APPLICATIONS OF PHYSICAL MODELING TO THE INVESTIGATIONS OF AIR POLLUTION PROBLEMS IN URBAN AREAS

by

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36

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ABSTRACT

Wind tunnel modeling of atmospheric flow and diffusion in the boundary layer over an urban area are discussed. Measurements were made over a model of an urban area composed of a network of uniform city blocks and streets. Two line sources emitting a radioactive tracer gas represented automobile emissions in a one-block length of a city street. Pollutant concentrations were calculated from samples of the tracer gas collected on building faces, in street canyons, and in the flow field above the model. Non-dimensionalized concentration patterns were constructed from the analysis of the samples. Three wind directions were considered. The effects of a simple modification of the uniform model were evaluated.

Introduction

Wind tunnels have been used traditionally in experimental investigations of airfoil and aircraft characteristics. This paper describes the use of wind tunnels in modeling the atmospheric boundary layer over urban areas for the purpose of investigating pollutant transport characteristics.

The transport study was made in conjunction with the National Science Foundation Tri-University Airborne Lead Research Project. The urban area studied was an idealization -- a city network of uniform street canyons and city blocks. Line sources in city streets were used to simulate ground-level auto emissions. A tracer gas was released and sampled at various points downwind to determine time-averaged values of the contaminant levels in the wind-tunnel atmosphere.

The dispersion of contaminants released at the street level of an urban area is strongly influenced by local topography, buildings that surround the streets and local climatological factors (e.g. thermal stratification and wind velocity). The primary variables in this study are the local geometry of the buildings and the wind direction. Two primary transport mechanisms are active -- turbulent and advective transport. The major objective of the study was to develop a method for predicting pollutant concentrations in city streets when the source characteristics, local geometry and meteorological conditions are prescribed.

The data presented were measured in the Colorado State University environmental wind tunnel. This environmental tunnel (Figures 1 and 2) is an open-circuit wind tunnel with a cross section of 3.7 m by 2.4 m. The test section is 18 m long. This facility is used primarily for simulation of neutrally stable atmospheric flows, as was the case for this study.

Study of contaminant dispersal by means of physical modeling entails the construction of a model with urban features; such as buildings, streets, hills, etc.; the development of the appropriate approach flow conditions; installation of sources for tracer gas release; measurement of wind and temperature profiles; sampling over an array of points; and the analysis of gas samples to determine the tracer gas concentration. These facets of the study are described and some of the data obtained are presented in the following sections.

Criteria and Techniques for Physical Modeling

Modeling the atmospheric boundary layer requires that certain similarity conditions be satisfied. The requirements for similarity of the atmospheric and wind-tunnel boundary layers can be obtained directly from the fundamental equations for conservation of mass, momentum and energy. These requirements have been formulated by Cermak[1] for boundary layers which are stable, neutral or unstable over the entire boundary-layer depth. The requirements which must be met for an exact wind-tunnel simulation of an atmospheric flow and their allowable relaxations are outlined in Table 1.

Many previous studies, such as those by Cermak and Peterka,[2] Chaudhry and Cermak,[3] Teunissen[4] and Halitsky[5] support the use of wind tunnels in atmospheric simulations of this type. Comparisons of their laboratory data with field data show good agreement.

The approach flow characteristics in the wind tunnel were adjusted to simulate those in the atmosphere. The mean velocity and turbulence intensities (15% near ground level) approximate those found in the atmosphere. Finally, the longitudinal pressure gradient was eliminated by adjusting the test-section ceiling height so that flow (above the boundary layer) did not accelerate through the test section.

The parameters that were monitored in this study are

1. mean wind speeds and directions,
2. turbulence intensities,
3. turbulence spectra, and
4. mean concentration distributions resulting from continuous line sources located in the street canyons.

A city model of uniform blocks and uniform streets shown in Figure 2 was built to a scale of 1:200 and located in the 18.3 m long and 3.7 m wide test section of the wind tunnel. The city blocks are 20.3 x 20.3 x 5 cm and the streets are 7.6 cm wide. The blocks were constructed of styrofoam. The 6.1 m upwind fetch developed a boundary layer about 0.6 m thick which corresponded to a 130 m atmospheric boundary layer.

The overall character of the flow was recorded on motion pictures using the smoke from titanium tetrachloride as the tracer. These films* demonstrate the complexity of flow over the street canyons and buildings. Of particular interest is the formation of vortices in the street canyons and their movement down the streets. An irregular transport of smoke over the building tops is also observed. The smoke visualizations also provide information for selecting significant positions in the city network for measurement of concentration distributions.

Located about 6.7 m downwind from the beginning of the model are plexiglas data-acquisition blocks (Figure 3). There are approximately 80 sampling ports located on the building faces and plexiglas streets in the vicinity of the traffic lanes. Also built into the data-acquisition model are two line sources embedded in the streets. The line sources are shown in Figure 3 and the method in which they are constructed is shown in the insert of the same figure. These sources simulate two lanes of traffic through one city

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*Available on loan.

block. Radioactive Krypton-85 was emitted as a tracer gas into the wind tunnel atmosphere through these sources.

The Kr-85 tracer is used in a highly diluted mixture with air. Sampling was accomplished by an array of probes which simultaneously drew up to twenty-five samples. Each sample was drawn into a glass bottle as water was displaced from the bottle. Individually, each sample was transferred to a lead enclosed chamber containing a stainless steel jacketed Geiger-Mueller tube. Radioactivity levels (tracer concentration) were determined by reading the G-M tube output. This system designed by Chaudhry,[3] enables the mean concentrations to be determined for steady sources. Because of long sample lines and large volumes of sample gas required (125 cc) unsteady concentration fields cannot be measured by this method.

Samples of contaminant levels were drawn through the sample ports on the data-acquisition model. Samples were also drawn at locations downwind from the source by the use of adjustable rakes. The rakes were composed of small tubes that can be located at a variety of positions on the model.

Measurements of mean velocities and turbulence were made with a hot-wire anemometer. The hot-wire anemometer was suspended from a motorized carriage to allow detailed analysis of the turbulence at several locations in the flow field above the model. The boundary-layer development over the idealized urban area is shown in Figure 4. The mean velocity distributions are plotted for various test section locations.

Concentration Distributions

Samples to determine the pollutant (Krypton-85) level were collected in four specified areas as follows:

1. on the faces of blocks that surround the sources,
2. at street level in the vicinity of the sources,

3. at street level over a large area downwind from the sources and
4. at points above the blocks for various distances downwind from the sources.

These measurements were made for three wind directions. Only neutrally stable atmospheres have been investigated.

To facilitate the analysis of the data (and for purposes of comparing the laboratory results with field data), nondimensional concentration coefficients are defined by the relation $C = \chi UH/(Q/L)$ where C is the nondimensional concentration coefficient, U is the mean wind speed at the block height, H is the block height and Q/L is the source strength per unit length of the source. The concentration determined from the gas samples extracted from the wind tunnel are denoted by χ .

Sufficient data were taken to plot profiles of concentration coefficients at various locations on the model. Figures 5 through 12 are examples of the concentration distributions formulated from measurements taken in the laboratory for different wind directions.

Figure 5 illustrates the distribution of concentration with downwind distance in the vertical plane, parallel with the wind direction, that intersects the midpoint of the line sources. Of note are the large concentration gradients. A fairly symmetrical cross-section concentration pattern in the street centered vertical plane is exhibited in Figure 6. This is a reasonable result in view of the fact that the model is symmetrical. The wind direction for this distribution is into the page. These are a composite of measurements made one block downwind from the line sources. Of note are the large plume width and the large vertical concentration gradient.

The drastic effects of the canyon geometry on concentration distributions are seen in Figures 7 and 8, for the case of the line source oriented perpendicular and parallel to the wind direction, respectively. When the wind direction is at a 45° angle with the line source, concentration profiles develop as shown in Figure 9. For both wind normal and at 45° to the source (Figures 7 and 9) higher concentrations develop on the upwind face. This is due to mass transport by the canyon vortex.

Attempts to determine the effects caused by a simple modification of the model were also made. Figure 10 can be contrasted with Figure 7 to note the effects of a single tall structure. This geometrical nonuniformity induces stronger vertical mixing and generally a reduction of concentrations in the canyon.

The decay of concentration coefficient with downwind distance is logarithmic. Figure 11 shows the values of C for ground level positions at various distances from the sources.

Bearing in mind that the model used is of a city with uniform city blocks and streets, the data taken can be extended to yield more pertinent information about the dispersion of gases in the streets. Since the model is uniform and symmetrical, one can expect that the profile produced by a finite line source would be repeated in any direction if the line source were extended (or displaced) in the same direction. It is also important to note that any finite line source that emits pollutants contaminates not only the street in which it is located, but also streets downwind and to either side of the direction of mean flow. Figure 12 shows ground-level concentrations 2 blocks from the sources. Note the channeling effect of street canyons (wind is into page). The measurements show levels of contamination seven blocks downwind from a source to be two orders-of-magnitude lower than the level over the street containing the source. The plume (plume edge defined by the point at which the concentration is a tenth of the centerline concentration) at a distance seven blocks downwind is three blocks wide.

To obtain a representation of what occurs in a city block with many significant sources of length greater than a single city block, the concentration profiles can be superimposed. Figure 13 shows the profile that results by extending a line source across the extent of the model. These are the results shown in Figure 12 superimposed upon themselves. The profile shown is the ground concentration measured across any one city block two streets downwind of the polluting source.

Superposition can also be made to incorporate the effects of streets that are aligned perpendicular to each other. For example, the profile produced by a source normal to the mean wind can be superimposed upon the profile produced by a source that is parallel to the mean wind. This method yields a composite profile of the concentrations that are measured in any street that is produced by all line sources that affect that street. If the traffic levels of the streets differ significantly, an appropriate linear combination of the effects of each street will provide an estimate of the total pollutant burden at a given site.

The method described above will predict the actual concentration that would be measured at any point in the field in the vicinity of any city block. Its importance lies in the fact that the effect of any major thoroughfare on the surrounding area can be estimated by the use of these results.

Significance

Information of the type obtained in this study is essential to determination of pollutant concentration levels that may develop within the complex street systems of a city. With a knowledge of how city geometry affects movement of airborne pollutants, urban planners can make rational decisions for arrangement of new cities or for urban renewal schemes for existing cities to minimize exposure of urban dwellers to contaminants from automobile exhausts. Results of this study provide the starting point for a comprehensive investigation to determine the effects of topography and more complex geometry (factors not included in this study) upon local dispersion in a city.

Continuing Work

Concentration measurements over a 1:400 scale model of downtown Fort Collins, Colorado are currently in progress for the purpose of making direct comparisons with concentration measurements made at corresponding points in the real city. Additional concentration measurements and flow measurements will be made over the idealized city of uniform blocks for at least four more wind directions. When these measurements are completed the uniform blocks will be modified by adding blocks to represent a distribution of tall buildings in the city. Mean concentration measurements for wind directions studied with the uniform blocks will be made.

A computer program is being formulated to construct the superposition of concentrations for a network of line source segments of varying source strength. This will make maximum use of laboratory data and provide a means for determining the effects of high density traffic arteries on surrounding portions of the city.

Concluding Remarks

Some general statements can be made from the analysis of the concentration patterns observed. When the wind direction is at an angle to the city streets a helical vortex develops which produces highest concentrations on the upstream building face. The simple modification of a uniform block distorts the velocity and contaminant concentration patterns. Mixing is enhanced and concentrations are generally reduced across the face of the block.

Physical modeling is a practical and economically feasible method of performing air-pollution transport investigations for urban areas. Building and city geometry, local meteorology and local topography make each study a special case. The urban diffusion study discussed above provides an example of the type of specific information which can be obtained from physical models.

There are many practical applications for this type of investigation--evaluation of alternative urban designs on air quality and development of air-pollution control strategies are important examples. Another example is selection of locations for air-quality monitoring stations and evaluation of the data obtained with respect to concentrations at other points in the area.

Acknowledgement

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Nomenclature

C_p = specific heat at constant pressure, L^2/t^2T

g = gravitational acceleration, L/t^2

H = block height, L

k = thermal conductivity of fluid, ML/t^3T

L_o = reference length, L

Q/L = line source strength per unit length, $M\ /tL$

U = mean velocity, L/t

T = instantaneous temperature, T

T_w = mean temperature at $z = 0$, T

$\Delta\overline{T}$ = $\overline{T} - \overline{T}_w$, T

ρ = mass density, M/L^3

ν = kinematic viscosity, L^2/t

Ω = angular velocity of Earth, t^{-1}

χ = concentration M/L^3

$(\ )_o$ = reference quantity

Dimensions:

L = length

M = mass

t = time

T = temperature

References

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2. Cermak, J. E. and Peterka, J., "Simulation of Wind Field Over Point Arguello, California, by Wind-Tunnel Flow Over a Topographical Model," Tech. Rept. CER65JEC-JAP64, 1966, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado.

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4. Teunissen, H. W., "Simulation of the Planetary Boundary Layer in a Multiple-Jet Wind Tunnel," Institute for Aerospace Studies, Report 182, 1972, University of Toronto, Toronto, Canada.

5. Halitsky, James, "Validation of Scaling Procedures for Wind-Tunnel Model Testing of Diffusion Near Buildings," Geophysical Sciences Laboratory, Report No. TR-69-8, Department of Meteorology, New York University, New York, N. Y.

FIGURE LIST

FIGURE LIST (Continued)

Table I

Similarity Criteria

Parameter	Requirement for Exact Simulation	Allowable Relaxation of Exact Requirements
Geometry Scaling	Lengths must be scaled equally in all directions.	Requirement is satisfied.
Rossby No. $Ro = U_o/L_o\Omega_o$	Effects due to Earth's rotation should be produced by rotation of wind tunnel.	For length and velocity scales considered, rotational effects are negligible; therefore, requirement may be set aside.[1]
Richardson No. $(\Delta\overline{T}_o/T_o)L_o g_o/U_o^2$	Density stratification must be same for proper incorporation of buoyancy effects in model.	Requirement can be met with thermal controls developed in the CSU meteorological wind tunnel.[1]
Reynolds No. $Re = U_o L_o/\nu_o$	For typical length scales, equality of Re demands extremely high wind tunnel velocities.	For rough surfaces, flow characteristics are independent of Re above a minimum value; therefore, requirement can be relaxed.[1]
Prandtl No. $Pr = \nu_o/(k_o/\rho_o C_{po})$	Molecular properties of flows must have some relative effect.	Model and prototype fluids are both air; therefore, requirement is satisfied.
Eckert No. $Ec = U_o^2/C_{po}\ \Delta\overline{T}_o$	For thermally stratified flow Ec cannot be made equal for both flows if Richardson No. equality exists.	Requirement may be relaxed for flows of low Mach number.
Approach Flow	Mean and fluctuating velocity distributions must be similar.	Condition is met by wind-tunnel boundary-layer development through a long test section.
Longitudinal Pressure Gradient	Shall be set equal to zero above boundary layer.	Requirement is met through use of ceiling-height adjustment.

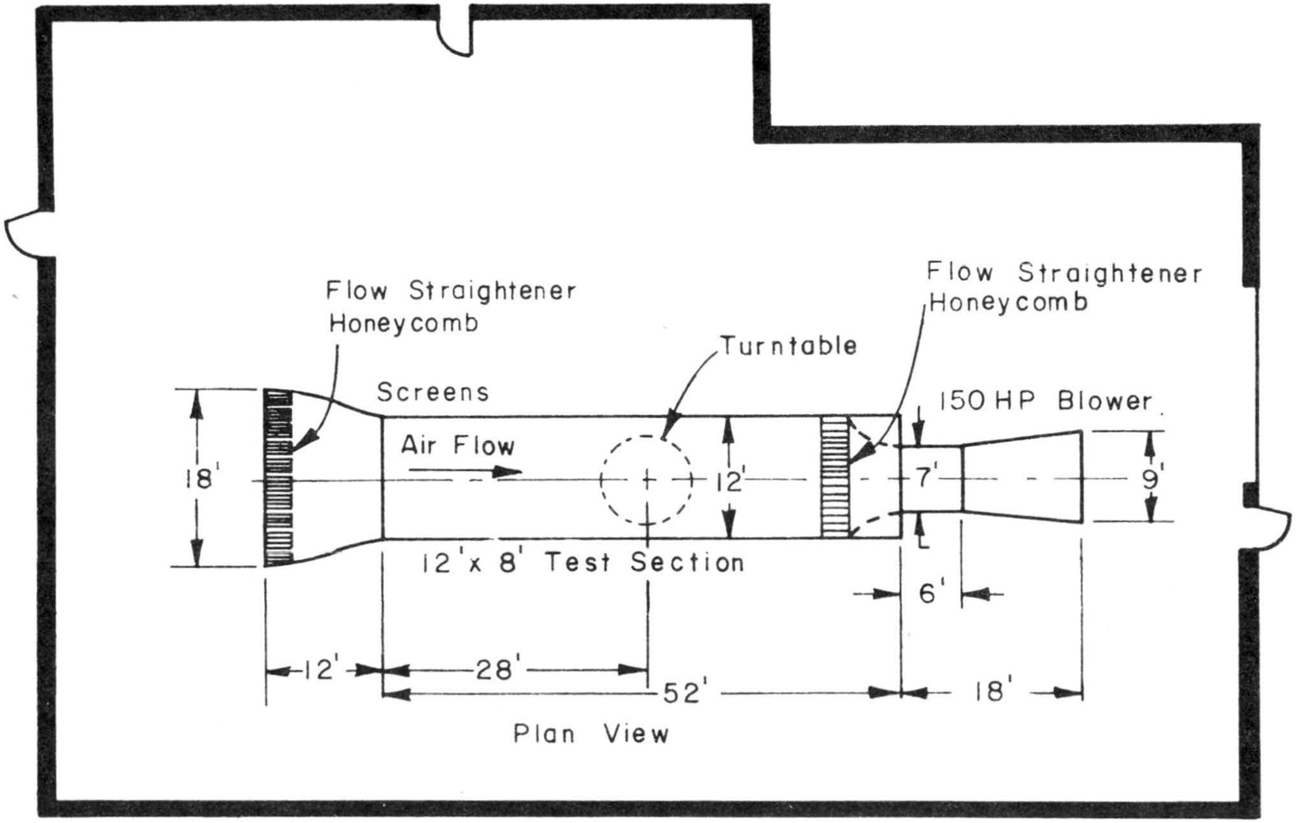

Figure 1

Environmental wind tunnel - Fluid Dynamics and Diffusion Laboratory
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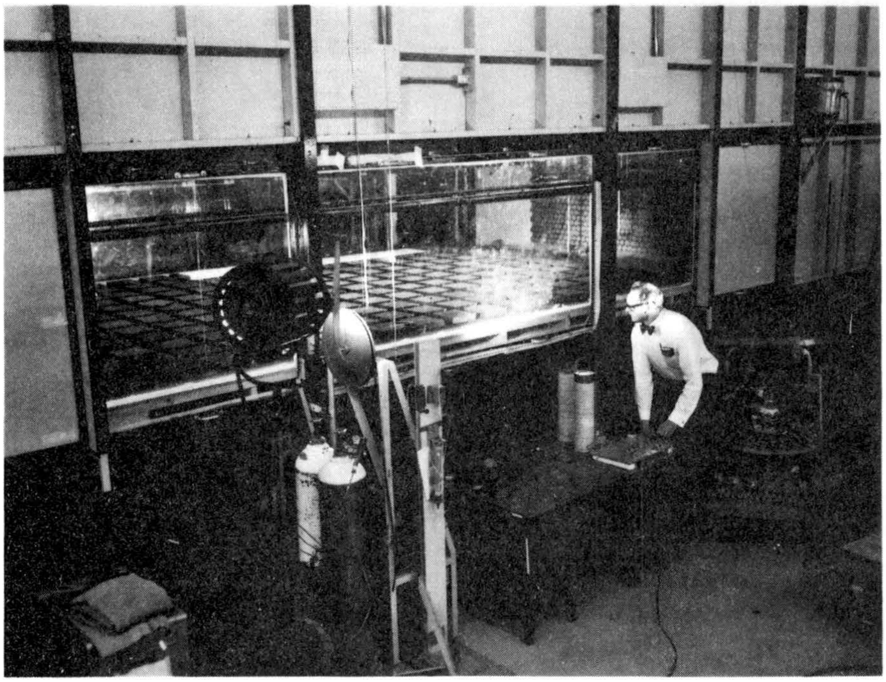
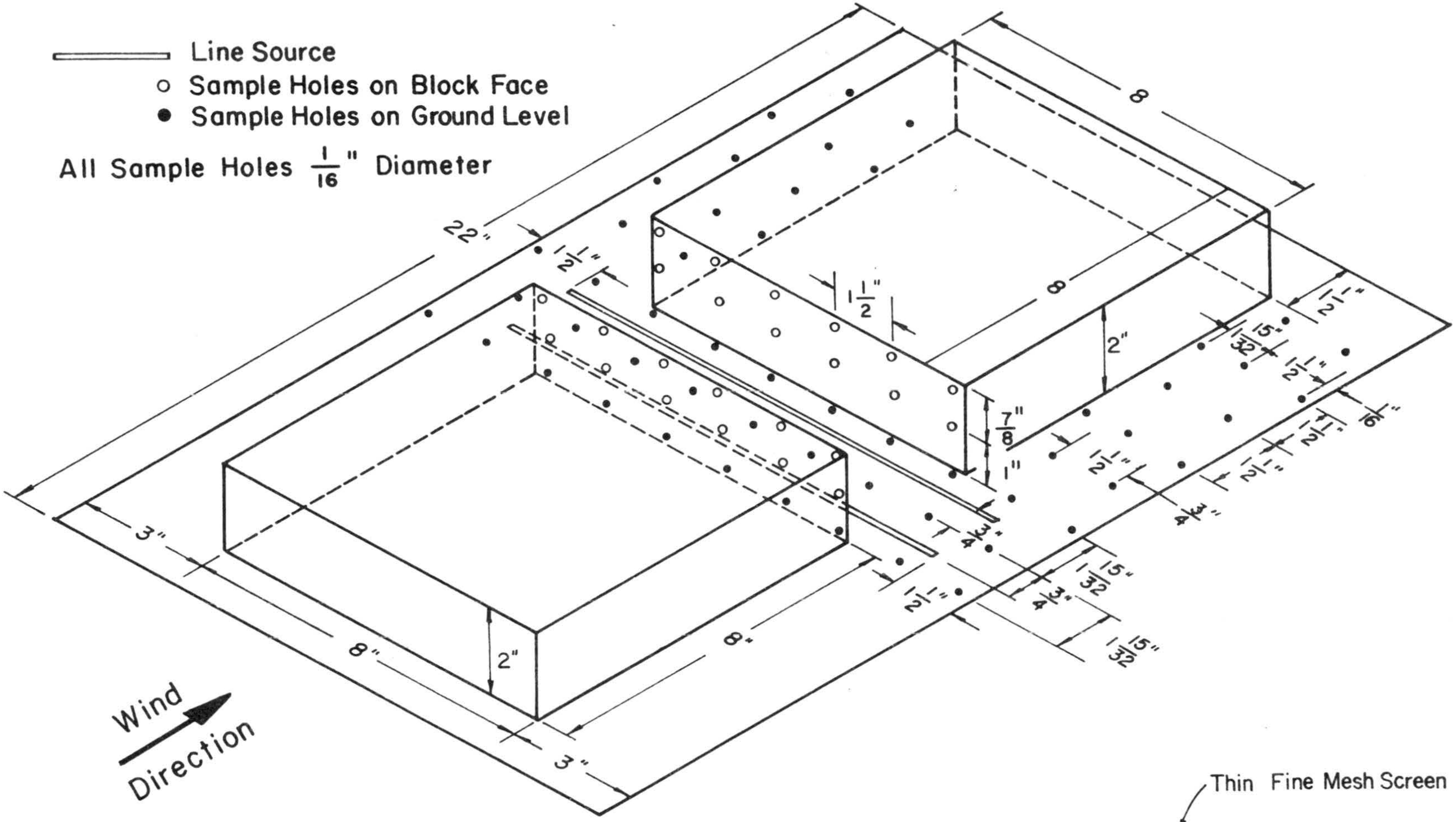


Figure 2

Simulation arrangement for modeling an idealized city..



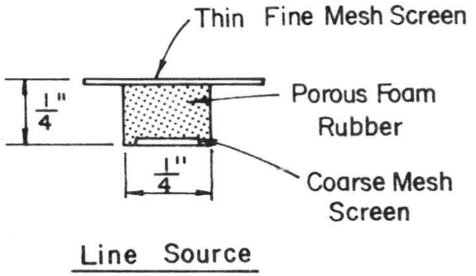


Figure 3

Idealized city data-acquisition model

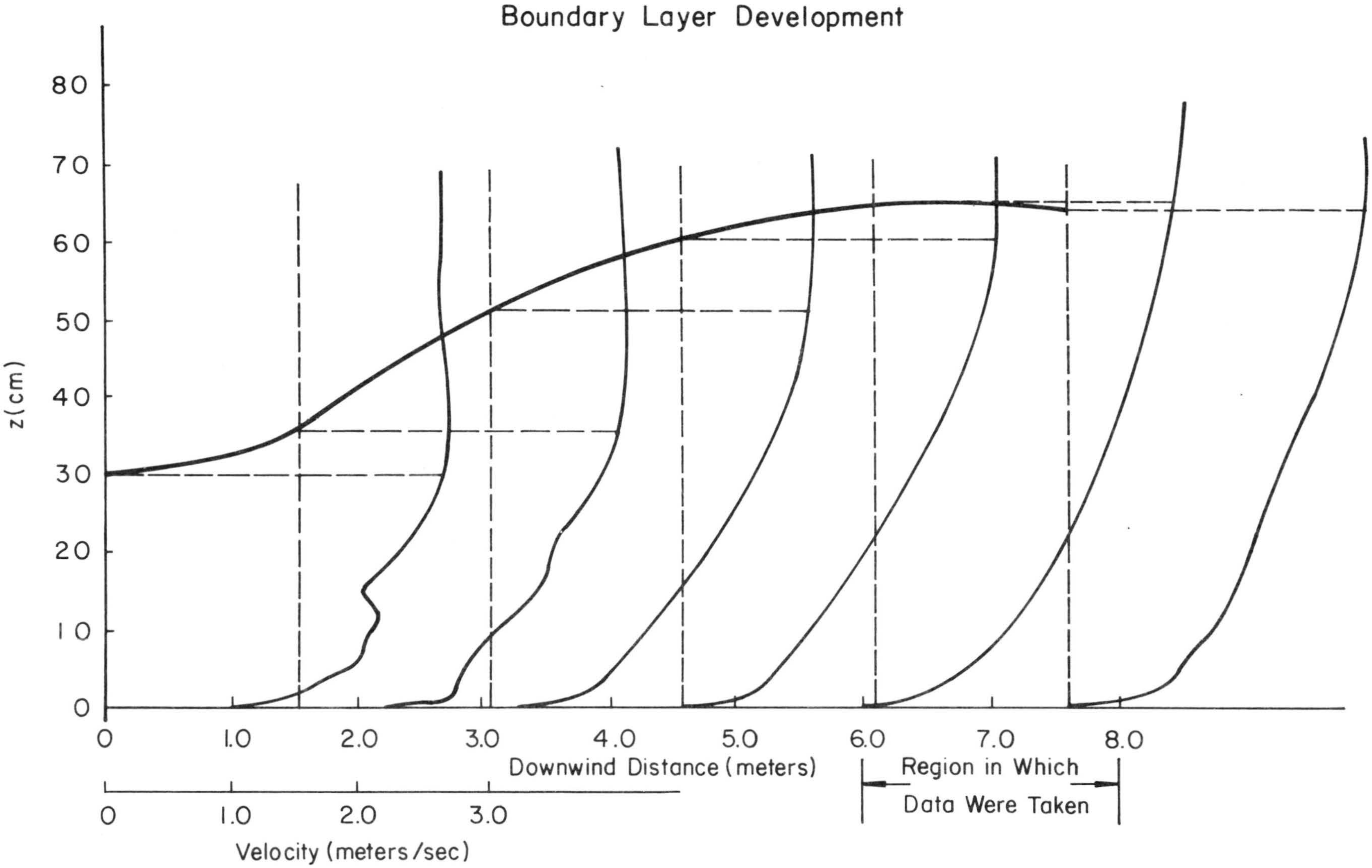


Figure 4

Boundary-layer development over idealized city model

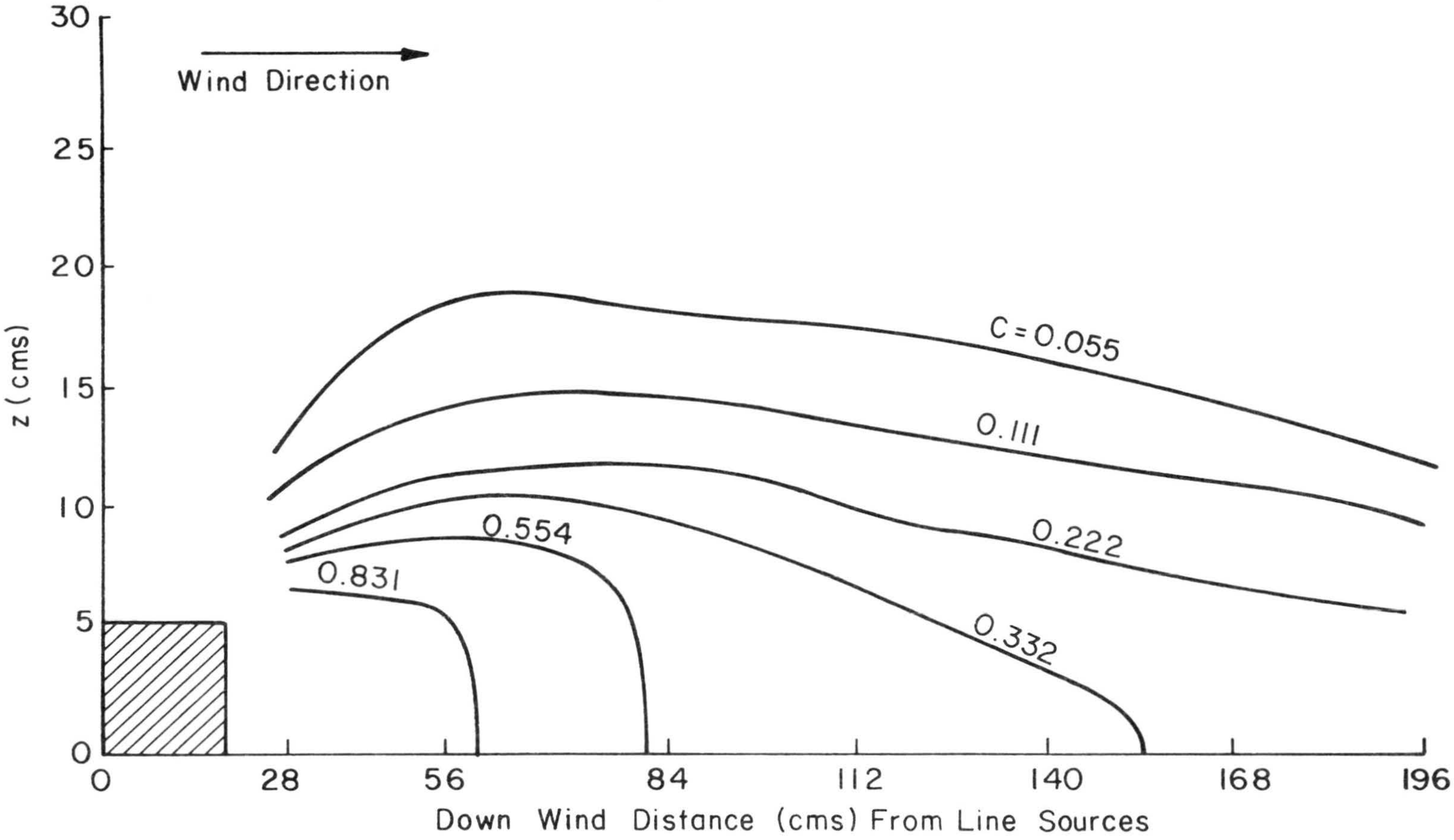


Figure 5

Concentration coefficients measured over the center of blocks at various distances downwind from the sources. Wind direction is normal to line sources.

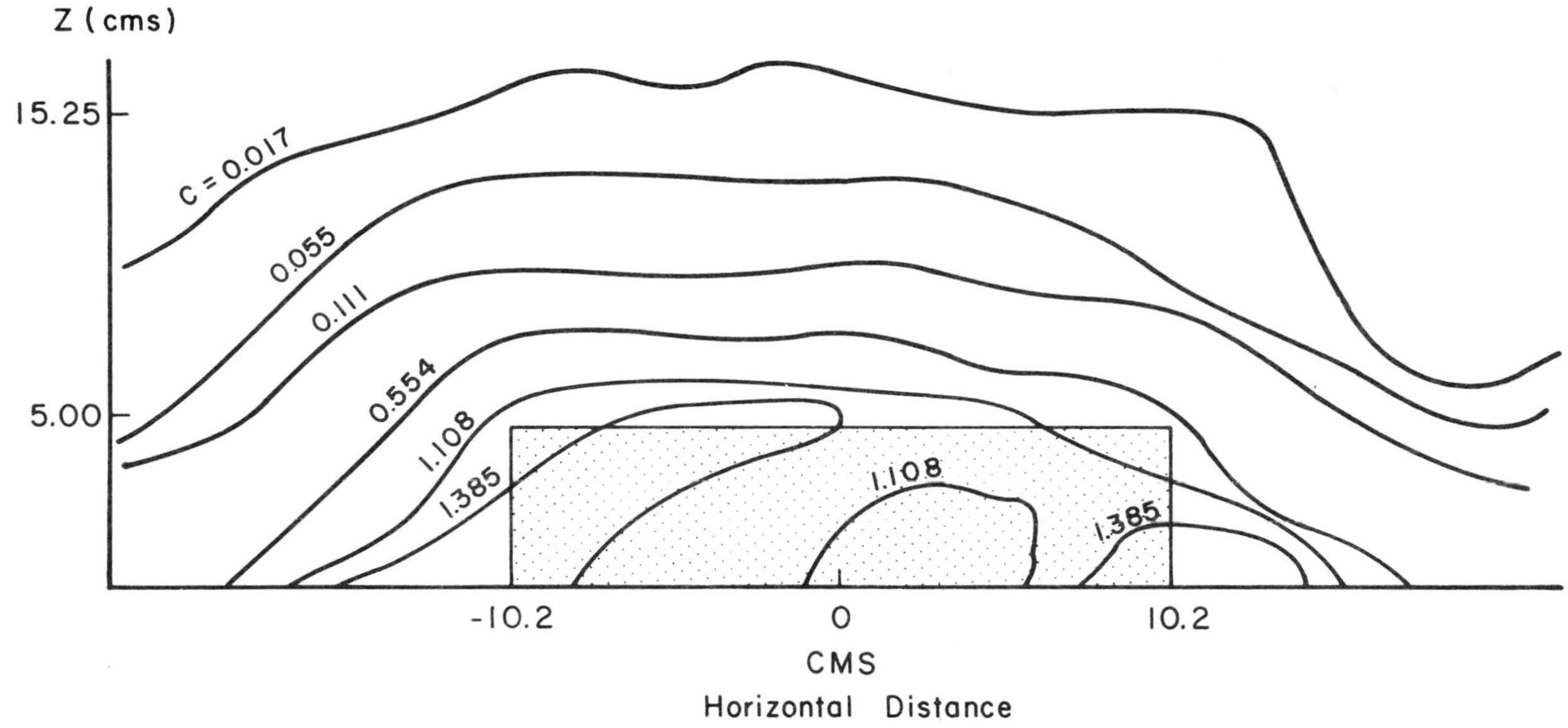


Figure 6

Concentration coefficients measured one block downwind from line sources in the plane normal to the wind direction. Wind direction is normal to the line sources (into the page).

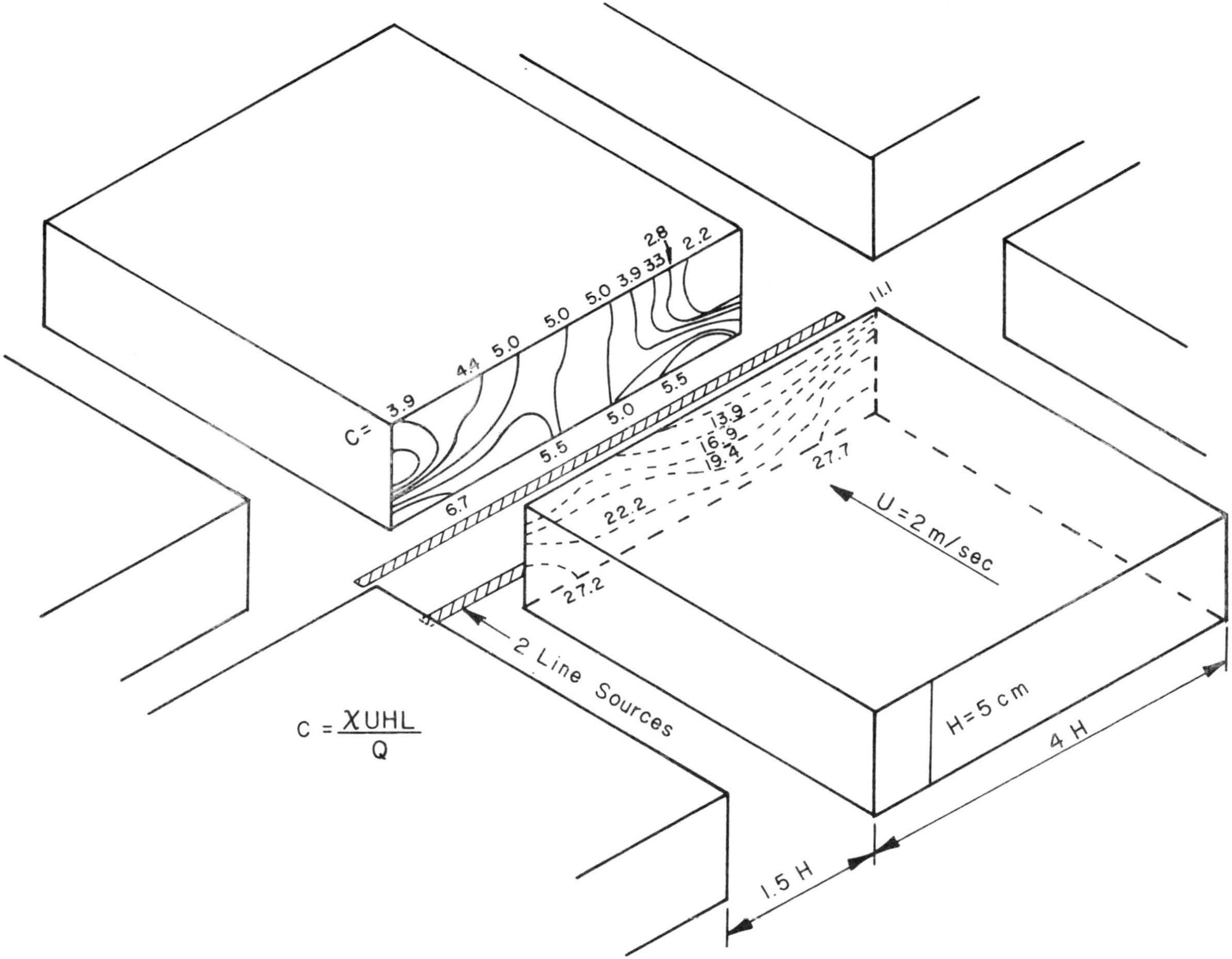


Figure 7

Concentration coefficients measured on walls of street canyons. Wind direction is shown.

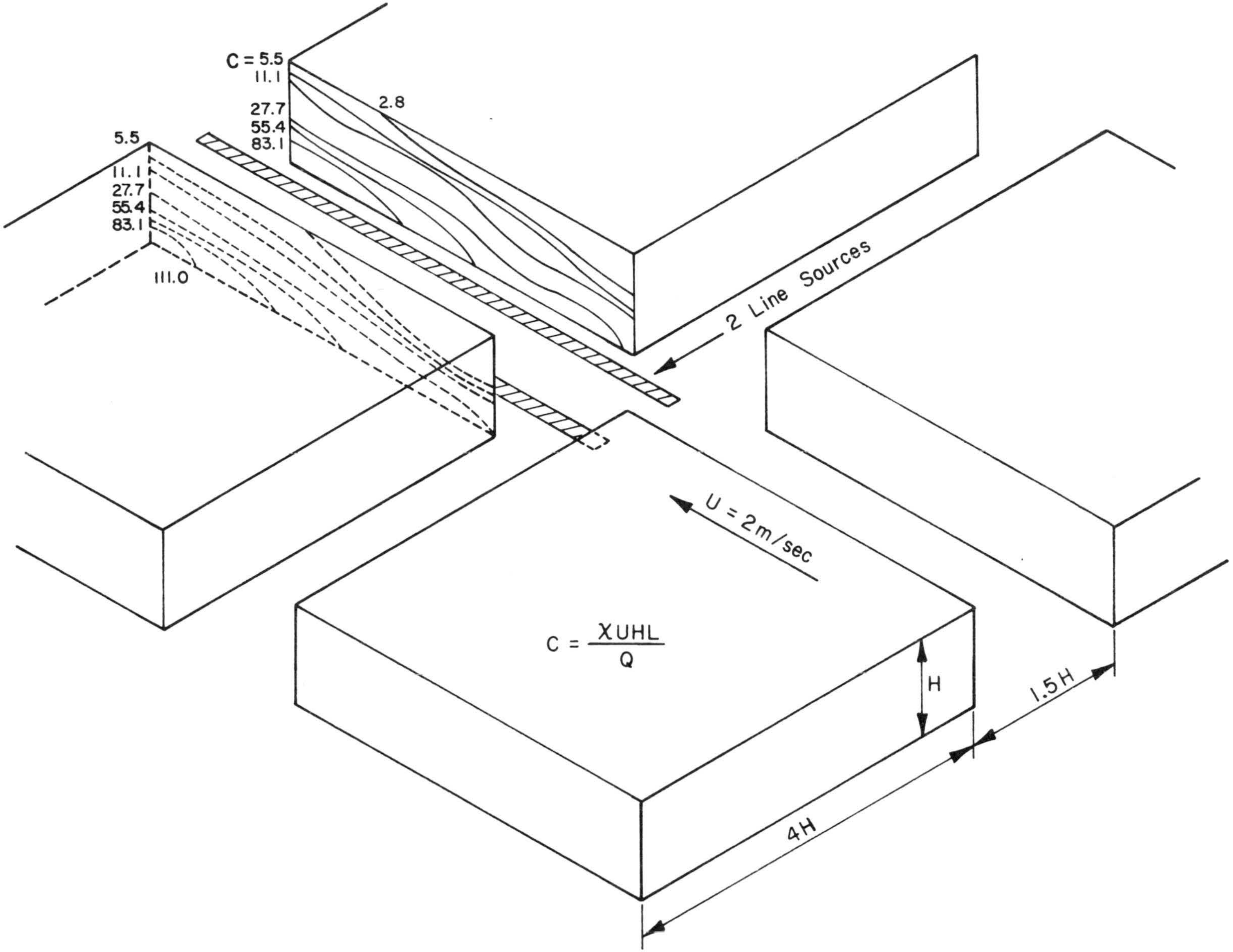


Figure 8

Concentration coefficients measured on walls of street canyons. Wind direction is shown.

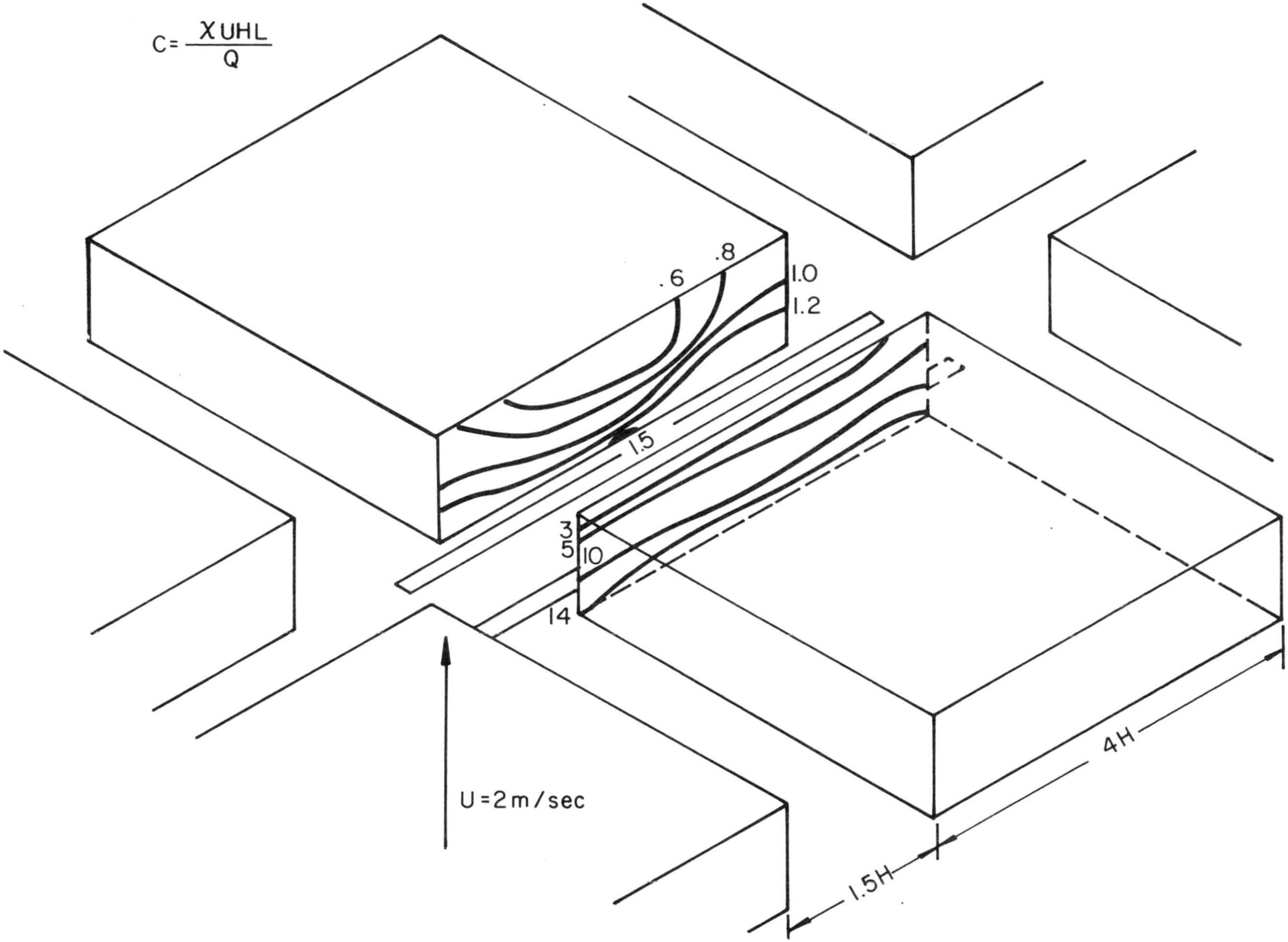


Figure 9

Concentration coefficients measured on walls of street canyons. Wind direction is shown.

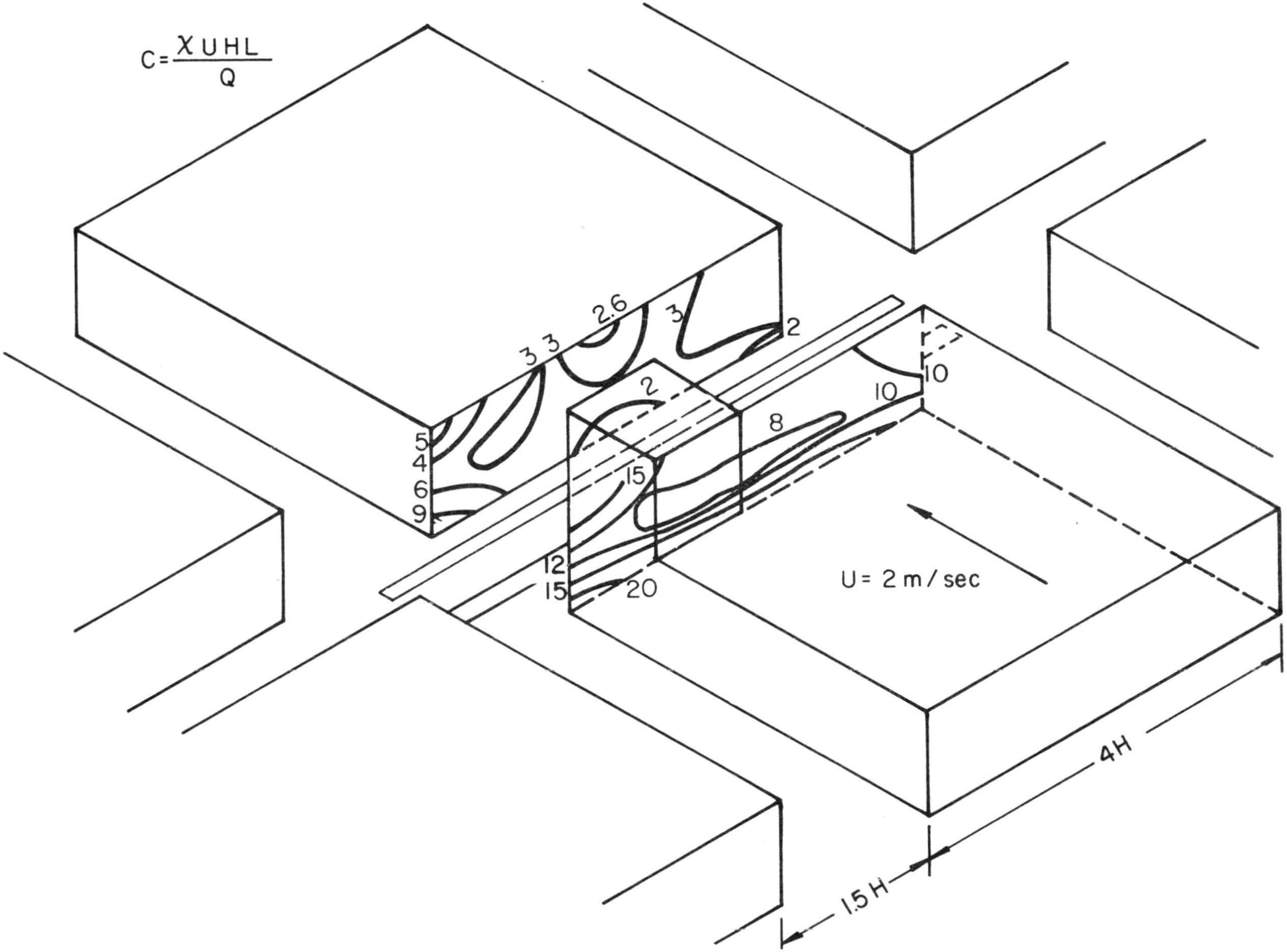


Figure 10

Concentration coefficients measured on walls of street canyons. Building is modified. Wind direction is shown.

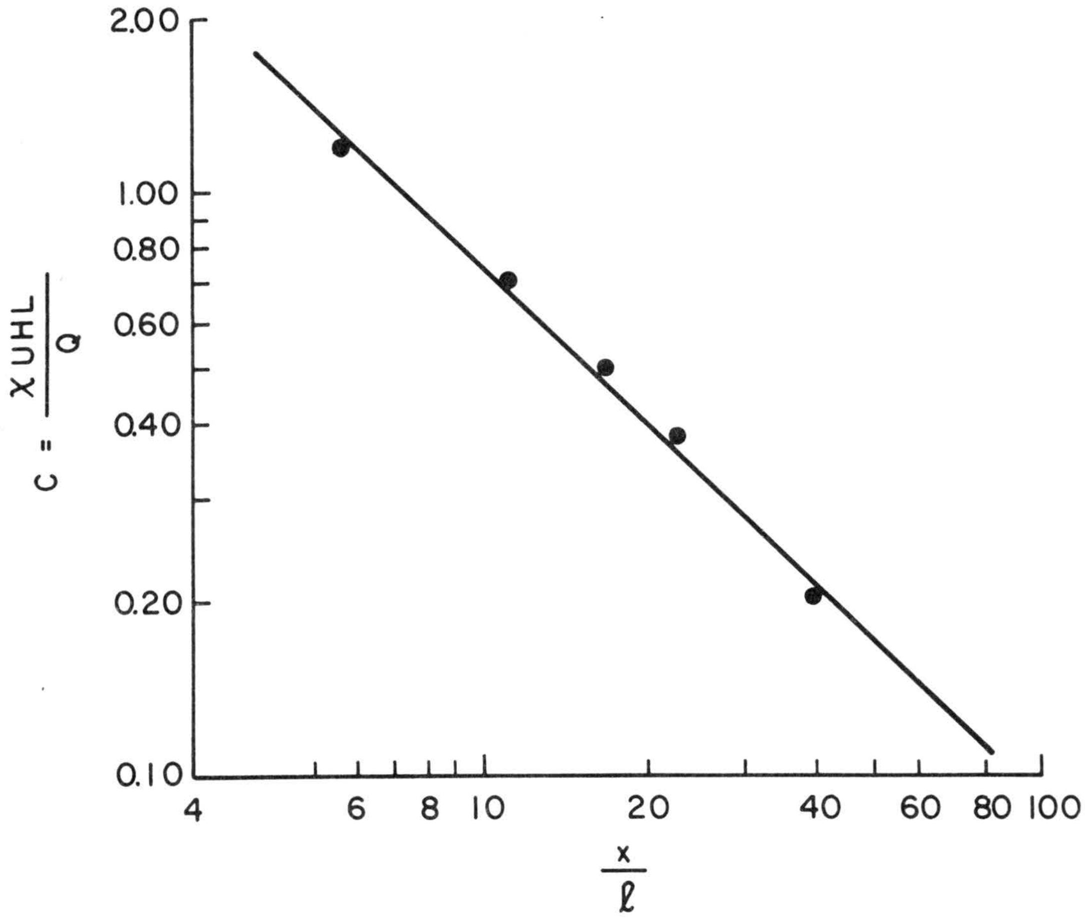


Figure 11

Ground concentrations vs. distance downwind from line sources. Concentrations are those above the center line of the city blocks. Wind direction is normal to line sources.

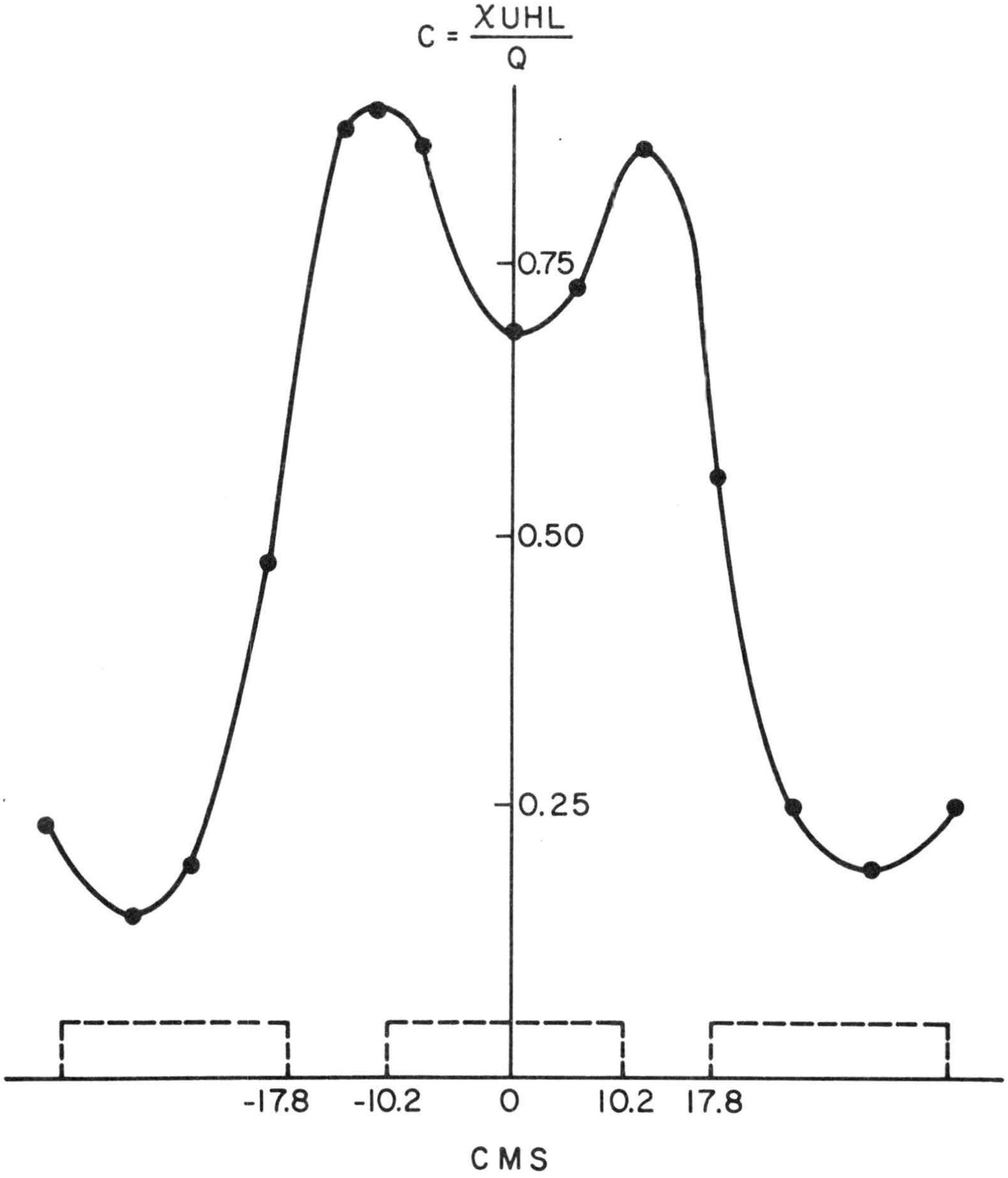


Figure 12

Ground concentration profile measured in the direction normal to the wind direction at a distance of two blocks in the downwind direction from the line sources. Wind direction is normal to the line sources.

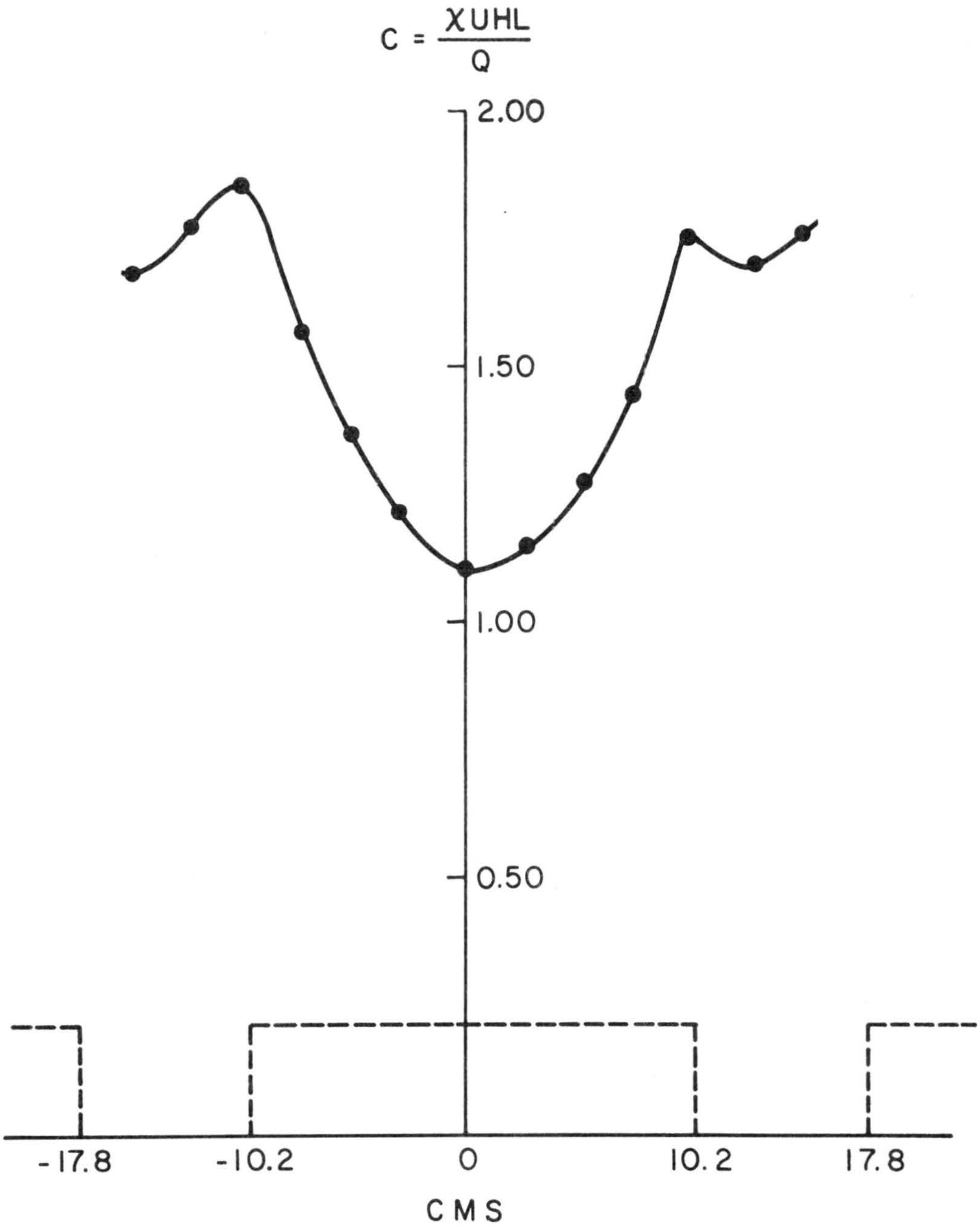


Figure 13

Ground concentration profile produced by an infinite line source. This profile was determined using superposition of the profile in Figure 12 upon itself.