94

# WIND TUNNEL STUDY OF VENTILATION SYSTEM ENTRAINMENT OF BUILDING EXHAUSTS AT COOLBAUGH HALL,

## COLORADO SCHOOL OF MINES CAMPUS, GOLDEN, COLORADO

Prepared by

Dr. David E. Neff

Dr. Hesham El-Badry

for

Mr. Brit Probst

Davis Partnership

1775 Sherman, Suite 3100

Denver, CO 80203

FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

CSU Contract No. 53-6809

CER93-94-DEN-3

September 1993

# WIND TUNNEL STUDY OF VENTILATION SYSTEM ENTRAINMENT OF BUILDING EXHAUSTS AT COOLBAUGH HALL, COLORADO SCHOOL OF MINES CAMPUS

Prepared by

David E. Neff
Hesham El-Badry

**FINAL REPORT**
**(September 9, 1993)**

for

Mr. Brit Probst
Davis Partnership
1775 Sherman, Suite 3100
Denver, CO 80203

FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# 1 REPORT SUMMARY

Mr. Brit Probst of Davis Partnership requested Dr. David Neff of Colorado State University to perform a wind tunnel measurement program designed to study the recirculation of exhaust gases into air intake units on the roof of Coolbaugh Hall at the Colorado School of Mines campus. Subsequently Colorado School of Mines issued a contract with Colorado State University to fund this research. This report describes all work performed by Colorado State University staff.

A 1:120 scale model of Coolbaugh Hall (including surrounding terrain features and adjacent buildings) was constructed and tested in a wind tunnel facility. These tests, both visual and concentration measurements, covered twenty wind directions, two wind speeds, nine effluent release locations, three air intake structures and two building configurations (with and without the addition). The results from these tests determined that:

1) *Exhaust gases will recirculate into the rooftop air intake units for all nine effluent sources tested whenever the wind is directed from an effluent stack towards an air intake unit.*

2) *This recirculation occurred for both rooftop wind speeds tested, 5 and 10 meters per second.*

3) *Recirculation from effluent sources to the ground level air intake units appeared to be small.*

4) *Several test conditions showed effluent fumigation over the addition rooftop area.*

5) *The highest concentration of recirculated effluents were 2.4 percent from the additions room air and fume hood exhaust units, 1.3 percent from the existing fume hood exhausts, 0.15 percent from the radioisotope stacks and 0.076 percent from the perchloric stacks.*

6) *Some leeward building downwash from all the effluent plumes tested was observed in a majority of the conditions tested.*

Full documentation of the testing conducted on Coolbaugh Hall is provided in this report. The organization of major topics discussed in this report are as follows:

Section 2 The fluid model design with discussion of the similarity criteria employed.
Section 3 Wind tunnel testing program and results documenting the stacks tested.
Section 4 Discussion of the instrumentation and measurement methodologies used.

## 2 FLUID MODEL DESIGN

### 2.1 SITE SPECIFICATIONS

This boundary layer wind tunnel fluid model is a 1:120 reduced scale representation of:

1) the Coolbaugh Hall's existing and additional buildings,
2) the topography and structures within 220 meters of the site,
3) the atmospheric wind structure of interest approaching the site,
4) the roof top stack discharges, and
5) the air handling unit intake characteristics.

A twelve foot diameter turntable model of the Colorado School of Mines Campus area is depicted in Figure 1. Coolbaugh Hall is located in the center of this model. Figure 3 shows pictures of the Coolbaugh Hall wind tunnel model.

### 2.2 WIND SPEED AND DIRECTION SPECIFICATIONS

The top part of Table 1 displays the annual wind speed and direction frequencies observed at Denver Stapleton Airport. The lower part of Table 1 displays the annual wind speed and direction frequencies that would be observed at a height equivalent to the roof top height of Coolbaugh Hall. This table should only be considered a crude guide to wind conditions approaching Coolbaugh Hall but will suffice for the present purpose of determining a reasonable set of testing wind speeds. Design prototype wind speeds at roof height of 5 m/s and 10 m/s were selected. Model testing wind speeds at roof height of 1.5 m/s and 3 m/s were selected. The model Reynolds number based on building height and wind speed was always greater than 11,000.

Visual documentation of all sixteen primary wind directions along with four worst case wind directions for both wind speeds are to be tested. Concentration documentation, at both wind speeds, of only the worst case wind directions for each of the effluent stacks is desired.

### 2.3 WIND SPEED VARIATION WITH HEIGHT SPECIFICATIONS

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 log-linear velocity profile relationship should be used for heights up to 100 meters. This relationship is expressed as:

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

$u_*$ ≡ friction velocity,

$d$ ≡ displacement height,

$z_o$ ≡ roughness length.

Several references suggested values of the roughness length for various types of ground cover. A roughness length of 0.2 to 0.4 meters is an appropriate value for all wind directions approaching the Coolbaugh Hall site.

The mean velocity through the entire depth of the boundary layer is represented by the power law equation:

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

$U$ ≡ mean wind speed at height z,

$U_\infty$ ≡ wind speed at boundary layer height $\delta$,

$\delta$ ≡ boundary layer height = 600 meters

$p$ ≡ power law index.

A power law index of ~0.2 is an appropriate value for all wind directions approaching the Coolbaugh Hall site.

## 2.4 EXHAUST AND INTAKE SPECIFICATIONS

A diagram detailing the pertinent air handling equipment is shown in Figure 2. Table 2 is a schedule detailing the flow specifications of the prototype air handling equipment. Included in this table is a statement as to which effluent stacks and air handling units were modelled. The last column in Table 2 shows how the different effluents were grouped together as common sources of either air, smoke or tracer gas. The flow specifications for the different intake and exhaust structures in these tests are listed in Table 3 for the lower wind speed model conditions (field velocity of 5 m/s) and Table 4 for the higher wind speed model conditions (field velocity of 10 m/s). Equality of all momentum and velocity ratios were maintained in this fluid model.

## 2.5 BOUNDARY LAYER WIND TUNNEL CONFIGURATION

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 13 m/s and a flexible test section roof. A description of this facility is provided in Appendix C.2 and a facility drawing is provided in Figure C-2. Appropriate boundary layer development techniques were utilized to accurately represent wind conditions approaching the Coolbaugh Hall site. The Coolbaugh Hall model was placed 13.6 meters from the start of the EWT's test section. This placement provides sufficient upwind fetch and a sufficient downwind measurement zone. The zone upwind of the turntable area was modeled with a generic roughness (2.54 cm blocks) designed to create the desired model boundary layer. Eight 1.8 meter high vortex generators and an 18 cm floor trip were placed at the beginning of the EWT's test section.

# 3 TEST PROGRAM

## 3.1 WIND PROFILE MEASUREMENTS

Two approach flow reference vertical velocity profiles were obtained at the upwind edge of the model turntable. The turntable was in the north position during both velocity profiles. Table 5 lists the data for the lower speed velocity profile and Table 6 lists the data for the higher speed velocity profile. These tables list measured model values, equivalent field values and normalized values. Log-linear and power law regression constants for the profiles are also summarized here. Figure 4 shows the velocity profiles and the turbulence profiles in both model and field units for the lower speed velocity setting. Figure 5 shows both the power law and log-linear law curve fits to the velocity profile data.

The velocity profile regression values of 0.23 meters for roughness length 0.22 for power law index agree well the design values expected for the Colorado School of Mines Campus site.

The wind tunnel reference velocities of 1.5 and 3.0 m/s at model building height were set via the correlation between a pitot probe, 1.5 meters above model center, and measured velocities at 14 cm above model ground level (Coolbaugh Hall roof height) at model center. The Coolbaugh Hall model was removed during these measurements and the turntable was in the north position. Subsequent tunnel velocity settings were adjusted via the pitot probe which was present in all tests.

## 3.2 STACK PLUME VISUALIZATION

Visualization of the effluent plume motion for 86 different run conditions was documented on the video cassette VHS tape and included with this report in Appendix A. The flow specifications for the different intake and exhaust structures in these tests are listed in Table 2 for field conditions, Table 3 for the lower wind speed model conditions (field velocity of 5 m/s) and Table 4 for the higher wind speed model conditions (field velocity of 10 m/s). Table 7 lists the wind speed, wind direction and effluents tagged with smoke for each of the 86 visual runs.

The camera position for this film sequence was directly outside the wind tunnel from the model center at a height above model ground level. The film test observes the plume trajectories from the model stacks down to the end of the model turntable, approximately 220 meters field equivalent distance, and zooms in on each stack to document downwash and near stack plume rise characteristics.

## 3.3 CONCENTRATION MEASUREMENTS

Concentration measurements were obtained at ten sample locations for ten different run conditions. The sampling locations all located near the roof top air intake units are shown in Figure 2. The flow specifications for the different intake and exhaust structures in these tests are listed in Table 2 for field conditions, Table 3 for the lower wind speed model conditions (field velocity of 5 m/s) and Table 4 for the higher wind speed model conditions (field velocity of 10 m/s). Table 8 lists the wind speed, wind direction and effluents tagged with tracer gas for each of the ten concentration runs. Table 9 lists the concentration data in parts per millions (ppm) values. Table 10 lists the concentration data in normalized field concentrations, $K_p = (\chi U_H/Q)_p$ $[m^{-2}]$. Appendix B documents the measured tracer concentrations and associated setup information for all ten concentration runs.

# 4 INSTRUMENTATION AND MEASUREMENT METHODOLOGY

Laboratory measurement techniques are discussed in this section, along with conversion methods used to convert measured model quantities to their meaningful field equivalents.

## 4.1 VELOCITY MEASUREMENT AND PRESENTATION

The techniques employed in the acquisition of velocity profiles are discussed in detail in Appendix C.3 including basic equations and errors associated with each technique. Single-hot-film (TSI 1220 Sensor) and pitot-static probes are used to measure velocity statistics. TSI 1125 Velocity Calibrator System and Pitot-static Probes are used for velocity calibration.

The approach mean velocity and turbulent statistics profiles are obtained from velocity measurement techniques. The approach mean velocity profiles for a suburban roughness condition are regressed to find the best log-log and log-linear fit. The log-log regression will find a power law exponent, p, such that $U/U_r = (z/z_r)^p$. The log-linear regression ($U/u_* = 2.5\ln\{(z-d)/z_o\}$) will find a best fit roughness length $z_o$, friction velocity $u_*$, and displacement height d.

Velocity measurements obtained in this study are summarized and presented through plots of vertical profiles of mean velocity and longitudinal turbulence intensity. 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.

## 4.2 PLUME VISUALIZATION TECHNIQUES

Techniques employed to obtain a visible plume are discussed in Appendix C.4. A Smoke Generator System and a Video Camera System are used for plume visualization. Given a field to model wind speed ratio of 3.33 ( =[5m/s]/[1.5m/s] or =[10m/s]/[3.0m/s]) and a model to field length scale ratio of 120, then the time scale ratio between the model and the field is 1:36. Thus phenomena observed over the model in the wind tunnel will occur 36 times faster than observed at full scale. If the TV tapes were replayed in slow motion (36 times slower than the recorded speed) the observed plume trajectories and motions would appear realistic.

## 4.3 CONCENTRATION MEASUREMENT AND PRESENTATION

Techniques employed to obtain the concentration data are discussed in Appendix C.5. A gas chromatograph with flame ionization detector is used to measure gas concentrations. Figure C-5 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, $\chi_p$ $[gm/m^3]$, 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 reference height, H. The conversion from model units to field units is as follows:

$K_p = K_m * (H_m/H_p)^2$ $[m^{-2}]$; with $K_m = (\chi U_H/Q)_m$ $[cm^{-2}]$.
$\chi_m$ is the source normalized model concentration (ppm/$10^6$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 reference height, and
$H_p$ [m] is the field reference height.

## 4.4 STACK FLOW RATE AND COMPOSITION TECHNIQUES

An Omega mass flow controlling system was used to monitor and control some of the 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. Other stack flow settings were monitored by two 50 SLPM mass flowmeters, a Matheson and a Union Carbide, and a Fisher Porter flowrator.

The air intake flow rates into the three rooftop air handling units was maintained via a vacuum pump connected to a Fisher Porter flowrator that pulled air through three preset valves.

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 11 lists the settings and type of gas used to achieve the proper model stack effluent discharge velocities and specific gravities.

# TABLES

## Denver Stapleton Airport Annual Wind Frequency Table from NOAA

*WFRQ DEN.WK3 Sheet A: 04/08/93*

| Wind Direction | Wind Speed (Knots) 0-3 | 4-6 | 7-10 | 11-16 | 17-21 | 22-27 | 28-33 | 34-40 | Over 40 | Total | Avg. Speed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 0.6 | 2.9 | 3.2 | 1.6 | 0.3 | 0.1 | | | | 8.9 | 8.3 |
| NNE | 0.4 | 1.5 | 1.6 | 0.8 | 0.2 | | | | | 4.5 | 8.1 |
| NE | 0.4 | 1.6 | 1.6 | 0.6 | 0.1 | | | | | 4.3 | 7.4 |
| ENE | 0.4 | 1.5 | 1.3 | 0.5 | 0.0 | | | | | 3.8 | 6.9 |
| E | 0.7 | 2.6 | 1.9 | 0.5 | 0.0 | | | | | 5.7 | 6.6 |
| ESE | 0.5 | 1.9 | 1.4 | 0.3 | 0.0 | | | | | 4.2 | 6.6 |
| SE | 0.5 | 1.8 | 1.3 | 0.4 | 0.0 | | | | | 4.1 | 6.6 |
| SSE | 0.5 | 1.9 | 1.4 | 0.5 | 0.1 | | | | | 4.4 | 7.2 |
| S | 1.2 | 7.2 | 8.9 | 2.5 | 0.3 | | | | | 20.1 | 7.6 |
| SSW | 0.7 | 4.6 | 4.4 | 1.0 | 0.1 | | | | | 10.8 | 7.0 |
| SW | 0.7 | 2.4 | 1.6 | 0.4 | 0.1 | | | | | 5.2 | 6.6 |
| WSW | 0.4 | 1.3 | 0.7 | 0.2 | 0.1 | | | | | 2.7 | 6.4 |
| W | 0.2 | 0.8 | 0.9 | 0.8 | 0.3 | 0.1 | | | | 3.1 | 9.8 |
| WNW | 0.2 | 0.7 | 0.9 | 0.9 | 0.4 | 0.1 | | | | 3.5 | 10.8 |
| NW | 0.3 | 1.4 | 1.3 | 0.9 | 0.3 | 0.1 | | | | 4.2 | 9.2 |
| NNW | 0.3 | 1.5 | 1.4 | 0.7 | 0.1 | | | | | 4.0 | 8.0 |
| Calm | 6.5 | | | | | | | | | 6.5 | |
| Total | 14.6 | 35.8 | 33.7 | 12.6 | 2.6 | 0.6 | 0.1 | 0.0 | | 100.0 | 7.1 |

Notes
1) 1965-1974; 29215 observations
2) Anemometer Height of 20 feet (6.1 meters)

## Denver Stapleton Airport Annual Wind Frequency Table

**Wind Speed values are converted to m/s at a 16.8 meter height via a 0.22 power law index**

*WFRQ DEN.WK3 Sheet A: 04/08/93*

| Wind Direction | Wind Speed (m/s at 55 feet with 1/n=0.2) 0-1.9 | 2.6-3.9 | 4.5-6.4 | 7.1-10.3 | 10.9-13.5 | 14.1-17.4 | 18-21.2 | 21.8-25.7 | Over 25.7 | Total | Avg. Speed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 0.6 | 2.9 | 3.2 | 1.6 | 0.3 | 0.1 | | | | 8.9 | 5.3 |
| NNE | 0.4 | 1.5 | 1.6 | 0.8 | 0.2 | | | | | 4.5 | 5.2 |
| NE | 0.4 | 1.6 | 1.6 | 0.6 | 0.1 | | | | | 4.3 | 4.8 |
| ENE | 0.4 | 1.5 | 1.3 | 0.5 | 0.0 | | | | | 3.8 | 4.4 |
| E | 0.7 | 2.6 | 1.9 | 0.5 | 0.0 | | | | | 5.7 | 4.2 |
| ESE | 0.5 | 1.9 | 1.4 | 0.3 | 0.0 | | | | | 4.2 | 4.2 |
| SE | 0.5 | 1.8 | 1.3 | 0.4 | 0.0 | | | | | 4.1 | 4.2 |
| SSE | 0.5 | 1.9 | 1.4 | 0.5 | 0.1 | | | | | 4.4 | 4.6 |
| S | 1.2 | 7.2 | 8.9 | 2.5 | 0.3 | | | | | 20.1 | 4.9 |
| SSW | 0.7 | 4.6 | 4.4 | 1.0 | 0.1 | | | | | 10.8 | 4.5 |
| SW | 0.7 | 2.4 | 1.6 | 0.4 | 0.1 | | | | | 5.2 | 4.2 |
| WSW | 0.4 | 1.3 | 0.7 | 0.2 | 0.1 | | | | | 2.7 | 4.1 |
| W | 0.2 | 0.8 | 0.9 | 0.8 | 0.3 | 0.1 | | | | 3.1 | 6.3 |
| WNW | 0.2 | 0.7 | 0.9 | 0.9 | 0.4 | 0.1 | | | | 3.5 | 6.9 |
| NW | 0.3 | 1.4 | 1.3 | 0.9 | 0.3 | 0.1 | | | | 4.2 | 5.9 |
| NNW | 0.3 | 1.5 | 1.4 | 0.7 | 0.1 | | | | | 4.0 | 5.1 |
| Calm | 6.5 | | | | | | | | | 6.5 | |
| Total | 14.6 | 35.8 | 33.7 | 12.6 | 2.6 | 0.6 | 0.1 | 0.0 | | 100.0 | 4.6 |

**Table 1** Wind Speed and Direction Frequency Table

**Colorado School of Mines**

CSM_PROG.WK3 Sheet A: 04/12/93

*Prototype Intake and Exhaust Flow Summary*

| Port Number | Port Type | Building Unit | Gas Type | Flow Rate (cfm) | Intake Velocity (fpm) | Exhaust Velocity (fpm) | Intake Area (ft²) | Exhaust Area (ft²) | Exhaust Height (ft) | Presently Modelled | Model Flow Number |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EF1 | Vert. Exh. | Addition | Lab&fume Air | 25,000 | | 3,000 | | 8.33 | 10.0 | yes | Qex1 |
| EF2 | Vert. Exh. | Addition | Lab&fume Air | 25,000 | | 3,000 | | 8.33 | 10.0 | yes | Qex1 |
| EF3 | Vert. Exh. | Addition | Perchloric | 785 | | 2,000 | | 0.39 | 15.0 | yes | Qex2 |
| EF4 | Vert. Exh. | Addition | Perchloric | 600 | | 2,200 | | 0.27 | 15.0 | yes | Qex2 |
| EF5 | Vert. Exh. | Addition | Radioisotope | 980 | | 2,200 | | 0.45 | 15.0 | yes | Qex3 |
| EF6 | Vert. Exh. | Addition | Radioisotope | 785 | | 2,200 | | 0.36 | 15.0 | yes | Qex3 |
| EF7 | Vert. Exh. | Addition | Radioisotope | 980 | | 2,200 | | 0.45 | 15.0 | yes | Qex3 |
| EF8 | Horz. Exh. | Addition | Mechroom Air | 5,500 | | 1,300 | | 4.23 | 4.0 | no | |
| EF12 | Vert. Exh. | Existing | Room Air | 19,000 | | 3,000 | | 6.33 | 7.0 | w/o tracer | Qex4 |
| EF13 | Vert. Exh. | Existing | Room Air | 19,000 | | 3,000 | | 6.33 | 7.0 | w/o tracer | Qex4 |
| EF14 | Vert. Exh. | Existing | Fume Air | 17,500 | | 3,000 | | 5.83 | 7.0 | yes | Qex5 |
| EF15 | Vert. Exh. | Existing | Fume Air | 17,500 | | 3,000 | | 5.83 | 7.0 | yes | Qex5 |
| EF16 | Vert. Exh. | Existing | Toilet Air | 2,100 | | 1,200 | | 1.75 | - | no | |
| EF17 | Horz. Exh. | Existing | Mechroom Air | 12,000 | | 1,570 | | 7.64 | 5.0 | no | |
| AHU1 | Intake | Addition | Room Air | 52,000 | 400 | | 130.00 | | | no | |
| AHU2 | Intake/Exh. | Existing | Room Air | 23,000 | 1,000 | 1,500 | 23.00 | 15.33 | | Intake only | Qin1 |
| AHU3 | Intake/Exh. | Existing | Room Air | 7,000 | 1,000 | 1,500 | 7.00 | 4.67 | | Intake only | Qin2 |
| AHU4 | Intake/Exh. | Existing | Room Air | 47,000 | 1,000 | 1,500 | 47.00 | 31.33 | | Intake only | Qin3 |
| AHU5&6 | Intake | Existing | Room Air | 70,000 | 400 | | 175.00 | | | no | |
| CT1 | Intake/Exh. | Addition | Room Air | 99,500 | | 2,488 | | 40.00 | 16.0 | Exh. only | Qex6 |
| CT2 | Intake/Exh. | Addition | Room Air | 99,500 | | 2,488 | | 40.00 | 16.0 | Exh. only | Qex6 |

note: 1) All flows are from Gary Schaffer at Cator Roma written on M6.3 Drawing
2) Some of these flows are different from that specified on Drawings M3.1 & M3.2

**Table 2** Field Intake and Exhaust Flow Summary

**Colorado School of Mines**

CSM_PROG.WK3 Sheet B: 04/12/93

Href (cm) 14
Up (m/s) = 5
Um (cm/s) 150
Flow Re# 14,000

*Model Intake and Exhaust Flow Summary (Ref. Velocity = 5 m/s)*

| Port Number | Port Type | Building Unit | Gas Type | Flow Rate (ccs) | Intake Velocity (cm/s) | Exhaust Velocity (cm/s) | Intake Area ($cm^2$) | Exhaust Area ($cm^2$) | Exhaust Height (cm) | Presently Modelled | Model Flow Number | Stack Diameter (cm) | Velocity Ratio (W/U) | Stack Re# | Combined FlowRate (ccs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EF1 | Vert. Exh. | Addition | Air | 246 | | 457 | | 0.54 | 2.5 | yes | Qex1 | 0.83 | 3.0 | 2,522 | 492 |
| EF2 | Vert. Exh. | Addition | Air | 246 | | 457 | | 0.54 | 2.5 | yes | Qex1 | 0.83 | 3.0 | 2,522 | |
| EF3 | Vert. Exh. | Addition | Air | 7.7 | | 305 | | 0.03 | 3.8 | yes | Qex2 | 0.18 | 2.0 | 365 | 13.6 |
| EF4 | Vert. Exh. | Addition | Air | 5.9 | | 335 | | 0.02 | 3.8 | yes | Qex2 | 0.15 | 2.2 | 335 | |
| EF5 | Vert. Exh. | Addition | Air | 9.6 | | 335 | | 0.03 | 3.8 | yes | Qex3 | 0.19 | 2.2 | 428 | 27.0 |
| EF6 | Vert. Exh. | Addition | Air | 7.7 | | 335 | | 0.02 | 3.8 | yes | Qex3 | 0.17 | 2.2 | 383 | |
| EF7 | Vert. Exh. | Addition | Air | 9.6 | | 335 | | 0.03 | 3.8 | yes | Qex3 | 0.19 | 2.2 | 428 | |
| EF8 | Horz. Exh. | Addition | Air | 54 | | 198 | | 0.27 | 1.0 | no | | 0.59 | 1.3 | 779 | |
| EF12 | Vert. Exh. | Existing | Air | 187 | | 457 | | 0.41 | 1.8 | w/o tracer | Qex4 | 0.72 | 3.0 | 2,198 | 374 |
| EF13 | Vert. Exh. | Existing | Air | 187 | | 457 | | 0.41 | 1.8 | w/o tracer | Qex4 | 0.72 | 3.0 | 2,198 | |
| EF14 | Vert. Exh. | Existing | Air | 172 | | 457 | | 0.38 | 1.8 | yes | Qex5 | 0.69 | 3.0 | 2,110 | 344 |
| EF15 | Vert. Exh. | Existing | Air | 172 | | 457 | | 0.38 | 1.8 | yes | Qex5 | 0.69 | 3.0 | 2,110 | |
| EF16 | Vert. Exh. | Existing | Air | 21 | | 183 | | 0.11 | | no | | 0.38 | 1.2 | 462 | |
| EF17 | Horz. Exh. | Existing | Air | 118 | | 239 | | 0.49 | 1.3 | no | | 0.79 | 1.6 | 1,264 | |
| AHU1 | Intake | Addition | Air | 511 | 61 | | 8.39 | | | no | | | | | |
| AHU2 | Intake/Exh. | Existing | Air | 226 | 152 | 229 | 1.48 | 0.99 | | Intake only | Qin1 | 1.12 | 1.5 | 1,710 | 226 |
| AHU3 | Intake/Exh. | Existing | Air | 69 | 152 | 229 | 0.45 | 0.30 | | Intake only | Qin2 | 0.62 | 1.5 | 944 | 69 |
| AHU4 | Intake/Exh. | Existing | Air | 462 | 152 | 229 | 3.03 | 2.02 | | Intake only | Qin3 | 1.60 | 1.5 | 2,445 | 462 |
| AHU5&6 | Intake | Existing | Air | 688 | 61 | | 11.29 | | | no | | | | | |
| CT1 | Intake/Exh. | Addition | Air | 978 | | 379 | | 2.58 | 4.1 | Exh. only | Qex6 | 1.81 | 2.5 | 4,581 | 1,957 |
| CT2 | Intake/Exh. | Addition | Air | 978 | | 379 | | 2.58 | 4.1 | Exh. only | Qex6 | 1.81 | 2.5 | 4,581 | |

**Table 3** Model Intake and Exhaust Flow Summary ($U_{ref}$ = 5 m/s)

**Colorado School of Mines**

CSM_PROG.WK3 Sheet B: 04/12/93

| | |
|---|---|
| Href (cm) | 14 |
| Up (m/s) = | 10 |
| Um (cm/s) | 300 |
| Flow Re# | 28,000 |

*Model Intake and Exhaust Flow Summary (Ref. Velocity = 10 m/s)*

| Port Number | Port Type | Building Unit | Gas Type | Flow Rate (ccs) | Intake Velocity (cm/s) | Exhaust Velocity (cm/s) | Intake Area ($cm^2$) | Exhaust Area ($cm^2$) | Exhaust Height (cm) | Presently Modelled | Model Flow Number | Stack Diameter (cm) | Velocity Ratio (W/U) | Stack Re# | Combined FlowRate (ccs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EF1 | Vert. Exh. | Addition | Air | 246 | | 457 | | 0.54 | 2.5 | yes | Qex1 | 0.83 | 1.5 | 2,522 | 492 |
| EF2 | Vert. Exh. | Addition | Air | 246 | | 457 | | 0.54 | 2.5 | yes | Qex1 | 0.83 | 1.5 | 2,522 | |
| EF3 | Vert. Exh. | Addition | Air | 7.7 | | 305 | | 0.03 | 3.8 | yes | Qex2 | 0.18 | 1.0 | 365 | 13.6 |
| EF4 | Vert. Exh. | Addition | Air | 5.9 | | 335 | | 0.02 | 3.8 | yes | Qex2 | 0.15 | 1.1 | 335 | |
| EF5 | Vert. Exh. | Addition | Air | 9.6 | | 335 | | 0.03 | 3.8 | yes | Qex3 | 0.19 | 1.1 | 428 | 27.0 |
| EF6 | Vert. Exh. | Addition | Air | 7.7 | | 335 | | 0.02 | 3.8 | yes | Qex3 | 0.17 | 1.1 | 383 | |
| EF7 | Vert. Exh. | Addition | Air | 9.6 | | 335 | | 0.03 | 3.8 | yes | Qex3 | 0.19 | 1.1 | 428 | |
| EF8 | Horz. Exh. | Addition | Air | 54 | | 198 | | 0.27 | 1.0 | no | | 0.59 | 0.7 | 779 | |
| EF12 | Vert. Exh. | Existing | Air | 187 | | 457 | | 0.41 | 1.8 | w/o tracer | Qex4 | 0.72 | 1.5 | 2,198 | 374 |
| EF13 | Vert. Exh. | Existing | Air | 187 | | 457 | | 0.41 | 1.8 | w/o tracer | Qex4 | 0.72 | 1.5 | 2,198 | |
| EF14 | Vert. Exh. | Existing | Air | 172 | | 457 | | 0.38 | 1.8 | yes | Qex5 | 0.69 | 1.5 | 2,110 | 344 |
| EF15 | Vert. Exh. | Existing | Air | 172 | | 457 | | 0.38 | 1.8 | yes | Qex5 | 0.69 | 1.5 | 2,110 | |
| EF16 | Vert. Exh. | Existing | Air | 21 | | 183 | | 0.11 | | no | | 0.38 | 0.6 | 462 | |
| EF17 | Horz. Exh. | Existing | Air | 118 | | 239 | | 0.49 | 1.3 | no | | 0.79 | 0.8 | 1,264 | |
| AHU1 | Intake | Addition | Air | 511 | 61 | | 8.39 | | | no | | | | | |
| AHU2 | Intake/Exh. | Existing | Air | 226 | 152 | 229 | 1.48 | 0.99 | | Intake only | Qin1 | 1.12 | 0.8 | 1,710 | 226 |
| AHU3 | Intake/Exh. | Existing | Air | 69 | 152 | 229 | 0.45 | 0.30 | | Intake only | Qin2 | 0.62 | 0.8 | 944 | 69 |
| AHU4 | Intake/Exh. | Existing | Air | 462 | 152 | 229 | 3.03 | 2.02 | | Intake only | Qin3 | 1.60 | 0.8 | 2,445 | 462 |
| AHU5&6 | Intake | Existing | Air | 688 | 61 | | 11.29 | | | no | | | | | |
| CT1 | Intake/Exh. | Addition | Air | 978 | | 379 | | 2.58 | 4.1 | Exh. only | Qex6 | 1.81 | 1.3 | 4,581 | 1,957 |
| CT2 | Intake/Exh. | Addition | Air | 978 | | 379 | | 2.58 | 4.1 | Exh. only | Qex6 | 1.81 | 1.3 | 4,581 | |

**Table 4** Model Intake and Exhaust Flow Summary ($U_{ref}$ = 10 m/s)

# Reference Velocity Profile Data

VEL_REF.WK3 04/30/93

## *Model Values (length scale = 1:120)*

| Height (cm) | Local Velocity (cm/s) | Turbulent Intensity (%) | Normalized Height | Normalized Velocity |
|---|---|---|---|---|
| 2 | 78 | 30 | 0.02 | 0.36 |
| 3 | 92 | 27 | 0.03 | 0.42 |
| 4 | 98 | 28 | 0.03 | 0.45 |
| 5 | 105 | 26 | 0.04 | 0.48 |
| 8 | 129 | 22 | 0.06 | 0.59 |
| 10 | 134 | 21 | 0.08 | 0.62 |
| 15 | 142 | 19 | 0.13 | 0.65 |
| 20 | 151 | 17 | 0.17 | 0.70 |
| 30 | 164 | 15 | 0.25 | 0.76 |
| 40 | 173 | 14 | 0.33 | 0.80 |
| 50 | 182 | 13 | 0.42 | 0.84 |
| 60 | 189 | 12 | 0.50 | 0.87 |
| 80 | 199 | 10 | 0.67 | 0.91 |
| 100 | 207 | 7 | 0.83 | 0.95 |
| 120 | 217 | 6 | 1.00 | 1.00 |

| | |
|---|---|
| Reference Velocity (cm/s) = | 217 |
| Reference Height (cm) = | 120.0 |

## *Field Values*

| Height (m) | Local Velocity (m/s) | Turbulent Intensity (%) | Normalized Height | Normalized Velocity |
|---|---|---|---|---|
| 2.4 | 2.9 | 30 | 0.02 | 0.36 |
| 3.6 | 3.4 | 27 | 0.03 | 0.42 |
| 4.8 | 3.6 | 28 | 0.03 | 0.45 |
| 6.0 | 3.9 | 26 | 0.04 | 0.48 |
| 9.0 | 4.7 | 22 | 0.06 | 0.59 |
| 12.0 | 4.9 | 21 | 0.08 | 0.62 |
| 18.0 | 5.2 | 19 | 0.13 | 0.65 |
| 24.0 | 5.6 | 17 | 0.17 | 0.70 |
| 36.0 | 6.0 | 15 | 0.25 | 0.76 |
| 48.0 | 6.4 | 14 | 0.33 | 0.80 |
| 60.0 | 6.7 | 13 | 0.42 | 0.84 |
| 72.0 | 7.0 | 12 | 0.50 | 0.87 |
| 96.0 | 7.3 | 10 | 0.67 | 0.91 |
| 120.0 | 7.6 | 7 | 0.83 | 0.95 |
| 144.0 | 8.0 | 6 | 1.00 | 1.00 |

| | |
|---|---|
| Reference Velocity (m/s) = | 8.0 |
| Reference Height (m) = | 144.0 |
| Displacement Height (m) = | 0.0 |
| Friction Velocity (m/s) = | 0.48 |
| Roughness Length (m) = | 0.23 |
| Power Law Index = | 0.22 |

**Table 5** Reference Velocity and Turbulence Profile Data ($U_{ref}$ ~ 5 m/s)

# Reference Velocity Profile Data

VEL_REF.WK3 04/30/93

## *Model Values (length scale = 1:120)*

| Height (cm) | Local Velocity (cm/s) | Turbulent Intensity (%) | Normalized Height | Normalized Velocity |
|---|---|---|---|---|
| 2 | 157 | 32 | 0.02 | 0.35 |
| 3 | 190 | 28 | 0.03 | 0.42 |
| 4 | 205 | 27 | 0.03 | 0.45 |
| 5 | 230 | 26 | 0.04 | 0.51 |
| 8 | 254 | 22 | 0.06 | 0.56 |
| 10 | 287 | 18 | 0.08 | 0.63 |
| 15 | 304 | 16 | 0.13 | 0.67 |
| 20 | 318 | 16 | 0.17 | 0.70 |
| 30 | 344 | 14 | 0.25 | 0.76 |
| 40 | 351 | 14 | 0.33 | 0.77 |
| 50 | 381 | 11 | 0.42 | 0.84 |
| 60 | 382 | 11 | 0.50 | 0.84 |
| 80 | 409 | 9 | 0.67 | 0.90 |
| 100 | 437 | 7 | 0.83 | 0.96 |
| 120 | 453 | 6 | 1.00 | 1.00 |
| Reference Velocity (cm/s) = | | 453 | | |
| Reference Height (cm) = | | 120.0 | | |

## *Field Values*

| Height (m) | Local Velocity (m/s) | Turbulent Intensity (%) | Normalized Height | Normalized Velocity |
|---|---|---|---|---|
| 2.4 | 5.6 | 32 | 0.02 | 0.35 |
| 3.6 | 6.7 | 28 | 0.03 | 0.42 |
| 4.8 | 7.2 | 27 | 0.03 | 0.45 |
| 6.0 | 8.1 | 26 | 0.04 | 0.51 |
| 9.0 | 9.0 | 22 | 0.06 | 0.56 |
| 12.0 | 10.1 | 18 | 0.08 | 0.63 |
| 18.0 | 10.7 | 16 | 0.13 | 0.67 |
| 24.0 | 11.2 | 16 | 0.17 | 0.70 |
| 36.0 | 12.2 | 14 | 0.25 | 0.76 |
| 48.0 | 12.4 | 14 | 0.33 | 0.77 |
| 60.0 | 13.5 | 11 | 0.42 | 0.84 |
| 72.0 | 13.5 | 11 | 0.50 | 0.84 |
| 96.0 | 14.5 | 9 | 0.67 | 0.90 |
| 120.0 | 15.4 | 7 | 0.83 | 0.96 |
| 144.0 | 16.0 | 6 | 1.00 | 1.00 |
| Reference Velocity (m/s) = | | 16.0 | | |
| Reference Height (m) = | | 144.0 | | |
| Displacement Height (m) = | | 0.0 | | |
| Friction Velocity (m/s) = | | 0.48 | | |
| Roughness Length (m) = | | 0.23 | | |
| Power Law Index = | | 0.22 | | |

**Table 6** Reference Velocity and Turbulence Profile Data ($U_{ref}$ ~ 10 m/s)

**Colorado School of Mines**

CSM_PROG.WK3 Sheet C: 04/23/93

*Visualization Tests (Tape 1)*

| Run Number | Building Config. | Wind Direction | Wind Speed (m/s) | Smoke Plume no. |
|---|---|---|---|---|
| 1 | Existing | 0.0 | 5 | EF 14,15 |
| 2 | Existing | 22.5 | 5 | EF 14,15 |
| 3 | Existing | 45.0 | 5 | EF 14,15 |
| 4 | Existing | 67.5 | 5 | EF 14,15 |
| 5 | Existing | 90.0 | 5 | EF 14,15 |
| 6 | Existing | 112.5 | 5 | EF 14,15 |
| 7 | Existing | 135.0 | 5 | EF 14,15 |
| 8 | Existing | 157.5 | 5 | EF 14,15 |
| 9 | Existing | 180.0 | 5 | EF 14,15 |
| 10 | Existing | 202.5 | 5 | EF 14,15 |
| 11 | Existing | 225.0 | 5 | EF 14,15 |
| 12 | Existing | 247.5 | 5 | EF 14,15 |
| 13 | Existing | 270.0 | 5 | EF 14,15 |
| 14 | Existing | 292.5 | 5 | EF 14,15 |
| 15 | Existing | 315.0 | 5 | EF 14,15 |
| 16 | Existing | 337.5 | 5 | EF 14,15 |
| 17 | Existing | 65.0 | 5 | EF 14,15 |
| 18 | Existing | 70.0 | 5 | EF 14,15 |
| 19 | Existing | 75.0 | 5 | EF 14,15 |
| 20 | Existing | 80.0 | 5 | EF 14,15 |
| 21 | Existing | 0.0 | 10 | EF 14,15 |
| 22 | Existing | 22.5 | 10 | EF 14,15 |
| 23 | Existing | 45.0 | 10 | EF 14,15 |
| 24 | Existing | 67.5 | 10 | EF 14,15 |
| 25 | Existing | 90.0 | 10 | EF 14,15 |
| 26 | Existing | 112.5 | 10 | EF 14,15 |
| 27 | Existing | 135.0 | 10 | EF 14,15 |
| 28 | Existing | 157.5 | 10 | EF 14,15 |
| 29 | Existing | 180.0 | 10 | EF 14,15 |
| 30 | Existing | 202.5 | 10 | EF 14,15 |
| 31 | Existing | 225.0 | 10 | EF 14,15 |
| 32 | Existing | 247.5 | 10 | EF 14,15 |
| 33 | Existing | 270.0 | 10 | EF 14,15 |
| 34 | Existing | 292.5 | 10 | EF 14,15 |
| 35 | Existing | 315.0 | 10 | EF 14,15 |
| 36 | Existing | 337.5 | 10 | EF 14,15 |
| 37 | Existing | 65.0 | 10 | EF 14,15 |
| 38 | Existing | 70.0 | 10 | EF 14,15 |
| 39 | Existing | 75.0 | 10 | EF 14,15 |
| 40 | Existing | 80.0 | 10 | EF 14,15 |

*Visualization Tests (Tape 2)*

| Run Number | Building Config. | Wind Direction | Wind Speed (m/s) | Smoke Plume no. |
|---|---|---|---|---|
| 41 | Addition | 0.0 | 5 | EF 3,4,5,6,7 |
| 42 | Addition | 22.5 | 5 | EF 3,4,5,6,7 |
| 43 | Addition | 45.0 | 5 | EF 3,4,5,6,7 |
| 44 | Addition | 67.5 | 5 | EF 3,4,5,6,7 |
| 45 | Addition | 90.0 | 5 | EF 3,4,5,6,7 |
| 46 | Addition | 112.5 | 5 | EF 3,4,5,6,7 |
| 47 | Addition | 135.0 | 5 | EF 3,4,5,6,7 |
| 48 | Addition | 157.5 | 5 | EF 3,4,5,6,7 |
| 49 | Addition | 180.0 | 5 | EF 3,4,5,6,7 |
| 50 | Addition | 202.5 | 5 | EF 3,4,5,6,7 |
| 51 | Addition | 225.0 | 5 | EF 3,4,5,6,7 |
| 52 | Addition | 247.5 | 5 | EF 3,4,5,6,7 |
| 53 | Addition | 270.0 | 5 | EF 3,4,5,6,7 |
| 54 | Addition | 292.5 | 5 | EF 3,4,5,6,7 |
| 55 | Addition | 315.0 | 5 | EF 3,4,5,6,7 |
| 56 | Addition | 337.5 | 5 | EF 3,4,5,6,7 |
| 57 | Addition | 345.0 | 5 | EF 3,4,5,6,7 |
| 58 | Addition | 350.0 | 5 | EF 3,4,5,6,7 |
| 59 | Addition | 320.0 | 5 | EF 1,2 |
| 60 | Addition | 330.0 | 5 | EF 1,2 |
| 61 | Addition | 0.0 | 10 | EF 1,2,3,4,5,6,7 |
| 62 | Addition | 22.5 | 10 | EF 1,2,3,4,5,6,7 |
| 63 | Addition | 45.0 | 10 | EF 1,2,3,4,5,6,7 |
| 64 | Addition | 67.5 | 10 | EF 1,2,3,4,5,6,7 |
| 65 | Addition | 90.0 | 10 | EF 1,2,3,4,5,6,7 |
| 66 | Addition | 112.5 | 10 | EF 1,2,3,4,5,6,7 |
| 67 | Addition | 135.0 | 10 | EF 1,2,3,4,5,6,7 |
| 68 | Addition | 157.5 | 10 | EF 1,2,3,4,5,6,7 |
| 69 | Addition | 180.0 | 10 | EF 1,2,3,4,5,6,7 |
| 70 | Addition | 202.5 | 10 | EF 1,2,3,4,5,6,7 |
| 71 | Addition | 225.0 | 10 | EF 1,2,3,4,5,6,7 |
| 72 | Addition | 247.5 | 10 | EF 1,2,3,4,5,6,7 |
| 73 | Addition | 270.0 | 10 | EF 1,2,3,4,5,6,7 |
| 74 | Addition | 292.5 | 10 | EF 1,2,3,4,5,6,7 |
| 75 | Addition | 315.0 | 10 | EF 1,2,3,4,5,6,7 |
| 76 | Addition | 337.5 | 10 | EF 1,2,3,4,5,6,7 |
| 77 | Addition | 345.0 | 10 | EF 1,2,3,4,5,6,7 |
| 78 | Addition | 350.0 | 10 | EF 1,2,3,4,5,6,7 |
| 79 | Addition | 320.0 | 10 | EF 1,2,3,4,5,6,7 |
| 80 | Addition | 330.0 | 10 | EF 1,2,3,4,5,6,7 |
| 81 | Both | 75.0 | 10 | EF 14,15 |
| 82 | Both | 75.0 | 5 | EF 14,15 |
| 83 | Both | Rotation | 5 | EF 14,15 |
| 84 | Both | Rotation | 10 | EF 14,15 |
| 85 | Both | Rotation | 10 | EF 1,2,14,15 |
| 86 | Both | Rotation | 5 | EF 1,2,14,15 |

**Table 7** Visual Test Results Program

**Colorado School of Mines**

CSM_PROG.WK3 Sheet D: 04/23/93

*Concentration Test Program*

| Run Number | Building Config. | Effluent Modelled | Model Flow Number | Wind Direction | Wind Speed (m/s) |
|---|---|---|---|---|---|
| | | | | | |
| 1 | Addition | EF 1,2 | Qex1 | 320.0 | 5 |
| 2 | Addition | EF 1,2 | Qex1 | 320.0 | 10 |
| 3 | Addition | EF 3,4 | Qex2 | 305.0 | 5 |
| 4 | Addition | EF 3,4 | Qex2 | 305.0 | 10 |
| 5 | Addition | EF 5,6,7 | Qex3 | 350.0 | 5 |
| 6 | Addition | EF 5,6,7 | Qex3 | 350.0 | 10 |
| 7 | Addition | EF 5,6,7 | Qex3 | 355.0 | 5 |
| 8 | Addition | EF 5,6,7 | Qex3 | 355.0 | 10 |
| 9 | Addition | EF 14,15 | Qex5 | 75.0 | 5 |
| 10 | Addition | EF 14,15 | Qex5 | 75.0 | 10 |

**Table 8** Concentration Test Program

# Colorado School of Mines Coolbaugh Hall

## Concentration Summary Table (ppm)

CSM_CON1.WK3 Sheet A: 04/27/93

| Run Number | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) | 5 | 10 | 5 | 10 | 5 | 10 | 5 | 10 | 5 | 10 |
| Wind Dir. | 320 | 320 | 305 | 305 | 350 | 350 | 355 | 355 | 75 | 75 |
| Effuent No. | EF 1,2 | EF 1,2 | EF 3,4 | EF 3,4 | EF 5,6,7 | EF 5,6,7 | EF 5,6,7 | EF 5,6,7 | EF 14,15 | EF 14,15 |
| Meas. Location | Parts per Million | | | | | | | | | |
| 1 | 9,796 | 15,117 | 237 | 299 | 2,884 | 1,613 | 2,250 | 1,580 | 10,626 | 9,491 |
| 2 | 16,217 | 14,246 | 889 | 547 | 355 | 460 | 89 | 272 | 11,516 | 12,931 |
| 3 | 17,977 | 12,271 | 230 | 248 | 340 | 374 | 194 | 316 | 3,715 | 7,991 |
| 4 | 2,940 | 4,625 | 7 | 19 | 1,950 | 1,042 | 1,568 | 1,083 | 10,081 | 9,496 |
| AUH2-1 | 20,312 | 16,667 | 758 | 522 | 1,246 | 614 | 995 | 597 | 9,696 | 8,641 |
| AUH2-2 | 21,983 | 19,442 | 339 | 391 | 1,477 | 946 | 775 | 825 | 11,106 | 10,366 |
| AUH3-1 | 23,658 | 18,817 | 664 | 512 | 720 | 670 | 276 | 486 | 12,061 | 11,176 |
| AUH3-2 | 23,398 | 18,392 | 707 | 521 | 561 | 582 | 200 | 402 | 11,091 | 10,931 |
| AUH4-1 | 24,348 | 20,187 | 354 | 411 | 448 | 517 | 165 | 371 | 9,581 | 12,836 |
| AUH4-2 | 23,903 | 18,187 | 371 | 424 | 203 | 359 | 61 | 231 | 5,540 | 10,506 |

*Note:*
*1) Wind Speed is at Roof Height*
*2) Wind Direction is degrees from North*
*3) Model Length Scale 120*

**Table 9** Concentration Test Results (ppm values)

# Colorado School of Mines Coolbaugh Hall

**Concentration Summary Table (K value)**

CSM_CON1.WK3 Sheet B: 04/26/93

| Run Number | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 | #10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Wind Speed (m/s) | 5 | 10 | 5 | 10 | 5 | 10 | 5 | 10 | 5 | 10 |
| Wind Dir. | 320 | 320 | 305 | 305 | 350 | 350 | 355 | 355 | 75 | 75 |
| Effuent No. | EF 1,2 | EF 1,2 | EF 3,4 | EF 3,4 | EF 5,6,7 | EF 5,6,7 | EF 5,6,7 | EF 5,6,7 | EF 14,15 | EF 14,15 |
| Meas. Location | Concentration Coefficient *10^6 (m^-2) | | | | | | | | | |
| 1 | 2,074 | 6,401 | 1,818 | 4,586 | 11,125 | 12,443 | 8,681 | 12,189 | 3,218 | 5,748 |
| 2 | 3,433 | 6,033 | 6,811 | 8,372 | 1,368 | 3,551 | 342 | 2,096 | 3,487 | 7,831 |
| 3 | 3,806 | 5,196 | 1,759 | 3,801 | 1,312 | 2,889 | 749 | 2,441 | 1,125 | 4,839 |
| 4 | 623 | 1,959 | 54 | 290 | 7,522 | 8,038 | 6,051 | 8,359 | 3,053 | 5,751 |
| AUH2-1 | 4,301 | 7,057 | 5,809 | 8,002 | 4,806 | 4,735 | 3,838 | 4,607 | 2,936 | 5,233 |
| AUH2-2 | 4,654 | 8,233 | 2,596 | 5,990 | 5,699 | 7,302 | 2,990 | 6,366 | 3,363 | 6,278 |
| AUH3-1 | 5,009 | 7,968 | 5,087 | 7,845 | 2,778 | 5,173 | 1,066 | 3,752 | 3,652 | 6,768 |
| AUH3-2 | 4,954 | 7,788 | 5,416 | 7,979 | 2,166 | 4,494 | 770 | 3,103 | 3,358 | 6,620 |
| AUH4-1 | 5,155 | 8,548 | 2,714 | 6,298 | 1,730 | 3,988 | 637 | 2,860 | 2,901 | 7,774 |
| AUH4-2 | 5,061 | 7,701 | 2,839 | 6,498 | 784 | 2,769 | 234 | 1,786 | 1,678 | 6,363 |

*Note:*
1) *Wind Speed is at Roof Height*
2) *Wind Direction is degrees from North*
3) *Model Length Scale* *120*

**Table 10** Concentration Test Results (K values)

**Colorado School of Mines**

CSM_PROG.WK3 Sheet D: 04/23/93

*Model Concentration Test Flow Rate Schedule (no tracer gas settings)*

| Model Flow Number | Source Gas Type | Gas Percent | Total Flow Rate (ccs) | Instrument Type | Flow Rate (ccs) | Flow Rate (slpm) | Instrument Setting |
|---|---|---|---|---|---|---|---|
| Qex1 | Air | 100.0 | 492.0 | Matheson | 492.0 | 24.5 | 24,478 |
| Qex4 | Air | 100.0 | 374.0 | FP Med#2 | 374.0 | 18.6 | M21.6 @ 10psig |
| Qex5 | Air | 100.0 | 344.0 | Union Carbide | 344.0 | 17.1 | 17,114 |
| Qex6 | Air | 100.0 | 1957.0 | Omega 100slpm | 1957.0 | 97.4 | 97.4 %FS |
| Qin | Air | 100.0 | 757.0 | FP Med#1 | 757.0 | 37.7 | M77 @ -7"H2O |

*Model Concentration Test Flow Rate Schedule (individual tracer gas settings)*

| Model Flow Number | Source Gas Type | Gas Percent | Total Flow Rate (ccs) | Instrument Type | Flow Rate (ccs) | Flow Rate (slpm) | Instrument Setting |
|---|---|---|---|---|---|---|---|
| Qex1 | Air | 98.0 | 492.0 | Matheson | 482.2 | 24.0 | 23,988 |
| | C2H6 | 2.0 | 492.0 | Omega 1slpm | 9.8 | 0.99 | 98.7 %FS |
| Qex2 | C2H6 | 100.0 | 13.6 | Omega 10slpm | 13.6 | 1.36 | 13.6 %FS |
| Qex3 | C2H6 | 100.0 | 27.0 | Omega 10slpm | 27.0 | 2.71 | 27.1 %FS |
| Qex5 | Air | 98.0 | 344.0 | Union Carbide | 337.1 | 16.8 | 16,772 |
| | C2H6 | 2.0 | 344.0 | Omega 1slpm | 6.9 | 0.7 | 69.0 %FS |

*Model Visual Test Flow Rate Schedule*

| Model Flow Number | Source Gas Type | Gas Percent | Total Flow Rate (ccs) | Instrument Type | Flow Rate (ccs) | Flow Rate (slpm) | Instrument Setting |
|---|---|---|---|---|---|---|---|
| Qex1 | Air,fog | 100.0 | 492.0 | Matheson | 492.0 | 24.5 | 2.45 volts |
| Qex2 | Air,smoke | 100.0 | 13.6 | Omega 1slpm | 13.6 | 0.7 | 68 %FS |
| Qex3 | Air,smoke | 100.0 | 27.0 | Omega 10slpm | 27.0 | 1.3 | 13.4 %FS |
| Qex4 | Air | 100.0 | 374.0 | FP Med#2 | 374.0 | 18.6 | M21.6 @ 10psig |
| Qex5 | Air,fog | 100.0 | 344.0 | Union Carbide | 344.0 | 17.1 | 1.71 volts |
| Qex6 | Air | 100.0 | 1957.0 | Omega 100slpm | 1957.0 | 97.4 | 97.4 %FS |
| Qin | Air | 100.0 | 757.0 | FP Med#1 | 757.0 | 37.7 | M77 @ -7"H2O |

Note
1) Qex2 and Qex3 are inactive when not used as a tracer
2) These were set individually
AHU2> 226ccs> M17.7@12psia
AHU3> 69ccs> M5.4@12psia
AHU4> 462ccs> M36.3@12psia

**Table 11** Stack Gas Flow Settings and Composition

# FIGURES

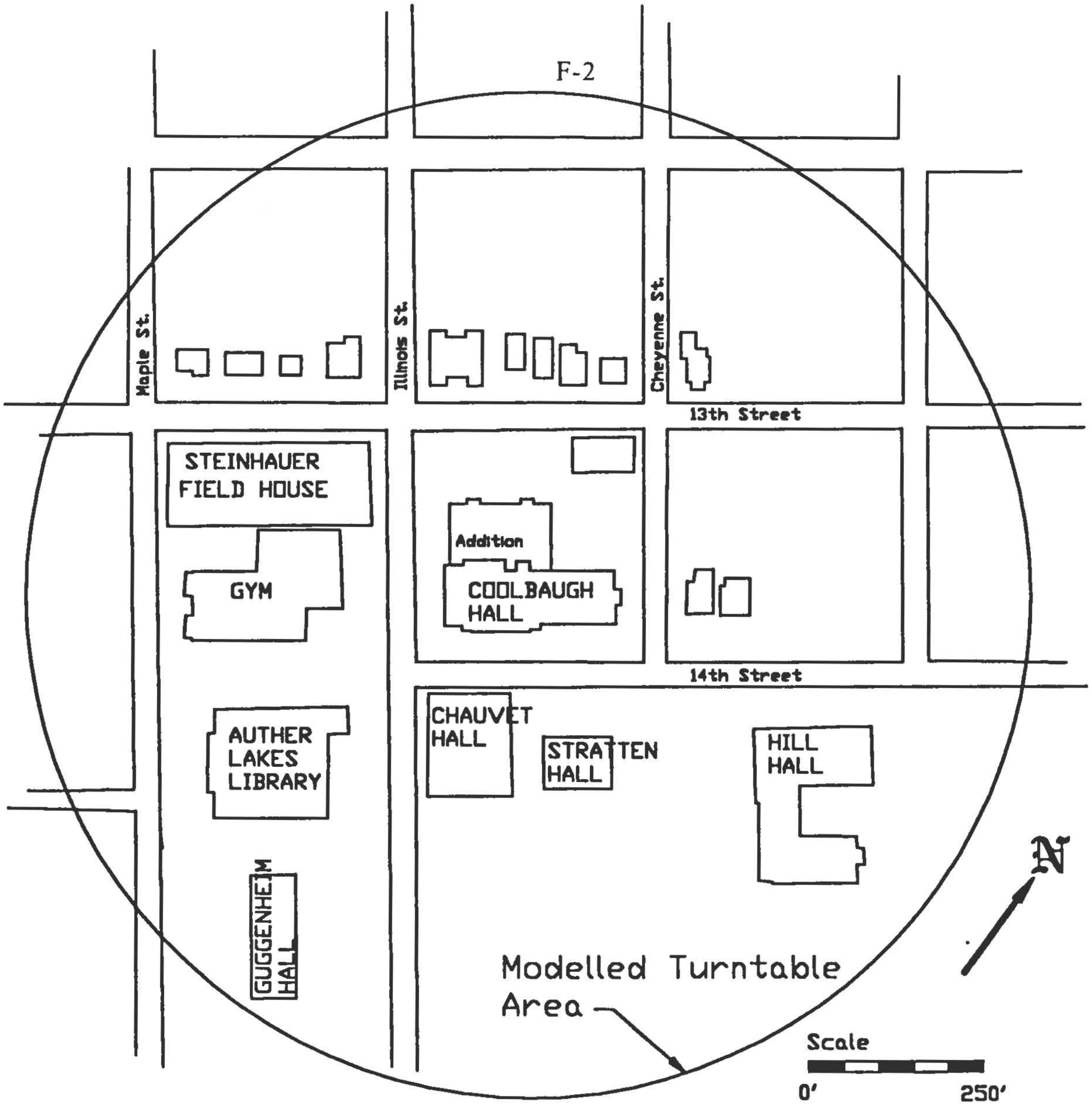



**Figure 1** Model Turntable Area Drawing

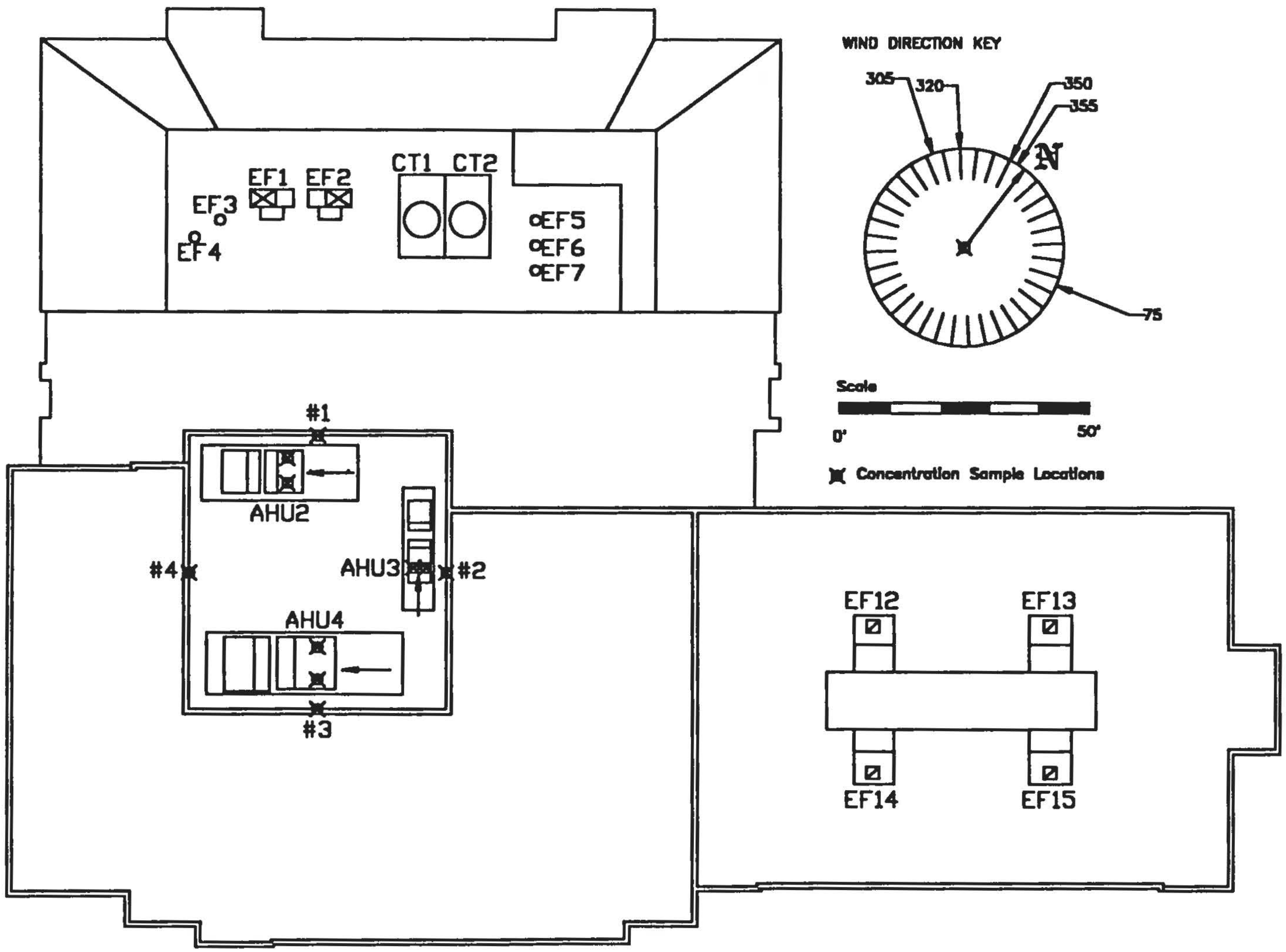
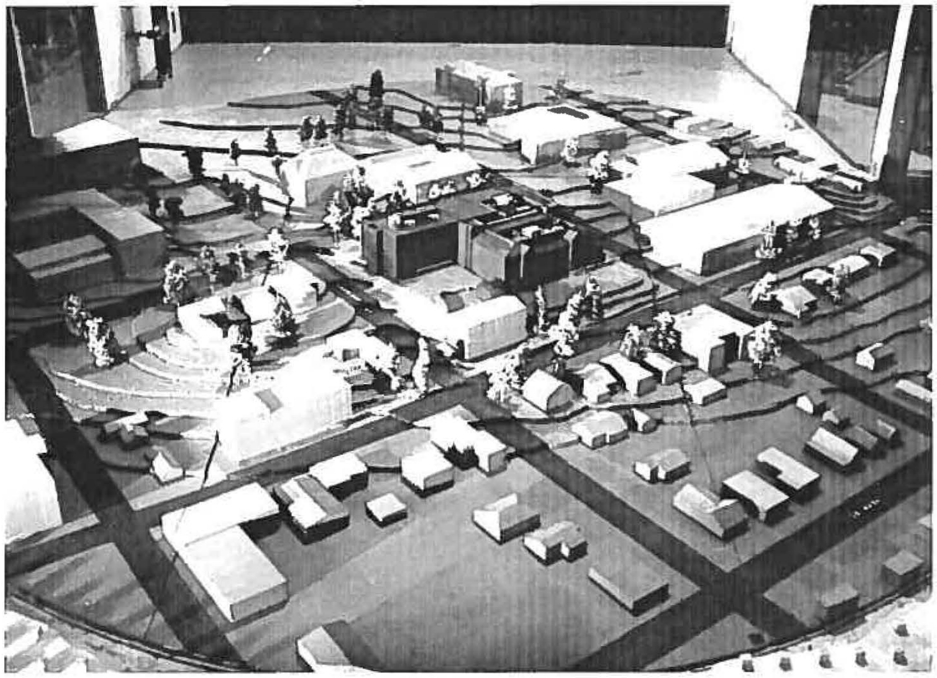



**Figure 2** Coolbaugh Hall Roof Intake and Exhaust Drawing



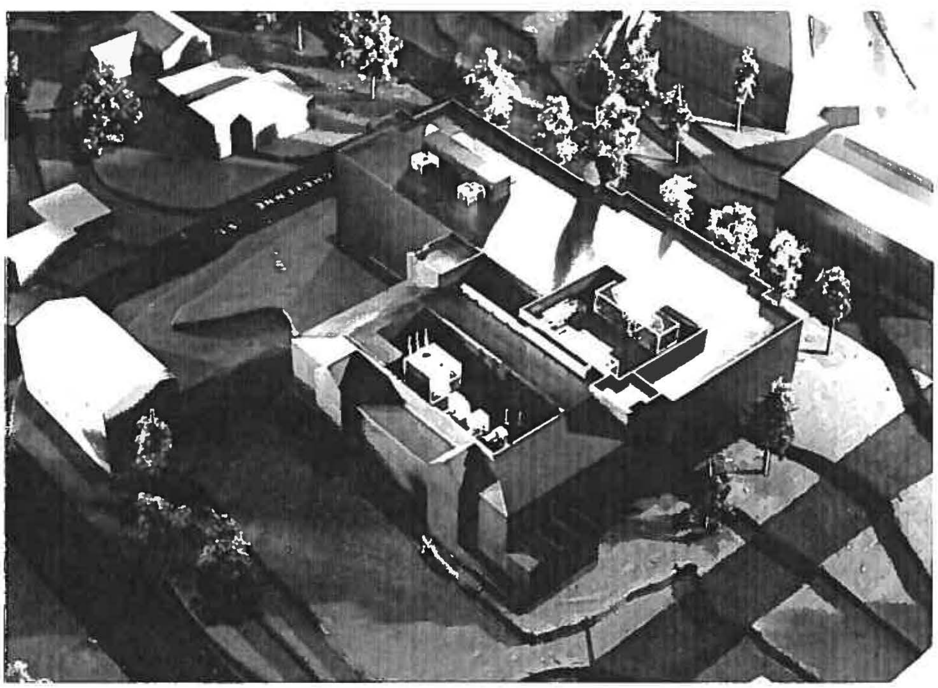


**Figure 3** Model Turntable and Coolbaugh Hall Roof Pictures

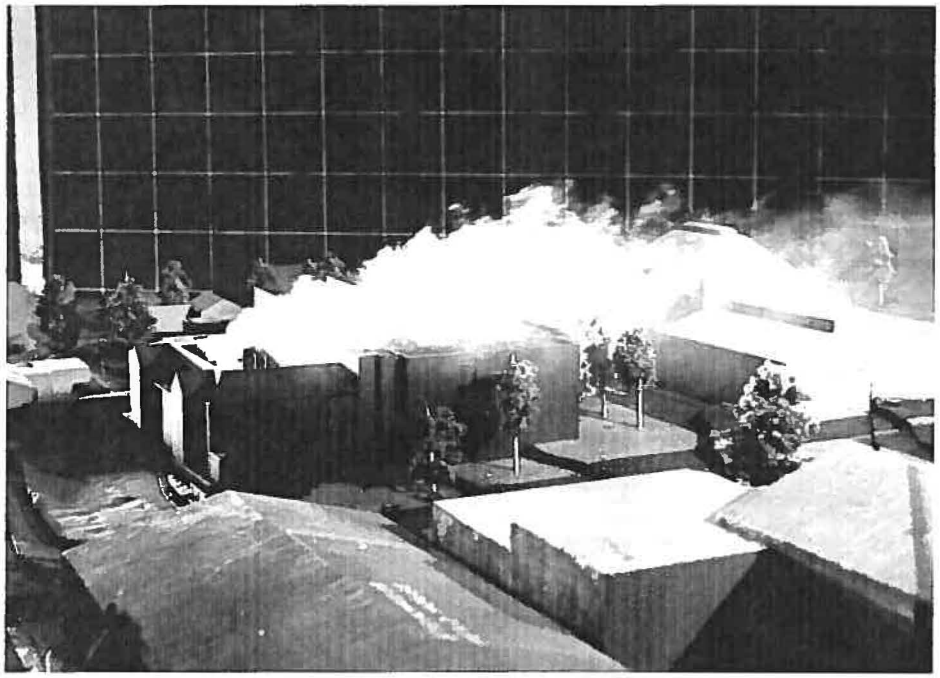


**Figure 4** Model Visual Plume Pictures

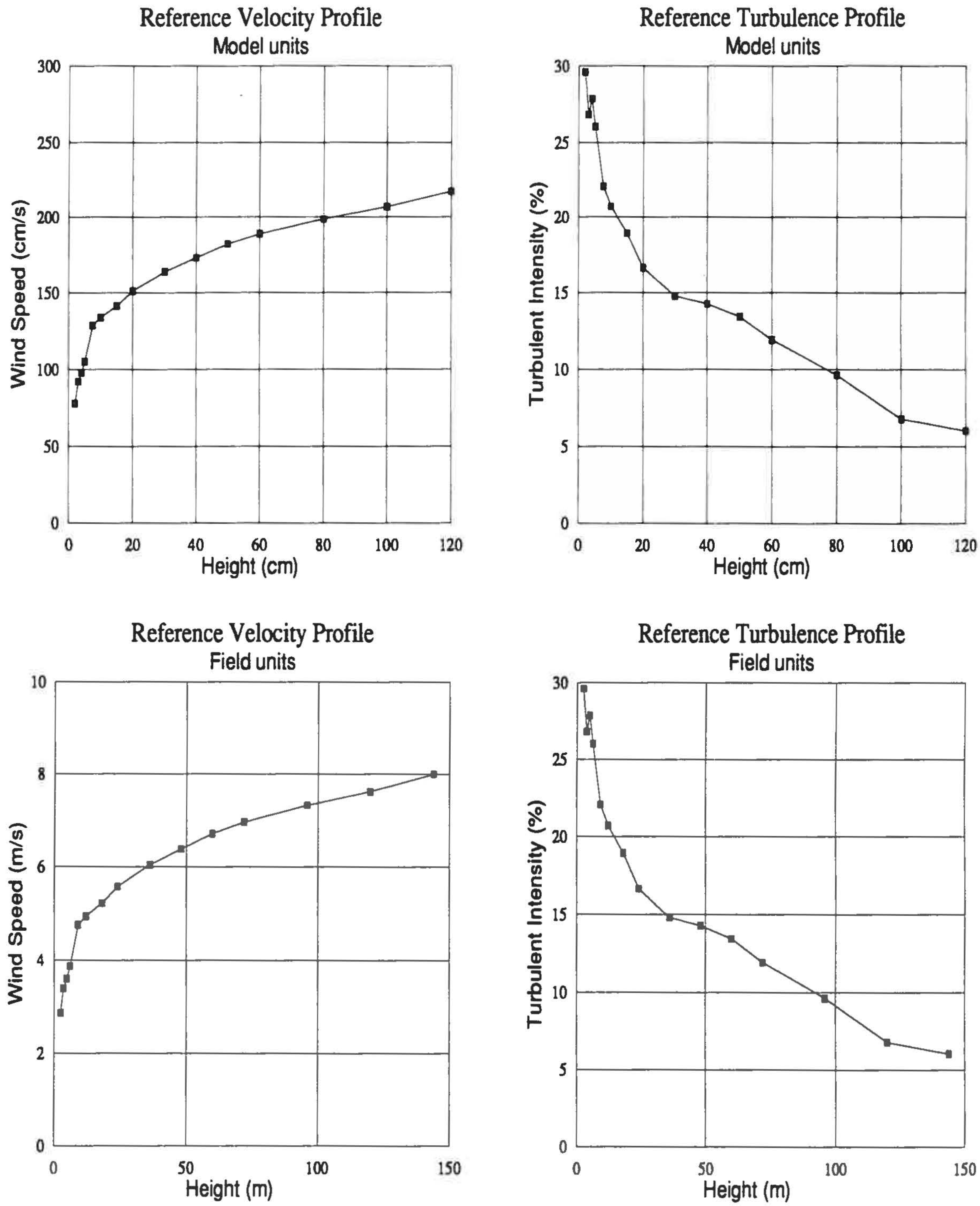



**Figure 5** Reference Velocity and Turbulence Profiles

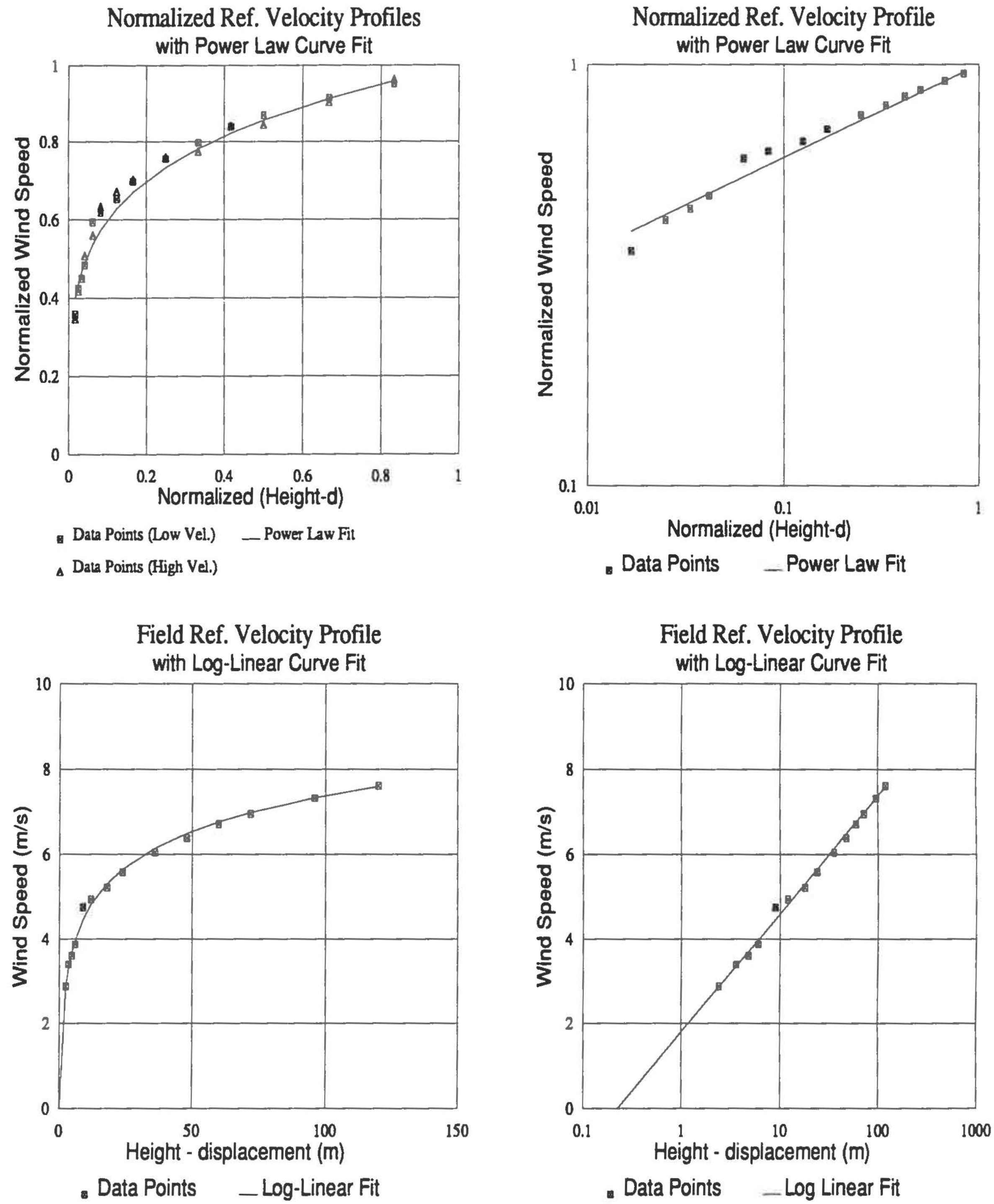



**Figure 6** Reference Velocity Profile Regression Curve Fits

# APPENDIX A: VIDEO TAPE ENCLOSURE

# APPENDIX B: CONCENTRATION FILE PRINTOUTS

# Colorado School of Mines Coolbaugh Hall

## Concentration Data Tables

CSM_CON0.WK3 Sheet A: 04/26/93

| | | | | |
|---|---|---|---|---|
| File Name CSM001.GC | Run# 1 | HEB | 04-25-93 | 22:28:42 |
| Wind Speed (cm/s) = | 150 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 492 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 20000 | | | |
| Background Conc. (ppm) | 2 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| | | | |
| 1 | 198 | 9796 | 2987 |
| 2 | 327 | 16217 | 4944 |
| 3 | 362 | 17977 | 5481 |
| 4 | 61 | 2940 | 896 |
| 5 | 409 | 20312 | 6193 |
| 6 | 442 | 21983 | 6702 |
| 7 | 475 | 23658 | 7213 |
| 8 | 470 | 23398 | 7133 |
| 9 | 489 | 24348 | 7423 |
| 10 | 480 | 23903 | 7287 |

| | | | | |
|---|---|---|---|---|
| File Name CSM002.GC | Run# 2 | HEB | 04-25-93 | 22:53:14 |
| Wind Speed (cm/s) = | 300 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 492 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 20000 | | | |
| Background Conc. (ppm) | 2 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| | | | |
| 1 | 304 | 15117 | 9217 |
| 2 | 287 | 14246 | 8687 |
| 3 | 247 | 12271 | 7482 |
| 4 | 95 | 4625 | 2820 |
| 5 | 335 | 16667 | 10163 |
| 6 | 391 | 19442 | 11855 |
| 7 | 378 | 18817 | 11474 |
| 8 | 370 | 18392 | 11215 |
| 9 | 406 | 20187 | 12309 |
| 10 | 366 | 18187 | 11090 |

**Table B-1** Concentration Data File, Runs 1 and 2

# Colorado School of Mines Coolbaugh Hall

## Concentration Data Tables

CSM_CON0.WK3 Sheet B: 04/26/93

| | | | | |
|---|---|---|---|---|
| File Name CSM003.GC | Run# 3 | HEB | 04-25-93 | 23:47:43 |
| Wind Speed (cm/s) = | 150 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 14 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 1000000 | | | |
| Background Conc. (ppm) | 3 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 240 | 237 | 2617 |
| 2 | 892 | 889 | 9808 |
| 3 | 233 | 230 | 2533 |
| 4 | 10 | 7 | 77 |
| 5 | 761 | 758 | 8365 |
| 6 | 342 | 339 | 3738 |
| 7 | 667 | 664 | 7325 |
| 8 | 710 | 707 | 7799 |
| 9 | 357 | 354 | 3908 |
| 10 | 373 | 371 | 4088 |

| | | | | |
|---|---|---|---|---|
| File Name CSM004.GC | Run# 4 | HEB | 04-25-93 | 23:18:56 |
| Wind Speed (cm/s) = | 300 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 14 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 1000000 | | | |
| Background Conc. (ppm) | 2 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 302 | 299 | 6604 |
| 2 | 549 | 547 | 12055 |
| 3 | 250 | 248 | 5473 |
| 4 | 21 | 19 | 417 |
| 5 | 525 | 522 | 11524 |
| 6 | 393 | 391 | 8625 |
| 7 | 514 | 512 | 11296 |
| 8 | 523 | 521 | 11490 |
| 9 | 413 | 411 | 9068 |
| 10 | 426 | 424 | 9357 |

**Table B-2** Concentration Data File, Runs 3 and 4

# Colorado School of Mines Coolbaugh Hall

## Concentration Data Tables

CSM_CON0.WK3 Sheet C: 04/26/93

File Name CSM005.GC Run# 5 HEB 04-26-93 0:22:20
Wind Speed (cm/s) = 150 Hr (cm) = 14
Air Temp. (C) = 20 Hr (cm) = 14
Source Designation = 1
Source Flow Rate (ccs) = 27
Source Gas Temp. (C) = 20
Tracer Type = C2H6
Tracer Conc. (ppm) = 1000000
Background Conc. (ppm) 6
Position Grid Filename > GCPOS.INP

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 2889 | 2884 | 16020 |
| 2 | 361 | 355 | 1971 |
| 3 | 346 | 340 | 1889 |
| 4 | 1956 | 1950 | 10832 |
| 5 | 1252 | 1246 | 6921 |
| 6 | 1483 | 1477 | 8207 |
| 7 | 726 | 720 | 4001 |
| 8 | 567 | 561 | 3119 |
| 9 | 454 | 448 | 2491 |
| 10 | 209 | 203 | 1128 |

File Name CSM006.GC Run# 6 HEB 04-26-93 1:47:52
Wind Speed (cm/s) = 300 Hr (cm) = 14
Air Temp. (C) = 20 Hr (cm) = 14
Source Designation = 1
Source Flow Rate (ccs) = 27
Source Gas Temp. (C) = 20
Tracer Type = C2H6
Tracer Conc. (ppm) = 1000000
Background Conc. (ppm) 4
Position Grid Filename > GCPOS.INP

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 1617 | 1613 | 17918 |
| 2 | 465 | 460 | 5113 |
| 3 | 379 | 374 | 4160 |
| 4 | 1046 | 1042 | 11574 |
| 5 | 618 | 614 | 6819 |
| 6 | 951 | 946 | 10514 |
| 7 | 675 | 670 | 7449 |
| 8 | 587 | 582 | 6471 |
| 9 | 521 | 517 | 5743 |
| 10 | 363 | 359 | 3987 |

**Table B-3** Concentration Data File, Runs 5 and 6

# Colorado School of Mines Coolbaugh Hall

## Concentration Data Tables

CSM_CON0.WK3 Sheet D: 04/26/93

| | | | | |
|---|---|---|---|---|
| File Name CSM007.GC | Run# 7 | HEB | 04-26-93 | 0:55:52 |
| Wind Speed (cm/s) = | 150 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 27 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 1000000 | | | |
| Background Conc. (ppm) | 7 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 2257 | 2250 | 12501 |
| 2 | 96 | 89 | 492 |
| 3 | 201 | 194 | 1079 |
| 4 | 1575 | 1568 | 8713 |
| 5 | 1002 | 995 | 5526 |
| 6 | 782 | 775 | 4306 |
| 7 | 283 | 276 | 1535 |
| 8 | 207 | 200 | 1109 |
| 9 | 172 | 165 | 918 |
| 10 | 68 | 61 | 337 |

| | | | | |
|---|---|---|---|---|
| File Name CSM008.GC | Run# 8 | HEB | 04-26-93 | 1:23:54 |
| Wind Speed (cm/s) = | 300 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 20 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 27 | | | |
| Source Gas Temp. (C) = | 20 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 1000000 | | | |
| Background Conc. (ppm) | 6 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| 1 | 1586 | 1580 | 17552 |
| 2 | 277 | 272 | 3018 |
| 3 | 322 | 316 | 3514 |
| 4 | 1089 | 1083 | 12037 |
| 5 | 603 | 597 | 6634 |
| 6 | 831 | 825 | 9167 |
| 7 | 492 | 486 | 5402 |
| 8 | 408 | 402 | 4468 |
| 9 | 377 | 371 | 4119 |
| 10 | 237 | 231 | 2571 |

**Table B-4** Concentration Data File, Runs 7 and 8

# Colorado School of Mines Coolbaugh Hall

## Concentration Data Tables

CSM_CON0.WK3 Sheet E: 04/27/93

| | | | | |
|---|---|---|---|---|
| File Name CSM009.GC | Run# 9 | NEFF | 04-27-93 | 13:30:37 |
| Wind Speed (cm/s) = | 150 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 22 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 344 | | | |
| Source Gas Temp. (C) = | 22 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 20000 | | | |
| Background Conc. (ppm) | 1 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| | | | |
| 1 | 214 | 10626 | 4633 |
| 2 | 232 | 11516 | 5021 |
| 3 | 76 | 3715 | 1620 |
| 4 | 203 | 10081 | 4396 |
| 5 | 195 | 9696 | 4228 |
| 6 | 223 | 11106 | 4843 |
| 7 | 243 | 12061 | 5259 |
| 8 | 223 | 11091 | 4836 |
| 9 | 193 | 9581 | 4178 |
| 10 | 112 | 5540 | 2416 |

| | | | | |
|---|---|---|---|---|
| File Name CSM010.GC | Run# 10 | HEB | 04-27-93 | 13:54:10 |
| Wind Speed (cm/s) = | 300 | Hr (cm) = | 14 | |
| Air Temp. (C) = | 22 | Hr (cm) = | 14 | |
| Source Designation = | 1 | | | |
| Source Flow Rate (ccs) = | 344 | | | |
| Source Gas Temp. (C) = | 22 | | | |
| Tracer Type = | C2H6 | | | |
| Tracer Conc. (ppm) = | 20000 | | | |
| Background Conc. (ppm) | 2 | | | |
| Position Grid Filename > | GCPOS.INP | | | |

| Tube No. | Meas.#1 (ppm) | Norm.#1 (ppm) | K1*10^6 (cm^-2) |
|---|---|---|---|
| | | | |
| 1 | 192 | 9491 | 8277 |
| 2 | 261 | 12931 | 11277 |
| 3 | 162 | 7991 | 6969 |
| 4 | 192 | 9496 | 8281 |
| 5 | 175 | 8641 | 7536 |
| 6 | 209 | 10366 | 9040 |
| 7 | 225 | 11176 | 9747 |
| 8 | 221 | 10931 | 9533 |
| 9 | 259 | 12836 | 11194 |
| 10 | 212 | 10506 | 9162 |

**Table B-5** Concentration Data File, Runs 9 and 10

# APPENDIX C:  FACILITIES AND TECHNIQUES

## C.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.

Figure C-1 below shows the plan view layout of the FDDL laboratory facilities including the meteorological wind tunnel, environmental wind tunnel and industrial aerodynamics wind tunnel.

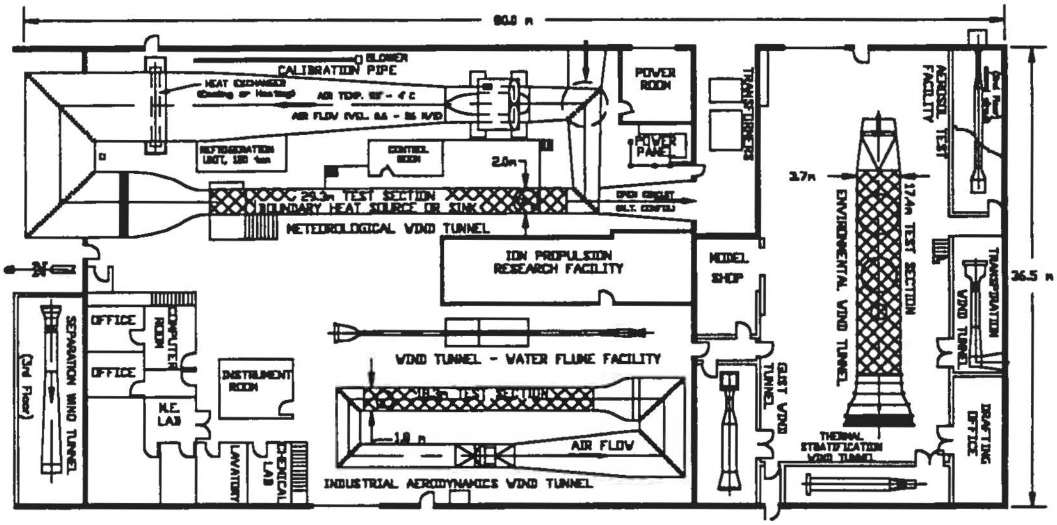


**Figure C-1** Fluid Dynamics and Diffusion Laboratory Layout

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.

## C.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 0.1 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.

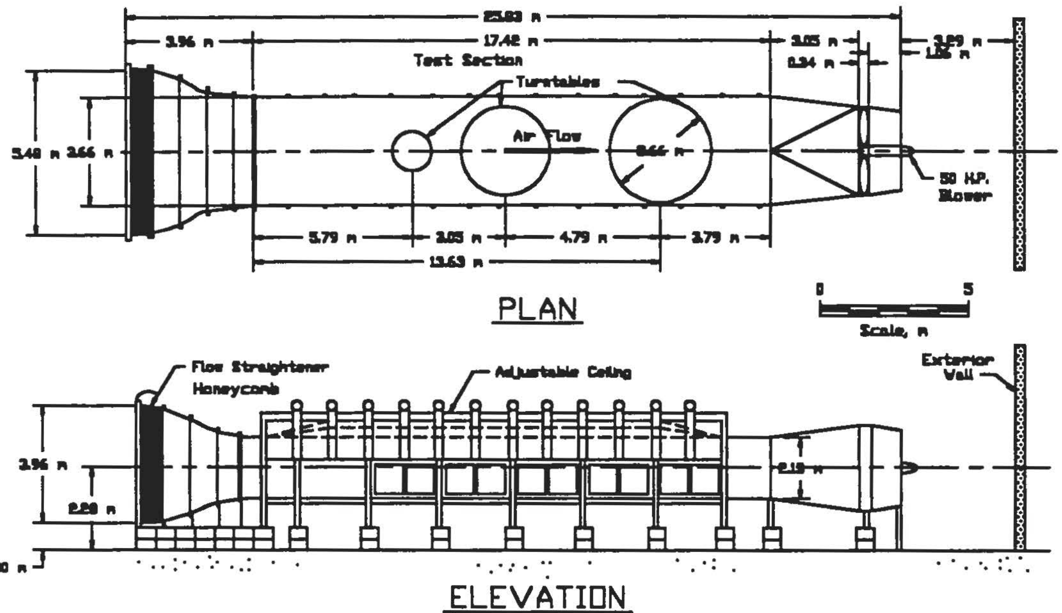



**Figure C-2** Environmental Wind Tunnel Schematic

## C.3: WIND SPEED MEASUREMENT DESCRIPTION

**Velocity Standards**

**a. 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.

**b. 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.

**c. 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, $\Delta P$ = difference between static and stagnation pressures, and $\rho$ is the air density. $\rho$ is calculated from ideal gas law and $\Delta P$ is measured using a Datametrics Electronic Manometer. The pitot-static probe measurements are accurate to within ± 2 percent of the actual velocity.

**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.

**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 $B_i' = B_i(\cos^2\phi_i + k^2\sin^2\phi_i)^{ci/2}$
$\phi_i$ = 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, ($E_i$, $\phi_i$; 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, $k_i$ 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 [1974],

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

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

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

$\alpha = 45°$,

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

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

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

**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.

**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 C-10 on the following page.

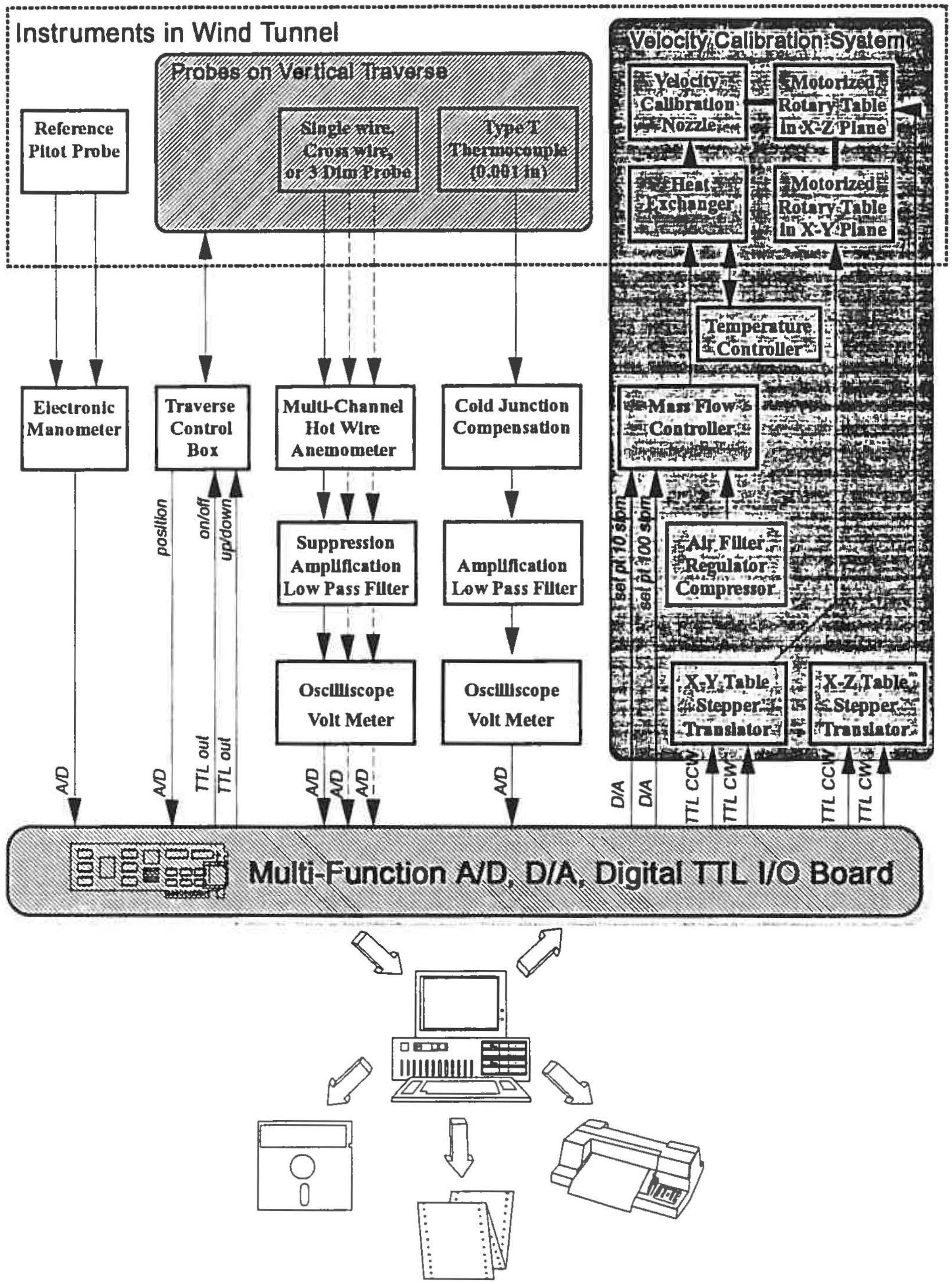



**Figure C-3** Velocity Calibration and Measurement System

## C.4: FLOW VISUALIZATION TECHNIQUES

### 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.

### 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 [Lee et al., 1988]. 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.

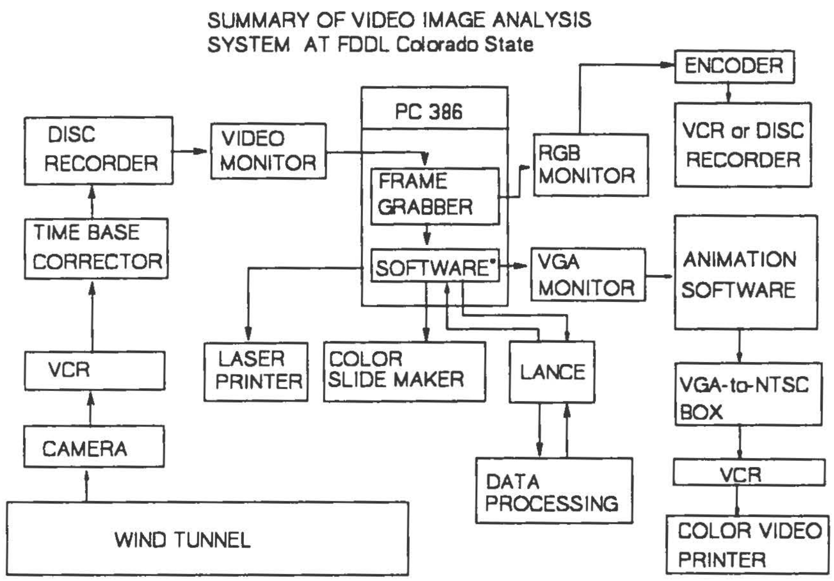



**Figure C-4** Video Image Analysis System

## C.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.

### 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.

### 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.

**Test Procedure**

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 a 200 s (approximate) 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, $\chi_{mea}$, along with the response levels for the background $\chi_{bg}$ and source $\chi_{source}$ 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, $\chi_{bg}$, (the result of previous tests within the laboratory), are measured to an accuracy of 20 percent. The larger measured concentrations, $\chi_{mea}$, are accurate to 2 percent. The source gas concentration, $\chi_{source}$, 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.

### Concentration Measurement System

A flow-logic chart of the source gas release, gas sampling, and concentration measurement systems is displayed in C-16 on the following page.

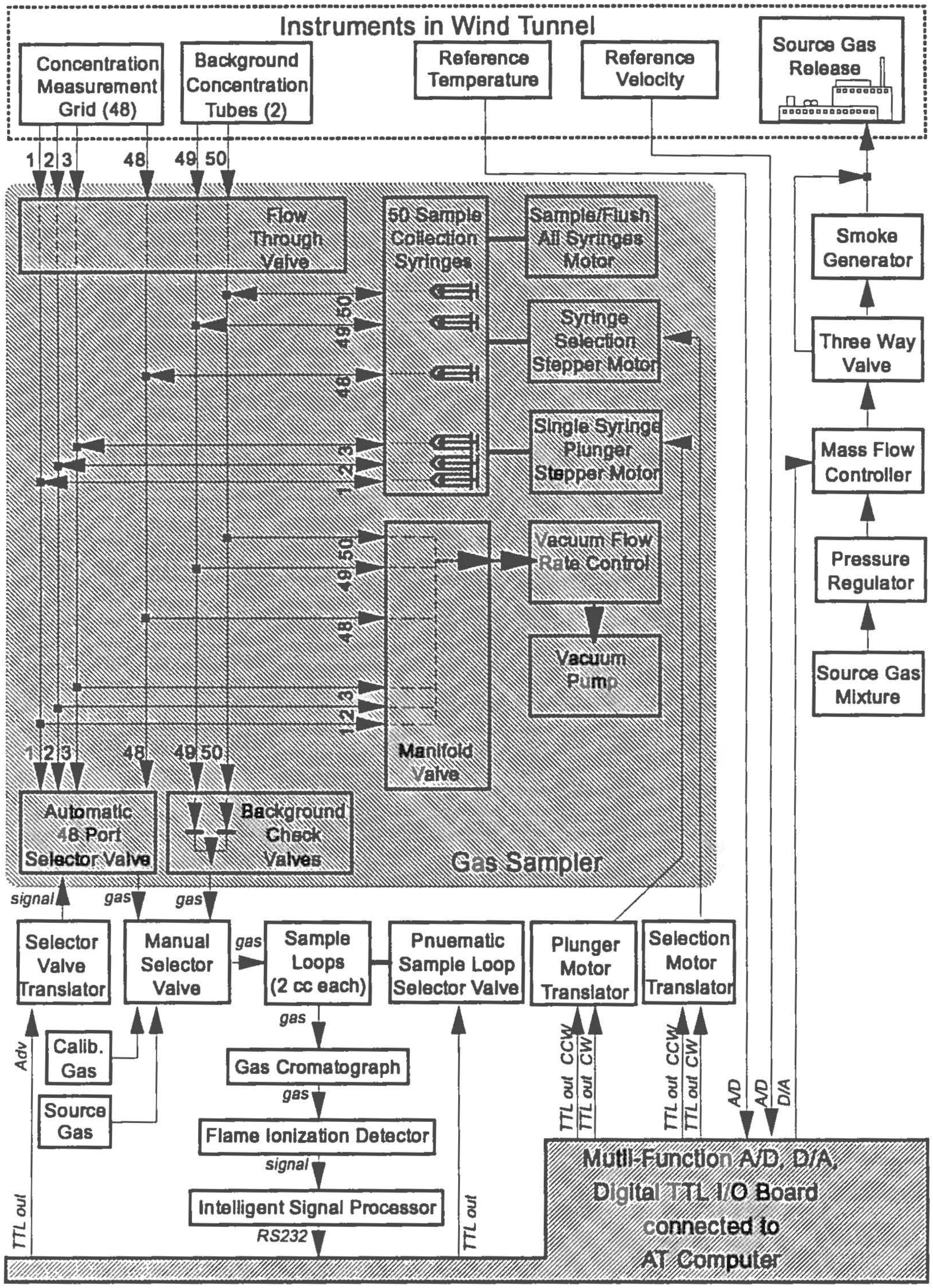



**Figure C-5** Concentration Sampling and Measurement System Schematic