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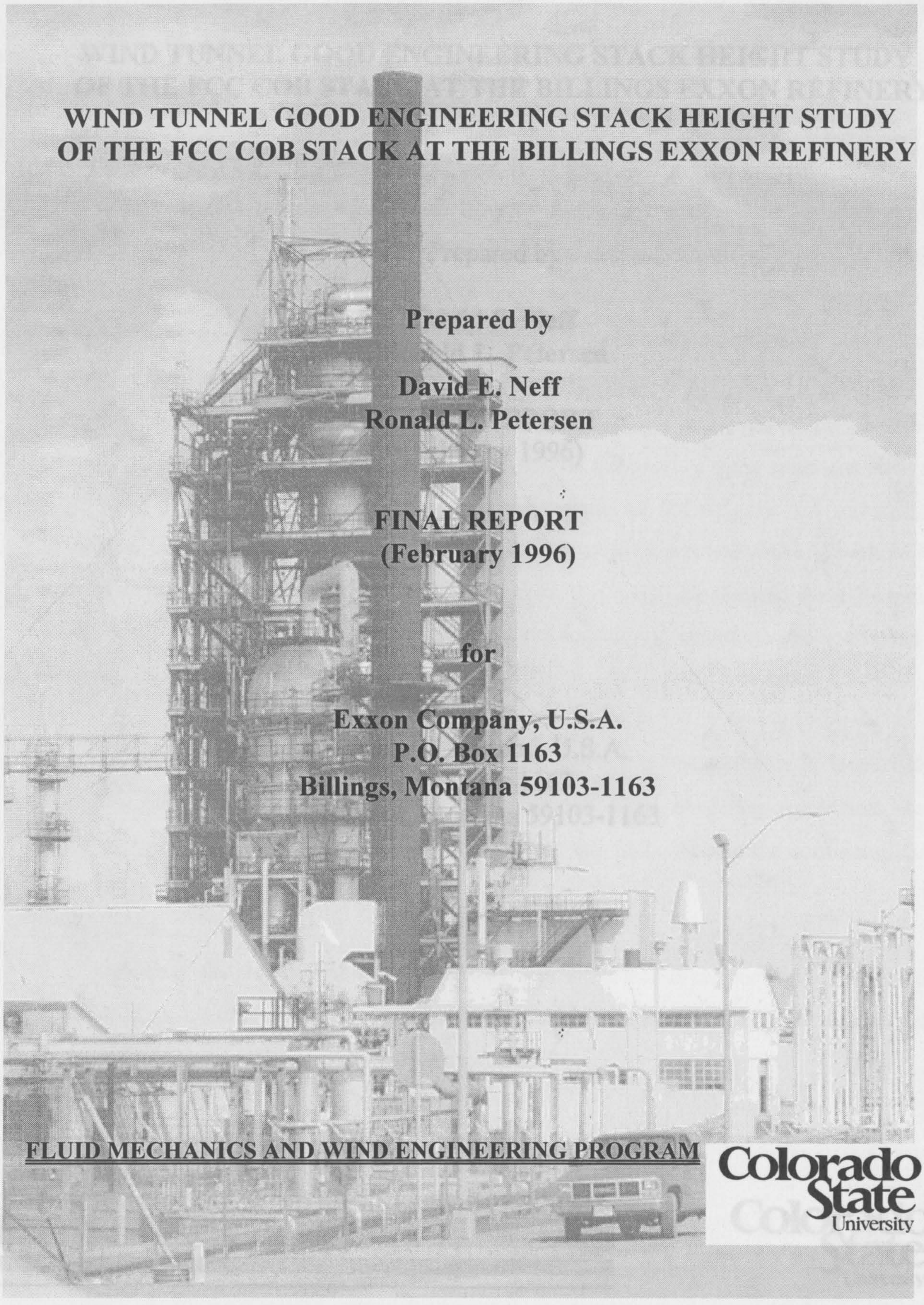

WIND TUNNEL GOOD ENGINEERING STACK HEIGHT STUDY OF THE FCC COB STACK AT THE BILLINGS EXXON REFINERY

Prepared by

David E. Neff
Ronald L. Petersen

FINAL REPORT
(February 1996)

for

Exxon Company, U.S.A.
P.O. Box 1163
Billings, Montana 59103-1163

FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

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EXECUTIVE SUMMARY

The purpose of this report is to describe the fluid modeling (wind-tunnel) studies conducted to verify that a 76.7 m stack height is creditable as "good engineering practice" (GEP) stack height for Exxon's FCC COB stack. Physical modeling of the atmospheric boundary layer and the plume was used to make this determination. A 1:400 scale model of the construction features of the Exxon's Billings refinery and surroundings, including portions of the neighboring Montana Sulphur Chemical Company and BGI/YELP facility and other offsite structures, was placed in CSU's environmental wind tunnel. Atmospheric transport of stack emissions from the FCC COB stack was investigated using the scale model of the refinery and surrounding structures. Ground-level concentrations of sulfur dioxide were determined with and without the nearby upwind structures by sampling concentrations of a tracer gas released from the model stack. Analysis of the results for various plant and meteorological conditions was conducted to demonstrate the creditable stack height.

The results of the wind tunnel testing demonstrated that a 76.7 meter stack is creditable as GEP. Excessive concentrations as defined in SIP Fluid Modeling Agreement were demonstrated at this stack height. This demonstration was made without the consideration of other background sources.

Testing was also conducted that showed a 40% increase in concentrations due to the presence of nearby structures for stack heights up to 100 meters. Future work is required to fully document whether the taller stack is creditable as GEP.

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1 INTRODUCTION

This report describes wind tunnel testing that was conducted to support Exxon's effort to increase the Fluid Catalytic Cracker CO Boiler (FCC COB) stack height at the Billings Refinery to the Good Engineering Practice (GEP) stack height. Increasing the stack height at the Refinery is part of the Billings/Laurel SO_2 State Implementation Program (SIP) compliance plan.

Background

Exxon Company, USA, operates a petroleum refinery located in Billings, Montana, known as the Exxon Billings Refinery. A dispersion modeling analysis performed by the Montana Department of Environmental Quality (DEQ) demonstrated the presence of building downwash associated with the Fluid Catalytic Cracker CO Boiler (FCC COB) stack and nearby structures at the refinery. To avoid the downwash problem, Exxon and the DEQ determined that the existing 63.4 m stack should be increased to the "good engineering practice" (GEP) stack height of 76.7 m. The GEP stack height calculation was based on the dimensions of the structures associated with FCC COB and the EPA recommended formula.

Accordingly, Exxon management proposed to raise the FCC COB stack to GEP formula height as part of the Billings/Laurel SO2 State Implementation Program (SIP) compliance plan. A technical support package for the refinery's proposal was submitted to the Montana Department of Environmental Quality (DEQ), and they, in turn, requested review by EPA Region VIII. In the Region VIII reply, they cited EPA rules which require "...sources wishing to raise existing below-formula height stacks up to formula height provide evidence that the additional height is necessary to avoid downwash-related concentrations raising health and welfare concerns." One method the EPA stated that could be utilized was through the use of fluid (wind-tunnel) modeling. While Exxon disputes the DEQ's and EPA's interpretation of the stack height regulations, Exxon has proposed and the Department agrees that fluid modeling shall constitute a valid and sufficient demonstration in support of the GEP formula height of 76.7 m for the FCC COB stack. The procedures agreed to (i.e., SIP Stack Height Fluid Modeling Agreement) are included in Appendix D.

Facility Description

The FCC COB stack is located in the process block known as the Fluid Catalytic Cracking (FCC) Unit. The FCC COB stack is 63.4 meters tall with an inside stack diameter of 2.96 meters. The existing SIP limit of FCC COB stack emission rate is 143 g/sec [Pechan, 1991]. The effluent is emitted at 12.5 m/s at about 497 K. The primary "nearby" structure (10 to 25 meters from the stack) which can produce plume downwash effects is composed of four solid components imbedded in the lattice framework. The four imbedded components are the elevator (3.2 m by 5 m by 49.2 m), the regenerator (7.6 m in diameter and 30 m high), the reactor (6.1 m diameter and 53.4 m high), and the fractionator (3.2 m in diameter and 45.3 m high). This structure was used to establish the GEP formula stack height of 76.7 meters pursuant to 40 CFR §51.100(ii)(2)(ii). A secondary "nearby" structure[1] (500 meters from the stack) which can produce plume downwash effects is the co-generation facility boiler building (33.5 m by 38 m by 38 m high). Other miscellaneous structures also surround the stack and are "nearby." The only significant terrain feature near to the refinery is an abrupt river bank that raises 23 meters to a plateau located 750 meters north of the FCC COB stack. The minimum terrain feature height which meets the 40 CFR 51.1(jj) definition of "nearby" is 26 meters thus this river bank cannot be considered as "nearby" for fluid modeling purposes.

Fluid Model Testing Program

A wind-tunnel measurement program was conducted that was consistent with the requirements in the SIP Fluid Modeling Agreement, as summarized below.

1. *The emission rate for the FCC COB stack was set to the existing SIP limits of 143 gm/s, as established in the E.H. Pechan & Associates, Inc. Report dated February 1991.*
2. *The representative area surrounding the FCC COB unit was simulated in the wind tunnel by appropriate surface roughness elements (i.e., $z_o = 20$ cm).*
3. *Representative meteorological conditions were used consistent with procedures in EPA's Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height.*
4. *The 40% differential in ground level concentrations due in whole or in part to downwash effects was determined by comparing the respective ground level concentrations produced by (1) running the wind tunnel simulation using scale models of both the FCC COB stack structure and its associated surrounding structures; and (2) running the simulation using scale models of the FCC COB stack alone with nearby structures removed.*
5. *Contributions to an exceedance of the NAAQS/MAAQS for SO_2 were determined by comparing the concentrations produced by the FCC COB wind tunnel simulations.*

Presented in this report are the technical aspects, experimental methods and results for the wind tunnel study designed to meet the above requirements. Section 5 of this report presents the results of the GEP stack height evaluation.

[1] for the purpose of a fluid model demonstration "nearby" structures are those that are within ½ mile of the FCC COB stack.

2 TECHNICAL CONSIDERATIONS

2.1 Similarity Requirement for Setting Model Operating Conditions

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion from an industrial facility. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion. A detailed discussion on these requirements is given in the EPA fluid modeling guideline (Snyder, 1981).

Based on past experience with GEP stack height and excessive concentration determination studies (Neff *et al.*, 1991; Petersen *et al.*, 1993; Iwanchuk *et al.*, 1992; Petersen, 1990a, 1990b, 1986, 1985; Greenway *et al.*, 1981; Halitsky *et al.*, 1986) and the requirements in the EPA stack height guideline (EPA, 1981; 1985), the criteria that were used for conducting the wind tunnel simulation are summarized below.

Plume Trajectory Simulation Criteria

- Match velocity ratio,

$$R = \frac{V_e}{U_h} \tag{1}$$

- Match density ratio,

$$\lambda = \frac{\rho_s}{\rho_a} \tag{2}$$

- Ensure that the stack Reynolds number exceeds 670 for buoyant plumes and 2000 for neutrally buoyant plumes (Arya and Lape, 1990). If these criteria cannot be met, a trip (i.e., turbulence enhancing device) should be installed in the stack to ensure an accurate plume rise simulation. A trip was used for these simulations.

Airflow and Dispersion Simulation Criteria

- All significant structures and terrain within a 732 m (2400 ft) radius of the stacks (see Figure 2) were modeled at a 1:400 scale reduction. This ensures that all major structures of interest whose critical dimension (lesser of height or width) exceeds 1/20th of the distance from the source are included in the model. Minor structures, such as guy wires, and piping were not considered.
- The mean velocity profile through the entire depth of the boundary layer was represented by a power law $U/U_\infty = (z/z_\infty)^n$ where the power law exponent, n, is dependent on the value of surface roughness, z_o, through the following equation:

$$n = 0.24 + 0.096 \log_{10} z_o + 0.016 (\log_{10} z_o)^2 \tag{3}$$

- Reynolds number independence was ensured: the building Reynolds number ($Re_b = U_b H_b / \nu_a$; the product of the wind speed, U_b, at the building height, H_b, times the building height divided by the viscosity of air, ν_a) was greater than 11,000 and Reynolds number independence tests were conducted.
- A neutral atmospheric boundary layer was established (Pasquill–Gifford D stability) by setting bulk Richardson number (Ri_b) equal to zero in model and full scale.

Using the above criteria and source characteristics specified in Table 1, the model test conditions were computed for the Exxon FCC COB stack. The tables in Appendix A show model and full-scale parameters for the FCC COB stack and wind speeds of 3, 5, 8, and 11 m/s (at a 7.6 m height at the Billings Airport). These are the wind speeds that were simulated during the course of the study. All wind speeds are less than or equal to the 2 percent wind speed which is discussed more fully in Section 2.5.

To make these computations, the following additional assumptions were made: 1) the approach surface roughness length 0.2 m for all wind directions; 2) the surface roughness length for the airport anemometer is 0.1 m; 3) the boundary layer thickness is 600 m; 4) the anemometer height at the airport is 7.6 m.

2.2 Determination of GEP Stack Height

In the stack height regulation (40 CFR 51.1 (ii)), GEP stack height is defined as the <u>greater</u> of:

" *(1) 65 meters, measured from the ground level elevation at the base of the stack;*

(2) (I) for stacks in existence on January 12, 1979, and for which the owner or operator had obtained all applicable permits or approvals required under 40 CFR Parts 51 and 52,

$$H_g = 2.5H \qquad (1)$$

provided the owner or operator produces evidence that this equation was actually relied on in establishing an emission limitation:

(ii) for all other stacks,

$$H_g = H + 1.5L \qquad (2)$$

where

H_g = *good engineering practice stack height, measured from the ground-level elevation at the base of the stack,*

H = *height of nearby structure(s) measured from the ground-level elevation at the base of the stack,*

L = *lesser dimension, height or projected width, of nearby structure(s),*

provided that the EPA, State or local control agency may require the use of a field study or fluid model to verify GEP stack height for the source; or

(3) The height demonstrated by a fluid model or a field study approved by the EPA, State or local control agency, which ensures that the emissions from a stack do not result in excessive concentrations of any air pollutant as a result of atmospheric downwash, wakes, or eddy effects created by the source itself, nearby structures or nearby terrain features."

It should be noted that the selective application of Equation (1) has been remanded but a revised regulation has not yet been provided. Equation (1) is essentially the formula specified by Congress in the Clean Air Act. Equation (2) is a more restrictive formula (for tall-thin structures) which simplifies to Equation (1) for structures that are wider than they are tall. EPA (1985) makes it clear that the highest height resulting from the application of the formula to multiple structures is formula height. Formula height is GEP unless a verification is required or unless a higher height is demonstrated under kk(3).

To quantitatively determine the GEP height through wind tunnel modeling, the stack height regulation defines an excessive concentration for sources seeking stack height credit where the State or EPA has required the use of a fluid modeling study to verify the GEP stack height, or for sources seeking stack height credit based on the aerodynamic influence of structures not adequately represented by the formula. The definition is as follows (40 CFR 51.1 (kk) (3)):

"A maximum ground-level concentration due in whole or part to downwash, wakes, or eddy effects that is at least 40 percent in excess of the maximum concentration experienced in the absence of such downwash, wakes, or eddy effects."

The above definition may be appropriate for this study; however, the agreed upon definition of an excessive concentration in the "Stack Height Fluid Modeling Agreement " and which also conforms to 51.1 (kk) (2) are as follows:

" a maximum ground-level concentration due in whole or part to downwash, wakes or eddy effects as provided in paragraph (kk) (1) of this section, except that the emission rate specified by any applicable State implementation Plan (or, in the absence of such a limit, the actual emission rate) shall be used ..."

Further, (kk) (1) states

" a maximum ground level concentration due in whole or part to downwash, wakes, and eddy effects produced by nearby structures or nearby terrain features which individually is at least 40% in excess of the maximum concentration experienced in the absence of such downwash, wakes, or eddy effects and which contributes to a total concentration due to emissions from all sources that is greater than an ambient air quality standard."

In short, the 76.7 m stack height will be justified as GEP if the wind tunnel study shows (1) the presence of ground level concentrations at certain locations which are at least 40% in excess of maximum concentration experienced in the absence of nearby building effects (i.e., referred to as the 40% test); and at the same locations (2) FCC COB emissions contribute to a total concentration from all sources that is greater than an ambient air quality standard for SO_2 (referred to as the ambient standard test).

2.3 Emission Rates

For creditable stack heights less than or equal to the formula GEP stack height of 76.7 m, the existing SIP emission will be used as established in the E.H. Pechan and Associates report dated February 1991. This emission rate is 143 g/s. If a creditable stack height taller than formula GEP is sought, a more stringent emission limit is required as specified in the Fluid Modeling Agreement. At this time credit for a stack height taller than 76.7 m is not being sought and the 143 g/s emission will be used throughout the study.

2.4 Nearby Structures and Terrain

To evaluate the effect of the nearby structures, tests are first conducted with all significant structures present in the model (referred to as "building in" tests). Next, the same meteorological conditions are simulated with the nearby structures indicated in Figure 3 removed (referred to as "building out" tests). For the structures to be considered nearby for wind tunnel modeling purposes, the stack must be within ½ mile of the structure (see 40 CFR 51.1 (jj) (2)). The ratio of maximum ground level concentration for the "building in" and "building out" tests are compared to the 40 percent criteria previously discussed. The maximum ground level concentrations from the building in tests are compared with an ambient air quality standard after appropriate time scaling is applied.

Figure 3 shows the aerial view of the structures that were included in the model. All of these structures were removed for the nearby building out tests when evaluating these wind vectors. The justification for removing multiple structures is found in EPA guidance (1981) on page 41 where it states to remove the building(s). In addition, 40 CFR 51.1 (ii) (3) states that the GEP stack height is that height that avoids excessive concentrations due to the downwash of nearby structures (plural). Multiple structures have been removed in previous GEP stack height studies conducted by Petersen (1987; 1987) that have been approved by EPA.

The only significant terrain feature near the refinery is an abrupt river bank that rises 23 m above grade to a plateau located about 750m north of the FCC COB stack according to USGS maps (see Figure 2). The minimum terrain feature height which meets the EPA definition of nearby is 26 m; thus, the river bank feature is not nearby for fluid modeling purposes. Terrain downwash effects were not considered in this study. Since terrain effects were not considered, terrain outside the model area shown in Figure 2 was not considered in this evaluation. Terrain contours, however, were modeled within the area shown in Figure 2.

2.5 Test Wind Speed and Wind Direction

The EPA stack height guideline (EPA, 1981) indicates that the design wind speed be less than the 2 percent wind speed (speed that is exceeded less than 2 percent of the time) unless it can be demonstrated that higher speeds cause exceedances of NAAQS or PSD limits. The 2 percent wind speed was determined by analyzing meteorological data collected at Logan Field, Billings, Montana, the site selected by DEQ for air modeling purposes (see Figure 1). The analysis showed that the 2 percent speed based on meteorological data for the period 1965–1974 is 11 m/s. All concentration tests to justify the GEP stack height were conducted with speeds at or below 11 m/s. Tests were conducted to determine the critical wind speed (i.e., that speed resulting in the highest excessive concentration).

Wind speeds in the tunnel were set at a reference height of 400 m above stack grade. The speed at this reference height is determined by scaling the 7.6 m airport wind speed up to the freestream height, 600 m (Snyder, 1981) above ground level. At this height, is it assumed that wind speeds at the site and at the anemometer location are the same (i.e., local topographic effects are not important). Next, the wind speed at the reference height is calculated using the wind speed at the freestream height and scaling down to the lower height using the following power law equation:

$$U_r = U_\infty \left(\frac{z_r}{z_\infty} \right)^{n_s} = U_{anem} \left(\frac{z_\infty}{z_{anem}} \right)^{n_a} \left(\frac{z_r}{z_\infty} \right)^{n_s} \qquad (4)$$

where

U_r	=	wind speed at reference height (m/s),
z_r	=	reference height above plant grade (300 m),
U_∞	=	wind speed at freestream height (m/s),
z_∞	=	freestream height (600 m),
U_{anem}	=	wind speed at 7.6 m height at the airport (m/s),
z_{anem}	=	height above grade for U_{anem} (7.6 m),
n_a	=	wind power law exponent at the anemometer (0.16),
n_s	=	wind power law exponent at the site (0.18).

Tables in Appendix A provide the calculated results using the above equations. It should be noted that the power law exponents were calculated using Equation (3) in Section 2.1 with z_o equal to 0.1 and 0.2 for the airport and site respectively.

2.6 Surface Roughness Length

As specified in the protocol, a suburban target surface roughness length of 20 cm was specified for the area surrounding the refinery model.

2.7 Background Concentration Determination

The evaluation in Section 5.3 shows that background concentrations are not needed to justify the 76.7 m stack height. If a taller creditable stack height is sought sometime in the future, a background concentration analysis will be required.

3 EXPERIMENTAL METHODS

3.1 Model Construction and Coverage

From an on-site inspection of the refinery complex three wind directions were identified as having the potential to create "excessive concentrations." These were the alignments of the FCC COB stack with the Lattice Tower, with the Co-Generation Facility, and with the complex structural group ENE of the stack. Figure 2 displays the extent of the modeled area on the primary wind direction overlaid on a USGS topographic map. An aerial photograph of the field site area is shown in Figure 3[2]. Figure 4 shows the Lattice Tower offset and behind the FCC COB stack at the field site. Figure 5 shows the complex structural group as seen from the Lattice Tower at the field site (looking ~ENE).

Based on atmospheric data over the site area, the size of the concentration measurement grid, and modeling constraints previously discussed, a model scale of 1:400 was selected. Since the Environmental Wind Tunnel at Colorado State University has a 3.66 meter turntable this allows for the reduced scale construction of all significant buildings within a 730 meter radius of the plant stack. The tunnel test section can extend 6.4 meters downwind of the stack location thus providing for scaled concentration measurements out to 2.5 km.

The buildings surrounding the plant stack were fabricated from Styrofoam and placed in their appropriate locations on a 3.66 meter diameter, 0.63 cm thick masonite sheet. All roads and railways were painted on this masonite sheet. Modeled upwind and downwind structural and terrain features were also fabricated if their heights exceeded 1/20th the distance to the plant stack. All significant topography changes within the modeled area were included on the model. The model plant stack was adjustable in height from 63.4m to 100m. It was constructed from brass tubing stock. The stack exteriors were scored to assist in creating turbulent flow separation. An orifice, one-half the inside diameter, was inside the stack to ensure fully turbulent exit flow. Roughness elements of 0.15 cm were spread over all model ground level surfaces to ensure proper Reynolds number performance.

Figure 6 shows the 1:400 model of the FCC COB stack and the Lattice Tower placed at the center of the turntable. Figure 7 shows a view of the model turntable looking past the FCC COB stack and the Lattice Tower towards the Co-Generation Facility.

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[2] Note that the new co-generation facility is not present in either the USGS map or the aerial photograph.

3.2 Boundary Layer Wind Tunnel

All model tests were performed in the Environmental Wind Tunnel (EWT) test facility at Colorado State University (CSU). This tunnel has a 3.66 m by 2.13 m cross section, a 17.4 m length, a wind speed range of 0 to 15 m/s and a flexible test section roof. A complete description of this facility is provided in Appendix C. Appropriate boundary layer development techniques were utilized to accurately represent wind conditions approaching the plant stack from all wind directions. The project model was placed on a 3.66 meter diameter turntable located ~9 meters into the test section. This placement provides sufficient upwind fetch, and a sufficient downwind measurement zone. The zones upwind and downwind of the turntable area were modeled with a generic roughness (chain rows every 15 cm on top of astroturf carpet) design to create the desired model boundary layer.

3.3 Velocity Measurements

The techniques employed in the acquisition of velocity profiles are discussed in detail in Appendix C including basic equations and errors associated with each technique. Single-hot-film (TSI 1220 Sensor), cross-film (TSI 1241) probes and pitot-static probes are used to measure velocity statistics. TSI 1125 Velocity Calibrator System and Pitot-static Probes are used for velocity calibration.

The approach mean velocity and turbulent statistics profiles are obtained from velocity measurement techniques. The approach mean velocity profiles for a suburban roughness condition are regressed to find the best log-log and log-linear fit. The log-log regression will find a power law exponent, p, such that;

$$U/U_r = (z/z_r)^p$$

The log-linear regression;

$$U/u_* = 2.5\ln\{(z-d)/z_o\}$$

will find a best fit roughness length z_o, friction velocity u_*, and displacement height d.

Velocity measurements obtained in this study are summarized and presented through plots of vertical profiles of mean velocity, longitudinal and vertical turbulence. Each of the vertical profiles of mean velocity are plotted on linear-linear and log-linear paper to display the best fit regressions.

3.4 Plume Visualization Techniques

Techniques employed to obtain a visible plume are discussed in Appendix C. A Smoke Generator System and a Video Camera System are used for plume visualization. Given a field to model wind speed ratio of 2.35 (= [10.1 m/s]/[4.3 m/s]) and a model to field length scale ratio of 400, then the time scale ratio between the model and the field is 1:170. Thus phenomena observed over the model in the wind tunnel will occur 170 times faster than observed at full scale. If the TV tapes were replayed in slow motion (170 times slower than the recorded speed) the observed plume trajectories and motions would appear realistic.

3.5 Concentration Measurements

Techniques employed to obtain the concentration data are discussed in Appendix C. A gas chromatograph with flame ionization detector is used to measure gas concentrations. A schematic of stack gas release, sampling, and analyzing methodology is included in Appendix C.

Concentration data are reported in terms of field scale normalized concentration, K_p, where $K_p = (\chi U_H/Q)_p$ [m^{-2}]. This normalized format is convenient because the concentration results, χ_p [gm/m^3], from a test at one particular combination of wind speed, $(U_H)_p$ [m/s], and source mass flow rate, Q_p [gm/sec], can be extrapolated to other $(U_H)_p$ and Q_p values provided that flow physics, such as plume rise, remains the same. $(U_H)_p$ is the field wind speed at the stack height. The conversion from model units to field units is as follows:

$K_p = K_m * (H_m/H_p)^2$ [m^{-2}]; with $K_m = (\chi U_H/Q)_m$ [cm^{-2}].

χ_m is the source normalized model concentration (ppm),

$(U_H)_m$ [cm/s] is model wind speed at stack height,

Q_m [ccs] is the model stack flow rate,

H_m [cm] is the model stack height, and

H_p [m] is the field stack height.

Full scale concentrations for comparison with ambient standards was computed as follows;

$\chi_p = K_p \; Q_p \; / (U_H)_p$.

3.6 Stack Flow Rate and Composition Techniques

An Omega mass flow controlling system was used to monitor and control all stack gas flow settings. This system has six mass flow channels with full scale responses of 0.1, 1, 5, 10, 50 and 100 SLPM for gases with unity gas factors. Different gases will have different gas factors and this must be taken into account when calculating the proper meter setting. The local atmospheric pressure (~631 mmHg at CSU) must also be accounted for in these calculations.

During a visual plume test the proper plume flow rate and specific gravity is attained by mixing metered quantities of Air (SG = 1) and Helium (SG = 0.14). This gas mixture is then pass through the smoke generator and then out the model stack. During a plume concentration test a hydrocarbon gas must be in the source mixture so that measurements of sample concentration can be made with a flame ionization type gas chromatograph. Depending upon many experimental considerations, a hydrocarbon, either methane (SG = 0.55), ethane (SG = 1.04), or propane (SG = 1.52) will be mixed with Helium (SG = 0.14), Nitrogen (SG = 0.967), or Argon

(SG = 1.38). This mixture is passed directly into the model stack. Table 3, Stack Gas Flow Settings and Composition, lists the settings and type of gas used to achieve the proper model stack effluent discharge velocities and specific gravities.

3.7 Atmospheric Dispersion Comparability (ADC) of the Test Facility

The EPA stack height guideline (EPA, 1981) requires that the wind tunnel testing facility demonstrate atmospheric dispersion comparability by acquiring and documenting a set of velocity and concentration profiles on a standardized stack plume released into a standardized model boundary layer. This guideline outlines in detail the testing requirements for this comparability demonstration. Appendix C is the documentation of this ADC testing program. From this ADC testing program it is concluded that the wind tunnel boundary layer is representative of a 1:400 scaled Pasquill-Gifford open C to D dispersion category. Table 4 summarizes the measurements that are required and that are discussed in Appendix C.

4 RESULTS OF FLUID MODELING TESTS

The goals of this testing program were to determine and fully document the GEP stack height for the FCC COB stack in complete compliance with the EPA Guideline. The required tests are summarized in Table 4. The Study Protocol (Neff, 1995a) lists the conditions for each type of data test that was to be performed in the original specification. The Atmospheric Dispersion Comparability Test Series is fully documented in Appendix C (Neff, 1995b). It is concluded in Neff, 1995b that the wind tunnel facility reproduces field plume behavior accurately at the selected model scale of 1:400.

Table 2 lists all pertinent field and model parameter values for the stack plume tests. In Table 2, under the heading of "Building Config.", Out refers to the removal of the all significant structures, In refers to the inclusion of all structures.

The concentration test results from the "Wind Direction Determination Test Series" (as defined in Table 2) indicated that the wind direction of 72° from the north produced the largest excessive concentrations.

4.1 Wind Profiles Measurements

To document the wind tunnel flow conditions, wind tunnel centerline wind profiles were measured just upwind of the stack, 250 cm (1 km field), and 500 cm (2 km field) downwind of the stack for a 5 m/s wind from 72° Table 5 presents model and field equivalent values for these profiles. These profiles were examined to determine the following model boundary layer similarity parameters; the roughness length, the displacement height, the friction velocity, and the power law index.

The left graph in Figure 8 displays the test data as symbols and the design power law curve (index = 0.18) as a line. This graph shows that the two downwind model profiles are representative of the field design power law index value of 0.18. The profile nearest the stack displays the influence of building wakes in the refinery complex. The right graph in Figure 8 displays the mean velocity profile test data and the design log-lin law on log-lin coordinates. This graph shows that the model profile is representative of the field design values of roughness length equal to 0.18 meters, friction velocity equal to 0.49 meters/second, and a displacement height of 0.0 meters.

The left graph in Figure 9 displays the longitudinal turbulent intensity profile test data and the EPA 1981 guideline suggested design curve. The guideline states that a model turbulent intensity greater than this curve maybe too turbulent of a condition. The measured test data is slightly less turbulent than the suggested curve and thus complies with the guidelines specifications. The right graph in Figure 9 displays the vertical turbulent intensity profile test data. It is seen that the ratio of the vertical to longitudinal turbulent intensity near the ground is ~ 0.5 as suggested in Snyder, 1981. Figure 10 displays the a vertical profile of the Reynolds stress divided by the friction velocity squared. It is observed that the magnitude of this profile near to the ground is close to one, as EPA 1981 guideline suggests it should be.

Lateral velocity profiles ($Y_f = \pm360, \pm240, \pm120, 0$ meters) at four heights ($Z_f = 40, 60, 80, 120$ meters) were taken at two downwind positions ($X_f = 0, 2000$ meters) to document the wind flow over the modeled area. These mean velocity and turbulent intensity data are presented in Table 6. Graphs of the lateral mean velocity and lateral turbulent intensity profiles for both downwind distances and for the heights of 10 cm model (40 meters field), 20 cm model (80 meters field), and 30 cm model (120 meters field) are presented in Figure 11. Here again it is seen that the scaled model produces wake regions of low mean velocity and high turbulent intensity.

4.2 Stack Plume Visualization

Model plant stack plume visualizations were performed. The visual records were documented on the video cassette VHS tape. The camera position for these film sequences was inside the wind tunnel, by the wall, slightly upwind of the plant stack, at a height slightly above model ground level. Each test observes the plume trajectories from the plant stack down to the end of the model turntable, approximately 1000 meters field equivalent distance.

The worst case wind direction decision with regards to "excessive concentrations" was observed to be in the vicinity of 72° where a complex structural group was directly upwind of the plant stack. VHS tape documents the 76.7 meter stack plume behavior for a 5 m/s wind at 72° for both the structures "in" and structures "out" test cases.

4.3 Concentration Measurements

Concentration measurements downwind of the model plant stack were measured for the tests listed in Table 2. Table 7 through Table 10 list the run conditions, the model and field position of the concentration measurements, and the model normalized concentrations (source and background adjusted ppm). These tables present the model data for the wind direction variation test series (series 300 in Table 2), the wind speed variation test series (series 400), the stack height variation test series (series 500), and the GEP stack height documentation test series ground level measurements (1st part of series 700 in Table 2) respectively.

Table 11 through Table 15 list for the GEP stack height documentation test series (series 700 in Table 2) the run conditions, the model and field position of the concentration measurements, the field normalized concentrations in [m^{-2}] for both buildings in and buildings out conditions, and field normalized concentrations predictions using the Pasquill-Gifford open C&D dispersion parameters. These tables present the averaged ground level values, the vertical and lateral profiles at downwind distances of 0.5 km, 0.9 km (at GLC_{max}), 1.0 km, and 2.0 km respectively. Table 8 through Table 11 also present the maximum ground level concentration observed in each test and the percent increase in this maximum ground level concentration between the runs with no buildings versus ones with buildings present, i.e. "excessive concentration."

The variation of ground level concentration (K in [m^{-2}] with U referenced to 400 meters at the site) with downwind distance for stack heights varying from 80 meters to 100 meters is presented in Figure 12 for both buildings in and buildings out configurations (test series 500 in Table 2).

The variation of averaged ground level concentration (K in [m^{-2}] with U referenced to 76.7 meters at the site) with downwind distance for 76.7 meter stack height is presented in Figure 13 for buildings in, buildings out, PG category C, and PG category D configurations (test series 700 in Table 2). Figure 14 presents several averaged ground level crosswind concentration profiles for both buildings in and buildings out configurations. Figure 15 through Figure 18 display the vertical and lateral concentration (K in [m^{-2}] with U referenced to 76.7 meters at the site) profiles for buildings in, buildings out, PG C&D configurations (test series 700) at downwind distances of 0.5 km, 0.9 km, 1.0 km, and 2.0 km respectively.

The variation of the vertical and lateral dispersion parameters with downwind distance for buildings in, buildings out, PG C,D&E configurations is presented in Figure 19. These dispersion coefficients were calculated via a fit of the data to the Gaussian dispersion equation.

5 EVALUATION OF GEP STACK HEIGHT

5.1 General

To ensure that the maximum creditable GEP stack height was obtained, a four-phase measurement program was undertaken as summarized in Table 16. The phases are referred to as: 1) worst wind direction tests (series 300 in Table 16); 2) worst wind speed tests (series 400 in Table 16); 3) additional stack height tests (series 500 in Table 16); and 4) GEP stack height documentation tests (series 700 in Table 16). The purpose of the first two series of tests was to find the wind direction and wind speed that produce the largest excessive concentration due to downwash effects. For these tests, the formula GEP stack height was evaluated (i.e., 76.7 m), since this was the maximum stack height for which Exxon is presently seeking credit. Ten wind directions were specified during a visualization (no recording of this visualization was made) that was conducted immediately preceding the quantitative testing. These wind directions were evaluated at a 5 m/s wind speed which is less than the 2 percent wind speed (11 m/s). This speed was selected since the stack exit velocity is low and past experience has shown that lower wind speeds produce the highest concentrations for low exit velocity exhausts. For the wind direction producing the largest excessive concentration, tests were next conducted at 3, 8 and 11 m/s to find the critical wind speed.

The next phase of testing was for taller stack heights. Tests were conducted at incrementally higher stack heights starting at 76.7 m until an excessive concentration (i.e., based on the 40 % criteria) was no longer demonstrated. The stack height immediately below this point is the GEP stack height using the 40% test alone. It should be noted that this testing was conducted at the wind direction and speed previously identified as producing the largest 40% excessive concentration (72 degrees and 11 m/s).

The final phase of testing was the documentation tests. For these tests, the test condition associated with the stack height for which credit is being sought (i.e., 76.7m) was repeated three times with and without the nearby buildings present. The maximum values for each similar case were then averaged together to provide a final maximum concentration with and without the structures present. These final values were then used to document the creditable stack height. Also during this phase, horizontal and vertical concentration profiles were obtained so that the plume dispersion characteristics could be documented. These results are discussed in Section 4.

The concentration data listings for each test in Table 2 are provided in Table 7 through Table 10. The following sections discuss the results in more detail as they pertain to the creditable stack height determination.

5.2 40 % Excessive Concentration Test

One of the criteria needed to determine the creditable GEP stack height is the ratio of maximum concentration with and without the nearby buildings. At the GEP stack height this ratio must equal or slightly exceed 1.4, which is defined as an excessive concentration. To test against this requirement, the maximum ground-level concentrations measured in the wind tunnel with and without nearby structure in place (see Section 2.4 for description of nearby structures) were compared. These concentration ratios[3] were calculated for each of the 300 and 400 series simulation listed in Table 2 and the resulting ratios are presented in Table 16. The table indicates that the minimum excessive concentration requirement of 1.4 was achieved for all meteorological conditions evaluated for the 76.7 m stack height except for the 27.5 and 338 degree wind directions. The largest excessive concentration occurred for the 72 degree wind direction with an 11 m/s wind speed.

Next, the 500 series tests were conducted at incrementally tall stack heights. These tests were all conducted at the 72 degree direction and 11 m/s wind speed. Table 16 shows that the 1.4 concentration ratio (40% test) is slightly exceeded for stacks as tall as 100 m. Hence, based on this criteria alone, a 100 m stack could be justified as GEP.

At this time Exxon is only seeking credit for a 76.7 m stack height. Accordingly, the 700 series documentation tests were conducted at this stack height. The wind speed selected for conducting the documentation tests was 5 m/s. This speed did not have the largest concentration ratio but it did have the largest maximum concentration with the buildings present. Hence this case will give the largest concentration when making the comparison with an ambient standard. The bottom of Table 16 shows that the average concentration ratio for this case is 1.79, which is above 1.4. Hence, the 76.7 m stack is creditable based on the 40% test.

5.3 Ambient Standard Comparison Test

The second requirement that must be met before the 76.7 m stack is deemed creditable is that an ambient standard is exceeded at the same location as a 40 % excessive concentration is shown. This demonstration can make use of the contribution due to other background sources.

First consider the maximum concentrations due to the FCC COB stack itself. The hourly maximum concentration of 1033.7 $\mu g/m^3$ was converted 3-hr, 24-hr and annual average SO_2 concentrations using scaling factors provided in EPA-454/R-92-019, 1992. That EPA reference states " to obtain the estimated maximum concentrations for 3-, 8-, 24-hour or annual averaging times, multiply the 1-hour (wind tunnel) value by the indicated factor:

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[3]The concentration ratios were computed for all wind directions (300 series tests) by assuming that the maximum concentration for the 72 degree wind direction building out case was nearly the same as it would have been for the other wind directions.

Averaging Time	Scaling or Multiplying Factors
3 hours	0.9 (± 0.1)
8 hours	0.7 (± 0.2)
24 hours	0.4 (± 0.2)
Annual	0.08 (± 0.02)

The average multiplication factors were used in the analysis. The bottom portion of Table 16 shows the results of this analysis. The table shows that the 24-hr and annual NAAQS and MAAQS are exceeded due to the FCC COB stack alone. Hence, an additional background concentration is not needed to make this demonstration. Based on this result alone, a 76.7 m FCC COB stack produces an excessive concentration and is a creditable stack height.

5.4 Summary

In summary, the above sections have demonstrated that a 76.7 m FCC COB stack height is creditable as GEP. The results have shown that for a 76.7 meter stack the maximum concentration with the structures present is 40% greater than that with the structures removed and that NAAQS/MAAQS are exceeded with all structures present. The results have further shown that a 100 m stack meets the 40% test. Future analysis may be able to show that NAAQS/MAAQS are exceeded at this height when other background sources are considered.

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TABLES

Source Parameters for Stack Being Evaluated

English Units

Source Description	Stack ID	Typical Building Height (ft)	Stack Height (ft)	Stack Base (ft, MSL)	Exit Diameter (ft)	Exit Temperature (deg F)	Ambient mperatu (deg F)	Volume Flow Rate (cfm)	Exit Velocity (fpm)	Emission Rates SO2 (lb/hr)
Exxon FCC COB	COB	175.2	251.58	947.0	9.71	435.0	46.0	182,164	2460.0	1134.9

Metric Units

Source Description	Stack ID	Typical Building Height (m)	Stack Height (m)	Stack Base (m, MSL)	Exit Diameter (m)	Exit Temperature (deg K)	Ambient mperatu (deg K)	Volume Flow Rate (m3/s)	Exit Velocity (m/s)	Emission Rates SO2 (g/s)
Exxon FCC COB	COB	53.40	76.7	288.7	2.96	497.0	280.9	86.0	12.5	143.0

Notes:

Other Simulation Factors	Full Scale	Model
1) Site Surface Roughness Length (m)	0.2	0.2
2) Anemometer Site Surface Roughness Length (m)	0.1	0.1
3) Anemometer Height (m)	7.62	0.019
4) Length Scaling Factor	400	1

Table 1 Source Parameters for Stacks Being Evaluated

Concentration Measurement Test Plan -- GEP Tests

Run No.	Stack ID 1	Stack ID 2	3	Wind Direction (Deg.)	Stack Height (m)	Uanem* (m/s)	Building Config	Zo (m)	Meas Type	V (cm3/s)	Reference Speed (m/s)	Reference Height (m)
Full Scale Conditions										Model Conditions		
Testing Phase 1 -- Worst Wind Direction Tests (Selected From Visualization)												
301	COB			72	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
302	COB			77	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
303	COB			67	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
304	COB			32.5	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
305	COB			27.5	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
306	COB			22.5	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
307	COB			17.5	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
308	COB			120	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
309	COB			338	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
310	COB			62	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
311	COB			72	76.7	5.0	Out	0.2	GL	230.02	4.00	1.00
312	COB			72	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
Testing Phase 2 -- Worst Wind Speed Tests												
401	COB			72	76.7	3.0	In	0.2	GL	383.36	4.00	1.00
402	COB			72	76.7	8.0	In	0.2	GL	143.76	4.00	1.00
403	COB			72	76.7	11.0	In	0.2	GL	104.55	4.00	1.00
404	COB			72	76.7	3.0	Out	0.2	GL	383.36	4.00	1.00
405	COB			72	76.7	8.0	Out	0.2	GL	143.76	4.00	1.00
406	COB			72	76.7	11.0	Out	0.2	GL	104.55	4.00	1.00
Preliminary GEP Stack Height Tests												
501	COB			72	80.0	11.0	In	0.2	GL	104.55	4.00	1.00
502	COB			72	85.0	11.0	In	0.2	GL	104.55	4.00	1.00
503	COB			72	90.0	11.0	In	0.2	GL	104.55	4.00	1.00
504	COB			72	95.0	11.0	In	0.2	GL	104.55	4.00	1.00
505	COB			72	100.0	11.0	In	0.2	GL	104.55	4.00	1.00
506	COB			72	80.0	11.0	Out	0.2	GL	104.55	4.00	1.00
507	COB			72	85.0	11.0	Out	0.2	GL	104.55	4.00	1.00
508	COB			72	90.0	11.0	Out	0.2	GL	104.55	4.00	1.00
509	COB			72	100.0	11.0	Out	0.2	GL	104.55	4.00	1.00
GEP Stack Height Documentation Tests												
701	COB			72	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
702	COB			72	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
703	COB			72	76.7	5.0	In	0.2	GL	230.02	4.00	1.00
704	COB			72	76.7	5.0	Out	0.2	GL	230.02	4.00	1.00
705	COB			72	76.7	5.0	Out	0.2	GL	230.02	4.00	1.00
706	COB			72	76.7	5.0	Out	0.2	GL	230.02	4.00	1.00
707	COB			72	76.7	5.0	In	0.2	Hor/Vert	230.02	4.00	1.00
708	COB			72	76.7	5.0	In	0.2	Hor/Vert	230.02	4.00	1.00
709	COB			72	76.7	5.0	In	0.2	Hor/Vert	230.02	4.00	1.00
710	COB			72	76.7	5.0	In	0.2	Hor/Vert	230.02	4.00	1.00
711	COB			72	76.7	5.0	Out	0.2	Hor/Vert	230.02	4.00	1.00
712	COB			72	76.7	5.0	Out	0.2	Hor/Vert	230.02	4.00	1.00
713	COB			72	76.7	5.0	Out	0.2	Hor/Vert	230.02	4.00	1.00
714	COB			72	76.7	5.0	Out	0.2	Hor/Vert	230.02	4.00	1.00

* - Wind Speed at Billings Airport, 7.6 m anemometer height

27-Feb

Table 2 Concentration Measurement Test Plan

Mass Flow System Settings

{SETTING1.WK4}

Field Wind Speed (mps)	Test Type	Gas Mixture Comp.#	Total Flow Rate (ccs)	Mix Specific Gravity	Gas Type	Percent of Total Mixture (%)	Comp. Flow Rate (ccs)	Meter Fullscale Range (SLPM)	Meter Setting (%FS)
3	Visual	1 of 1	104.6	0.565	Air	49.5	51.8	**10.0**	**25.8**
"	"	2 of 2	"	"	Helium	50.5	52.8	**5.0**	**36.1**
5	Visual	1 of 1	143.8	0.565	Air	49.5	71.2	**10.0**	**35.4**
"	"	2 of 2	"	"	Helium	50.5	72.6	**5.0**	**49.7**
8	Visual	1 of 1	230.0	0.565	Air	49.5	113.9	**10.0**	**56.7**
"	"	2 of 2	"	"	Helium	50.5	116.1	**5.0**	**79.5**
11	Visual	1 of 1	383.4	0.565	Air	49.5	189.9	**10.0**	**94.5**
"	"	2 of 2	"	"	Helium	50.5	193.5	**5.0**	**90.9**
3	Conc.	1 of 1	104.6	0.565	Methane	97.3	101.8	**10.0**	**70.0**
"	"	2 of 2	"	"	Nitrogen	2.7	2.8	**1.0**	**13.9**
5	Conc.	1 of 1	143.8	0.565	Methane	97.3	139.9	**10.0**	**96.3**
"	"	2 of 2	"	"	Nitrogen	2.7	3.8	**1.0**	**19.1**
8	Conc.	1 of 1	230.0	0.565	Methane	97.3	223.9	**100.0**	**15.4**
"	"	2 of 2	"	"	Nitrogen	2.7	6.1	**1.0**	**30.5**
11	Conc.	1 of 1	383.4	0.565	Methane	97.3	373.1	**100.0**	**25.7**
"	"	2 of 2	"	"	Nitrogen	2.7	10.2	**1.0**	**50.9**

Table 3 Stack Gas Flow Settings and Composition

Summary of Test Measurements as Required by EPA (1981)

		Measurement Locations					
Test Type	Measured Quantity	x	y	z	Traverse Direction	No. of Tests	
Atmospheric	T[1]	0	0	v	z	1	
Dispersion	$U, U'/U, W'/U, U_*/U$	0,L/2,L	0	v	z	3	
Comparability	$U, U'/U$	0,L	v	h/2,h,1.5h	y	6	
(ADC)	C	1,2,3	v	v	y,z	3	
Tests	C	v	v	0	x,y	1	
Documentation	$U, U'/U, W'/U, U_*/U$	0,L/2,L	0	v	z	3	
with	$U, U'/U$	0,L	v	h/2,h,1.5h	y	6	
Buildings	C	1,2,3,4	v	v	y,z	4	
Present	C	v	v	0	x,y	3	repeats
Documentation	C	1,2,3,4	v	v	y,z	4	
with	C	v	v	o	x,y	3	repeats
Buildings							
Removed							

Notation:

T	—	Ambient Temperature
U	—	Mean Velocity
U'/U	—	Longitudinal Turbulence Intensity
W'/U	—	Vertical Turbulence Intensity
U_*/U	—	Normalized Friction Velocity
C	—	Concentration
h	—	Stack Height
L	—	Length of Test Area from Stack
v	—	Variable
1,2,3,4	—	Locations to be Determined
x	—	Longitudinal
y	—	Lateral
z	—	Vertical

[1]May be omitted if U is greater than 3 m/s

Table 4 Summary of Test Measurements as Required by EPA (1981)

0.0 km Profile

Location = (0,0,Z)									
FIELD VALUES (6 m/s at airport)					MODEL VALUES				
Height (m)	Velocity (m/s)	Long TI (%)	Vert TI (%)	-uw/u*^2	Height (cm)	Velocity (cm/s)	Long TI (%)	Vert TI (%)	uw (cm/s)^2
4.0	2.1	51.0	16.5	0.02	1.0	90.5	51.0	16.5	-8.0
6.0	2.2	52.8	17.4	0.21	1.5	91.3	52.8	17.4	-92.7
8.0	2.3	51.7	18.1	0.38	2.0	96.5	51.7	18.1	-166.5
12.0	2.4	56.0	19.1	0.67	3.0	100.7	56.0	19.1	-291.5
16.0	2.6	52.5	19.4	0.74	4.0	108.3	52.5	19.4	-320.3
20.0	2.7	49.8	20.3	0.97	5.0	116.4	49.8	20.3	-419.6
30.0	3.6	38.3	19.7	1.50	7.5	152.4	38.3	19.7	-651.5
40.0	4.5	29.5	17.9	1.79	10.0	190.9	29.5	17.9	-777.5
60.0	6.4	18.6	11.2	1.44	15.0	272.0	18.6	11.2	-624.2
80.0	7.2	13.2	8.6	0.78	20.0	307.3	13.2	8.6	-337.9
120.0	7.7	11.0	8.5	0.70	30.0	326.8	11.0	8.5	-304.3
160.0	8.1	10.4	8.3	0.77	40.0	344.2	10.4	8.3	-333.4
200.0	8.3	9.6	8.1	0.82	50.0	351.2	9.6	8.1	-354.6
240.0	8.6	8.8	7.3	0.70	60.0	364.4	8.8	7.3	-302.2
320.0	9.3	6.4	5.9	0.40	80.0	394.2	6.4	5.9	-175.3
400.0	9.6	5.5	4.9	0.27	100.0	406.5	5.5	4.9	-117.0
480.0	9.6	6.0	5.0	0.10	120.0	409.0	6.0	5.0	-45.2
References					References				
400.0	9.4			0.49	7.6	400.0			

1.0 km Profile

Location = (1000,0,Z)									
FIELD VALUES (6 m/s at airport)					MODEL VALUES				
Height (m)	Velocity (m/s)	Long TI (%)	Vert TI (%)	-uw/u*^2	Height (cm)	Velocity (cm/s)	Long TI (%)	Vert TI (%)	uw (cm/s)^2
4.0	3.4	30.7	13.3	0.99	1.0	145.6	30.7	13.3	-430.5
6.0	4.0	26.6	11.9	0.98	1.5	170.7	26.6	11.9	-424.4
8.0	4.5	24.4	11.3	1.00	2.0	191.2	24.4	11.3	-432.0
12.0	5.1	21.5	10.0	0.93	3.0	218.3	21.5	10.0	-402.5
16.0	5.4	18.5	9.7	0.77	4.0	227.6	18.5	9.7	-334.6
20.0	5.7	17.5	9.7	0.86	5.0	243.2	17.5	9.7	-370.9
30.0	6.1	17.0	10.3	1.04	7.5	258.5	17.0	10.3	-450.6
40.0	6.4	16.3	10.0	1.04	10.0	269.9	16.3	10.0	-452.2
60.0	7.0	14.5	9.1	1.03	15.0	298.5	14.5	9.1	-446.4
80.0	7.4	13.7	9.1	1.21	20.0	313.6	13.7	9.1	-523.5
120.0	7.9	11.0	7.8	0.76	30.0	334.8	11.0	7.8	-331.5
160.0	8.2	9.9	7.5	0.80	40.0	349.7	9.9	7.5	-348.1
200.0	8.5	8.9	7.1	0.67	50.0	359.7	8.9	7.1	-290.9
240.0	8.8	7.9	6.3	0.54	60.0	375.2	7.9	6.3	-234.6
320.0	9.2	6.6	5.6	0.41	80.0	391.2	6.6	5.6	-177.3
400.0	9.7	5.2	4.8	0.27	100.0	411.8	5.2	4.8	-117.0
480.0	9.7	4.8	4.4	-0.02	120.0	412.3	4.8	4.4	10.2
References					References				
400.0	9.4			0.49	100.0	400.0			

2 km Profile

Location = (2000,0,Z)									
FIELD VALUES (6 m/s at airport)					MODEL VALUES				
Height (m)	Velocity (m/s)	Long TI (%)	Vert TI (%)	-uw/u*^2	Height (cm)	Velocity (cm/s)	Long TI (%)	Vert TI (%)	uw (cm/s)^2
4.0	3.7	29.0	13.5	0.93	1.0	155.5	29.0	13.5	-402.0
6.0	4.5	23.7	10.3	0.94	1.5	190.1	23.7	10.3	-406.8
8.0	5.0	20.9	9.3	0.79	2.0	210.4	20.9	9.3	-340.7
12.0	5.4	18.9	8.9	0.77	3.0	228.9	18.9	8.9	-333.5
16.0	5.8	17.8	8.8	0.81	4.0	247.0	17.8	8.8	-350.1
20.0	6.0	16.6	8.6	0.76	5.0	254.6	16.6	8.6	-328.7
30.0	6.4	14.6	8.4	0.71	7.5	273.2	14.6	8.4	-308.3
40.0	6.8	14.1	8.2	0.76	10.0	288.1	14.1	8.2	-329.0
60.0	7.1	13.0	8.3	0.83	15.0	301.9	13.0	8.3	-361.2
80.0	7.3	11.9	8.4	0.84	20.0	310.5	11.9	8.4	-362.1
120.0	7.7	11.0	8.0	0.78	30.0	325.8	11.0	8.0	-339.0
160.0	8.0	9.8	7.4	0.72	40.0	340.9	9.8	7.4	-310.7
200.0	8.4	9.0	6.9	0.65	50.0	356.9	9.0	6.9	-283.4
240.0	8.7	7.8	6.4	0.56	60.0	369.1	7.8	6.4	-242.5
320.0	9.2	6.7	5.4	0.42	80.0	390.1	6.7	5.4	-182.8
400.0	9.5	5.6	4.7	0.28	100.0	403.0	5.6	4.7	-122.1
480.0	9.7	4.4	3.8	0.03	120.0	412.7	4.4	3.8	-12.6
References					References				
400.0	9.4			0.49	100.0	400.0			

Table 5 Centerline Velocity and Turbulence Profile Data

GEP Model IN - Lateral Velocity Profiles

Field Wind Speed (cm/s) at X = 0 km

	Y (m)						
Z (m)	-360	-240	-120	0	120	240	360
40	5.0	5.6	6.1	3.5	5.9	5.5	5.3
60	5.7	6.2	6.7	5.4	6.2	5.7	5.8
80	5.9	6.6	6.9	6.4	6.5	5.9	6.6
120	6.5	6.9	7.3	7.2	6.7	6.3	7.1

Model Wind Speed (cm/s) at X = 0 cm

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
10	212	240	259	151	249	233	223
15	244	261	284	231	262	243	244
20	252	280	292	273	275	250	282
30	276	292	312	307	286	268	300

Field Wind Speed (cm/s) at X = 2 km

	Y (m)						
Z (m)	-360	-240	-120	0	120	240	360
40	6.0	6.1	6.0	6.5	6.3	6.1	6.0
60	6.4	6.5	6.9	6.9	6.8	6.3	6.2
80	6.4	7.1	7.2	7.1	7.2	6.6	6.6
120	7.2	7.3	7.7	7.8	7.5	6.9	6.9

Model Wind Speed (cm/s) at X = 500 cm

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
10	255	258	253	276	269	258	254
15	270	277	293	292	288	267	262
20	273	299	307	303	303	279	281
30	306	308	325	330	318	291	294

GEP Model IN - Lateral Turbulence Profiles

Field Long. Turb. Int. (%) at X = 0 km

	Y (m)						
Z (m)	-360	-240	-120	0	120	240	360
40	23	21	19	34	17	17	20
60	19	17	15	24	17	18	20
80	18	16	16	18	16	18	17
120	17	16	15	14	16	17	15

Model Long. Turb. Int. (%) at X = 0 cm

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
10	23	21	19	34	17	17	20
15	19	17	15	24	17	18	20
20	18	16	16	18	16	18	17
30	17	16	15	14	16	17	15

Field Long. Turb. Int. (%) at X = 2 km

	Y (m)						
Z (m)	-360	-240	-120	0	120	240	360
40	18	19	19	18	18	18	19
60	17	17	17	16	16	16	18
80	17	16	16	16	16	16	16
120	15	15	13	16	15	16	15

Model Long. Turb. Int. (%) at X = 500 cm

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
10	18	19	19	18	18	18	19
15	17	17	17	16	16	16	18
20	17	16	16	16	16	16	16
30	15	15	13	16	15	16	15

Table 6 Lateral Velocity and Turbulence Profiles

RUN NO.				303	301	302	307	306	305	304	308	309	310
STACK (m)				76.7	76.7	76.7	76.7	76.7	76.7	76.7	76.7	76.7	76.7
WIND DIR.				67.0	72.0	77.0	17.5	22.5	27.5	32.5	120.0	338.0	62
Nearby Building Config.				In	In	In	In	In	In	In	In	In	In
Model Wind (cm/s) at 100cm =				403	406	406	405	407	394	402	396	411	398
Model Stack Flow Rate (ccs) =				230	230	230	230	230	230	230	230	230	230
Field Wind Speed at Wind Instr.				~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s
Field Dist.		Model Dist.		Model	Model	Model	Model	Model	Model	Model	Model	Model	Model
X (m)	Y (m)	X (cm)	Y (cm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)
284	40	71	10	30	34	23	7	6	4	9	0	6	13
284	20	71	5	38	49	27	15	14	16	12	3	15	23
284	0	71	0	40	57	23	23	19	23	17	7	18	23
284	-20	71	-5	30	44	23	19	22	17	17	9	14	19
284	-40	71	-10	15	29	24	16	13	9	12	4	8	8
348	40	87	10	71	82	149	27	26	28	39	27	26	77
348	20	87	5	97	135	115	45	57	58	57	46	54	88
348	0	87	0	100	139	90	57	77	69	55	52	61	84
348	-20	87	-5	73	113	71	54	66	59	60	42	59	54
348	-40	87	-10	78	81	51	42	40	33	37	27	32	18
476	48	119	12	237	236	270	119	149	108	117	121	101	174
476	24	119	6	332	354	363	185	213	162	161	246	153	261
476	0	119	0	319	380	319	198	237	190	205	259	171	306
476	-24	119	-6	337	301	266	185	203	170	216	208	172	229
476	-48	119	-12	258	180	174	142	137	131	129	130	113	153
600	64	150	16	353	349	328	210	250	155	232	191	126	277
600	32	150	8	485	472	478	317	363	290	341	352	254	428
600	0	150	0								415	321	469
600	-32	150	-8	461	402	386	353	341	301	364	332	273	368
600	-64	150	-16	296	246	226	192	207	230	244	196	197	213
780	80	195	20	319	352	341	251	190	186	236	203	147	267
780	40	195	10	509	517	545	406	360	334	450	434	314	457
780	0	195	0	545	552	525	460	448	407	483	454	342	480
780	-40	195	-10	444	437	418	318	369	349	350	351	287	314
780	-80	195	-20	299	285	264	212	229	209	241	207	193	200
952	80	238	20	423	467	421	377	380	289	378	320	256	386
952	40	238	10	570	590	574	489	503	394	527	480	382	522
952	0	238	0	622	620	607	540	535	481	555	522	436	548
952	-40	238	-10	541	536	533	478	474	468	474	479	406	478
952	-80	238	-20	399	385	373	317	324	332	321	343	269	316
1200	80	300	20	463	448	450	390	405	288	433	343	277	411
1200	40	300	10	549	548	546	494	510	388	520	481	396	517
1200	0	300	0	585	578	571	535	530	452	539	521	462	537
1200	-40	300	-10	524	515	521	490	478	451	481	475	435	482
1200	-80	300	-20	413	411	412	406	371	367	351	394	335	378
Row maximum values repeated from above													
284	max	71	max	40	57	27	23	22	23	17	9	18	23
348	max	87	max	100	139	149	57	77	69	60	52	61	88
476	max	119	max	337	380	363	198	237	190	216	259	172	306
600	max	150	max	485	472	478	353	363	301	364	415	321	469
780	max	195	max	545	552	545	460	448	407	483	454	342	480
952	max	238	max	622	620	607	540	535	481	555	522	436	548
1200	max	300	max	585	578	571	535	530	452	539	521	462	537
Maximum Value			=	621.9	620.4	607.0	540.2	535.3	480.7	555.0	521.7	462.2	548.2
Field Dist. (m) to Max.			=	952	952	952	952	952	952	952	952	1200	952

Table 7 Conc. Data - Variation of Wind Direction - 5 m/s Wind

RUN NO.				404	401	312	311	405	402	406	403
STACK (m)				76.7	76.7	76.7	76.7	76.7	76.7	76.7	76.7
WIND DIR.				72	72	72	72	72	72	72	72
Nearby Building Config.				Out	In	Out	In	Out	In	Out	In
Model Wind (cm/s) at 100cm =				406	404	403	405	406	401	400	395
Model Stack Flow Rate (ccs) =				383	383	230	230	144	144	105	105
Field Wind Speed at Wind Instr.				~3m/s	~3m/s	~5m/s	~5m/s	~8m/s	~8m/s	~11m/s	~11m/s
Field Dist.		Model Dist.		Model		Model		Model		Model	
X (m)	Y (m)	X (cm)	Y (cm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)
284	40	71	10	4	10	0	25	0	51	0	61
284	20	71	5	5	20	0	38	0	85	1	95
284	0	71	0	4	24	0	39	0	102	1	99
284	-20	71	-5	4	12	0	19	0	61	2	63
284	-40	71	-10	4	5	0	11	0	23	1	27
348	40	87	10	5	32	3	70	3	119	5	128
348	20	87	5	7	69	5	140	6	216	9	217
348	0	87	0	7	71	5	147	7	216	9	226
348	-20	87	-5	6	59	4	128	5	195	11	191
348	-40	87	-10	5	28	5	60	3	104	6	109
476	48	119	12	16	142	23	209	27	255	34	232
476	24	119	6	28	236	42	346	41	404	49	360
476	0	119	0	30	277	53	419	46	459	58	437
476	-24	119	-6	31	215	59	344	42	383	55	365
476	-48	119	-12	23	119	38	205	23	231	33	227
600	64	150	16	42	262	55	323	58	338	62	280
600	32	150	8	66	384	96	486	100	477	101	416
600	0	150	0	82	427	117	555	114	524	120	464
600	-32	150	-8	64	384	93	482	102	439	101	409
600	-64	150	-16	54	209	67	267	49	250	59	237
780	80	195	20	80	323	100	310	104	284	90	239
780	40	195	10	171	445	211	497	182	405	167	330
780	0	195	0	192	535	232	611	213	478	196	398
780	-40	195	-10	167	381	187	495	170	322	146	273
780	-80	195	-20	107	266	105	301	85	225	81	195
952	80	238	20	175	460	182	414	162	341	139	278
952	40	238	10	267	591	282	574	240	437	197	352
952	0	238	0	296	639	303	651	265	480	230	388
952	-40	238	-10	264	591	261	580	229	432	191	346
952	-80	238	-20	182	424	185	410	142	304	125	255
1200	80	300	20	264	499	236	421	195	323	156	248
1200	40	300	10	352	651	332	563	273	404	216	314
1200	0	300	0	392	698	356	614	294	429	231	340
1200	-40	300	-10	366	654	318	572	258	402	212	315
1200	-80	300	-20	267	524	244	442	196	320	159	251
Row maximum values repeated from above											
284	max	71	max	5	24	0	39	0	102	2	99
348	max	87	max	7	71	5	147	7	216	11	226
476	max	119	max	31	277	59	419	46	459	58	437
600	max	150	max	82	427	117	555	114	524	120	464
780	max	195	max	192	535	232	611	213	478	196	398
952	max	238	max	296	639	303	651	265	480	230	388
1200	max	300	max	392	698	356	614	294	429	231	340
Maximum Value			=	391.5	698.0	356.4	651.2	293.8	523.8	230.6	464.1
Field Dist. (m) to Max.			=	1200	1200	1200	952	1200	600	1200	600
Percent Increase			=		78		83		78		101

Table 8 Conc. Data - Variation of Wind Speed - 72° Wind Dir.

RUN NO.				506	501	507	502	508	503	509	504	510	505
STACK (m)				80.0	80.0	85.0	85.0	90.0	90.0	95.0	95.0	100.0	100.0
WIND DIR.				72	72	72	72	72	72	72	72	72	72
Nearby Building Config.				Out	In	Out	In	Out	In	Out	In	Out	In
Model Wind (cm/s) at 100cm =				397	401	404	407	398	404	396	398	402	398
Model Stack Flow Rate (ccs) =				105	105	105	105	105	105	105	105	105	105
Field Wind Speed at Wind Instr.				~11m/s	~11m/s	~11m/s	~11m/s	~11m/s	~11m/s	~11m/s	~11m/s	~11m/s	~11m/s
Field Dist.		Model Dist.		Model	Model	Model		Model		Model		Model	
X (m)	Y (m)	X (cm)	Y (cm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)	Conc (ppm)
476	48	119	12	27	200	23	134	8	82	8	43	4	32
476	24	119	6	48	293	37	217	18	134	12	73	9	56
476	0	119	0	64	336	40	252	19	159	16	95	11	69
476	-24	119	-6	55	259	34	195	17	122	19	71	10	51
476	-48	119	-12	40	185	23	129	13	79	16	44	5	27
600	64	150	16	54	230	41	165	27	114	26	80	13	63
600	32	150	8	92	338	79	266	54	195	39	131	30	104
600	0	150	0	117	382	99	317	56	218	45	143	42	124
600	-32	150	-8	104	332	74	265	53	190	43	143	33	102
600	-64	150	-16	71	220	46	166	32	114	32	84	22	57
780	80	195	20	84	273	70	212	63	172	49	122	35	111
780	40	195	10	144	351	139	296	107	241	80	182	67	159
780	0	195	0	174	387	150	340	116	259	89	207	88	175
780	-40	195	-10	156	323	120	269	94	215	83	182	78	151
780	-80	195	-20	103	224	72	175	56	137	59	116	47	87
952	80	238	20	125	291	120	240	112	209	87	161	75	150
952	40	238	10	185	349	172	307	146	266	121	213	104	192
952	0	238	0	199	361	182	332	151	269	130	238	117	203
952	-40	238	-10	181	323	154	278	125	234	114	217	109	176
952	-80	238	-20	132	239	99	192	87	166	81	151	73	129
1200	80	300	20	158	275	155	244	146	218	122	187	109	173
1200	40	300	10	200	309	189	287	170	251	153	224	133	198
1200	0	300	0	201	312	192	290	171	250	159	228	143	205
1200	-40	300	-10	179	284	168	253	144	224	137	208	127	192
1200	-80	300	-20	143	215	120	189	105	163	106	165	97	146
1512	120	378	30	116	199	126	174	121	162	103	139	88	133
1512	60	378	15	172	251	174	231	157	210	142	189	131	174
1512	0	378	0	181	260	182	241	161	214	156	200	143	188
1512	-60	378	-15	159	224	146	199	132	181	134	175	124	165
1512	-120	378	-30	106	143	94	127	78	108	93	122	78	105
1704	120	426	30	113	182	125	161	112	148	98	129	88	120
1704	60	426	15	153	217	161	201	147	183	134	168	122	158
1704	0	426	0	166	225	167	210	152	193	150	179	140	169
1704	-60	426	-15	149	203	142	181	130	166	134	164	123	155
1704	-120	426	-30	110	151	100	128	86	112	97	125	85	111
Row maximum values repeated from above													
476	max	119	max	63.9	336.4	39.8	252.0	18.7	158.8	18.5	94.8	10.6	68.7
600	max	150	max	116.6	381.8	98.8	317.4	55.8	217.9	44.5	143.4	41.6	123.9
780	max	195	max	174.3	387.0	149.8	340.3	115.8	259.2	89.2	206.9	88.0	175.1
952	max	238	max	199.3	360.5	181.7	331.8	150.8	269.2	129.9	238.0	117.0	203.0
1200	max	300	max	201.2	311.9	192.4	289.5	170.6	251.4	158.6	227.8	143.0	204.7
1512	max	378	max	180.9	259.8	182.0	240.7	161.2	214.3	155.6	200.0	142.6	187.7
1704	max	426	max	166.1	225.4	166.8	210.4	151.8	193.4	150.2	178.5	140.1	169.4
Maximum Value			=	201.2	387.0	192.4	340.3	170.6	269.2	158.6	238.0	143.0	204.7
Field Dist. (m) to Max.			=	1200		1200		1200	952	1200	952	1200	1200
Percent Increase			=				77		58		50		43

Table 9 Conc. Data - Variation of Stack Height - 11 m/s, 72° Wind

RUN NO.				701	702	703	Avg.	704	705	706	Avg.
STACK (m)				76.7	76.7	76.7	76.7	76.7	76.7	76.7	76.7
WIND DIR.				72	72	72	72	72	72	72	72
Nearby Building Config.				In	In	In	In	Out	Out	Out	Out
Model Wind (cm/s) at 100cm =				400	401	402	401	402	395	400	399
Model Stack Flow Rate (ccs) =				230	230	230	230	230	230	230	230
Field Wind Speed at Wind Instr.				~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s	~5m/s
Field Dist.		Model Dist.		Model	Model	Model	Model	Model	Model	Model	Model
X	Y	X	Y	Conc	Conc	Conc	Conc	Conc	Conc	Conc	Conc
(m)	(m)	(cm)	(cm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
476	48	119	12	237	211	236	228	23	43	37	34
476	24	119	6	336	325	346	336	40	58	58	52
476	0	119	0	384	365	398	383	53	70	68	64
476	-24	119	-6	317	280	324	307	40	63	59	54
476	-48	119	-12	215	169	201	195	18	42	33	31
600	64	150	16	342	341	351	345	52	75	72	66
600	32	150	8	478	450	462	463	104	115	116	112
600	0	150	0	498	472	542	504	129	146	147	140
600	-32	150	-8	453	403	465	440	129	161	144	145
600	-64	150	-16	297	263	284	281	59	101	77	79
780	80	195	20	408	381	403	398	105	110	120	112
780	40	195	10	563	547	539	550	192	196	207	198
780	0	195	0	612	578	632	607	235	261	263	253
780	-40	195	-10	496	483	496	492	203	226	222	217
780	-80	195	-20	347	316	319	327	117	150	137	135
952	80	238	20	473	468	469	470	196	176	211	194
952	40	238	10	608	580	583	591	267	254	289	270
952	0	238	0	626	605	634	621	304	321	324	316
952	-40	238	-10	531	521	546	533	268	293	286	282
952	-80	238	-20	390	384	372	382	181	208	204	198
1200	80	300	20	485	497	481	488	250	231	277	253
1200	40	300	10	569	556	553	559	323	295	343	321
1200	0	300	0	573	558	563	565	338	344	351	345
1200	-40	300	-10	498	498	509	501	308	338	326	324
1200	-80	300	-20	400	379	382	387	246	265	251	254
1512	120	378	30	356	358	351	355	187	168	231	195
1512	60	378	15	471	468	467	469	296	275	327	299
1512	0	378	0	492	485	460	479	335	334	362	344
1512	-60	378	-15	411	396	383	397	290	312	303	301
1512	-120	378	-30	274	245	243	254	195	211	186	197
1704	120	426	30	322	328	328	326	185	168	219	191
1704	60	426	15	410	410	410	410	268	252	304	275
1704	0	426	0	437	435	417	430	322	309	333	321
1704	-60	426	-15	380	371	363	371	283	305	287	292
1704	-120	426	-30	261	245	241	249	202	216	189	202
Row maximum values repeated from above											
476	max	119	max	384	365	398	383	53	70	68	64
600	max	150	max	498	472	542	504	129	161	147	145
780	max	195	max	612	578	632	607	235	261	263	253
952	max	238	max	626	605	634	621	304	321	324	316
1200	max	300	max	573	558	563	565	338	344	351	345
1512	max	378	max	492	485	467	479	335	334	362	344
1704	max	426	max	437	435	417	430	322	309	333	321
Maximum Value			=	626.1	604.7	633.6	621.5	338.3	344.4	361.5	344.5
Field Dist. (m) to Max.			=	952	952	952	952	1200	1200	1200	1200
Percent Increase			=				80				

Table 10 Conc. Data - Ground Level Repeated Runs - 5 m/s, 72° Wind

76.7m Stack GEP Documentation Tests

Averaged Ground Level Profiles

Field Values (MKS)	Model Values (CGS)			References (CGS)	IN	OUT
	IN	OUT				
400 <Length Scale				Href =	100.0	100.0
5.0	297.9	296.7	< Wind Speed at Heff	Uref =	401.0	399.3
86.0	230.0	230.0	< Flow Rate	PL index	0.180	0.180
76.7	19.2	19.2	< Effective Stack Height			

Field Position X (m)	Y (m)	Z (m)	Model Position X (cm)	Y (cm)	Z (cm)	PG-C K*10^6 (m^-2)	IN K*10^6 (m^-2)	OUT K*10^6 (m^-2)	PG-D K*10^6 (m^-2)	IN Model (ppm)	OUT Model (ppm)
476	48	0	119	12	0	12	18	3	0	228	34
476	24	0	119	6	0	17	27	4	1	336	52
476	0	0	119	0	0	19	31	5	1	383	64
476	-24	0	119	-6	0	17	25	4	1	307	54
476	-48	0	119	-12	0	12	16	3	0	195	31
600	64	0	150	16	0	16	28	5	1	345	66
600	32	0	150	8	0	23	38	9	3	463	112
600	0	0	150	0	0	26	41	11	3	504	140
600	-32	0	150	-8	0	23	36	12	3	440	145
600	-64	0	150	-16	0	16	23	6	1	281	79
780	80	0	195	20	0	17	32	9	4	398	112
780	40	0	195	10	0	25	44	16	7	550	198
780	0	0	195	0	0	28	49	20	9	607	253
780	-40	0	195	-10	0	25	40	17	7	492	217
780	-80	0	195	-20	0	17	26	11	4	327	135
952	80	0	238	20	0	18	38	16	7	470	194
952	40	0	238	10	0	23	48	22	11	591	270
952	0	0	238	0	0	25	50	25	13	621	316
952	-40	0	238	-10	0	23	43	23	11	533	282
952	-80	0	238	-20	0	18	31	16	7	382	198
1200	80	0	300	20	0	16	39	20	11	488	253
1200	40	0	300	10	0	19	45	26	15	559	321
1200	0	0	300	0	0	20	46	28	17	565	345
1200	-40	0	300	-10	0	19	41	26	15	501	324
1200	-80	0	300	-20	0	16	31	20	11	387	254
1512	120	0	378	30	0	11	29	16	10	355	195
1512	60	0	378	15	0	14	38	24	15	469	299
1512	0	0	378	0	0	15	39	28	17	479	344
1512	-60	0	378	-15	0	14	32	24	15	397	301
1512	-120	0	378	-30	0	11	21	16	10	254	197
1704	120	0	426	30	0	10	26	15	11	326	191
1704	60	0	426	15	0	12	33	22	15	410	275
1704	0	0	426	0	0	13	35	26	17	430	321
1704	-60	0	426	-15	0	12	30	24	15	371	292
1704	-120	0	426	-30	0	10	20	16	11	249	202
Row maximum values repeated from above											
476	max	0	119	max	0	19	31	5	1	383	64
600	max	0	150	max	0	26	41	12	3	504	145
780	max	0	195	max	0	28	49	20	9	607	253
952	max	0	238	max	0	25	50	25	13	621	316
1200	max	0	300	max	0	20	46	28	17	565	345
1512	max	0	378	max	0	15	39	28	17	479	344
1704	max	0	426	max	0	13	35	26	17	430	321
2500	0	0				7			14		
4000	0	0				3			9		
Maximum Value			=				50.3	27.8			
Field Dist. (m) to Max.			=				952	1200			
Percent Increase			=				81				

Table 11 Normalized Conc. Data - GEP Ground Level Documentation

76.7m Stack GEP Documentation Tests

Vertical and Lateral Profiles at 0.5 km downwind

Field Values (MKS)	Model Values (CGS)			References (CGS)		IN	OUT
400 <Length Scale	IN	OUT					
					Href =	100.0	100.0
5.0	296.8	300.2	< Wind Speed at Heff		Uref =	399.5	404.1
86.0	230.0	230.0	< Flow Rate		PL index	0.180	0.180
76.7	19.2	19.2	< Effective Stack Height				

Field Position			Model Position			PG-C	IN	OUT	PG-D	IN	OUT
X (m)	Y (m)	Z (m)	X (cm)	Y (cm)	Z (cm)	K*10^6 (m^-2)	K*10^6 (m^-2)	K*10^6 (m^-2)	K*10^6 (m^-2)	Model (ppm)	Model (ppm)
500	0	0	125	0	0	21	31	5	1	384	61
500	0	16	125	0	4	26	50	23	5	623	278
500	0	32	125	0	8	40	80	55	26	987	674
500	0	48	125	0	12	59	109	93	81	1353	1146
500	0	64	125	0	16	74	117	114	154	1447	1400
500	0	80	125	0	20	77	109	115	178	1346	1407
500	0	96	125	0	24	68	78	98	125	968	1203
500	0	112	125	0	28	51	49	71	54	606	875
500	0	128	125	0	32	31	26	42	14	322	519
500	0	144	125	0	36	16	15	25	2	181	309
500	0	160	125	0	40	7	6	10	0	74	123
500	0	176	125	0	44	3	2	4	0	29	49
500	0	192	125	0	48	1	1	1	0	8	16
500	0	208	125	0	52	0	0	1	0	3	7
500	0	224	125	0	56	0	0	0	0	1	2
500	0	240	125	0	60	0	0	0	0	1	0
500	0	256	125	0	64	0	0	0	0	1	0
500	0	272	125	0	68	0	0	0	0	1	0
500	0	288	125	0	72	0	0	0	0	1	0
500	0	304	125	0	76	0	0	0	0	1	0
500	0	320	125	0	80	0	0	0	0	1	0
500	-300	80	125	-75	20	0	0	0	0	1	0
500	-276	80	125	-69	20	0	0	0	0	1	0
500	-252	80	125	-63	20	0	0	0	0	0	0
500	-228	80	125	-57	20	0	0	0	0	1	0
500	-204	80	125	-51	20	0	0	0	0	2	0
500	-180	80	125	-45	20	0	0	1	0	5	10
500	-156	80	125	-39	20	1	1	3	0	14	31
500	-132	80	125	-33	20	4	4	5	1	46	60
500	-108	80	125	-27	20	10	10	15	4	128	178
500	-84	80	125	-21	20	23	25	34	18	305	415
500	-60	80	125	-15	20	41	55	69	55	682	847
500	-36	80	125	-9	20	62	98	98	116		1198
500	-12	80	125	-3	20	76	102	112	170	1269	1367
500	12	80	125	3	20	76	108	109	170	1345	1342
500	36	80	125	9	20	62	90	82	116	1120	1009
500	60	80	125	15	20	41	69	57	55	852	698
500	84	80	125	21	20	23	38	24	18	474	293
500	108	80	125	27	20	10	16	9	4	196	108
500	132	80	125	33	20	4	5	2	1	68	22
500	156	80	125	39	20	1	1	0	0	15	3
500	180	80	125	45	20	0	0	0	0	2	0
500	204	80	125	51	20	0	0	0	0	2	2
500	228	80	125	57	20	0	0	0	0	0	0
500	252	80	125	63	20	0	0	0	0	0	0
500	276	80	125	69	20	0	0	0	0	0	0
500	300	80	125	75	20	0	0	0	0	0	0

Table 12 Normalized Conc. Data - GEP X = 0.5km Documentation

76.7m Stack GEP Documentation Tests

Vertical and Lateral Profiles at 0.9 km downwind (at GLCmax distance)

Field Values (MKS)		Model Values (CGS) IN	OUT		References (CGS)	IN	OUT
400	<Length Scale				Href =	100.0	100.0
5.0		299.1	297.9	< Wind Speed at Heff	Uref =	402.6	401.1
86.0		230.0	230.0	< Flow Rate	PL index	0.180	0.180
76.7		19.2	19.2	< Effective Stack Height			

Field Position X (m)	Y (m)	Z (m)	Model Position X (cm)	Y (cm)	Z (cm)	PG-C K*10^6 (m^-2)	IN K*10^6 (m^-2)	OUT K*10^6 (m^-2)	PG-D K*10^6 (m^-2)	IN Model (ppm)	OUT Model (ppm)
900	0	0	225	0	0	26	50	24	12	613	302
900	0	16	225	0	4	26	53	32	17	658	396
900	0	32	225	0	8	27	55	42	30	675	513
900	0	48	225	0	12	27	55	50	47	676	623
900	0	64	225	0	16	28	51	52	61	625	638
900	0	80	225	0	20	27	46	49	65	563	603
900	0	96	225	0	24	25	38	43	56	473	530
900	0	112	225	0	28	22	30	36	40	370	444
900	0	128	225	0	32	19	22	28	23	273	345
900	0	144	225	0	36	15	16	21	11	202	257
900	0	160	225	0	40	12	11	15	4	134	182
900	0	176	225	0	44	8	7	10	1	90	121
900	0	192	225	0	48	6	4	6	0	52	77
900	0	208	225	0	52	4	2	4	0	31	54
900	0	224	225	0	56	2	1	3	0	16	34
900	0	240	225	0	60	1	1	2	0	7	20
900	0	256	225	0	64	1	0	1	0	3	13
900	0	272	225	0	68	0	0	1	0	2	9
900	0	288	225	0	72	0	0	1	0	1	7
900	0	304	225	0	76	0	0	1	0	0	7
900	0	320	225	0	80	0	0	1	0	0	7
900	-300	80	225	-75	20	0	0	1	0	0	7
900	-276	80	225	-69	20	0	0	1	0	0	8
900	-252	80	225	-63	20	1	0	1	0	2	11
900	-228	80	225	-57	20	1	1	1	0	6	18
900	-204	80	225	-51	20	3	2	3	1	19	34
900	-180	80	225	-45	20	4	4	4	2	49	55
900	-156	80	225	-39	20	7	8	8	5	96	101
900	-132	80	225	-33	20	10	14	13	10	169	164
900	-108	80	225	-27	20	14	21	21	19	261	264
900	-84	80	225	-21	20	18	29	29	31	354	364
900	-60	80	225	-15	20	22	36	36	45	448	448
900	-36	80	225	-9	20	25		43	57		526
900	-12	80	225	-3	20	27	43	47	64	534	579
900	12	80	225	3	20	27	46	48	64	563	598
900	36	80	225	9	20	25	42	45	57	519	560
900	60	80	225	15	20	22	37	37	45	456	460
900	84	80	225	21	20	18	29	30	31	357	374
900	108	80	225	27	20	14	21	22	19	264	268
900	132	80	225	33	20	10	14	14	10	175	173
900	156	80	225	39	20	7	9	7	5	105	87
900	180	80	225	45	20	4	4	3	2	54	43
900	204	80	225	51	20	3	2	2	1	23	21
900	228	80	225	57	20	1	1	1	0	8	10
900	252	80	225	63	20	1	0	1	0	3	6
900	276	80	225	69	20	0	0	0	0	0	6
900	300	80	225	75	20	0	0	0	0	0	6

Table 13 Normalized Conc. Data - GEP X = 0.9km Documentation

76.7m Stack GEP Documentation Tests

Vertical and Lateral Profiles at 1.0 km downwind

Field Values (MKS)	Model Values (CGS)			References (CGS)	IN	OUT
400 <Length Scale	IN	OUT		Href =	100.0	100.0
5.0	299.0	293.6	< Wind Speed at Heff	Uref =	402.6	395.2
86.0	230.0	230.0	< Flow Rate	PL index	0.180	0.180
76.7	19.2	19.2	< Effective Stack Height			

Field Position			Model Position			PG-C	IN	OUT	PG-D	IN	OUT
X (m)	Y (m)	Z (m)	X (cm)	Y (cm)	Z (cm)	K*10^6 (m^-2)	K*10^6 (m^-2)	K*10^6 (m^-2)	K*10^6 (m^-2)	Model (ppm)	Model (ppm)
1000	0	0	250	0	0	24	47	24	14	584	305
1000	0	16	250	0	4	24	48	26	18	596	328
1000	0	32	250	0	8	24	49	34	28	607	422
1000	0	48	250	0	12	24	48	40	42	588	498
1000	0	64	250	0	16	24	45	43	52	559	539
1000	0	80	250	0	20	23	40	42	55	497	524
1000	0	96	250	0	24	21	33	37	48	408	466
1000	0	112	250	0	28	19	26	32	36	323	405
1000	0	128	250	0	32	17	20	26	22	243	329
1000	0	144	250	0	36	14	14	21	11	175	267
1000	0	160	250	0	40	11	9	16	5	116	205
1000	0	176	250	0	44	8	7	13	2	81	157
1000	0	192	250	0	48	6	3	8	1	43	105
1000	0	208	250	0	52	4	2	5	0	25	66
1000	0	224	250	0	56	3	1	3	0	13	40
1000	0	240	250	0	60	2	1	2	0	8	23
1000	0	256	250	0	64	1	0	1	0	5	14
1000	0	272	250	0	68	1	0	1	0	3	10
1000	0	288	250	0	72	0	0	1	0	2	7
1000	0	304	250	0	76	0	0	0	0	2	5
1000	0	320	250	0	80	0	0	0	0	1	5
1000	-300	80	250	-75	20	0	0	0	0	3	5
1000	-276	80	250	-69	20	1	0	1	0	5	6
1000	-252	80	250	-63	20	1	1	1	0	9	9
1000	-228	80	250	-57	20	2	1	1	1	17	17
1000	-204	80	250	-51	20	3	3	3	2	34	35
1000	-180	80	250	-45	20	5	5	5	3	56	68
1000	-156	80	250	-39	20	8	8	8	7	98	107
1000	-132	80	250	-33	20	10	13	13	12	163	159
1000	-108	80	250	-27	20	13	19	20	20	235	247
1000	-84	80	250	-21	20	17	25	26	30	306	330
1000	-60	80	250	-15	20	19	33	34	40	408	432
1000	-36	80	250	-9	20	22		40	49		496
1000	-12	80	250	-3	20	23	40	40	54	489	507
1000	12	80	250	3	20	23	41	41	54	511	510
1000	36	80	250	9	20	22	40	38	49	493	481
1000	60	80	250	15	20	19	36	35	40	449	433
1000	84	80	250	21	20	17	31	31	30	379	383
1000	108	80	250	27	20	13	25	21	20	306	270
1000	132	80	250	33	20	10	18	16	12	225	198
1000	156	80	250	39	20	8	12	10	7	149	120
1000	180	80	250	45	20	5	7	6	3	89	70
1000	204	80	250	51	20	3	4	4	2	47	45
1000	228	80	250	57	20	2	2	2	1	20	23
1000	252	80	250	63	20	1	1	1	0	9	9
1000	276	80	250	69	20	1	0	0	0	4	6
1000	300	80	250	75	20	0	0	0	0	2	5

Table 14 Normalized Conc. Data - GEP X = 1.0km Documentation

76.7m Stack GEP Documentation Tests

Vertical and Lateral Profiles at 2.0 km downwind

Field Values (MKS)		Model Values (CGS) IN	OUT		References (CGS)	IN	OUT
400	<Length Scale				Href =	100.0	100.0
5.0		299.7	299.7	< Wind Speed at Heff	Uref =	403.4	403.4
86.0		230.0	230.0	< Flow Rate	PL index	0.180	0.180
76.7		19.2	19.2	< Effective Stack Height			

Field Position X (m)	Y (m)	Z (m)	Model Position X (cm)	Y (cm)	Z (cm)	PG-C K*10^6 (m^-2)	IN K*10^6 (m^-2)	OUT K*10^6 (m^-2)	PG-D K*10^6 (m^-2)	IN Model (ppm)	OUT Model (ppm)
2000	0	0	500	0	0	10	29	22	16	359	268
2000	0	16	500	0	4	10	28	22	16	349	267
2000	0	32	500	0	8	10	26	21	17	313	255
2000	0	48	500	0	12	10	23	19	18	280	237
2000	0	64	500	0	16	9	20	18	19	249	221
2000	0	80	500	0	20	9	18	17	19	224	205
2000	0	96	500	0	24	8	16	15	18	191	190
2000	0	112	500	0	28	8	13	14	15	162	174
2000	0	128	500	0	32	7	11	13	13	138	158
2000	0	144	500	0	36	7	9	12	10	115	143
2000	0	160	500	0	40	6	8	10	8	95	125
2000	0	176	500	0	44	5	6	9	5	78	105
2000	0	192	500	0	48	5	5	7	3	58	89
2000	0	208	500	0	52	4	4	6	2	48	74
2000	0	224	500	0	56	4	3	5	1	34	59
2000	0	240	500	0	60	3	2	4	0	25	46
2000	0	256	500	0	64	3	1	3	0	18	33
2000	0	272	500	0	68	2	1	2	0	13	25
2000	0	288	500	0	72	2	1	2	0	10	19
2000	0	304	500	0	76	2	0	1	0	6	13
2000	0	320	500	0	80	1	0	1	0	4	9
2000	-300	80	500	-75	20	3	2	2	2	25	30
2000	-276	80	500	-69	20	3	3	3	3	33	43
2000	-252	80	500	-63	20	4	4	5	4	50	58
2000	-228	80	500	-57	20	5	5	6	6	67	75
2000	-204	80	500	-51	20	5	7	8	7	85	93
2000	-180	80	500	-45	20	6	9	9	9	107	116
2000	-156	80	500	-39	20	7	10	11	11	125	136
2000	-132	80	500	-33	20	7	12	13	12	149	159
2000	-108	80	500	-27	20	8	13	14	14	165	175
2000	-84	80	500	-21	20	8	15	15	16	183	189
2000	-60	80	500	-15	20	8	16	17	17	199	203
2000	-36	80	500	-9	20	9		0	18		
2000	-12	80	500	-3	20	9	18	17	19	217	204
2000	12	80	500	3	20	9	19	16	19	229	201
2000	36	80	500	9	20	9	19	17	18	230	204
2000	60	80	500	15	20	8	19	16	17	231	198
2000	84	80	500	21	20	8	18	15	16	221	186
2000	108	80	500	27	20	8	17	14	14	204	169
2000	132	80	500	33	20	7	15	12	12	187	149
2000	156	80	500	39	20	7	13	10	11	159	124
2000	180	80	500	45	20	6	11	9	9	138	106
2000	204	80	500	51	20	5	10	7	7	118	86
2000	228	80	500	57	20	5	8	5	6	94	56
2000	252	80	500	63	20	4	6	4	4	70	45
2000	276	80	500	69	20	3	4	2	3	51	30
2000	300	80	500	75	20	3	3	2	2	34	20

Table 15 Normalized Conc. Data - GEP X = 2.0km Documentation

Summary of Maximum Concentration And Excessive Concentration Analysis

Run No. Buidlings In	Out	Stack ID 1	Wind Direction (Deg.)	Stack Height (m)	Uanem* (m/s)	Maximum Concentrations Buildings In C/Co (ppm)	Buildings In C (ug/m3)	Buildings Out C/Co (ppm)	Buildings Out C (ug/m3)	Concentration Ratio In/Out
Worst Wind Direction Tests (Selected From Visualization)										
301	312	COB	72	76.7	5.0	620.4	1031.9	356.4	592.8	1.74
302	312	COB	77	76.7	5.0	607.0	1009.6	356.4	592.8	1.70
303	312	COB	67	76.7	5.0	621.9	1034.4	356.4	592.8	1.74
304	312	COB	32.5	76.7	5.0	555.0	923.1	356.4	592.8	1.56
305	312	COB	27.5	76.7	5.0	480.7	799.6	356.4	592.8	1.35
306	312	COB	22.5	76.7	5.0	535.3	890.4	356.4	592.8	1.50
307	312	COB	17.5	76.7	5.0	540.2	898.5	356.4	592.8	1.52
308	312	COB	120	76.7	5.0	521.7	867.8	356.4	592.8	1.46
309	312	COB	338	76.7	5.0	462.2	768.8	356.4	592.8	1.30
310	312	COB	62	76.7	5.0	548.2	911.8	356.4	592.8	1.54
311	312	COB	72	76.7	5.0	651.2	1083.2	356.4	592.8	1.83
Worst Wind Speed Tests										
401	404	COB	72	76.7	3.0	698.0	1161.0	391.5	651.2	1.78
402	405	COB	72	76.7	8.0	523.8	871.3	293.8	488.7	1.78
403	406	COB	72	76.7	11.0	464.1	772.0	230.6	383.6	2.01
Additional Stack Height Tests										
501	506	COB	72	80.0	11.0	387.0	643.7	201.2	334.7	1.92
502	507	COB	72	85.0	11.0	340.3	566.0	192.4	320.0	1.77
503	508	COB	72	90.0	11.0	269.2	447.8	170.6	283.8	1.58
504	509	COB	72	95.0	11.0	238.0	395.9	158.6	263.8	1.50
505	510	COB	72	100.0	11.0	204.7	340.5	143.0	237.9	1.43
GEP Stack Height Documentation Tests										
701	704	COB	72	76.7	5.0	626.1	1041.4	338.3	562.7	1.85
702	705	COB	72	76.7	5.0	604.7	1005.8	344.4	572.9	1.76
703	706	COB	72	76.7	5.0	633.6	1053.9	361.5	601.3	1.75
					Average		***1033.7***		***579.0***	***1.79***

Excessive Concentration Analysis	***Ambient Standard Test***					***40% Test***	
This analysis conducted using 700 series tests, 76.7 m stack height	**Maximum Concentration (ug/m3)**					**Concentration Ratio**	
	Averaging Time	NAAQS	MAAQS	Wind Tunnel		Criteria	Wind Tunnel
	1-hr		1300	1033.7		1.4	***1.79***
	3-hr	1300		930.3			**Excessive**
	24-hr	365	262	***413.5***	***Excessive***		
	annual	80	56	***82.7***	***Excessive***		

* - Wind Speed at Billings Airport, 7.6 m anemometer height

Table 16 Excessive Concentration Demonstration Test Results

FIGURES

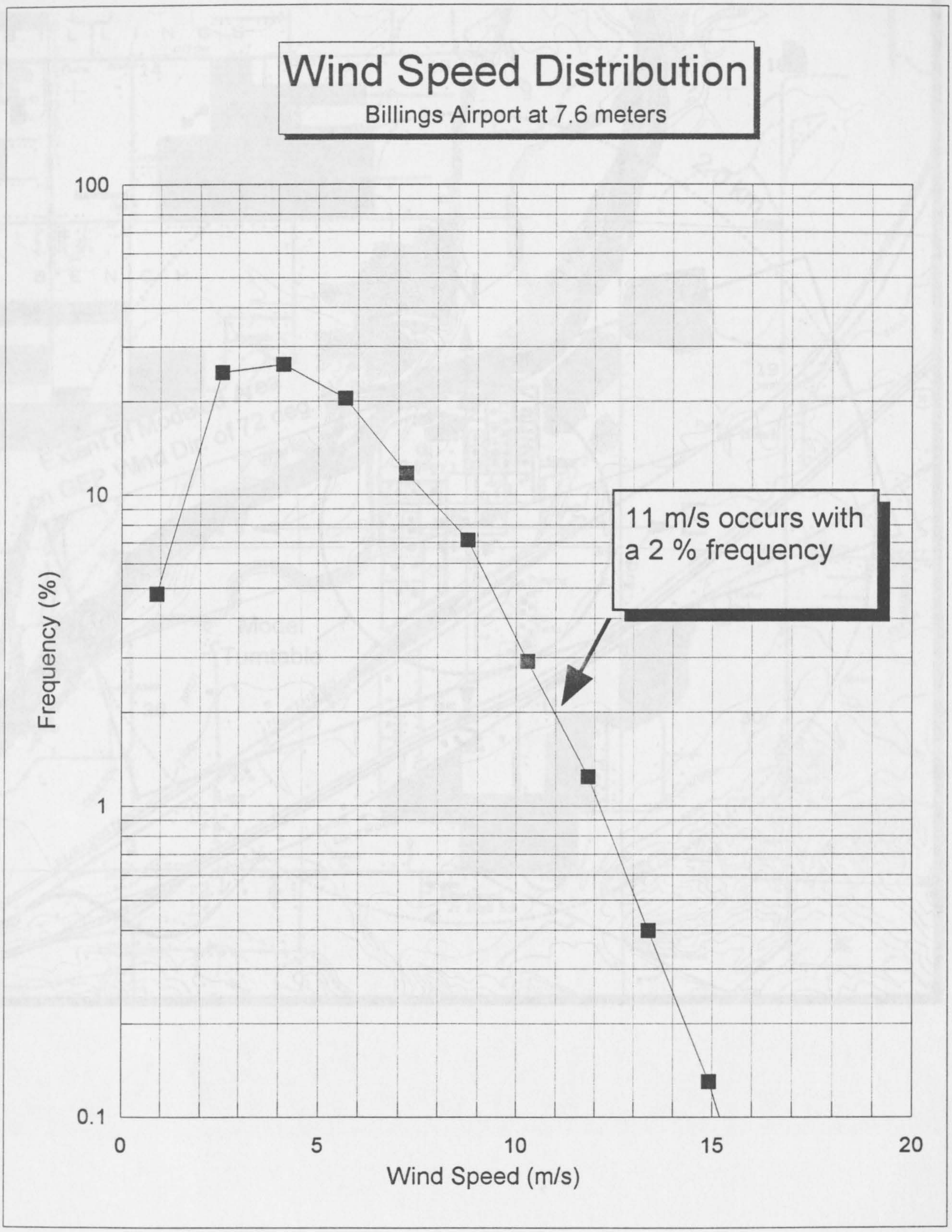


Figure 1 Wind Speed Distribution at Billings Airport

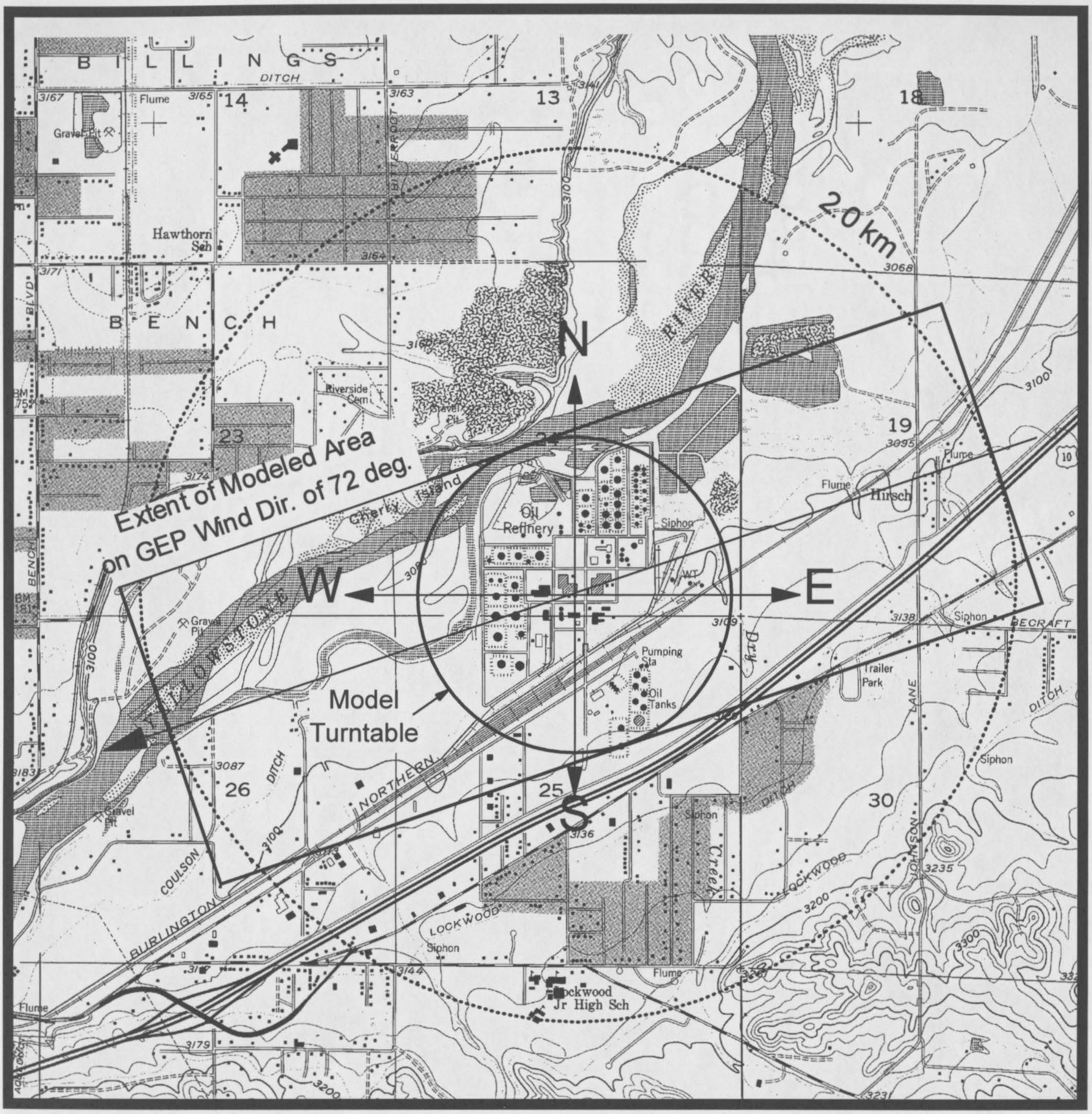


Figure 2 Site Topography and Model Study Area Extent

Figure 3 Aerial Photograph of Field Site

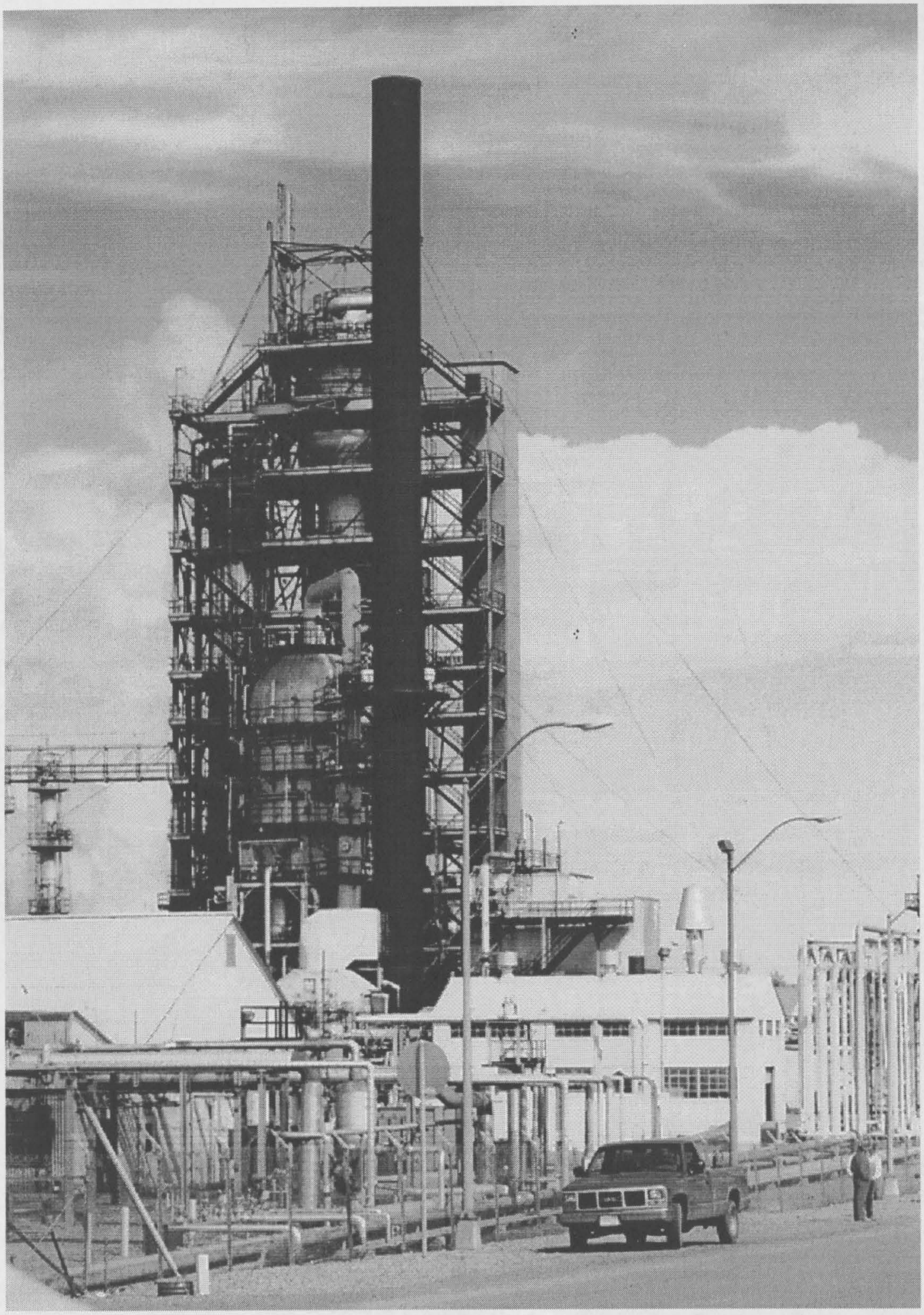


Figure 4 Field Site Photograph - FCC COB Stack

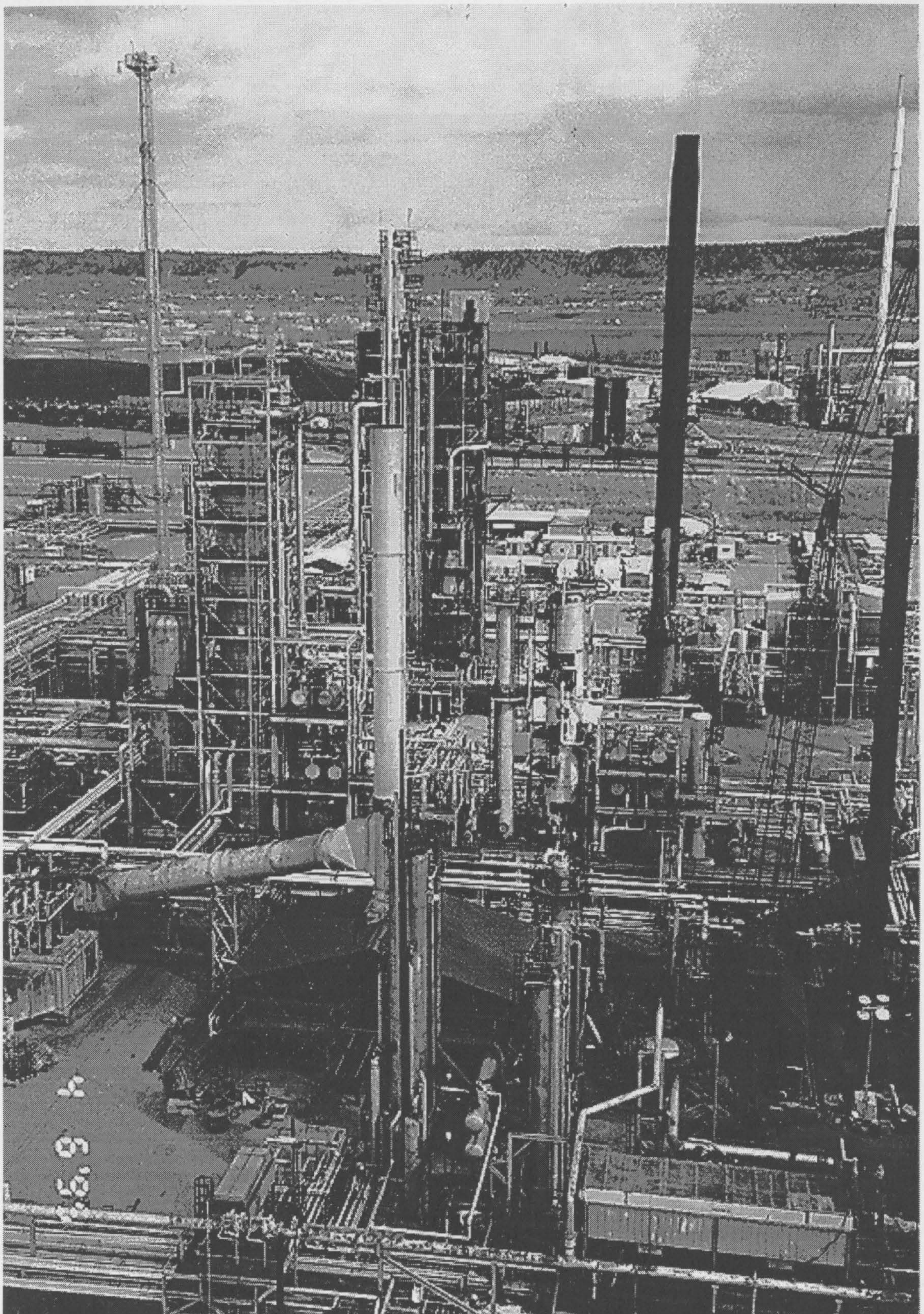


Figure 5 Field Site Photograph - Structures ENE of Stack

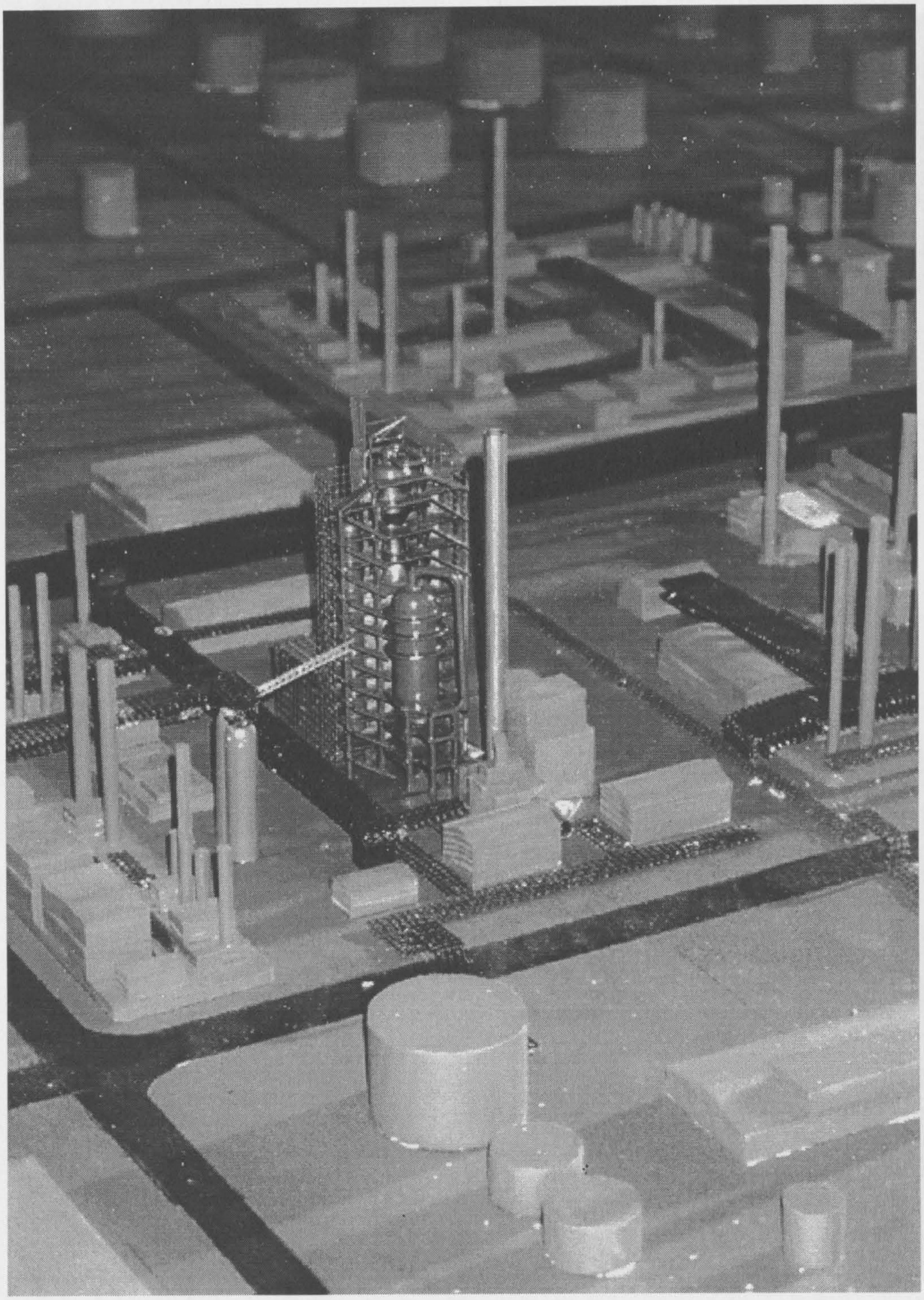


Figure 6 Model Site Photograph - FCC COB Stack

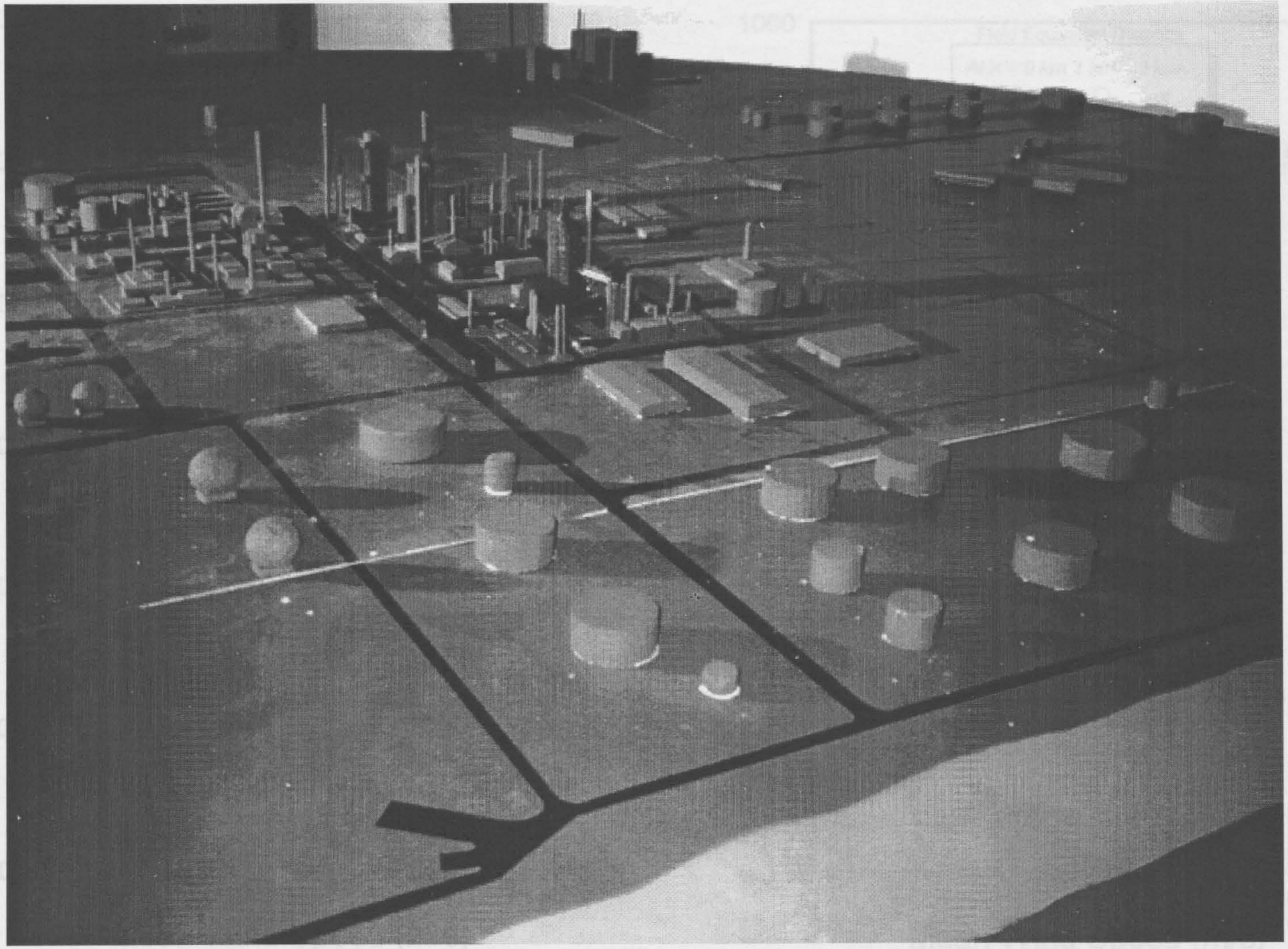


Figure 7   Model Site Photograph - Looking SE over Entire Site

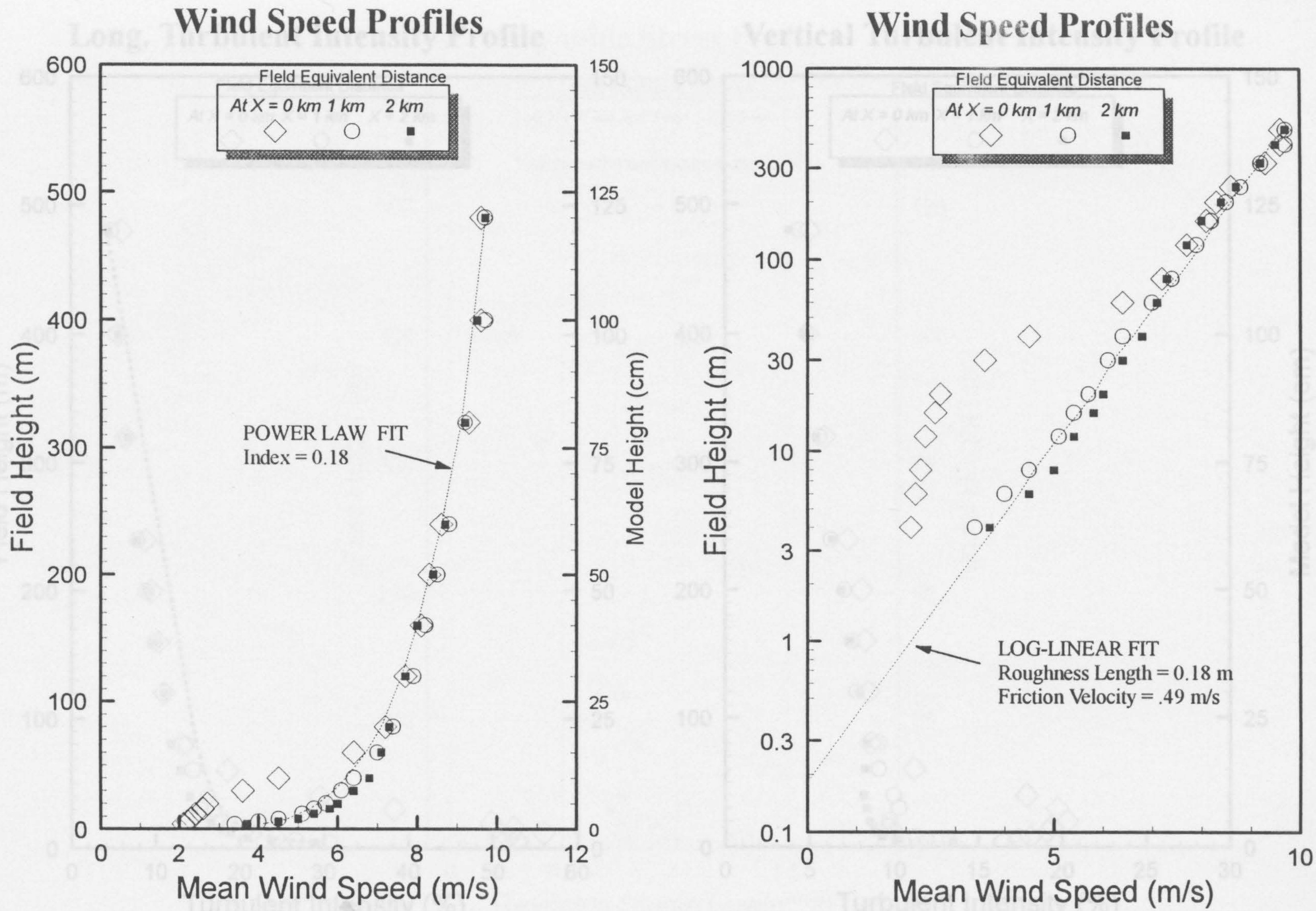


Figure 8 Mean Wind Speed Profiles

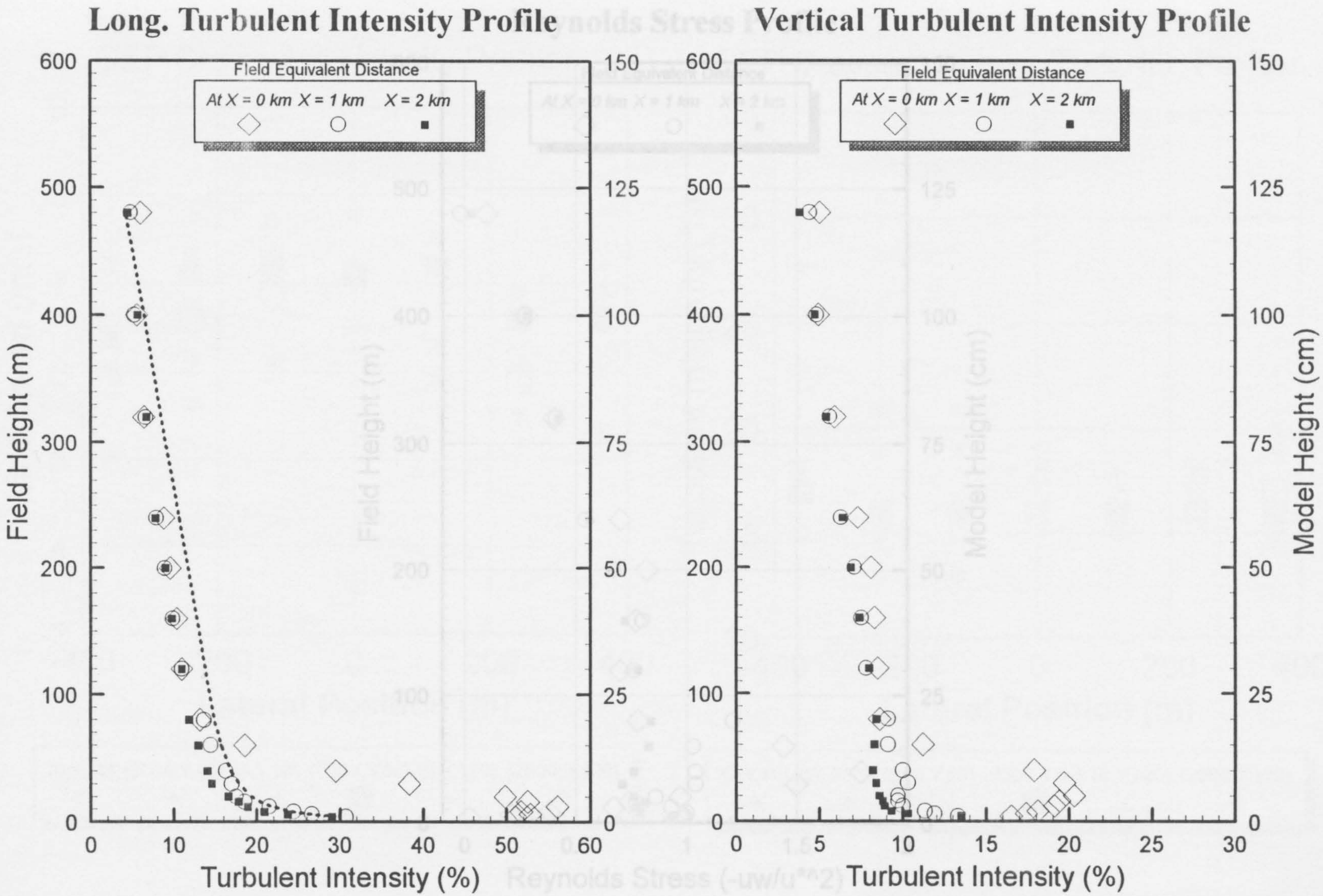


Figure 9 Wind Turbulence Profiles

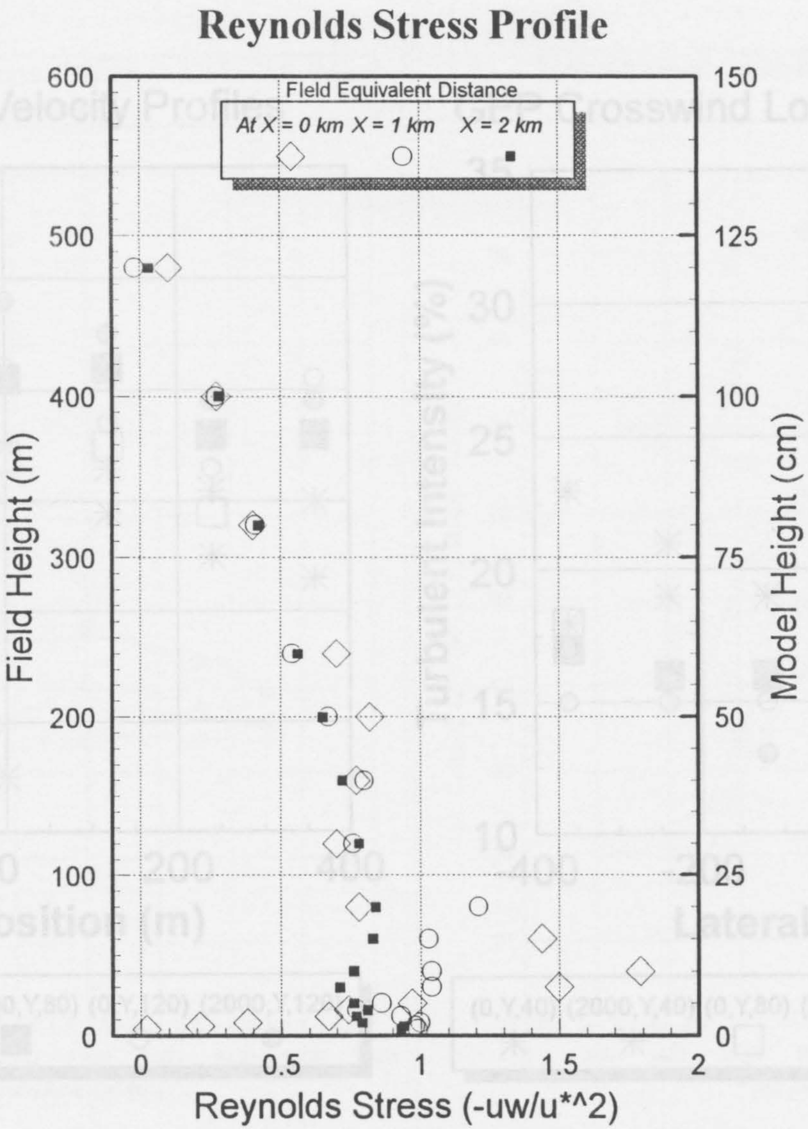


Figure 10 Wind Reynolds Stress Profiles

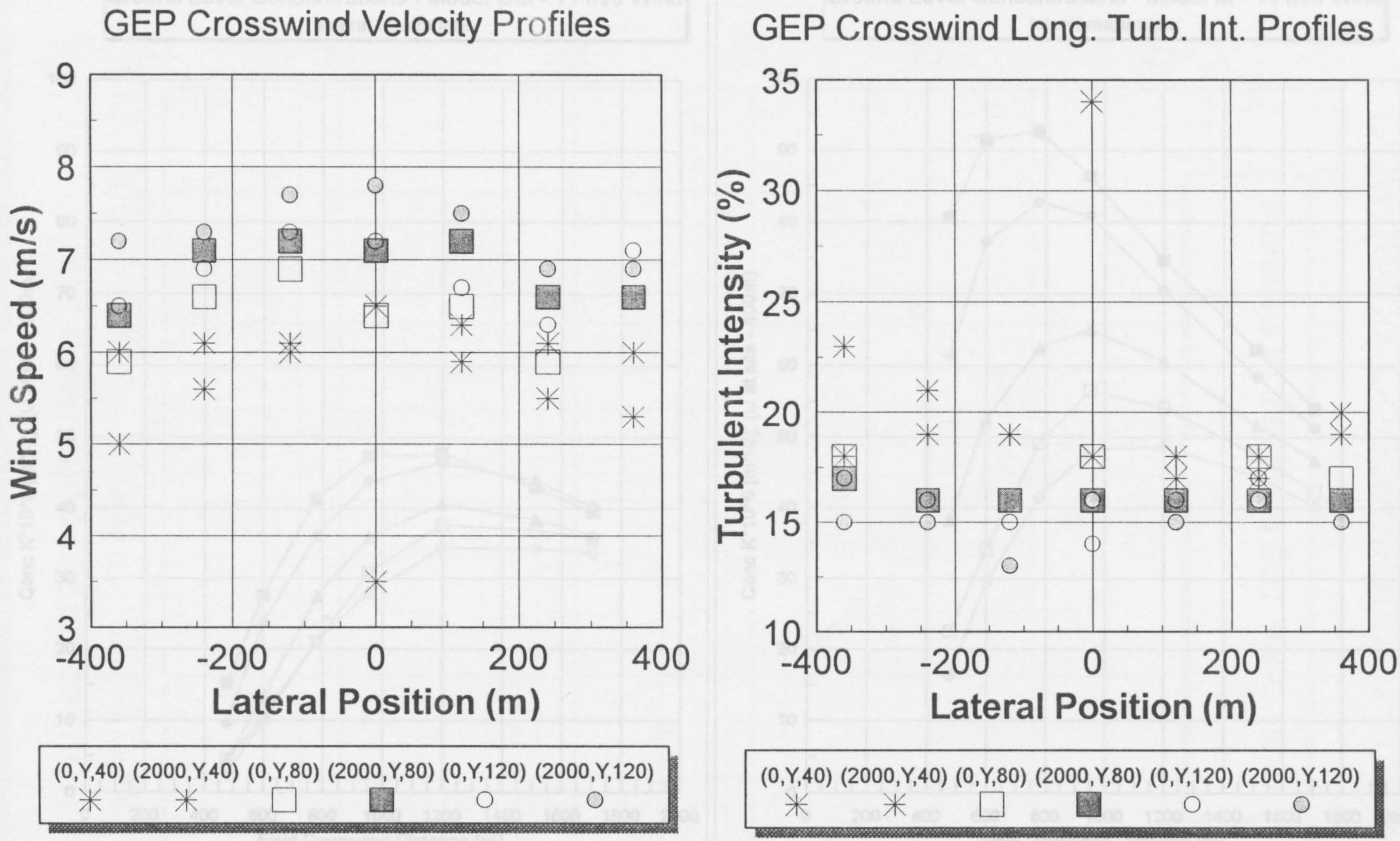


Figure 11 Lateral Wind Profiles

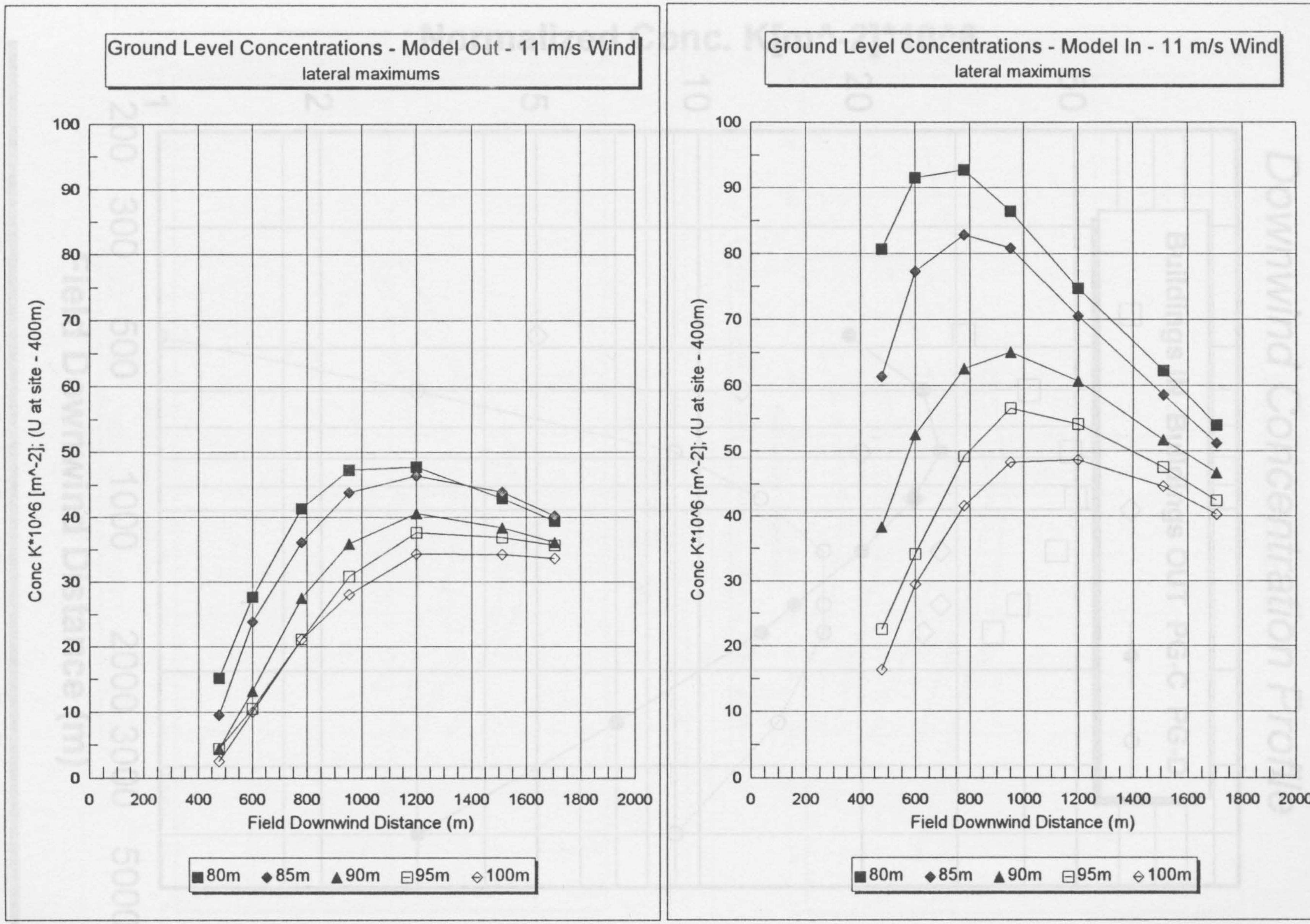


Figure 12 Ground Level Conc. Variation with Stack Height (11 m/s Wind)

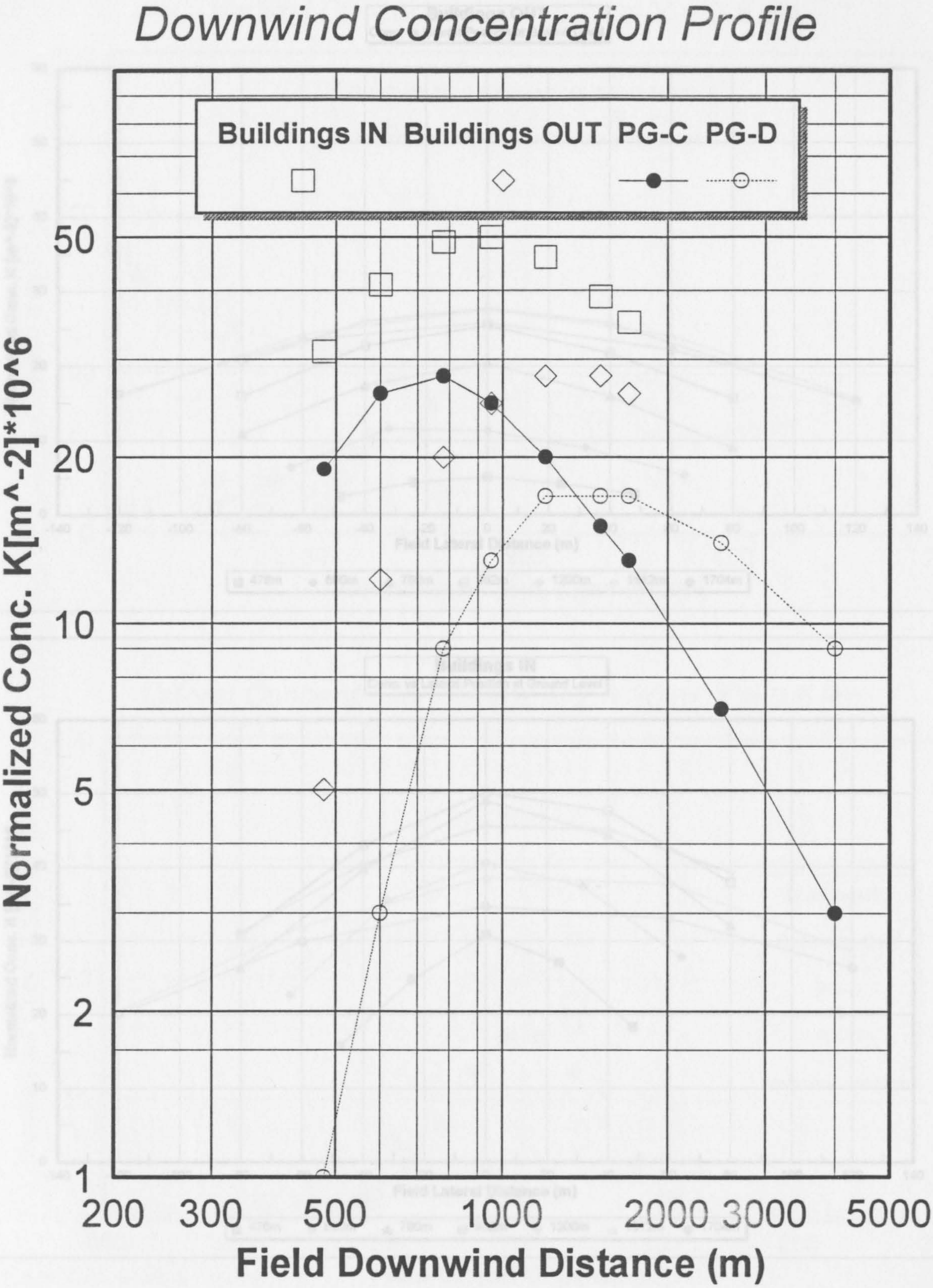
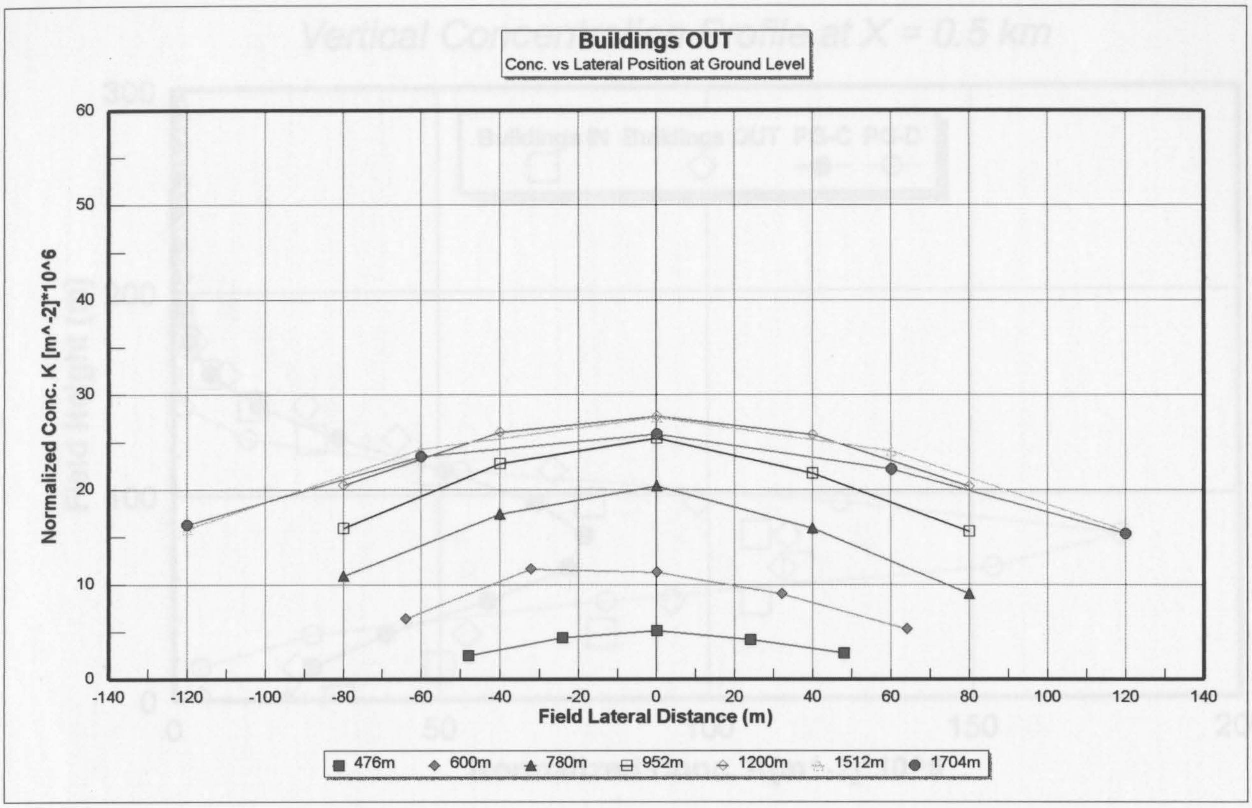


Figure 13 Long. Ground Level Concentration Profiles



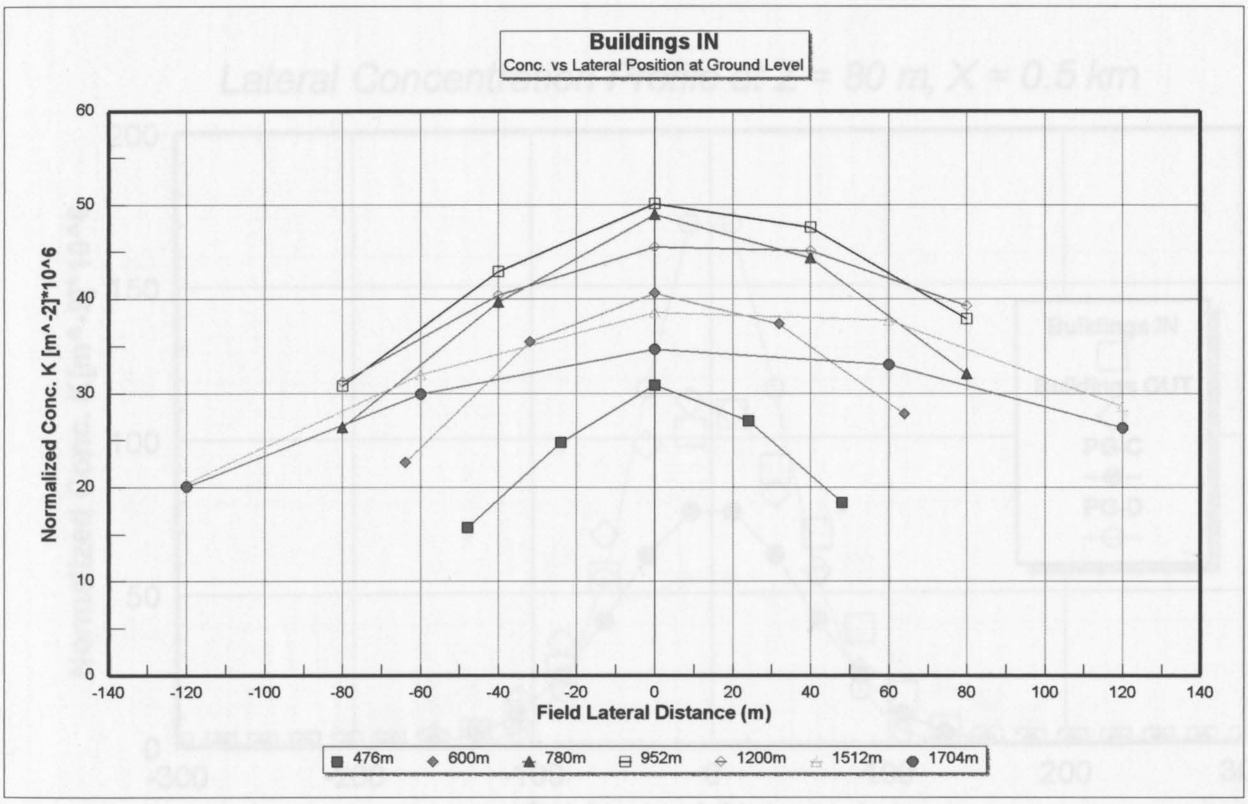
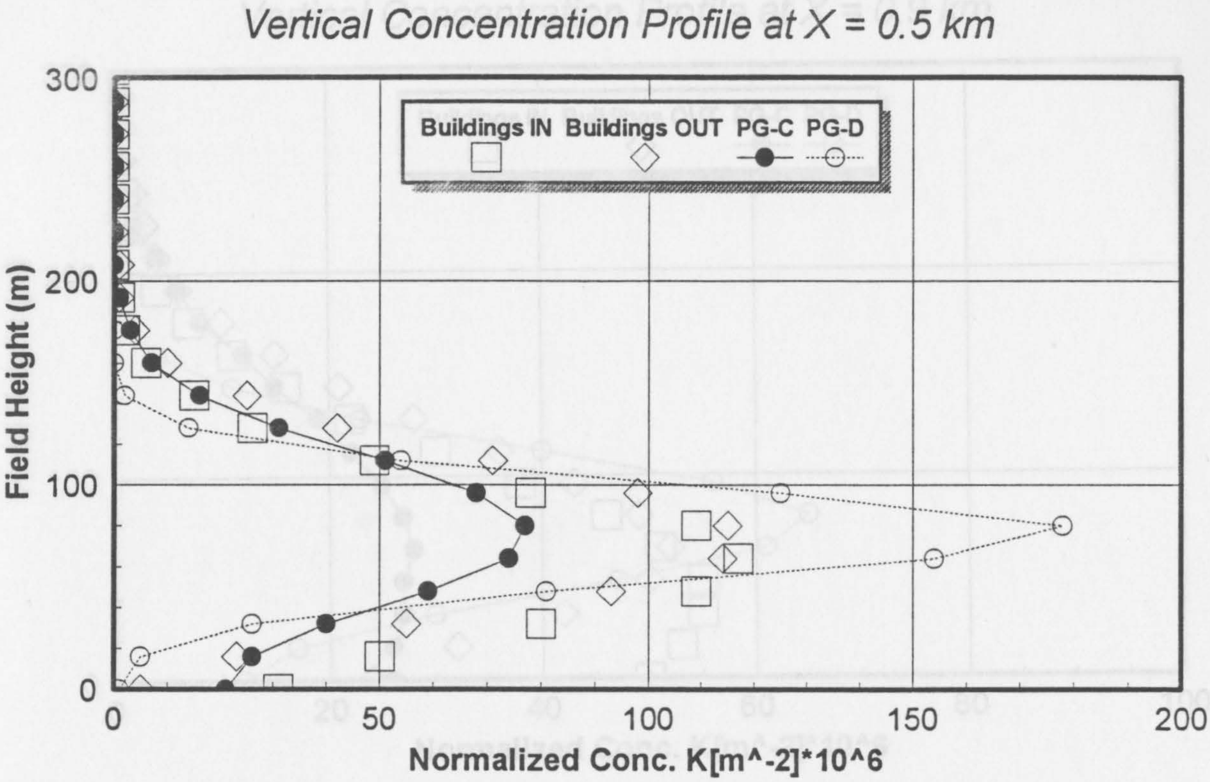


Figure 14 Lateral Ground Level Concentration Profiles



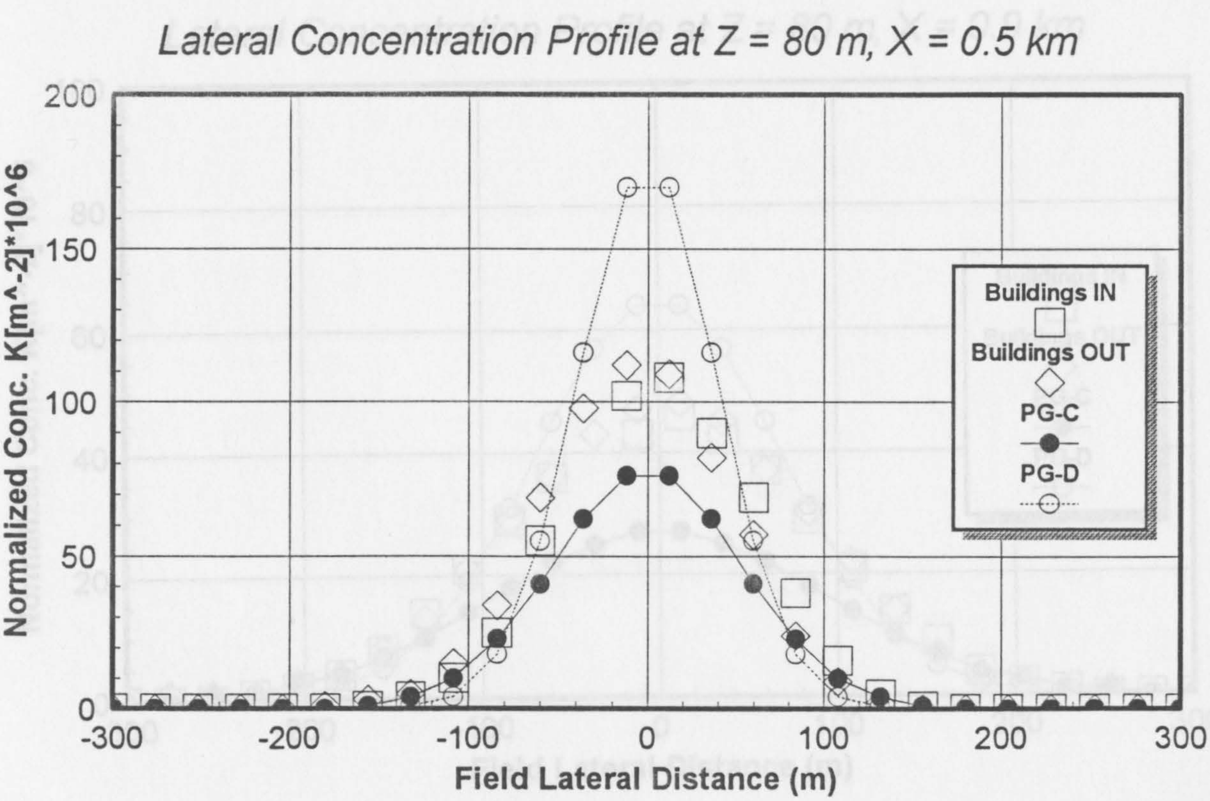
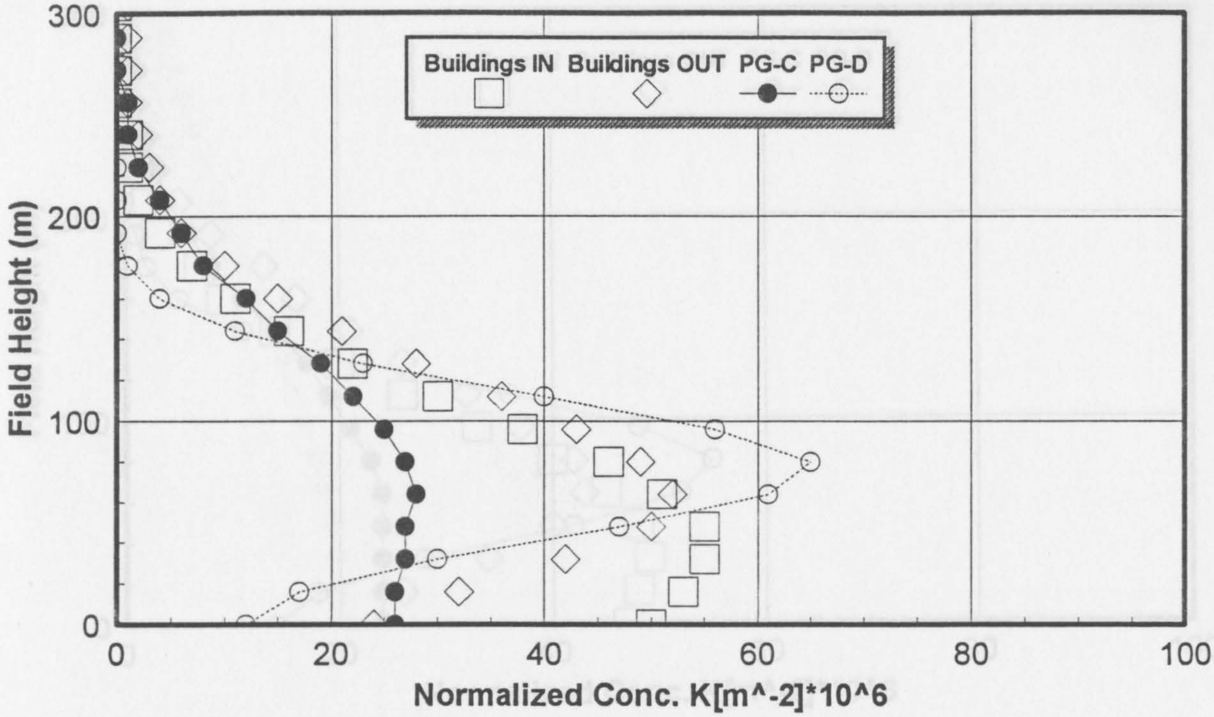


Figure 15 Vertical and Lateral Plume Profiles at 0.5 km Downwind

Vertical Concentration Profile at X = 0.9 km



Lateral Concentration Profile at Z = 80 m, X = 0.9 km

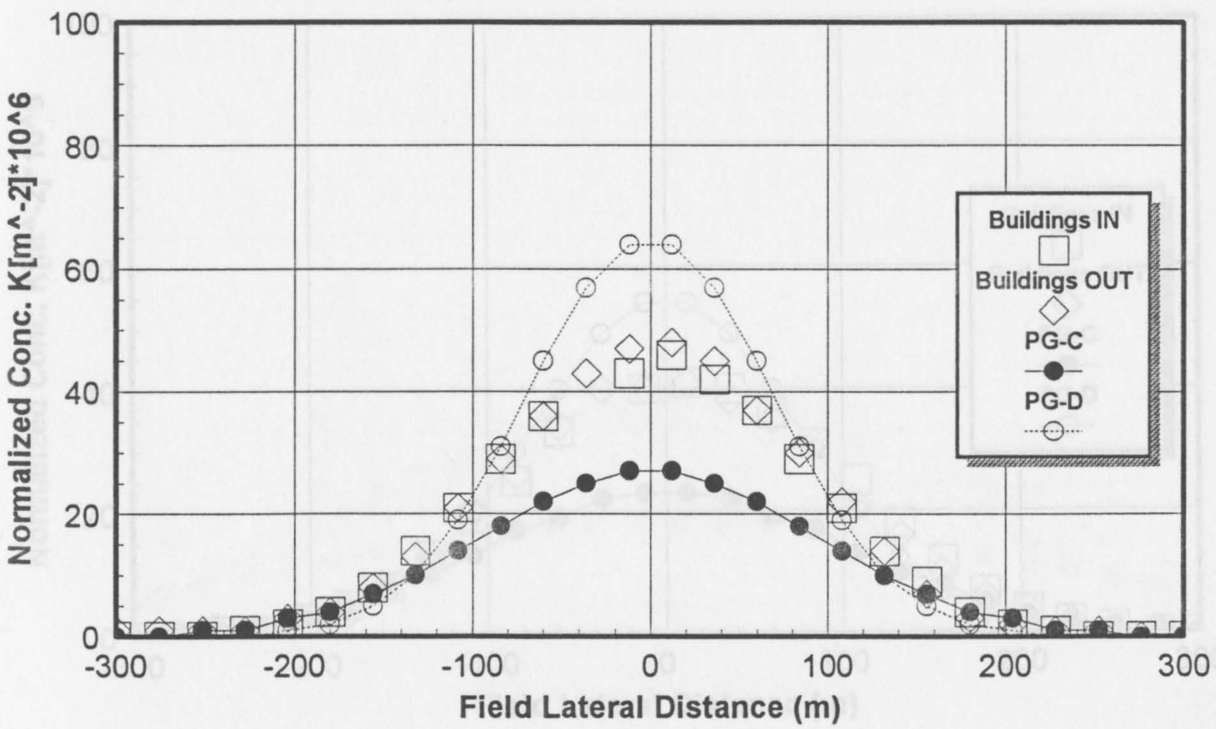


Figure 16 Vertical and Lateral Plume Profiles at 0.9 km Downwind

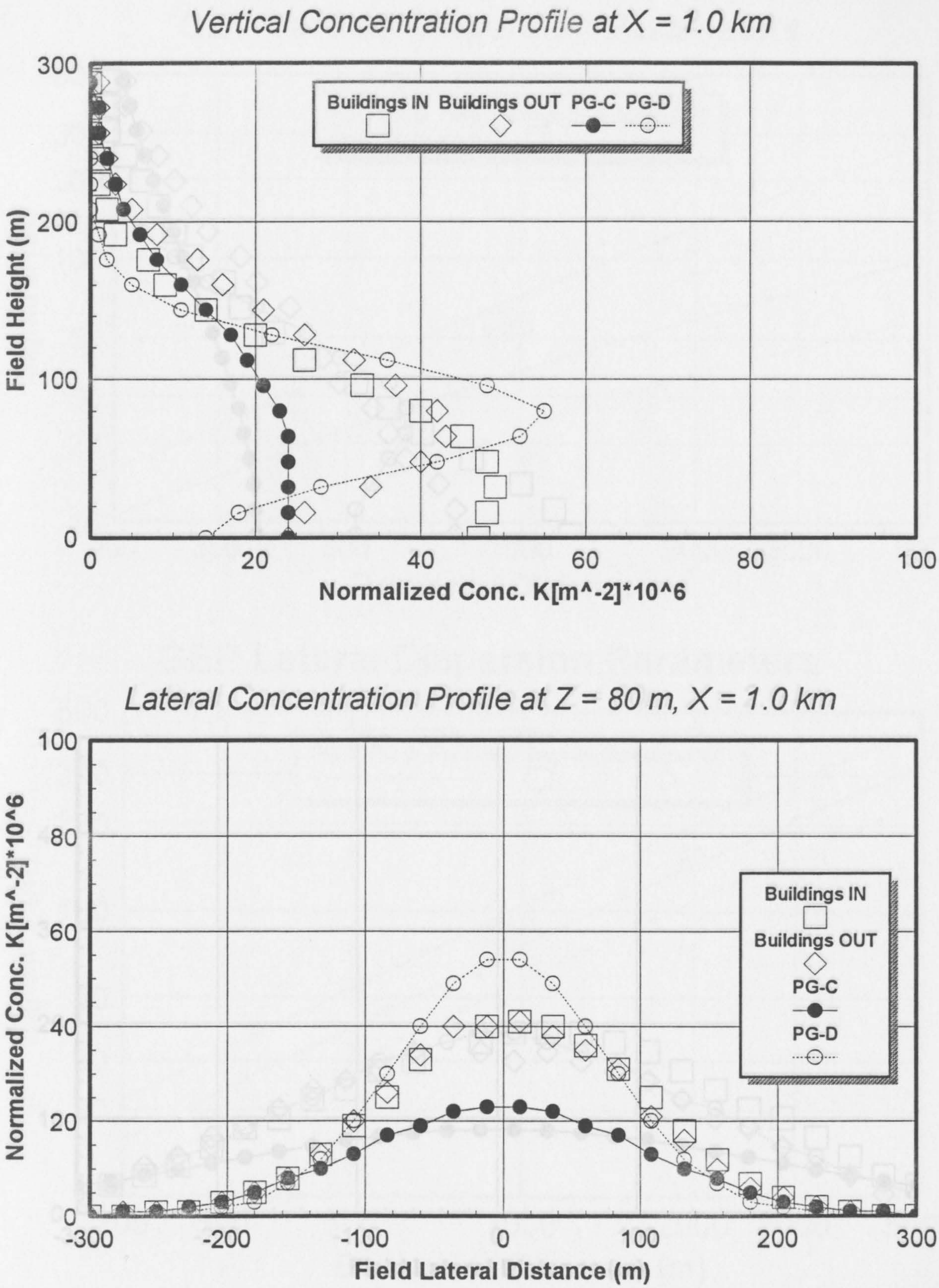
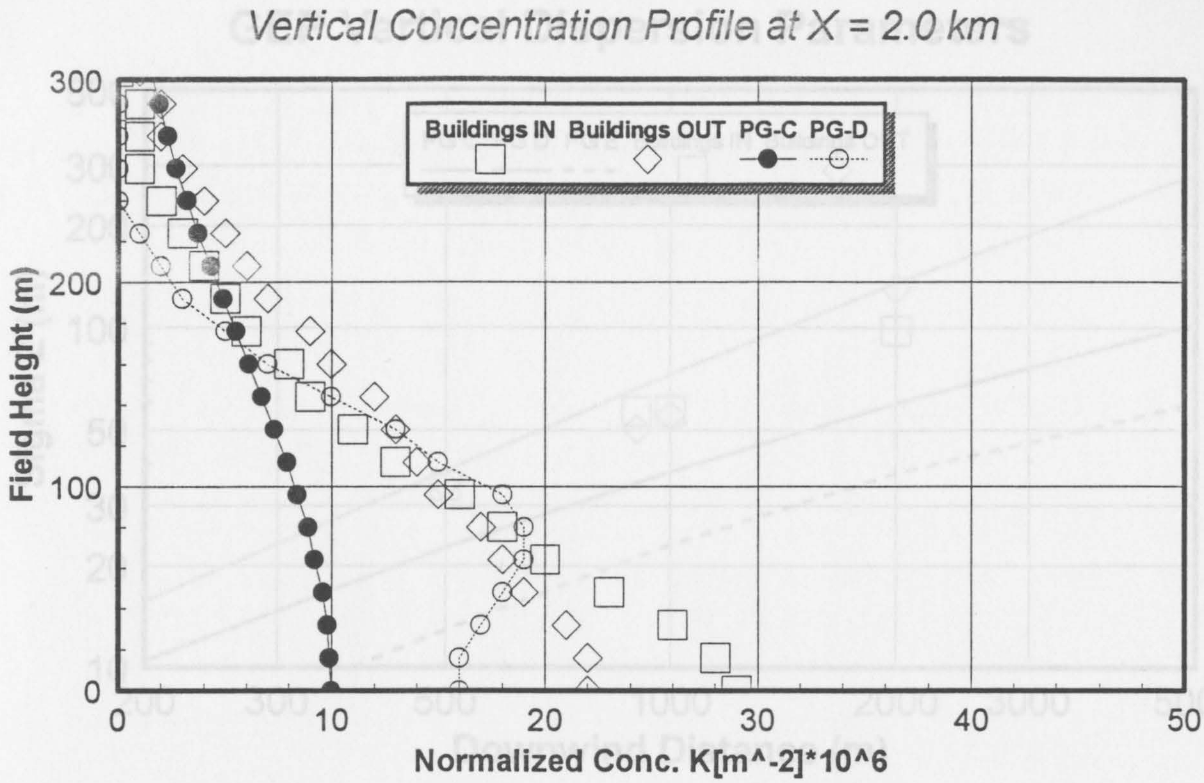


Figure 17 Vertical and Lateral Plume Profiles at 1.0 km Downwind



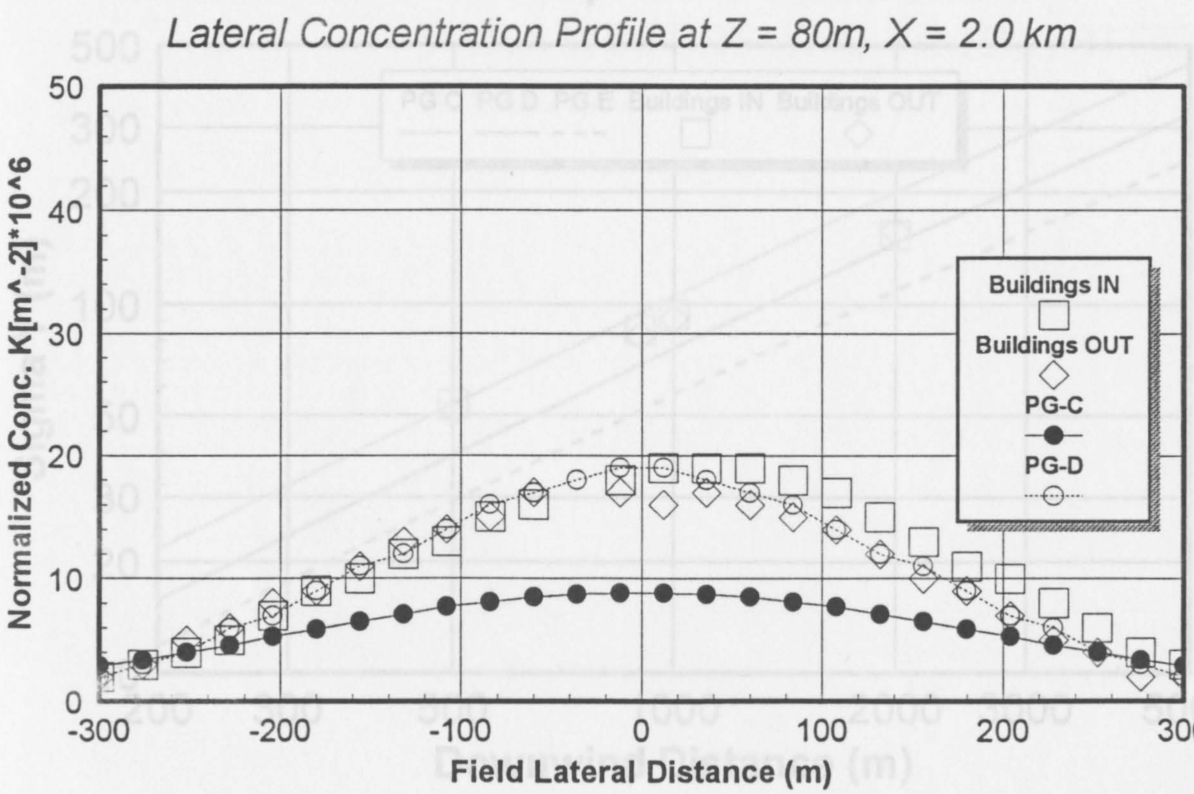
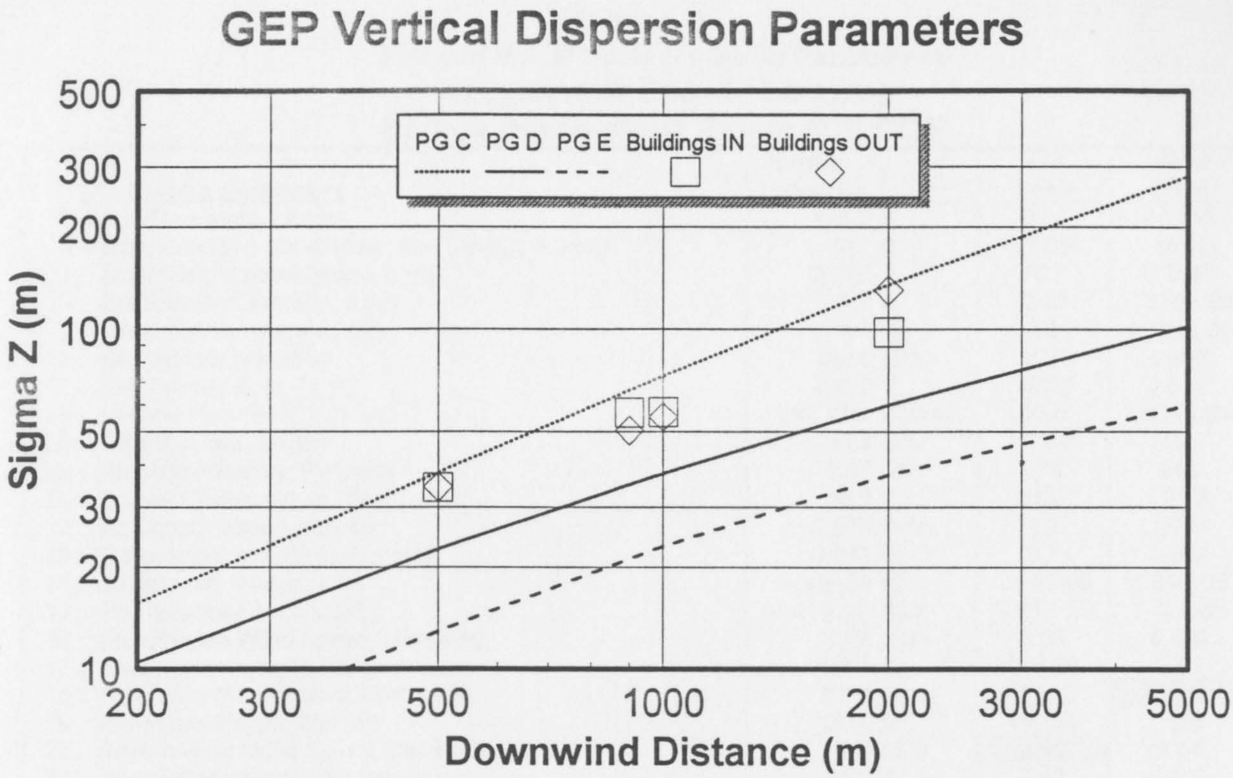


Figure 18 Vertical and Lateral Plume Profiles at 2.0 km Downwind



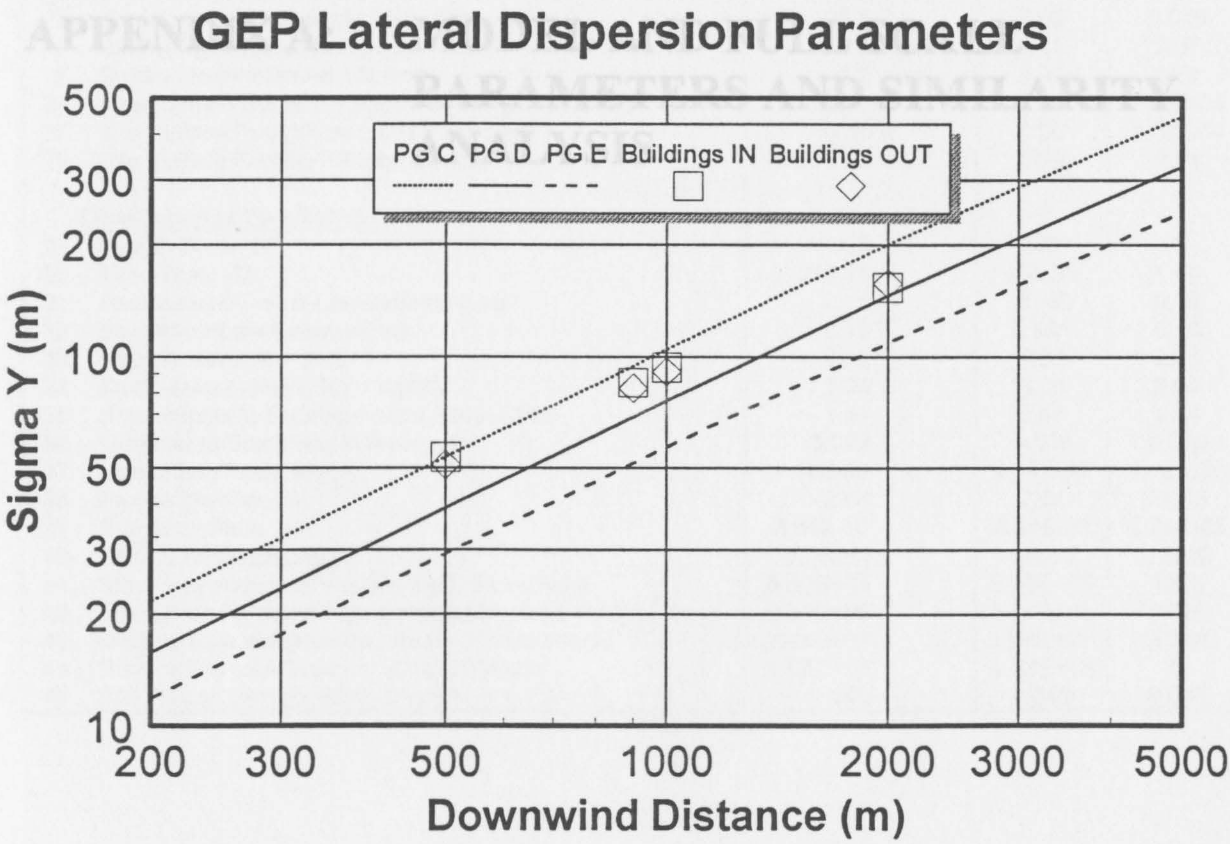


Figure 19 Vertical and Lateral Plume Dispersion Coefficients

APPENDIX A: MODEL AND FULL SCALE PARAMETERS AND SIMILARITY ANALYSIS

Table A-1
Full and Model Scale Similarity Parameters
Anemometer Speed 3.0 (m/s)
Source Description: Exxon FCC COB

	English Full-Scale		Full Scale	Model Scale
Dimensional Parameters				
1 . Building Height, Hb (m)	175.2	ft	53.4	0.1335
2 . Base Elevation above Mean Sea Level, z = 0 (m)	947	ft	288.6	1524
3 . Stack Height above grade, h (m)	251.6	ft	76.7	0.1917
4 . Stack Inside Diameter, d (m)	9.7	ft	2.96	7.399E-03
5 . Stack Inside Area, Ae (m2)	74.1	ft2	6.9	4.300E-05
6 . Exit Velocity, Ve (m/s)	2460	fpm	12.5	8.916
7 . Exit Temperature, Ts (K)	435.0	F	497.0	293.2
8 . Volume Flow Rate, V (m3/s)	182,164	ft3/min	86.0	3.834E-04
9 . Emission rate, Q (g/s)	1133.9	lb/hr	142.9	NA
10 . Ambient Pressure, Pa (hPa)	0.97	Atm	979	844
11 . Ambient Temperature, Ta (K)	46.0	F	280.9	293.2
12 . Air Density, Rho a (kg/m3)	0.076	lb/ft3	1.2	1.004
13 . Exhaust Density, Rho s (kg/m3)	0.043	lb/ft3	0.7	0.567
14 . Air Viscosity, Nu a (m2/s)	1.56E-04	ft2/s	1.44E-05	1.81E-05
15 . Gas Viscosity, Nu s (m2/s)	4.17E-04	ft2/s	3.88E-05	1.72E-05
16 . Free Stream Wind Speed, Uinf (m/s)	13.5	mph	6.03	4.304
17 . Free Stream Height, Zinf (m)	1969	ft	600.00	1.50
18 . Reference Wind Speed, Uref (m/s)	12.5	mph	5.61	4.000
19 . Reference Height, Zref (m)	1312	ft	400.00	1.00
20 . Anemometer Wind Speed, Uanem (m/s)	6.7	mph	3.00	2.14
21 . Anemometer Height, Zanem (m)	25.0	ft	7.62	0.019
22 . Site Wind Speed, Usite (m/s)	6.1	mph	2.74	1.96
23 . 'Site Anemometer' Height, Zsite (m)	25.0	ft	7.62	0.019
24 . Stack Height Speed, Uh (m/s)	9.3	mph	4.16	2.97
25 . Building Height Speed, Ub (m/s)	8.7	mph	3.90	2.78
26 . Anemometer Surface Roughness Length, Zo a (m)	0.33	ft	0.10	2.50E-04
27 . Site Surface Roughness Length, Zo s (m)	0.66	ft	0.20	5.00E-04
28 . Site Surface Friction Velocity, U* (m/s)	0.65	mph	0.29	0.21
Dimensionless Parameters				
29 . Length Scale, SF	400		400	1
30 . Time Scale, TS	285.38		285.38	1.00
31 . Anemometer Power Law Exponent, na	0.16		0.160	0.16
32 . Site Power Law Exponent, ns	0.18		0.181	0.18
33 . Velocity Ratio, R = Ve/Ur	2.23		2.23	2.23
34 . Stack Velocity Ratio, Rs = Ve/Uh	3.00		3.00	3.00
35 . Stack Height to Building Height Ratio, h/Hb	1.44		1.44	1.44
36 . Diameter to Stack Height Ratio, d/h	0.039		0.039	0.039
37 . Momentum Ratio, Mo	4.18E-03		4.18E-03	4.18E-03
38 . Froude Number, Fr	2.64		2.64	37.73
39 . Buoyancy Ratio, Bo	8.64E-03		8.64E-03	4.24E-05
40 . Density Ratio, Lambda	0.5652		0.5652	0.5652
41 . Stack Reynolds Number (Exterior), d Uh / Nu a	8.52E+05		8.52E+05	1215
42 . Stack Flow Reynolds Number (Interior), Re s = d Ve / Nu s	9.54E+05		9.54E+05	3826
43 . Building Reynolds Number, Re b = Hb Ub / Nu a	1.44E+07		1.44E+07	20534
44 . Surface Reynolds Number, Zo s U* / Nu a	4.03E+03		4.03E+03	6
45 . Site Friction Velocity Ratio, U*/Uinf	0.048		0.048	0.048

Table A-2
Full and Model Scale Similarity Parameters
Anemometer Speed 5.0 (m/s)
Source Description: Exxon FCC COB

	English Full-Scale	Full Scale	Model Scale
Dimensional Parameters			
1 . Building Height, Hb (m)	175.2 ft	53.4	0.1335
2 . Base Elevation above Mean Sea Level, z = 0 (m)	947 ft	288.6	1524
3 . Stack Height above grade, h (m)	251.6 ft	76.7	0.1917
4 . Stack Inside Diameter, d (m)	9.7 ft	2.96	7.399E-03
5 . Stack Inside Area, Ae (m2)	74.1 ft2	6.9	4.300E-05
6 . Exit Velocity, Ve (m/s)	2460 fpm	12.5	5.350
7 . Exit Temperature, Ts (K)	435.0 F	497.0	293.2
8 . Volume Flow Rate, V (m3/s)	182,164 ft3/min	86.0	2.300E-04
9 . Emission rate, Q (g/s)	1133.9 lb/hr	142.9	NA
10 . Ambient Pressure, Pa (hPa)	0.97 Atm	979	844
11 . Ambient Temperature, Ta (K)	46.0 F	280.9	293.2
12 . Air Density, Rho a (kg/m3)	0.076 lb/ft3	1.2	1.004
13 . Exhaust Density, Rho s (kg/m3)	0.043 lb/ft3	0.7	0.567
14 . Air Viscosity, Nu a (m2/s)	1.56E-04 ft2/s	1.44E-05	1.81E-05
15 . Gas Viscosity, Nu s (m2/s)	4.17E-04 ft2/s	3.88E-05	1.51E-05
16 . Free Stream Wind Speed, Uinf (m/s)	22.5 mph	10.05	4.304
17 . Free Stream Height, Zinf (m)	1969 ft	600.00	1.50
18 . Reference Wind Speed, Uref (m/s)	20.9 mph	9.34	4.000
19 . Reference Height, Zref (m)	1312 ft	400.00	1.00
20 . Anemometer Wind Speed, Uanem (m/s)	11.2 mph	5.00	2.14
21 . Anemometer Height, Zanem (m)	25.0 ft	7.62	0.019
22 . Site Wind Speed, Usite (m/s)	10.2 mph	4.57	1.96
23 . 'Site Anemometer' Height, Zsite (m)	25.0 ft	7.62	0.019
24 . Stack Height Speed, Uh (m/s)	15.5 mph	6.93	2.67
25 . Building Height Speed, Ub (m/s)	14.5 mph	6.49	2.78
26 . Anemometer Surface Roughness Length, Zo a (m)	0.33 ft	0.10	2.50E-04
27 . Site Surface Roughness Length, Zo s (m)	0.66 ft	0.20	5.00E-04
28 . Site Surface Friction Velocity, U* (m/s)	1.09 mph	0.49	0.21
Dimensionless Parameters			
29 . Length Scale, SF	400	400	1
30 . Time Scale, TS	171.23	171.23	1.00
31 . Anemometer Power Law Exponent, na	0.16	0.160	0.16
32 . Site Power Law Exponent, ns	0.18	0.181	0.18
33 . Velocity Ratio, R = Ve/Ur	1.34	1.34	1.34
34 . Stack Velocity Ratio, Rs = Ve/Uh	1.80	1.80	2.01
35 . Stack Height to Building Height Ratio, h/Hb	1.44	1.44	1.44
36 . Diameter to Stack Height Ratio, d/h	0.039	0.039	0.039
37 . Momentum Ratio, Mo	1.51E-03	1.51E-03	1.51E-03
38 . Froude Number, Fr	2.64	2.64	22.64
39 . Buoyancy Ratio, Bo	1.87E-03	1.87E-03	2.55E-05
40 . Density Ratio, Lambda	0.5652	0.5652	0.5652
41 . Stack Reynolds Number (Exterior), d Uh / Nu a	1.42E+06	1.42E+06	1091
42 . Stack Flow Reynolds Number (Interior), Re s = d Ve / Nu s	9.54E+05	9.54E+05	2622
43 . Building Reynolds Number, Re b = Hb Ub / Nu a	2.40E+07	2.40E+07	20534
44 . Surface Reynolds Number, Zo s U* / Nu a	6.72E+03	6.72E+03	6
45 . Site Friction Velocity Ratio, U*/Uinf	0.048	0.048	0.048

Table A-3
Full and Model Scale Similarity Parameters
Anemometer Speed 8.0 (m/s)
Source Description: Exxon FCC COB

	English Full-Scale	Full Scale	Model Scale
Dimensional Parameters			
1 . Building Height, Hb (m)	175.2 ft	53.4	0.1335
2 . Base Elevation above Mean Sea Level, z = 0 (m)	947 ft	288.6	1524
3 . Stack Height above grade, h (m)	251.6 ft	76.7	0.1917
4 . Stack Inside Diameter, d (m)	9.7 ft	2.96	7.399E-03
5 . Stack Inside Area, Ae (m2)	74.1 ft2	6.9	4.300E-05
6 . Exit Velocity, Ve (m/s)	2460 fpm	12.5	3.343
7 . Exit Temperature, Ts (K)	435.0 F	497.0	293.2
8 . Volume Flow Rate, V (m3/s)	182,164 ft3/min	86.0	1.438E-04
9 . Emission rate, Q (g/s)	1133.9 lb/hr	142.9	NA
10 . Ambient Pressure, Pa (hPa)	0.97 Atm	979	844
11 . Ambient Temperature, Ta (K)	46.0 F	280.9	293.2
12 . Air Density, Rho a (kg/m3)	0.076 lb/ft3	1.2	1.004
13 . Exhaust Density, Rho s (kg/m3)	0.043 lb/ft3	0.7	0.567
14 . Air Viscosity, Nu a (m2/s)	1.56E-04 ft2/s	1.44E-05	1.81E-05
15 . Gas Viscosity, Nu s (m2/s)	4.17E-04 ft2/s	3.88E-05	1.72E-05
16 . Free Stream Wind Speed, Uinf (m/s)	36.0 mph	16.09	4.304
17 . Free Stream Height, Zinf (m)	1969 ft	600.00	1.50
18 . Reference Wind Speed, Uref (m/s)	33.4 mph	14.95	4.000
19 . Reference Height, Zref (m)	1312 ft	400.00	1.00
20 . Anemometer Wind Speed, Uanem (m/s)	17.9 mph	8.00	2.14
21 . Anemometer Height, Zanem (m)	25.0 ft	7.62	0.019
22 . Site Wind Speed, Usite (m/s)	16.3 mph	7.31	1.96
23 . 'Site Anemometer' Height, Zsite (m)	25.0 ft	7.62	0.019
24 . Stack Height Speed, Uh (m/s)	24.8 mph	11.09	2.97
25 . Building Height Speed, Ub (m/s)	23.2 mph	10.39	2.78
26 . Anemometer Surface Roughness Length, Zo a (m)	0.33 ft	0.10	2.50E-04
27 . Site Surface Roughness Length, Zo s (m)	0.66 ft	0.20	5.00E-04
28 . Site Surface Friction Velocity, U* (m/s)	1.74 mph	0.78	0.21
Dimensionless Parameters			
29 . Length Scale, SF	400	400	1
30 . Time Scale, TS	107.02	107.02	1.00
31 . Anemometer Power Law Exponent, na	0.16	0.160	0.16
32 . Site Power Law Exponent, ns	0.18	0.181	0.18
33 . Velocity Ratio, R = Ve/Ur	0.84	0.84	0.84
34 . Stack Velocity Ratio, Rs = Ve/Uh	1.13	1.13	1.13
35 . Stack Height to Building Height Ratio, h/Hb	1.44	1.44	1.44
36 . Diameter to Stack Height Ratio, d/h	0.039	0.039	0.039
37 . Momentum Ratio, Mo	5.88E-04	5.88E-04	5.88E-04
38 . Froude Number, Fr	2.64	2.64	14.15
39 . Buoyancy Ratio, Bo	4.56E-04	4.56E-04	1.59E-05
40 . Density Ratio, Lambda	0.5652	0.5652	0.5652
41 . Stack Reynolds Number (Exterior), d Uh / Nu a	2.27E+06	2.27E+06	1215
42 . Stack Flow Reynolds Number (Interior), Re s = d Ve / Nu s	9.54E+05	9.54E+05	1435
43 . Building Reynolds Number, Re b = Hb Ub / Nu a	3.84E+07	3.84E+07	20534
44 . Surface Reynolds Number, Zo s U* / Nu a	1.08E+04	1.08E+04	6
45 . Site Friction Velocity Ratio, U*/Uinf	0.048	0.048	0.048

Table A-4

Full and Model Scale Similarity Parameters

Anemometer Speed 11.0 (m/s)

Source Description: Exxon FCC COB

Dimensional Parameters	English Full-Scale	Full Scale	Model Scale
1 . Building Height, Hb (m)	175.2 ft	53.4	0.1335
2 . Base Elevation above Mean Sea Level, z = 0 (m)	947 ft	288.6	1524
3 . Stack Height above grade, h (m)	251.6 ft	76.7	0.1917
4 . Stack Inside Diameter, d (m)	9.7 ft	2.96	7.399E-03
5 . Stack Inside Area, Ae (m2)	74.1 ft2	6.9	4.300E-05
6 . Exit Velocity, Ve (m/s)	2460 fpm	12.5	2.432
7 . Exit Temperature, Ts (K)	435.0 F	497.0	293.2
8 . Volume Flow Rate, V (m3/s)	182,164 ft3/min	86.0	1.046E-04
9 . Emission rate, Q (g/s)	1133.9 lb/hr	142.9	NA
10 . Ambient Pressure, Pa (hPa)	0.97 Atm	979	844
11 . Ambient Temperature, Ta (K)	46.0 F	280.9	293.2
12 . Air Density, Rho a (kg/m3)	0.076 lb/ft3	1.2	1.004
13 . Exhaust Density, Rho s (kg/m3)	0.043 lb/ft3	0.7	0.567
14 . Air Viscosity, Nu a (m2/s)	1.56E-04 ft2/s	1.44E-05	1.81E-05
15 . Gas Viscosity, Nu s (m2/s)	4.17E-04 ft2/s	3.88E-05	1.72E-05
16 . Free Stream Wind Speed, Uinf (m/s)	49.5 mph	22.12	4.304
17 . Free Stream Height, Zinf (m)	1969 ft	600.00	1.50
18 . Reference Wind Speed, Uref (m/s)	46.0 mph	20.56	4.000
19 . Reference Height, Zref (m)	1312 ft	400.00	1.00
20 . Anemometer Wind Speed, Uanem (m/s)	24.6 mph	11.00	2.14
21 . Anemometer Height, Zanem (m)	25.0 ft	7.62	0.019
22 . Site Wind Speed, Usite (m/s)	22.5 mph	10.05	1.96
23 . 'Site Anemometer' Height, Zsite (m)	25.0 ft	7.62	0.019
24 . Stack Height Speed, Uh (m/s)	34.1 mph	15.25	2.97
25 . Building Height Speed, Ub (m/s)	32.0 mph	14.29	2.78
26 . Anemometer Surface Roughness Length, Zo a (m)	0.33 ft	0.10	2.50E-04
27 . Site Surface Roughness Length, Zo s (m)	0.66 ft	0.20	5.00E-04
28 . Site Surface Friction Velocity, U* (m/s)	2.39 mph	1.07	0.21
Dimensionless Parameters			
29 . Length Scale, SF	400	400	1
30 . Time Scale, TS	77.83	77.83	1.00
31 . Anemometer Power Law Exponent, na	0.16	0.160	0.16
32 . Site Power Law Exponent, ns	0.18	0.181	0.18
33 . Velocity Ratio, R = Ve/Ur	0.61	0.61	0.61
34 . Stack Velocity Ratio, Rs = Ve/Uh	0.82	0.82	0.82
35 . Stack Height to Building Height Ratio, h/Hb	1.44	1.44	1.44
36 . Diameter to Stack Height Ratio, d/h	0.039	0.039	0.039
37 . Momentum Ratio, Mo	3.11E-04	3.11E-04	3.11E-04
38 . Froude Number, Fr	2.64	2.64	10.29
39 . Buoyancy Ratio, Bo	1.75E-04	1.75E-04	1.16E-05
40 . Density Ratio, Lambda	0.5652	0.5652	0.5652
41 . Stack Reynolds Number (Exterior), d Uh / Nu a	3.12E+06	3.12E+06	1215
42 . Stack Flow Reynolds Number (Interior), Re s = d Ve / Nu s	9.54E+05	9.54E+05	1044
43 . Building Reynolds Number, Re b = Hb Ub / Nu a	5.28E+07	5.28E+07	20534
44 . Surface Reynolds Number, Zo s U* / Nu a	1.48E+04	1.48E+04	6
45 . Site Friction Velocity Ratio, U*/Uinf	0.048	0.048	0.048

APPENDIX B:

VIDEO TAPE ENCLOSURE

(Available upon request)

APPENDIX C:

FACILITIES DOCUMENTATION

(Atmospheric Dispersion Comparability, ADC, Tests)
(Facilities and Techniques)
(Quality Assurance Information)

Separate Enclosed Report Titled

ATMOSPHERIC DISPERSION COMPARABILITY TESTING DOCUMENTATION

(July 1995)

APPENDIX D:

SIP STACK HEIGHT FLUID MODELING AGREEMENT

ATTACHMENT 2
STACK HEIGHT FLUID MODELING AGREEMENT

Introduction and Background

Exxon Company U.S.A. operates a petroleum refinery located in Billings, Montana which contains several SO_2 sources as more particularly described in Exhibit A, Section 1, of the above mentioned Stipulation.

The dispersion modeling analysis performed by the Department (utilizing EPA approved dispersion models to determine appropriate control strategies for the refinery to ensure compliance with the NAAQS for SO_2) referenced in paragraph 6 of the Stipulation, demonstrated the presence of downwash associated with a stack and nearby structures at the refinery, namely the Fluid Catalytic Cracker CO boiler (FCC COB) stack. As a result, Exxon and the Department performed an analysis of Good Engineering Practice (GEP) stack height as provided in 40 CFR § 51.100 (ii) for the FCC COB stack. That analysis established a GEP formula height of 76.7 meters for the FCC COB stack, an increase of 33.3 meters in height over the existing stack. The GEP formula height determination was further supported by additional dispersion modeling analysis and documentation of this analysis was provided to EPA by the Department in August 1994.[1,2] EPA responded to the GEP determination on September 16, 1994 and indicated modeling credit for increases up to GEP formula heights for existing stacks would not be allowed under existing EPA regulations and policy unless supported by fluid modeling, field study, or public nuisance demonstrations. In an October 24, 1994, letter the Department also addressed the issue of [illegible] for the FCC COB stack. The Department's analysis showed that the state and federal stack height rules required a fluid model or field study to obtain GEP credit to the formula height.

While Exxon disputes the Department's and EPA's interpretation of the stack height regulations, it has nevertheless proposed and the Department agrees that a fluid modeling [illegible] pursuant to a detailed fluid modeling protocol that follows this agreement, and is approved by the Department and EPA, and that follows existing EPA fluid modelling guidelines can constitute a valid and sufficient demonstration in support of the GEP formula height of 76.7 meters for the FCC COB stack.

Unit Description

The FCC COB stack is located in the process block of the refinery known as the Fluid Catalytic Cracking Unit. The FCC COB stack is presently 43.4 meters tall with an inside stack diameter of 2.36 meters. The effluent is emitted at 12.5 m/s at about 457 °K. One of the nearby process structures which produces the downwash effects on the emitted plume is the FCC structure. The four solid components imbedded in the lattice framework of the process unit are the elevator (3.2 m by 6 m by 49.2 m), the regenerator (7.6 m in diameter and 30 m high), the reactor (6.1 m diameter and 53.4 m high), and the fractionator (5.2 m in diameter and 45.3 m high). These structures were used

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1 Coefield, J., Exxon FCC-COB Stack Height Credit, Office Memoranda, Montana Department of Health and Environmental Sciences, Air Quality Division, Helena, MT, August 15, 1994.

2 Letter from Jeffrey T. Chaffee, Acting Division Administrator, Montana Department of Health and Environmental Sciences, Air Quality Division, to Douglas M. Skie, Chief, Air Programs Branch U.S. EPA, Region VIII, Denver, CO, August 17, 1994, with Coefield Memoranda, supra, fn. 1, attached.

ATTACHMENT 2
STACK HEIGHT FLUID MODELING AGREEMENT

Introduction and Background

Exxon Company U.S.A. operates a petroleum refinery located in Billings, Montana which contains several SO_2 sources as more particularly described in Exhibit A, Section 1, of the above mentioned Stipulation.

The dispersion modeling analysis performed by the Department (utilizing EPA approved dispersion models to determine appropriate control strategies for the refinery to ensure compliance with the NAAQS for SO_2) referenced in paragraph 6 of the Stipulation, demonstrated the presence of downwash associated with a stack and nearby structures at the refinery, namely the Fluid Catalytic Cracker CO boiler (FCC COB) stack. As a result, Exxon and the Department performed an analysis of Good Engineering Practice (GEP) stack height as provided in 40 CFR § 51.100 (ii) for the FCC COB stack. That analysis established a GEP formula height of 76.7 meters for the FCC COB stack, an increase of 13.3 meters in height over the existing stack. The GEP formula height determination was further supported by additional dispersion modeling analysis and documentation of this analysis was provided to EPA by the Department in August 1994.[1,2] EPA responded to the GEP determination on September 16, 1994 and indicated modeling credit for increases up to GEP formula heights for existing stacks would not be allowed under existing EPA regulations and policy unless supported by fluid modeling, field study, or public nuisance demonstrations. In an October 24, 1994, letter the Department also addressed the issue of stack height credit for the FCC COB stack. The Department's analysis showed that the state and federal stack height rules required a fluid model or field study to obtain GEP credit to the formula height.

While Exxon disputes the Department's and EPA's interpretation of the stack height regulations, it has nevertheless proposed and the Department agrees that a fluid modeling study conducted pursuant to a detailed fluid modeling protocol that follows this agreement, and is approved by the Department and EPA, and that follows existing EPA fluid modelling guidelines can constitute a valid and sufficient demonstration in support of the GEP formula height of 76.7 meters for the FCC COB stack.

Unit Description

The FCC COB stack is located in the process block of the refinery known as the Fluid Catalytic Cracking Unit. The FCC COB stack is presently 63.4 meters tall with an inside stack diameter of 2.96 meters. The effluent is emitted at 12.5 m/s at about 497 °K. One of the nearby process structures which produces the downwash effects on the emitted plume is the FCC structure. The four solid components imbedded in the lattice framework of the process unit are the elevator (3.2 m by 5 m by 49.2 m), the regenerator (7.6 m in diameter and 30 m high), the reactor (6.1 m diameter and 53.4 m high), and the fractionator (3.2 m in diameter and 45.3 m high). These structures were used

[1] Coefield, J., Exxon FCC-COB Stack Height Credit, Office Memoranda, Montana Department of Health and Environmental Sciences, Air Quality Division, Helena, MT, August 15, 1994.

[2] Letter from Jeffrey T. Chaffee, Acting Division Administrator, Montana Department of Health and Environmental Sciences, Air Quality Division, to Douglas M. Skie, Chief, Air Programs Branch U.S. EPA, Region VIII, Denver, CO, August 17, 1994, with Coefield Memoranda, supra, fn. 1, attached.

to establish the GEP formula height of 76.7 meters pursuant to 40 CFR § 51.100(ii)(2)(ii).

Wind Tunnel Test Methodology

Exxon shall construct a scale model of the FCC structures (the lattice framework and associated solid components, including process piping), the FCC COB stack and other nearby structures, as specified in the detailed fluid modeling protocol, in the fluid modeling facility (i.e., wind tunnel) to demonstrate that the GEP formula height of 76.7 meters is justified. Justification shall be deemed demonstrated by wind tunnel tests which demonstrate (1) the presence of ground level concentrations at certain locations which are at least 40% in excess of maximum concentrations experienced in the absence of FCC COB downwash effects; and (2) at the same locations, FCC COB emissions contribute to a total concentration from all sources that is greater than NAAQS for SO_2 as established by dispersion modeling.

The wind tunnel testing procedure shall be consistent with the following general requirements:

1. The emission rate for the FCC COB stack shall be the existing SIP limits (prior to December 16, 1994) as established in the E.H. Pechan & Associates, Inc. report dated February 1991 and set forth in Table 1 of said report.[3]

2. The representative area surrounding the FCC unit structure shall be simulated in the wind tunnel by appropriate surface roughness elements.

3. Representative meteorological conditions will be used consistent with procedures in EPA's Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height.

4. The 40% differential in ground level concentrations due in whole or in part to downwash effects shall be determined by comparing the respective ground level concentrations produced by (1) running the wind tunnel simulation using scale models of both the FCC COB stack structure and its associated surrounding structures; and (2) running the simulation using scale models of the FCC COB stack alone.

5. Contribution to an exceedance of the NAAQS for SO_2 shall be determined by comparing the concentrations produced by the FCC COB wind tunnel simulation with the background concentrations of all other sources as established by dispersion modeling analysis using the existing SIP limits for all other sources as established in the Pechan report (prior to December 16, 1994).

If the results of the wind tunnel simulations indicate that the GEP formula derived height of 76.7 meters for the FCC COB stack is inadequate to eliminate excessive concentrations due to downwash, then Exxon may run additional simulations. The purpose of additional simulations would be to determine the increase above formula height required to eliminate such concentrations. GEP demonstrations for "above formula" stack heights must meet the more stringent requirements contained in 40 CFR § 51.100(kk)(1).

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[3] "Development of a Sulfur Dioxide Emissions Inventory for Billings and Laurel Montana -- Volume 1, Project Summary EPA Contract No. 68-02-4400, Work Assignment No. 53, Final Report, February 1991. E.H. Pechan & Associates, Inc. 3514 University Drive, Durham, NC 27707.

At the conclusion of the simulations, Exxon shall prepare a technical report of the fluid modeling results and submit it to the Department. The report shall contain an analysis, accompanied by any necessary dispersion modeling, of the effect on, or any proposed changes to, the emission limitations established in the Stipulation Requirements (Exhibit A, Section 3(A)). To the extent that the fluid modeling study completed by Exxon (according to the approved protocol) demonstrates that Exxon is entitled to credit for increasing the FCC COB stack height the emission limitations established in the Stipulation Requirements (Exhibit A, Section 3(A)) shall be modified as per (Part B, BINDING EFFECT, Item ~~14~~20) consistent with the results of the fluid modeling report, provided that Exxon has also demonstrated through appropriate dispersion modeling that any change in those limitations will assure attainment and maintenance of the primary and secondary SO_2 NAAQS.