Air-Quality Evaluation of Stacks: Building No. 3
Chiron Corporation, Emeryville: A Wind-Tunnel Study
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Executive Summary

Wind-tunnel tests were conducted to assess the impact of the proposed development of Building #3 on the air quality of the Chiron site and nearby residential neighborhoods. Testing modeled the individual and cumulative effects of Building Nos. 3 and 4 stacks on their own and other buildings' HVAC inlets and other off-campus areas. After testing the initial design and after minor modifications to the design, the final results from the wind-tunnel studies predicted no violations of the EIR established dilution standard of 70:1.

When effective cumulative dilution (i.e., dilution calculated based on the cumulative concentration at a receptor due to all upwind stacks of Building Nos. 3 and 4) was considered, all receptor locations, both on and off site, exceeded the minimum 70:1 dilution criterion.

All individual and cumulative exposures of off-site locations (residential, schools, etc.) exceeded the recommended dilution standard 100:1 and the required dilution criterion of 70:1; and, most individual and cumulative exposures of on-site locations exceeded the minimum dilution standard of 70:1. While these dilution criteria judged are sufficient to protect on-site workers and visitors from known potential routine chemical exposures, the criteria do not necessarily provide sufficient dilution to protect against accidental releases of larger amounts of some chemicals, or from release of smoke from a fire, or of contagious biological or radioactive materials. For site locations subject to these contingencies (i.e., exhaust stacks serving laboratories where such special chemicals or highly contagious biological or radioactive materials would be used, or those proximate to office building HVAC air intakes), dilution factors far in excess of 70:1 standard would be needed. These were not addressed in this study.

Emergency Diesel Generators located on Building Nos. 3 and 4 and Building CMF were tested at ten receptor locations for three wind directions, west, north-northwest and south-southeast. Almost all receptors showed dilution values less than standards (2000:1 for failure, 5000:1 for caution) for all wind directions and wind speeds tested. The biggest contributor to the low dilution levels was the diesel generator located at Building CMF. Table 2 shows the cumulative hours per year that each diesel generator causes less than standard conditions at each receptor location tested. It is recommended that Building CMF's diesel generator use a plenum air makeup unit to increase dilution measurements at all receptor locations, and that all receptor locations on Chiron Way use a control system to automatically shut down while the emergency diesel generators on Building Nos. 3 and 4 are active.

Stack Elevation [ft]:	15	15	15
Emission Rate [g/s]:	1	1	1
Scale Factor:	360		

Receptor ID	Less than Standards [hrs/yr]													
	#3		#4		CMF		#3, #4		#3, CMF		#4, CMF		#3, #4, CMF	
	caution	fail	caution	fail	caution	fail	caution	fail	caution	fail	caution	fail	caution	fail
20	1417	0	0	1417	518	2978	0	1417	1935	2978	518	4395	518	4395
21	0	0	2209	1417	0	3496	2209	1417	1056	3496	0	4913	0	4913
22	0	0	0	1417	0	3496	0	1417	0	3496	0	4913	0	4913
23	0	0	0	1171	0	3496	0	1171	0	3496	0	4667	0	4667
24	2052	518	0	1171	0	3496	2052	1689	361	3496	0	4667	361	4667
25	361	1056	297	1171	3496	0	64	2524	3857	1056	3793	1171	3560	2524
26	0	1417	0	1171	0	3496	0	2588	0	4913	0	4667	0	6084
27	0	6084	0	1171	0	3496	0	6084	0	6084	0	4667	0	6084
29	0	0	0	0	518	2978	0	0	518	2978	518	2978	518	2978
30	0	0	0	0	518	2978	0	0	518	2978	518	2978	518	2978

*Results based on ESMUD Wind Data
**Caution dilution standard is 5000:1, failing dilution standard is 2000:1
***Results assume a 24 hr/day operation.

1. Background

The wind-tunnel tests were conducted by constructing a scale model of the project, including surrounding buildings on site, and testing it in a wind tunnel to examine how the building design effects stack performance, or how well emissions are diluted in the atmosphere. The model was constructed to be consistent with the design plans provided by Flad & Associates and AEI, Inc. The model reflected the most current information available regarding Chiron's proposed design at the time of testing. Typical receptor locations, including HVAC intakes, building entrances, courtyards, and nearby residences in the vicinity of the project, were identified and wind-tunnel testing was conducted to determine the minimum level of dilution that would occur at these receptors for emissions from the proposed Building Nos. 3 and 4 stacks. In addition, tests were conducted on the effect of the emergency diesel generators in Building Nos. 3 and 4, and the CMF building's emergency diesel generator.

The EIR analysis (after considering the toxic air contaminant emission rates estimated to result from the project, toxic characteristics of emitted substances, types of receptors near emission sources, and proposed stack designs) developed an operational dilution goal (or dilution standard) to minimize potential health and safety effects at receptor locations (Johnson, 1994; and, ESA, 1995). The dilution goal (or minimum dilution criterion) represents the minimum desired ratio between the relative concentration of the air-mixed emission when it reaches a receptor location and the relative concentration of emissions at the stack exit. The recommended dilution criterion was 100:1 and the minimum dilution criterion was 70:1 (Johnson, 1994; and, ESA, 1995).

For testing roof-top exhaust stacks in the wind-tunnel, a neutrally buoyant tracer gas (ethane) was emitted from various representative stacks on the scale model with the resultant concentration of the tracer gas at the receptor locations measured. Receptor measurements were conducted using the upwind directions (i.e., the included wind angle that resulted in measurable levels of effluent at a receptor). From these tests, expected minimum dilution factors could be determined for various combinations of stacks and receptors tested.

2. Introduction

Project Location

This report addresses the Phase II project of the Chiron Emeryville Campus Expansion Program. The Phase II project involves the addition of Building Nos. 3 and 7B to the existing buildings on the current Chiron campus. Building #3 will be a six-level laboratory-office building complementing the existing Building #4; and, Building #7B will be a two-story central utility plant, complementing the existing Building #7A.

The Chiron campus is located in Emeryville, California, east of the San Francisco Bay, as shown in Fig. 1. The campus site is approximately bounded by Stanford Street on the north, Horton Street on the west, Hollis Street on the east, and 53rd and 47th Streets on the south. Fig. 2 displays the site location.

Campus-Project Description

The Phase II project includes the construction of Building Nos. 3 and 7B on Chiron's Emeryville campus. The existing campus buildings will remain. Fig. 3 indicates the Phase II campus layout.

Floors one and two of Building #3 are a combination of two-story high building support spaces, mechanical/electrical rooms, and several areas of two levels of offices, lab and pilot plant and building support type spaces. Air handling units for floors 1-5 will be located on the 1st floor, with an additional unit on the 6th floor to serve floor six office space. Floors three, four and five contain laboratories and office areas. Floor six includes office areas and mechanical rooms. There is a mechanical penthouse on level seven, which houses mechanical equipment. The building exhaust systems will include four central exhaust systems and numerous dedicated exhaust systems. The exhaust stacks from these systems, will be grouped into four areas on the roof. The first and second group of stacks will be at the sixth floor (northwest and southeast cones) and the third and fourth group of stacks at the seventh floor (southeast and northwest cones). The third and fourth group of stacks will be at the seventh floor located on top of the mechanical penthouse. The main exhaust stacks will be sized to provide an average exhaust air

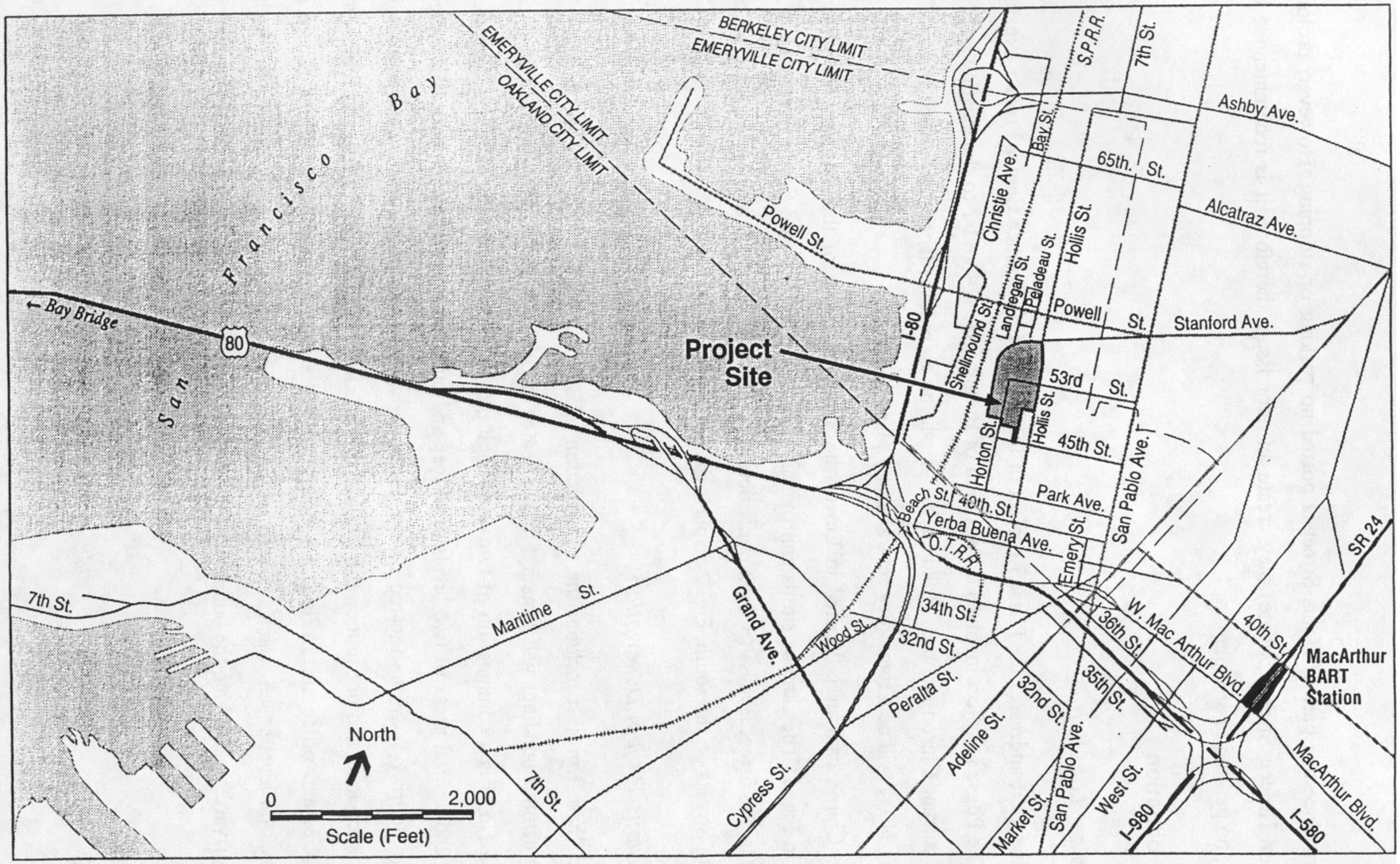

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Fig. 1 Vicinity map of the Chiron Life Sciences project within the Bay Area (Emeryville), California.

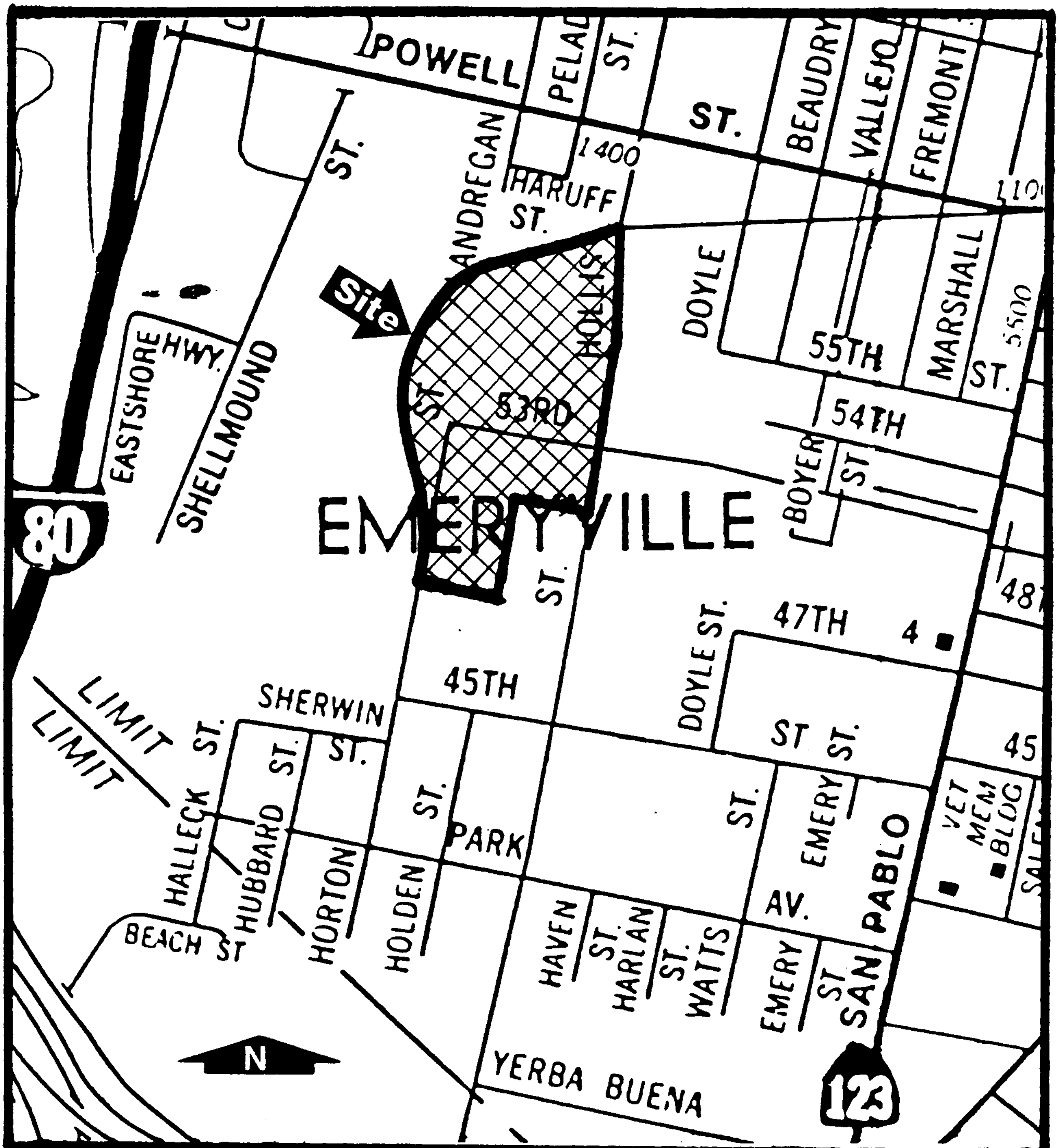

Fig. 2 Location of the project site within the city of Emeryville.

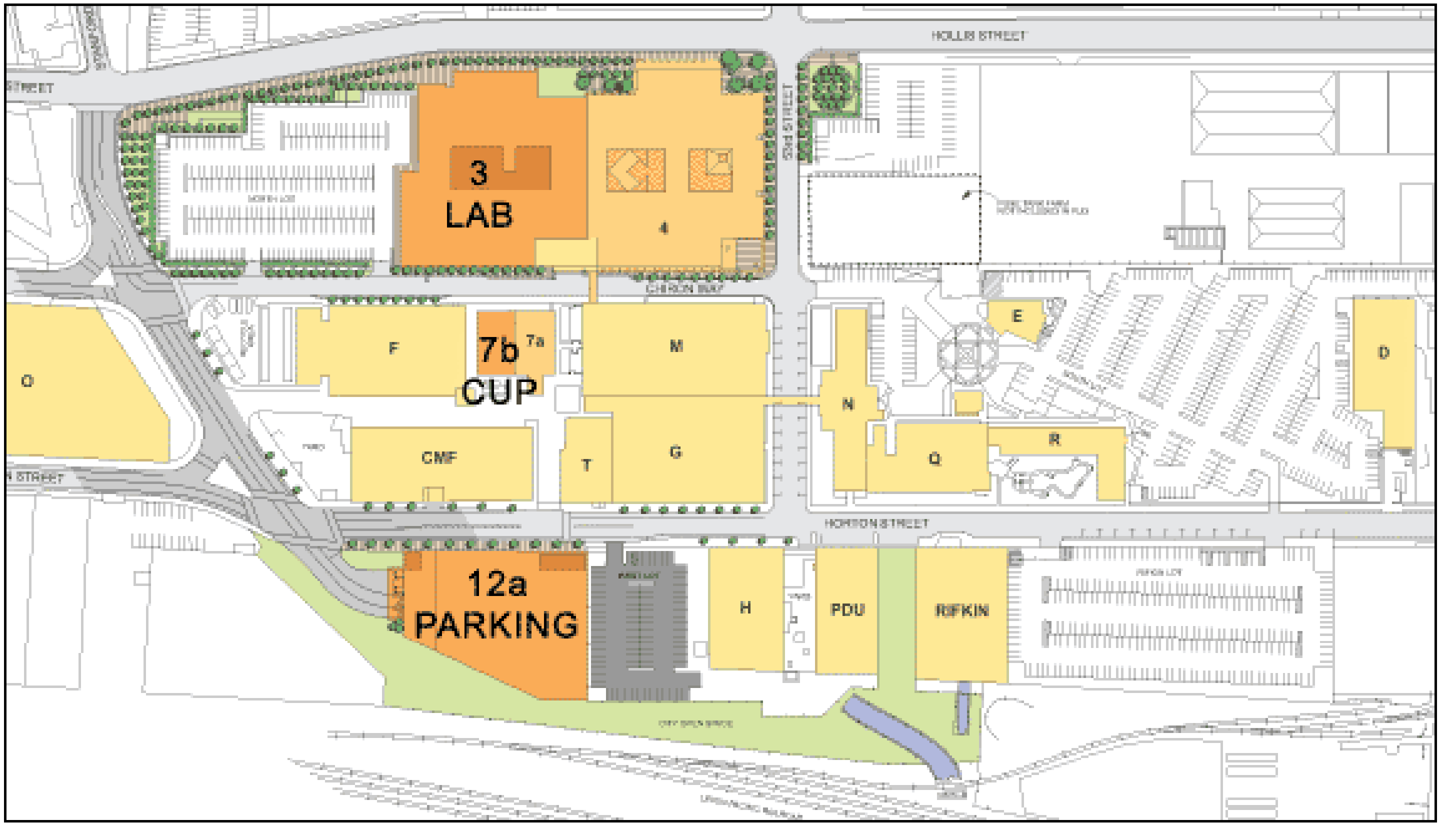

Figure 3. Current Phase II of the Chiron campus expansion.

velocity of 3,500 fpm with energy saving VFD's allowing an operating range between 4,000 fpm and 2,500 fpm. In addition to the HVAC exhaust systems, there is a diesel emergency generator set on the first floor with an exhaust outlet at the west side terrace areas of the second level of both Building Nos. 3 and 4. Also, the diesel emergency generator of Building CMF, located on the west side of Building F, was tested.

Buildings No. 7B is a two-story central utility plant addition to building 7A. The first floor will house chillers, with boilers located on the second floor. The cooling towers and boiler exhaust stacks will be located on the roof.

Study Objective

The objective of the present study is to determine the potential for re-entrainment of exhausts from Building Nos. 3 and 4 into its own HVAC intakes and/or other HVAC intakes within close proximity. This study also estimates the levels of contamination at other sensitive areas on the campus (i.e., courtyards, building entrances, etc.) and at adjacent properties. These properties include the Pacific Rim School (corner of Doyle and Stanford Streets), the Artists' Cooperative Housing, neighboring residences, MEI (Maximum Exposed Individual) previously identified by computer simulation (ESA, 1995), Day Care Center, and Emeryville High School. This study also includes analysis of Building Nos. 3 and 4 and CMF emergency diesel fuel generators on Building Nos. 3 and 4 and Building CMF.

3. Analysis of Near-field Air Toxics

The dispersion of potentially hazardous exhaust is of great concern, and several different methods for prediction and analysis of the atmosphere's ability to dilute pollutants before the gases impact sensitive receptors have been developed. In the environmental assessment of an exhaust stack, empirical or computer analysis may be employed, full-scale tests may be conducted, and/or wind-tunnel tests may be carried out. Which of these methods to use depends on such factors as economic constraints, the physical region of interest, and quality and accuracy of the desired results.

Various kinds of empirical-analytical methods have been developed to evaluate dispersion; however, each method generally applies only to specific areas of concern. Also, most numerical models are limited by failing to account adequately for local building wake effects or by requiring input of locally measured building wake and turbulence data.

Full-scale dispersion tests can provide useful concentration data. However, full-scale testing of different wind directions and speeds along with varied atmospheric stability is usually impractical. Interpretation of full-scale data is complicated by changing atmospheric conditions; and, the evaluation of an unbuilt structure is, of course, not possible.

Wind-tunnel tests can be conducted under ideal, steady wind conditions. Such tests, conducted properly, account for the effects of building aerodynamics and site specific wind-flow patterns created by the test building and surrounding buildings, trees, and topography. The results can be used to identify potential dilution problems. ASHRAE (1997) provides a good discussion of the validity of wind-tunnel modeling as a proven accurate means to simulate the dispersion of stack exhausts in the atmosphere. ASHRAE acknowledges the superiority of wind-tunnel data over that of empirically calculated predictions.

Wind-tunnel tests can precisely simulate critical conditions occurring in full scale. Wind-tunnel tests can simulate the average or mean wind speed dispersion of exhausts, as well as the so-called “worst-case” dispersion of exhausts, and other types of conditions that may be of interest. The “worst-case” dispersion of exhaust is generally used to determine the minimum level of dilution from an exhaust source that might occur under an accidental-release condition. This test represents a single wind direction at a single wind speed; this combination produces the minimum dilution of all possible wind directions and speeds. Usually, the occurrence of such a specific condition is statistically small and typically will comprise only a few hours or less of an annual meteorological data set. Thus, the “worst-case” dispersion case refers to an accident situation that is used to determine if short-term exposure limits (e.g., 15 minutes, 1 hour, etc.) are exceeded at sensitive receptor locations.

In contrast to the “worst-case” analysis is the “routine release” analysis. Under routine release testing, the normally expected exposure of emissions over a specified time period is estimated. Typically the time period is one year thus predicting annual exposure levels, although any time period could be used (i.e., one month, etc.). For annual routine exposure analysis, the average concentration contribution from each of the 16 wind directions in 22.5 degree increments is measured (ASHRAE, 1997). The 16 major wind-direction measurements then can be integrated into the meteorological data for frequency to estimate individual receptor annual exposure levels.

In contrast, the worst-case dispersion of exhausts is assumed to occur when a given sensitive location is located directly downwind of the emission source for the so-called “critical wind speed.” The “critical wind speed” lies between lower wind speeds which generally create a large exhaust dilution due to enhanced plume rise, and higher wind speeds, where the vertical exhaust stream is rapidly diffused horizontally and mixed with the turbulent moving air. At this single “critical” wind speed, the beneficial effects of plume rise (low speed) and mixing (high speeds) are compromised, and the minimal dilution of exhaust stack emissions results.

4. Critical Wind Speed

The “critical wind speed”, as mentioned above, represents the minimum dilution condition for a given exhaust emission at a specific receptor location. The value of the “critical wind speed” is not constant for all stacks; it depends on the size of the stack, the exhaust speed, and the distance between the emission source and the specific receptor location. Thus, for a single stack there will be as many critical wind speeds as there are receptor locations. ASHRAE (1997) provides an equation for theoretically calculating the “critical wind speed” which is given as

$$\frac{U_{crit,0}}{V_e} = 3.6 B_1^{-0.5} A_e^{0.5} / S$$

$U_{crit,o}$ is the critical wind speed producing the smallest minimum dilution for an uncapped vertical exhaust with negligible stack height. V_c is the exhaust speed of the stack. B_1 is called the distance dilution parameter. B_1 depends on the exhaust plume trajectory, turbulence intensity of the approach wind and turbulence generated by the building. The upwind level of turbulence is given by σ_θ, the standard deviation (in degrees) of wind direction fluctuations averaged over a 10 minute period. Wilson and Lamb (1994) give

$$B_1 = 0.027 + 0.0021 \sigma_\theta \,.$$

The recommended design value for buildings in an urban terrain (Category B, α= 0.22, δ = 370 m) is σ_θ equals 15 degrees, which makes B_1 equal to 0.0059 (ASHRAE, 1997).

For the present case, the experimentally determined "critical wind speeds" were found from wind-tunnel testing by varying the approach wind speed in the tunnel. The more conservative of the measured values (i.e., the one that resulted in the lower value of minimum dilution) was used to assess the minimum dilution standard. This technique should be applied since the theoretical "critical wind speed" from the ASHRAE dilution equations addresses only simple building shapes and the equation was empirically determined from full-scale and wind-tunnel tests. The theoretical estimate of "critical wind speed" does not account for site specific building geometry and surrounding topographic conditions.

5. Atmospheric Stability

Plume behavior will vary sufficiently for different atmospheric conditions. The thermal stratification of the atmosphere has great influence on the long-range dispersion of an exhaust plume. Vertical wind shear, due to thermal effects, also can result in unexpected plume rise.

A common classification scheme used to categorize atmospheric diffusion by its stability is Pasquill stability. Table 3 shows the six stability classes by Pasquill (1961) and later modified by Turner (1967). Classes A to C represent unstable conditions, characterized by strong vertical diffusion due to the buoyancy and shear production of turbulence. Class D represents near-neutral conditions, where buoyancy effects are unimportant and nearly all turbulence kinetic energy is taken from the shear in the mean flow. Classes E and F represent stable conditions, characterized by weak diffusion and turbulence, inhibiting mixing and dilution of the plume with the ambient air. Stability Class F has the potential to be the worst-case condition if the wind direction aligns the plume centerline trajectory with the height of the receptor.

The wind-tunnel simulations represent near neutral to slightly unstable atmospheric conditions. Therefore, the wind-tunnel tests cannot reproduce the worst-case condition that might occur for a stable atmosphere. However, in the near field (distances less than 100 meters), the stability of the atmosphere will not greatly alter the dispersion from that which occurs under the neutral conditions (which are modeled in the wind tunnel), since the presence of the building would mechanically introduce turbulence (through vorticity shedding and wake formation), which would effectively negate the stratification effect on the dispersion process. In addition, the wind tunnel does model site-scientific dispersion characteristics unique to the specific case considered, which in general results in more accurate estimates than other methods.

Table 3. Meteorological Conditions Defining Pasquill Turbulence Type /a/

Surface Wind Speed m/s		Daytime Insulation			Nighttime Conditions /c/	
low	high	strong	moderate	slight	thin overcast or > 4/8 low clouds	< 3/8 cloudiness
	<2	A	AB	B		
2	3	AB	B	C	E	F
3	4	B	BC	C	D	E
4	6	C	CD	D	D	D
	>6	C	D	D	D	D

A. Extremely unstable conditions
B. Moderately unstable conditions
C. Slightly unstable conditions
D. Neutral conditions
E. Slightly stable conditions
F. Moderately stable conditions

/a/ From F. A Gifford, Turbulent diffusion typing schemes: a review. *Nuclear Safety*, 17(1):71, 1976.

/b/ Applies to heavy overcast day or night.

/c/ Degree of cloudiness is that fraction of sky above the local apparent horizon that is covered by clouds.

In the immediate building and stack vicinity, local mechanical turbulence is primarily governed by the building, roof and stack-flow interactions. Therefore, the plume behavior is not greatly influenced by the atmospheric stability. However, the further away the plume travels, the greater the influence of the thermal stratification of the atmosphere becomes. Atmospheric stability may affect the dispersion at sensitive receptors that are located at distances greater than a few building lengths downwind from the source. For the Chiron site, the "building length" is effectively square (200 m in an east-west direction and about 200 m in a north-south direction). Thus, the closest residences and the locations of concern are within this criterion distance. Therefore, the neutral atmospheric stability is appropriate for the present testing situation.

Further reason for using a neutral atmosphere in the present wind-tunnel testing is provided by consideration of the existing meteorological conditions at the Chiron site. For the conditions at the Chiron site, the one-year East Bay Municipal Utility District meteorological data set indicates that Pasquill stabilities A through C occur only about 6.6% of the time, D stability occurs 61.8% of the time, and E and F stabilities occur about 29.5% and 2.2% of the time, respectively. The wind tunnel models the Pasquill stability class D.

A reasonable technique to account for adverse atmospheric stability is to utilize the wind-tunnel site-specific results and apply an atmospheric correction factor, as necessary, to account for the non-neutral atmosphere. However, since the distances from the emission sources are all within the range of one or two effective “building-lengths” and because the dominant stability class is Class D, the wind-tunnel conditions adequately represents the site stability. Therefore, no atmospheric “stability correction factor” was applied to the wind-tunnel data. ASHRAE (1997) also states, “For most applications related to airflow around buildings, neutral stratification is assumed (for physical modeling),” (i.e., no stability correction factor is required).

6. Meteorological Data/Wind Climate

Knowledge of the typical prevailing wind speeds and directions is important in properly assessing the wind-tunnel results. This information is useful for determining the distributions of occurrence of certain wind flow directions which may give rise to minimal dilution levels for some emission source - receptor combinations. The wind meteorological data records (met data) that previously was used in the E.I.R. for the ISCST computer analysis of the Chiron Development Plan also was used in the present study. A one-year period of met data was available from the East Bay Municipal Utility District (EBMUD) wastewater treatment planet located approximately one mile South of the Chiron site. This met data record had been prepared and approved by the BAAQMD for use in the screening level ISCST2 computer model calculations. Therefore, this same met data set was used for the present study. Table 4 presents the met data in tabular form.

7. Dilution Criteria

Exhaust Stack Dilution Criteria

A primary goal in this study was to determine if exhaust emissions from the proposed Building No. 3 and existing Building No. 4 would meet the established dilution standard for routine chemical releases (as opposed to an accidental or unintended chemical release). At the same time, it is desirable to avoid possibly "over-designing" the exhaust systems by requiring, for example, excessively tall stacks. Rather than relying solely on non-site specific estimates provided by the analytical methods, (i.e., ASHRAE models), or by computer models (such as ISCST2), physical modeling was used to provide a more realistic site-specific evaluation of stack dispersion of the near-field dispersion process in the vicinity of the project site.

Table 4. EBMUD Wind Data

Wind	Direction	Duration in hours for each wind speed bin, in m/s								
Direction	Azimuth	23.15	13.89	10.8	8.75	5.66	3.09	1.54	0.26	0	Total
N	0.0	0	0	3	21	48	171	46	0	3	292
NNE	22.5	0	0	0	0	15	59	42	0	0	116
NE	45.0	0	0	4	2	14	49	36	0	1	106
ENE	67.5	0	0	0	7	50	87	69	0	0	213
E	90.0	0	0	0	2	37	97	89	0	2	227
ESE	112.5	0	0	0	3	35	117	117	5		277
SE	135.0	0	0	10	45	150	170	101	0	5	481
SSE	157.5	0	1	5	64	169	184	107	0	1	531
S	180.0	0	2	4	30	140	219	108	0	0	503
SSW	202.5	0	0	1	23	170	260	97	0	0	551
SW	225.0	0	0	1	18	197	266	62	0	0	544
WSW	247.5	0	0	6	87	347	251	44	0	0	735
W	270.0	0	0	21	279	654	361	45	0	0	1360
WNW	292.5	0	2	7	152	690	675	29	0	3	1558
NW	315.0	0	0	0	39	153	562	45	0	8	807
NNW	337.5	0	0	0	4	96	323	35	0	1	459
											Total
											8760

ESA (1994 and 1995) used two methods considered for use in developing conservative dilution criteria for the project. The first method considered only anticipated *routine releases* (Johnson, 1994), and ignored accidental releases of emissions. The second ignored routine releases and focused on *accidental releases* of chemicals in a laboratory.

The *routine release* standard was selected for the present study as specified by Chiron (Johnson, 1996). The objective of this analysis was to evaluate the routine operational health and safety effects of the development of the project. The dilution calculation, using the *routine release* premise (Johnson, 1994; and, ESA, 1994 and 1995), resulted in the following dilution standards based on five distinct health-related criteria, as shown in Table 5.

What is required, then, is to meet the most stringent of the criteria above. Consequently, if wind-tunnel testing indicates that the project can feasibly meet a dilution criterion of about 70 to

1, then it is clear that the project can be constructed to avoid significant impacts related to cancer risk, non-cancer health effects, and acute health effects of *routine releases.*

The second method uses a worst-case analysis based on an *accidental release*, a spill, during critical dispersion wind conditions. That criterion has been used by the University of California at Davis (White et al., 1991) as a minimum dilution criterion for exhausts from laboratory fume hoods.

Table 5. Dilution Criteria for Routine Release

Health Effect Standard	Dilution Criterion
Cancer Risk (residential)	69 to 1
Cancer Risk (occupational)	45 to 1
Non-Cancer Chronic Health Effects (residential)	57 to 1
Non-Cancer Chronic Health Effects (occupational)	38 to 1
Acute Health Effects	3.3 to 1

That standard applied to non-cancer health effects; the cancer health risks specifically were not considered. For this standard, no more than one accidental release was assumed to occur at any one time (multiple releases could occur as long as their occurrences do not overlap) and the maximum event would be the spill of a four-liter bottle of solvent. The Davis campus dilution criterion (Seabury, 1991 a, b, c and d) was 600:1 and amended around 2000 to 1000:1, meaning that one part fume-hood emissions diluted by 1000 parts uncontaminated air would not exceed that exposure standard. The accidental release criterion was not used as the standard in this study since the present intent was to evaluate only long-term operational health and safety effects.

In summary, the minimum dilution criterion or standard used in this study is 70:1 with a recommended level of 100:1 if possible (Johnson, 1994 and 1996; and, ESA, 1994 and 1995). This minimum criterion addresses only routine releases of chemicals that would be expected from operations of the project. The 70:1 criterion does not provide the level of protection which might be needed to avoid adverse acute health effects that might occur as the result of accidental releases of toxic materials under certain combinations of wind direction and speed.

Diesel Exhaust Dilution Criteria

For exhausts from emergency diesel generators located at Building Nos. 3 and 4 and Building CMF, different dilution criteria is necessary. Diesel exhaust is a complex mixture of thousands of organic compounds, of which hundreds contribute to its odor. Odor intensity has been well correlated with the oxygenated (smoky-burnt) portion of the emitted hydrocarbons, although odorous non-hydrocarbons are also present. Therefore, it would be difficult to evaluate diesel exhaust in the same manner utilized for fume hood exhaust. Instead, diesel exhaust is evaluated as a single entity to identify odor thresholds. Odor panel data presented in Cernansky (*Journal of The Air Pollution Control Association, 1983*) indicates that approximately 20 percent of persons would object to odors when exhaust is diluted by a factor of 4000:1. Recent data from Vanderheyden (*87th Annual Meeting of the Air & Waste Management Association, 1994*) indicate that a dilution level of 2000:1 correlates to the 20 percent objection level. The 2000:1 dilution level is typically used as an odor threshold as it was in this project. Odors at this dilution level will still be detectable by most persons and will be objectionable to only about 20 percent of the population.

Health limits for diesel exhausts are above their respective normalized odor thresholds (*Air Quality and Pedestrian Level Wind Evaluation Walker Hall Seismic Replacement Facility University of California at Davis, 1997* (*CPP Project 97-1485*)).

Therefore, the design criteria for both sources is based on a more conservative cautionary odor threshold value of 5000:1, and a failing odor threshold of 2000:1.

8. Stack Parameters

Dilution of source emissions from a given stack can be improved by either increasing the height of the stack, or by increasing the exhaust velocity through the stack. In some instances, however, increasing the stack velocity may not be an effective means to increase dilution depending upon where the trajectory of the exhaust plume impacts either the ground or another building, i.e., HVAC inlets. Both design variables, stack height and speed, were considered in this analysis. However, increasing the stack height would most likely prove to be the most effective and economical means to increase the level of dilution at sensitive receptors.

9. Wind-Tunnel Testing

The atmospheric boundary layer is that layer of air covering the earth that is directly affected by friction between the ground and atmosphere as the air flows over the planet's surface. In order to study the dispersion of gases in the atmosphere, the flow characteristics of the atmosphere in the region referred to as the atmospheric boundary layer must be considered. Physical modeling of dispersion in this region is conducted in an "environmental" or "atmospheric boundary layer" wind tunnel. The Atmospheric Boundary Layer Wind Tunnel (ABLWT) at U.C. Davis is such a facility and was used for all gas dispersion tests made for this study. Testing was carried out on a 1 inch equals 30 feet (1:360) scaled model that included the project buildings as well as major off-site buildings within a diameter of one-half mile from the site. The area modeled in the wind tunnel was about one-quarter mile normal to the approaching wind direction and approximately one mile in the direction of the wind flow.

A hydrocarbon analyzer was used to measure qualitatively the downwind dispersion of building emission sources. A tracer gas, ethane, injected through modeled exhaust stacks was sampled at specific critical locations (courtyard locations, ventilation intakes, etc.) downstream of the stack in the wind-tunnel test section. Vertical wind speed to exhaust speed momentum similarity was matched in all wind-tunnel tests. A time-averaged concentration measurement was made per sensitive receptor. An individual measurement was a time average of 30,000 individual digitized samples collected over a 30 second period to produce a mean concentration, after being corrected to account for the variable background level of ethane concentration.

Wind-tunnel testing of emissions from all buildings examined representative exhaust stacks for a range of stack characteristics, including various approach and exhaust velocities. Generally, a "representative" stack within a grouping of several stacks was modeled in the wind tunnel. This approach allowed for all stacks to be accounted for by either direct testing or through the extension of wind-tunnel results to adjacent stacks in the same stack grouping area.

Over 20 selected receptor locations were sampled in a general test program to characterize the dilutions at on-site locations on and around the individual buildings of the Chiron site. On-site measurement receptor locations were selected to identify potential low-dilution conditions at building entrances, HVAC intakes, and pedestrian walkways and plazas. Using ethane as a tracer gas, wind-tunnel measurements were made for the dilution of emission sources at the specified downwind receptor locations, such as future courtyards, pedestrian areas, ventilation intakes and roof-top locations on surrounding buildings.

The measured dilution values were compared with the primary exhaust dilution acceptability criterion (the *routine release* standard) of 70 to 1 to evaluate the feasibility that the project would reliably meet the health and safety goals for long-term *routine release* operations. This criterion, when taken together with the evaluations carried out in the environmental impact report, provides a sufficient basis to reach valid conclusions about the ability of the project to be built to satisfy those goals within acceptable health and safety standards.

The testing focused on determining if the project exhaust would meet the minimum dilution criterion at all identified sensitive receptor locations. If the desired dilution levels were not met, an effort would be mounted first to identify and characterize potential mitigation measures, and then to evaluate the effectiveness of the measures to meet the dilution criterion, such as increase the stack height, alter the flow velocity or adjust the stack location until the minimum dilution criterion was achieved.

10. Wind-tunnel Test Results

A 1 inch equals 30 feet model was constructed from Phase II scope of work plan provided by Flad & Associates and AEI, Inc. After completion of the model, an approval meeting was held at Chiron in Emeryville (April, 2002) in which representatives from Chiron and Affiliated Engineers, Inc. (AEI) approved the model accuracy with the inclusion of several then recent design changes that were subsequently incorporated into the model. Therefore, the most current version of the model at the time of wind tunnel testing was used.

The location of the measurement receptors is shown in Figs. 4 and 5. Table 6 provides a brief description of each receptor location. These measurement locations are comprised of all HVAC inlet areas of Buildings Nos. 3, 4, M, F, and CMF. Adjacent properties receptor locations were identified at the closest residential housing area, Pacific Rim School, The Day Care Center, Emeryville High School, Artists' Cooperative Housing and the MEI (Most Exposed Individual) previously determined from the air dispersion computer modeling U.S. EPA-approved Industrial Source Complex Short Term (ISCST2) air pollutant dispersion model for a similar type emission source (ESA, 1994).

Table 6. Receptor Locations

Receptor	Building	Location
16	4	East side of bldg, 2nd floor intake
17	4	East side of eastern penthouse
18	4	North side of eastern penthouse
19	4	5th floor rooftop near elevator
20	4	West side of bldg, 6th floor
21	4	West side of bldg, southern end of 2nd floor
22	4	West side of bldg near bridge, 2nd floor
23	3	West side of bldg, north of bridge, 2nd floor
24	3	West side of bldg, northern end of 2nd floor
25	3	South side of bldg, 6th floor
26	3	West side of bldg, 6th floor
27	3	North side of bldg, 6th floor, above diesel generator
28	3	South side of eastern penthouse
29	3	West side of eastern penthouse
30	3	North side of eastern penthouse
31	3	East side of eastern penthouse
32	3	East side of bldg, 2nd floor
34	M	East side of penthouse
35	CMF	Eastern rooftop, southern end of bldg
36	F	Middle of southern quadrant of roof
99	M	South side of northern penthouse

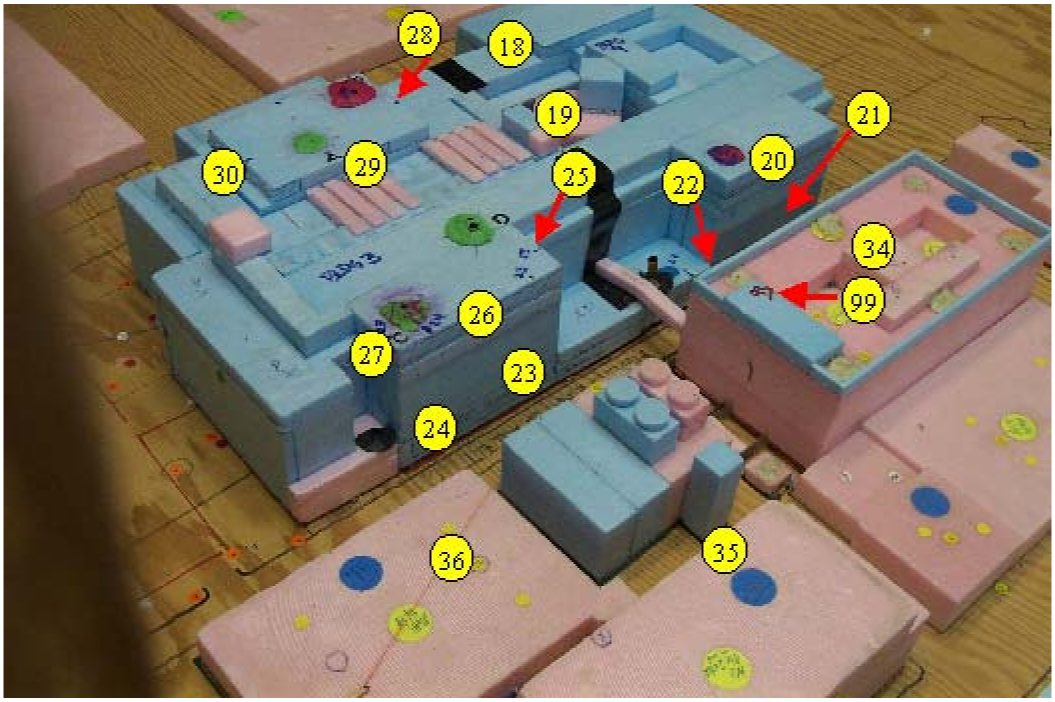

Figure 4. Receptor locations on model, picture taken of the West side of Building Nos. 3 and 4.

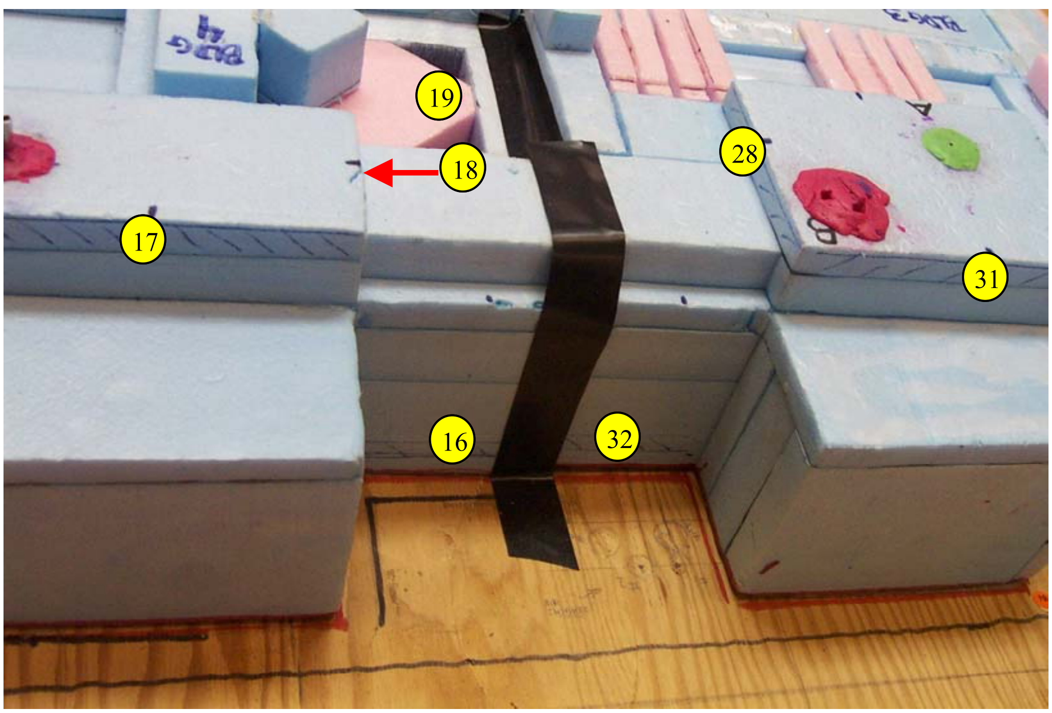

Figure 5. Receptor locations in model, picture taken of the East side of the Building Nos. 3 and 4.

Building Nos. 3 and 4 Receptor Tests

The receptors represent areas of interest such as HVAC intakes, courtyard areas, pedestrian walkways and off-site sensitive areas: day care center, school, residential housing areas, and medical facilities. Twenty of the receptor locations were on site and five receptor locations were off site to address residential and community concerns. Table 6 provides a description of each of the receptors measured. Each of the six representative stack source areas, also referred to as cones, from the four emission areas of the roof of Building #3 and the two emission areas of Building #4, that were tested in the wind tunnel, are given in the tables. For a given receptor, only certain wind directions resulted in exposure to stack emissions. These wind directions were primarily upwind of a specified stack-receptor combination. Accordingly, only concentration measurements at receptors in the general downstream area were measured in accordance with ASHRAE specification, which are: "the test program must include specifications of the meteorological variables to be considered. These include wind direction, wind speed and thermal stability. Data taken at the nearest meteorological station should be reviewed to obtain a realistic assessment of wind climate for a particular site. Ordinarily, local winds around a building (Building #4), pressure, and/or concentrations are measured for 16 wind directions in 22.5 degree intervals (i.e., east wind, east northeast wind, northeast wind, etc.). If only local wind information and pressures are of interest, testing at one wind speed (average for that direction with neutral stability) is sufficient."

Following these ASHRAE guidelines, the test program was designed to measure concentration exposures at each receptor location due to each of the 22.5 degree wind directions. The tests were conducted at the scaled respective average wind speed from the meteorological data for each of the 16 wind speed directions being tested.

The analysis of the wind-tunnel concentration measurements involved determining two features of the dispersion process:

i) estimate the individual stack-receptor dilution for all stack receptor locations possible (multiple stacks in each of the 6 cones time 20 receptors); and,

ii) a calculation of "effective cumulative dilution" for each single receptor for each 22.5 degree wind direction to insure it does not drop below "effective dilution" criterion of 70:1 (for any hour averaged time interval).

Wind-tunnel tests were conducted for each of the major sixteen 22.5 degree meteorological wind directions. For each of these 16 wind directions, each one of the nine representative stacks were tested separately to identify individual contributions to the total or cumulative concentration. All nine representative stacks were wind-tunnel tested. All downwind receptors within the included wind angle of 22.5 degrees were measured for each of the five representative stacks tested. For the purposes of evaluating the standard, the total concentration exposure was determined by first multiplying the concentration of the representative stack by the actual number of stacks that would operate in that given emissions area; and, secondly, adding them together the concentration exposure from all operational stacks at the receptors for that particular wind direction.

Individual and Cumulative Stack-Receptor Measurements

For each stack tested, the receptors downwind for a specified wind direction were measured. Individual as well as cumulative stack results for all receptors are found in the Appendix of this report. Individual fumehood exhaust toxicities, given in Appendix F, were applied to the result in Appendix G, which presents the individual stack-receptor combination and cumulative concentrations and dilutions for the 20 receptor locations that were measured. The wind direction that will deliver the stack emission effluent to the receptor is given in the second column of the table. Typically, only one to three wind directions will produce effluent at a given receptor as observed in the second column. The other wind directions would not contribute to the concentration. The concentrations are given in columns in parts per million (ppm). The emission source is one million parts per million; therefore, the concentration measured at the receptor represents the inverse of the dilution level that would be achieved. The cumulative concentrations of all Building Nos. 3 and 4 stacks are also included in the final "effective dilution" numbers.

The lower listings in Appendix G present the same data; however, concentration is converted to dilution levels. For cumulative effects of multiple stack effluent at a single receptor, the cumulative concentrations of all contributing stacks are added together to produce a total exposure concentration, which is then converted into a dilution factor. This factor is called the "effective dilution" since it incorporates cumulative effects of all stacks into a single dilution. The effective dilutions ranged from 49:1 to thousands-one as observed in Appendix G.

Over 20 receptor locations were measured to determine dilution levels caused by the stacks on the roof of Building Nos. 3 and 4. The receptor locations included HVAC intakes of Buildings Nos. 3 and 4, M, CMF and F. Additionally; all off-site sensitive areas previously identified (ESA, 1995) were tested. Pedestrian walkways, courtyard area, bus stops, etc., were also tested for locations both on and off site. For cumulative effects of multiple stack effluent at a single receptor location, the cumulative concentrations of all stacks were added together to produce a total exposure concentration, which was then converted into a dilution number (called the "effective dilution") since it incorporates cumulative effects of all stacks. All dilutions of individual stacks were well in excess of the recommended and minimum dilution standards (i.e., 100:1 and 70:1, respectively).

All other cumulative effects of the stacks resulted in dilutions greater than the recommended standard of 100:1, for the sensitive on- and off-site receptors (i.e., residual, schools, HVAC intakes, etc.).

Emergency Diesel Generator-Receptor Measurements

Emergency Diesel Generators located at Building Nos. 3 and 4 and CMF were tested at ten receptor locations for three wind directions, west, north-northwest and south-southeast. Virtually all receptors showed dilution values less than standards (2000:1 for failure, 5000:1 for caution) for all wind directions and wind speeds tested. The biggest contributor to the low dilution levels was the diesel generator located at Building CMF. Appendix H shows the individual diesel stack results for each wind speed and direction, and Table 2 in the Executive Summary shows the cumulative hours per year that each diesel generator causes less than standard conditions at each receptor location tested, and shows that Building CMF's diesel generator causes dilutions of less than 5000:1 at all receptor location for 3496 hours per year, or approximately 40% of the time over a one-year period of time. Building #3's diesel generator produces cautionary dilution levels (less than 5000:1) for Receptors #20, #24 and #25 for 16, 23 and 4 percent of time per year, respectively, and failing dilution levels (less than 2000:1) for

Receptor #24, #25, #26 and #27 for 6, 12, 16 and 70 percent of time per year, respectively. The emergency generator at Building #4 causes dilution values less than the caution standard at receptor locations #21 and #25, 25 and 3 percent of time annually, and failing dilution values at receptor locations #20-#22 and #23-#27 for 16 and 14 percent of time annually, respectively.

It is recommended that Building CMF's diesel generator use a plenum air makeup unit to increase dilution measurements at all receptor locations, and that all receptor locations on Chiron Way use a control system to automatically shut down while the emergency diesel generators on Building Nos. 3 and 4 are active.

11. Wind-Tunnel Test Conclusions

The Chiron campus established minimum dilution standard of 70:1 was used in accessing the acceptability of stack dispersion, regardless of receptor location. Using ethane as a tracer gas, wind-tunnel measurements were made of the dilution of roof exhausts at specific receptor locations, such as HVAV intakes on both Building Nos. 3 and 4 and the existing nearby buildings on and off site. A minimum dilution standard of 2000:1 was applied to receptor locations exposed to the exhaust of emergency diesel generators located on Building Nos. 3 and 4 and Building CMF.

Wind-tunnel testing of emissions from Building Nos. 3 and 4, as well as stacks of nearby buildings, examined representative exhaust stacks for a range of stack characteristics. Generally, a "representative" stack within a grouping of similar stacks was modeled in the tunnel (this resulted in testing several "representative" stacks thus accounting for all types of stack-emission-diffusion processes). This approach allowed for all stacks, whether on an individual basis or cumulative-effect basis, to be accounted for by either direct testing or through reasonable extension of wind-tunnel results to nearby untested stacks within the same cluster or group, of similar stacks. The wind-tunnel analysis included testing of seven separate representative stacks on Building #3 and two stacks on Building #4.

In testing, measurements of exhaust dilution were made at downwind locations under ASHRAE-specified conditions for routine stack dispersion processes (i.e., the worst-case accident release situation was not tested). Measured dilution values were compared with the 70:1

minimum dilution criterion (or the less stringent 100:1 recommended criterion) at each receptor. Diesel exhaust testing was conducted for three specific wind conditions, west, north-northwest and south-southeast instead of worst-case conditions.

While above dilution criteria are judged sufficient to protect on-site worker and visitor health for expected chemical exposures (ESA 1994 and 1995), the criteria do not necessarily provide sufficient dilution to protect against accidental releases of relatively larger quantities of some chemicals, or for release of smoke from a fire, or for releases of contagious biological or radioactive materials. For these contingencies, dilution factors far in excess of 1000:1 or higher may be a desirable design goal. Selections of such a stringent dilution standard would be warranted for exhaust stacks servicing laboratories where such special chemicals or highly contagious biological or radioactive materials would be used, or for exhaust stacks proximate to office building HVAC air intakes. These were not addressed in this study.

12. Acknowledgments

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APPENDIX A: THE ATMOSPHERIC BOUNDARY LAYER WIND TUNNEL AT UNIVERSITY OF CALIFORNIA, DAVIS

In the present investigation, the Atmospheric Boundary Layer Wind Tunnel (ABLWT) located at University of California, Davis was used (Figure A-1). Built in 1979 the wind tunnel was originally designed to simulate turbulent boundary layers comparable to wind flow near the surface of the earth. In order to achieve this effect, the tunnel requires a long flow-development section such that a mature boundary-layer flow is produced at the test section. The wind tunnel is an open-return type with an overall length of 21.3 m and is composed of five sections: the entrance, the flow-development section, the test section, the diffuser section, and the fan and motor.

The entrance section is elliptical in shape with a smooth contraction area that minimizes the free-stream turbulence of the incoming flow. Following the contraction area is a commercially available air filter that reduces large-scale pressure fluctuations of the flow and filters larger-size particles out of the incoming flow. Behind the filter, a honeycomb flow straightener is used to reduce large-scale turbulence.

The flow development section is 12.2 m long with an adjustable ceiling for longitudinal pressure-gradient control. For the present study, the ceiling was diverged ceiling so that a zero-pressure-gradient condition is formed in the stream wise direction. At the leading edge of the section immediately following the honeycomb flow straightener, four triangularly shaped spires are stationed on the wind-tunnel floor to provide favorable turbulent characteristics in the boundary-layer flow. Roughness elements are then placed all over the floor of this section to artificially thicken the boundary layer. For a free-stream wind speed of 4.0 m/s, the wind-tunnel boundary layer grows to a height of one meter at the test section. With a thick boundary layer, larger models could be tested and thus measurements could be made at higher resolution.

Dimensions of the test section are 2.44 m in stream wise length, 1.66 m high, and 1.18 m wide. Similar to the flow-development section, the test section ceiling can also be adjusted to obtain the desired stream wise pressure gradient. Experiments can be observed from both sides of the test section through framed Plexiglas windows. One of the windows is also a sliding door that allows access into the test section. When closed twelve clamps distributed over the top and lower edges are used to seal the door. Inside the test section, a three-dimensional probe-positioning system is installed at the ceiling to provide fast and accurate sensor placement. The traversing system scissor-type extensions, which provide vertical probe motion, are also made of aerodynamically shaped struts to minimize flow disturbances.

The diffuser section is 2.37 m long and has an expansion area that provides a continuous transition from the rectangular cross-section of the test section to the circular cross-sectional area of the fan. To eliminate upstream swirl effects from the fan and avoid flow separation in the diffuser section, fiberboard and honeycomb flow straighteners are placed between the fan and diffuser sections.

The fan consists of eight constant-pitch blades 1.83 m in diameter and is powered by a 56 kW (75 hp) variable-speed DC motor. A dual belt and pulley drive system is used to couple the motor and the fan.

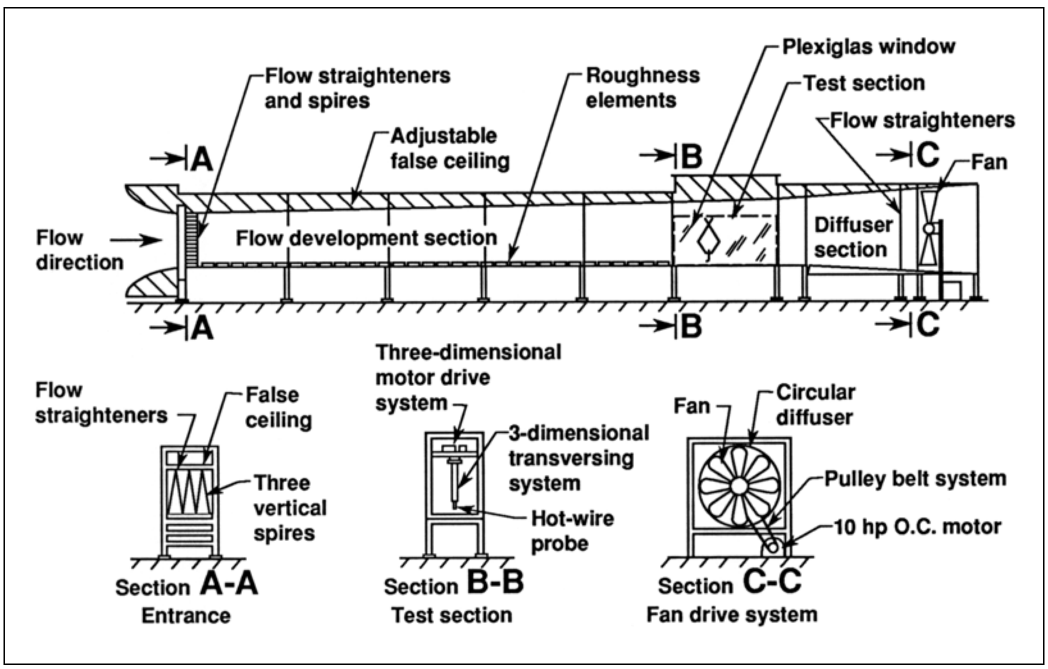

Figure A-1: Schematic diagram of the UC Davis Atmospheric Boundary Layer Wind Tunnel.

APPENDIX B: INSTRUMENTATION AND MEASUREMENT SYSTEMS

Wind tunnel measurements of the mean velocity and turbulence characteristics were performed using hot-wire anemometry. A standard Thermo Systems Inc. (TSI) single hot-wire sensor model 1210-60 was used to measure the wind quantities. The sensor was installed at the end of a TSI model 1150 50-cm probe support, which was secured onto the support plate of the three-dimensional sensor positioning system in the U.C. Davis Atmospheric Boundary Layer Wind Tunnel (ABLWT) test section. A 10-m shielded tri-axial cable was then used to connect the probe support and sensor arrangement to a TSI model IFA 100 constant temperature thermal-anemometry unit with signal conditioner.

Hot-wire sensor calibrations were conducted in the ABLWT test section over the range of common velocities measured in the wind-tunnel boundary layer. Signal-conditioned voltage readings of the hot-wire sensor were then matched against the velocity measurements from a Pitot-static tube connected to a Meriam model 34FB2 oil micro-manometer, which had a resolution of 25.4 μm of oil level. The specific gravity of the oil was 0.934. The Pitot-static tube was secured to an aerodynamically shaped stand and was positioned so that its flow-sensing tip is normal to the flow and situated near the volumetric center of the test section. Normal to the flow, the end of the hot-wire sensor was then traversed to a position 10 cm next to the tip of the Pitot-static tube.

Concentration measurements of an ethane tracer gas were conducted with the use of a Rosemount Analytical model 400A hydrocarbon analyzer. This instrument uses a flame-ionization detection method to determine trace concentrations in the air. Operation of this analyzer involves iso-kinetically aspirating ethane-air samples into a burner where the sample is burned with a mixture of medical-rated air and 40% hydrogen and 60% nitrogen. Figure B-1 displays a schematic of the concentration measurement system. A 1/4-inch-diameter, copper refrigeration-grade tubing, 12 inches in length, was used as the gas-analyzer sensing probe, mitered 45° at the end. This copper probe was secured to the test-section traverse-system mounting plate, where an additional length of the same type tubing was used to connect the probe to a pressure-regulated vacuum pump, which sends samples into the analyzer at a constant pressure of 5 psig.

Calibration of the hydrocarbon analyzer system was accomplished with two known samples of ethane-air mixtures, one certified with 52.4 parts per million (ppm) and the other with 524.8 ppm. Calibration gas samples were accurate to less than 0.5% of the stated value. The precision of the gas analyzer was within 1% of full scale. Prior to the calibration, the analyzer voltage output was first mechanically zeroed using a sample of pure air (hydrocarbon-free).

Ethane tracer gas emissions from the stacks were controlled by a model B-250-1 ball-type flow meter. Flow meter volumetric flow rates for a tracer gas of some ethane mixture are calibrated by measuring the time elapsed for the tracer gas to fill a container of known volume. Since the ethane mixture was virtually invisible, the gas level needs to be monitored by using a traceable substance such as water. This was done by first filling and completely submerging the calibration container in a water tank. The ethane gas mixture is released in the container by inserting a tube extension from the flow meter into the water-drowned container. A complete fill of tracer gas can then be detected when the decreasing water level reaches the mark corresponding to a known volume. For a thorough calibration, elapsed times are collected for at least three height settings on the flow meter gage. Dividing these times by the known volume gives a volumetric flow rate for a corresponding flow meter height setting.

Raw voltage data sets of hot-wire velocity measurements and of tracer gas concentrations were digitally collected using a LabVIEW data acquisition system, which was installed in a Gateway personal computer with a Pentium 166Mhz processor. Concentration voltages were collected from the hydrocarbon analyzer analog output, while hot wire voltages were obtained from the signal conditioner output of the IFA 100 anemometer. The two outputs were connected to a multi-channel daughter board linked to a United Electronics Inc. (UEI) analog-to-digital (A/D) data acquisition board, which is installed in one of the ISA motherboard slots of the Gateway PC. LabVIEW software was used to develop virtual instruments (VI) that would initiate and configure the A/D board, then collect the voltage data given by the measurement equipment, display appropriately converted results on the computer screen, and finally save the raw voltage data into a designated filename.

Since velocity and concentration measurements were individually performed, a VI was developed for each type of acquisition. For the hot-wire acquisition, the converted velocity data and its histogram is displayed along with the mean voltages, mean velocity, root-mean-square velocity, and turbulence intensity. In the concentration VI, the converted concentration data is shown with the corresponding mean voltage and mean concentration. For both programs, the raw voltage data can be saved in the computer hard drive. For both hot-wire and concentration acquisition 30,000 samples were collected at a sampling rate of 1000 Hz. This acquisition setting greatly satisfies the Nyquist sampling theorem such that the average tunnel turbulence signal was 300 Hz.

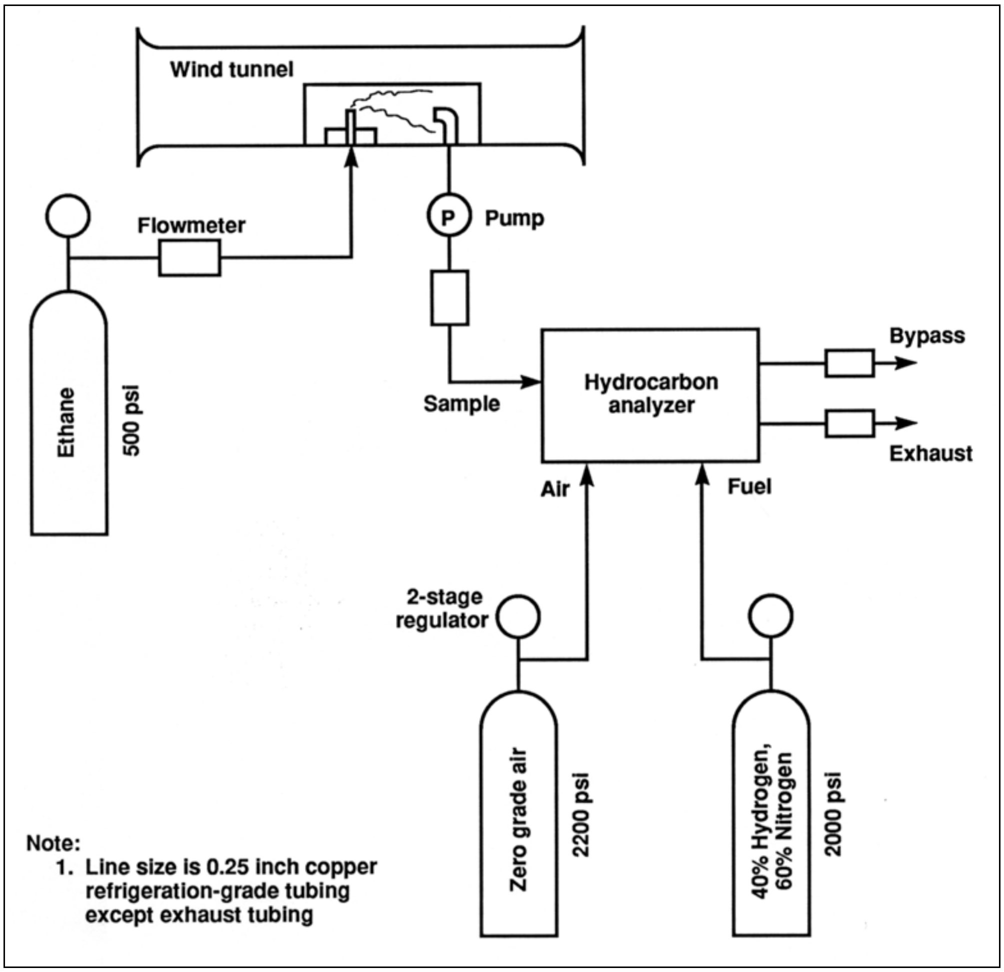

Figure B-1: Schematic diagram of gas dispersion concentration measurement system.

APPENDIX C: WIND-TUNNEL ATMOSPHERIC FLOW SIMILARITY PARAMETERS

Wind-tunnel models of a particular test site are typically several orders of magnitude smaller than the full-scale size. In order to appropriately simulate atmospheric winds in the U.C. Davis Atmospheric Boundary Layer Wind Tunnel (ABLWT), certain flow parameters must be satisfied between a model and its corresponding full-scale equivalent. Similitude parameters can be obtained by non-dimensionalizing the equations of motion, which build the starting point for the similarity analysis. Fluid motion can be described by the following time-averaged equations.

Conservation of mass:

$$\frac{\partial \overline{U}_i}{\partial t_i} = 0 \text{ and } \frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{U}_i)}{\partial x_i} = 0$$

Conservation of momentum:

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{u}\,\frac{\partial \overline{U}_i}{\partial x_j} + 2\varepsilon_{ijk}\Omega_j \overline{U}_k = -\frac{1}{\rho_0}\frac{\partial \overline{\delta P}}{\partial x_i} - \frac{\overline{\delta T}}{T_0} g\delta_{i3} + \nu_0 \frac{\partial^2 \overline{U}_i}{\partial x_j} + \frac{\partial (-\overline{u_j u_i})}{\partial x_j}$$

Conservation of energy:

$$\frac{\partial \overline{\delta T}}{\partial t} + \overline{U}_i \frac{\partial \overline{\delta T}}{\partial x_i} = \left[\frac{\kappa_0}{\rho_0 c_{p_0}}\right] \frac{\partial^2 \overline{\delta T}}{\partial x_k \partial x_k} + \frac{\partial (-\overline{\theta u_i})}{\partial x_i} + \frac{\overline{\phi}}{\rho_0 c_{p_0}}$$

Here, the mean quantities are represented by capital letters while the fluctuating values by small letters. δP is the deviation of pressure in a neutral atmosphere. ρ_0 and T_0 are the density and temperature of a neutral atmosphere and ν_0 is the kinematic viscosity. In the equation for the conservation of energy, ϕ is the dissipation function, $\overline{\delta T}$ is the deviation of temperature from the temperature of a neutral atmosphere, κ_0 is the thermal diffusivity, and c_{p_o} is the heat capacity.

Applying the Boussinesq density approximation, application of the equations is then restricted to fluid flows where $\overline{\delta T} << T_0$. Defining the following non-dimensional quantities and then substituting into the above equations.

$$\overline{U}_i' = \overline{U}_i' / U_0 \; ; \; u_i' = u_i / U_0 \; ; \; x_i' = x_i / L_0 \; ; \; t' = tU_0 / L_0 \; ; \; \Omega_j' = \Omega_j / \Omega_0 \; ; \; \overline{\delta P}' = \overline{\delta P} / \rho_0 U_0^2 \; ;$$

$$\overline{\delta T}' = \overline{\delta T} / \delta T_0 \; ; \; g' = g / g_0 \; ; \; \overline{\varphi}' = \overline{\varphi} / \varphi_0$$

The equations of motion can be presented in the following dimensionless forms.

Continuity Equation:

$$\frac{\partial u_i'}{\partial k_i'} = 0 \text{ and } \frac{\partial \rho'}{\partial t'} + \frac{\partial(\rho' u_i')}{\partial x_i'} = 0$$

Momentum Equation:

$$\frac{\partial \overline{U}_i'}{\partial t'} + \overline{U}_j' \frac{\partial \overline{U}_i'}{\partial x_j'} + \frac{2}{Ro} \varepsilon_{ijk} \overline{U}_k' \Omega_j' = -\frac{\partial \overline{\delta P}'}{\partial x_i'} + \frac{1}{Fr^2} \overline{\delta T}' \delta_{3i} + \frac{1}{Re} \frac{\partial^2 \overline{U}_i'}{\partial x_j' \partial x_j'} + \frac{\partial(-\overline{u_j' u_i'})}{\partial x_j'}$$

Turbulent Energy Equation:

$$\frac{\partial \overline{\delta T}'}{\partial t'} + \overline{U}_i' \frac{\partial \overline{\delta T}'}{\partial x_i'} = Pr \cdot \frac{1}{Re} \frac{\partial^2 \overline{\delta T}'}{\partial x_k' \partial x_k'} + \frac{\partial(-\overline{\theta' u_i'})}{\partial x_i'} + \frac{1}{Re} \cdot Ec \cdot \overline{\varphi}'$$

Although the continuity equation gives no similarity parameters, coefficients from both other equations do provide the following desired similarity parameters.

1. Rossby number: $R_0 \equiv U_0 / L_0 \Omega_0$
2. Densimetric Froude number: $Fr \equiv U_0 / (g L_0 \delta T_0 / T_0)^{1/2}$
3. Prandtl number: $Pr \equiv \rho_0 c_{p_0} \nu_0 / \kappa_0$
4. Eckert number: $Ec \equiv U_0^2 / c_{p_0} \delta T_0$
5. Reynolds number: $Re \equiv U_0 L_0 / \nu_0$

In the dimensionless momentum equation, the Rossby number is extracted from the denominator of the third term on the left hand side. The Rossby number represents the ratio of advective acceleration to Coriolis acceleration due to the rotation of the earth. If the Rossby number is large, Coriolis accelerations are small. Since UC Davis ABLWT is not rotating, the Rossby number is infinite allowing the corresponding term in the dimensionless momentum equation to approach zero. In nature, however, the rotation of the earth influences the upper layers of the atmosphere; thus, the Rossby number is small and becomes important to match, and the corresponding term in the momentum equation is sustained.

Most modelers have assumed the Rossby number to be large, thus, neglecting the respective term in the equations of motion and ignoring the Rossby number as a criterion for modeling. Snyder (1981) showed that the characteristic length scale, L_0, must be smaller than 5 km in order to simulate diffusion under neutral or stable conditions in relatively flat terrain. Other researchers discovered similar findings. Since UC Davis ABLWT produces a boundary layer with a height of about one meter, the surface layer vertically extends 10 to 15 cm above the ground. In this region the velocity spectrum would be accurately modeled. The Rossby number can then be ignored in this region. Since testing is limited to the lower 10% to 15% of the boundary layer, the length in longitudinal direction, which can be modeled, has to be no more than a few kilometers.

Derived from the denominator of the second term on the right hand side of the dimensionless momentum equation, the square of the Froude number represents the ratio of inertial forces to buoyancy forces. High values of the Froude number infer that the inertial forces are dominant. For values equal or less than unity, thermal effects become important. Since the conditions inside the UC Davis ABLWT are inherently isothermal, the wind tunnel generates a neutrally stable boundary layer; hence, the Froude number is infinitely large allowing the respective term in the momentum equation to approach zero.

The third parameter is the Prandtl number, which is automatically matched between the wind-tunnel flow and full-scale winds if the same fluid is been used. The Eckert number criterion is important only in compressible flow, which is not of interest for a low-speed wind tunnel.

Reynolds number represents the ratio of inertial to viscous forces. The reduced scale of a wind tunnel model results in a Reynolds number several orders of magnitude smaller than in full scale. Thus, viscous forces are more dominant in the model than in nature. No atmospheric flow could be modeled, if strict adherence to the Reynolds number criterion was required. However, several arguments have been made to justify the use of a smaller Reynolds number in a model. These arguments include laminar flow analogy, Reynolds number independence, and dissipation scaling. With the absence of thermal and Coriolis effects, several test results have shown that the scaled model flow will be dynamically similar to the full-scale case if a critical Reynolds number is larger than a minimum independence value. The gross structure of turbulence is similar over a wide range of Reynolds numbers. Nearly all modelers use this approach today.

APPENDIX D: WIND-TUNNEL ATMOSPHERIC BOUNDARY-LAYER SIMILARITY

Wind-tunnel simulation of the atmospheric boundary layer under neutrally stable conditions must also meet non-dimensional boundary-layer similarity parameters between the scaled-model flow and its full-scale counterpart. The most important conditions are:

1. The normalized mean velocity, turbulence intensity, and turbulent energy profiles.

2. The roughness Reynolds number, $Re_z = z_0 u_* / \nu$.

3. Jensen's length-scale criterion of z_0/H.

4. The ratio of H/δ for H greater than $H/\delta > 0.2$.

In the turbulent core of a neutrally stable atmospheric boundary layer, the relationship between the local flow velocity, U, versus its corresponding height, z, may be represented by the following velocity-profile equation.

$$\frac{U}{U_\infty} = \left(\frac{z}{\delta}\right)^{\alpha}$$

Here, U_∞ is the mean velocity of the inviscid flow above the boundary layer, δ is the height of the boundary layer, and α is the power-law exponent, which represents the upwind surface conditions. Wind-tunnel flow can be shaped such that the exponent α will closely match its corresponding full-scale value, which can be determined from field measurements of the local winds. The required power-law exponent, α, can then be obtained by choosing the appropriate type and distribution of roughness elements over the wind tunnel flow-development section.

Full-scale wind data suggest that the atmospheric wind profile at the site of the Lawrence Berkeley National Laboratory yields a nominal value of $\alpha = 0.3$. This condition was closely matched in the UC Davis Atmospheric Boundary Layer Wind Tunnel by systematically arranging an pattern of 2" x 4" wooden blocks of 12" in length along the entire surface of the flow-development section. The pattern generally consisted of alternating sets of four and five blocks in one row. A typical velocity profile is presented in Figure D-1, where the simulated power-law exponent is $\alpha = 0.33$.

In the lower 20% of the boundary layer height, the flow is then governed by a rough-wall or "law-of-the-wall" logarithmic velocity profile.

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

Here, u_* is the surface friction velocity, κ is von Karman's constant, and z_o is the roughness height. This region of the atmospheric boundary layer is relatively unaffected by the Coriolis force, the only region that can be modeled accurately by the wind tunnel (i.e., the lowest 100 m of the atmospheric boundary layer under neutral stability conditions). Thus, it is desirable to have the scaled-model buildings and its surroundings contained within this layer.

The geometric scale of the model should be determined by the size of the wind tunnel, the roughness height, z_o, and the power-law index, α. With a boundary-layer height of 1 m in the test section, the surface layer would be 0.2 m deep for the U.C. Davis ABLWT. For the current study, this boundary layer corresponds to a full-scale height of the order of 800 m. Since the highest elevation of the modeled site investigated in this study is about 160 m full-scale, a majority of the model is contained in this region of full-scale similarity.

Due to scaling effects, full-scale agreement of simulated boundary-layer profiles can only be attained in wind tunnels with long flow-development sections. For full-scale matching of the normalized mean velocity profile, an upwind fetch of approximately 10 to 25 boundary-layer heights can be easily constructed. To fully simulate the normalized turbulence intensity and energy spectra profiles, the flow-development section needs to be extended to about 50 and 100 to 500 times the boundary-layer height, respectively. These profiles must at least meet full-scale similarities in the surface layer region. However, with the addition of spires and other flow tripping devices, the flow development length can be reduced to less than 20 boundary layer heights for most engineering applications.

In the U.C. Davis Atmospheric Boundary Layer Wind Tunnel, the maximum values of turbulence intensity near the surface range from 35% to 40%, similar to that in full scale. Thus, the turbulent intensity profile, u'/u versus z, should agree reasonably with the full-scale, particularly in the region where testing is performed. Figure D-2 displays a typical turbulence intensity profile of the boundary layer in the ABLWT test section.

The second boundary-layer condition involves the roughness Reynolds number, Re_z. According to the criterion given by Sutton (1949), Reynolds number independence is attained when the roughness Reynolds number is defined as follows.

$$Re_z = \frac{u_* z_0}{\nu} \geq 2.5$$

Here, u_* is the friction speed, z_0 is the surface roughness length and ν is the kinematic viscosity. Re_z larger than 2.5 ensures that the flow is aerodynamically rough. Therefore, wind tunnels with a high enough roughness Reynolds numbers simulate full-scale aerodynamically rough flows exactly. To generate a rough surface in the wind tunnel, roughness elements are placed on the wind tunnel floor. The height of the elements must be larger than the height of the viscous sub-layer in order to trip the flow. The UC Davis ABLWT satisfies this condition, since the roughness Reynolds number is about 40, when the wind tunnel free stream velocity, U_{∞}, is equal 3.8 m/s, the friction speed, u_*, is 0.24 m/s, and the roughness height, z_o, is 0.0025 m. Thus, the flow setting satisfies the Re number independence criterion and dynamically simulates the flow.

To simulate the pressure distribution on objects in the atmospheric wind, Jensen (1958) found that the surface roughness to object-height ratio in the wind tunnel must be equal to that of the atmospheric boundary layer, i.e., z_o/H in the wind tunnel must match the full-scale value. Thus, the geometric scaling should be accurately modeled.

The last condition for the boundary layer is the characteristic scale height to boundary layer ratio, H/δ. There are two possibilities for the value of the ratio. If $H/\delta \geq 0.2$, then the ratios must be matched. If $(H/\delta)_{F.S.} < 0.2$, then only the general inequality of $(H/\delta)_{W.T.} < 0.2$ must be met (F.S. stands for full-scale and W.T. stands for wind tunnel). Using the law-of-the-wall logarithmic profile equation, instead of the power-law velocity profile, this principle would constrain the physical model to the 10% to 15% of the wind tunnel boundary layer height.

Along with these conditions, two other constraints have to be met. First, the mean stream wise pressure gradient in the wind tunnel must be zero. Even if high- and low-pressure systems drive atmospheric boundary layer flows, the magnitude of the pressure gradient in the flow direction is negligible compared to the dynamic pressure variation caused by the boundary layer. The other constraint is that the model should not take up more than 5% to 15% of the cross-sectional area at any down wind location. This assures that local flow acceleration affecting the stream wise pressure gradient will not distort the simulation flow.

Simulations in the U.C. Davis ABLWT were not capable of producing stable or unstable boundary layer flows. In fact, proper simulation of unstable boundary layer flows could be a disadvantage in any wind tunnel due to the artificial secondary flows generated by the heating that dominate and distort the longitudinal mean-flow properties, thus, invalidating the similitude criteria. However, this is not considered as a major constraint, since the winds that produce annual an average dispersion are sufficiently strong, such that for flow over a complex terrain, the primary source of turbulence is due to mechanical shear and not due to diurnal or heating and cooling effects in the atmosphere.

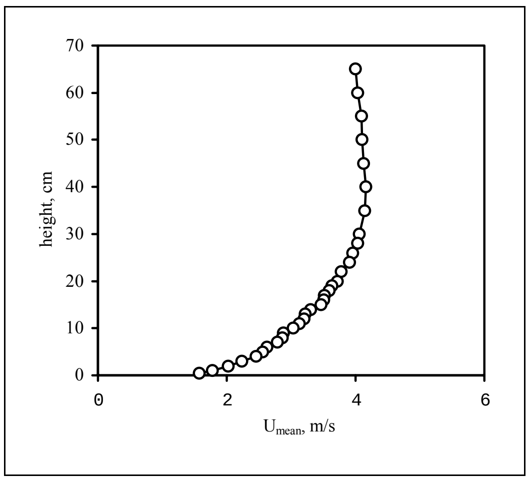

Figure D-1: Mean velocity profile for a typical wind direction in the wind tunnel. The power law exponent α is 0.33. The reference velocity at 65 cm height is 3.55 m/s.

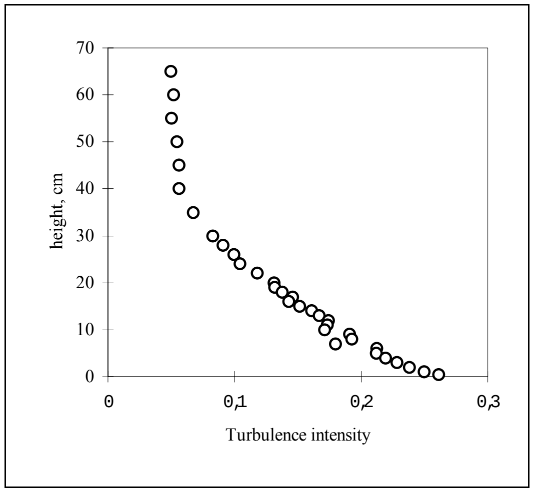

Figure D-2: Turbulence intensity profile for a typical wind direction in the wind tunnel.

APPENDIX E: WIND-TUNNEL STACK MODELING PARAMETERS

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

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

For lower building Re numbers the critical value for flow independence must be determined experimentally. This was accomplished by repeating tests of ground-level concentration at increased tunnel free-stream velocity and stack flow rate.

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

$$\mathrm{Re}_s = \frac{U_s D_s}{\nu} > 2300$$

Values as low as 530 may be adequate if trips are used to enhance turbulence. The tunnel stack, for concentration-measurement experiments, has an inside diameter, D_s, of 0.81 cm; for expected stack velocities, U_s, of 12.9 m/s and 2.0 m/s, the stack Re numbers are 6970 and 1080, respectively. The criteria for turbulent stack flow will be achieved if trips are used to enhance the turbulence. For smoke tests the stack inside diameter was exaggerated to 0.25 cm and for a tunnel stack velocity of 5.2 m/s, the stack Re number was 867. The stack again will be tripped to enhance turbulence.

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

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

Here, L is a vertical length scale, and U_w is the wind speed at the stack height. For non-buoyant stack exhausts, the stack exhaust density, ρ_s, equals that of the ambient air, ρ_a, and the above relation reduces to:

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

For a free-stream wind-tunnel air speed of 3.8 m/s, U_w is equal to 2.6 m/s. Thus, for a tunnel stack velocity of 13.7 m/s, satisfaction of the above relation corresponds to a full-scale wind speed at the stack of 5.4 m/s (12 mph) while the full-scale stack velocity, U_s, is 16.3 m/s. For tests with a tunnel stack velocity of 30 m/s, the corresponding full-scale wind speed at the stack outlet is 2.5 m/s (6 mph).

Concentrations measured in the tunnel, C, may be related to full-scale values by the relation

$$\left(\frac{CU_w}{C_s U_s A_s}\right)_{FS} S^2 = \left(\frac{CU_w}{C_s U_s A_s}\right)_{WT}$$

Under similar atmospheric conditions, concentrations measured in the wind tunnel may be related to those in full-scale by this relationship.

Appendix F: Individual Exhaust Stack Information

WIND TUNNEL STUDY CONE INFORMATION

Subject: Wind Tunnel Study - Cone Stack Information

By: TDB
Date: 05/13/01

Cone #1: 7th Floor - Southeast Cone

Exhaust Fan	Exhaust Type	Airflow (cfm)	Exhaust Fan Size	Exhaust Duct Size (in)	Variable Volume	Max Exit Velocity (fpm)	Min Exit Velocity (fpm)	Fumehood Exhaust (%)
EF HV-0303	Lab General & Fume Exhaust	90,000	73	81	Yes	4,000	2,500	60%
EF HV-0304	Lab General & Fume Exhaust	90,000	73	81	Yes	4,000	2,500	60%
EF HV-0305 (0306)	Lab Radio-Isotope	2,000	12	18	No	3,500	--	100%
EF HV-0355	Pilot Plant-Cell Culture	2,530	16	22	No	3,500	--	50%
EF HV-0356	Pilot Plant-Microbial	2,124	15	22	No	3,500	--	60%
EF HV-0359	Pilot Plant-H-class	784	9	14	No	3,500	--	0%
EF HV-0360	Pilot Plant-H class xp	1,456	18	14	No	3,500	--	82%

Cone #2: 7th Floor - Northwest Cone

Exhaust Fan	Exhaust Type	Airflow (cfm)	Exhaust Fan Size	Exhaust Duct Size (in)	Variable Volume	Max Exit Velocity (fpm)	Min Exit Velocity (fpm)	Fumehood Exhaust (%)
EF HV-0310	Lab Bio-Safety Cabinet	2,000	12	18	No	3,500	--	100%
EF HV-03XX (0323)	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-03XX	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-03XX	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-0351	Pilot Plant-Dust collector	1,200	18	14	No	3,500	--	0%
EF HV-0356	Pilot Plant-Fluid bed	1,000	18	14	No	3,500	--	0%
EF HV-0352	Pilot Plant-Equip.wash	1,691	18	14	No	3,500	--	0%

Cone #3: 6th Floor - Southeast Cone

Exhaust Fan	Exhaust Type	Airflow (cfm)	Exhaust Fan Size	Exhaust Duct Size (in)	Variable Volume	Max Exit Velocity (fpm)	Min Exit Velocity (fpm)	Fumehood Exhaust (%)
EF HV-0301	Lab General & Fume Exhaust	90,000	73	82	Yes	4,000	2,500	35%
EF HV-0302	Lab General & Fume Exhaust	90,000	73	82	Yes	4,000	2,500	35%
EF HV-0357	Pilot Plant-Fermentation	18,970	36	42	Yes	3,500	--	15%
EF HV-0361	Pilot Plant-Recovery	16,350	36	40	Yes	3,500	--	10%

Cone #4: 6th Floor - Northwest Cone

Exhaust Fan	Exhaust Type	Airflow (cfm)	Exhaust Fan Size	Exhaust Duct Size (in)	Variable Volume	Max Exit Velocity (fpm)	Min Exit Velocity (fpm)	Fumehood Exhaust (%)
EF HV-0305	Lab Radio-Isotope	2,000	12	18	No	3,500	--	100%
EF HV-0307	Lab BL-3 Suite	5,000	18	24	Yes	4,000	2,500	75%
EF HV-0308	Lab BL-3 Suite	5,000	18	24	Yes	4,000	2,500	75%
EF HV-0309	Lab Bio-Safety Cabinet	2,000	12	18	No	3,500	--	100%
EF HV-0316	Lab Pharmacy H-room	1,000	12	14	No	3,500	--	0%
EF HV-0317	Lab Pharmacy H-room	500	8	10	No	3,500	--	0%
EF HV-0318	Lab Pharmacy H-room	500	8	10	No	3,500	--	0%
EF HV-0319	Lab Pharmacy H-room	500	8	10	No	3,500	--	0%
EF HV-0320	Lab Pharmacy H-room	500	8	10	No	3,500	--	0%
EF HV-0321	Lab Pharmacy H-room	500	8	10	No	3,500	--	0%
EF HV-03XX (0322)	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-03XX	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-03XX	Lab H-room	900	13	20	No	3,500	--	0%
EF HV-0358	Pilot Plant- Glasswash	1,700	10	16	No	3,500	--	0%
EF HV-0354	Pilot Plant-Purification	28,440	40	46	YES	3,500	--	5%
EF HV-0362	Pilot Plant-Aseptic fill	3,800	16	20	YES	3,500	--	0%
EF HV-0353	Pilot Plant-Purification reagant	12,800	24	34	Yes	3,500	--	0%
EF HV-03XX	Pilot Plant Pharmacy H-room	500	8	10	No	3,500	--	0%

Appendix G: Individual Exhaust Stack Emission Results

Appendix H: Emergency Diesel Generator Emission Results