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

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ATMOSPHERIC DISPERSION COMPARABILITY TESTING DOCUMENTATION

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for

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FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

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1 INTRODUCTION

This document summarizes wind tunnel atmospheric dispersion comparability test (ADCT) results as stipulated in "Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Height" (EPA-450/4-81-003, July, 1981), hence forth this document is referred to as EPA-FM-GEP Guideline. The EPA-FM-GEP Guideline 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. The EPA-FM-GEP Guideline outlines in detail the testing requirements for this comparability demonstration.

These wind tunnel simulations are in support of 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. The report "Wind Tunnel Good Engineering Stack Height Study of the FCC Stack at the Billings Refinery - Study Protocol" by D. E. Neff (June 1995) specifies all fluid modeling study design criteria and testing parameters. Specifically related to the ADCT testing program in protocol report are Tables 4, 5 and 6 which are reproduced here as Table 1, Table 2 and Table 3. Table 1, Atmospheric Dispersion Comparability Test Parameters, lists the different prototype and model parameter values for this atmospheric dispersion comparability test program. Table 2, ADCT Field Test Conditions, details the field conditions for each type of data test performed in this test series. Table 3, ADCT Model Test Conditions, details the model conditions for each type of data test performed in this test series. These tables will be discussed more throughly in the following sections.

2 ATMOSPHERIC DISPERSION COMPARABILITY TEST SPECIFICATIONS

2.1 Overview of EPA Guideline Requirements

The EPA-FM-GEP Guideline 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. The EPA-FM-GEP Guideline similarity requirements for these atmospheric dispersion comparability tests (ADCT) are summarized below:

(1) All ADCT length scaling (stack height, study area distances, boundary layer height and roughness length, etc.) should be at the same ratio, 1:400, as for the GEP model tests,

(2) The ADCT flow velocity should match the GEP model design flow velocity at the proposed stack height; i.e., 267 cm/s at 16.3cm (65m/400),

(3) The ADCT stack is to be the field equivalent of 100 meters high with an inside diameter of 5 meters and is placed at the same location within the test facility as the GEP stack tests,

(4) The ADCT wind boundary layer is represented by a characteristic roughness length, z_o, of less than 0.2 meters,

(5) The ADCT stack gas exit velocity is to be 1.5 times the ADCT wind speed at the stack top.

The EPA-FM-GEP Guideline requires that the following ADCT data be acquired and documented:

(6) Vertical profiles of mean velocity, longitudinal turbulent intensity, vertical turbulent intensity and Reynolds stress at the stack location, at the end of the planned study area (prototype 2 km downwind) and midway between these two locations,

(7) Lateral profiles of mean velocity and longitudinal turbulent intensity at three elevations (prototype 25 m, 45.7m, 100 m) near the stack and at three elevations (prototype 25 m, 45.7m, 100 m) at the end of the study area (prototype 2 km downwind),

(8) Vertical and lateral mean concentration profiles through the plume centerline at quarter intervals between the stack and the end of study area (prototype 0.5 km, 1.0 km and 1.5 km),

(9) Ground level longitudinal concentration profile through the ground level plume centerline with lateral points verifying location of ground level plume centerline.

The EPA-FM-GEP Guideline requires that the following ADCT data be analyzed:

(10) The velocity profiles are to be regressed upon to determine their power law index, roughness length, and friction velocity. These values are to be compared to the expected atmospheric values for this site.

(11) The concentration data are to be converted to the equivalent field values of $\chi U_H/Q$ [m^{-2}] and compared to estimates from the Pasquill-Gifford diffusion categories C and D (H = 100m).

(12) The measured model plume rise is to be compared to estimates from the EPA-FM-GEP Guidelines suggested model.

2.2 Similarity Criteria Compliance

The ADCT model scale and flow velocity were set to equal that of the site model test program, i.e. model scale of 1:400 and U_s = 267 cm/s (where s = 65m/400 =16.3cm). The ADCT boundary layer roughness length, z_o ~ 0.2 meters, is the same as the GEP test program. The model stack represents a field stack of 100 m height and 5 m inside diameter, i.e. 25 cm high with I.D. = 1.25 cm. This stack was placed at the same location in the wind tunnel as that used in the main test program. A neutrally buoyant stack gas (100% ethane) was released at a flow rate such that the exhaust velocity was 1.5 times the mean velocity at the stack top. Table 1, Atmospheric Dispersion Comparability Test Parameters, lists the different prototype and model parameter values for this atmospheric dispersion comparability test program. This table shows that all of the required Guideline similarity criteria are satisfied.

3 ATMOSPHERIC DISPERSION COMPARABILITY TEST RESULTS

3.1 Wind Profile Measurements

The field scale specifications for the EPA-FM-GEP ADCT velocity profile requirements are listed in Table 2. The model scale specifications are listed in Table 3. The lateral profiles were determined from abbreviated vertical velocity profiles at each of the required test positions and thus no run numbers and file names are included in this portion of these tables. Table 4 presents model, normalized, and field values of the average of the three tunnel centerline wind profiles, one at the stack location (X_m = 0 cm), one at the end of the study area (X_m = 500 cm), and one at half way between these two (X_m = 250 cm).

The averaged profile, mentioned in the previous paragraph, was 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 top graph in Figure 1 displays the test data as symbols and the design power law curve (index = 0.18, see Table 1) as a line. This graph shows that the model profile is representative of the field design power law index value of 0.18. The middle graph in Figure 1 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 0.2 meters, friction velocity equal to 1.25 meters/second, and a displacement height of 0.0 meters. The bottom graph in Figure 1 displays the longitudinal turbulent intensity profile test data and the EPA-FM-GEP suggested design curve. The EPA-FM-GEP 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.

Table 5 through Table 7 present model, normalized and field values of the three tunnel centerline wind profiles, one at the stack location (X_m = 0 cm), one at the end of the study area (X_m = 500 cm), and one at half way between these two (X_m = 250 cm). The field values of mean velocity, longitudinal, and vertical turbulent intensity for all three locations are presented in the graphs in Figure 2. The consistency in profile shape between these three measurement locations is demonstrated.

Vertical velocity profiles of four heights each (Z_f = 10, 25, 43.7, 100 meters) were taken at six different crosswind positions ($Y_f = \pm 360, \pm 240, \pm 120$ meters) and two different downwind positions ($X_f = 0$, 2000 meters) to test the flow uniformity of the wind tunnel. These mean velocity and turbulent intensity data along with the appropriate height data from the tunnel centerline velocity profiles ($Y_f = 0$ meters) are presented in Table 8. Graphs of the lateral mean velocity and lateral turbulent intensity profiles for both downwind distances and for the heights of 6.3 cm model (43.7 meters field) and 25 cm model (100 meters field) are presented in Figure 3. Here again it is seen that the wind tunnel uniformity is within the bounds of acceptability.

3.2 Stack Plume Visualization

Visualization of the atmospheric dispersion comparability stack plume was documented on the video cassette VHS tape and included with this report in Appendix A. The specifications for this test is listed in Table 2 for field conditions and Table 3 for model conditions. The camera position for this film sequence was directly outside the wind tunnel from the model stack at a height slightly above model ground level. The film test observes the plume trajectories from the model stack down to the end of the model turntable, approximately 730 meters field equivalent distance, and zooms in on the stack to document downwash and near stack plume rise characteristics.

The EPA-FM-GEP Guideline states that for the conditions of this test there should be little stack downwash and low plume rise. The ADCT plume visualization shows that the model plume had little stack downwash and low plume rise.

3.3 Concentration Measurements

The specifications for these tests are listed in Table 2 for field conditions and Table 3 for model conditions. Seven concentration profiles of the test plume were measured, lateral and vertical profiles at field downwind distances of 500, 1000, and 1500 meters and a ground level profile with additional off-centerline line points. Table 9 through Table 15 lists for each of these concentration profiles field and model sample positions, measured model concentrations in both ppm, χ, and normalized model concentrations, $K_m = \chi U_m / Q_m$ [cm^{-2}], the equivalent field normalized concentration, K_f, and Pasquill-Gifford estimates of K_f for both dispersion categories C and D. Figure 4 through Figure 10 display plots of each concentration profile for the measured test data converted to field equivalent normalized concentrations and the Pasquill-Gifford dispersion estimates for both stability categories C and D.

The EPA-FM-GEP Guideline desires that the ADCT plume be representative of plume dispersion between Pasquill-Gifford dispersion categories C and D and it requires that the ADCT plume not be more stable then estimates based on dispersion category D. Observation of the test data with respect to the PG dispersion estimates for categories C and D in Figure 4 through Figure 10 for the vertical and lateral plume centerline profiles out to 1500 meters shows that the test plume meets the EPA requirements. The test data ground level concentration profile shown in Figure 10 stays between dispersion classes C and D out to 1500 meters. At distances greater than 1500 meters the test data display greater ground level concentrations than dispersion class C indicates and much greater than dispersion class D indicates. The increased model ground level concentrations at distances greater than 1500 meters is due to the model boundary layer being rougher ($z_o \sim 20$ cm) than the PG open plume classifications ($z_o \sim 3$ cm). This behavior of being outside of the specification on the unstable side is considered "not critical" in the EPA-FM-GEP Guideline. Figure 11 displays the dispersion parameters, σ_y and σ_z, calculated from a fit of the model data with the Pasquill-Gifford dispersion equation. This fit also yielded an effective plume height of 110 meters at each of the three model profile locations.

4 INSTRUMENTATION AND MEASUREMENT METHODOLOGY

4.1 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 D. 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 ~11 meters into the test section. This placement permits convenient changing of wind directions, provide sufficient upwind fetch, and provide a sufficient downwind measurement zone. The zones upwind and downwind of the turntable area were modeled with a generic roughness design to create the desired model boundary layer.

4.2 Velocity Measurements

The techniques employed in the acquisition of velocity profiles are discussed in detail in Appendix D 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 variation of mean wind speed with height above the ground (referred to as the boundary layer) at the study site is deduced from empirical equations known to correlate atmospheric data. The EPA-FM-GEP Guideline states that for heights up 100 meters the log-linear velocity profile relationship be used:

$U/u_* = 2.5*\ln[(z-d)/z_o]$; where

u_* ≡ friction velocity,

d ≡ displacement height,

z_o ≡ roughness length.

Table 1 in the EPA-FM-GEP Guideline lists suggested values of the roughness length for various types of ground cover. The displacement height is estimated from Equation 6 in the

EPA-FM-GEP Guideline: $d = H - z_o/2.5$; where H = the general roof-top level.

The mean velocity through the entire depth of the boundary layer (which the Guideline states to be 600 meters) is represented by the power law equation:

$U/U_\infty = (z/\delta)^p$; where

$U \equiv$ mean wind speed at height z,

$U_\infty \equiv$ wind speed at boundary layer height δ,

$\delta \equiv$ boundary layer height = 600 meters

$p \equiv$ power law index.

The EPA-FM-GEP Guideline suggests that the power law index be estimated from the equation

$p = 0.24 + 0.096 * \log_{10}(z_o) + 0.016 * [\log_{10}(z_o)]^2$

Velocity measurements obtained in this study are summarized and presented through plots of vertical profiles of mean velocity, longitudinal and vertical turbulence intensity, and Reynolds stress. The height and velocity coordinates are normalized by a model reference height and the model velocity at the reference height. Since a neutral boundary layer's velocity is invariant with respect to wind speed, the normalized profiles can be converted to any field velocity at a specific height by the appropriate multiplicative constant. Each of the vertical profiles of mean velocity are plotted on linear-linear and log-linear paper to display the best fit regressions.

4.3 Plume Visualization Techniques

Techniques employed to obtain a visible plume are discussed in Appendix D. A Smoke Generator System and a Video Camera System are used for plume visualization. Given a field to model wind speed ratio of 6.075 (= [16.1 m/s]/[2.65 m/s]) and a model to field length scale ratio of 400, then the time scale ratio between the model and the field is 1:58.8. Thus phenomena observed over the model in the wind tunnel will occur 65.8 times faster than observed at full scale. If the TV tapes were replayed in slow motion (65.8 times slower than the recorded speed) the observed plume trajectories and motions would appear realistic.

4.4 Concentration Measurements

Techniques employed to obtain the concentration data are discussed in Appendix D. A gas chromatograph with flame ionization detector is used to measure gas concentrations. Figure

5 in Appendix D shows a schematic of stack gas release, sampling, and analyzing methodology.

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.

4.5 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 four mass flow channels with full scale responses of 0.1, 1, 10, 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 (~630 mmHg at CSU) must also be accounted for in these calculations.

During a visual plume test the proper plume flow rate and specific gravity would be attained by mixing metered quantities of Air (SG = 1) and Helium (SG = 0.14) or Argon (SG = 1.38). 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 16 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.

REFERENCES

Following is a list of reference materials related to this study. This list is not meant to be all inclusive.

1. EPA, Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height. EPA-450/4-81-003, U.S. Environmental Protection Agency, Research Triangle Park, NC, July, 1981.

2. EPA, Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document For the Stack Height Regulations (revised). EPA-450/4-80-023R, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1985.

3. EPA, Determination of Good Engineering Practice Stack Height - A Fluid Model Demonstration Study for a Power Plant. EPA/600/3-85/022, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1983.

4. EPA, Fluid Model Demonstration of Good Engineering Practice Stack Height in Complex Terrain. EPA/600/3-85/022, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1985.

5. Snyder, W.H., "Guideline for Fluid Modeling of Atmospheric Diffusion", EPA-600/8-8cl-009. U.S. Environmental Protection Agency, Research Triangle Park, NC, 1981.

6. Turner, D. B.,"Workbook of Atmospheric Dispersion Estimates, 2nd Edition" CRC Press, Inc., 2000 Corporate Blvd., Boca Raton, Florida, ISBN 1-56670-023-X, 1994.

TABLES

SCALE =	Full	Units	400	Units
SELECTED HEIGHT DIMENSIONS				
Airport Wind Instr. Height =	7.6	m	1.9	cm
Ref Height 10 m =	10.0	m	2.5	cm
Base Case Stack Height =	65.0	m	16.3	cm
ADCT Stack Height =	100.0	m	25.0	cm
Boundary Layer Height =	600.0	m	150.0	cm
SELECTED DISTANCE DIMENSIONS				
Distance to 0.5 km downwind =	500.0	m	125.0	cm
Distance to 1.0 km downwind =	1000.0	m	250.0	cm
Distance to 1.5 km downwind =	1500.0	m	375.0	cm
Distance to 2.0 km downwind =	2000.0	m	500.0	cm
APPROACH FLOW CHARACTERISTICS				
Roughness Length < or = to 0.2m	0.20	m	0.050	cm
Power Law Index =	0.18		0.18	
Friction Velocity =	1.18	m/s	19.4	cm/s
Max. Design Wind Speed @ airport =	11.0	m/s	180.8	cm/s
Wind Speed @ 10m =	11.6	m/s	190.0	cm/s
Wind Speed @ Base Case Stack =	16.2	m/s	266.5	cm/s
Wind Speed @ ADCT Stack =	17.5	m/s	288.0	cm/s
Wind Speed @ BL =	24.2	m/s	398.2	cm/s
ADCT STACK FLOW CHARACTERISTICS				
Stack I.D. =	5.00	m	1.25	cm
Stack Exit Velocity =	26.3	m/s	432.1	cm/s
Stack Flow Rate =	516.1	m^3/s	530.2	ccs
Stack gas Temp. =	20.0	C	20.0	C
Ambient Temp. =	20.0	C	20.0	C
Stack Gas Equivalent MW =	29.0		29.0	
DIMENSIONLESS PARAMETERS				
Roughness RE # =	158		6.5	
ADCT Stack RE # =	87623		3601	
ADCT W/U velocity ratio =	1.50		1.50	
ADCT Stack Gas Specific Gravity =	1.000		1.000	

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Table 1 Atmospheric Dispersion Comparability Test Parameters

Measurement Type	Model Config	Stack Config	Building Config	Wind Dir. (deg)	Ref. Velocity (m/s)	Ref. Height (m)	Stack Height (m)	Effluent Velocity (m/s)	Position X (m)	Position Y (m)	Position Z (m)
ADCT Series											
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			0	Profile	25.0
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			0	Profile	45.7
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			0	Profile	100.0
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			2000	Profile	25.0
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			2000	Profile	45.7
Vel. Lateral Profile U,u'	Generic	Out	No		17.5	100.0			2000	Profile	100.0
Vel. Vertical Profile U,u',w',uw	Generic	Out	No		17.5	100.0			0	0	Profile
Vel. Vertical Profile U,u',w',uw	Generic	Out	No		17.5	100.0			1000	0	Profile
Vel. Vertical Profile U,u',w',uw	Generic	Out	No		17.5	100.0			2000	0	Profile
Visualization of Plume Elevation	Generic	In	No		17.5	100.0	100.0	26.3	Profile	0	Profile
Concentration Vertical Profile	Generic	In	No		17.5	100.0	100.0	26.3	500	0	Profile
Concentration Vertical Profile	Generic	In	No		17.5	100.0	100.0	26.3	1000	0	Profile
Concentration Vertical Profile	Generic	In	No		17.5	100.0	100.0	26.3	1500	0	Profile
Concentration Lateral Profile	Generic	In	No		17.5	100.0	100.0	26.3	500	Profile	H_{eff}
Concentration Lateral Profile	Generic	In	No		17.5	100.0	100.0	26.3	1000	Profile	H_{eff}
Concentration Lateral Profile	Generic	In	No		17.5	100.0	100.0	26.3	1500	Profile	H_{eff}
Conc. Ground Level Profile	Generic	In	No		17.5	100.0	100.0	26.3	Profile	Profile	0.0

Table 2 Field Test Conditions

Measurement Type	Model Config	Stack Config	Building Config	Wind Dir. (deg)	Reference Velocity (cm/s)	Reference Height (cm)	Stack Height (cm)	Effluent Velocity (cm/s)	Position X (cm)	Y (cm)	Z (cm)
ADCT Series											
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			0	Profile	6.3
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			0	Profile	11.4
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			0	Profile	25.0
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			500	Profile	6.3
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			500	Profile	11.4
Vel. Lateral Profile U,u'	Generic	Out	No	-	288.0	25.0			500	Profile	25.0
Vel. Vertical Profile U,u',w',uw	Generic	Out	No	-	288.0	25.0			0	0	Profile
Vel. Vertical Profile U,u',w',uw	Generic	Out	No	-	288.0	25.0			250	0	Profile
Vel. Vertical Profile U,u',w',uw	Generic	Out	No	-	288.0	25.0			500	0	Profile
Visualization of Plume Elevation	Generic	In	No	-	288.0	25.0	25.0	432.1	Profile	0	Profile
Concentration Vertical Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	125	0	Profile
Concentration Vertical Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	250	0	Profile
Concentration Vertical Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	375	0	Profile
Concentration Lateral Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	125	Profile	H_{eff}
Concentration Lateral Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	250	Profile	H_{eff}
Concentration Lateral Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	375	Profile	H_{eff}
Conc. Ground Level Profile	Generic	In	No	-	288.0	25.0	25.0	432.1	Profile	Profile	0.0

Table 3 Model Test Conditions

Billings Project - ADCT Centerline Velocity and Turbulence Profiles

Average of 0, 1 and 2 km Profiles

Run No. =	Average of 43, 44, 45				Location =		(avg,0,Z)							
FIELD VALUES					NORMALIZED VALUES					MODEL VALUES				
Height (m)	Velocity (m/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height	Velocity	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height (cm)	Velocity (cm/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres $(cm/s)^2$
0.2														
4.0	9.7	26.5	13.1	0.62	0.088	0.570	26.5	13.1	0.62	1.0	142.4	26.5	13.1	-210.5
10.0	12.7	20.7	10.7	0.60	0.219	0.747	20.7	10.7	0.60	2.5	186.7	20.7	10.7	-202.6
16.0	13.9	19.4	10.0	0.59	0.350	0.820	19.4	10.0	0.59	4.0	204.9	19.4	10.0	-200.6
25.0	15.4	16.8	9.7	0.64	0.547	0.903	16.8	9.7	0.64	6.3	225.9	16.8	9.7	-217.4
30.0	15.8	16.1	9.1	0.57	0.656	0.931	16.1	9.1	0.57	7.5	232.8	16.1	9.1	-193.3
45.7	16.9	14.7	9.2	0.66	1.000	0.992	14.7	9.2	0.66	11.4	248.0	14.7	9.2	-225.0
60.0	17.7	13.0	8.7	0.58	1.313	1.043	13.0	8.7	0.58	15.0	260.7	13.0	8.7	-195.0
80.0	18.4	12.2	8.8	0.61	1.751	1.084	12.2	8.8	0.61	20.0	271.1	12.2	8.8	-206.4
100.0	19.2	11.2	8.6	0.62	2.188	1.127	11.2	8.6	0.62	25.0	281.6	11.2	8.6	-211.0
140.0	19.9	10.9	8.5	0.63	3.063	1.171	10.9	8.5	0.63	35.0	292.7	10.9	8.5	-211.7
200.0	21.4	9.9	8.0	0.67	4.376	1.259	9.9	8.0	0.67	50.0	314.6	9.9	8.0	-226.9
300.0	23.7	8.2	7.1	0.58	6.565	1.394	8.2	7.1	0.58	75.0	348.4	8.2	7.1	-195.6
400.0	26.0	7.0	6.3	0.58	8.753	1.528	7.0	6.3	0.58	100.0	381.9	7.0	6.3	-196.0
500.0	27.6	5.5	5.3	0.32	10.941	1.624	5.5	5.3	0.32	125.0	406.0	5.5	5.3	-109.0
References										References				
45.7	17.0			1.25					18.4	11.4	250.0			250.0
Roughness Length (m) =				0.20						Roughness Length (cm) =				0.05
Displacement Height (m) =				0.00						Displacement Height (cm) =				0.00
Friction Velocity (m/s) =				1.25						Friction Velocity (cm/s) =				18.40
Power Law Index =				0.18						Power Law Index =				0.18

Table 4 ADCT Reference Velocity and Turbulence Profiles

Billings Project - ADCT Centerline Velocity and Turbulence Profiles

0 km Profile

Run No. =	43				Location =		(0,0,Z)							
FIELD VALUES					NORMALIZED VALUES					MODEL VALUES				
Height (m)	Velocity (m/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height	Velocity	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height (cm)	Velocity (cm/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres $(cm/s)^2$
0.0														
4.0	9.3	27.2	13.5	0.66	0.088	0.547	27.2	13.5	0.66	1.0	136.7	27.2	13.5	-223.9
10.0	13.0	20.1	10.7	0.64	0.219	0.764	20.1	10.7	0.64	2.5	191.0	20.1	10.7	-217.9
16.0	13.9	19.1	10.1	0.65	0.350	0.815	19.1	10.1	0.65	4.0	203.8	19.1	10.1	-220.5
25.0	15.4	16.5	9.7	0.66	0.547	0.908	16.5	9.7	0.66	6.3	227.1	16.5	9.7	-224.5
30.0	15.8	15.6	9.3	0.54	0.656	0.927	15.6	9.3	0.54	7.5	231.7	15.6	9.3	-183.7
45.7	16.6	14.8	9.8	0.65	1.000	0.975	14.8	9.8	0.65	11.4	243.8	14.8	9.8	-220.5
60.0	17.7	12.3	9.2	0.57	1.313	1.039	12.3	9.2	0.57	15.0	259.8	12.3	9.2	-193.4
80.0	18.2	11.6	8.9	0.49	1.751	1.071	11.6	8.9	0.49	20.0	267.7	11.6	8.9	-165.3
100.0	19.2	10.4	8.5	0.40	2.188	1.130	10.4	8.5	0.40	25.0	282.6	10.4	8.5	-134.8
140.0	19.6	10.8	9.0	0.52	3.063	1.154	10.8	9.0	0.52	35.0	288.4	10.8	9.0	-177.6
200.0	21.2	9.8	8.2	0.56	4.376	1.248	9.8	8.2	0.56	50.0	311.9	9.8	8.2	-190.8
300.0	23.0	7.9	7.4	0.46	6.565	1.354	7.9	7.4	0.46	75.0	338.5	7.9	7.4	-155.9
400.0	25.4	7.1	6.7	0.58	8.753	1.494	7.1	6.7	0.58	100.0	373.6	7.1	6.7	-195.1
500.0	27.3	5.6	5.9	0.22	10.941	1.606	5.6	5.9	0.22	125.0	401.5	5.6	5.9	-76.0
References										References				
45.7	17.0			1.25					18.4	11.4	250.0			250.0

Table 5 Downwind (0 km) Velocity and Turbulence Profile Data

Billings Project - ADCT Centerline Velocity and Turbulence Profiles

1 km Profile

Run No. =	44				Location =	(1000,0,Z)								
FIELD VALUES					NORMALIZED VALUES					MODEL VALUES				
Height (m)	Velocity (m/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height	Velocity	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height (cm)	Velocity (cm/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres $(cm/s)^2$
0.0														
0.0	9.9	26.5	12.6	0.56	0.000	0.581	26.5	12.6	0.56		145.2	26.5	12.6	-188.9
10.0	12.5	20.8	10.7	0.57	0.219	0.738	20.8	10.7	0.57	2.5	184.4	20.8	10.7	-193.9
16.0	13.9	19.6	10.4	0.61	0.350	0.815	19.6	10.4	0.61	4.0	203.8	19.6	10.4	-208.1
25.0	15.3	17.3	9.6	0.69	0.547	0.900	17.3	9.6	0.69	6.3	224.9	17.3	9.6	-232.0
30.0	15.5	16.6	9.4	0.63	0.656	0.910	16.6	9.4	0.63	7.5	227.6	16.6	9.4	-212.7
45.7	16.6	15.1	9.0	0.64	1.000	0.976	15.1	9.0	0.64	11.4	244.0	15.1	9.0	-215.1
60.0	17.5	13.6	8.7	0.56	1.313	1.032	13.6	8.7	0.56	15.0	258.0	13.6	8.7	-190.0
80.0	18.3	12.6	9.0	0.72	1.751	1.077	12.6	9.0	0.72	20.0	269.3	12.6	9.0	-242.7
100.0	19.2	11.7	8.6	0.77	2.188	1.130	11.7	8.6	0.77	25.0	282.6	11.7	8.6	-260.4
140.0	19.6	11.3	8.5	0.66	3.063	1.154	11.3	8.5	0.66	35.0	288.6	11.3	8.5	-224.6
200.0	21.2	10.0	8.0	0.60	4.376	1.248	10.0	8.0	0.60	50.0	312.0	10.0	8.0	-201.6
300.0	23.7	8.2	7.0	0.63	6.565	1.394	8.2	7.0	0.63	75.0	348.5	8.2	7.0	-213.1
400.0	25.9	7.3	6.2	0.56	8.753	1.521	7.3	6.2	0.56	100.0	380.3	7.3	6.2	-190.7
500.0	27.6	5.4	5.1	0.31	10.941	1.625	5.4	5.1	0.31	125.0	406.3	5.4	5.1	-106.3
References										References				
45.7	17.0			1.25					18.4	11.4	250.0			250.0

Table 6 Downwind (1 km) Velocity and Turbulence Profile Data

Billings Project - ADCT Centerline Velocity and Turbulence Profiles

2 km Profile

Run No. =	45				Location =	(2000,0,Z)								
FIELD VALUES					NORMALIZED VALUES					MODEL VALUES				
Height (m)	Velocity (m/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height	Velocity	Long. T.I. (%)	Vert. T.I. (%)	Re Stres	Height (cm)	Velocity (cm/s)	Long. T.I. (%)	Vert. T.I. (%)	Re Stres (cm/s)^2
0.0														
0.0	9.9	25.9	13.0	0.65	0.000	0.582	25.9	13.0	0.65		145.4	25.9	13.0	-218.6
10.0	12.6	21.2	10.7	0.58	0.219	0.739	21.2	10.7	0.58	2.5	184.7	21.2	10.7	-195.9
16.0	14.1	19.6	9.6	0.51	0.350	0.829	19.6	9.6	0.51	4.0	207.2	19.6	9.6	-173.1
25.0	15.3	16.4	9.6	0.58	0.547	0.902	16.4	9.6	0.58	6.3	225.6	16.4	9.6	-195.6
30.0	16.3	16.1	8.7	0.54	0.656	0.956	16.1	8.7	0.54	7.5	239.0	16.1	8.7	-183.6
45.7	17.4	14.3	8.9	0.71	1.000	1.025	14.3	8.9	0.71	11.4	256.2	14.3	8.9	-239.5
60.0	18.0	13.0	8.2	0.60	1.313	1.058	13.0	8.2	0.60	15.0	264.4	13.0	8.2	-201.5
80.0	18.8	12.3	8.6	0.62	1.751	1.105	12.3	8.6	0.62	20.0	276.3	12.3	8.6	-211.3
100.0	19.0	11.6	8.6	0.70	2.188	1.119	11.6	8.6	0.70	25.0	279.7	11.6	8.6	-237.7
140.0	20.5	10.7	8.1	0.69	3.063	1.204	10.7	8.1	0.69	35.0	301.0	10.7	8.1	-232.8
200.0	21.8	10.1	7.8	0.85	4.376	1.280	10.1	7.8	0.85	50.0	320.0	10.1	7.8	-288.4
300.0	24.4	8.4	6.8	0.64	6.565	1.433	8.4	6.8	0.64	75.0	358.2	8.4	6.8	-217.7
400.0	26.7	6.6	6.1	0.60	8.753	1.568	6.6	6.1	0.60	100.0	392.0	6.6	6.1	-202.2
500.0	27.9	5.4	5.0	0.43	10.941	1.641	5.4	5.0	0.43	125.0	410.4	5.4	5.0	-144.8
References										References				
45.7	17.0			1.25					18.4	11.4	250.0			250.0

Table 7 Downwind (2 km) Velocity and Turbulence Profile Data

Fluid Dynamics and Diffusion Laboratory - Colorado State University
Wind Engineering Research and Application Specialists

Billings Project - ADCT Lateral Velocity and Turbulence Profiles

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

	Y (cm)							
Z (cm)	-90	-60	-30	0	30	60	90	Avg. Values
2.5	191	180	199	191	189	184	200	*193.5*
6.3	258	235	235	227	237	241	216	***236.4***
11.4	270	241	257	244	242	267	255	*256.3*
25.0	286	280	266	283	278	272	273	*283.7*
Run#=	54	53	52	43	55	56	57	

Normalized Mean Wind at X = 0 cm (Uref = 236.4 cm/s)

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	0.81	0.76	0.84	0.81	0.80	0.78	0.85
6.3	1.09	0.99	0.99	0.96	1.00	1.02	0.91
11.4	1.14	1.02	1.09	1.03	1.02	1.13	1.08
25.0	1.21	1.19	1.13	1.20	1.18	1.15	1.15
Run#=	54	53	52	43	55	56	57

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

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	220	207	180	185	183	209	192
6.3	233	239	238	226	247	229	250
11.4	270	260	251	256	252	245	279
25.0	281	286	275	280	316	287	309
Run#=	48	47	46	45	49	50	51

Normalized Mean Wind at X = 500 cm (Uref = 236.4 cm/s)

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	0.93	0.87	0.76	0.78	0.77	0.88	0.81
6.3	0.98	1.01	1.01	0.95	1.05	0.97	1.06
11.4	1.14	1.10	1.06	1.08	1.07	1.04	1.18
25.0	1.19	1.21	1.16	1.18	1.34	1.21	1.31
Run#=	48	47	46	45	49	50	51

Local Longitudinal Turbulent Intensity (%) at X = 0 cm

	Y (cm)							
Z (cm)	-90	-60	-30	0	30	60	90	Avg. Values
2.5	20	22	21	20	19	20	22	*20.1*
6.3	14	17	16	17	16	16	19	***16.6***
11.4	16	15	12	15	14	12	18	*14.0*
25.0	12	13	13	10	13	14	12	*12.0*
Run#=	54	53	52	43	55	56	57	

Normalized Local Long. Turb. Int. at X = 0 cm (T.I.ref = 16.6%)

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	1.2	1.3	1.3	1.2	1.2	1.2	1.3
6.3	0.9	1.0	0.9	1.0	1.0	0.9	1.1
11.4	1.0	0.9	0.8	0.9	0.9	0.7	1.1
25.0	0.7	0.8	0.8	0.6	0.8	0.8	0.7
Run#=	54	53	52	43	55	56	57

Local Longitudinal Turbulent Intensity (%) at X = 500 cm

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	18	23	19	21	19	16	21
6.3	20	14	16	16	18	18	17
11.4	14	14	13	14	13	13	13
25.0	13	13	11	12	8	12	12
Run#=	48	47	46	45	49	50	51

Normalized Local Long. Turb. Int. at X = 500 cm (T.I.ref = 16.6%)

	Y (cm)						
Z (cm)	-90	-60	-30	0	30	60	90
2.5	1.1	1.4	1.2	1.3	1.2	1.0	1.3
6.3	1.2	0.8	1.0	1.0	1.1	1.1	1.0
11.4	0.9	0.8	0.8	0.9	0.8	0.8	0.8
25.0	0.8	0.8	0.6	0.7	0.5	0.7	0.7
Run#=	48	47	46	45	49	50	51

Table 8 ADCT Crosswind Velocity and Turbulence Profile Variation

Billings Project - ADCT Stack Concentration Measurements

Vertical Profile at 0.5 km downwind

Field Values (MKS)	Model Values (CGS)		RUN # 11
400	1	< Length Scale	
17.5	288.0	< Wind Speed	
516.1	530.2	< Flow Rate	
22.0	22.0	< Stack Gas Temp. (C)	
22.0	22.0	< Ambient Temp. (C)	
110.0	27.5	< Effective Stack Height	

Field Position			Model Position			PG-C	Field	PG-D	Model	Model
X	Y	Z	X	Y	Z	K*10^6	K*10^6	K*10^6	K*10^6	Conc.
(m)	(m)	(m)	(cm)	(cm)	(cm)	(m^-2)	(m^-2)	(m^-2)	(cm^-2)	(ppm)
500	0	0	125	0	0	2	1	0	9	17
500	0	16	125	0	4	4	2	0	26	47
500	0	32	125	0	8	10	7	0	113	208
500	0	40	125	0	10	14	12	2	185	340
500	0	48	125	0	12	21	21	4	340	626
500	0	56	125	0	14	29	31	11	498	917
500	0	64	125	0	16	38	38	23	612	1127
500	0	72	125	0	18	47	60	44	964	1775
500	0	80	125	0	20	57	80	75	1280	2356
500	0	88	125	0	22	66	92	112	1476	2717
500	0	96	125	0	24	73	104	149	1661	3058
500	0	104	125	0	26	77	105	174	1678	3089
500	0	112	125	0	28	78	107	179	1713	3153
500	0	120	125	0	30	75	100	163	1602	2949
500	0	128	125	0	32	70	91	131	1457	2681
500	0	136	125	0	34	62	77	93	1235	2273
500	0	144	125	0	36	52	67	58	1079	1987
500	0	152	125	0	38	42	53	32	845	1557
500	0	160	125	0	40	33	41	16	658	1211
500	0	176	125	0	44	17	24	3	376	692
500	0	192	125	0	48	8	10	0	161	296
500	0	208	125	0	52	3	4	0	70	129
500	0	224	125	0	56	1	2	0	30	56
500	0	240	125	0	60	0	1	0	12	22
500	0	256	125	0	64	0	0	0	4	7
500	0	272	125	0	68	0	0	0	2	3
500	0	288	125	0	72	0	0	0	2	3
500	0	304	125	0	76	0	0	0	2	3
500	0	320	125	0	80	0	0	0	1	3
500	0	336	125	0	84	0	0	0	1	2
500	0	352	125	0	88	0	0	0	1	2
500	0	368	125	0	92	0	0	0	2	3
500	0	384	125	0	96	0	0	0	1	2
500	0	400	125	0	100	0	0	0	1	2
500	0	416	125	0	104	0	0	0	1	2
500	0	432	125	0	108	0	0	0	1	2
500	0	448	125	0	112	0	0	0	1	2
500	0	464	125	0	116	0	0	0	1	2

Table 9 ADCT Vertical Concentration Profile Data; X = 500 meters

Billings Project - ADCT Stack Concentration Measurements

Lateral Profile at 0.5 km downwind

Field Values (MKS)	Model Values (CGS)		RUN # 14
400	1	< Length Scale	
17.5	288.0	< Wind Speed	
516.1	530.2	< Flow Rate	
22.0	22.0	< Stack Gas Temp. (C)	
22.0	22.0	< Ambient Temp. (C)	
110.0	27.5	< 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)	Field K*10^6 (m^-2)	PG-D K*10^6 (m^-2)	Model K*10^6 (cm^-2)	Model Conc. (ppm)
500	-32	104	125	-8	26	64	95	124	1527	2811
500	-24	104	125	-6	26	69	94	144	1497	2757
500	-16	104	125	-4	26	73	103	160	1646	3030
500	-8	104	125	-2	26	76	99	170	1589	2925
500	0	104	125	0	26	77	104	174	1663	3062
500	8	104	125	2	26	76	95	170	1521	2801
500	16	104	125	4	26	73	91	160	1451	2671
500	24	104	125	6	26	69	79	144	1268	2334
500	32	104	125	8	26	64	64	124	1019	1876
500	40	104	125	10	26	58	61	103	979	1802
500	48	104	125	12	26	51	50	82	808	1487
500	56	104	125	14	26	45	40	62	643	1184
500	64	104	125	16	26	38	29	45	467	859
500	72	104	125	18	26	31	22	32	350	645
500	80	104	125	20	26	25	15	21	246	453
500	88	104	125	22	26	20	11	14	173	319
500	96	104	125	24	26	16	7	8	113	207
500	104	104	125	26	26	12	5	5	81	150
500	112	104	125	28	26	9	4	3	58	106
500	120	104	125	30	26	6	3	2	42	77
500	128	104	125	32	26	4	2	1	27	49
500	144	104	125	36	26	2	1	0	11	20
500	160	104	125	40	26	1	0	0	3	5
500	176	104	125	44	26	0	0	0	2	3
500	192	104	125	48	26	0	0	0	1	2
500	208	104	125	52	26	0	0	0	1	1
500	224	104	125	56	26	0	0	0	1	1
500	240	104	125	60	26	0	0	0	1	1
500	256	104	125	64	26	0	0	0	1	1
500	272	104	125	68	26	0	0	0	2	4
500	288	104	125	72	26	0	0	0	0	1
500	304	104	125	76	26	0	0	0	0	1
500	320	104	125	80	26	0	0	0	0	1
500	336	104	125	84	26	0	0	0	5	9
500	352	104	125	88	26	0	0	0	0	1

Table 10 ADCT Lateral Concentration Profile Data; X = 500 meters

Billings Project - ADCT Stack Concentration Measurements

Vertical Profile at 1 km downwind

Field Values (MKS)			Model Values (CGS)						RUN # 10	
400			1			< Length Scale				
17.5			288.0			< Wind Speed				
516.1			530.2			< Flow Rate				
22.0			22.0			< Stack Gas Temp. (C)				
22.0			22.0			< Ambient Temp. (C)				
110.0			27.5			< Effective Stack Height				
Field Position			Model Position			PG-C	Field	PG-D	Model	Model
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 (cm^-2)	Conc. (ppm)
1000	0	0	250	0	0	13	8	2	129	238
1000	0	16	250	0	4	14	11	3	170	313
1000	0	32	250	0	8	15	16	7	264	486
1000	0	48	250	0	12	16	24	14	378	696
1000	0	64	250	0	16	18	25	26	395	727
1000	0	72	250	0	18	19	31	33	503	926
1000	0	80	250	0	20	20	34	40	551	1014
1000	0	88	250	0	22	20	34	46	545	1003
1000	0	96	250	0	24	21	37	51	591	1088
1000	0	104	250	0	26	21	37	54	596	1097
1000	0	112	250	0	28	21	36	55	581	1070
1000	0	120	250	0	30	21	35	53	563	1037
1000	0	128	250	0	32	20	34	49	544	1001
1000	0	144	250	0	36	19	30	37	480	884
1000	0	160	250	0	40	16	25	23	405	746
1000	0	176	250	0	44	14	21	12	331	609
1000	0	192	250	0	48	11	15	5	234	430
1000	0	208	250	0	52	8	11	2	178	328
1000	0	224	250	0	56	6	8	1	129	238
1000	0	240	250	0	60	4	5	0	85	157
1000	0	256	250	0	64	3	3	0	52	95
1000	0	272	250	0	68	2	2	0	32	59
1000	0	288	250	0	72	1	1	0	18	33
1000	0	304	250	0	76	1	1	0	10	19
1000	0	320	250	0	80	0	0	0	6	10
1000	0	336	250	0	84	0	0	0	3	6
1000	0	352	250	0	88	0	0	0	2	3
1000	0	368	250	0	92	0	0	0	2	4
1000	0	384	250	0	96	0	0	0	2	3
1000	0	400	250	0	100	0	0	0	2	3
1000	0	416	250	0	104	0	0	0	2	3
1000	0	432	250	0	108	0	0	0	2	3
1000	0	448	250	0	112	0	0	0	2	3
1000	0	464	250	0	116	0	0	0	2	3

Table 11 ADCT Vertical Concentration Profile Data; X = 1000 meters

Billings Project - ADCT Stack Concentration Measurements

Lateral Profile at 1 km downwind

Field Values (MKS)			Model Values (CGS)			RUN # 13				
400			1			< Length Scale				
17.5			288.0			< Wind Speed				
516.1			530.2			< Flow Rate				
22.0			22.0			< Stack Gas Temp. (C)				
22.0			22.0			< Ambient Temp. (C)				
110.0			27.5			< Effective Stack Height				
Field Position			Model Position			PG-C	Field	PG-D	Model	Model
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 (cm^-2)	Conc. (ppm)
1000	-32	104	250	-8	26	20	37	50	590	1087
1000	-24	104	250	-6	26	20	35	52	563	1037
1000	-16	104	250	-4	26	21	38	53	614	1130
1000	-8	104	250	-2	26	21	36	54	579	1066
1000	0	104	250	0	26	21	39	54	629	1157
1000	8	104	250	2	26	21	37	54	592	1090
1000	16	104	250	4	26	21	37	53	592	1090
1000	24	104	250	6	26	20	34	52	549	1011
1000	32	104	250	8	26	20	29	50	471	867
1000	40	104	250	10	26	20	32	47	510	939
1000	48	104	250	12	26	19	30	45	481	886
1000	56	104	250	14	26	18	27	41	433	798
1000	64	104	250	16	26	17	26	38	424	780
1000	72	104	250	18	26	17	22	35	355	654
1000	80	104	250	20	26	16	21	31	335	616
1000	88	104	250	22	26	15	18	28	286	526
1000	96	104	250	24	26	14	17	25	273	503
1000	104	104	250	26	26	13	14	21	229	422
1000	112	104	250	28	26	12	13	18	213	393
1000	120	104	250	30	26	11	11	16	176	325
1000	128	104	250	32	26	10	9	13	152	280
1000	144	104	250	36	26	8	7	9	105	193
1000	160	104	250	40	26	7	4	6	65	120
1000	176	104	250	44	26	5	3	4	44	81
1000	192	104	250	48	26	4	2	2	30	56
1000	208	104	250	52	26	3	1	1	20	37
1000	224	104	250	56	26	2	1	1	10	18
1000	240	104	250	60	26	2	0	0	5	9
1000	256	104	250	64	26	1	0	0	3	5
1000	272	104	250	68	26	1	0	0	1	2
1000	288	104	250	72	26	0	0	0	1	2
1000	304	104	250	76	26	0	0	0	1	1
1000	320	104	250	80	26	0	0	0	0	1
1000	336	104	250	84	26	0	0	0	1	2
1000	352	104	250	88	26	0	0	0	0	1

Table 12 ADCT Lateral Concentration Profile Data; X = 1000 meters

Billings Project - ADCT Stack Concentration Measurements

Vertical Profile at 1.5 km downwind

Field Values (MKS)	Model Values (CGS)	RUN # 9
400	1	< Length Scale
17.5	288.0	< Wind Speed
516.1	530.2	< Flow Rate
22.0	22.0	< Stack Gas Temp. (C)
22.0	22.0	< Ambient Temp. (C)
110.0	27.5	< Effective Stack Height

Field Position			Model Position			PG-C	Field	PG-D	Model	Model
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 (cm^-2)	Conc. (ppm)
1500	0	0	375	0	0	11	15	5	233	429
1500	0	16	375	0	4	11	15	6	237	436
1500	0	32	375	0	8	11	16	9	261	481
1500	0	48	375	0	12	11	18	13	285	525
1500	0	64	375	0	16	11	16	19	262	482
1500	0	80	375	0	20	11	20	24	326	600
1500	0	96	375	0	24	11	21	27	330	607
1500	0	112	375	0	28	11	21	28	330	608
1500	0	128	375	0	32	10	20	27	318	586
1500	0	144	375	0	36	10	18	23	284	523
1500	0	160	375	0	40	9	15	17	247	454
1500	0	176	375	0	44	8	13	12	213	392
1500	0	192	375	0	48	7	11	7	178	327
1500	0	208	375	0	52	6	9	4	146	269
1500	0	224	375	0	56	6	7	2	119	219
1500	0	240	375	0	60	5	6	1	92	170
1500	0	256	375	0	64	4	4	0	68	126
1500	0	272	375	0	68	3	3	0	50	92
1500	0	288	375	0	72	2	2	0	36	67
1500	0	304	375	0	76	2	1	0	24	43
1500	0	320	375	0	80	1	1	0	16	29
1500	0	336	375	0	84	1	1	0	10	19
1500	0	352	375	0	88	1	0	0	7	13
1500	0	368	375	0	92	0	0	0	5	9
1500	0	384	375	0	96	0	0	0	3	6
1500	0	400	375	0	100	0	0	0	2	4
1500	0	416	375	0	104	0	0	0	2	3
1500	0	432	375	0	108	0	0	0	2	3
1500	0	448	375	0	112	0	0	0	1	2
1500	0	448	375	0	112	0	0	0	1	2
1500	0	464	375	0	116	0	0	0	2	3
1500	0	464	375	0	116	0	0	0	2	3

Table 13 ADCT Vertical Concentration Profile Data; X = 1500 meters

Billings Project - ADCT Stack Concentration Measurements

Lateral Profile at 1.5 km downwind

Field Values (MKS)	Model Values (CGS)	RUN # 12
400	1	< Length Scale
17.5	288.0	< Wind Speed
516.1	530.2	< Flow Rate
22.0	22.0	< Stack Gas Temp. (C)
22.0	22.0	< Ambient Temp. (C)
110.0	27.5	< Effective Stack Height

Field Position			Model Position			PG-C	Field	PG-D	Model	Model
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 (cm^-2)	Conc. (ppm)
1500	-32	104	375	-8	26	11	21	27	332	612
1500	-24	104	375	-6	26	11	20	28	316	582
1500	-16	104	375	-4	26	11	21	28	342	629
1500	-8	104	375	-2	26	11	20	28	324	596
1500	0	104	375	0	26	11	22	28	345	635
1500	8	104	375	2	26	11	21	28	332	612
1500	16	104	375	4	26	11	22	28	351	646
1500	24	104	375	6	26	11	21	28	338	622
1500	32	104	375	8	26	11	18	27	290	533
1500	40	104	375	10	26	11	21	27	332	611
1500	48	104	375	12	26	11	22	26	348	640
1500	56	104	375	14	26	10	20	25	323	594
1500	64	104	375	16	26	10	20	24	326	601
1500	80	104	375	20	26	10	18	22	292	538
1500	96	104	375	24	26	9	16	20	256	471
1500	112	104	375	28	26	8	14	17	224	411
1500	128	104	375	32	26	8	12	15	188	346
1500	144	104	375	36	26	7	10	12	157	290
1500	160	104	375	40	26	6	7	10	116	213
1500	176	104	375	44	26	6	5	8	88	162
1500	192	104	375	48	26	5	4	6	69	127
1500	208	104	375	52	26	4	3	5	48	89
1500	224	104	375	56	26	4	2	4	32	59
1500	240	104	375	60	26	3	1	3	19	35
1500	256	104	375	64	26	3	1	2	15	27
1500	272	104	375	68	26	2	1	1	10	18
1500	288	104	375	72	26	2	0	1	6	11
1500	304	104	375	76	26	2	0	1	4	7
1500	320	104	375	80	26	1	0	0	2	4
1500	336	104	375	84	26	1	0	0	2	4
1500	352	104	375	88	26	1	0	0	1	1
1500	368	104	375	92	26	1	0	0	1	1
1500	384	104	375	96	26	0	0	0	0	1
1500	400	104	375	100	26	0	0	0	0	1
1500	416	104	375	104	26	0	0	0	0	1
1500	432	104	375	108	26	0	0	0	0	1

Table 14 ADCT Lateral Concentration Profile Data; X = 1500 meters

Billings Project - ADCT Stack Concentration Measurements

Ground Level Profiles

Field Values (MKS)			Model Values (CGS)			RUN # 15				
400			1			< Length Scale				
17.5			288.0			< Wind Speed				
516.1			530.2			< Flow Rate				
22.0			22.0			< Stack Gas Temp. (C)				
22.0			22.0			< Ambient Temp. (C)				
110.0			27.5			< Effective Stack Height				
Field Position			Model Position			PG-C	Field	PG-D	Model	Model
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 (cm^-2)	Conc. (ppm)
200	0	0	50	0	0	0	0	0	0	1
300	0	0	75	0	0	0	0	0	0	0
400	0	0	100	0	0	0	0	0	1	2
500	0	0	125	0	0	2	1	0	9	17
700	0	0	175	0	0	9	2	0	29	54
800	0	0	200	0	0	11	4	0	68	125
900	0	0	225	0	0	13	6	1	94	174
1000	0	0	250	0	0	13	8	2	131	241
1100	0	0	275	0	0	13	10	2	156	287
1200	0	0	300	0	0	13	11	3	184	339
1300	0	0	325	0	0	13	12	4	199	366
1400	0	0	350	0	0	12	13	4	210	387
1500	0	0	375	0	0	11	14	5	217	400
1600	0	0	400	0	0	11	14	6	224	412
1700	0	0	425	0	0	10	15	6	234	430
1800	0	0	450	0	0	10	15	6	235	432
1900	0	0	475	0	0	9	15	7	233	429
2000	0	0	500	0	0	8	14	7	232	426
2100	0	0	525	0	0	8	14	7	228	420
500	-60	0	125	-15	0	1	0	0	7	13
500	-40	0	125	-10	0	2	1	0	16	29
500	-20	0	125	-5	0	2	2	0	25	47
500	20	0	125	5	0	2	1	0	15	28
500	40	0	125	10	0	2	0	0	7	13
500	60	0	125	15	0	1	0	0	2	4
1000	-60	0	250	-15	0	11	6	1	99	183
1000	-40	0	250	-10	0	12	7	1	119	219
1000	-20	0	250	-5	0	13	8	2	132	242
1000	0	0	250	0	0	13	8	2	131	241
1000	20	0	250	5	0	13	8	2	134	246
1000	40	0	250	10	0	12	8	1	127	235
1000	60	0	250	15	0	11	7	1	111	205
1500	-60	0	375	-15	0	11	12	4	186	343
1500	-40	0	375	-10	0	11	13	5	204	376
1500	-20	0	375	-5	0	11	13	5	215	397
1500	0	0	375	0	0	11	14	5	217	400
1500	20	0	375	5	0	11	13	5	215	396
1500	40	0	375	10	0	11	13	5	205	377
1500	60	0	375	15	0	11	11	4	183	337
2000	-60	0	500	-15	0	8	12	6	200	368
2000	-40	0	500	-10	0	8	14	7	218	401
2000	-20	0	500	-5	0	8	14	7	227	419
2000	0	0	500	0	0	8	14	7	232	426
2000	20	0	500	5	0	8	14	7	227	419
2000	40	0	500	10	0	8	14	7	216	399
2000	60	0	500	15	0	8	12	6	190	350

Table 15 ADCT Ground Level Concentration Profile Data

Omega Mass Flow Controller System Settings {FLOW_SET.WK4}

Test rogram	Test Type	Total Flow Rate (ccs)	Specific Gravity	Gas mixture component 1					Gas mixture component 2				
				Type	Percent of Total (%)	Flow Rate (ccs)	Meter FS Range (SLPM)	Meter Setting (%FS)	Type	Percent of Total (%)	Flow Rate (ccs)	Meter FS Range (SLPM)	Meter Setting (%FS)
ADCT	Visual	530.2	1.000	Air	100.0	530.2	100.0	26.4					
ADCT	Conc.	530.2	1.036	Ethane	100.0	530.2	100.0	53.2					
Re Inv.	Conc.	82.7	1.036	Ethane	100.0	82.7	10.0	82.9					
GEP	Visual	88.4	0.590	Air	52.4	46.3	*10.0*	*23.1*	Helium	47.6	42.1	10.0	14.4
GEP	Conc.	88.4	0.590	Methane	90.9	80.4	10.0	55.3	Nitrogen	9.1	8.0	1.0	39.8

> Matheson 50slpm set at 0.237 volt

Table 16 Stack Gas Flow Settings and Composition

FIGURES

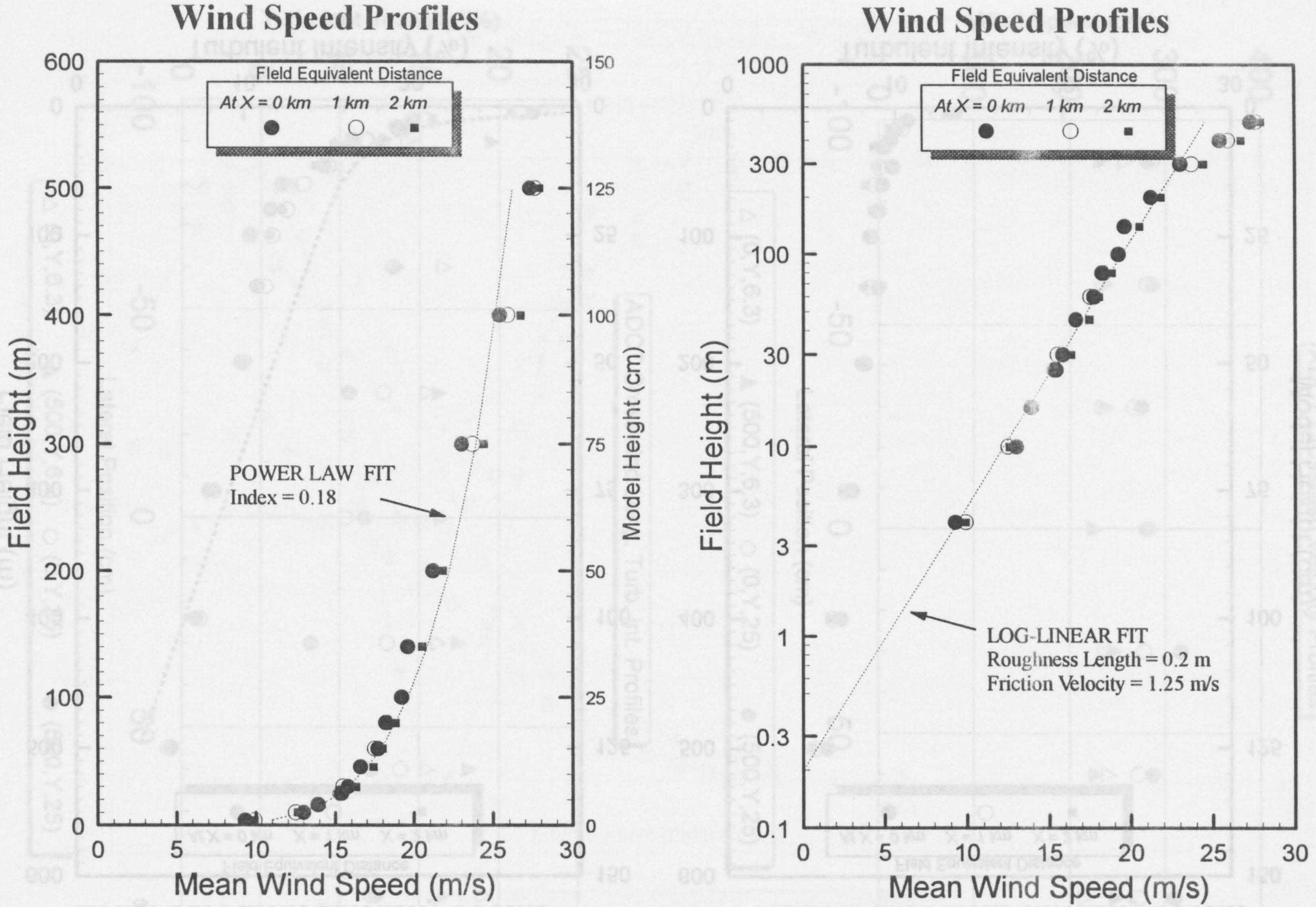


Figure 1 ADCT Reference Velocity Profiles

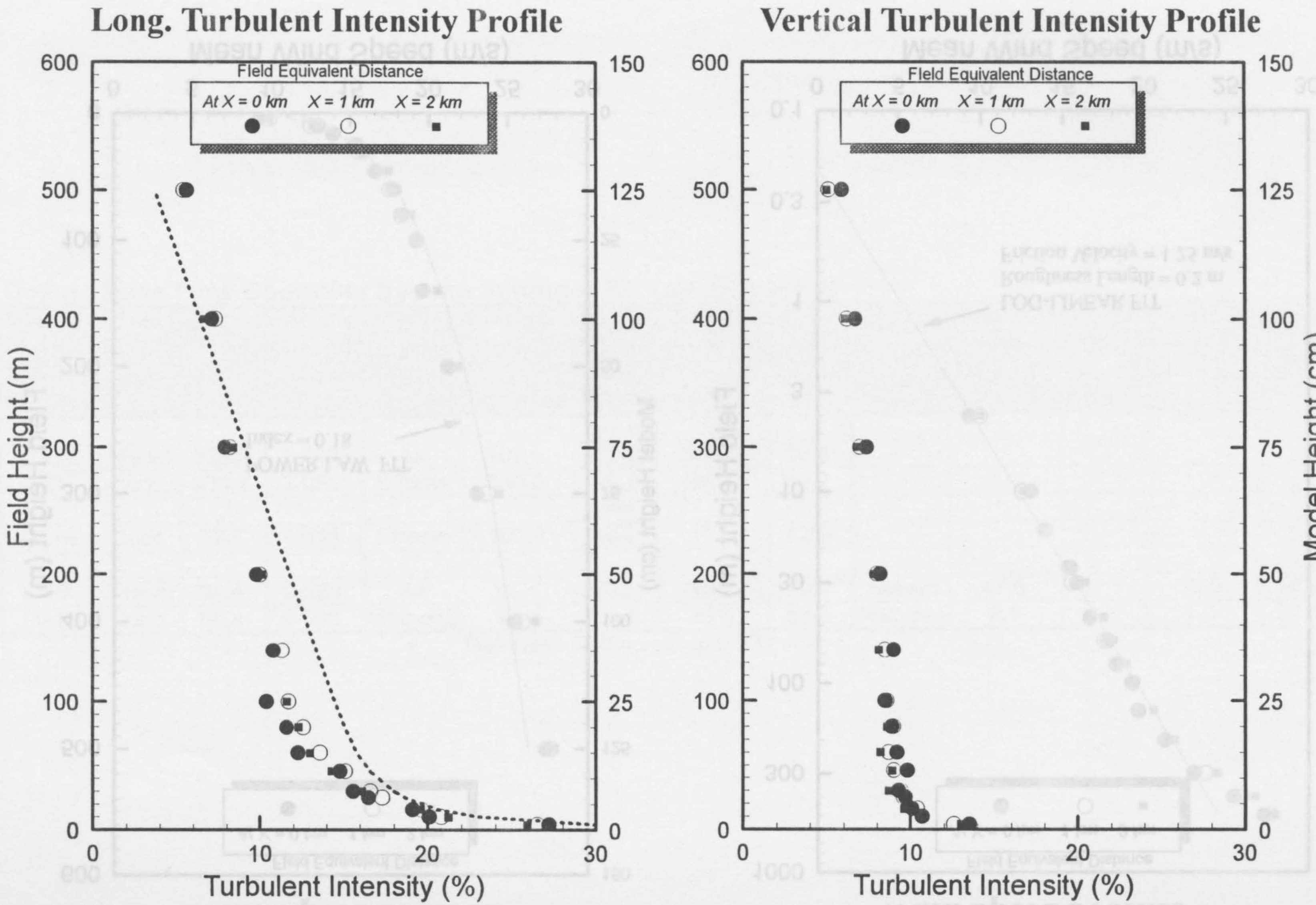
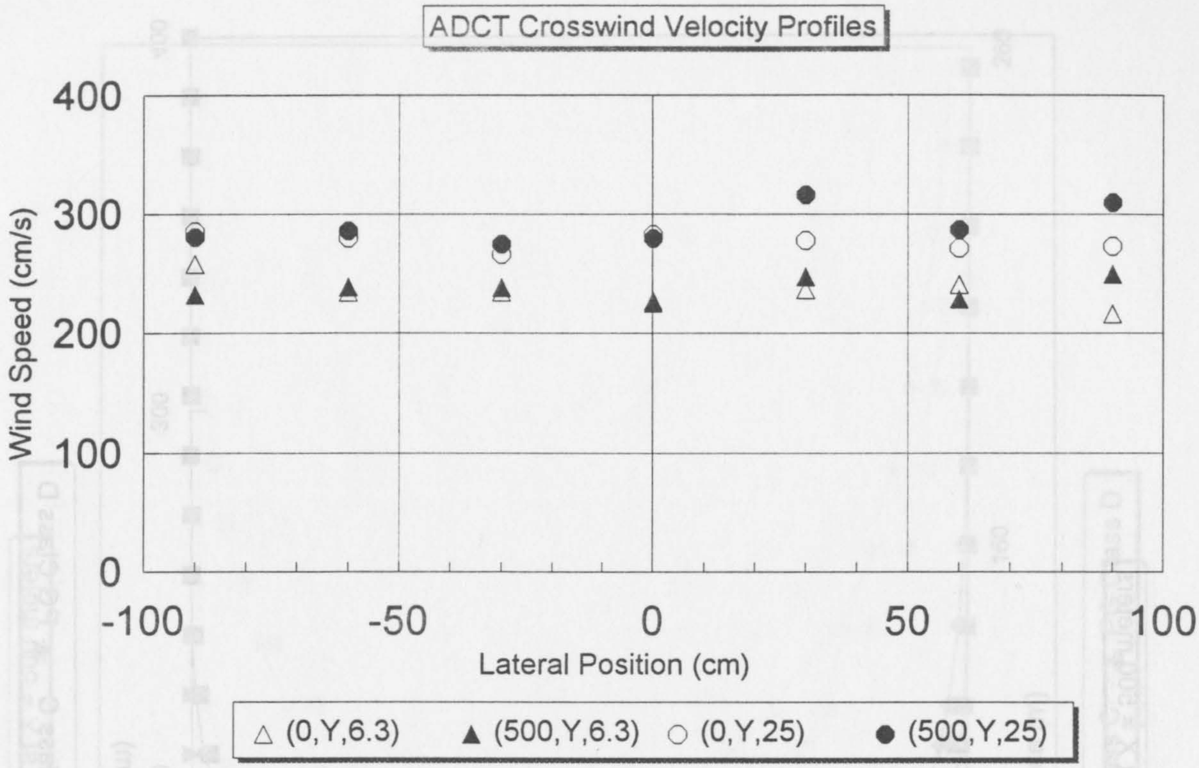


Figure 2 ADCT Reference Turbulence Profiles



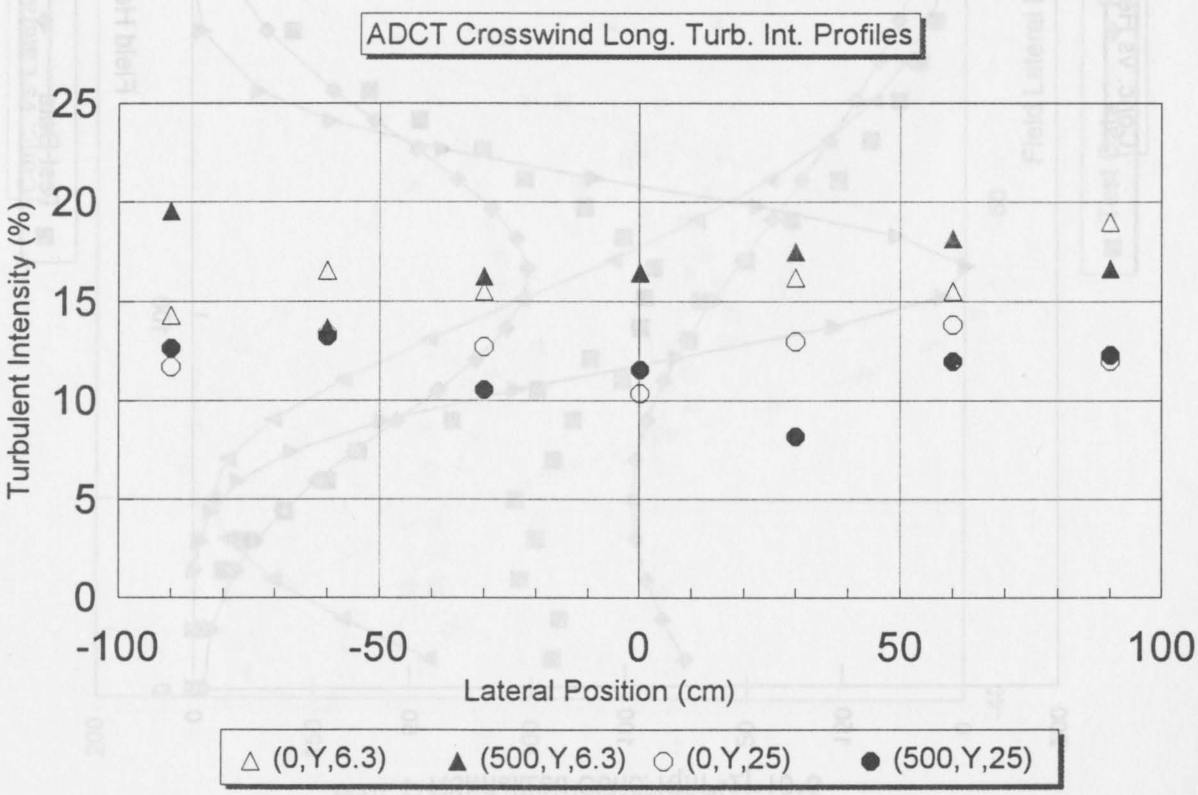


Figure 3 ADCT Crosswind Velocity and Turbulence Profile Variations

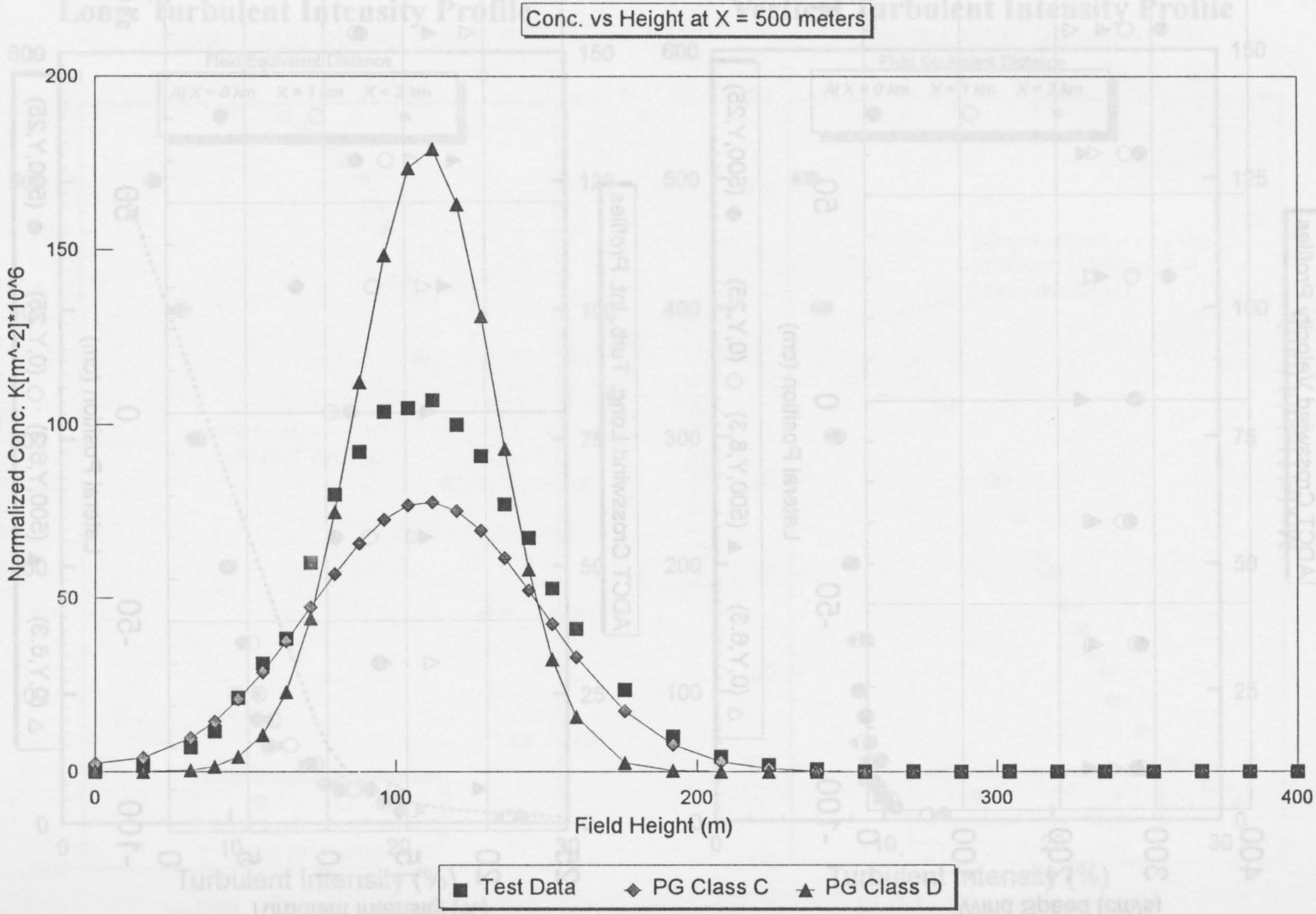


Figure 4 ADCT Vertical Concentration Profile; X = 500 meters

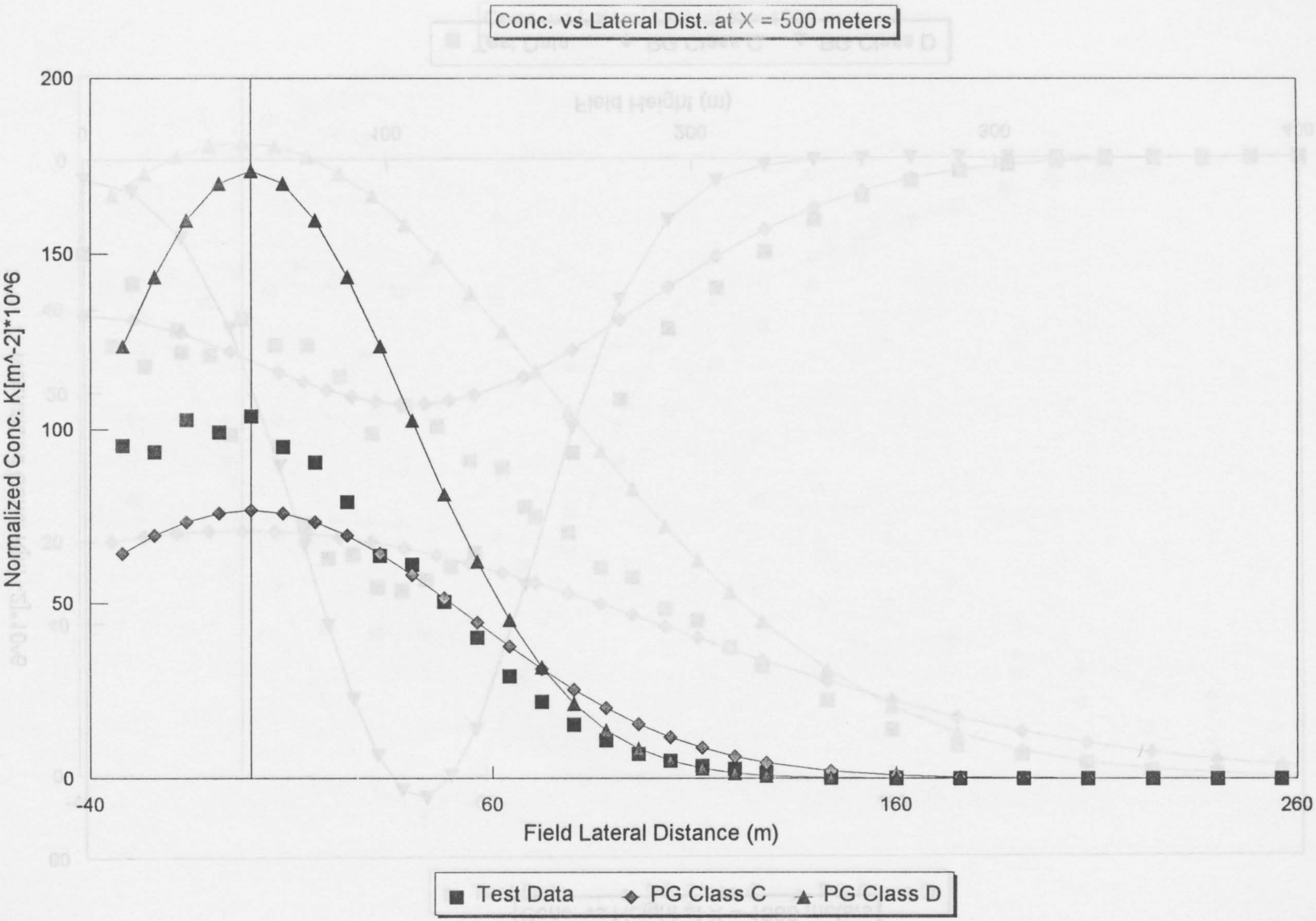


Figure 5 ADCT Lateral Concentration Profile; X = 500 meters

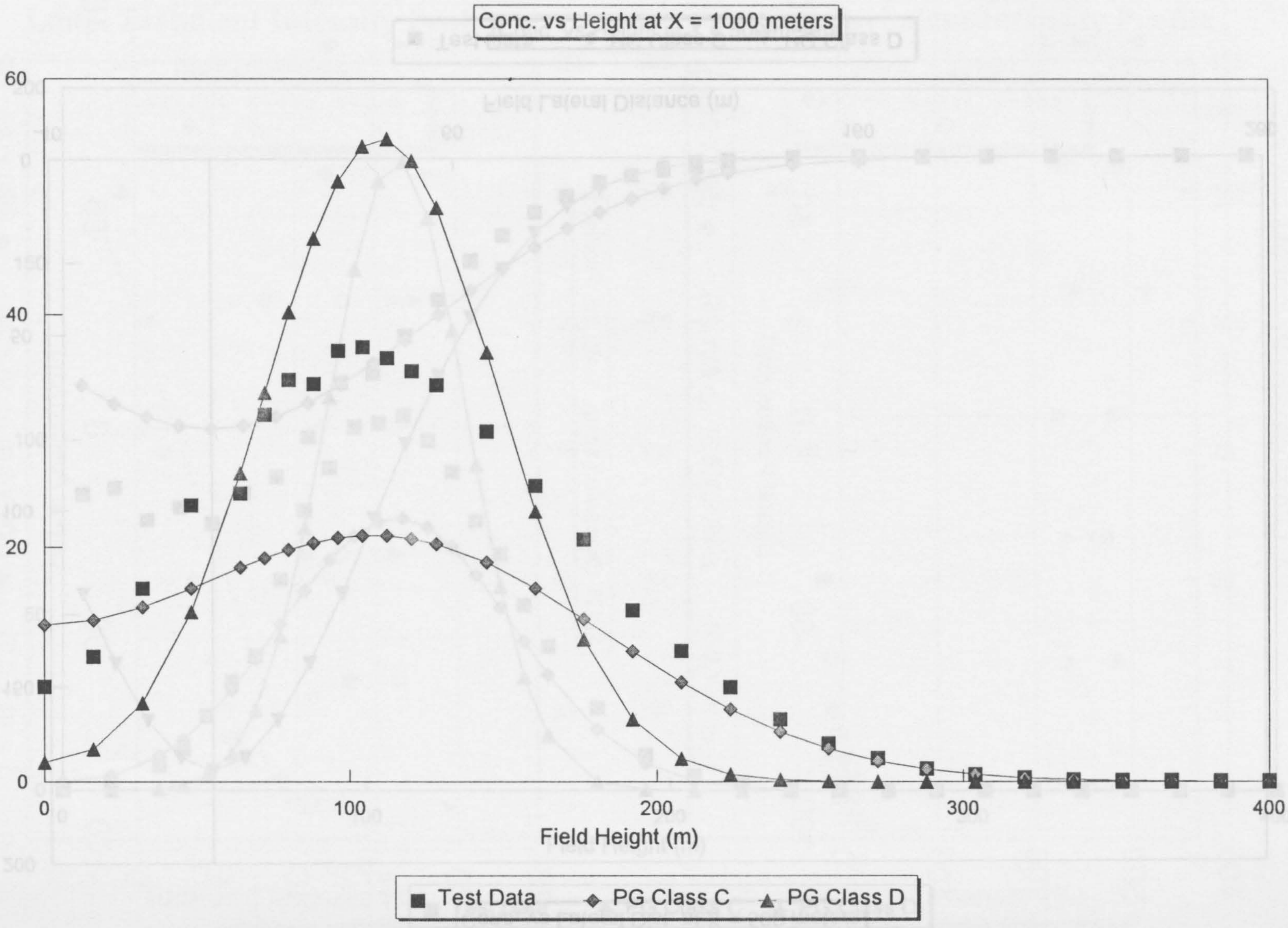


Figure 6 ADCT Vertical Concentration Profile; X = 1000 meters

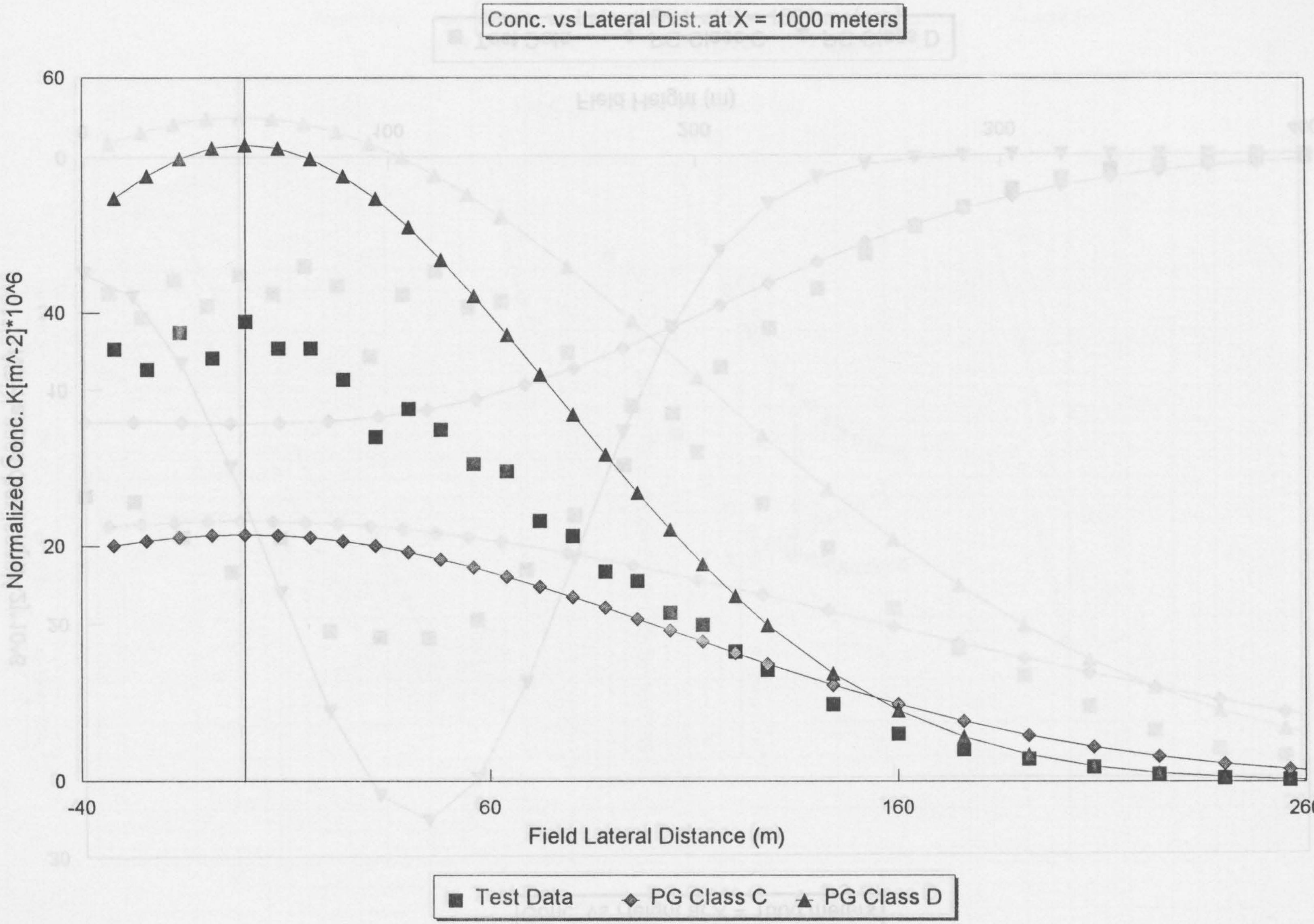


Figure 7 ADCT Lateral Concentration Profile; X = 1000 meters

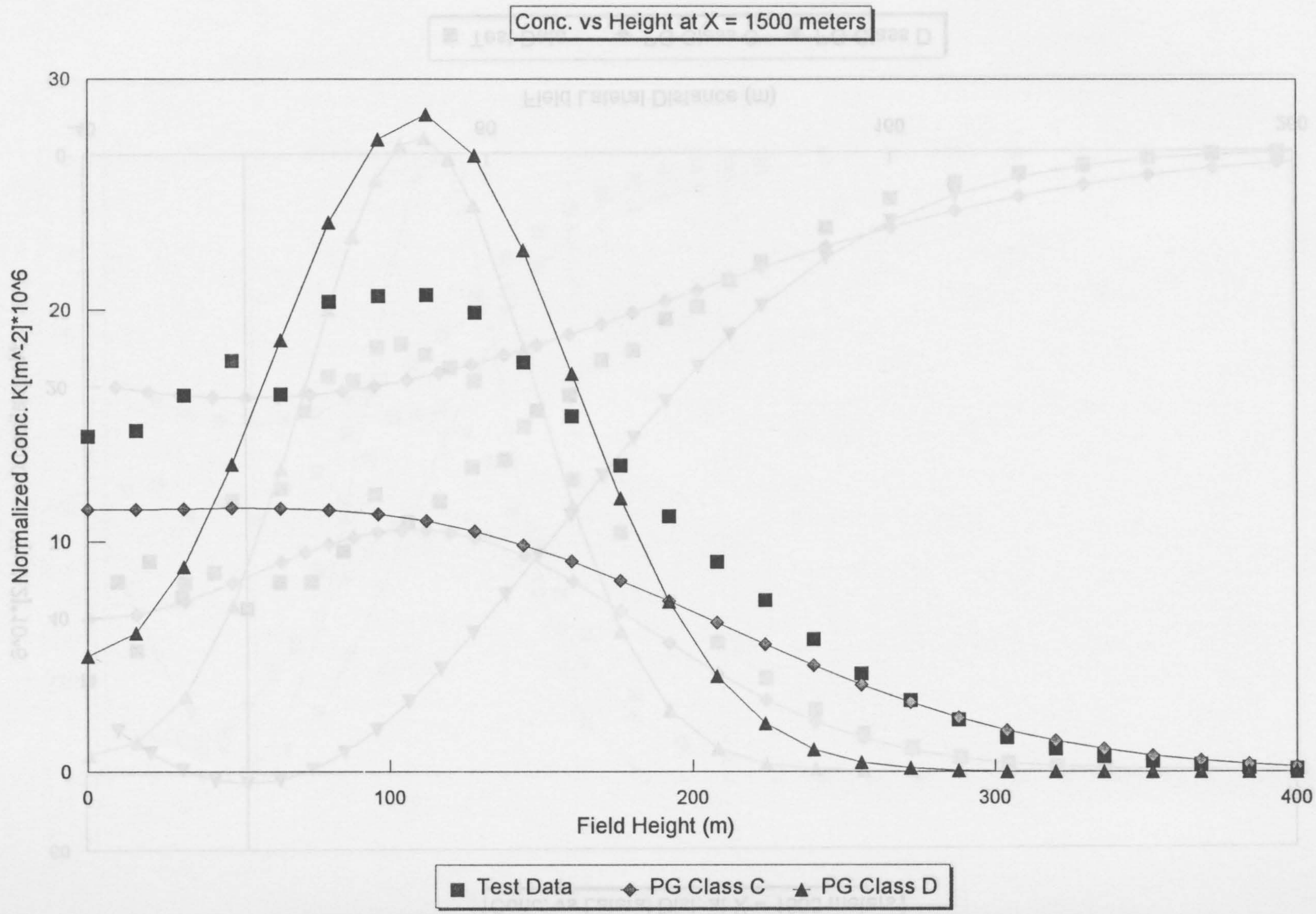


Figure 8 ADCT Vertical Concentration Profile; X = 1500 meters

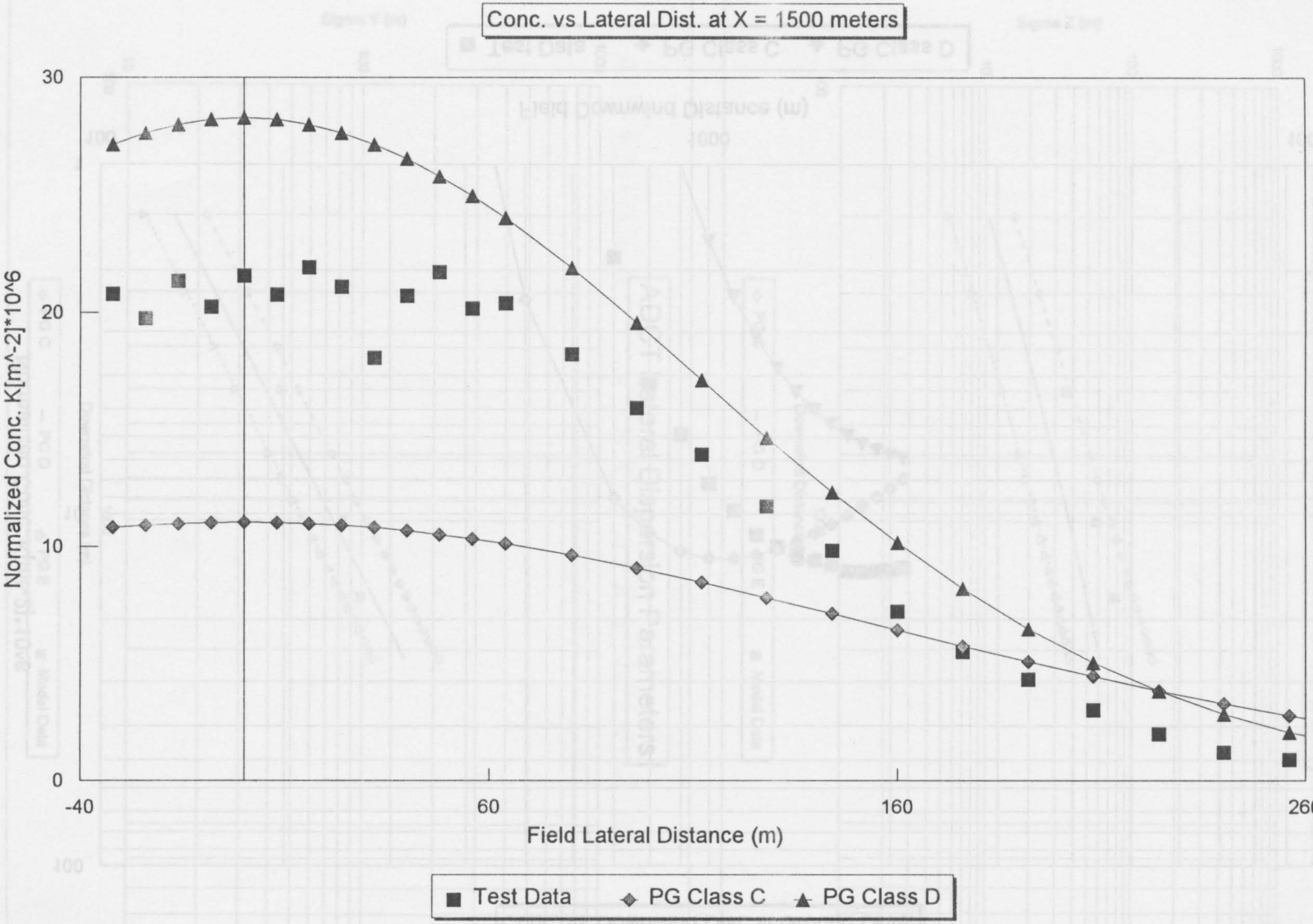


Figure 9 ADCT Lateral Concentration Profile; X = 1500 meters

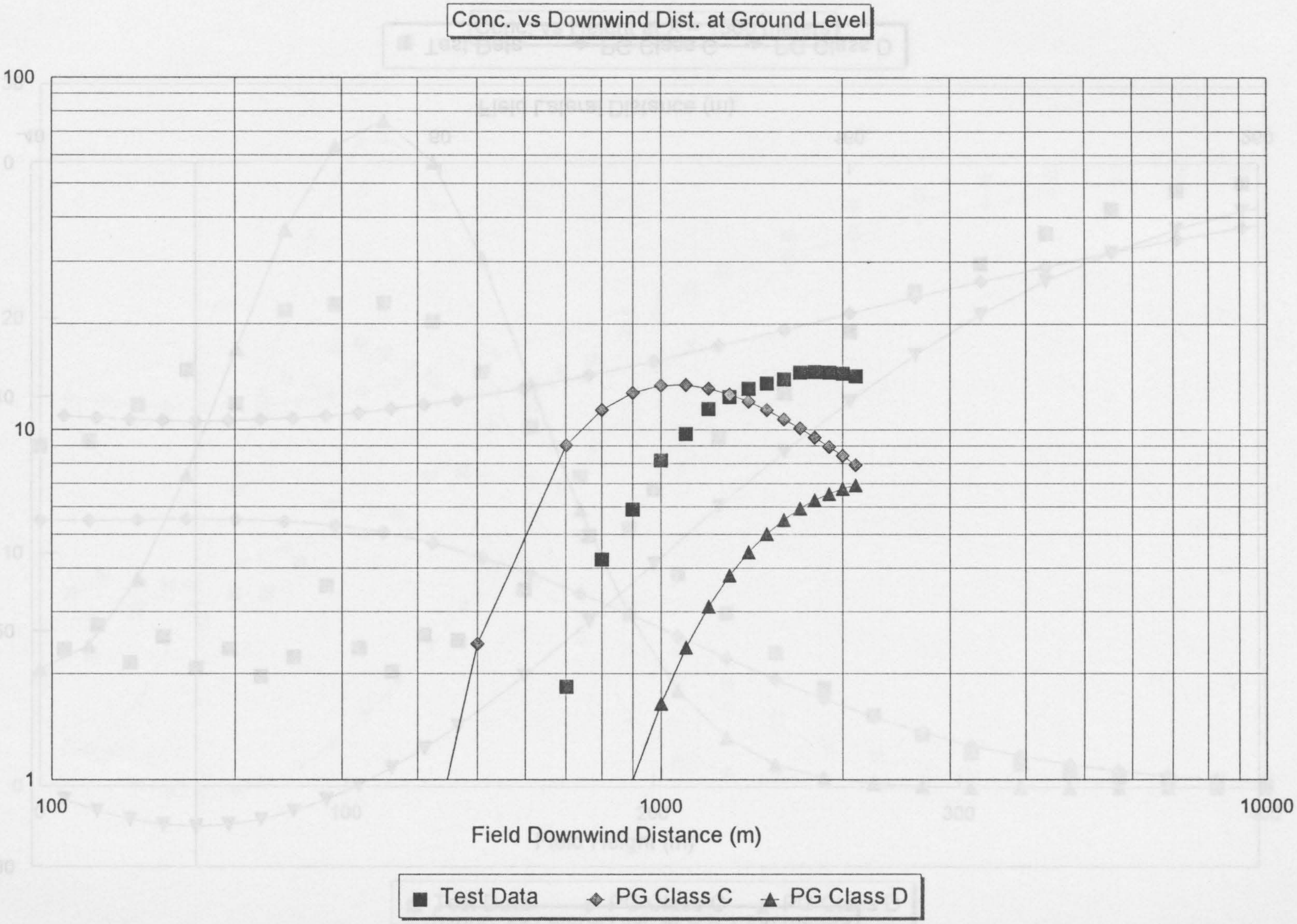
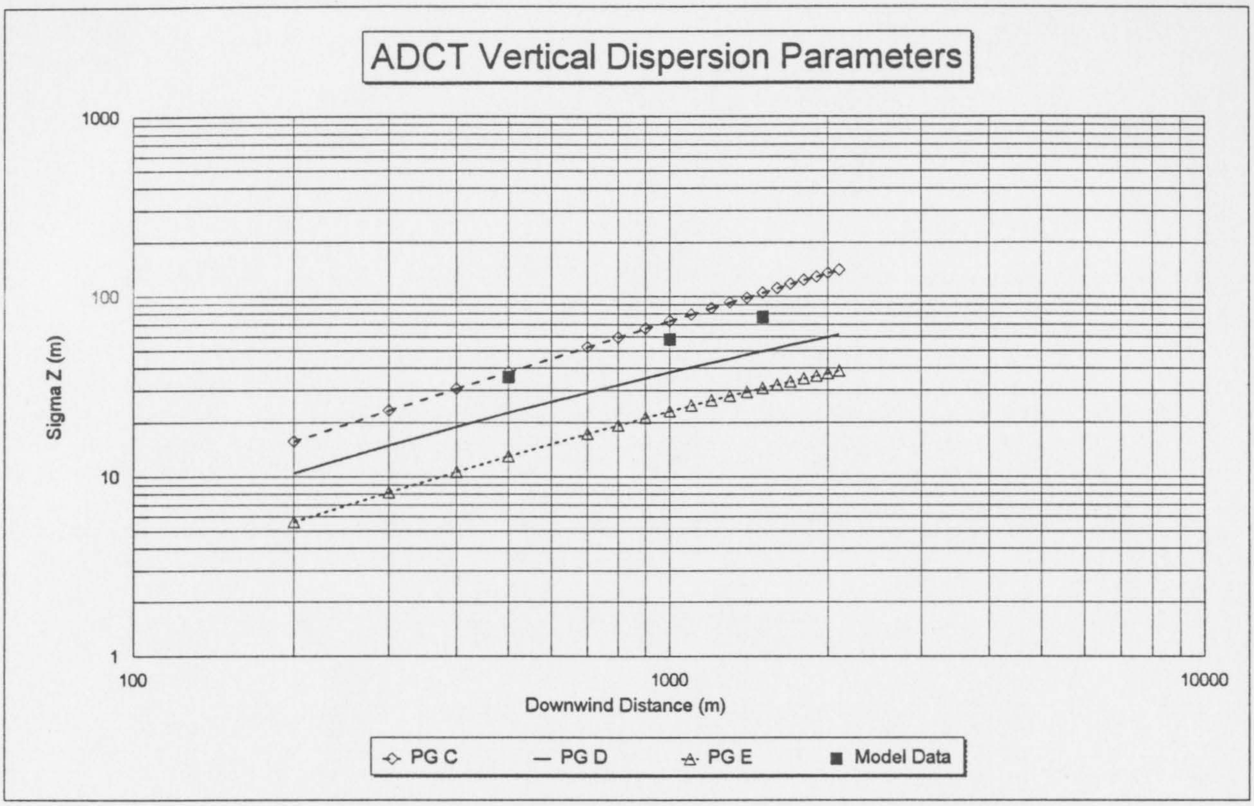


Figure 10 ADCT Ground Level Concentration Profile



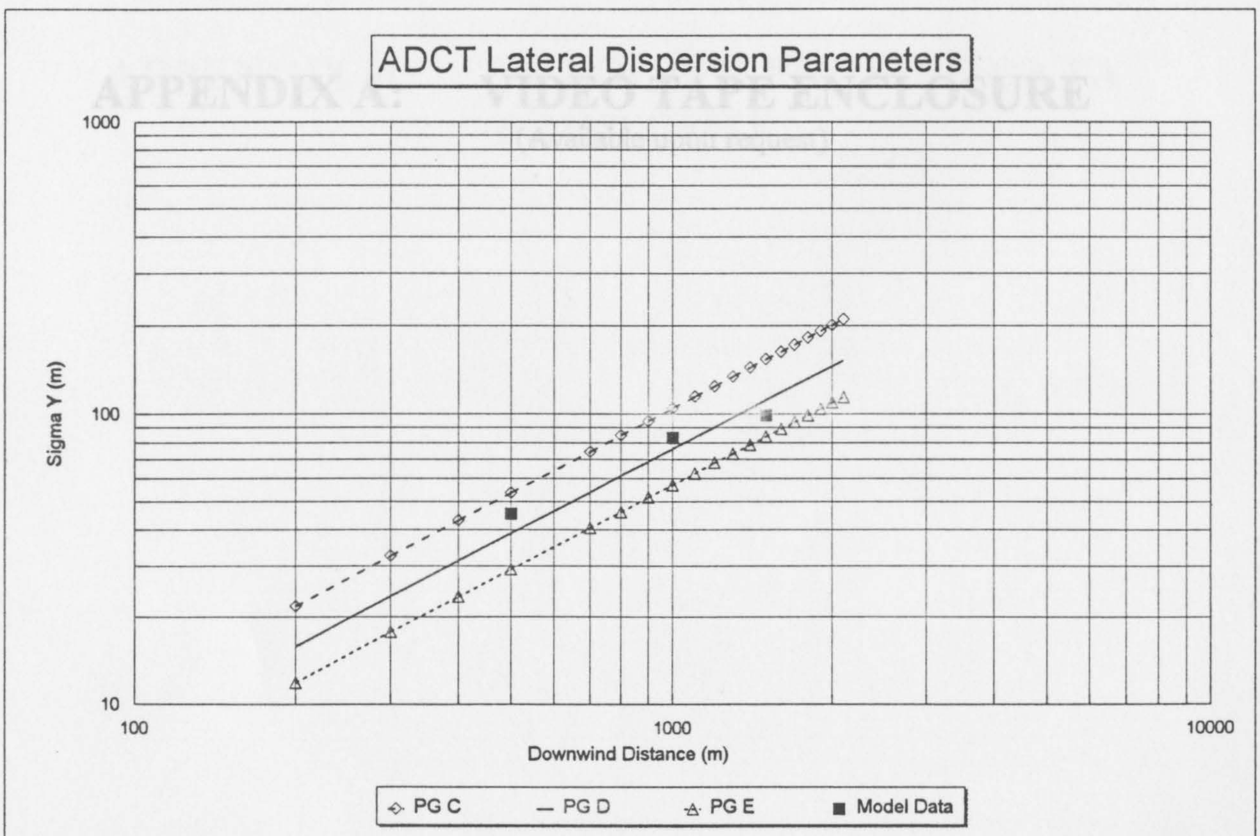


Figure 11 ADCT Vertical and Lateral Dispersion Parameters

APPENDIX A: VIDEO TAPE ENCLOSURE

(Available upon request)

File Name = GEP043.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.87	27.21	13.53	-.0224
2	2.66	1.91	20.11	10.68	-.0218
3	4.09	2.04	19.15	10.07	-.0221
4	5.43	2.27	16.51	9.74	-.0225
5	7.47	2.32	15.57	9.31	-.0184
6	11.43	2.44	14.75	9.76	-.0221
7	14.96	2.60	12.27	9.21	-.0193
8	19.92	2.68	11.61	8.90	-.0165
9	25.04	2.83	10.37	8.47	-.0135
10	34.95	2.88	10.78	8.96	-.0178
11	49.93	3.12	9.78	8.20	-.0191
12	75.09	3.39	7.94	7.39	-.0156
13	100.10	3.74	7.09	6.68	-.0195
14	124.95	4.01	5.59	5.89	-.0076

File Name = GEP044.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.45	26.46	12.63	-.0189
2	2.67	1.84	20.82	10.75	-.0194
3	3.97	2.04	19.55	10.38	-.0208
4	6.36	2.25	17.32	9.64	-.0232
5	7.64	2.28	16.64	9.38	-.0213
6	11.17	2.44	15.07	9.00	-.0215
7	14.79	2.58	13.69	8.68	-.0190
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	24.91	2.85	11.71	8.64	[illegible]
10	34.95	[illegible]	[illegible]	8.54	-.0225
11	50.00	[illegible]	[illegible]	7.99	-.0202
12	75.17	3.48	8.22	6.96	-.0213
13	100.16	3.80	7.27	6.21	-.0191
14	124.78	4.06	5.41	5.13	-.0106

APPENDIX B: VELOCITY PROFILE DATA PRINTOUTS

File Name = GEP045.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.45	25.91	13.01	-.0219
2	2.41	1.85	21.24	10.68	-.0196
3	4.15	2.07	19.57	9.62	-.0173
4	6.19	2.26	16.45	9.63	-.0196
5	7.60	2.39	16.10	8.73	-.0184
6	11.55	2.58	14.35	8.94	-.0239
7	14.77	2.64	12.99	8.22	-.0202
8	19.96	2.76	12.28	8.61	-.0211
9	25.00	2.80	11.58	8.57	-.0236
10	35.20	3.01	10.66	8.09	-.0233
11	50.06	3.20	10.06	7.78	-.0288
12	75.10	3.58	8.40	6.83	-.0218
13	100.22	3.92	6.61	6.07	-.0202
14	124.83	4.10	5.40	5.02	-.0145

File Name = GEP043.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.37	27.21	13.53	-.0224
2	2.66	1.91	20.11	10.68	-.0218
3	4.09	2.04	19.15	10.07	-.0221
4	6.43	2.27	16.51	9.74	-.0225
5	7.47	2.32	15.57	9.31	-.0184
6	11.43	2.44	14.75	9.76	-.0221
7	14.96	2.60	12.27	9.21	-.0193
8	19.92	2.68	11.61	8.90	-.0165
9	25.04	2.83	10.37	8.47	-.0135
10	34.95	2.88	10.78	8.96	-.0178
11	49.93	3.12	9.78	8.20	-.0191
12	75.09	3.39	7.94	7.39	-.0156
13	100.10	3.74	7.09	6.68	-.0195
14	124.95	4.01	5.59	5.89	-.0076

File Name = GEP044.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.45	26.46	12.63	-.0189
2	2.67	1.84	20.82	10.75	-.0194
3	3.97	2.04	19.55	10.38	-.0208
4	6.36	2.25	17.32	9.64	-.0232
5	7.64	2.28	16.64	9.38	-.0213
6	11.17	2.44	15.07	9.00	-.0215
7	14.79	2.58	13.59	8.68	-.0190
8	19.90	2.69	12.65	8.97	-.0243
9	24.91	2.83	11.71	8.64	-.0260
10	34.95	2.89	11.30	8.54	-.0225
11	50.00	3.12	9.96	7.99	-.0202
12	75.17	3.48	8.22	6.96	-.0213
13	100.16	3.80	7.27	6.21	-.0191
14	124.78	4.06	5.41	5.13	-.0106

File Name = GEP045.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	1.00	1.45	25.91	13.01	-.0219
2	2.41	1.85	21.24	10.68	-.0196
3	4.15	2.07	19.57	9.62	-.0173
4	6.19	2.26	16.45	9.63	-.0196
5	7.60	2.39	16.10	8.73	-.0184
6	11.55	2.56	14.35	8.94	-.0239
7	14.77	2.64	12.99	8.22	-.0202
8	19.96	2.76	12.28	8.61	-.0211
9	25.00	2.80	11.58	8.57	-.0238
10	35.20	3.01	10.66	8.09	-.0233
11	50.06	3.20	10.06	7.78	-.0288
12	75.10	3.58	8.40	6.83	-.0218
13	100.22	3.92	6.61	6.07	-.0202
14	124.83	4.10	5.40	5.02	-.0145

File Name = GEP046.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.80	19.17	10.53	-.0127
2	6.12	2.38	16.28	8.96	-.0169
3	11.22	2.51	12.93	8.66	-.0151
4	25.17	2.75	10.56	8.98	-.0178

File Name = GEP047.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	2.07	22.98	10.15	-.0207
2	6.46	2.39	13.69	8.82	-.0150
3	11.18	2.60	13.89	9.34	-.0175
4	25.15	2.86	13.25	9.25	-.0248

File Name = GEP048.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	2.20	17.58	10.34	-.0230
2	6.21	2.33	19.55	10.91	-.0262
3	11.47	2.70	14.28	9.12	-.0254
4	24.81	2.81	12.68	9.88	-.0407

File Name = GEP049.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.83	19.15	10.43	-.0178
2	6.37	2.47	17.52	9.05	-.0112
3	11.17	2.52	12.64	9.49	-.0191
4	25.09	3.16	8.20	8.29	-.0033

File Name = GEP050.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	2.09	16.10	10.39	-.0226
2	6.24	2.29	18.16	9.93	-.0223
3	11.56	2.45	13.08	8.76	-.0129
4	24.89	2.87	12.00	9.65	-.0215

File Name = GEP051.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.92	21.39	11.06	-.0220
2	6.24	2.50	16.66	8.59	-.0226
3	11.56	2.79	13.21	9.50	-.0185
4	25.06	3.09	12.31	8.14	-.0250

File Name = GEP052.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.99	21.29	9.96	-.0216
2	6.44	2.35	15.52	9.12	-.0116
3	11.53	2.57	12.45	8.85	-.0186
4	24.79	2.66	12.74	9.10	-.0143

File Name = GEP053.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.80	21.51	10.53	-.0115
2	6.40	2.35	16.58	9.79	-.0263
3	11.19	2.41	15.00	9.66	-.0187
4	24.80	2.80	13.38	10.21	-.0258

File Name = GEP054.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.91	19.85	10.17	-.0138
2	6.50	2.58	14.34	8.98	-.0129
3	11.41	2.70	16.08	9.82	-.0209
4	25.10	2.86	11.73	10.96	-.0440

File Name = GEP055.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.89	19.45	9.52	-.0150
2	6.27	2.37	16.21	8.54	-.0243
3	11.20	2.42	14.16	9.53	-.0188
4	24.80	2.78	13.00	10.23	-.0281

File Name = GEP056.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	1.84	19.57	9.46	-.0163
2	6.38	2.41	15.53	9.38	-.0177
3	11.37	2.67	11.95	8.77	-.0137
4	24.95	2.72	13.84	9.97	-.0420

File Name = GEP057.PRF APRFL.FOR Output

RECORD NO.	HEIGHT (cm)	VELOCITY (m/s)	TURB.INT U(%)	TURB.INT W(%)	STRESS $(m/s)^2$
1	2.50	2.00	22.04	10.13	-.0256
2	6.36	2.16	19.00	10.05	-.0195
3	11.63	2.55	17.82	10.55	-.0359
4	24.89	2.73	12.02	10.35	-.0216

APPENDIX C: CONCENTRATION DATA FILE PRINTOUTS

RUN NUMBER 9 FILE NAME GEP009.GC
BY NEFF ON 07-10-91
WIND SPEED 250.00 CM/S AT 11.4 CM
AIR TEMP. 27.0 C AT 11.4 CM
SOURCE DESIGNATION 1
SOURCE FLOW RATE (CCS) 530.2
SOURCE GAS TEMPERATURE © 27.0
TRACER TYPE C2H6
TRACER CONCENTRATION (PPM) 1000000.0
BACKGROUND CONCENTRATION (PPM) 19.22

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	375.0	.0	.0	428.6	447.8
2	375.0	.0	4.0	436.1	455.3
3	375.0	.0	8.0	480.7	499.9
4	375.0	.0	12.0	524.9	544.1
5	375.0	.0	16.0	482.0	501.2
6	375.0	.0	20.0	599.8	619.0
7	375.0	.0	24.0	606.9	626.1
8	375.0	.0	28.0	608.2	627.4
9	375.0	.0	32.0	586.0	605.2
10	375.0	.0	36.0	522.9	542.1
11	375.0	.0	40.0	454.3	473.5
12	375.0	.0	44.0	391.7	410.9
13	375.0	.0	48.0	326.9	346.1
14	375.0	.0	52.0	269.1	288.3
15	375.0	.0	56.0	219.4	238.6
16	375.0	.0	60.0	169.8	189.1
17	375.0	.0	64.0	126.0	145.3
18	375.0	.0	68.0	91.6	110.8
19	375.0	.0	72.0	66.7	85.9
20	375.0	.0	76.0	43.4	62.6
21	375.0	.0	80.0	28.8	48.0
22	375.0	.0	84.0	19.2	38.4
23	375.0	.0	88.0	13.4	32.6
24	375.0	.0	92.0	9.3	28.5
25	375.0	.0	96.0	5.5	24.7
26	375.0	.0	100.0	3.8	23.0
27	375.0	.0	104.0	3.2	22.4
28	375.0	.0	108.0	3.0	22.2
29	375.0	.0	112.0	2.4	21.6
30	375.0	.0	116.0	2.8	22.0

```
RUN NUMBER 10           FILE NAME GEP010.GC
BY NEFF      ON 07-10-91
WIND SPEED 250.00 CM/S AT   11.4 CM
AIR TEMP.   27.0  C    AT   11.4 CM
SOURCE DESIGNATION                1
SOURCE FLOW RATE (CCS)          530.2
SOURCE GAS TEMPERATURE ©       27.0
TRACER TYPE                    C2H6
TRACER CONCENTRATION (PPM)  1000000.0
BACKGROUND CONCENTRATION (PPM)    28.21
```

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	250.0	.0	.0	238.4	266.6
2	250.0	.0	4.0	313.4	341.6
3	250.0	.0	8.0	485.8	514.0
4	250.0	.0	12.0	696.3	724.5
5	250.0	.0	16.0	726.8	755.0
6	250.0	.0	20.0	1014.0	1042.2
7	250.0	.0	24.0	1087.7	1115.9
8	250.0	.0	28.0	1069.9	1098.1
9	250.0	.0	32.0	1000.7	1028.9
10	250.0	.0	36.0	883.7	911.8
11	250.0	.0	40.0	746.0	774.2
12	250.0	.0	44.0	609.2	637.4
13	250.0	.0	48.0	430.4	458.6
14	250.0	.0	52.0	327.9	356.1
15	250.0	.0	56.0	237.7	265.9
16	250.0	.0	60.0	156.5	184.7
17	250.0	.0	64.0	95.5	123.7
18	250.0	.0	68.0	59.4	87.6
19	250.0	.0	72.0	32.8	61.1
20	250.0	.0	76.0	18.8	47.0
21	250.0	.0	80.0	10.3	38.5
22	250.0	.0	84.0	6.1	34.3
23	250.0	.0	88.0	3.3	31.5
24	250.0	.0	92.0	4.3	32.5
25	250.0	.0	96.0	3.1	31.3
26	250.0	.0	100.0	3.0	31.2
27	250.0	.0	104.0	3.0	31.2
28	250.0	.0	108.0	3.1	31.3
29	250.0	.0	112.0	3.1	31.4
30	250.0	.0	116.0	3.5	31.7
35	250.0	.0	18.0	925.7	953.9
36	250.0	.0	22.0	1003.1	1031.3
37	250.0	.0	26.0	1096.7	1124.9
38	250.0	.0	30.0	1036.7	1064.9

RUN NUMBER 11 FILE NAME GEP011.GC
BY NEFF ON 07-10-91
WIND SPEED 250.00 CM/S AT 11.4 CM
AIR TEMP. 27.0 C AT 11.4 CM
SOURCE DESIGNATION 1
SOURCE FLOW RATE (CCS) 530.2
SOURCE GAS TEMPERATURE © 27.0
TRACER TYPE C2H6
TRACER CONCENTRATION (PPM) 1000000.0
BACKGROUND CONCENTRATION (PPM) 25.03

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	125.0	.0	.0	16.6	41.7
2	125.0	.0	4.0	47.5	72.5
3	125.0	.0	8.0	208.0	233.0
4	125.0	.0	12.0	626.4	651.5
5	125.0	.0	16.0	1126.9	1151.9
6	125.0	.0	20.0	2355.5	2380.5
7	125.0	.0	24.0	3058.2	3083.2
8	125.0	.0	28.0	3152.7	3177.7
9	125.0	.0	32.0	2681.4	2706.4
10	125.0	.0	36.0	1987.0	2012.0
11	125.0	.0	40.0	1211.2	1236.2
12	125.0	.0	44.0	692.5	717.5
13	125.0	.0	48.0	296.2	321.3
14	125.0	.0	52.0	129.5	154.5
15	125.0	.0	56.0	56.1	81.1
16	125.0	.0	60.0	22.4	47.4
17	125.0	.0	64.0	6.6	31.6
18	125.0	.0	68.0	3.3	28.4
19	125.0	.0	72.0	2.9	27.9
20	125.0	.0	76.0	3.0	28.0
21	125.0	.0	80.0	2.6	27.6
22	125.0	.0	84.0	2.4	27.4
23	125.0	.0	88.0	2.4	27.5
24	125.0	.0	92.0	3.4	28.5
25	125.0	.0	96.0	2.3	27.3
26	125.0	.0	100.0	2.3	27.3
27	125.0	.0	104.0	2.4	27.5
28	125.0	.0	108.0	2.4	27.5
29	125.0	.0	112.0	2.2	27.2
30	125.0	.0	116.0	2.5	27.5
33	125.0	.0	10.0	340.3	365.4
34	125.0	.0	14.0	917.2	942.2
35	125.0	.0	18.0	1775.3	1800.3
36	125.0	.0	22.0	2717.2	2742.2
37	125.0	.0	26.0	3088.6	3113.6
38	125.0	.0	30.0	2948.6	2973.6
39	125.0	.0	34.0	2272.7	2297.7
40	125.0	.0	38.0	1556.5	1581.5

```
RUN NUMBER 12          FILE NAME GEP012.GC
BY NEFF     ON 07-11-91
WIND SPEED 250.00 CM/S AT   11.4 CM
AIR TEMP.   27.0  C    AT   11.4 CM
SOURCE DESIGNATION                1
SOURCE FLOW RATE (CCS)          530.2
SOURCE GAS TEMPERATURE ©         27.0
TRACER TYPE                      C2H6
TRACER CONCENTRATION (PPM)  1000000.0
BACKGROUND CONCENTRATION (PPM)  37.12
```

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	375.0	-8.0	26.0	612.1	649.2
2	375.0	-4.0	26.0	628.8	665.9
3	375.0	.0	26.0	635.3	672.4
4	375.0	4.0	26.0	646.0	683.1
5	375.0	8.0	26.0	533.0	570.1
6	375.0	12.0	26.0	640.0	677.1
7	375.0	16.0	26.0	601.0	638.1
8	375.0	20.0	26.0	537.5	574.6
9	375.0	24.0	26.0	470.5	507.6
10	375.0	28.0	26.0	411.5	448.6
11	375.0	32.0	26.0	345.7	382.8
12	375.0	36.0	26.0	289.8	327.0
13	375.0	40.0	26.0	212.9	250.0
14	375.0	44.0	26.0	162.0	199.1
15	375.0	48.0	26.0	126.9	164.0
16	375.0	52.0	26.0	88.6	125.7
17	375.0	56.0	26.0	58.5	95.6
18	375.0	60.0	26.0	35.2	72.3
19	375.0	64.0	26.0	26.7	63.9
20	375.0	68.0	26.0	17.7	54.8
21	375.0	72.0	26.0	11.1	48.3
22	375.0	76.0	26.0	6.6	43.7
23	375.0	80.0	26.0	4.2	41.3
24	375.0	84.0	26.0	3.7	40.9
25	375.0	88.0	26.0	1.4	38.5
26	375.0	92.0	26.0	1.2	38.3
27	375.0	96.0	26.0	.8	37.9
28	375.0	100.0	26.0	.8	38.0
29	375.0	104.0	26.0	.6	37.7
30	375.0	108.0	26.0	.8	37.9
31	375.0	-6.0	26.0	582.0	619.1
32	375.0	-2.0	26.0	596.3	633.4
33	375.0	2.0	26.0	611.9	649.0
34	375.0	6.0	26.0	621.8	658.9
35	375.0	10.0	26.0	610.7	647.8
36	375.0	14.0	26.0	594.5	631.6

```
RUN NUMBER 13              FILE NAME GEP013.GC
BY NEFF     ON 07-11-91
WIND SPEED 250.00 CM/S AT    11.4 CM
AIR TEMP.    27.0  C    AT    11.4 CM
SOURCE DESIGNATION                   1
SOURCE FLOW RATE (CCS)           530.2
SOURCE GAS TEMPERATURE ©          27.0
TRACER TYPE                       C2H6
TRACER CONCENTRATION (PPM)   1000000.0
BACKGROUND CONCENTRATION (PPM)   24.34
```

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	250.0	-8.0	26.0	1087.1	1111.4
2	250.0	-4.0	26.0	1129.9	1154.2
3	250.0	.0	26.0	1157.2	1181.5
4	250.0	4.0	26.0	1090.4	1114.7
5	250.0	8.0	26.0	867.0	891.3
6	250.0	12.0	26.0	886.1	910.4
7	250.0	16.0	26.0	780.1	804.5
8	250.0	20.0	26.0	616.0	640.3
9	250.0	24.0	26.0	502.6	526.9
10	250.0	28.0	26.0	392.6	416.9
11	250.0	32.0	26.0	279.6	303.9
12	250.0	36.0	26.0	192.9	217.3
13	250.0	40.0	26.0	120.1	144.4
14	250.0	44.0	26.0	80.6	104.9
15	250.0	48.0	26.0	56.0	80.3
16	250.0	52.0	26.0	36.6	60.9
17	250.0	56.0	26.0	18.4	42.7
18	250.0	60.0	26.0	9.5	33.8
19	250.0	64.0	26.0	4.8	29.2
20	250.0	68.0	26.0	2.1	26.5
21	250.0	72.0	26.0	1.9	26.3
22	250.0	76.0	26.0	1.1	25.4
23	250.0	80.0	26.0	.9	25.2
24	250.0	84.0	26.0	1.6	25.9
25	250.0	88.0	26.0	.7	25.1
31	250.0	-6.0	26.0	1037.2	1061.5
32	250.0	-2.0	26.0	1065.6	1089.9
33	250.0	2.0	26.0	1090.5	1114.8
34	250.0	6.0	26.0	1011.5	1035.8
35	250.0	10.0	26.0	938.5	962.8
36	250.0	14.0	26.0	797.6	821.9
37	250.0	18.0	26.0	653.6	677.9
38	250.0	22.0	26.0	526.3	550.7
39	250.0	26.0	26.0	421.6	445.9
40	250.0	30.0	26.0	324.8	349.1

RUN NUMBER 14 FILE NAME GEP014.GC
BY NEFF ON 07-11-91
WIND SPEED 250.00 CM/S AT 11.4 CM
AIR TEMP. 27.0 C AT 11.4 CM
SOURCE DESIGNATION 1
SOURCE FLOW RATE (CCS) 530.2
SOURCE GAS TEMPERATURE © 27.0
TRACER TYPE C2H6
TRACER CONCENTRATION (PPM) 1000000.0
BACKGROUND CONCENTRATION (PPM) 23.08

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	125.0	-8.0	26.0	2810.8	2833.8
2	125.0	-4.0	26.0	3030.0	3053.0
3	125.0	.0	26.0	3062.0	3085.0
4	125.0	4.0	26.0	2671.2	2694.2
5	125.0	8.0	26.0	1876.0	1899.0
6	125.0	12.0	26.0	1487.5	1510.5
7	125.0	16.0	26.0	859.1	882.2
8	125.0	20.0	26.0	453.1	476.2
9	125.0	24.0	26.0	207.5	230.6
10	125.0	28.0	26.0	106.4	129.5
11	125.0	32.0	26.0	49.3	72.4
12	125.0	36.0	26.0	20.2	43.3
13	125.0	40.0	26.0	5.3	28.4
14	125.0	44.0	26.0	2.8	25.9
15	125.0	48.0	26.0	1.7	24.7
16	125.0	52.0	26.0	1.5	24.6
17	125.0	56.0	26.0	1.4	24.5
18	125.0	60.0	26.0	1.3	24.4
19	125.0	64.0	26.0	1.0	24.0
20	125.0	68.0	26.0	3.5	26.6
21	125.0	72.0	26.0	.9	24.0
22	125.0	76.0	26.0	.8	23.9
23	125.0	80.0	26.0	.9	23.9
24	125.0	84.0	26.0	9.5	32.5
25	125.0	88.0	26.0	.8	23.9
31	125.0	-6.0	26.0	2756.6	2779.6
32	125.0	-2.0	26.0	2925.5	2948.5
33	125.0	2.0	26.0	2801.0	2824.0
34	125.0	6.0	26.0	2334.0	2357.0
35	125.0	10.0	26.0	1801.7	1824.7
36	125.0	14.0	26.0	1183.9	1207.0
37	125.0	18.0	26.0	645.1	668.2
38	125.0	22.0	26.0	318.7	341.8
39	125.0	26.0	26.0	149.5	172.6
40	125.0	30.0	26.0	76.8	99.9

```
RUN NUMBER 15                FILE NAME GEP015.GC
BY NEFF      ON 07-11-91
WIND SPEED 250.00 CM/S AT    11.4 CM
AIR TEMP.   27.0  C    AT    11.4 CM
SOURCE DESIGNATION                   1
SOURCE FLOW RATE (CCS)             530.2
SOURCE GAS TEMPERATURE ©          27.0
TRACER TYPE                       C2H6
TRACER CONCENTRATION (PPM)     1000000.0
BACKGROUND CONCENTRATION (PPM)      23.50
```

TUBE NO.	X (cm)	Y (cm)	Z (cm)	CONCENTRATIONS (PPM) Source 1	Tracer 1
1	50.0	.0	.0	.5	24.0
2	75.0	.0	.0	.0	20.0
3	100.0	.0	.0	1.6	25.1
6	175.0	.0	.0	54.0	77.5
7	200.0	.0	.0	125.1	148.6
8	225.0	.0	.0	173.7	197.2
9	250.0	.0	.0	240.6	264.1
10	275.0	.0	.0	286.7	310.2
11	300.0	.0	.0	338.5	362.0
12	325.0	.0	.0	366.3	389.8
13	350.0	.0	.0	386.7	410.2
14	375.0	.0	.0	400.4	423.9
15	400.0	.0	.0	411.6	435.1
16	425.0	.0	.0	430.1	453.6
17	450.0	.0	.0	431.7	455.2
18	475.0	.0	.0	429.3	452.8
19	500.0	.0	.0	426.2	449.7
20	525.0	.0	.0	419.7	443.2
21	125.0	-15.0	.0	13.3	36.8
22	125.0	-10.0	.0	29.1	52.6
23	125.0	-5.0	.0	46.7	70.2
24	125.0	5.0	.0	28.1	51.6
25	125.0	10.0	.0	12.6	36.1
26	125.0	15.0	.0	4.2	27.7
27	250.0	-15.0	.0	183.1	206.6
28	250.0	-10.0	.0	219.0	242.5
29	250.0	-5.0	.0	242.3	265.8
30	250.0	5.0	.0	246.1	269.6
31	250.0	10.0	.0	234.5	258.0
32	250.0	15.0	.0	205.2	228.7
33	375.0	-15.0	.0	343.1	366.6
34	375.0	-10.0	.0	375.8	399.3
35	375.0	-5.0	.0	396.6	420.1
36	375.0	5.0	.0	395.6	419.1
37	375.0	10.0	.0	376.5	400.0
38	375.0	15.0	.0	336.9	360.4
39	500.0	-15.0	.0	367.7	391.2
40	500.0	-10.0	.0	401.0	424.5
41	500.0	-5.0	.0	418.6	442.1
42	500.0	5.0	.0	418.5	442.0
43	500.0	10.0	.0	398.5	422.0
44	500.0	15.0	.0	350.3	373.8

APPENDIX D: FACILITIES AND TECHNIQUES

1 FLUID DYNAMICS AND DIFFUSION LABORATORY

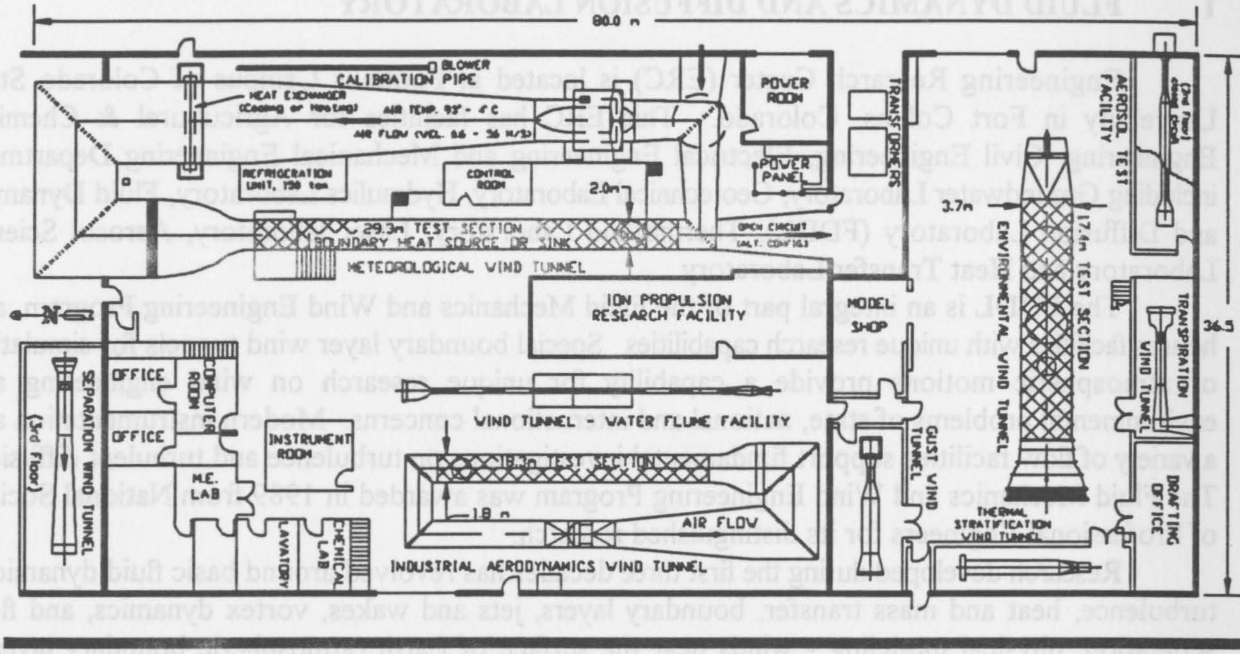
Engineering Research Center (ERC) is located at Foothills Campus of Colorado State University in Fort Collins, Colorado. This ERC has facilities for Agricultural & Chemical Engineering, Civil Engineering, Electrical Engineering and Mechanical Engineering Department including Groundwater Laboratory, Geotechnical Laboratory, Hydraulics Laboratory, Fluid Dynamics and Diffusion Laboratory (FDDL), Thermofluid Laboratory, Laser laboratory, Aerosol Science Laboratory and Heat Transfer Laboratory.

The FDDL is an integral part of the Fluid Mechanics and Wind Engineering Program, and houses facilities with unique research capabilities. Special boundary layer wind tunnels for simulation of atmospheric motions provide a capability for unique research on wind engineering and environmental problems of state, national and international concerns. Modern instrumentation and a variety of flow facilities support fundamental investigations on turbulence and turbulent diffusion. The Fluid Mechanics and Wind Engineering Program was awarded in 1989 from National Society of Professional Engineers for its distinguished research.

Research developed during the first three decades has revolved around basic fluid dynamics - turbulence, heat and mass transfer, boundary layers, jets and wakes, vortex dynamics, and flow separation; physical modeling - winds near the surface of Earth (atmospheric boundary layers), atmospheric diffusion, and mountain and urban winds; basic studies in aerosol mechanics - particle generation techniques, sampling and collection investigations, development of ambient aerosol samplers and fractional systems, behavior of particles in turbulent shear flows, deposition of particles in plant canopies; wind engineering - air pollution control, behavior of smoke plumes from power plant stacks, hazard analysis of liquid natural gas (LNG) storage, industrial aerodynamics, environmental design for urban centers, wind power, heat transfer from buildings, and wind forces on buildings and bridges; turbomachinery - effects of turbulence on the performance of blade cascades; and instrumentation - aerosol and tracer gas concentration sensors and hot wire anemometry. Research in these areas is sponsored primarily by the National Science Foundation, the Office of Naval Research, Project SQUID, the National Aeronautics and Space Administration, the Department of Energy, the Gas Research Institute, the Department of Transportation, the Nuclear Regulatory Commission, the Environmental Protection Agency, and the Electric Power Research Institute.

Research in the Program is complemented by a wide variety of laboratory investigations of wind forces on structures, atmospheric diffusion, and other wind engineering problems associated with the design and planning of major engineering projects. These investigations, sponsored by leading consulting and industrial firms throughout the country, utilize many of the research results obtained by the Program staff and students and help identify areas that will be productive for new research.

The following figure shows the plan view layout of the FDDL laboratory facilities including the meteorological wind tunnel, environmental wind tunnel and industrial aerodynamics wind tunnel.



Fluid Dynamics and Diffusion Laboratory Layout

The unique meteorological wind tunnel has an overall length of 200 feet with a 6-foot by 6-foot test or working section 100 feet long. Heating and cooling of air in the 18-foot by 18-foot return flow section of the recirculating tunnel provides extreme flexibility for simulating a wide range of atmospheric thermal stratifications, as well as elevated inversions. This thermal control, coupled with well-controlled flow speeds from 0.0 to 100 miles per hour and a long test section, enables boundary layer flows similar to those found in the real atmosphere to be modeled with accuracy. Thus, this facility provides an ideal medium for fundamental studies on the relationship of mean wind speed and turbulence to surface roughness, thermal stratification and topography. On the other hand, the simulation of natural winds for specific sites provides an ideal means for physical modeling of wind effects on existing or proposed buildings, urban developments, or any other of man's activities on earth's surface.

The FDDL houses an environmental wind tunnel with working section 60 feet long and a cross section of 12 by 8 feet. Using wind speed from 0.5 miles per hour up to 34 miles per hour, this facility provides excellent capability for investigation of wind effects on large areas. Dispersion of cloud seeding materials over mountain ranges, dispersion of automobile exhaust in new urban developments and existing cities, effects of buildings and topography on power plant plumes, and heat island effects over large urban areas have been investigated successfully in this facility.

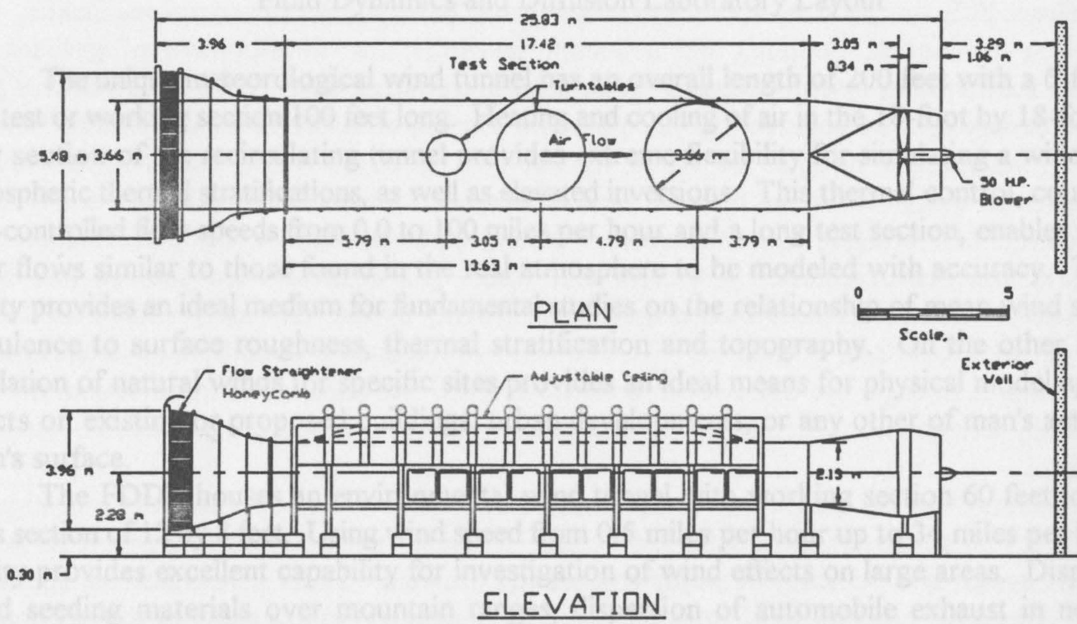
The industrial aerodynamics wind tunnel with a working section 60 feet long and 6 feet by 6 feet in cross section provides additional capabilities for basic studies of boundary layer characteristics. Many studies of evaporation from soil and water surfaces, wind pressures on model structures, ventilation of buildings, and the movement of soil and snow by wind have been made in this wind tunnel, which has a speed range of 1 to 70 miles per hour.

A gust wind tunnel equipped with two arrays of oscillating air foils provides opportunities for research on the effects of turbulence scale on the aerodynamics of bluff bodies and aerodynamic stability of long-span bridge decks.

Instrumentation for measurement of flow variables and tracer gas concentrations is available to support either the most advanced studies on turbulence and diffusion or the applied investigations of wind engineering. This instrumentation includes hot wire anemometer system; electronic pressure transducers and meters; aerosol, radioactive gas, and helium and hydrocarbon concentration measurement systems; optical systems; and strain gage balances. Data processing equipment includes analog-to-digital converters connected to PC, AT and 386 type computer, spectral analyzers, probability density analyzers, and a variety of special purpose systems. Additional data processing and numerical analyses are accomplished on the University CDC 170 model 720 digital computer, or the CRAY 1 digital computer of the National Center for Atmospheric Research (NCAR). Recording capabilities are provided by 50 FM magnetic tape channels, 25 digital tape channels, floppy disks, and a variety of motion and still picture cameras.

2 ENVIRONMENTAL WIND TUNNEL DESCRIPTION

This wind tunnel, especially designed to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling, a rotating turntable and a long test section to permit adequate reproduction of micrometeorological behavior. Mean wind speeds of 0 to 15 m/sec in the EWT can be obtained. A boundary-layer thickness up to 1.5 m can be developed over the downwind portion of the EWT test section by using vortex generators at the test section entrance and surface roughness on the floor. The flexible test section on the EWT roof is adjustable in height to permit the longitudinal pressure gradient to be set at zero.



Environmental Wind Tunnel Schematic

3 WIND SPEED MEASUREMENT DESCRIPTION

3.1 Velocity Standards

3.1.1 *CSU Mass Flow System*

The velocity standard used in the present study consisted of a Omega Model FMA-78P4 mass controller and a profile conditioning section designed and calibrated by the Fluid Dynamics and Diffusion (FDDL) staff at Colorado State University (CSU). The mass flow controller sets mass flow rate independent of temperature and pressure. The profile conditioning section forms a flat velocity profile of very low turbulence at the position where the hot-film-probe is located. Incorporating a measurement of the ambient atmospheric pressure, temperature and a profile correction factor permits the calibration of velocity at the measurement station from 0.1 - 2.0 m/s to within ± 5 percent and from 2.0 - 4.7 m/s to within ± 3 percent. This calibration nozzle is mounted on two computer controlled rotary tables for precise flow angle calibrations of multi-film probes.

3.1.2 *TSI Calibrator*

The TSI Model 1125 Velocity Calibrator System is designed to calibrate hot wire and hot film sensors over wide ranges of velocities. It is primarily for air but can also be modified for use in water and other fluids. In air the velocity range is from approximately 0.1 m/s to 305 m/s. This wide range can be covered using manometers with a range of 0.5 inch of water to approximately 400 inch of water (30 inch of mercury). The calibrator has been designed to be as simple and flexible as possible, while still maintaining good calibration accuracy.

In using the calibrator for air, the unit can be connected to a shop compressed air line. An On-Off line valve, pressure regulator, needle valve, and a heat exchanger are installed in line with the calibrator. This arrangement gives good control of the velocity through the calibrator. Essentially the same arrangement can be used for calibrating in other gases. Rather than the compressed air line the source can be a tank of bottled gas or other convenient supply.

The accuracy of the system is primarily dependent on the accuracy of the pressure measurement. When using the inside chambers with the exterior nozzle in place, the accuracy is ± 2 percent down to 3 m/s. Below 3 m/s, the accuracy is ± 5 percent down to approximately 0.1 m/s. Below 0.1 m/s, approximately ± 10 percent accuracy can be expected.

3.1.3 *Pitot Probe*

Pitot-static probes are used as a velocity standard during the calibration of the different hot film systems and to provide the reference upwind velocity measurement. The principles of operation of pitot-static probes are described in any fundamental text on fluid mechanics and will not be discussed in detail here. The operational relationship for these probes is $U = (2g_c\Delta P/\rho)^{1/2}$, where U = velocity, g_c = gravitational conversion constant, ΔP = difference between static and stagnation pressures, and ρ is the air density. ρ is calculated from ideal gas law and ΔP is measured using a Datametrics Electronic Manometer. The pitot-static probe measurements are accurate to within ± 2 percent of the actual velocity.

3.2 Single-Hot-Film Probe Measurements

Single-hot-film (TSI 1220 Sensor) measurements are used to document the longitudinal turbulence levels. During calibration the probe voltages are recorded at several velocities covering the range of interest. These voltage-velocity (E,U) pairs are then regressed to the equation $E^2 = A + BU^c$ via a least squares approach for various assumed values of the exponent c. Convergence to the minimum residual error was accelerated by using the secant method to find the best new estimate for the exponent c.

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

Error Statement

The calibration curve yields hot film anemometer velocities that were always within 2 percent of the known calibrator velocity. Considering the accumulative effect of calibrator, calibration curve fit and other errors the model velocity time series should be accurate to within 5 percent.

3.3 Cross-Film Probe Measurements

Cross-film measurements are used to document longitudinal, lateral and vertical turbulence levels along with cross-component correlations such as Reynolds stresses.

During the calibration of the TSI 1241 X-film probe it is placed at the nozzle of the calibrator with the probe support axis parallel to air flow. In this position the angle between each sensor and the flow vector is 45°. Thus, the yaw angles for each sensor are 45°. The voltage from each anemometer channel are digitized for several velocities covering the range of interest. These voltage-velocity pairs (E_i, U_i; i = 1,2), at a fixed angle, are fit to the equation

$$E_{i,j}^{\,2} = A_i + B_i'(U_j)^{ci}\ ;\ i = 1,2;\ j = 1,n$$

where $B_i' = B_i(\cos^2\phi_i + k^2\sin^2\phi_i)^{ci/2}$

ϕ_i = yaw angle between velocity vector and film i

k = yaw factor

n = number of the calibration points

via a least squares fit with the secant method to find the best new estimate of exponent, c_i.

Note that if the yaw factor, k, equals zero then a sample cosine law dependence of the heat flux exists. To determine the yaw factor, k, the air velocity is set at a constant value, and the probe is rotated about its third axis so that voltage samples are taken for a wide range of yaw angle variation on both films. These voltage-yaw angle pairs, (E_i, ϕ_i; i = 1,2) are regressed to the equation

$$B_i' = (E_{i,j}^{\,2} - A_i)/U^{ci} = B_i(\cos^2\phi_{i,j} + k_i^2\sin^2\phi_{i,j})^{ci/2}$$

where i = 1,2 and j = 1,n

via a least squares approach with the secant method to find the best new estimate for the yaw factor,

k_i. A_i, B_i, c_i and k_i for both films are thus obtained. For the reduction algorithm used, k must be equal for both films and not a function of velocity. Providing that both films have similar aspect ratio, then both k_i values should be of similar magnitude; hence, setting them equal does not introduce large errors. Once a value for k is specified then a least squares fit will determine the optimal values for B_i. Once the value of k is determined for a specific probe, it is no longer necessary to perform further angle calibrations.

Given the calibration constants A_i, B_i, and c_i, then the equations

$$E_i^2 = A_i + B_i(V_{eff,i})^{ci} \; ; \; i = 1,2;$$

where $V_{eff,i} = V(\cos^2\phi_i + k^2\sin^2\phi_i)^{1/2}$; $i = 1,2$;

$V_{eff,i}$ = effective cooling velocity for film i, and

V = total velocity vector approaching sensor array

are defined. To take measurements with this calibrated X-film probe, both anemometer signals and the temperature signal are digitized and stored on a disk file within an IBM AT computer. These voltage time series are converted to u and v (or w) velocity time series using the following algorithm proposed by Brunn [1978],

$$u = (V_{eff,1} + V_{eff,2})/[2(\cos^2\alpha + k^2\sin^2\alpha)^{1/2}],$$

$$v \text{ (or } w) = (V_{eff,1} \;\; V_{eff,2})/[(\cos^2\alpha + k^2\sin^2\alpha)^{1/2} A \tan\alpha],$$

where $A = \cos^2\alpha(1-k^2)/[\cos^2\alpha(1 - k^2) + k^2]$,

$$\alpha = 45°,$$

$$V_{eff,i} = [E_i^2 - A_i^*)/B_i^*]^{1/ci},$$

$$A_i^* = A_i T_{factor}, \quad B_i^* = B_i T_{factor},$$

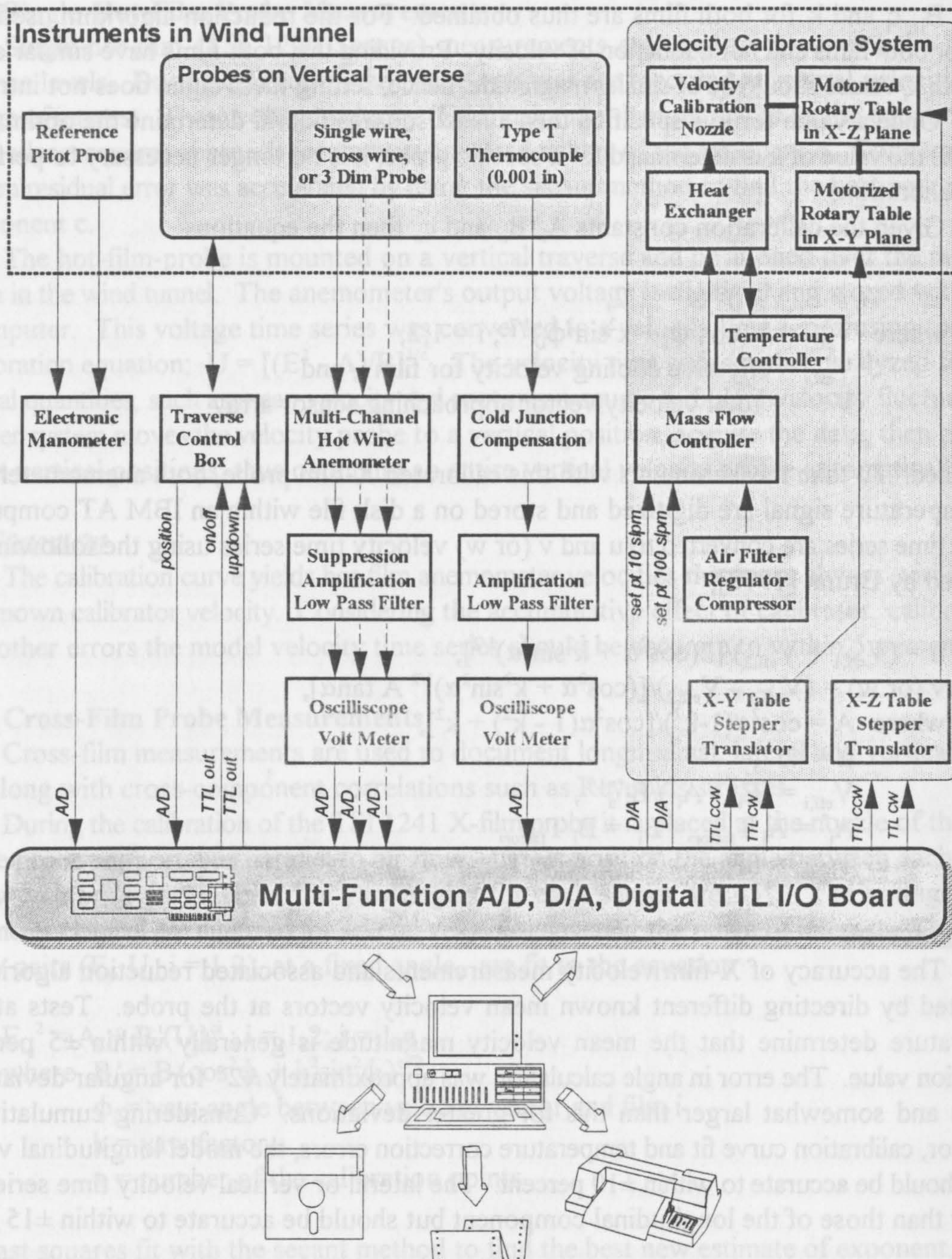
$$T_{factor} = (T_{sensor} - T_{environment})/(T_{sensor} - T_{calibration}).$$

Error Statement

The accuracy of X-film velocity measurements and associated reduction algorithms can be estimated by directing different known mean velocity vectors at the probe. Tests at calibration temperature determine that the mean velocity magnitude is generally within ±5 percent of the calibration value. The error in angle calculation was approximately ±2° for angular deviations of 15° or less and somewhat larger than this for greater deviations. Considering cumulative effect of calibrator, calibration curve fit and temperature correction errors, the model longitudinal velocity time series should be accurate to within ±10 percent. The lateral or vertical velocity time series errors are greater than those of the longitudinal component but should be accurate to within ±15 percent.

3.4 Velocity Measurement System

A flow-logic chart of velocity calibration system, velocity measurement system, and the positioning system with the wind tunnel is displayed in the following figure.



Velocity Calibration and Measurement System

4 FLOW VISUALIZATION TECHNIQUES

4.1 Smoke Generator System

A visible plume is produced by passing the metered simulant gas through a Rosco Model 8215 Fog/Smoke Machine located outside the wind tunnel and then out of the model stack. The plume is illuminated with high intensity back lighting. The visible plumes for each test are recorded on VHS video cassettes with a Panasonic Omnivision II camera/recorder system. Run number titles are placed on the video cassette with a title generator.

4.2 Video Image Analysis System

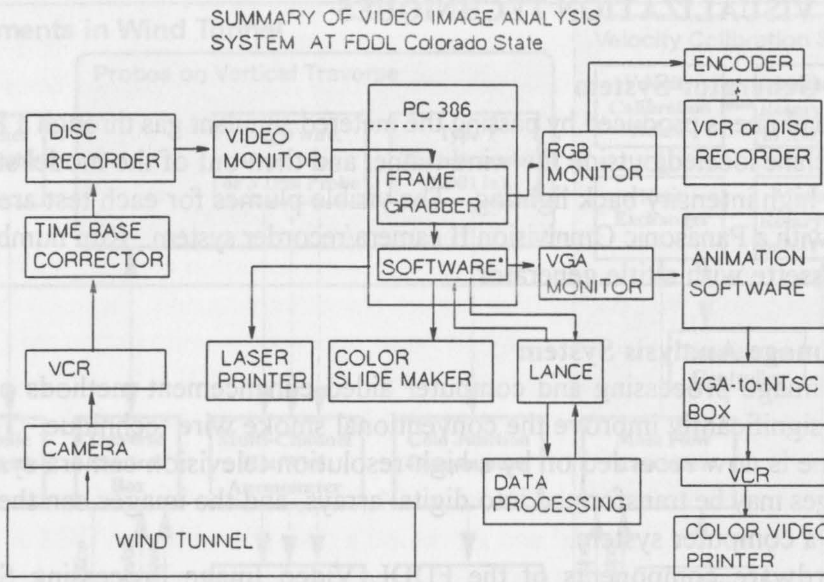
Digital image processing and computer aided enhancement methods provide a means to modernize and significantly improve the conventional smoke wire technique. The visible behavior of the smoke line is now recorded on by a high-resolution television camera system on VCR tape. The analog images may be transformed into digital arrays, and the images can then be enhanced and manipulated by a computer system.

The hardware components of the FDDL Video Image Processing System (VIPS) are presented in the figure on the following page. The image capturing part of the system includes a SVHS camcorder and a four-head one-half inch tape VCR recorder. These images may be edited into convenient sequences using a dual-monitor, dual-SVHS VCR recorder editing system. Unfortunately, most VCR systems can not be controlled well enough to maintain adequate picture registration when advancing frame-by-frame under computer control. Hence, the edited VCR tape must be additionally recorded onto a video disk. Currently this transfer is being accomplished at another laboratory.

Computer control may be used to command a video-disk player to project each individual video frame to a high-resolution video monitor. We use a high-resolution image capturing board installed in a PC-386 compatible microcomputer to digitize the image. A standard NTSC video signal (30 frames/sec) can be digitized with 8-bit precision. The board we use produces an intensity field of 512 x 512 pixels at 256 possible grey levels. Given the image interweaving typical of an NTSC signal the frames can be split to provide images at 60 frames/sec.

Once the video picture is digitized, the image may be enhanced by a) subtracting the background, b) overlaying a coordinate system, c) enhancing front, center, or back edge of the image, or d) assigning colors to different intensity levels. One can also extract edge pixel locations to calculate velocities or combine images to provide animation.

Often it is appropriate to print or restore enhanced images. The FDDL VIPS includes hardware to project the image to a RGB or VGA monitor; store the digital image to floppy or hard disks, streaming tapes, optical digital disk, or on network file-servers; or print to a laser printer or color slide maker. Alternatively, a VGA-to-NTSC hardware card can reformulate the signal to record to a conventional VCR or a color video printer.



Video Image Analysis System

5 CONCENTRATION MEASUREMENT DESCRIPTION

The experimental measurements of concentration were performed using a Hewlett Packard gas-chromatograph and a sampling systems designed by Fluid Dynamics and Diffusion Laboratory staff.

5.1 Gas Chromatograph

A gas chromatograph (Hewlett-Packard Model 5710A) (GC) with flame ionization detector (FID) operates on the principle that the electrical conductivity of a gas is directly proportional to the concentration of charged particles within the gas. The ions in this case are formed by the burning a mixture of hydrogen and the sample gas in the FID. The ions and electrons formed pass between an electrode gap and decrease the gap resistance. The resulting voltage drop is amplified by an electrometer and passed to a Hewlett-Packard Model 3390A integrator. When no effluent gas is flowing, a carrier gas (nitrogen) flows through the FID. Due to certain impurities in the carrier, some ions and electrons are formed creating a background voltage or zero shift. When the effluent gas enters the FID, the voltage increase above this zero shift is proportional to the degree of ionization or correspondingly the amount of tracer gas present. Since the chromatograph used in this study features a temperature control on the flame and electrometer, there is very low drift of the zero shift. Even given any zero drift, the HP 3390A, which integrates the effluent peak, also subtracts out the zero drift.

The lower limit of measurement is imposed by the instrument sensitivity and the background concentration of tracer within the air in the wind tunnel. Background concentrations are measured and subtracted from all data.

5.2 Sampling System

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

The sampling system is periodically calibrated to insure proper function of each of the valves and tubing assemblies. To calibrate the sampler each intake is connected to a manifold. The manifold, in turn, is connected to a gas cylinder having a known concentration of tracer gas. The gas is turned on, and a valve on the manifold is opened to release the pressure produced in the manifold. The manifold is allowed to flush for about one minute. Normal sampling procedures are carried out during calibration to insure exactly the same procedure is reproduced as when taking a sample from the tunnel. Each sample is then analyzed for tracer gas concentration. Percent error is calculated, and "bad" syringe/tube systems (error > 2 percent) are not used or repaired.

<u>*Test Procedure*</u>

The test procedure consisted of:

1) Setting the proper tunnel wind speed,
2) Releasing the metered mixtures of source gas from the plant stack,

3) Withdrawing samples of air from the tunnel designated locations, and
4) Analyzing the samples with a FID.

The samples were drawn into each syringe over an ~200 second (adjustable) time period and then consecutively injected into the GC.

The procedure for analyzing the samples from the tunnel is:

1) Introduce the sample into the GC which separates the ethane tracer gas from other hydrocarbons,
2) The voltage output from the chromatograph FID electrometer is sent to the HP 3390A Integrator,
3) the HP 3390A communicates the measured concentration in ppm to an IBM computer for storage, and
4) These values, χ_{mea} along with the response levels for the background χ_{bg} and source χ_{source} are converted into source normalized model concentration by the equation:
$$\chi_m = (\chi_{mea}-\chi_{bg})/(\chi_{source}-\chi_{bg})$$
5) Field equivalent concentration values are related to model values by the equation:
$$\chi_p = \frac{\chi_m}{\chi_m + (1-\chi_m)[V(T_a/T_s)]_m/[V(T_a/T_s)]_p}$$
where $V = Q/U_H L^2$

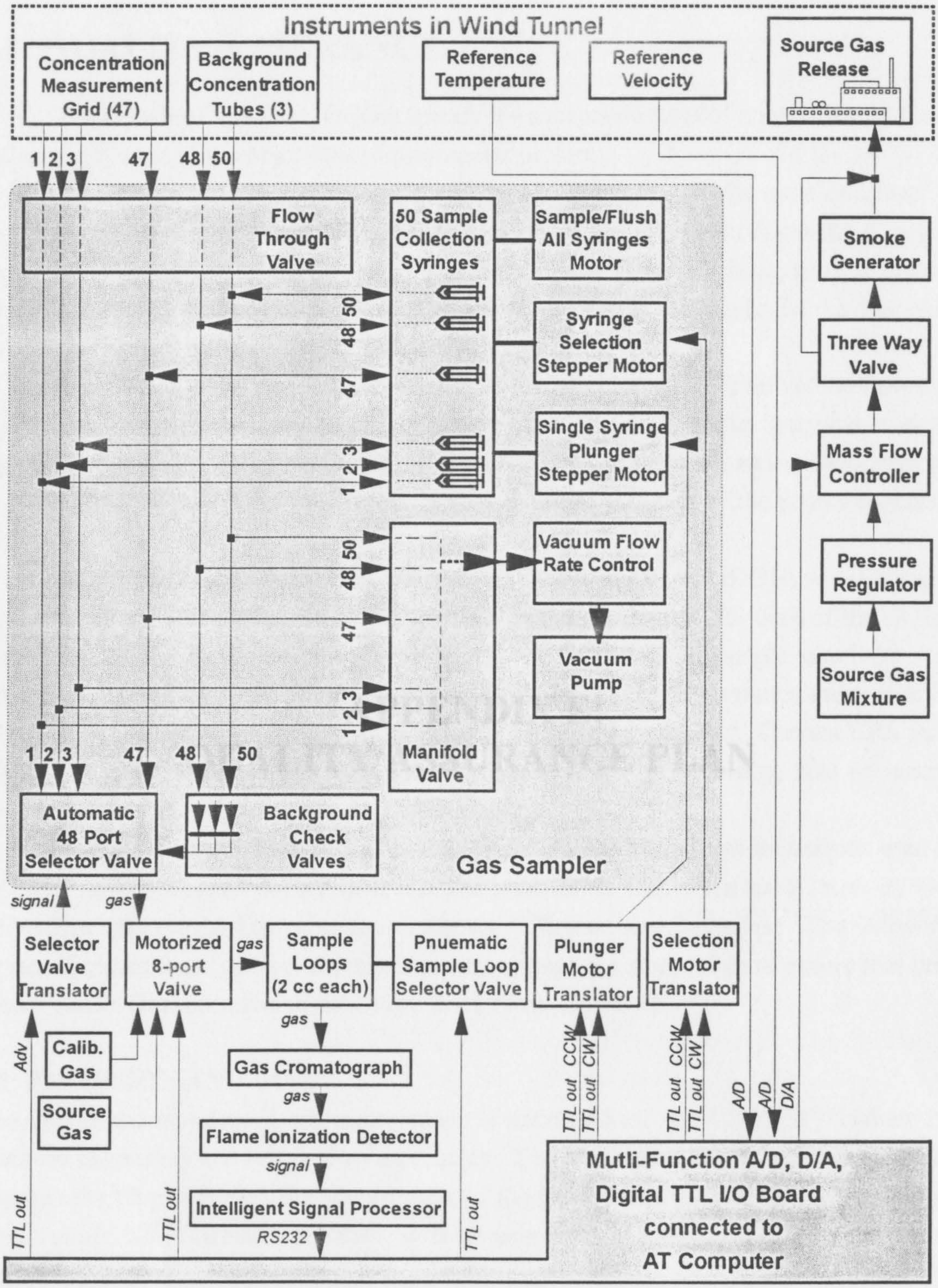
and L is the characteristic length scale. When there is no distortion in the model-field volume flux ratio, V, and the plumes are isothermal this equation reduces to $\chi_p = \chi_m$.

Error Statement

Background concentrations, χ_{bg}, (the result of previous tests within the laboratory), are measured to an accuracy of 20 percent. The larger measured concentrations, χ_{mea}, are accurate to 2 percent. The source gas concentration, χ_{source}, is known to within 10 percent. Thus the source normalized concentration for $\chi_{mea} >> \chi_{bg}$ is accurate to approximately 3 percent. For low concentration values, $\chi_{mea} > \chi_{bg}$, the errors are larger.

5.3 Concentration Measurement System

A flow-logic chart of the source gas release, gas sampling, and concentration measurement systems is displayed in the following figure.



Concentration Sampling and Measurement System Schematic

APPENDIX E:
QUALITY ASSURANCE PLAN

1.0 QUALITY ASSURANCE

Data Quality Objectives (DQOs) specify the acceptable level of uncertainty in data being collected, in view of the objectives of a particular project.

In the current project, there are two issues which the DQOs must consider: 1) the accuracy, representativeness, etc., with which the wind tunnel in fact reproduces the flow patterns and plume dispersion that would in fact exist in the field; and 2) the precision, accuracy, etc., with which the sampling and analysis techniques in fact reveal what is existing in the wind tunnel. The QA on this project must address both of these issues.

The overall DQOs for this project are: 1) the wind tunnel must reflect the flow patterns and plume dispersions that would be expected in the field within reasonable accuracy, representativeness, and comparability; and 2) the tracer gas sampling and analysis system must be able to detect tracer gas concentrations equal to 0.1% to 0.005 % of the source concentration with a confidence of ±5 %.

In the Quality Assurance Project Plan, Data Quality Indicators (DQIs) are selected which serve as a measure of whether the DQOs are being met. Goals are set for each of the DQIs, such that if these DQI goals are met, the project DQOs will be met. For example, one DQI would be the analytical accuracy of the GC/FID in measuring tracer gas concentrations; the corresponding DQI goal would be the specific analytical accuracy that is to be achieved. Current EPA guidance (QAMS 005/80) specifies that DQI goals be set in terms of: precision; bias (or accuracy); completeness; representativeness; and comparability.

Table 1 lists the DQI goals for the wind tunnel measurement techniques used in this project. The footnotes to the table list the procedures that were used (such as GC/FID calibrations with standard gases) to ensure that the DQI goals were being met. The following text further discusses these goals and procedures, along with the steps taken to ensure that the wind tunnel was in fact reproducing field experience reasonably well.

1.1 PRECISION AND BIAS

The combined uncertainty U_c of a measurement is calculated as: $U_c = (P^2 + B^2)^{1/2}$ where P is the precision uncertainty and B is the bias uncertainty. The precision uncertainty, P, about a nominal result is the 95 percent confidence estimate of the band within which the mean of many such results would fall. The bias uncertainty, B, is an estimate of the magnitude of the fixed, constant error.

The uncertainties U_c in the velocity and turbulence measurements (with the hot-film anemometer and the pitot-static probe) are presented in Table 1. For the velocity and turbulence measurements, the accuracy of the hot-film anemometer was determined by calibrations, before and after velocity profile measurements, using a pitot tube. Duplicate measurements determined the precision. These accuracy and precision results confirmed that the uncertainty, U_c, in the hot-film anemometer measurements was within the DQI goal of ±10% shown in Table 1.

The pitot-static probe system was calibrated through the manufacturer. The pitot probe was reported by the manufacturer to meet the DQI goals.

The accuracy of the GC/FID was determined through direct injection of standard gases. A standard gas containing 76.4 ppm ethane was used daily; a second gas, containing 200 ppm ethane, was also used occasionally. The FID responses to the 76.4 ppm gas remained within ±0.75 ppm during the entire test period, confirming that accuracy and precision goals were being met.

The accuracy and precision of the automated multi-syringe sampling system was determined by sampling a standard gas sample, 200 ppm ethane, with all 50 syringes. The results from this test showed no bias in the sampling system and yielded a random error of ±1%.

The resulting combined uncertainty in the tracer gas sampling and analysis was acceptably close to the DQI goal for the GC/FID system in Table 1. The system measured 0.1 % of the source concentration (i.e., 0.1 % of pure ethane, or 1000 ppm) within an uncertainty on the order of ±3 %, and 0.005 % of the source concentration (50 ppm) within an uncertainty of ±3 %, consistent with the DQO.

During the tracer gas sampling, in addition to the designated location samples drawn from the wind tunnel model, three samples were drawn from upwind of the model to provide background ethane concentrations in the Laboratory.

1.2 COMPLETENESS OF DATA ACQUISITION

Since the goal of this project is to achieve the highest degree of completeness, all measurement devices were logged at the time of use on this project. The loss of any data may be due to recorder errors, empty paper rolls, thermal drift, or an operator error. Fortunately, few data were lost in both the velocity and the concentration tests. In some cases, the tests or measurements were repeated if the loss of data had a major effect.

Completeness was better than 98%, in accordance with the goals in Table 1.

1.3 REPRESENTATIVENESS

Wind tunnel modeling is based on the principle that full-scale and model flows can be related through appropriate simulation parameters. As discussed in the Atmospheric Dispersion Comparability Tests (ADCT) document extensive testing was conducted prior to initiation of the main test effort to demonstrate that both the velocity and turbulence profiles in the wind tunnel, and the standard plume concentration profiles, were representative of what would be expected in the field. These tests were designed to show that the wind tunnel boundary layer represents a reasonable approximation of the atmospheric surface layer in the field. They were also designed to show that the normalized velocity profiles are independent of the Reynolds number (the absolute value of the wind speed U), as suggested by EPA (EPA 1981), and that concentration profiles are also independent of U as long as the W/U ratio remains the same.

The ADCT document explains the wind tunnel boundary layer configuration tests and the Reynolds number invariance tests, confirming the representativeness of both velocity and concentration.

These results indicate that the wind tunnel is reasonably representative of expected field experience.

1.4 COMPARABILITY

Measurements made from an isolated source within the simulated atmospheric boundary layer were compared with the characteristic growth of height and width and the decay of concentrations as predicted by the Pasquill-Gifford open dispersion model. The results demonstrate that Pasquill-Gifford C-D behavior was obtained.

1.5 QA AUDITS

No independent quality assurance audits were conducted during this project.

1.6 CORRECTIVE ACTION

The quality assurance efforts under this project resulted in the need for very little corrective action. In a few isolated cases, improper data entry had to be corrected.

1.7 CONCLUSIONS

The preceding discussion shows that the DQI goals in Table 1 were met.

TABLE 1. QUALITY ASSURANCE: GOALS FOR DATA QUALITY INDICATORS (DQIs)

Measurement Parameter	Precision Accuracy (Bias)	Completeness	Representativeness
Sampling and analysis of tracer gas using GC/FID	± 3%[1,2,3], or 1.5 ppm whichever is greater	≥ 98%[4]	--
Source gas Strength	±0.5%[5]	--	
Source Normalized Concentration	± 5%[1,2,3], or 1.5 ppm whichever is greater	≥ 98%[4]	± 10%[6]
Source Flow Rate	± 5%[9]		
Velocity/ Turbulence measurements with hot-film anemometer	± 10%[7]	≥ 98%[4]	± 5%[6]
Flow measurements using pitot tube	±2%[8]	≥ 98%[4]	--

Footnotes

1. The DQI in this row addresses combined sampling plus analytical error.
2. The analytical accuracy of the GC/FID system was determined daily by direct injection of an standard gas containing 76.4 ppm ethane into the GC. A standard gas containing 200 ppm ethane was also used at the beginning each test series.
3. The combined sampling/analytical accuracy of the automated syringe/tube sampling system and the GC/FID was determined through sampling atmospheres consisting of standard gases: 0, 76.4 and 200 ppm ethane.
4. Very minor data loss occurred during the concentration tests, due to isolated errors in data entry.
5. 100% tracer gas in the source gas was used. The tracer gas is certified through the manufacturer to be 99.5% pure. No independent confirmation of the tracer gas composition was performed.
6. Reynolds Number invariance tests for velocity and concentration would indicate errors of this magnitude (Re# tests not performed in this study, Re magnitudes were sufficiently large to maintain this level of representativeness).
7. The accuracy of the hot-film was determined by calibrations, before and after velocity profile measurements, using a pitot tube.
8. The pitot tube velocity measurement system was calibrated through the manufacturer.
9. The mass flow accuracy is certified through the manufacturer to be ±1% of the units full scale value or ±4% of the flow rate, which ever is greater.