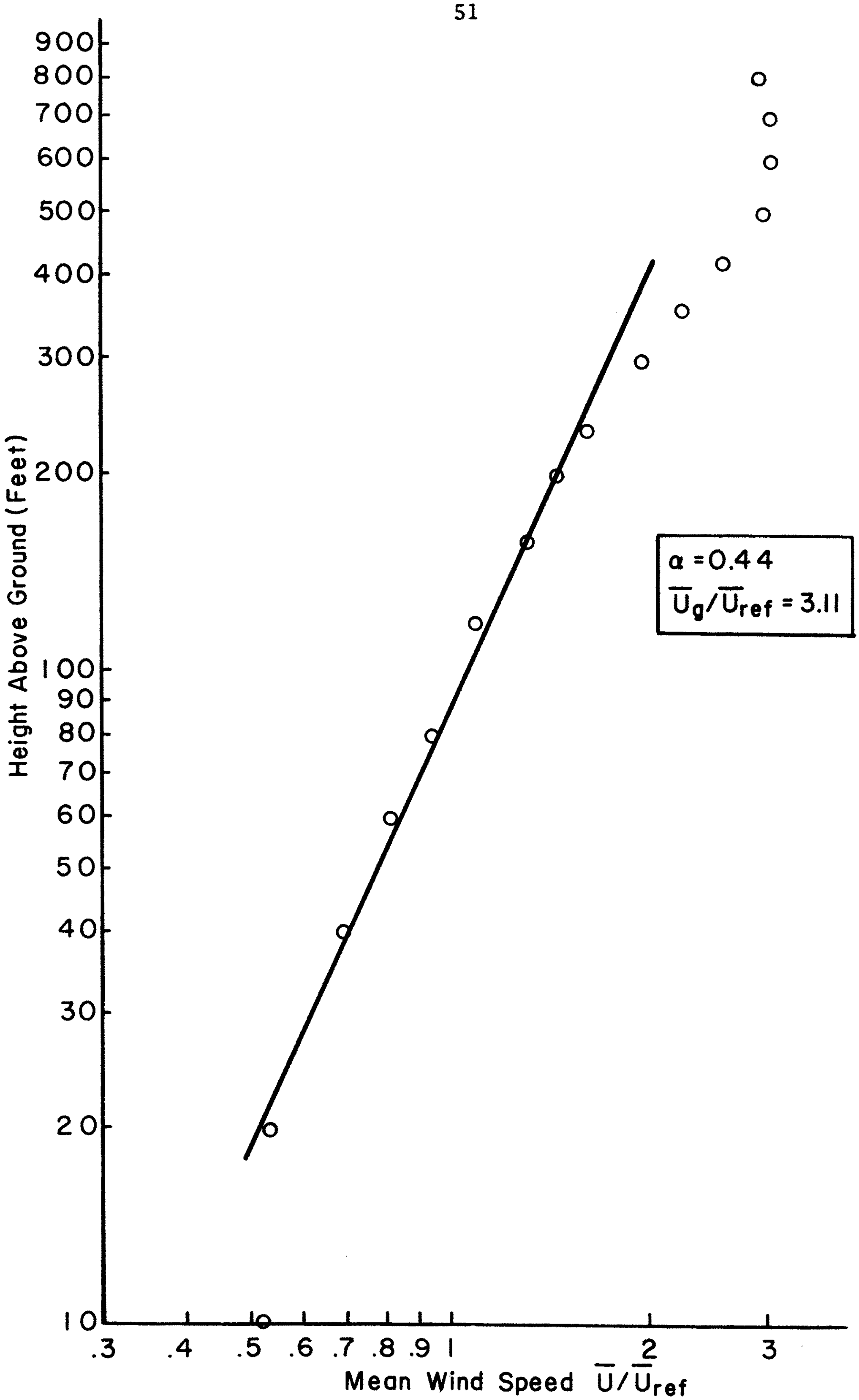


Fig. 18 Log-log plot of the mean wind profile of Fig. 14. (south wind)

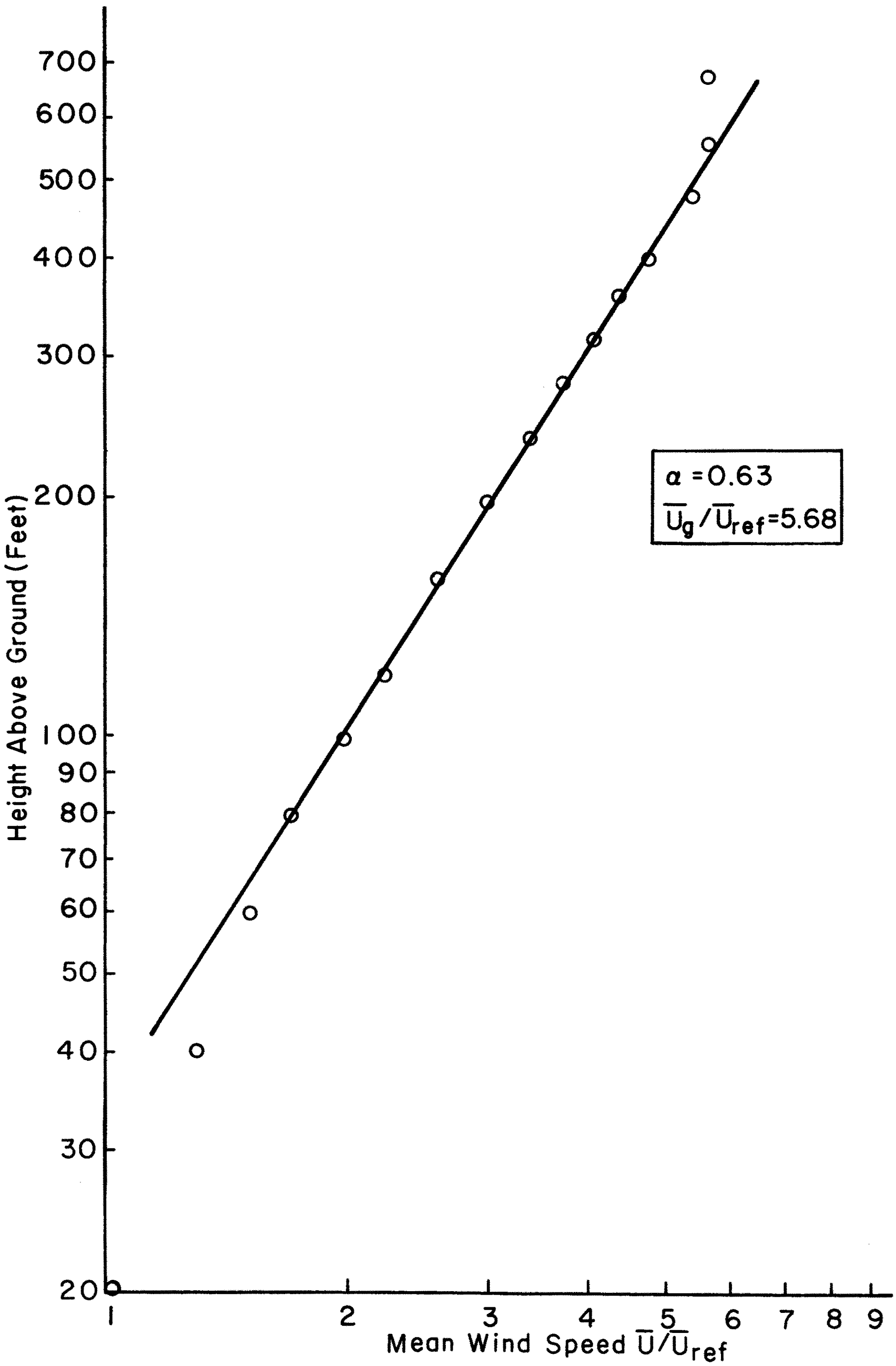


Fig. 19 Log-log plot of the mean wind profile of Fig. 15. (west wind)

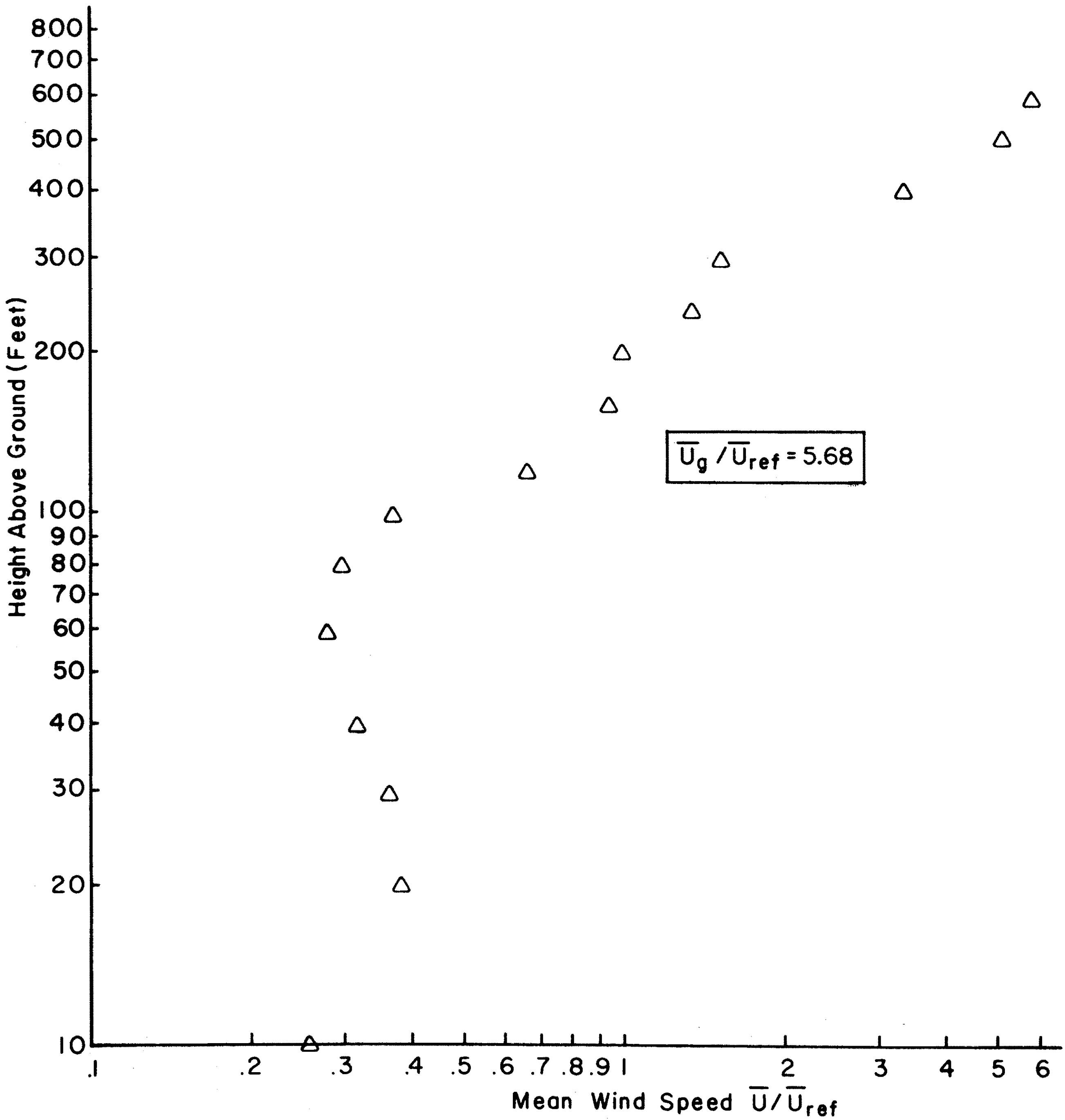


Fig. 20 Log-log plot of the mean wind profile of Fig. 16. (northwest wind)

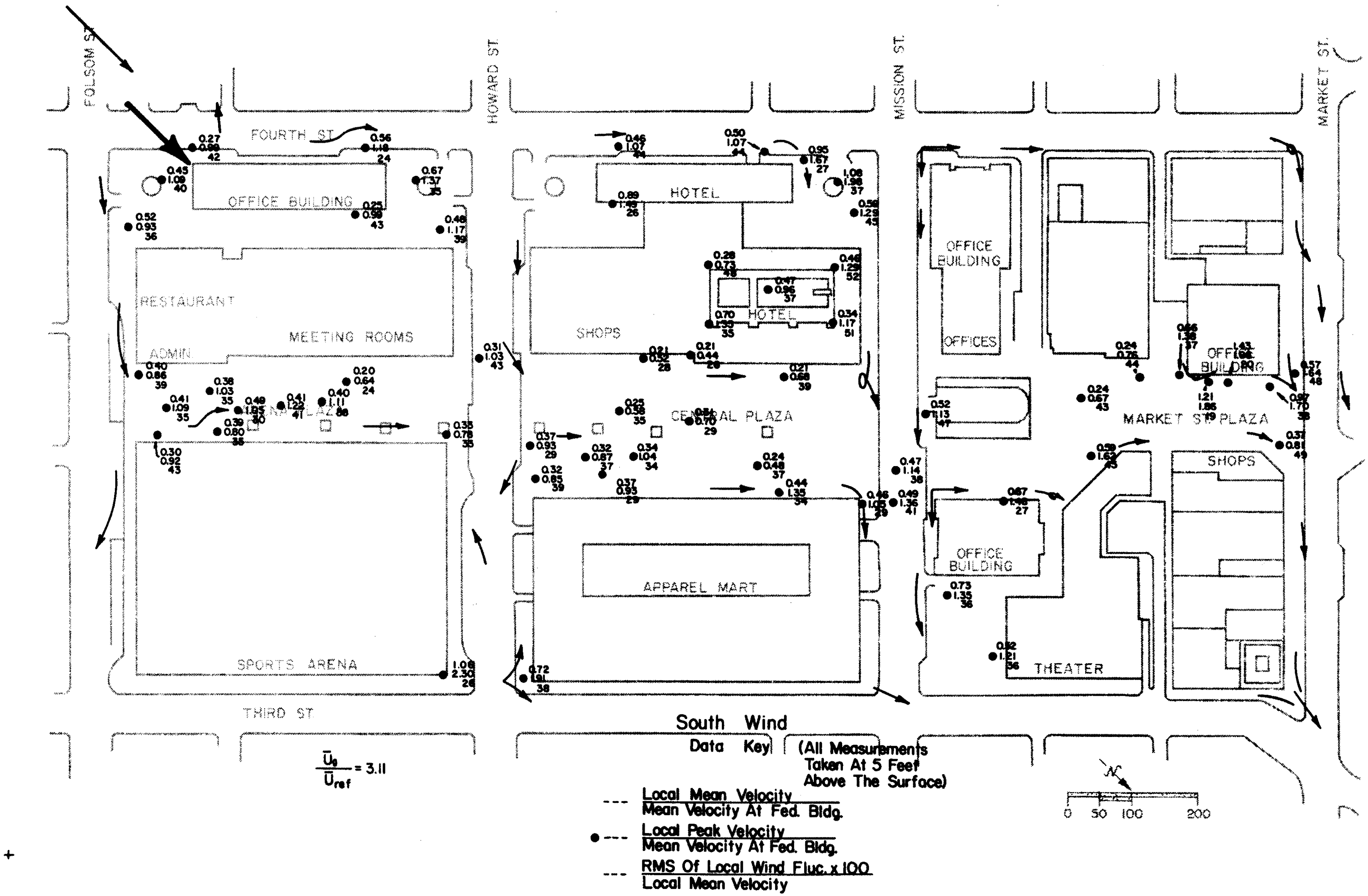


Fig. 21 South wind flow through the Yerba Buena Center.

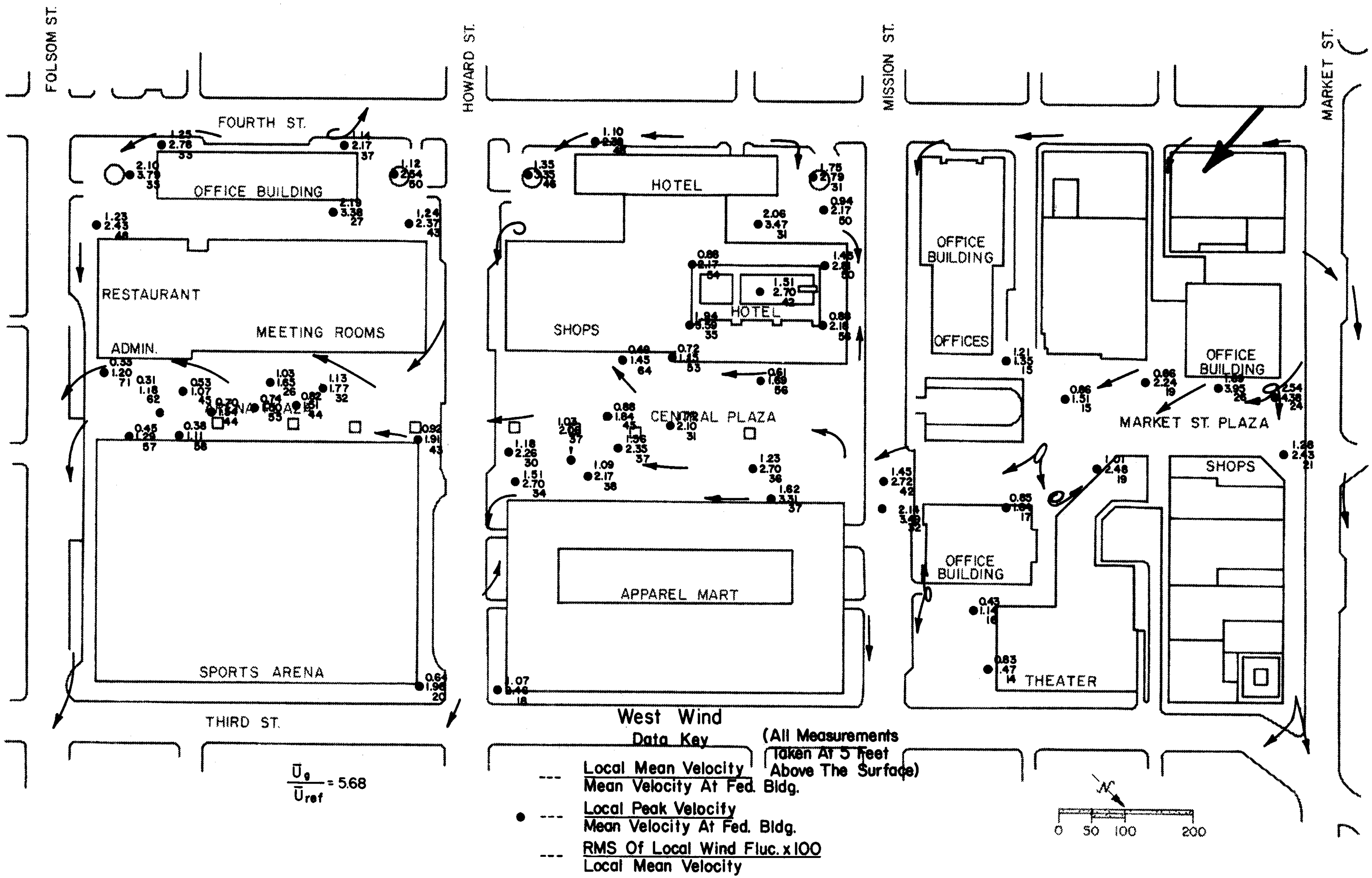


Fig. 22 West wind flow through the Yerba Buena Center.

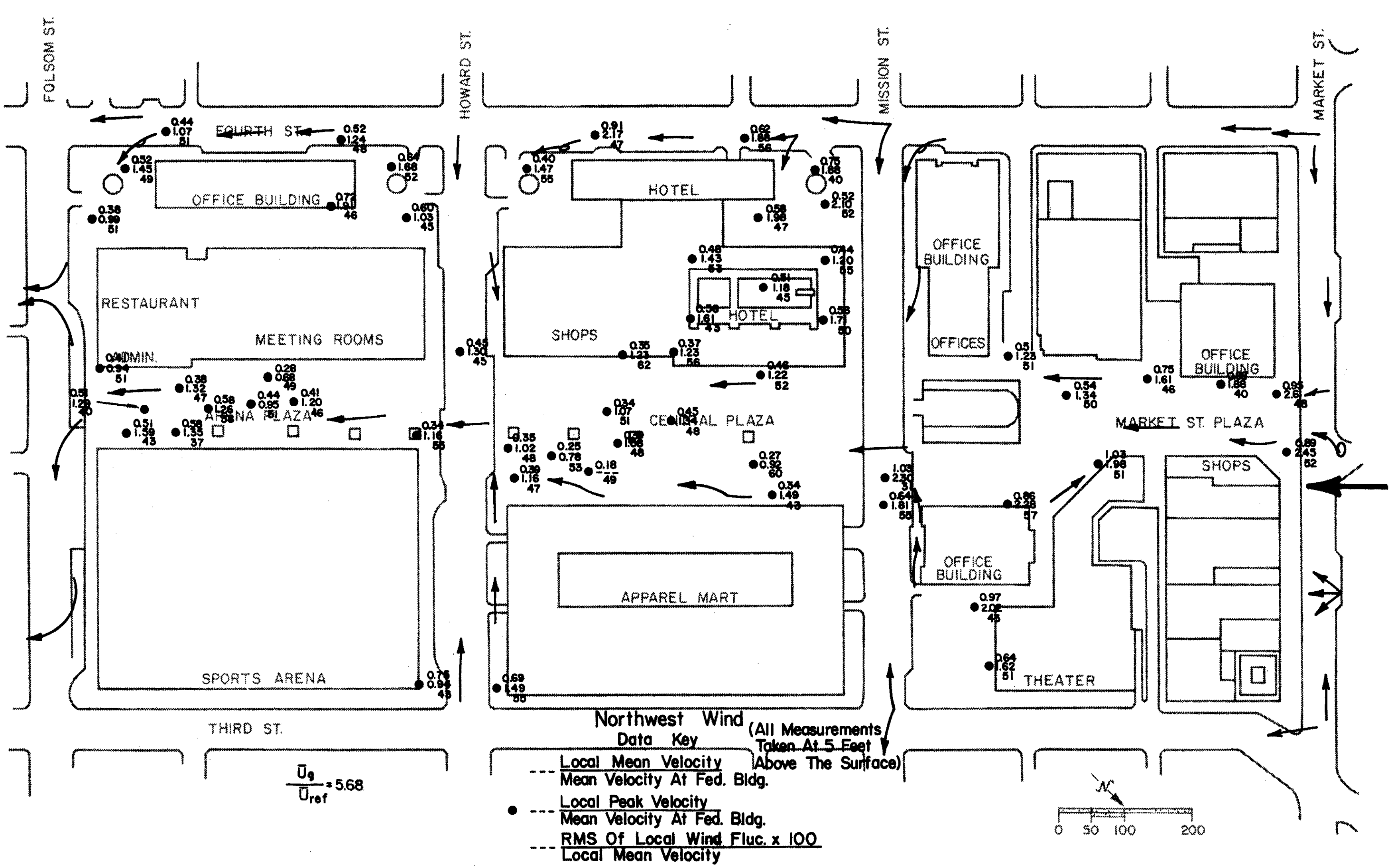


Fig. 23 Northwest wind flow through the Yerba Buena Center.

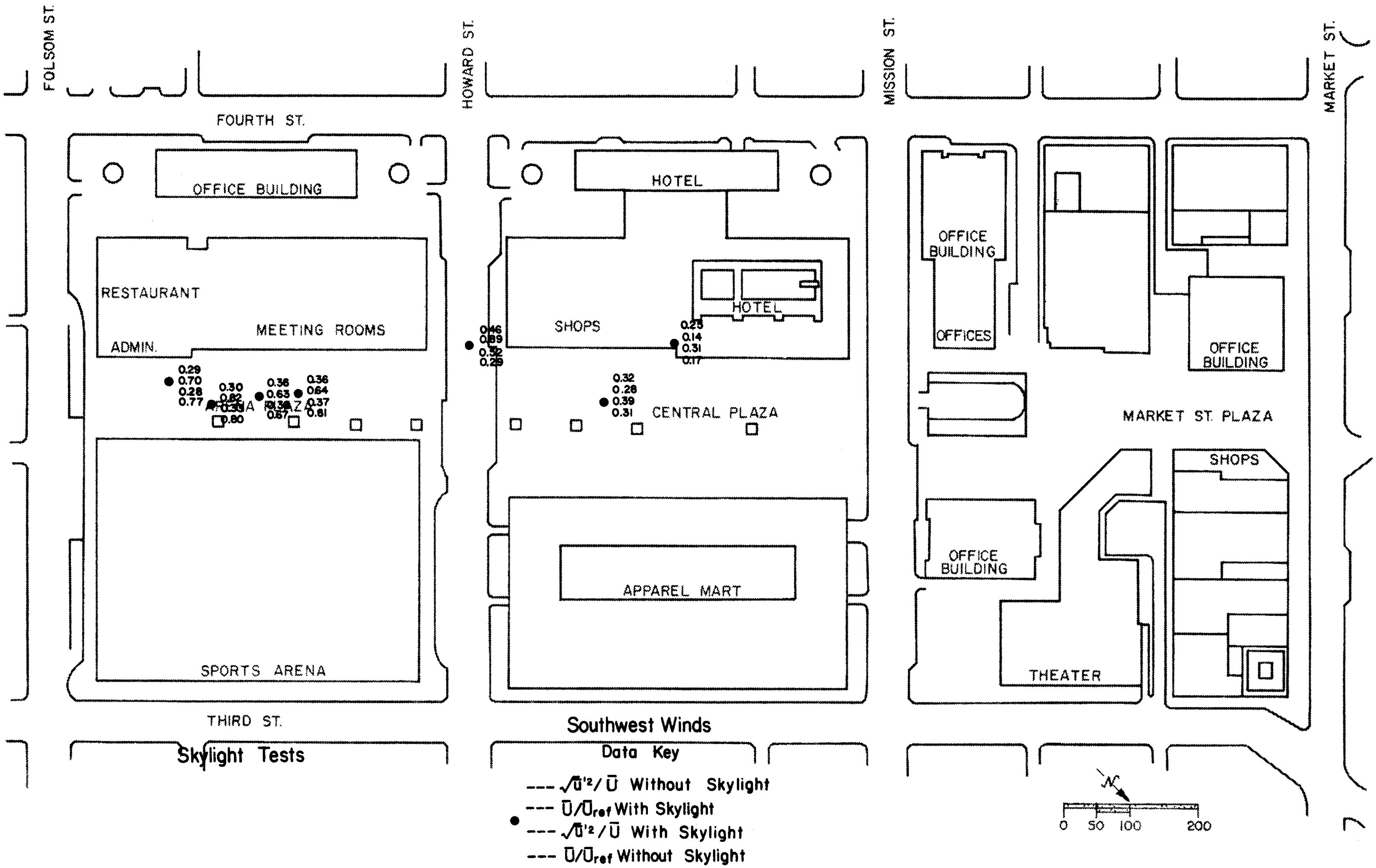


Fig. 24 Skylight test results for the south wind.

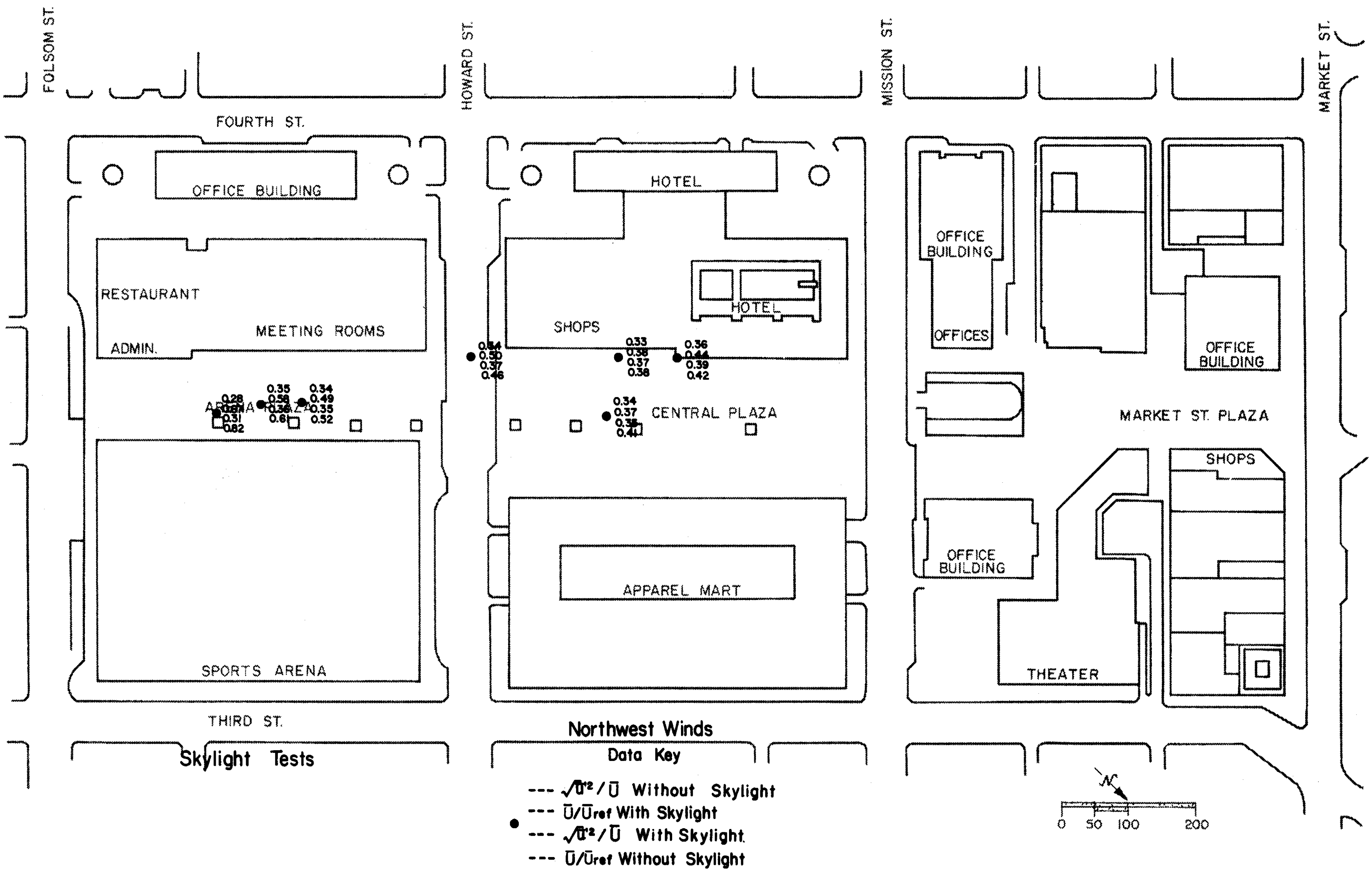


Fig. 25 Skylight test results for the northwest wind.

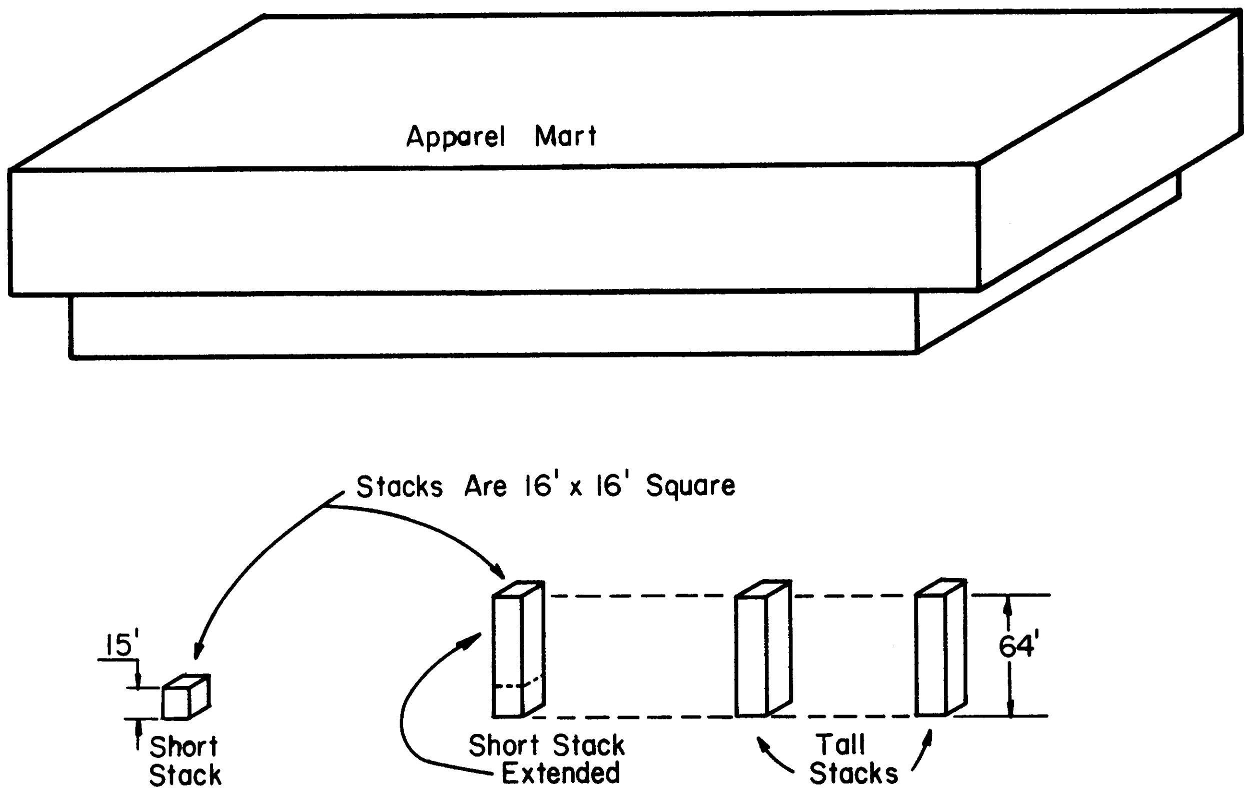


Fig. 26 A schematic showing the three stack configurations tested.

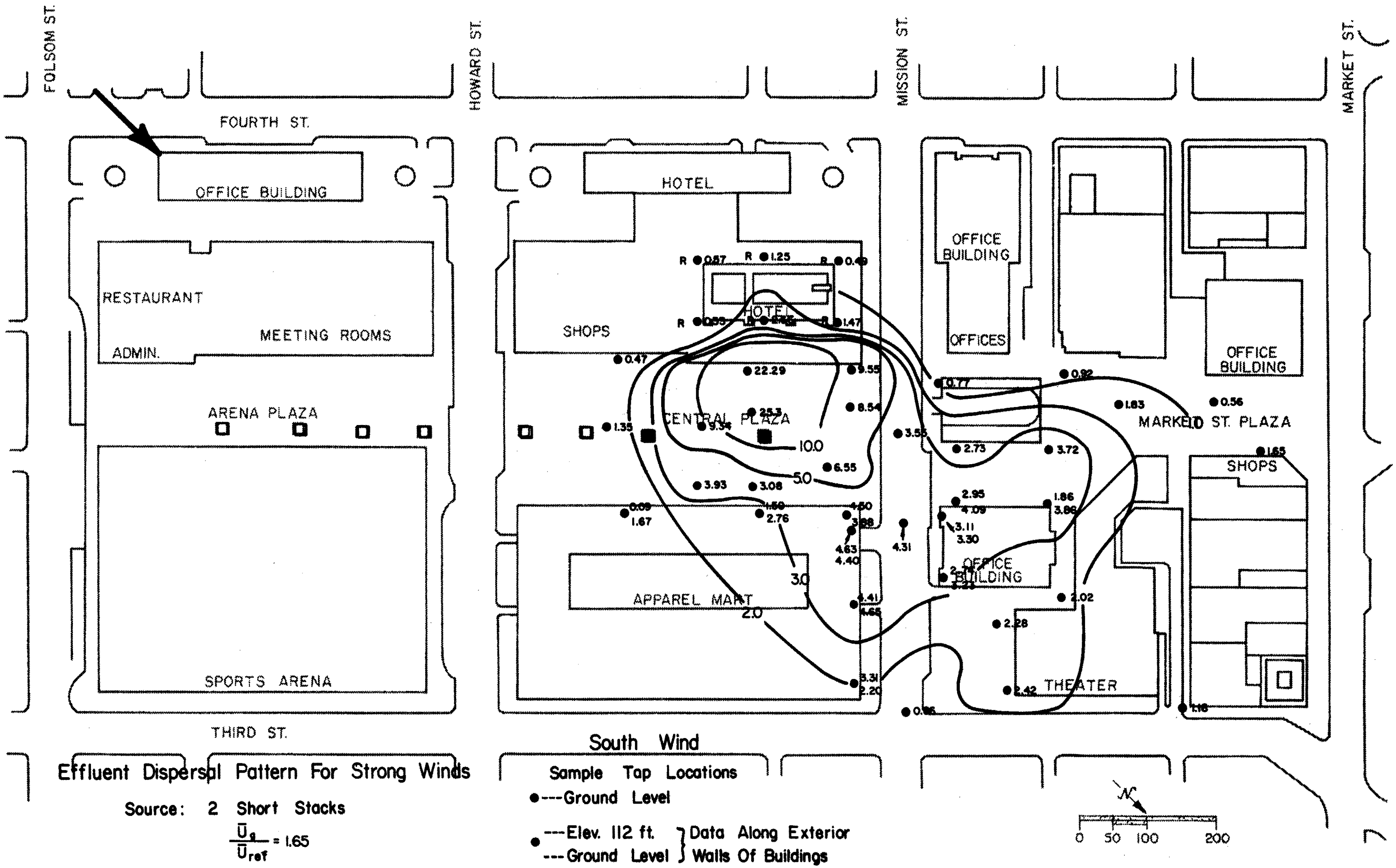


Fig. 27 Diffusion from two short stacks in a strong south wind.

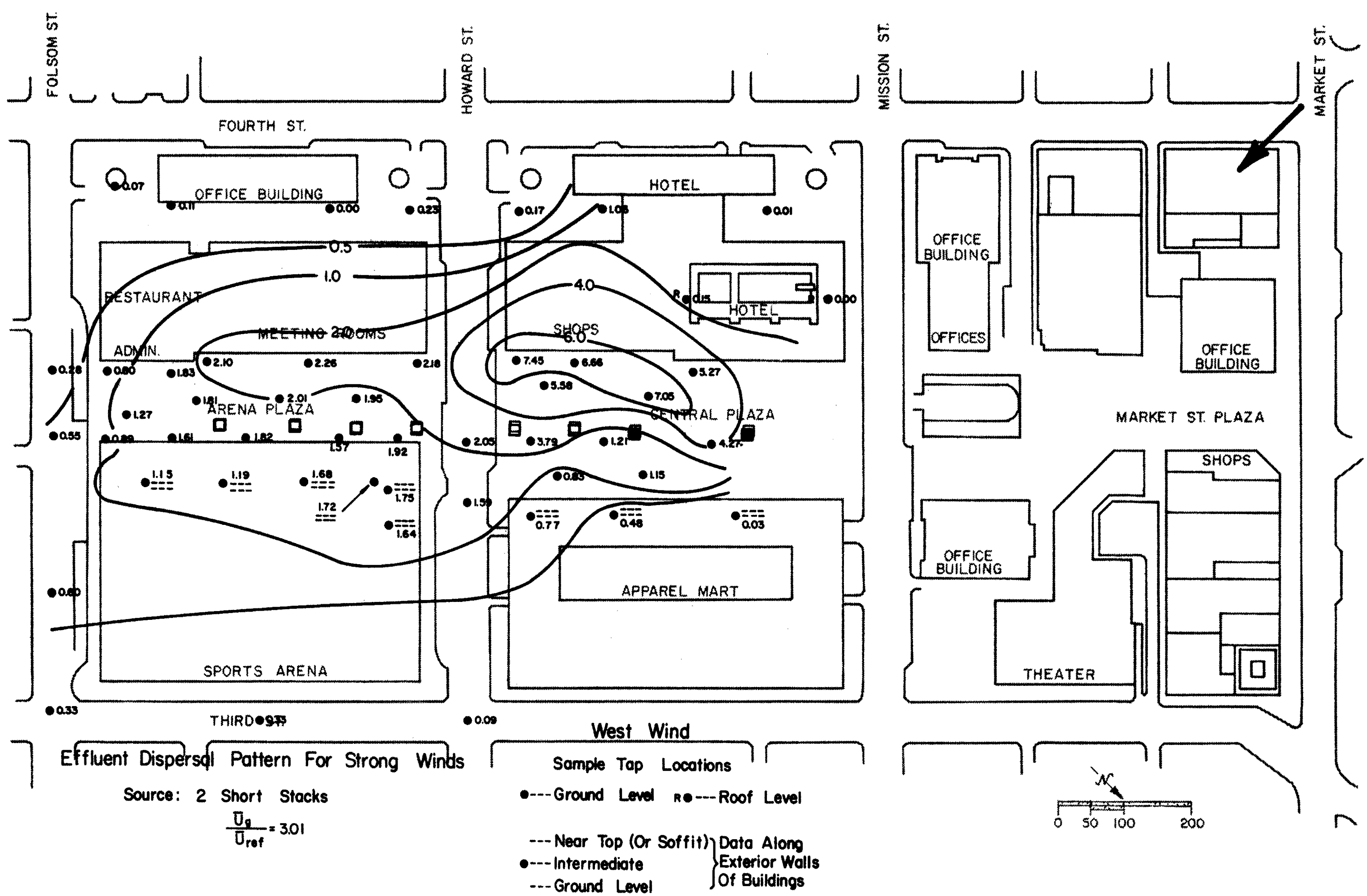


Fig. 28 Diffusion from two short stacks in a strong west wind.

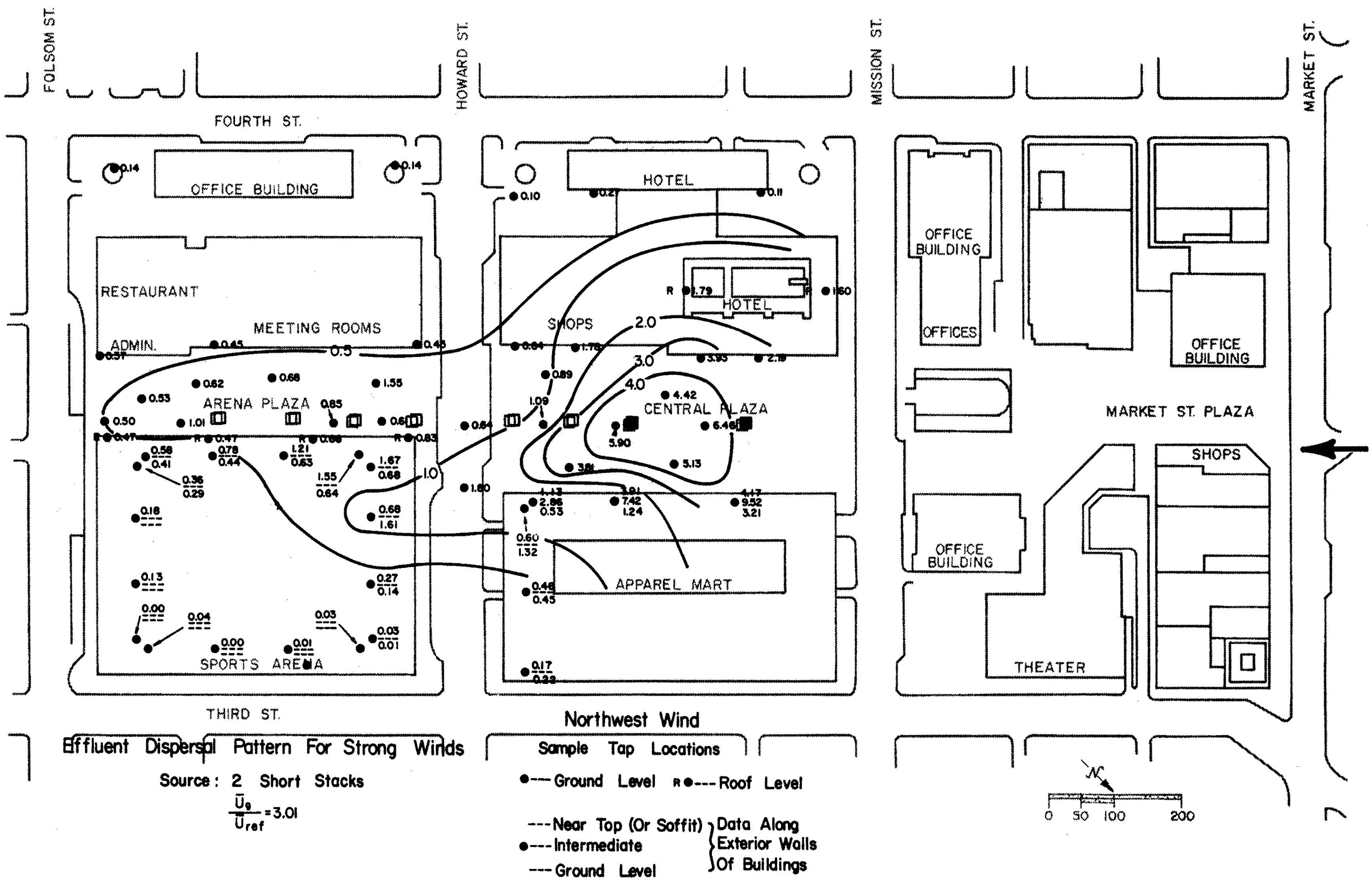


Fig. 29 Diffusion from two short stacks in a strong northwest wind.

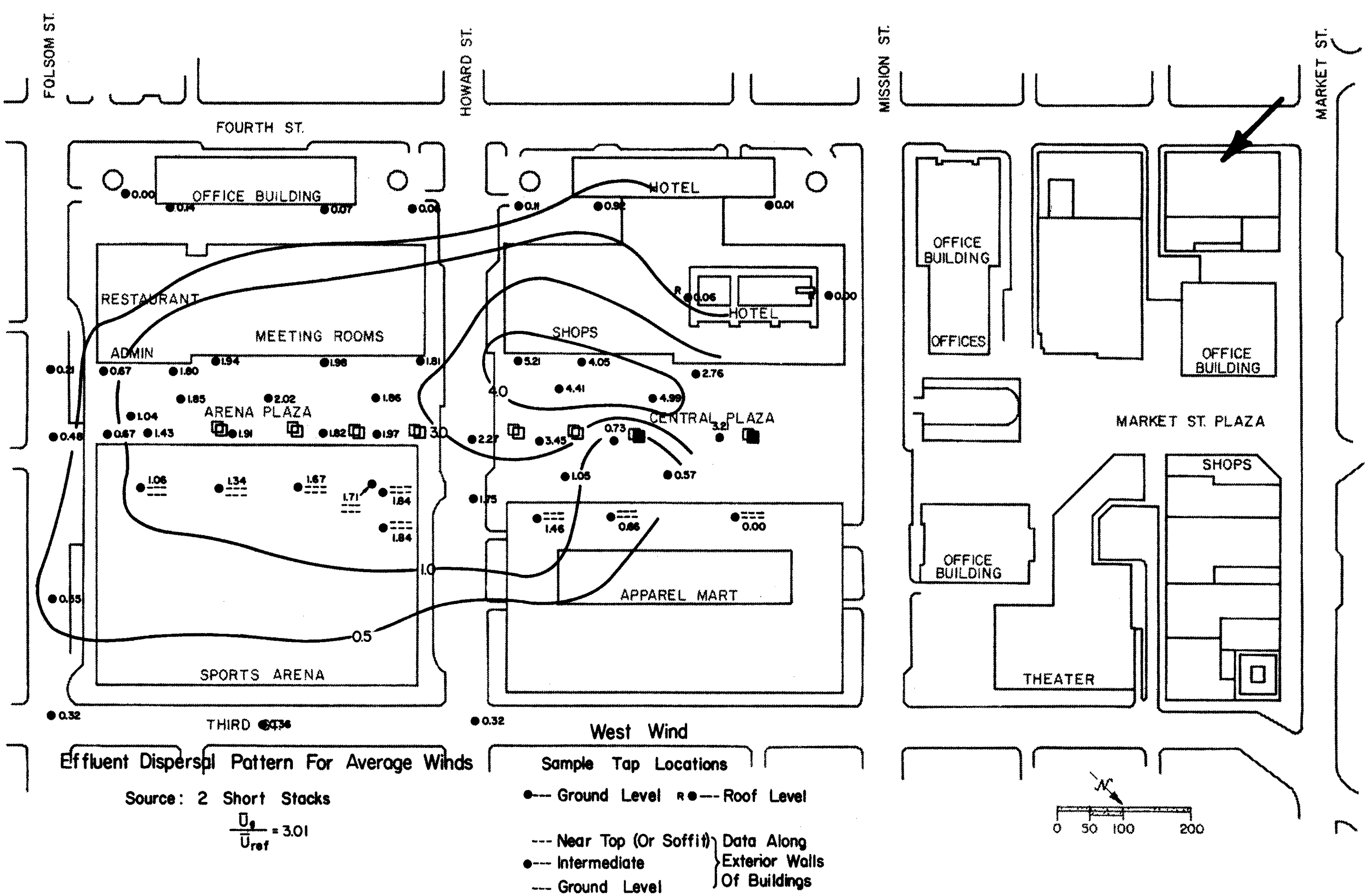


Fig. 30 Diffusion from two short stacks in an average west wind.

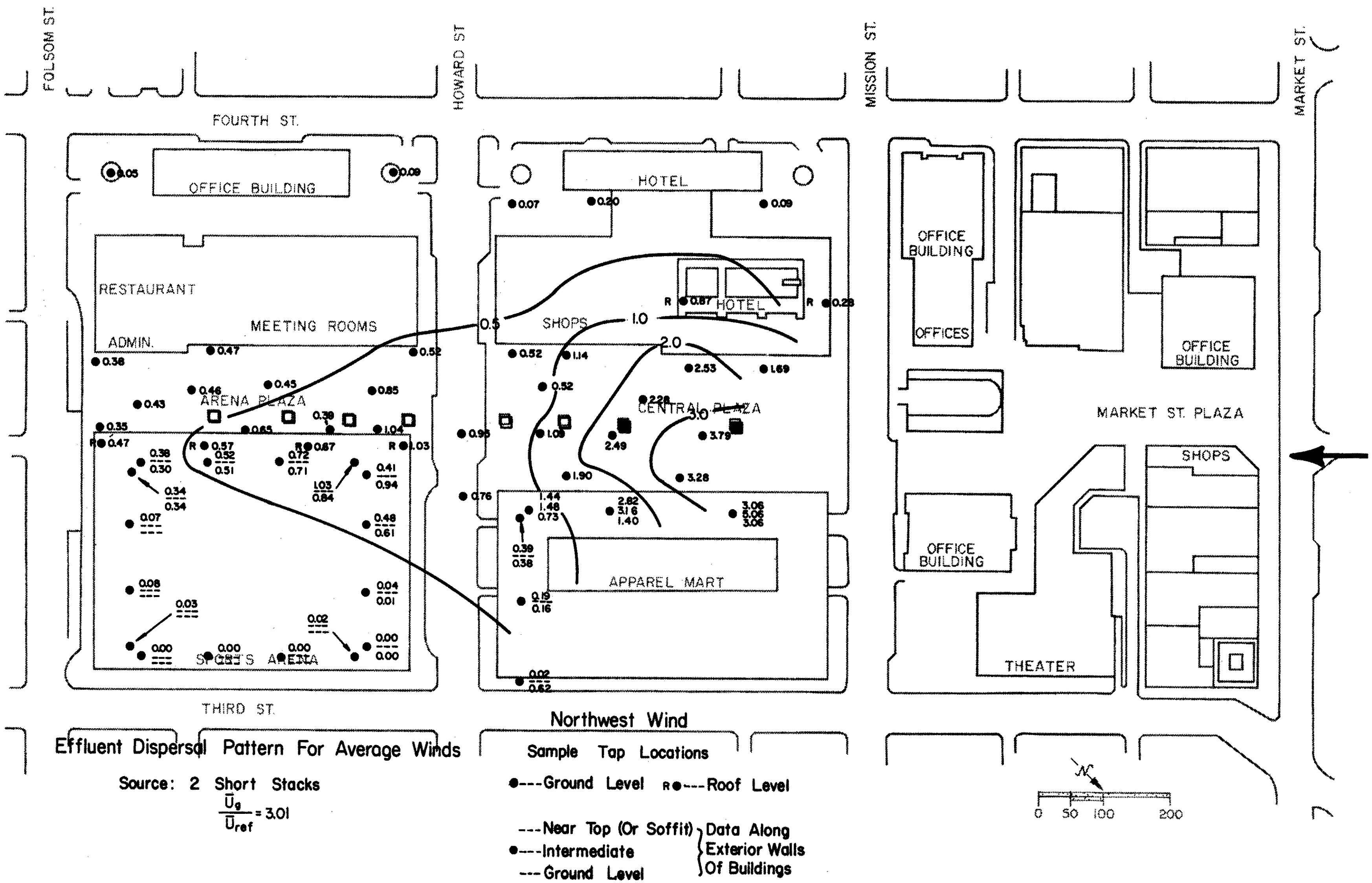


Fig. 31 Diffusion from two short stacks in an average northwest wind.

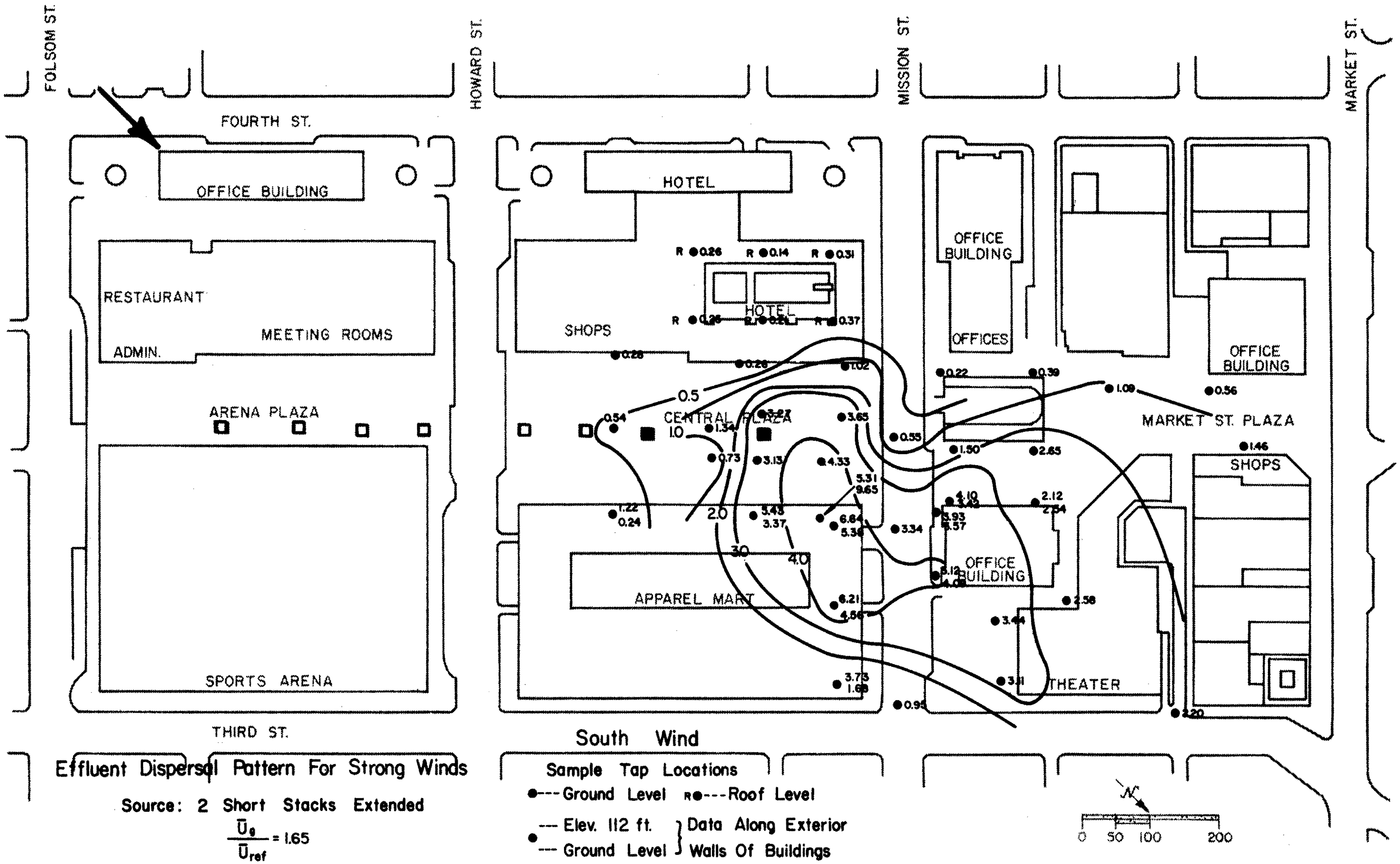


Fig. 32 Diffusion from two extended stacks in a strong south wind.

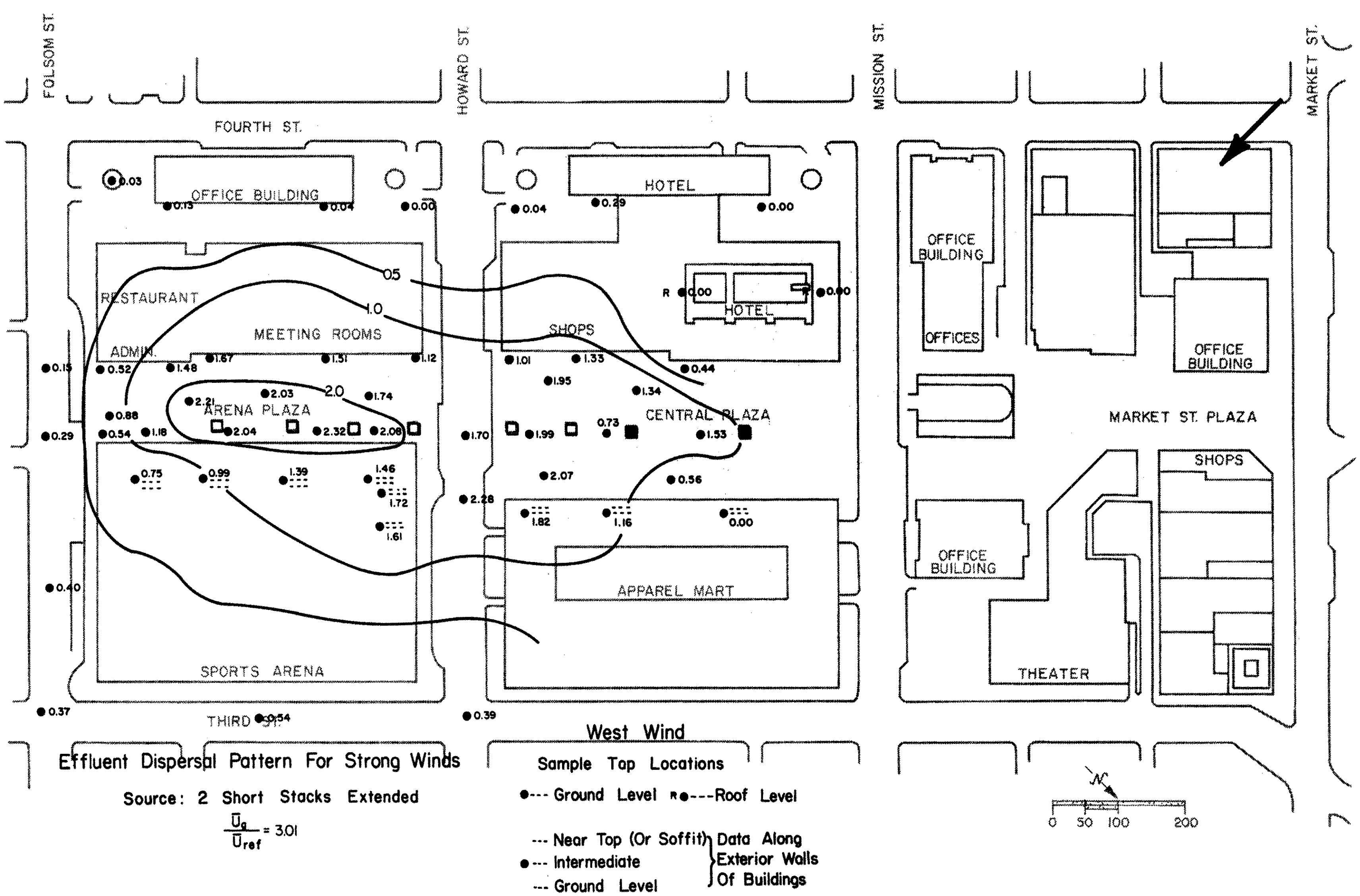


Fig. 33 Diffusion from two extended stacks in a strong west wind.

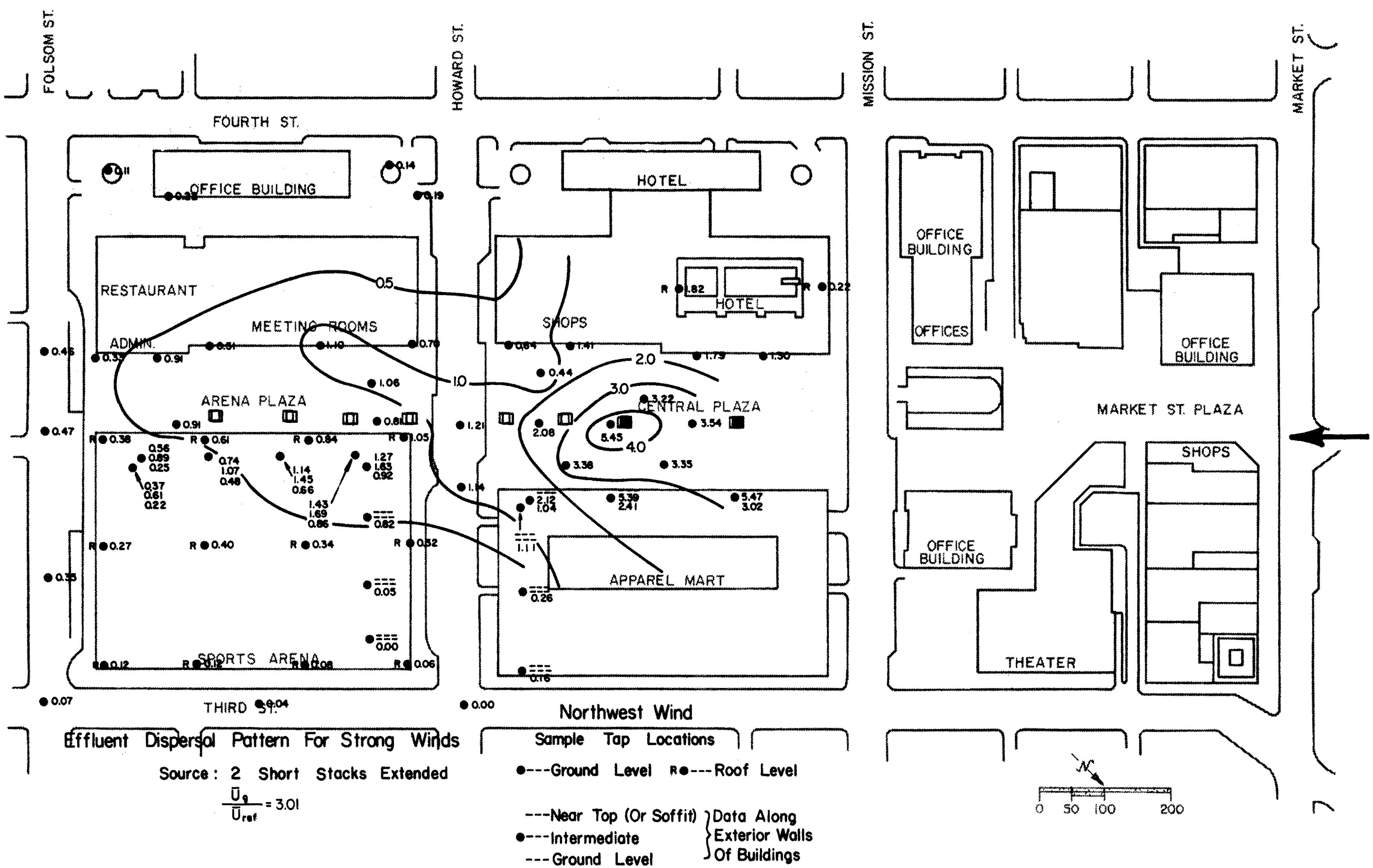


Fig. 34 Diffusion from two extended stacks in a strong northwest wind.

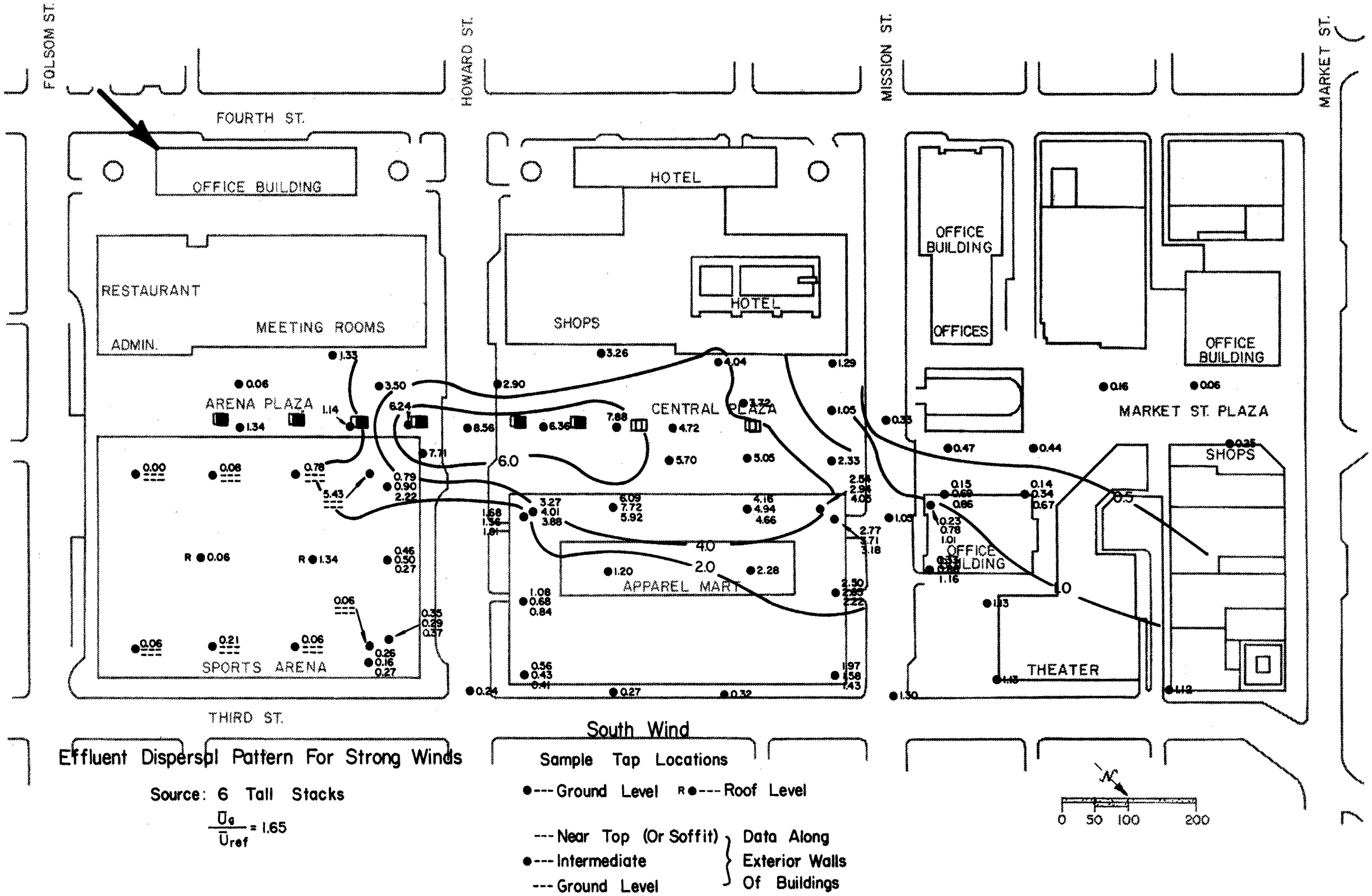


Fig. 35 Diffusion from six tall stacks in a strong south wind.

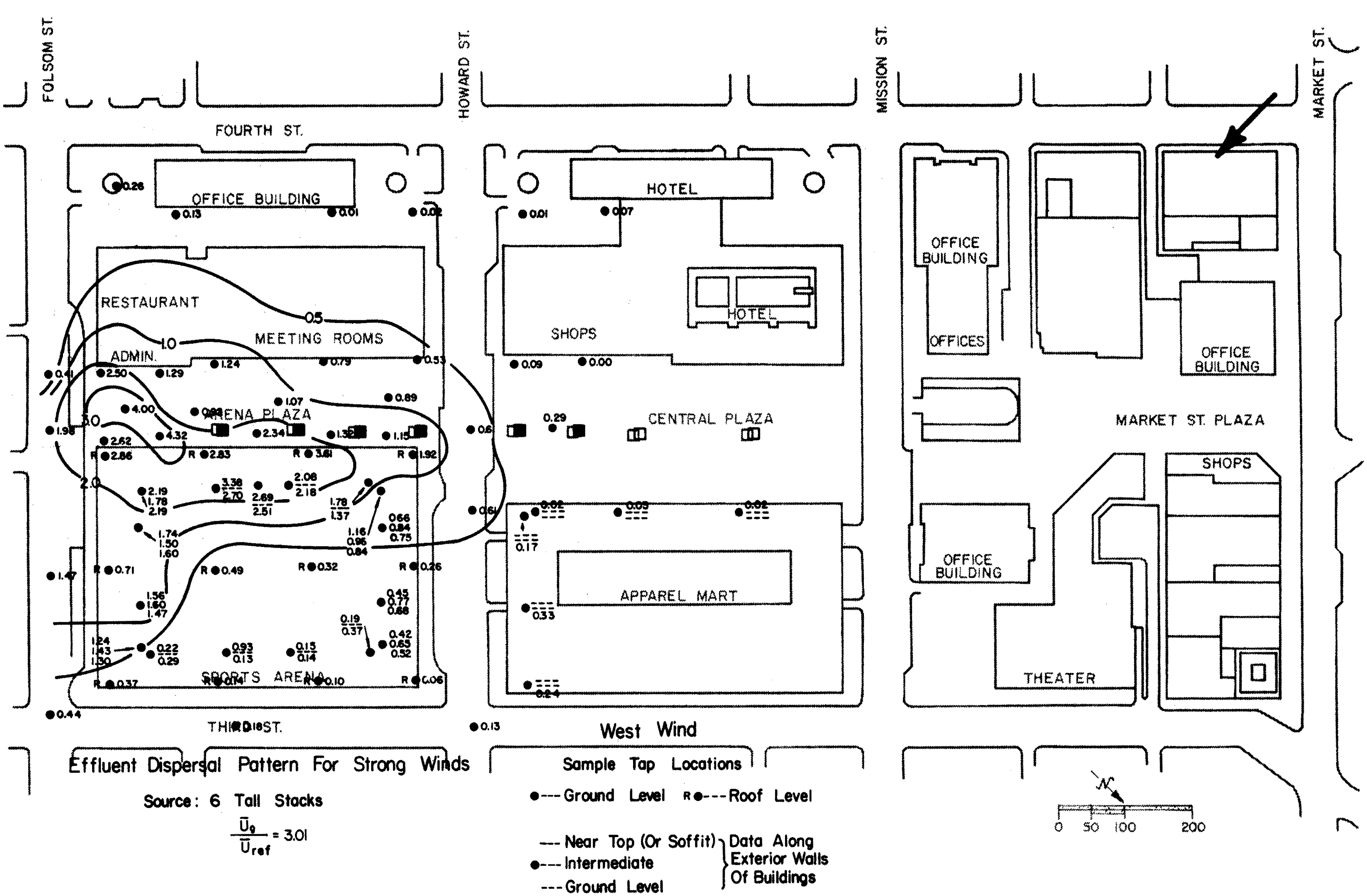


Fig. 36 Diffusion from six tall stacks in a strong west wind.

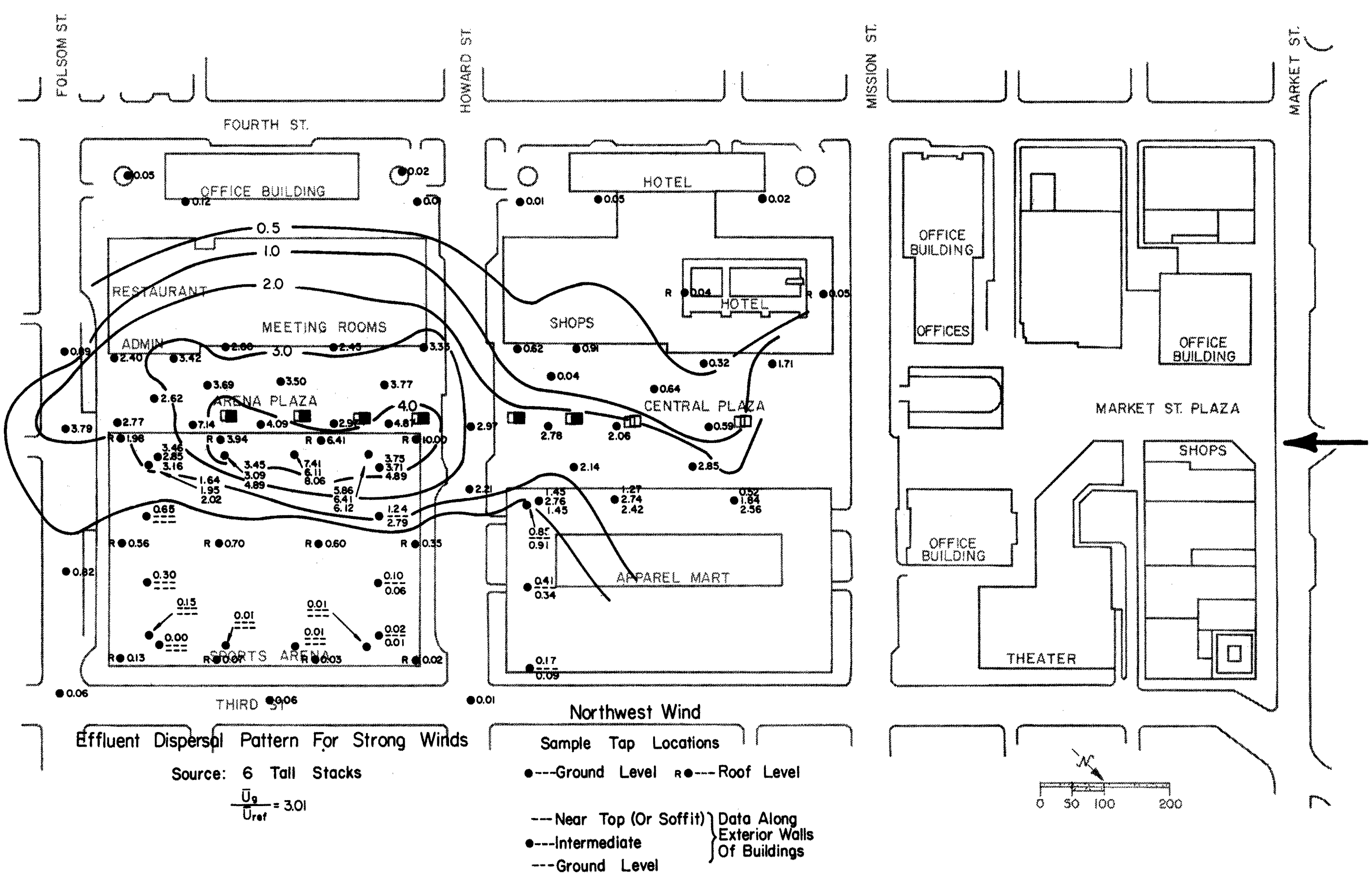


Fig. 37 Diffusion from six tall stacks in a strong northwest wind.

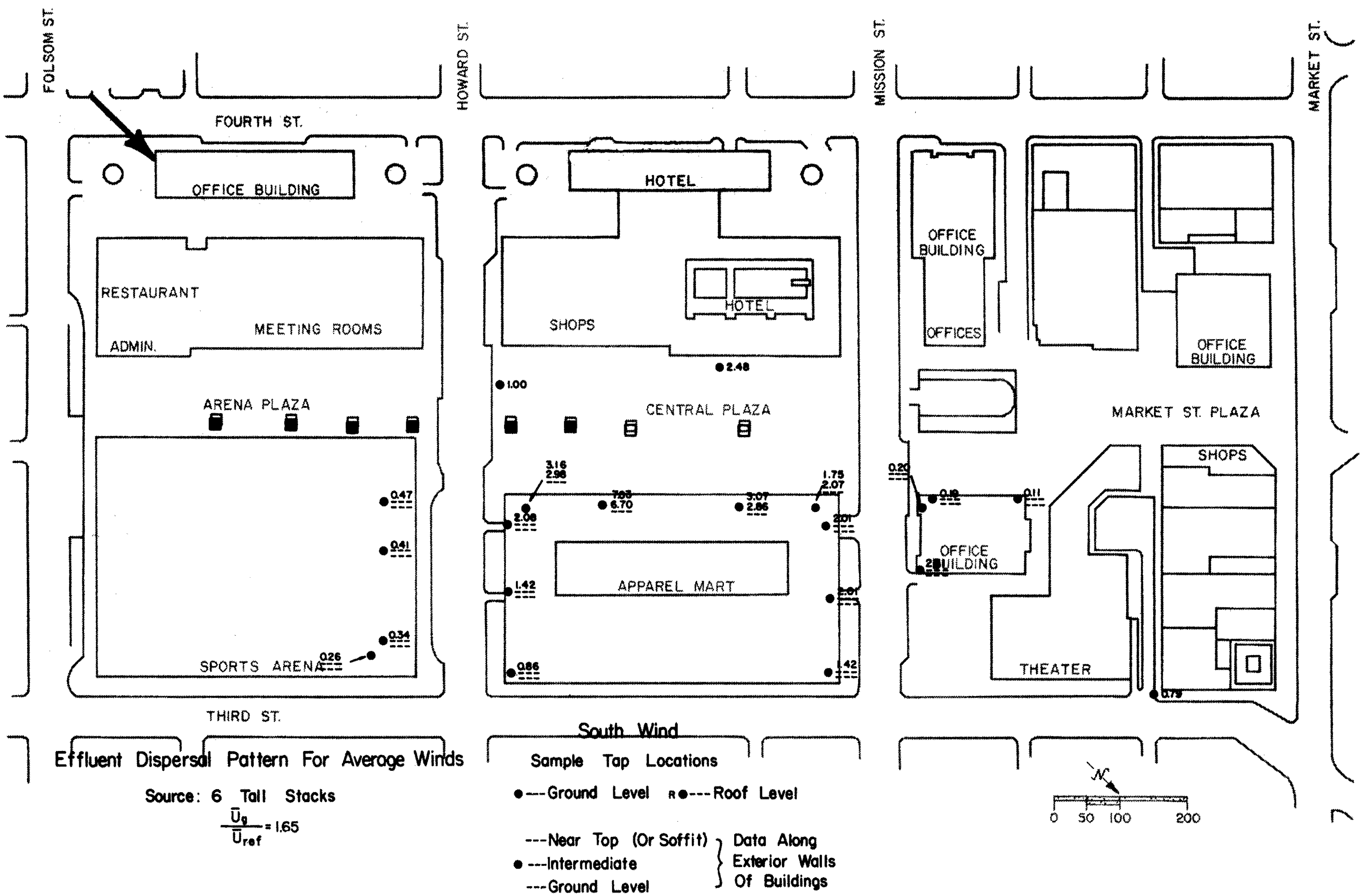


Fig. 38 Diffusion from six tall stacks in an average south wind.

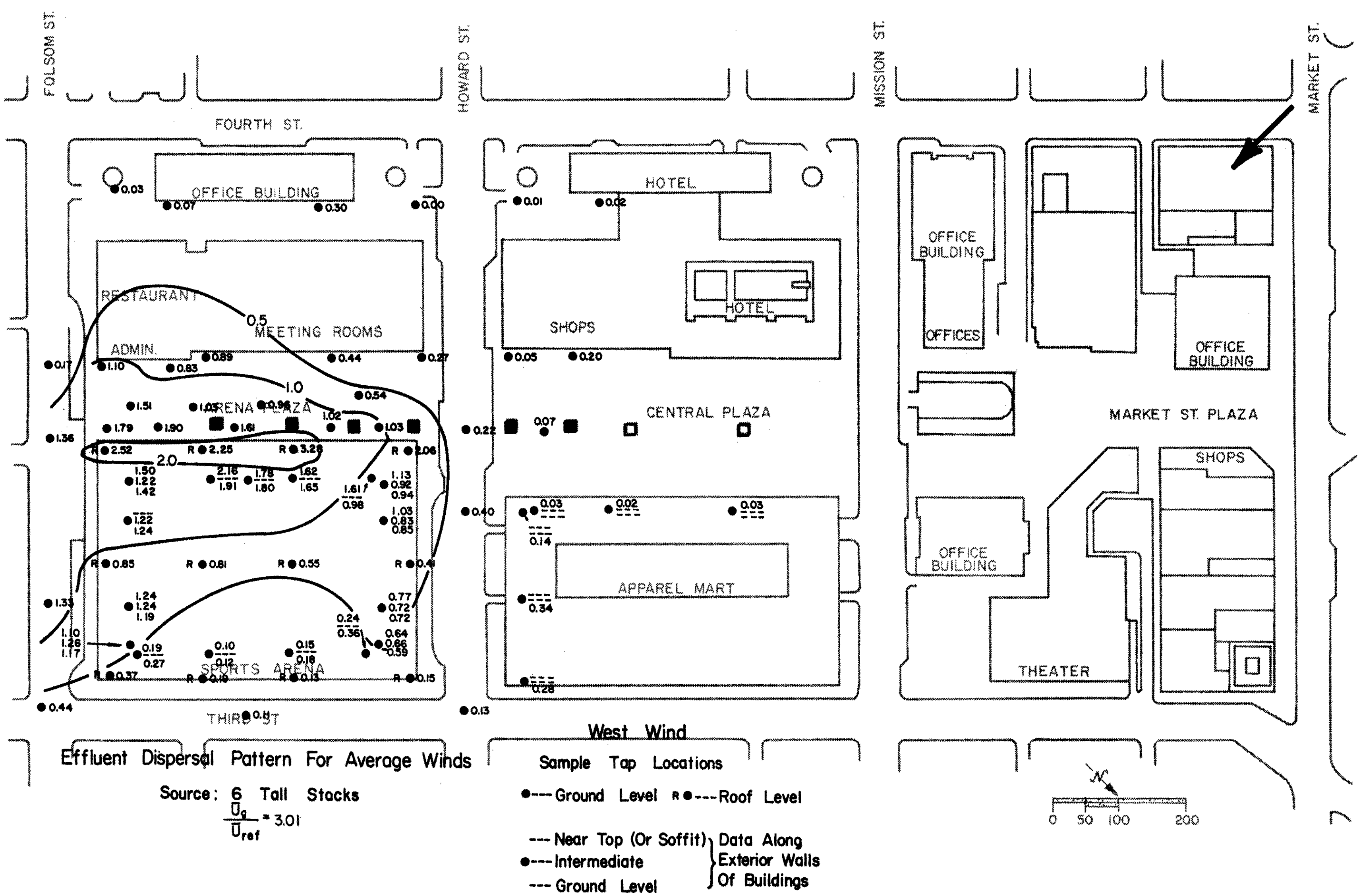


Fig. 39 Diffusion from six tall stacks in an average west wind.

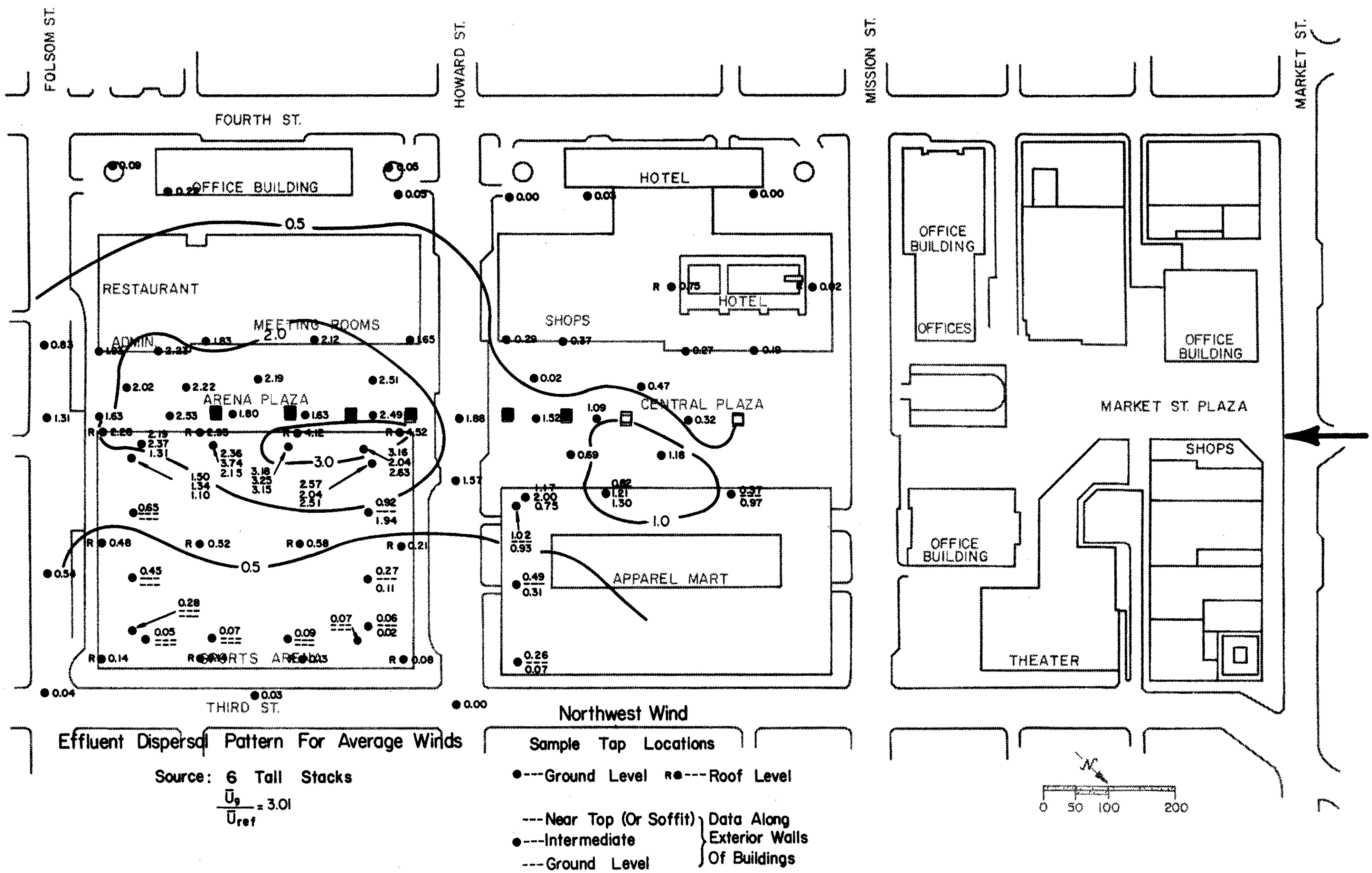


Fig. 40 Diffusion from six tall stacks in an average northwest wind.