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A Fluid Modeling Case Study of Exhaust Gas Dispersion from Automobile Tunnels Located Under the City of Boston

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INTRODUCTION

The Commonwealth of Massachusetts proposes to depress and bury sections of the Central Artery through downtown Boston in buried tunnels. Three of the ventilation buildings are located in congested, heavily populated areas within the confines of downtown Boston. The complicated airflow patterns associated with these sites caused by the arrangement of large building towers within the financial district necessitated the use of wind-tunnel modeling to define exhaust and inlet configurations for the ventilation buildings. The design goal was the avoidance of significant air pollution levels at the ground surface or elevated locations on nearby high-rise building air-handling systems. A 1:384 scale model was constructed of an 0.87 mile diameter section of downtown Boston centered near City Hall. Simulant gases were released from different ventilator stack configurations, and concentrations were sampled at locations distributed at ground and elevated locations over the region. Data are presented in terms of relative dimensionless concentration K-factors for alternative traffic, exhaust and wind speed conditions. The final stack-exhaust rate configuration was determined to produce concentration levels which fall below state and federal air-quality standards.

MODELING OF PLUME DISPERSION FROM TUNNEL VENTILATOR SITES

Simulation criteria for fluid modeling of atmospheric phenomena are discussed by Cermak[1], Meroney[2] and Snyder[3]. Only those simulation details unique to this tunnel ventilator study will be considered in detail. The exhaust air released from the tunnel ventilators will exit at ambient temperatures and densities; hence, the source gas used in the model was primarily nitrogen released at room temperatures (specific gravity ≈ 1.0). Thus the plume mass flux, momentum flux and volume flux are essentially equivalent ratios, and the plume Froude number is not a relevant parameter.

Neutral stratification in the laboratory was used to reproduce the dispersion dynamics of the windy Boston area. Wind-tunnel floor roughness was adjusted to produce properly scaled wind shear and turbulent structure. Model wind speed and stack exit velocity were set at large enough magnitudes to assure Reynolds number independence of approach flow and stack flow. Model wind velocity to plume velocity ratios were set equal to the field values; thus assuring similarity of plume trajectories.

DATA ACQUISITION AND ANALYSIS TECHNIQUES

The experiments were performed in the Environmental Wind Tunnel (EWT) at Colorado State University. This wind tunnel, especially designed to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling, a rotating turntable and a long test section to permit adequate reproduction of micrometeorological behavior. Mean wind speeds of 0.1 to 15 m/sec in the EWT can be obtained. Boundary-layer thickness up to 1.2 m can be developed "naturally" over the downstream 6 m of the EWT test section by using vortex generators at the test section entrance and surface roughness on the floor. The flexible test section on the EWT roof is adjustable in height to permit the longitudinal pressure gradient to be set at zero.

Wind Profile Measurements

Single-hot-film (TSI 1210 Sensor) measurements were used to document the longitudinal mean velocity and turbulence levels for the approach flow conditions. During calibration the probe voltages were recorded at several velocities covering the range of interest. These voltage-velocity (E,U) pairs were then regressed to the equation $E^2 = A + BU^c$ via a least squares approach for various assumed values of the exponent c. Convergence to the minimum residual error was accelerated by using the secant method to find the best new estimate for the exponent c. The calibration curve yielded hot film anemometer velocities that were always within 2 percent of the known calibrator velocity. Considering the accumulative effect of calibrator, calibration curve fit and other errors the model velocity time series should be accurate to within 10 percent.

The hot-film-probe was mounted on a vertical traverse and positioned over the measurement location in the wind tunnel. The anemometer's output voltage was digitized and stored within an IBM AT computer. This voltage time series was converted to a velocity time series using the inverse of the calibration equation; $U = [(E^2 - A)/B]^{1/c}$. The velocity time series was then analyzed for pertinent statistical quantities, such as mean velocity and root-mean-square turbulent velocity fluctuations. The computer system would move the velocity probe to a vertical position, acquire the data, then move on to the next vertical positions, thus obtaining an entire vertical velocity profile automatically.

Flow Visualization Techniques

A visible plume was produced by passing the metered simulant gas through a smoke generator (Fog/Smoke Machine manufactured by Roscolab, Ltd.) and then out of the modeled stack. The visible plumes for each test were recorded on VHS video cassettes with a Panasonic Omnivision II camera/recorder system.

Concentration Measurements

Measurements of concentration were obtained using a Hewlett Packard flame-ionization gas-chromatograph (Hewlett-Packard Model 5710A) and sampling systems designed by Fluid Dynamics and Diffusion Laboratory staff. The lower limit of measurement is imposed by the instrument sensitivity and the background concentration of tracer within the air in the wind tunnel. Background concentrations were measured and subtracted from all data quoted herein.

The tracer gas sampling system consists of a series of fifty 30 cc syringes mounted between two circular aluminum plates. A variable-speed motor raises a third plate, which lifts the plunger on all 50 syringes, simultaneously. Computer controlled valves and tubing are connected such that airflow from each tunnel sampling point passes over the top of each designated syringe. When the syringe plunger is raised, a sample from the tunnel is drawn into the syringe container. The sampling procedure consists of flushing (taking and expending a sample) the syringe three times after which the test sample is taken. The draw rate is variable and generally set to be approximately 6 cc/min.

The sampling system was periodically calibrated to insure proper function of each of the valves and tubing assemblies. Normal sampling procedures were carried out during calibration to insure exactly the same procedure is reproduced as when taking a sample from the tunnel. Each sample was then analyzed for tracer gas concentration. Percent error was calculated, and "bad" syringe/tube systems (error > 2 percent) were not used or repaired. Measured concentration values, χ_{meas}, along with the response levels for the background χ_{bg} and source χ_{source} are converted into source normalized model concentration by the equation:

$$\chi_m = \frac{\chi_{meas} - \chi_{bg}}{\chi_{source} - \chi_{bg}}$$

Field equivalent concentration values are related to model values by the equation:

$$\chi_p = \frac{\chi_m}{\chi_m + (1-\chi_m)[(\frac{T_a}{T_s})V]_m/[(\frac{T_a}{T_s})V]_p}$$

where $V = Q/U_H L^2$, and L is a characteristic length scale. When there is no distortion in the model-field volume flux ratio, V, and the plumes are isothermal this equation reduces to $\chi_p = \chi_m$.

Finite background concentrations, χ_{bg}, resulted from previous tests within the laboratory, these low levels could be measured to accuracies of twenty percent. The larger measured concentrations, χ_{meas}, were accurate to two percent. The source gas concentration, χ_{source}, was known to within ten percent. Thus the source normalized concentration for $\chi_{meas} >> \chi_{bg}$ was accurate to approximately ten percent. For low concentration values, $\chi_{meas} > \chi_{bg}$, the errors are larger.

TEST PROGRAM AND DATA ACQUISITION

A physical modeling study of a downtown ventilation building site was performed to assist in predicting environmental impacts for several proposed stack-building configurations.

Model Construction

Based on atmospheric data over the Boston area, the size of the concentration grid, and modeling constraints a model scale of 1:384 was selected. Since the Environmental Wind Tunnel had a 12 foot turntable this allowed for the reduced scale construction of all significant buildings within a 2300 foot radius of the vent building site. The location of the site along with a circle demarking the portion of downtown Boston which was replicated is shown in Figure 1.

The buildings surrounding the vent structure were fabricated from styrofoam and were placed in their appropriate locations on a 12 foot diameter 1/4 inch masonite sheet. All roads and waterways were painted on this masonite sheet. The topography changes were modeled by layering several 1/4 inch sheet to match the land contours within the modeled area. Figure 2 is a picture looking upwind of the entire 12 foot turntable model located inside the wind tunnel. Note in this picture that the terrain upwind of the turntable area was modeled with a generic roughness with a field equivalent height of 32 feet (1 inch cubes).

The vent building was built in a modular form so that an array of different building, garage and stack heights could be tested. The different building heights possible were 53, 75, 90 and 375 feet. The garage heights varied from 42, 75 and 90 feet. The stack heights were 100, 115, 125, 150, 225 and 400 feet. Figure 3 shows a picture of one of the configurations of building-garage-stack heights tested. The different building and garage modules were constructed of masonite, whereas the stacks were fabricated from tack board. The smallest building module contained a manifold through which metered simulate gases were directed to the stacks. The ventilator building used 14 vent fans to blow exhaust gases through 10 by 14 foot (inside measure) openings. These individual stacks were arranged into 2 groups of 4 openings and 2 groups of 3 openings. The spacing between these 4 stack groups could also be varied. The intake ports for the complex were modeled by connecting a metered vacuum source to the inlet portion of the building that was constructed of screen.

Velocity Profiles

The wind approaches the Boston city center over either suburban roughness or the harbor sea surface. The downtown site is located within the central portion of downtown Boston surrounded by large buildings. An approach flow upwind of the turntable model, typical of a suburban environment, was created through the placement of vortex generators at the tunnel entrance followed by 30 feet of 1 inch cube roughness on the tunnel floor. The site model was located on a turntable, thus it could be rotated to simulate the different wind directions.

Measured model wind speed profiles verified that there was crosswind uniformity of the flow approaching the modeled site. Other profiles confirmed that the flow was invariant to different wind-tunnel reference wind speeds. The approach mean velocity profiles were regressed to find the best log-log and log-linear fit. The log-log regression produced a power law exponent, p, equal to 0.24; i.e. $U/U_r = (z/z_r)^p$. The log-linear regression $(U/u_* = 2.5 \ln\{(z-d)/z_o\})$ found a best fit roughness length, z_o, of 0.9 meters (field scale) and a displacement thickness, d, of 4.8 meters. These values of the power law exponent and the roughness length are appropriate for a suburban roughness condition.

Visualization Test Results

Many flow visualization tests (197) were performed over the downtown building site region. Three different stack exhaust flow rates were considered for a variety of wind directions and various building configurations. The field equivalent wind velocity for all these tests was 5 m/s at 30 meters height approaching the modeled area. The model velocity was 0.5 m/s at 0.078 meter height (0.078 m = 30/384) approaching the model area. This wind speed was chosen to maintain flow similarity between the wind tunnel and the actual conditions. For each of the 197 visual test runs observations on stack downwash, building downwash, cavity mixing, plume descent, plume lofting, skyscraper impingement and other pertinent comments were recorded.

Concentration Data Results

By maintaining flow similarity between model and field conditions, relative concentrations (χ/Q) for a given source configuration, building configuration and wind direction will be invariant. The wind tunnel relative concentration measurements for the vent building will be the same as those that could be obtained during full-scale measurements under the same ambient conditions. Since the initial plume path depends upon the ratio of exhaust velocity, W , to wind speed, U, the distribution of the relative concentration field will change for different values of W/U.

From the smoke visualization tests it was determined that varying the vent stack grouping produced very little noticeable differences in plume trajectories. Varying the garage building heights produced a similar effect to varying the building height. The WSW and SE wind directions were identified as critical directions having the potential for high concentrations. Hence concentration measurements were performed over a test matrix of 67 conditions to evaluate the quantitative influence of those parameters which did appear to influence concentrations--stack height, stack velocity, and building orientation. Figure 4 shows all the concentration sampling locations marked on a map of the modeled area.

Normalized concentration data, $(\chi U_H/Q)*10^9$, were recorded for all tests. This normalized format is convenient because the concentration results, χ, from a test at one particular combination of wind speed, U_H, and flow rate, Q, can be extrapolated to other U_H, Q values provided that the ratio, U_H/Q, remains the same. Note that U_H is the wind speed at 30 meters height approaching the model area and not the value of wind speed above the vent site. The total flow rate, Q, out of the stacks is the exit velocity for a particular run times the total stack exit area. The total exit area for the vent stacks was always 1960 ft^2. The total exit area for the Charles river site was always 840 ft^2

DISCUSSION AND RECOMMENDATIONS

Selection of the final building and exhaust stack configuration for the ventilator building will be based upon the consideration of its visual appearance within the Boston historic district, zoning regulations, and minimization of environmental impact. The environmental effects of exhaust from the ventilator stacks will depend upon tunnel traffic volume, ventilator flow rates, state and federal ambient air-quality regulations, building and plume aerodynamics, and local meteorology. This study evaluated through fluid modeling the influence of building and plume aerodynamics on plume dilution. Data is reported in terms of normalized concentrations, $K = \varkappa U/Q$, to permit concentration estimates for alternative traffic, exhaust and wind speed conditions. Concentrations can be estimated for alternative configurations, but acceptability must depend upon current air-quality standards.

The following discussion will first consider implications of the visualization tests. Next it will focus upon evidence for reliability and consistency within the concentration data set, and ,finally, comments will be made on the advantages or disadvantages of different building and stack configurations.

Smoke Visualization Results

Smoke test cases were performed to evaluate the relative dispersion that occurs for various vent stack heights, vent stack groupings, exit flow velocities, vent building configurations and site orientations. Tests were grouped to examine the relative effects of stack height, exit flow velocity, vent stack grouping, vent building height, adjacent garage height, and site orientation. The observations noted the presence or absence of

i) Stack downwash - plume flagging or suction of smoke into stack wake
ii) Building downwash - suction of plume downward into building cavity
iii) Cavity mixing - mixing of plume throughout downwind building cavity
iv) Plume descent - deflection of plume groundward over building cavity
v) Plume lofting - plume little influenced by building, plume remains aloft
vi) Skyscraper impingement - Elevated plume stagnates against faces of downwind tall buildings

The cases studied were categorized and grouped to reveal data trends. Examination of the visual records of these experiments revealed:

a) Stack Height (ft): 100, 125, 150, 225 and 400.

Examination of runs with equivalent building and garage heights as well as constant exhaust velocities reveals the relative value of increased stack height. A 100 foot stack permits significant building downwash, whereas the building geometry does not appear to perturb the plume for stacks greater than 150 feet. Plumes released at heights greater than 150 feet loft above the building cavity and enter the building wake after it has merged with perturbations produced by other obstructions. For some situations with a 100 foot stack the plume was brought to the ground in the street directly downwind of the ventilation building.

b) Exit Flow Velocity (ft/min): 800, 1600, 3200.

The vent gases are expected to exhaust at near ambient temperatures; hence, the vent plume will have little or no thermal buoyancy. Thus, plume rise will occur only as a result of vertical momentum. Higher exit flow velocities will add effective height to the vent stack. In addition low exhaust velocities ($W/U < 1.5$) may permit local downwash behind the vent stack, reducing the effective stack height significantly. Tests show that the 800 ft/min exhaust velocity permits severe downwash of the plume down the side of the stack directly into the building cavity. A 1600 ft/min exhaust velocity in a 5 m/sec wind field ($W/U = 1.6$) minimizes local stack downwash effects. Exhaust velocities greater than 1600 ft/min increase the effective plume release height, but the apparent reduction in plume/building interaction is small once stack downwash is eliminated.

c) Vent Stack Grouping: Separate vs combined.

Several tests were performed to determine if different roof top arrangements of the vent stacks might reduce downwash effects. The conditions varied from separate stacks to a case with all vents combined. Unfortunately, the roof area was not great enough to permit significant separation; hence, no significant differences were observed.

d) Vent Building Height (ft): 53, 75, 90, and 375.

Several vent building heights were examined to determine if an optimum building height could be identified. For a constant stack height downwash was greater as the building height to stack height ratio decreased. On the other hand apparent dilution of the smoke also occurred as the smoke mixed over greater building cavity volumes. When tall buildings were combined with tall stacks the exhaust gases often lofted over the immediate neighborhood entirely, since the effective stack height now exceeded 2.5 times the minimum building dimension. If the 90 and 375 foot building heights are judged to be unacceptable, a 75 foot building would produce acceptable plume trajectories when combined with stack heights equal to or greater than 125 feet.

e) Adjacent Connected Garage Height (ft): 42, 75, 90, 375.
Various garage building heights were combined with the different vent building heights. They were analyzed to evaluate their combined influence on the vent plume. At no time was the combined building height greater than the vent building height; hence, the general shape of the building wake cavity was only slightly perturbed. The results were similar to those of the building height tests with minimum garage heights with only small changes in plume trajectory or dilution.

f) Site Orientation: 16 compass points.
The model was rotated to allow approach winds from the 16 major compass points. As the flow interacted with upwind buildings and the shape of the vent building the vent plume trajectory was modified by the variation in streamline patterns. Several patterns reoccurred no matter the building configuration examined. Winds over the Boston financial district from the W through NW directions were blocked by the tall buildings, which produced a sheltered low-wind region at the downtown site. Plumes exhausting into this wind environment were lofted quite high by their initial momentum; hence, they rarely penetrated the local wake region, and the plume touched down farther downwind.

Winds from the SE direction passed over only low rise residential areas before reaching the downtown site. High wind speeds at stack height deflected the plume immediately; hence, downwash was often significant behind the Government Center garage. Furthermore, even plumes which did not reach ground level quickly often impacted the tall skyscrapers which stand to the NW. Such conditions will result in maximum concentrations at elevated samplers located on roof tops.

Winds from the WSW channeled their way along Sudbury Street in the commercial district. The resulting high winds appeared to cause a low pressure region behind the JFK Federal Building which shifted the wind over the downtown site toward the E. Often these winds produced vent plume downwash which resulted in a groundlevel plume extending eastward over the eastern part of the Boston peninsula.

Conclusions from Smoke Visualization Tests. The visualization tests provided observations which permitted focus for the concentration experiments. The major conclusions were:

1. For a given exit flow velocity, wind speed and site orientation, the higher the stack, the lower the ground smoke concentration.

2. Vent exit velocities which exceeded 1.5 times the reference wind speed reduced stack and building downwash. Consequently exit velocities 1600 ft/min and greater were more desirable than the 800 ft/min flow velocity.

3. The roof space available on top of the ventilator building was not great enough to permit significant separation of the individual vents. Varying stack grouping did not produce noticeable differences in smoke concentration on the ground.

4. A tall stack and short building is the most desirable combination to avoid local building downwash. A tall building with a short stack will always result in some downwash to street level. Short buildings result in large ground level concentrations because the plume is mixed over a smaller building cavity; whereas a taller building will produce a larger cavity region to dilute the gas plume. Based on qualitative evaluation of the smoke visualization results concentration measurements focused on building heights greater than or equal to 75 feet and stack heights greater than or equal to 125 feet.

5. Adjacent garage heights ranging from 42 to 90 feet did not produce great differences in plume behavior. Surface smoke was somewhat greater for 75 foot garage buildings attached to a 75 foot ventilator building.

6. The WSW and SE wind directions were identified as critical directions having the potential for high concentrations.

Verification of Fluid Model Reliability

Similarity of flow and dispersion of gas plumes over the Boston city complex must exist to obtain reliable estimates of concentrations. Equivalence is generally assured if the characteristic Reynolds number (or model velocity) is sufficiently large. Ten concentration test runs were performed to determine the minimum tunnel wind speed at which the K coefficients did not vary. Although runs were performed over a five-fold range in magnitude of wind speeds and ventilator flow rates, the ratio of exhaust velocity to wind speed was held constant at 0.81. Thus, sample point concentrations in terms of ppm or K coefficient should remain constant if similarity holds. Values for prototype reference wind speeds greater than 5 m/s were equivalent; whereas the K values were less for a prototype wind speed of 2.5 m/s. Since Reynolds number independence holds for wind speeds at 5 m/s and greater, all subsequent test runs were performed at prototype wind speeds of 5 m/s or greater.

Building Aerodynamics Effects on Ventilator Plumes

Test runs were performed with a 125 ft stack located on the downtown site in place of the proposed building and ventilator system. These data may be compared with other tests to determine the influence of building downwash on plume concentrations. Figure 5 displays typical results for the SE wind direction. Note that when the ventilator structure is present concentrations are often ten times larger. The building has reduced the effective plume release height by deflecting the plume toward the ground resulting in larger concentrations. Depending upon the resultant plume trajectory elevated concentrations may be either smaller or greater.

The Boston city complex which surrounds the downtown site will also influence plume trajectories and mixing rates. The plume can stagnate on tall buildings, deflect around tall buildings, or be diverted into street canyons or between buildings by local low pressure regions. The buildings also produce a complex structure of turbulence and wake regions which can dilute the plume or mix it toward the ground. These effects can sometimes mask the effect of the source building upon the exhaust plume. Tests were performed with the Boston city model removed from the wind tunnel. Data were measured at ground level on crosswind trajectories located at distances of 256, 1664 and 2369 feet downwind of the ventilators. Wind orientations considered were N, E, SE and SW. Figure 6 displays typical cross-wind concentration distributions at 256, 1664 and 2369 feet respectively. At 256 feet the patterns suggest that maximum downwash occurs for easterly winds, whereas maximum plume deflection occurs for south-westerly winds. At 2369 feet downwind the plumes appear uniformly distributed, and only the easterly results show the effects of downwash.

Influence of Alternative Stack Configurations Upon Concentrations

Given no other controlling factors (such as zoning regulations or cost) it is evident minimum surface concentrations will occur for maximum stack height, minimum building height, and maximum exhaust velocity. In order to avoid all building aerodynamic effects, wind engineers recommend releasing plumes stacks at elevations greater than or equal to 2.5 times the minimum of building height or width. In the case of a 75 foot ventilation building this would require an effective stack height greater than 188 feet. Shorter stacks permit plume interaction with the separation cavity which forms about the building, and, consequently, larger surface concentrations occur.

<u>Effect of Variations in Stack Height</u>. Figure 7 compares sampler concentrations for the SE wind direction for stack heights varying from 100 to 225 feet with an exhaust gas velocity of 1600 fpm. Taller stacks generally produce smaller sampler concentrations, but the 75 foot tall building and garage complex tends to produce some plume downwash for all the stacks shorter than 225 feet. Given a restriction to stack heights less than 150 feet, concentrations are all of the same order of magnitude.

Effects of Variations in Exhaust Velocity. Significant reductions in sample point concentrations can be obtained by increasing stack gas velocity. Figure 8 compares sampler concentrations from a 125 foot stack for the SE wind direction for exhaust velocities varying from 400 to 3200 fpm. A four-fold increase in stack velocity produces about a six-fold decrease in concentration, whereas an eight-fold increase in stack velocity produces about a twenty-fold decrease in concentration. Stack downwash may occur for exhaust velocity to wind speed ratios less than 1.5. For the complex a 5 m/sec wind speed the 400 and 800 fpm conditions permit significant stack downwash ($W/U < 1$); whereas, downwash is usually absent at large exhaust velocities ($W/U \geq 1.6$).

Joint Influence of Stack Height and Exhaust Velocity. Consideration of smoke visualization and concentration results suggests that a 125 foot stack height with an exit flow velocity of 1600 ft/min is the lowest stack height and exit flow velocity reasonable for the vent building. This stack height and exhaust velocity should suffice to avoid stack downwash and loft the ventilator plume above the building cavity for wind speeds below 5 m/sec.

Influence of Building Orientation. Wind orientation combines with building orientation, building and stack downwash, exhaust velocity and sample location to produce a wide variance in sample concentrations. Figure 9 considers sample location concentration variation for a 125 ft stack exhausting at 1600 fpm in a 5 m/sec wind. Maximum K concentrations lie between 3 to 4 x 10^{-6}. These concentrations can occur for winds from the N, NE, SE, SW and W.

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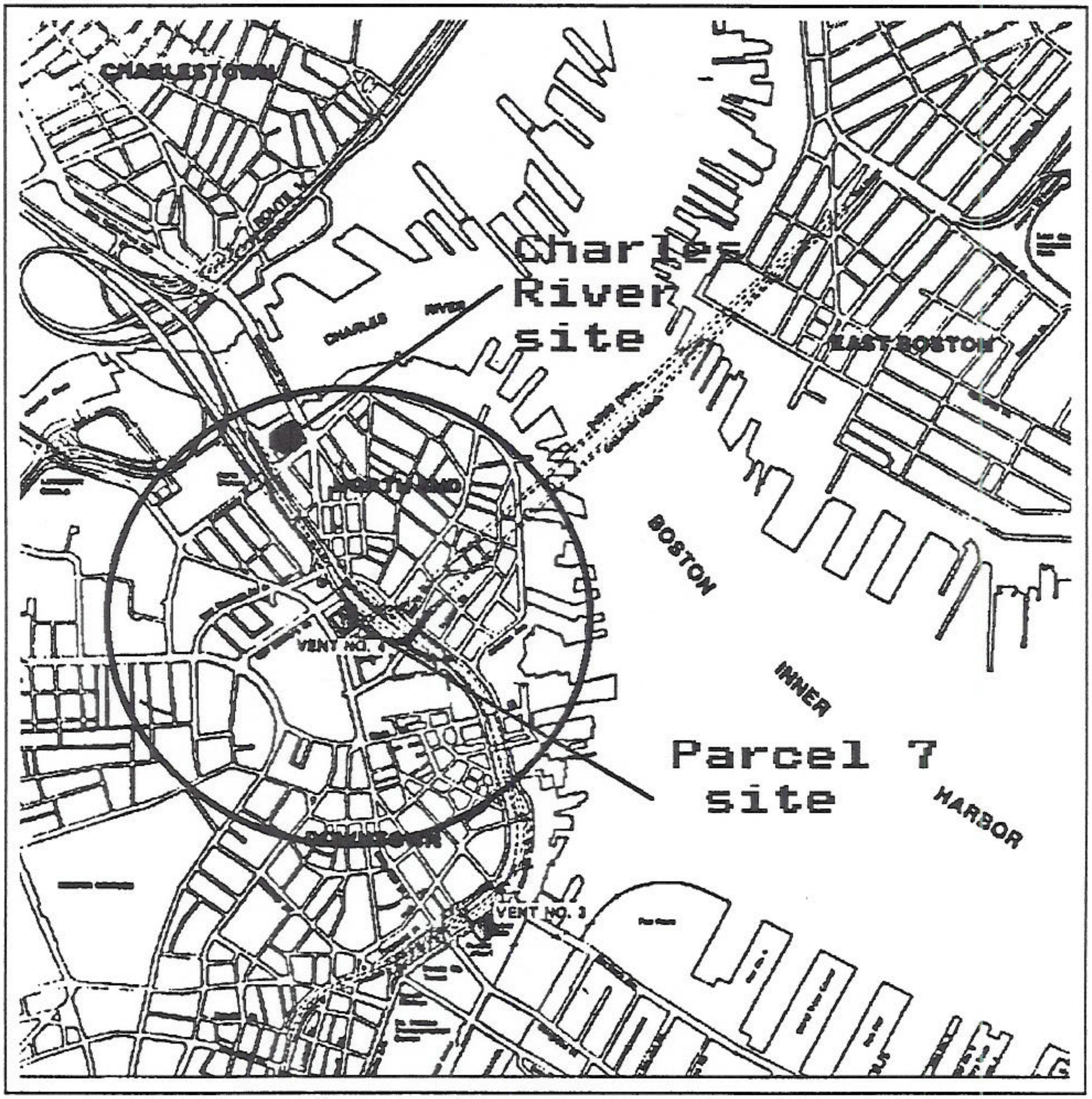

Figure 1 Parcel 7 model site on a map of Boston.

Figure 2 Parcel 7 model site picture.

Figure 3 Paecel 7 vent building model with 225 foot stacks.

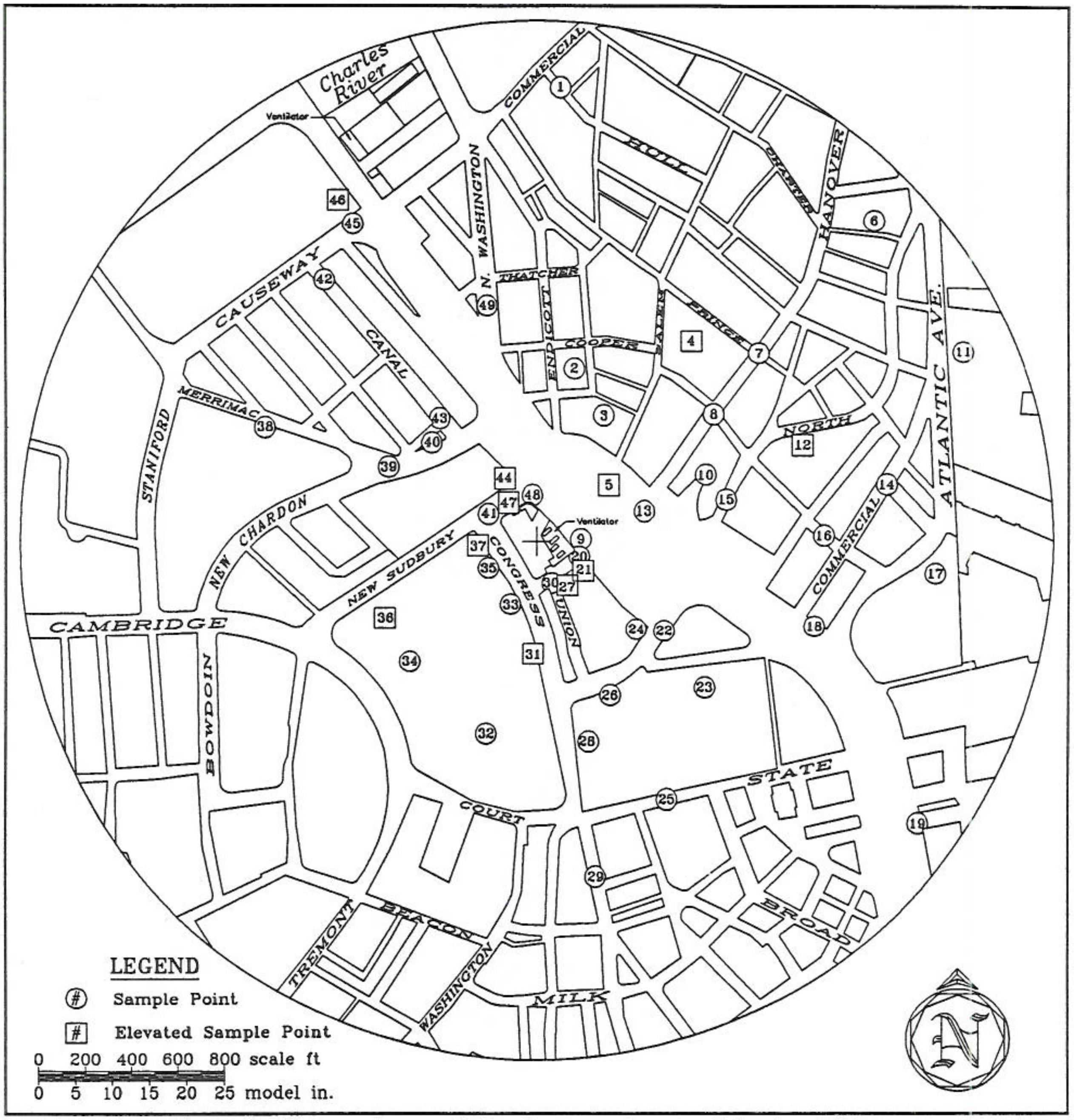

Figure 4 Concentration sample locations on a site map of the city of Boston.

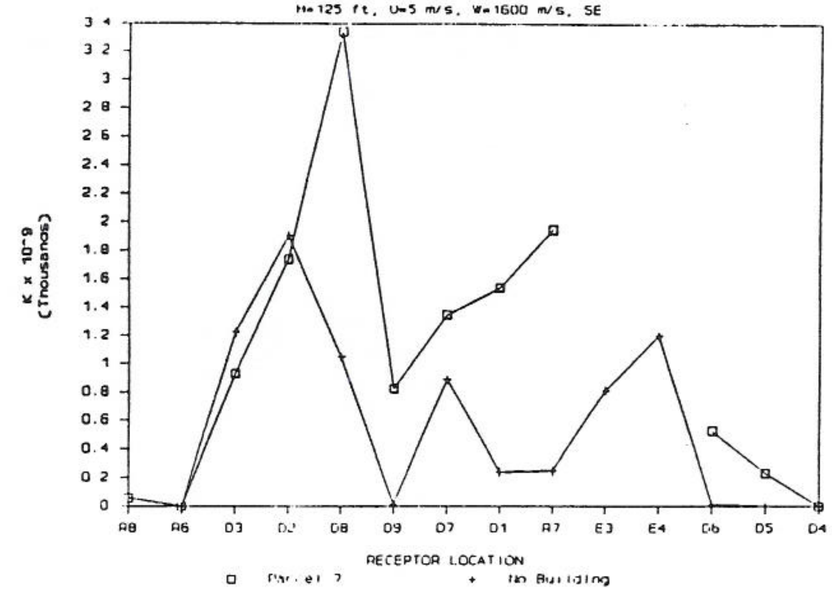

Figure 5 Building downwash effects through comparison between isolated 125 ft stack and ventilators on Parcel 7 ventilation building.

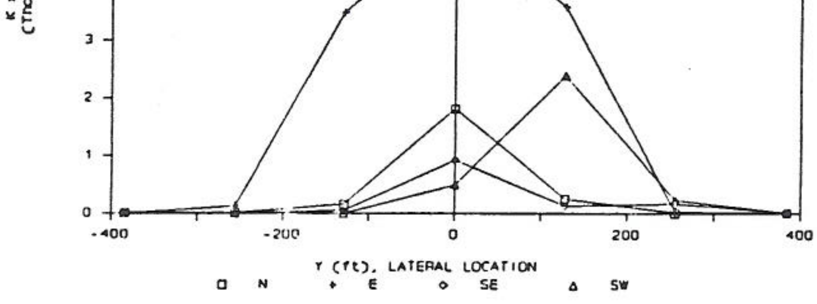

Figure 6 Groundlevel plume cross-sections downwind of Parcel 7 building, no city model present, X = 256 ft.

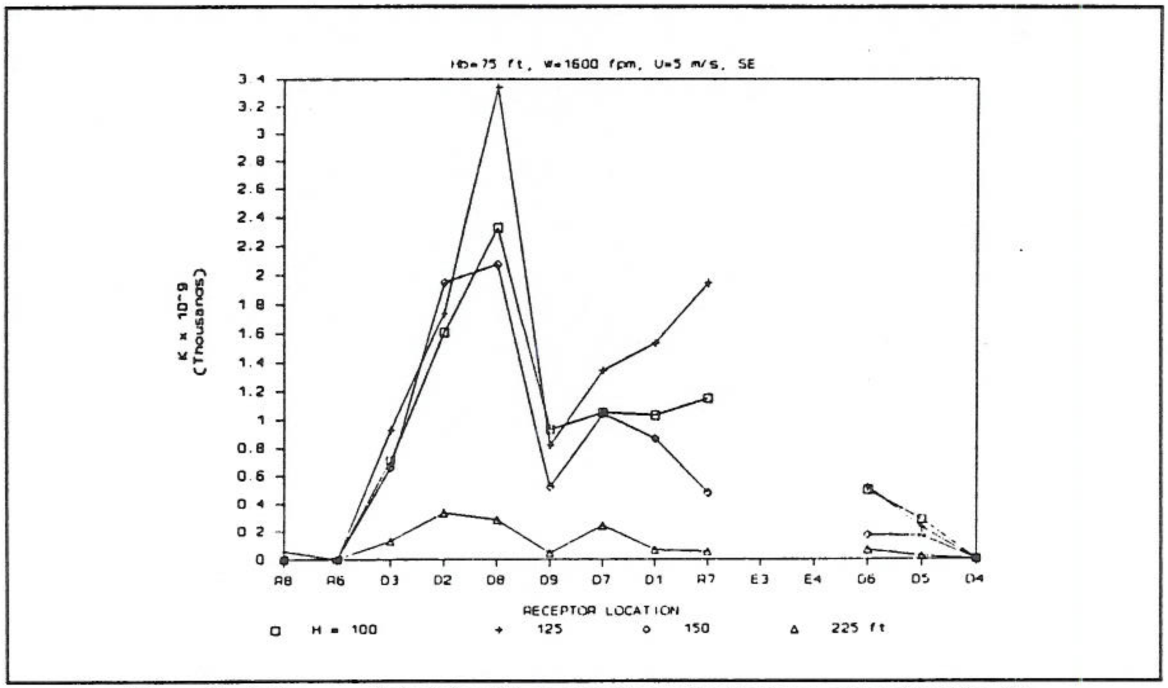

Figure 7 Influence of stack height on sampler concentrations, wind direction SE.

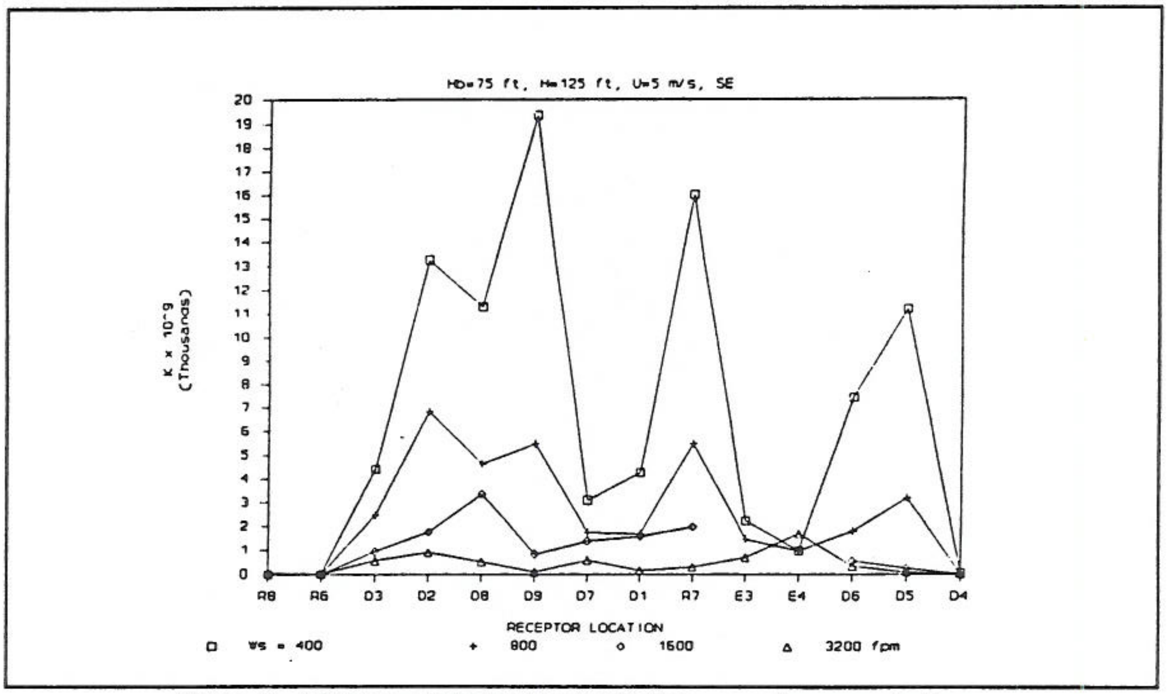

Figure 8 Influence of stack exhaust velocity on sampler concentrations.

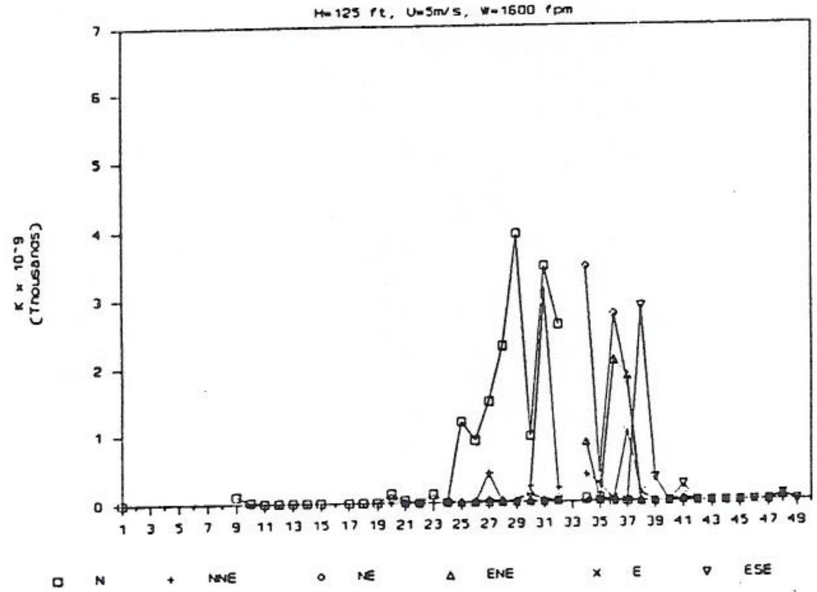

Figure 9 Influence of wind direction on sampler concentrations, N through ESE.