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Wind-Tunnel Studies of Variable Stack Heights for a Low-Profile Building

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ABSTRACT

An experimental wind-tunnel study of a proposed building with an exhaust stack was carried out. Smoke tracer techniques were employed to identify the wake and vortex shedding that was caused by the upstream edges or corners of the building. The data was used to determine a stack height required for the stack outlet to be free of the upstream wake effects. Additionally, smoke tracer experiments where smoke was emitted from the stack were conducted to identify the downwind dispersion of the smoke plume. Results from this data indicated if stack exhausts impacted upon the building roof or the downwind distance for the plume to reach ground level. An atmospheric wind tunnel was used to conduct the experiments. A 1:300 scale model of the building and its surroundings was placed in the tunnel and experiments were carried out to represent wind directions from the north, south, east, and west. Two different stack locations and three different stack heights were used in the experiments.

INTRODUCTION

The dispersion of potentially hazardous exhausts from a building stack is of great concern when addressing the possible consequences of such releases on the health and safety of people and the environment in the vicinity of the stack. Many variables affect the dispersion of exhausts from a stack such as wind speed and direction, stability of the atmosphere, stack height, surrounding buildings, trees and topography, stack exhaust velocity and initial pollutant concentrations.

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This report describes and presents results of a wind-tunnel experimental study of a proposed building at Lawrence Livermore National Laboratory in Livermore, California. The building is anticipated to be approximately 18.2 m (60 feet) tall and have an exhaust stack on its roof, at one of two possible locations. One objective for the wind-tunnel study is to determine an adequate stack height to ensure that stack emissions are not engulfed by the wakes, recirculation zones, and vortices of the proposed building and/or surrounding buildings. Other objectives are to determine if stack emissions may be re-entrained into the building and to determine the downwind dispersion of the plume.

The atmospheric wind tunnel at the University of California, at Davis was used to perform a series of experiments. A 1:300 scale model of the proposed building and the surroundings within one-half mile of the building were constructed for placement into the wind tunnel. Test conditions in the tunnel were set up to simulate atmospheric boundary layer air flow similar to the actual conditions at the building site. The wind-tunnel simulations represent wind velocity conditions of 11 m/s (25 mph) at a height of 40 m. Wind flow from the directions north, south, east, and west, were modeled in the tunnel.[+] Dispersion data for tracer smoke emitted from the wind tunnel modeled stack shows that a 45.5 m or taller stack would not result in smoke contacting the NDERF building roof for an east or west wind. The smoke plume is observed to reach ground level at 100 m downstream of the building edge. For the north or south wind directions, smoke contacts the building roof for the stack heights up to 54.5 m above the ground (three building heights above the ground).

BACKGROUND

In the evaluation of a stack design, the local wind-speed distribution plays an important role in stack design as well as the local topography. The expected near maximum wind speed at the stack height is used to estimate the required stack exit velocity. When the exit velocity is less than 1.5 times the wind speed at the stack, downwash from the stack may occur and possibly lead to higher roof concentrations (Ashrae, 1981). The local wind characteristics for LLNL, as obtained from an on-site meteorological tower, was examined for consideration of wind speed, direction, and frequency of occurrence. Typical data over a year's time was analyzed and the predominant wind direction is found to be from the west to southwest to south; however, the current interest

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+ In meterorology, a wind blowing from the west direction to the east direction is termed a westerly wind or simply west wind.

is not only in these directions but also from the less frequented directions of north and east.

The air flow patterns around a large flat-roofed building are characterized by flow patterns as shown in Figure 1. Upstream of the building is a stagnation recirculation region and downstream of the building a recirculation cavity generally occurs. On the roof a relatively small recirculation bubble exists near the leading edge. A wake extends from the leading edge of the building which increases with distance.

Atmospheric stability conditions may greatly influence the dispersion of a stack pollutant. Typically the near-ground atmosphere exhibits stable stratification conditions during nighttime hours and unstable conditions during daytime hours. For moderate to higher wind speeds, however, enough atmospheric turbulence is generated such that near neutral stability conditions prevail. Wind-tunnel modeling of unstable conditions is difficult, although stable conditions may be modeled without excessive difficulty by cooling the tunnel floor. Neutral conditions exhibit considerable atmospheric turbulence and mixing and are the conditions under which most wind tunnel simulations are conducted. Neutral conditions occur frequently at LLNL (Chapman and Gouveia, 1988) and are considered for this study to be approximately representative of the atmosphere near the proposed building stack. It is the atmospheric stability condition under which the wind tunnel simulations were conducted. Wind speed varies considerably at the LLNL site.

In performing the experiments, an atmospheric wind tunnel is required to obtain an accurate simulation of the atmospheric boundary layer. An atmospheric wind tunnel contains a relatively long entrance region that conditions the flow to develop a thick mature boundary layer with proper velocity profiles, turbulence intensity profiles, and turbulence energy spectra. Similarity criteria based on dimensional analysis have been developed to allow accurate simulation of dispersion in the atmosphere (Isyumov, 1980; Snyder, 1981; and others).

WIND-TUNNEL FACILITY

The Atmospheric Boundary-Layer Wind Tunnel Research Facility located at U.C. Davis was used for the present study. The tunnel was an open-return type and its overall length was 21.5 m, see Figure 2.

The entrance section had a bell mouth shape with a contraction area ratio of 4:1 as well as several lateral spires to condition the inlet flow. The flow development section was 12 m long and had divergent walls to reduce the streamwise pressure gradient. The test section was 2.44 m long, 1.68 m high, and

1.22 m wide. The ceilings of the flow development and test sections were adjustable for longitudinal pressure gradient control. The present test configuration provided zero-pressure-gradient flow.

In the test section a three-dimensional probe positioning mechanism provided fast and accurate (within 0.003 m) sensor placement. The scissor arms of the mechanism, which provided vertical probe motion, were made of aerodynamically shaped struts to minimize flow disturbances.

The diffuser section was 2.44 m long and had an expansion area that provided a continuous transition from the rectangular cross-sectional area of the test section to the circular cross-sectional area of the fan. To eliminate upstream fan swirl effects and avoid flow separation in the diffuser section, a large scale fiberboard honeycomb and smaller aluminum Hexcel honeycomb (0.019 m x 0.152 m) were placed between the fan and the diffuser section.

SIMILARITY REQUIREMENTS

An accurate simulation of the full-scale turbulent atmospheric boundary layer can be achieved only if the wind-tunnel boundary-layer also is turbulent. Flow over a roughened surface is fully turbulent if the roughness Reynolds number, Re_z, is (Isyumov and Tanaka, 1980) greater than 2.5 or:

$$Re_z = \frac{u_* z_o}{\nu} > 2.5$$

where u_* is the friction velocity, ν is the kinematic viscosity and z_o is the measured aerodynamic roughness height. At a tunnel freestream velocity, u_{max}, equal to 1.0 m/s, the value of z_o is approximately 0.005 m and the measured value of u_* is 0.02 m/s to give a value of $Re_z = 7$. The non-dimensionalized horizontal turbulence intensity and the turbulent kinetic energy spectrum were measured and found to be suitable for the present testing conditions. The spectrum exhibits the typical variation with wave number of - 5/3.

Velocity Profile in Turbulent Flow

The relationship for velocity, U, versus height, z in the turbulent core of a neutrally stable atmospheric boundary layer may be represented by:

$$\frac{U}{U_{max}} = \left(\frac{z}{z_{max}}\right)^{\alpha}$$

and the wind tunnel flow can be conditioned such that the exponent α will closely match the full-scale value of α. U_{max} is the wind speed at the height of the boundary layer, z_{max}, for full-scale flows. In the wind tunnel, this relationship is limited to the lower 10 to 20% of the boundary layer height due to simulation constraints. Full-scale measurements for LLNL (Chapman and Gouveia, 1988) give a nominal value of α = 0.3 and the tunnel value of 0.28 closely matched this value. In the lower 20% of the boundary layer height, which is governed by a rough wall logarithmic velocity profile:

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z}{z_0}\right) ,$$

it is desirable to have the scaled model building and its surroundings contained within this layer. The depth of this layer is approximately 0.16 m and corresponds to a full-scale height of 48 m (160 feet). This region of the boundary layer is relatively unaffected by the Coriolis forces and it is the only region which can be modeled accurately by the wind tunnel, i.e., the lowest 100 m of the atmospheric boundary layer under neutral stability conditions.

Building Reynolds Number

Wind-tunnel simulations use the same fluid, air, as in the full scale. The building Reynolds number, Re, represents a ratio of inertial to viscous forces per unit area and it is often used as a similarity parameter that must be matched between the full scale and the model to insure similitude. Full-scale building Re numbers exceed the tunnel building Re number by several orders of magnitude due to scale reductions. For the purpose of wind tunnel roof concentration profile measurements, flow above a critical building Reynolds number of 11,000 (Snyder, 1981) was found to be essentially Reynolds number independent for model cubes placed in the wind tunnel. The Re number is given by

$$Re = \frac{U_H H}{\nu}$$

where U_H is the velocity at the building or significant obstruction height, H. However, for complex flow geometry, the critical Reynolds number for flow independence must be determined experimentally in situ as was done for the present study. For present wind tunnel smoke plume dispersion tests, a value of building Re of 3300 was found to be satisfactory and flow independence was demonstrated by varying the wind tunnel freestream velocity. This corresponded to a freestream wind speed of 1 m/s. Additionally, the minimum Reynolds number necessary for flow independence appeared to approximately correspond to a wind-tunnel free stream wind speed of 0.5 m/s.

Stack Reynolds Number

Stack emissions in full scale are turbulent; however, in the wind-tunnel simulations matching the full-scale stack Reynolds number, Re_S, to that of the model is not possible. However, in wind-tunnel simulations adequate similarity is achieved by ensuring that the tunnel stack flow also is turbulent (Snyder, 1981). This condition is generally achieved (for neutral stability conditions) for stack Reynolds number, Re_S, greater than

$$Re_S = \frac{U_s D_s}{\nu} > 2300$$

and lower values are adequate if trips are used to enhance turbulence. D_s is the stack internal diameter and U_s is the smoke-air velocity up the stack. Hoult and Weil (1972) showed a stack Reynolds number as low as 300 was adequate for buoyant flows and Lape (1987) showed a Reynolds number of 700 was adequate. For smoke tests the stack inside diameter was 0.0008 m and for a tunnel stack velocity of 1.0 m/s, the stack Reynolds number was 533. The stack flow was tripped to enhance turbulence.

Momentum Scaling

Maintaining a correct ratio of plume momentum to ambient flow requires that (Isyumov, 1980)

$$\frac{\rho_s D_s^2 U_s^2}{\rho_a L^2 U_w^2} = \text{constant}$$

where L is a vertical length scale, and U_w is the wind speed at the stack height.

For non-buoyant stack exhausts the stack exhaust density, ρ_s, equals that of the ambient air, ρ_a, and the above relation reduces to:

$$\frac{D_s^2 U_s^2}{L^2 U_w^2} = \text{constant}$$

Momentum scaling was maintained for smoke plume experiments with a 0.008 m diameter stack and a stack exit velocity to 1.0 m/s. This case corresponds to the full scale case of 11 m/s (25 mph) wind speed at the stack height.

EXPERIMENTAL PROCEDURES AND INSTRUMENTATION

The smoke experiments were video taped for a duration of five minutes. For plume smoke tests a neutrally buoyant air-smoke mixture exited the wind-tunnel stack at a velocity of 1.0 m/s.

White smoke was utilized for the flow visualization tests. The smoke was produced by burning mineral oil droplets. The smoke was passed through a model smoke stack attached to the proposed building.

Video tapes of the four wind directions for each of the two stack locations were viewed frame-by-frame on a high-resolution Sony Trinitron video monitor (model PVM-2030) using a Panasonic video-cassette recorder (model AG-1950). Each wind-stack scenario setting was divided into twenty-five time intervals, approximately 2 seconds apart. The sketches of the smoke were traced directly on the monitor screen. To study the dispersion of smoke from the stack, these sketches outlined the smoke as it came out of the stack and flowed downstream.

Qualitative "probability density functions (PDF) of sorts" were made for each set of twenty-five sketches using observable smoke as a measuring medium. In the case of smoke dispersion from the stack, "PDF's" were done at two locations: at the trailing edge of the building, and at 100 m downstream of this trailing edge (or somewhat less than 100 m if testing conditions did not allow such an extensive view of the downstream region). Upper and lower boundaries of the smoke were determined from each of the twenty-five sketches and then the percentage of time that smoke was present at any given height, for a given location, was determined and plotted as the "PDF" versus height.

ANALYSIS OF DATA

Experimental data is presented in Figures 3 to 7 for smoke releases from the modeled stack. The figures show how smoke disperses for various stack heights downwind of the stack for wind directions indicated and for the location of the stack, i.e., primary or secondary. The figures show the extent of the vertical spread of the smoke with the visible upper and lower bounds shown by solid lines extended from the stack. At the downstream leading edge of the building, and at 100 m further downstream, the probability of smoke versus height is presented. As previously described, the probability represents the likelihood of finding smoke (which represents the stack emissions) at a particular height at a particular downstream distance. A value of 0% represents the case where no smoke was visible at this height and 100% represents the case where smoke was continuously visible.

Some general interpretation of the results is possible. Cases where smoke is visible at the level of the roof, at the downstream edge, represent conditions where possible re-entrainment of stack emissions may occur into the building ventilation system. Also this case will result in smoke entrainment in the downstream building wake recirculation region and thus suggests that the smoke will reach ground level. A comparison of the shape of the "PDF's"may be made. Shapes that are relatively narrow and of small area, represent conditions where higher concentrations of stack emissions may be found. Cases where the area is relatively large, represent conditions where lower concentrations would be found.

Figure 3 presents data for a 36.6 m high stack (2 building heights high relative to ground level) at the primary location for wind directions from the north, south, east or west. In each case, smoke is contacting the roof as indicated by the "PDF" at the downwind edge of the building, and also smoke is entrained in the downwind building wake region and reaches down to ground level. The maximum vertical height to which smoke reaches for a north wind direction, Figure 3a, at 100 m downwind of the building is 130 m. Lower heights were reached for the other directions.

Figure 4 presents further data for the north wind direction for stack heights of 45.5 m and 54.5 m (2.5 and 3 building heights relative to ground level) at the primary and secondary location. For primary stack locations and stack heights of 45.5 m and 54.5 m, Figures 4a and 4c, the smoke contacts the roof as shown by the downwind building edge "PDF". Smoke, therefore, also is entrained to ground level by the wake downstream of the building. For the secondary stack location for stack heights of 45.5 m and 54.5 m the smoke plume does not contact the roof. At the location 100 m downstream of the building edge, Figures 4b and 4d, the lower portions of the :PDF" were obstructed but smoke was observed within 5 m of ground level. Smoke plume touchdown on the ground can then be considered to occur soon thereafter.

Figure 5 presents data for the south wind direction for stack heights of 45.5 and 54.5 m and primary and secondary locations. For the primary location, Figures 5a and 5c, the smoke plume does not touch down on the building roof. At 100 m from the building, the plume has touched the ground in Figure 5a but in Figure 5c for the 54.5 stack the plume has a touchdown beyond 100 m. The plume is, however, very close to the ground and low enough to encounter trees and low buildings and thus disperse to ground level. For the secondary location the plume contacts the building roof for both the 45.5 m and 54.5 m stacks and the plume also is entrained to ground level in the downstream building wake region.

For east wind cases, Figure 6, with a stack height of 45.5 m and 54.5 m, the plume does not contact the roof but does contact the ground before 100 m downstream of the building.

For west wind cases, Figure 7, the smoke plume does not contact the roof for stack heights of 45.5 m and 54.5 m and the stack located at either the primary or secondary location. Plume touchdown for the 45.5 m stack occurs at approximately 100 m downstream of the building. For the 54.5 m stack at the primary location, Figure 7c, touchdown occurs at 100 m downstream of the building. For the secondary location and 54.5 m stack height, touchdown occurs beyond 100 m, Figure 7d, but by extrapolating the data an estimate of 140 m for touchdown can be made.

SUMMARY

A series of smoke tracer wind tunnel tests were conducted for two possible locations of the NDERF stack.

The wind-tunnel flow simulated the atmospheric boundary layer at LLNL by obtaining similar velocity and turbulent logarithmic velocity profile boundary layer that would engulf the scale-model stack.

Experimental flow conditions represent a full scale wind velocity of 11 m/s (25 mph) at a height of 40 m. The smoke tracer results show that, for an east or west wind, the exhaust from a 45.5 m high stack (2.5 building heights off the ground) will not be affected by upstream wake effects and also the exhaust plume will not contact the building roof for either the two stack locations investigated.

The downwind dispersion of tracer smoke exiting from the stack top was determined for stack heights of 36.6 m, 45.5 m, and 54.5 m for both stack locations. For an east or west wind, the plume was observed to contact the roof of the building for 36.6 m high stack. For a 45.5 m and 54.5 m stack, the plume does not contact the building roof and the plume touches the ground at approximately 100 m downstream of the downstream edge of the building. For north or south winds, plume roof contact occurs for a 54.5 m high or less stack when it is located nearer the upwind building edge. When the stack is farther from the upstream edge, the plume contacts the roof for a 36.6 m high stack but not for the higher stacks.

For a north or southwind, with the stack at its relatively farther location from the leading edge of the building, building wake effects extend to heights of 78 m. For all wind directions and stack heights considered, the exhaust plume will reach ground level within 100 m downwind of the building edge. also, the height of the roof recirculation bubble extends to 9 m above the roof and suggests that a minimum stack height should be higher than 9 m.

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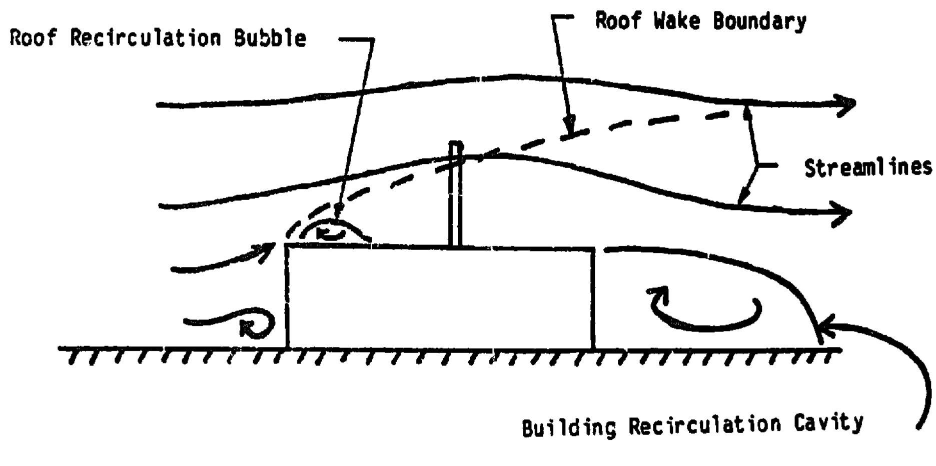

Figure 1. Air flow patterns around a long flat-roofed building.

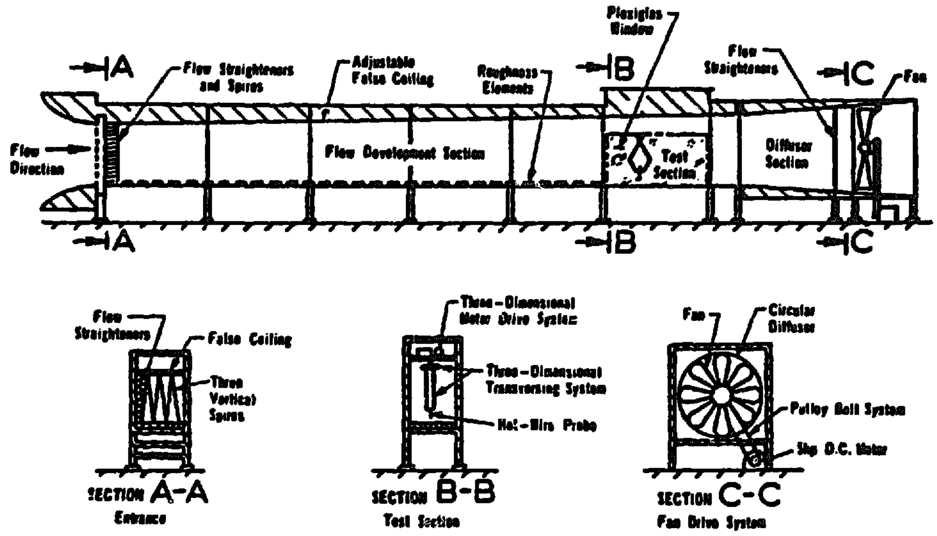

Figure 2. Diagram of the wind tunnel showing entrance cone and flow straighteners (Section A-A), test section with various probes (Section B-B), and diffuser-drive system (Section C-C.)

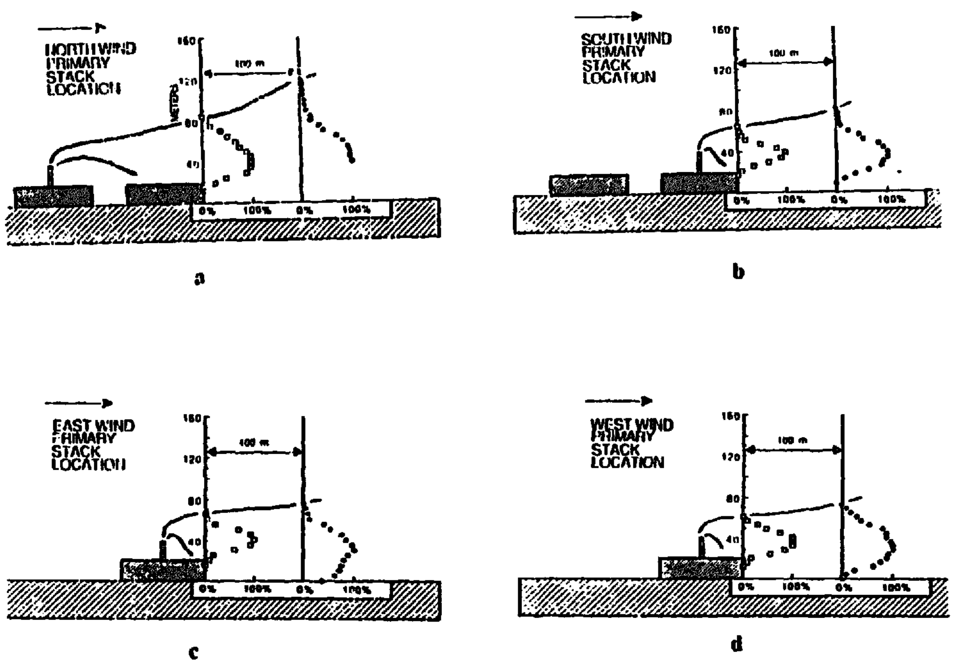

Figure 3 Wind-tunnel dispersion "PDF's" and plume outline for tracer smoke emitted from a 36.4 m high stack.

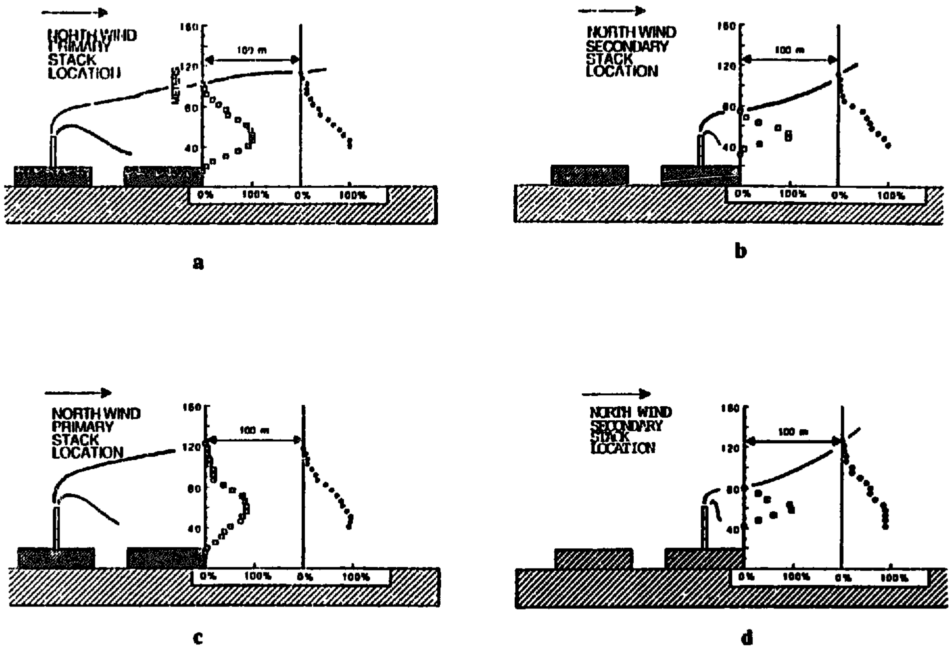

Figure 4 Wind-tunnel dispersion "PDF's" and plume outline for tracer smoke emitted from a 45.5 m high (a and b) and a 54.5 m high (c and d) stack.

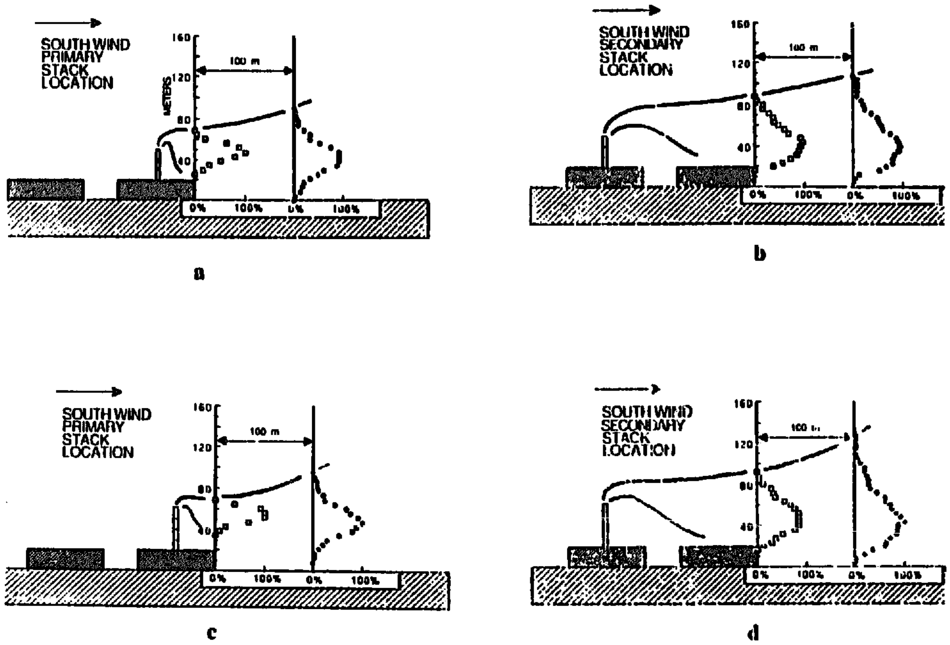

Figure 5 Wind-tunnel dispersion "PDF's" and plume outline for tracer smoke emitted from a 45.5 m high (a and b) and a 54.5 m high (c and d) stack.

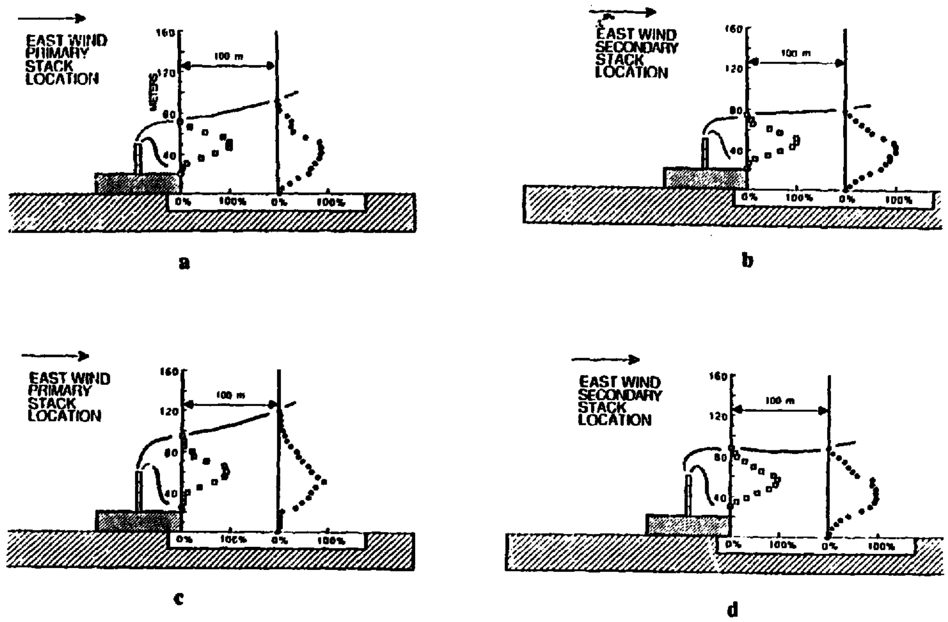

Figure 6 Wind-tunnel dispersion "PDF's" and plume outline for tracer smoke emitted from a 45.5 m high (a and b) and a 54.5 m high (c and d) stack.

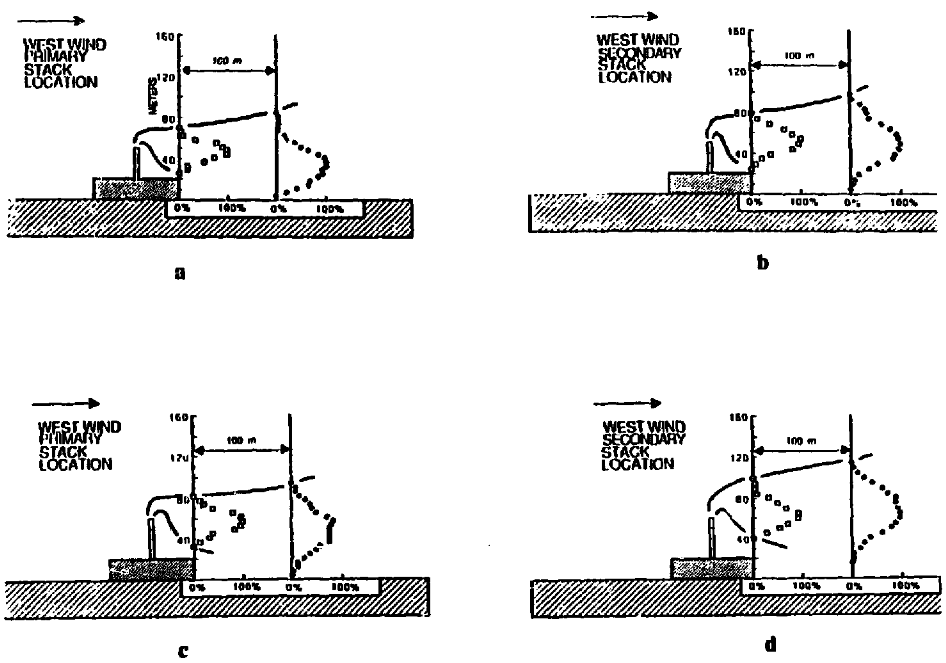

Figure 7 Wind-tunnel dispersion "PDF's" and plume outline for tracer smoke emitted from a 45.5 m high (a and b) and a 54.5 m high (c and d) stack.