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WIND ENGINEERING AND AIR QUALITY CONSULTANTS

Engineering Report - Final Design

Air Quality Assessment For The

National Renewable Energy Laboratory
Energy Systems Integrated Facility

SmithGroup
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CPP Project: 5837
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AIR QUALITY ASSESSMENT FOR THE NATIONAL RENEWABLE ENERGY LABORATORY ENERGY SYSTEMS INTEGRATED FACILITY

CPP Project 5837

22 March 2012

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

AGL	Above Ground Level	(m)
A	Calibration Constant	(-)
B	Calibration Constant	(-)
B_o	Buoyancy Ratio	(-)
C	Concentration	(ppm or $\mu g/m^3$)
C_o	Tracer Gas Source Strength	(ppm or $\mu g/m^3$)
C_{max}	Maximum Measured Concentration	(ppm or $\mu g/m^3$)
C_s	Concentration of Calibration Gas	(ppm or $\mu g/m^3$)
	Concentration Estimate for Full-scale Sampling Time, t_s	($\mu g/m^3$)
C_k	Concentration Estimate for Wind-tunnel Sampling Time, t_k	($\mu g/m^3$)
Δ	Difference Operator	(-)
$\Delta\theta$	Potential Temperature Difference	(K)
δ	Boundary-Layer Height	(m)
d	Stack Diameter	(m)
E	Voltage Output	(Volts)
Fr	Froude Number	(-)
g	Acceleration Due to Gravity	(m/s^2)
h	Stack Height Above Roof Level	(m)
H	Stack Height Above Local Grade	(m)
H_t	Terrain Height	(m)
H_b	Building Height	(m)
I_s	Gas Chromatograph Response to Calibration Gas	(Volts)
I_{bg}	Gas Chromatograph Response to Background	(Volts)
k	von Kármán Constant	(-)
L	Length Scale	(m)
λ	Density Ratio	(-)
M_o	Momentum Ratio	(-)
n	Calibration Constant, Power Law Exponent	(-)
v	Kinematic Viscosity	(m^2/s)
m	Emission Rate	(g/s)
ρ_a	Density of Ambient Air	(kg/m^3)
ρ_s	Density of Stack Gas Effluent	(kg/m^3)
R	Velocity Ratio	(-)
R_i	Richardson Number	(-)
Re_b	Building Reynolds Number	(-)
Re_k	Roughness Reynolds Number	(-)
Re_s	Effluent Reynolds Number	(-)

T	Mean Temperature	(K)
t_s	Full-scale sampling time	(s)
t_k	Wind-tunnel sampling time	(s)
U_a	Wind Speed at Anemometer	(m/s)
U_H	Wind Speed at Stack Height	(m/s)
U_r	Wind Speed at Reference Height Location	(m/s)
U_∞	Free Stream Wind Velocity	(m/s)
U_*	Friction Velocity	(m/s)
U	Mean Velocity	(m/s)
U'	Longitudinal Root-Mean-Square Velocity	(m/s)
V	Volume Flow Rate	(m^3/s)
V_e	Exhaust Velocity	(m/s)
z	Height Above Local Ground Level	(m)
z_o	Surface Roughness Factor	(m)
z_r	Reference Height	(m)
z_∞	Free Stream Height – 600 m above ground level	(m)

Subscripts

m	pertaining to model
f	pertaining to full scale

EXECUTIVE SUMMARY

This report documents the wind-tunnel study conducted by CPP, Inc. on behalf of the preceding SmithGroup for the proposed National Renewable Energy Laboratory Energy Systems Integrated Facility (NREL ESIF) in Golden, Colorado. The objective of the study was to obtain accurate concentration estimates at building air intakes and other sensitive locations due to emissions from various exhaust sources located on and around the NREL ESIF. The various exhaust sources may periodically emit chemicals or other contaminants that may enter nearby buildings through air intakes, or be present at other sensitive locations, and impact staff or the general public. If adverse impacts were found, mitigation measures were evaluated.

Additional analysis was conducted to determine the optimum fan operating parameters that will meet the air quality design criteria such that a given exhaust fan may be able to run at less than 100% of the planned flow and exit velocity. This may allow the volume flow rate out of the exhaust stacks to more closely match the airflow into the building, resulting in potentially significant energy savings.

To meet the objectives of the study, a 1:240 scale model of the NREL ESIF and nearby surroundings within a 1360 ft radius was constructed and placed in CPP's boundary-layer wind tunnel. Concentration measurements were obtained in the wind tunnel to define the impact of emissions from the various exhaust sources at building air intake and other sensitive locations.

The exhaust system design for the NREL ESIF was tested in the wind tunnel in March 2011. A draft final report was provided in July 2011 (CPP, July 2011). In November 2011, volume flow rates of the laboratory exhaust sources (EF-L1,2,3,4,5,6) decreased and the exhaust stack locations on the NREL ESIF roof changed, thereby nullifying the results of the previous study. Furthermore, three additional laboratory exhaust sources (EF-L7,8,9) were added to the NREL ESIF design and an additional wind-tunnel study was conducted to obtain accurate concentration estimates at building air intakes and other sensitive locations due to emissions from the new Central HEPA System Fume Hoods (EF-L7,8,9) located on the NREL ESIF roof. Furthermore, sensitivity tests were conducted in the wind tunnel to confirm worst case concentrations for the laboratory exhaust sources (EF-L3 and EF-L4). Results of this additional analysis were provided in the preliminary report provided in November 2011.

This report document combines the findings of the two wind tunnel studies conducted and summarizes the results for the final design of the NREL ESIF. The final conclusions of the study are listed in the following table.

Wind condition independent results of the fan optimization analysis are also presented in Table ES-1. Lower volume flow rates and exit velocities can be utilized if a local anemometer is tied into the HVAC control system. Minimum exhaust turndown ratios versus wind speed and wind direction are provided in Tables 5 a-b. The corresponding polynomial curve fit coefficients are provided in Tables 6 a-b. Plots of the minimum volume flow rate versus wind speed and wind direction are provided in Figures 7 a-d.

Table ES-1
Summary of Results of the Air Quality Study

<table>
<tr><th>Source Type (ID)</th><th>Stack Base Height (ft) (description)</th><th>100% Load Volume Flow Rate and Exit Velocity cfm (fpm)</th><th>Stack Height Above Base (ft)</th><th>Comment</th></tr>
<tr><td colspan="5">NREL ESIF</td></tr>
<tr><td>Level 2 General Lab Exhaust

(EF-L1,2,3)</td><td>78.0
(Main Roof)</td><td>13,520
(3,161)</td><td>20.0</td><td>Meets recommended criteria at 100% of full load.[1]</td></tr>
<tr><td>Level 3 General Lab Exhaust

(EF-L4,5,6)</td><td>78.0
(Main Roof)</td><td>14,000
(2,852)</td><td>20.0</td><td>Meets recommended criteria at 85% of full load or greater.[1]</td></tr>
<tr><td>Central HEPA System Fume Hood Exhaust

(EF-L7,8,9)</td><td>78.0
(Main Roof)</td><td>8,320
(3,153)</td><td>20.0</td><td>Meets recommended criteria at 100% of full load.</td></tr>
<tr><td rowspan="2">Perchloric Hood Exhaust

(C329)</td><td rowspan="2">78.0
(Main Roof)</td><td>910
(1,159)</td><td>20.0</td><td>Meets ‘as installed’ criterion at all locations evaluated.</td></tr>
<tr><td colspan="3">Note: 670 cfm/1919 fpm was evaluated during wind tunnel testing. With the final design values as specified above, concentrations are expected to increase by 5% but the ‘as installed’ design criterion will still be met.

Future Conversion from Perchloric Hood to Standard Fume Hood: The ASHRAE criterion is predicted to be exceeded approximately 5% of the time at the ESIF roof test area and the east and west sidewall intakes. To meet the ASHRAE criterion, the volume flow rate and exit velocity would need to be increased to at least 1,667 cfm/4,773 fpm.</td></tr>
</table>

[1] Lower volume flow rates and exit velocities can be utilized if a local anemometer is tied into the HVAC control system. The results of this analysis are presented in Tables 5 and 6.

Table ES-1
Summary of Results of the Air Quality Study

<table>
<tr><th>Source Type
(ID)</th><th>Stack Base Height
(ft)
(description)</th><th>100% Load
Volume Flow Rate
and Exit Velocity
cfm (fpm)</th><th>Stack
Height
Above
Base
(ft)</th><th>Comment</th></tr>
<tr><td colspan="5">NREL ESIF</td></tr>
<tr><td rowspan="3">900 kW Diesel Generators

(DG-1,2)</td><td rowspan="2">0.0
(Local Grade)</td><td rowspan="2">6950
(7313)</td><td rowspan="2">13.0</td><td><u>Single unit operating:</u>
Design criteria met/exceeded as follows:
<u>Health</u>
NIOSH[2]: met
<u>Odor</u>
Standard: 32% of operating hours[3]
Filtered[4]: 1% of operating hours[3]</td></tr>
<tr><td><u>Two units operating simultaneously:</u>[5]
Design criteria met/exceeded as follows:
<u>Health</u>
NIOSH: less than 1% of operating hours at the ESIF west sidewall and S&TF east air intakes
<u>Odor</u>
Standard: 39% of operating hours
Filtered: 17% of operating hours</td></tr>
<tr><td colspan="4">Note: During a loss of power situation (both units operating) the ESIF west sidewall and ESIF Data Center intakes are not operating.

Health Mitigation: To meet NIOSH health criterion at the S&TF intake, restrict NO_x emissions for each unit to 3.64 g/kW-hr.

Odor Mitigation:
1) install an appropriate exhaust oxidizer in the exhaust stream or install appropriate filters at the air intakes (reduces probability of exceedance); or
2) ensure ESIF office windows for natural ventilation are closed during testing (odors may still be present at the ESIF Data Center air intake and the S&TF east air intake).</td></tr>
</table>

[2] The National Institute of Occupational Safety and Health <u>recommended</u> exposure limit for NO_2.

[3] Based on client communication, operating hours are assumed to be 136 hours per year.

[4] Assumes an 80% efficient exhaust oxidizing filter is installed.

[5] Represents a future condition that occurs only with loss of power on the site. Based on client communication, generator testing will be done one unit at a time.

Table ES-1
Summary of Results of the Air Quality Study

<table>
<tr><th>Source Type
(ID)</th><th>Stack Base Height
(ft)
(description)</th><th>100% Load
Volume Flow Rate
and Exit Velocity
cfm (fpm)</th><th>Stack Height Above Base
(ft)</th><th>Comment</th></tr>
<tr><td colspan="5">NREL ESIF</td></tr>
<tr><td rowspan="2">500 kW Diesel Test Generator

(T-Gen-1 and 2)</td><td>0.0
(Local Grade)</td><td>4,291
(7,867)</td><td>10.0</td><td><u>Health</u> criterion (NIOSH[5]) is predicted to be met at the S&TF east intake if NO_x emissions are limited to 1.65 g/s.

<u>Odor</u> threshold is predicted to be exceeded up to 3% (T-Gen-1) of operating hours at ESIF west sidewall air intake. Odor threshold is predicted to be exceeded up to 9% (T-Gen-1) and 6% (T-Gen-2) of operating hours at S&TF east air intake.</td></tr>
<tr><td colspan="4">Health Mitigation: To meet NIOSH health criterion, restrict total NO_x emissions to 1.90 g/s (T-Gen-1) and 1.65 g/s (T-Gen-2), respectively.

Odor Mitigation:
Install an appropriate exhaust oxidizer in the exhaust stream or install appropriate filters at the air intakes (reduces probability of exceedance).</td></tr>
</table>

Table ES-1
Summary of Results of the Air Quality Study

Source Type (ID)	Stack Base Height (ft) (description)	100% Load Volume Flow Rate and Exit Velocity cfm (fpm)	Stack Height Above Base (ft)	Comment
NREL S&TF				
Lab Exhaust (S&TF Lab)	54.0 (Penthouse)	16,500 (2,954)	15.0	Meets recommended criteria based on a standard fume hood spill. Health criteria based on the release of 1.5 ppm of arsine predicted to be exceeded up to 2% of the time at the ESIF west sidewall air intake.
	Health Mitigation: **1)** reduce arsine emissions to 0.00816 g/s (0.33 ppm); or **2)** investigate taller stack heights.			

1. INTRODUCTION

This report documents the wind-tunnel study conducted by CPP, Inc. on behalf of the preceding SmithGroup for the proposed National Renewable Energy Laboratory Energy Systems Integrated Facility (NREL ESIF) in Golden, Colorado. The objective of the study was to obtain accurate concentration estimates at building air intakes and other sensitive locations due to emissions from various exhaust sources located on and around the NREL ESIF. The various exhaust sources may periodically emit chemicals or other contaminants that may enter nearby buildings through air intakes, or be present at other sensitive locations, and impact staff or the general public. If adverse impacts were found, mitigation measures were evaluated.

Additional analysis was conducted to determine the optimum fan operating parameters that will meet the air quality design criteria such that a given exhaust fan may be able to run at less than 100% of the planned flow and exit velocity. This may allow the volume flow rate out of the exhaust stacks to more closely match the airflow into the building, resulting in potentially significant energy savings.

To meet the objectives of the study, a 1:240 scale model of the NREL ESIF and nearby surroundings within a 1360 ft radius was constructed and placed in CPP's boundary-layer wind tunnel. Concentration measurement tests were conducted for a variety of meteorological conditions and source/receptor combinations. The concentration measurements were converted to full-scale normalized concentrations (*C/m*). These normalized concentration values were then compared to normalized odor threshold and health limit values (i.e., a design concentration). The design concentration was specified such that health and odor effects due to any expected chemical release would be minimal at sensitive locations.

Included in this report are a description of various site-specific issues, a discussion of the experimental methods, and the results of the study. The results are also summarized in an executive summary, which is located at the beginning of the report.

2. PROJECT SPECIFIC INFORMATION

2.1 DESCRIPTION OF SITE

The National Renewable Energy Laboratory Energy Systems Integrated Facility is located in Golden, Colorado, east of the NREL Science and Technology Facility, as shown in Figure 1. Figure 2a is a detailed view of the area modeled on the turntable, showing surrounding receptor locations. From aerial photographs and the site visit it was determined that the region surrounding the area modeled on the turntable is generally open country. Using the EPA tool AERSURFACE (EPA, 2008) a target surface roughness length of 0.20 m was selected for use in the wind-tunnel modeling.

2.2 EXHAUST SOURCES

The NREL ESIF is equipped with laboratory fume hood, perchloric hood, and tail pipe exhaust stacks located on the roof and multiple diesel generators in the service yard. These exhaust sources may periodically emit chemicals or other contaminants that may adversely affect the air quality in the ESIF or surrounding buildings. The cooling tower, hydrogen vent, smoke removal, welding hood and paint booth exhausts located on the NREL ESIF roof were not simulated in the wind tunnel.

Laboratory exhausts on the existing Science and Technology Facility (S&TF) were evaluated to determine their impact on the planned NREL ESIF. All of the exhaust locations are shown in Figure 2b. The full-scale exhaust parameters for each source are listed in Table 1.

2.3 RECEPTOR LOCATIONS

The emissions from the exhaust sources described above have the potential for causing health or odor problems at sensitive locations such as air intakes for building ventilation, plazas, entrances and nearby buildings. The various receptor locations where concentrations were measured during the course of the study are identified in Figures 2a-b. Table 2 provides a list of abbreviated receptor identifications with additional explanation.

It should be noted that not all receptors were sampled for each source. Only those receptors of most interest (i.e. air intakes for building ventilation, operable windows and nearby neighborhood) or those likely to give the highest concentration for a particular source were evaluated.

2.4 METEOROLOGY

The meteorological information of primary interest for this evaluation is the wind frequency distribution. This information is used to specify a reasonable upper limit wind speed to be used for testing. This information is also used in conjunction with the wind-tunnel measured concentrations to determine the percent time a certain concentration is predicted to be exceeded.

Figure 3 shows the wind frequency distribution, in the form of a wind rose, at the NREL SRRL BMS anemometer. The anemometer is located approximately half a mile west of the National Renewable Energy Laboratory campus, as shown in Figure 1. The data was collected during the period from 2001 to 2007. The wind rose indicates that the most frequent winds are from the W through WNW. The strongest winds, greater than 16.0 m/s (35.8 mph), occur primarily from the WNW and NNE. All wind directions occur at least 1% of the time, so wind-tunnel testing considered all wind directions.

Figure 4 shows the cumulative frequency distribution of wind speed at the NREL SRRL BMS anemometer. The wind speed distribution was used to determine the wind speed at the anemometer that is exceeded 1% of the time (i.e., the 1% wind speed). The figure shows that the 1% wind speed is approximately 12.3 m/s (27.5 mph) at the anemometer. To ensure that concentration measurements were only obtained for likely wind conditions during the wind-tunnel testing, testing was restricted to wind speeds from 1 m/s to approximately the 1% wind speed (i.e., the maximum wind speed evaluated was 12.3 m/s).

2.5 CONCENTRATION DESIGN CRITERIA

Developing concentration acceptance criteria can be as important as predicting exhaust concentrations. Concentration predictions from wind tunnels or numerical methods by themselves are not useful for examining source designs unless some maximum acceptable concentration, or design criterion, is specified. This criterion will vary with source type and each source type may have a criterion that varies depending upon such things as chemical utilization, chemical inventory, boiler or engine size, or number of vehicles.

An air quality "acceptability question" can be written:

$$C_{max} < C_{health/odor}\ ? \tag{1}$$

where C_{max} is the maximum concentration expected at a sensitive location (air intakes, operable windows, pedestrian areas), C_{health} is the health limit concentration and C_{odor} is the odor threshold concentration of any emitted chemical. When a large number of potential chemicals are emitted from a pollutant source, a variety of mass emission rates, health limits, and odor thresholds need to be examined. It then becomes operationally simpler to recast the acceptability question by normalizing (dividing) Equation 1 by the mass emission rate, *m*:

$$\left(\frac{C}{m}\right)_{max} < \left(\frac{C}{m}\right)_{health\,/\,odor} \; ? \qquad \textbf{(2)}$$

The left side of Equation 2, $(C/m)_{max}$, is only dependent on external factors such as stack design, receptor location, and atmospheric conditions. The right side of the equation is related to the emissions and is defined as the ratio of the health limit, or odor threshold, to the emission rate. Therefore, a highly toxic chemical with a low emission rate may be of less concern than a less toxic chemical emitted at a very high emission rate. Three types of information are needed to develop normalized health limits and odor thresholds:

1) a list of the toxic or odorous substances that may be emitted,
2) the health limits and odor thresholds for each emitted substance, and
3) the maximum potential emission rate for each substance.

It should be noted that the normalized concentration design criteria discussed below are derived from occupational exposure limits, odor thresholds and estimated mass emission rates. The occupational exposure limits are based on a mixture of guidelines, recommendations, and regulatory limits from the ACGIH, OSHA or NIOSH. The limits provided by ACGIH and NIOSH were developed as guidelines to assist in the control of health hazards, and are not intended for use as legal standards. The limits provided by OSHA are regulatory limits on the amount or concentration of an airborne substance that may be present in the workplace, and are enforceable.

The mass emission rates are based on an assumed accidental release scenario. Therefore, no safety factor has been applied per ANSI/AIHA Laboratory Ventilation Standard Z9.5-2003 (Z9.5-2003). The odor thresholds were obtained from published information with no safety factor applied. CPP recommends that the user employ an Industrial Hygienist to review both the design criteria development procedure described in this report and the user's anticipated laboratory procedures to determine the appropriateness of the established design criteria, discussed below. CPP further recommends that this document be reviewed each time the user experiences either a program change or a change in laboratory procedures. Failure to do so may nullify the recommendations presented in this report. A detailed explanation of the calculation is presented in an internal CPP document "CPP Simulation and Analysis Techniques for Air Quality Assessments" (April 2010). This document is available on request.

The following paragraphs discuss the specific design criteria used in this study as well as potential mitigation measures. The sources of concern for this evaluation and the design criterion for each source type are summarized in Table 3. The table also summarizes the basis from which each design criterion was developed.

2.5.1 Chemical Hood Exhaust Sources

Design criteria specific for the chemicals used in a laboratory facility can be developed using chemical-specific information. However, Z9.5-2003 states "toxic and hazardous substances may be used at some point during the lifetime of the facility." This implies that one needs to assume that the chemical utilization will change over time and specifying the criteria based on current chemical utilization may not be appropriate.

2.5.1.1 NREL ESIF

No proposed chemical inventory was provided for the NREL ESIF. Therefore, the normalized health limit (*HL/m*) and normalized odor threshold (*OT/m*) design criteria were set at 400 $\mu g/m^3$ per g/s, which corresponds to the ASHRAE example criterion discussed in Chapter 14 of the 2007 ASHRAE Handbook HVAC Applications (ASHRAE, 2007). This criterion assumes a 7.5 L/s chemical emission rate (i.e., due to a liquid spill or lecture bottle fracture) and a concentration of 3 mg/kg or less at an intake. Chapter 14 (ASHRAE, 2007) includes the following disclaimers regarding this criterion: 1) laboratories using extremely hazardous substances should conduct a chemical specific analysis based on published health limits; 2) a more lenient limit may be justified for laboratories with low levels of chemical usage; and 3) project specific requirements must be developed in consultation with the safety officer.

The ASHRAE criterion may be put into perspective by considering the "as manufactured" and "as installed" chemical hood containment requirements outlined in Z9.5-2003 (i.e., a concentration at a manikin outside the chemical hood of 0.05 ppm or less for "as manufactured" and 0.10 ppm or less for "as installed" with a 4 L/m accidental release in the hood as measured using the ANSI/ASHRAE 110-1995 test method). The "as manufactured" requirement is equivalent to a design criterion of 750 $\mu g/m^3$ per g/s and the "as installed' requirement is equivalent to a design criterion of 1500 $\mu g/m^3$ per g/s. Hence, the criterion for a manikin (i.e., worker outside the chemical hood) is 1.9 to 3.8 times less restrictive than that for the air intake or other outdoor locations. This seems reasonable (i.e., that the air intake has more strict criteria) since the worker at the chemical hood can shut the hood or walk away to avoid adverse exposure. Also, the ANSI/ASHRAE 110-1995 test is not necessarily a "worst-case" exposure scenario for the worker.

For reference purposes, CPP has provided the following information in Table 7 for chemicals with published occupational exposure values (ACGIH, 2009) and odor thresholds (Ruth, 1986; ACGIH, 1989).

- the normalized health limit and odor threshold associated with a 1 L spill or 1 minute lecture bottle release; and
- the limiting value (i.e. lowest value of the normalized health limit or odor threshold) associated with a 1 L spill or 1 minute lecture bottle; and
- the maximum allowable quantity (for liquids) or emission rate (for gasses) to be handled in the fume hood to meet design criteria.

The facility owner should review the table to determine whether they will be using chemicals in a manner that could create a problem. If a problem seems likely, then mitigation measures such as those described in Section 2.5.4 below, may be required for some chemicals. Also, a detailed hazard assessment should be carried as outlined in Z9.5-2003, which states:

"The first step in a hazard assessment is to identify what chemicals can be released including normally uncharacterized by-products. After characterizing the inherent hazard potential (largely based on physical properties, toxicity, and routes of entry), the next step is to ascertain at least qualitatively, the release "picture". At what points within the control zone will chemicals be evolved and at what release rate? Will the chemical release have velocity? How has the maximum credible accidental release been accounted for? Finally, how many employees are/could be exposed and what means are available for emergency response?"

2.5.1.2 NREL S&TF

Based on client communication Arsine gas can be emitted from the laboratory exhaust at a maximum emission rate of half of the Immediately Dangerous to Life and Health (IDLH) concentration. According to the Center for Disease Control (CDC, 2011) the IDLH for Arsine is 3 ppm_v. Therefore, an arsine emission rate of 0.037 g/s (1.5 ppm_v) was used to calculate the normalized health limit (*HL/m*) design criterion for the S&TF laboratory exhaust. The ASHRAE example criterion of 400 $\mu g/m^3$ per g/s was used for the health and odor threshold (*OT/m*) design criterion (see Section 2.5.1.1) for all non-Arsine releases. The normalized concentration design criteria (*HL/m* and *OT/m*) for the S&TF laboratory exhaust are listed in Table 3.

2.5.2 Combustion Exhaust Sources

The normalized health limit (*HL/m*) design criteria for the diesel emergency generator and idling diesel vehicle sources are based on NO_x emissions obtained from manufacturer data, information published by the Environmental Protection Agency (EPA, 1985 and 1996b), or information listed in the Code of Federal Regulations (CFR, 2002). Details regarding each combustion source are presented in the following paragraphs.

900 kW Diesel Generators. The normalized health limit (*HL/m*) design criteria for the diesel emergency generators were based on information obtained from the manufacturer (for EPA Tier 2 generators). The normalized odor threshold (*OT/m*) design criteria were based on a 20% objection level to an exhaust dilution of 1:2000 (Vanderheyden, 1994). After-market filters are available for some diesel combustion sources as discussed in Section 2.5.4 below. These filters typically reduce unburned hydrocarbons (the odorous exhaust components), by about 80%. If these filters are installed, the 1:2000 dilution requirement stated above is reduced to a 1:400 dilution requirement. The normalized concentration design criteria (*HL/m* and *OT/m*) for the diesel emergency generators, including criteria for each multiple-units-operating scenario, are listed in Table 3. The emission rates used for the design criteria calculations are listed in Table 8.

500 kW Test Diesel Generators. The size of the test generators in the test yard was assumed to be 500 kW. No emissions information was available. Therefore, no health limit was used. The normalized odor threshold (*OT/m*) design criterion was based on a 20% objection level to an exhaust dilution of 1:2000 (Vanderheyden, 1994). Based on the wind tunnel measured concentrations, maximum allowable NO_x emission rates can be calculated. The normalized concentration design criteria (*HL/m* and *OT/m*) for the test diesel generators are listed in Table 3.

Tailpipe/Generator Exhausts. No size of the units to be tested or emissions information was available. Therefore, no health limit was used. The normalized odor threshold (*OT/m*) design criterion was based on a 20% objection level to an exhaust dilution of 1:2000 (Vanderheyden, 1994). Based on the wind tunnel measured concentrations, maximum allowable NO_x emission rates can be calculated. The normalized odor threshold design criteria (*OT/m*) for the tailpipe/generator exhausts are listed in Table 3.

Idling Diesel Truck. The normalized health limit (*HL/m*) design criterion for the idling diesel truck at the loading dock was based on information provided by the Environmental Protection Agency (EPA, 1985). The normalized odor threshold (*OT/m*) design criterion was based on a 20% objection level to an exhaust dilution of 1:2000 (Vanderheyden, 1994). The *HL/m* and *OT/m* are initially calculated assuming a single vehicle operating at one time. If multiple vehicles are expected to be operating simultaneously, the *HL/m* and *OT/m* for one vehicle are simply divided by the total number of vehicles expected to be operating. The normalized design criteria for the idling diesel truck are listed in Table 3.

2.5.3 Perchloric Acid Exhaust Sources

There are currently no published health limits for perchloric acid, which is odorless. However, there is extensive qualitative information describing its toxic effects. It is anticipated that very limited quantities, in the range of milliliters, will be used. Therefore, the 'as installed' chemical hood requirement outlined in Z9.5-2003 of 1500 μg/m³ per g/s, based on CPPs experience with chemical fume hoods, was used.

Based on client communication, the perchloric acid hood may be converted to a standard fume hood. Therefore, an additional criterion was evaluated: the ASHRAE example criterion discussed in Chapter 14 of the 2007 ASHRAE Handbook HVAC Applications (ASHRAE, 2007) of 400 μg/m^3 per g/s. For more information on these criteria refer to Section 2.5.1.

2.5.4 Mitigation Measures

There may be conditions when the wind-tunnel estimated concentration exceeds the design criterion. This may occur because the chemical may have a low health limit or odor threshold, because of an unsatisfactory exhaust and intake design, or both. Several options are then available. One is to examine a better exhaust design or intake location. Another is to consider reducing the emissions of the problem chemicals, either with administrative controls or with emission controls. Finally, some consideration of the probability of exceeding the health and odor design criteria can be made. In actual practice, emissions for accidental spills will occur infrequently. In addition, emissions for other sources (i.e., an emergency generator, diesel vehicles at the loading dock, etc.) will not occur for all hours of the year. These options are discussed in more detail in the following paragraphs.

Examine Exhaust/Intake Design. Physically altering the initial exhaust/intake design is often the simplest alternative available to mitigate excessive concentrations at sensitive locations. Alternate exhaust designs such as increased stack height, increased volume flow and/or increased exit velocity may be readily evaluated in the wind tunnel. Alternate exhaust or intake locations may also be easily evaluated in the wind tunnel. Activated carbon filters, which may adsorb a significant amount of odor, may also be installed at the air intakes.

Reduce Emissions. *Chemical Fume Hoods:* One method for achieving the reduced emission rate is to limit the maximum quantity that may potentially be spilled within the fume hood by the corresponding factor. Thus, to achieve a normalized health limit design criterion of 400 μg/m^3 per g/s for a specific chemical, the maximum storage quantity (and thus, maximum volume available to be spilled) may need to be limited. Emission controls for gaseous emissions can be obtained through emergency shut-off valves and in-line restrictor orifices.

Combustion Sources: Many forms of emission controls are available from manufacturers of combustion exhaust sources (i.e., diesel engines, boilers, etc.); for example: low NO_x burners are readily available for boilers; many diesel engine manufacturers provide low emission versions of popular models; and chemical specific catalytic converters are available from some manufacturers or third party suppliers. Alternate fuels or exhaust oxidizers may also be available to aid in reducing odor complaints.

Probability Analysis. If a source is determined to produce concentrations in excess of a design criterion at air intakes or other sensitive locations, and none of the methods described above adequately address the problem, the probability that the health or odor design criterion is exceeded may be assessed. The probability (or likelihood that the design concentration would be exceeded) may be estimated by first determining the probability that the design criterion will be exceeded during an emission event (i.e., the probability that the meteorological conditions are such that the plume impacts the receptor in sufficient quantity such that the design concentration would be exceeded). This probability is then multiplied by the probability that an emission event occurs to determine the overall probability of exceeding the design criterion. If this probability is sufficiently low, the design may be deemed acceptable.

Consider the following example. The wind-tunnel analysis shows that meteorological conditions exist such that the design concentration may be exceeded up to 1.1% of the time. Now assume that emission events will occur for 10 hours per year on a random basis. This translates into probability of 0.0011 or 0.11% of the time. The probability that the design criterion would be exceeded is the product of these two probabilities. Thus, for the above example, the probability that the design criterion would be exceeded is 0.0012% or 0.1 hours per year. This gives a recurrence interval of once every ten years.

3. WIND-TUNNEL MODELING METHODOLOGY

3.1 WIND-TUNNEL SIMILARITY CRITERIA

An accurate simulation of the boundary-layer winds and stack gas flow is an essential prerequisite to any wind-tunnel study of diffusion. The similarity requirements can be obtained from dimensional arguments derived from the basic equations governing fluid motion. A detailed discussion on these requirements is given in the EPA fluid modeling guideline (EPA, 1981a) and Cermak (1971, 1975, 1976). Using scaling criteria and source parameters supplied by the client, as noted in Table 1, wind-tunnel model test conditions were computed for the sources under evaluation.

3.2 SCALE MODEL AND WIND TUNNEL SETUP

3.2.1 Scale Model

A 1:240 scale model of the NREL ESIF and nearby surroundings was constructed and placed on a 3.45 m diameter turntable. The area modeled is depicted in Figure 2a. A close-up plan view of the test buildings showing source and receptor locations is provided in Figure 2b. Photographs of the model from various directions are shown in Figure 5.

3.2.2 Wind-tunnel Configuration

All testing was carried out in CPP's closed-circuit wind tunnel shown in Figure 6. Turning vanes at the tunnel elbows were used to maintain a homogeneous flow at the test-section entrance. Spires and a trip at the leading edge of the test section begin the development of the atmospheric boundary layer. The long boundary layer development region between the spires and the site model was filled with roughness elements in a pattern experimentally set to develop the appropriate approach boundary layer wind profile and approach surface roughness length. Testing was conducted with the target approach surface roughness length specified in Table 1.

3.2.3 Exhaust Sources

The exhaust sources discussed in Section 2.2 were simulated by installing stacks constructed of brass tubes at the appropriate locations. Trips were installed within the stacks as required to ensure that the stack flow was fully turbulent upon exit. The stacks were supplied with a tracer gas (ethane) and nitrogen mixture with a density similar to room temperature air. Precision mass flow controllers were used to monitor and regulate the discharge momentum.

3.2.4 Receptors

The receptor locations (concentration sampling points) discussed in Section 2.3 were evaluated by installing a small diameter brass tube at the specified location. This brass tube was then connected to the analysis instrumentation to determine the amount of tracer gas present at the receptor location. It is assumed that the plume is sufficiently large that there is not a significant concentration gradient across the receptor location. As such, the local concentration can be assessed by collecting a single point air sample at or near the receptor location of interest.

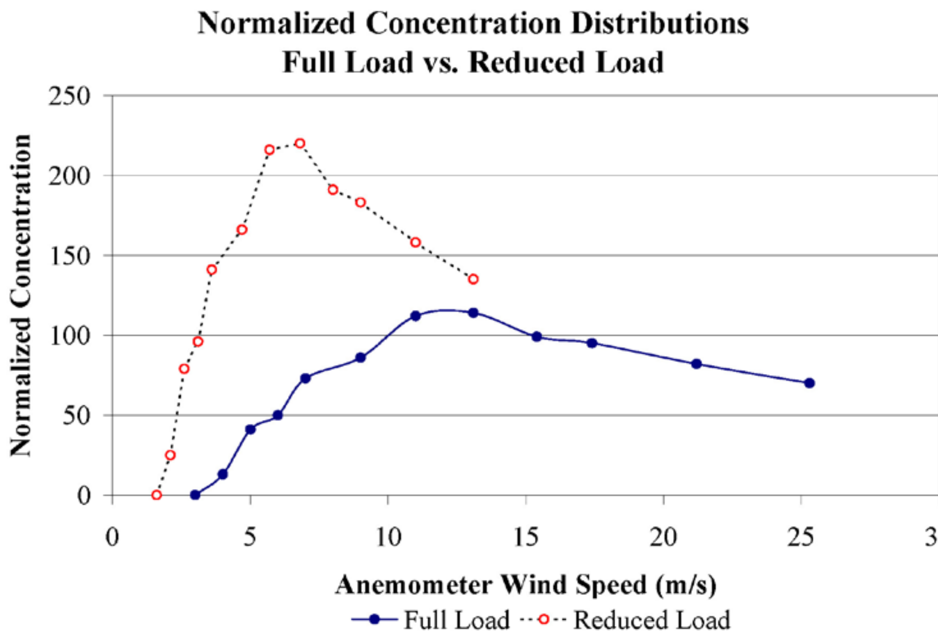
3.3 DATA ACQUISITION AND PROCESSING

3.3.1 Data Collection

The primary data of interest collected during the course of this study was concentration due to the tracer gas release from each source being simulated. Table 4 summarizes the various source/receptor combinations that were evaluated during the study. The table also includes the overall maximum concentration measurement results for each source/receptor pair, which will be discussed in subsequent sections.

3.3.2 Concentration Data Post-processing

Normalized concentration results for multiple operating modes for a given exhaust source may be obtained by post-processing the initial results. This ability to determine C/m values for alternate exhaust volume flow rates, assuming the same exit diameter, is inherent in the physics of the physical model. In the wind tunnel simulation, the ratio of exhaust momentum to wind momentum, R, is matched to that in full scale. This allows post-processing of the data for any exhaust flow rate, provided the stack diameter remains constant. The use of this technique requires that the momentum ratios be selected such that the full range of desired wind speeds is simulated for each volume flow rate. In other words, wind speeds outside the 1 m/s to 12.3 m/s range are defined to ensure that the extreme wind speeds (at both ends of the specified range of wind speeds) are included in the post-processed data set. However, this tool may be used at any time assuming the maximum *C*/*m* value for the base run was bounded by lower *C*/*m* values at wind speeds greater than and less than the critical wind speed. *C*/*m* values occurring for wind speeds outside the range typically are not included in the Table 4. Typical results of such an analysis are demonstrated graphically in the chart below.



The chart shows the measured concentration distribution for a full load volume flow rate, as initially simulated in the wind tunnel (solid line and circles). The chart shows that the maximum measured normalized concentration was 107 $\mu g/m^3$ per g/s at an anemometer wind speed of 13 m/s. When the data is reprocessed for a 50% reduced load, the resulting maximum normalized concentration is increased to 214 $\mu g/m^3$ per g/s and the critical wind speed is decreased to 6.5 m/s (dashed line and open circles).

4. RESULTS

4.1 CONCENTRATION MEASUREMENTS

Normalized concentrations (*C/m*) due to emissions from the various sources were measured and evaluated following the procedures discussed in the earlier sections and the appendices. A compilation of the maximum steady-state *C/m* value for each source/receptor combination tested is presented in Table 4. The conclusions derived from these results are presented in the tables included in the Executive Summary at the front of this report. *C/m* values versus wind speed and wind direction for each test are archived at CPP and available upon request.

In addition to presenting the maximum measured steady-state normalized concentration for each source/receptor combination evaluated, the table also indicates the percent time that the design criterion may be exceeded, if applicable. The percent time exceeded is calculated by determining the wind conditions that are predicted to result in an exceedance of the design criteria. The summation of the frequency that these wind conditions are expected to occur is then the percent time exceeded presented in Table 4. This value does not take into consideration the probability of the emission event associated with the specified design criteria. Therefore, to determine the probability of exceeded the design criteria, the value listed in Table 5 should be multiplied by the frequency of occurrence of the emission event. For example, if an emergency generator is expected to operate for 12 hours per year, 1 hour per month for routine testing, and the percent time exceeded for the normalized odor threshold indicated in Table 4 is 10.0%, objectionable odors are expected to be present at the specified receptor location 1.2 hours per year (12 hours/yr x 0.10).

4.2 FAN OPTIMIZATION ANALYSIS

In an effort to save energy costs, modern laboratories may be equipped with Variable Air Volume (VAV) HVAC systems. These systems control the level of fresh air that is brought into the laboratory and conditioned. However, on the exhaust side, these VAV systems may be designed with constant volume fans that are either off or running at 100% flow. The difference between the building interior airflow and the flow out of the exhaust stack is controlled with by-pass dampers that feed additional air into the exhaust fans to allow them to run at 100% flow. For large laboratory exhaust systems, it may be possible to operate the fans at reduced volume rates, i.e., VAV, and still maintain adequate air quality at all nearby receptor locations. With a VAV exhaust system, the volume flow rate out of the exhaust stack may more closely match the airflow into the building, possibly eliminating the need for by-pass air, resulting in the potential for significant energy savings.

To determine the minimum acceptable volume flow rate, while maintaining adequate air quality, the data presented in Table 4 was post-processed, following the procedures discussed in Section 3.3.2, to determine the volume flow rate at which the maximum normalized concentration meets the design criteria. The results of this analysis are included in the Executive Summary at the beginning of this report. If this value is less than the minimum operating load on the fan, the results indicate that the fan can be operated over its full range of volume flow rates without exceeding the design criteria. If the minimum acceptable volume flow rate is greater than the minimum operating load, a by-pass damper may still be required to make up the difference.

Further volume flow rate reductions, and thus energy savings, may be obtained by correlating the minimum operating conditions to the local wind conditions. As described in Section 2.4, the upper limit design wind speed used in this analysis to define the maximum concentrations at nearby receptor locations that occurs no more than one percent of the time. Thus, the other 99 percent of the time it may be possible to further reduce the volume flow rates. Depending upon the relative location of the nearby receptors, the predominant wind directions, and the minimum building loads, the energy savings can be significant. The results of this analysis, shown in Table 5, relate the minimum volume flow rates as a function of the local wind speed and wind direction. Polynomial functions were fit to these load percentages. Table 6 shows the load percentage coefficients for the polynomial fit for specific wind directions and wind speeds. The load percentages for the specific wind directions and wind speeds can be used to control the minimum set point value on the fan controllers. However, it does require real time monitoring of a nearby anemometer.

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FIGURES

Figure 1. Site location and project anemometer .

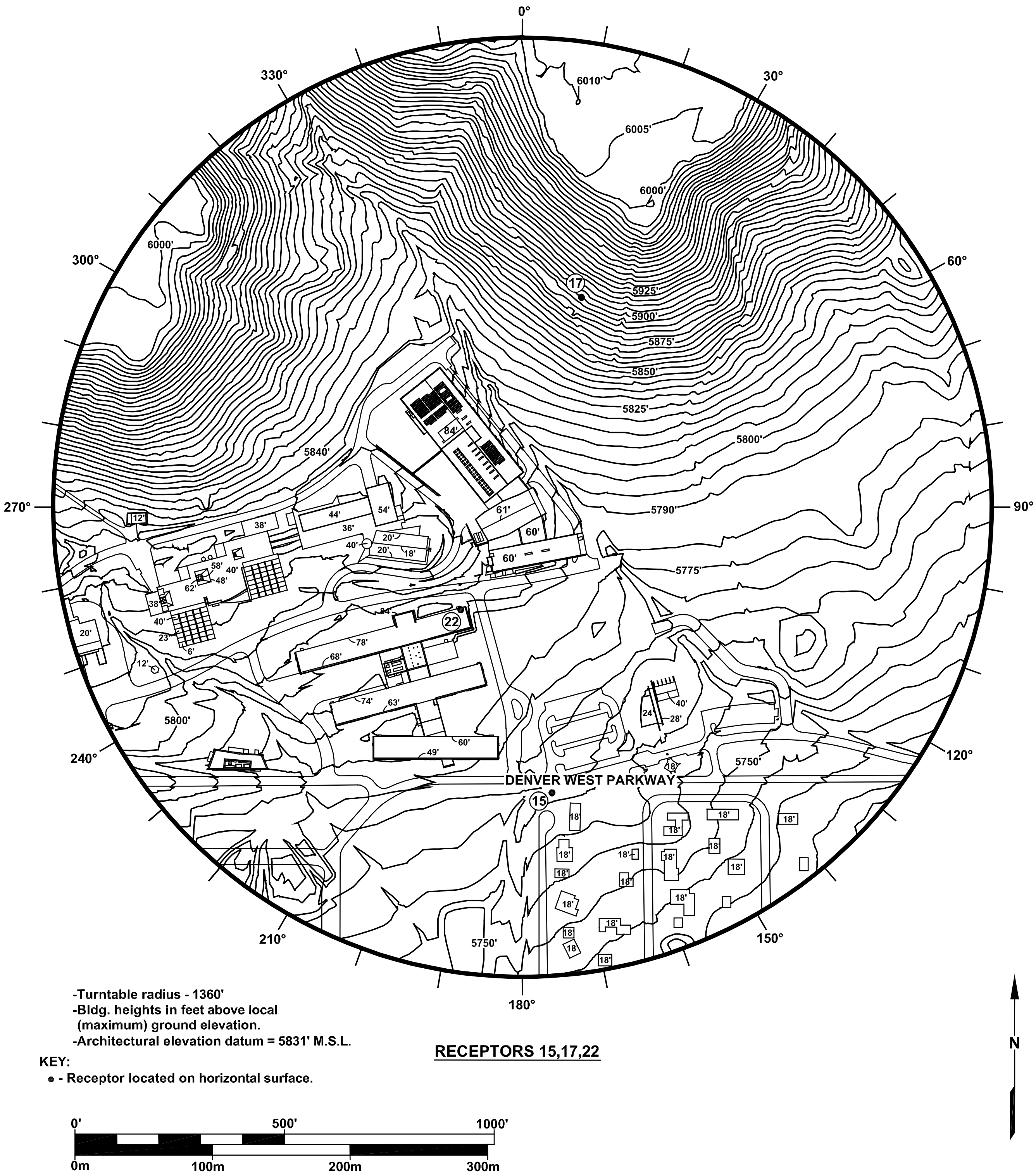


Figure 2. Plan views of the area modeled: a) turntable model with building heights and surrounding receptor locations.

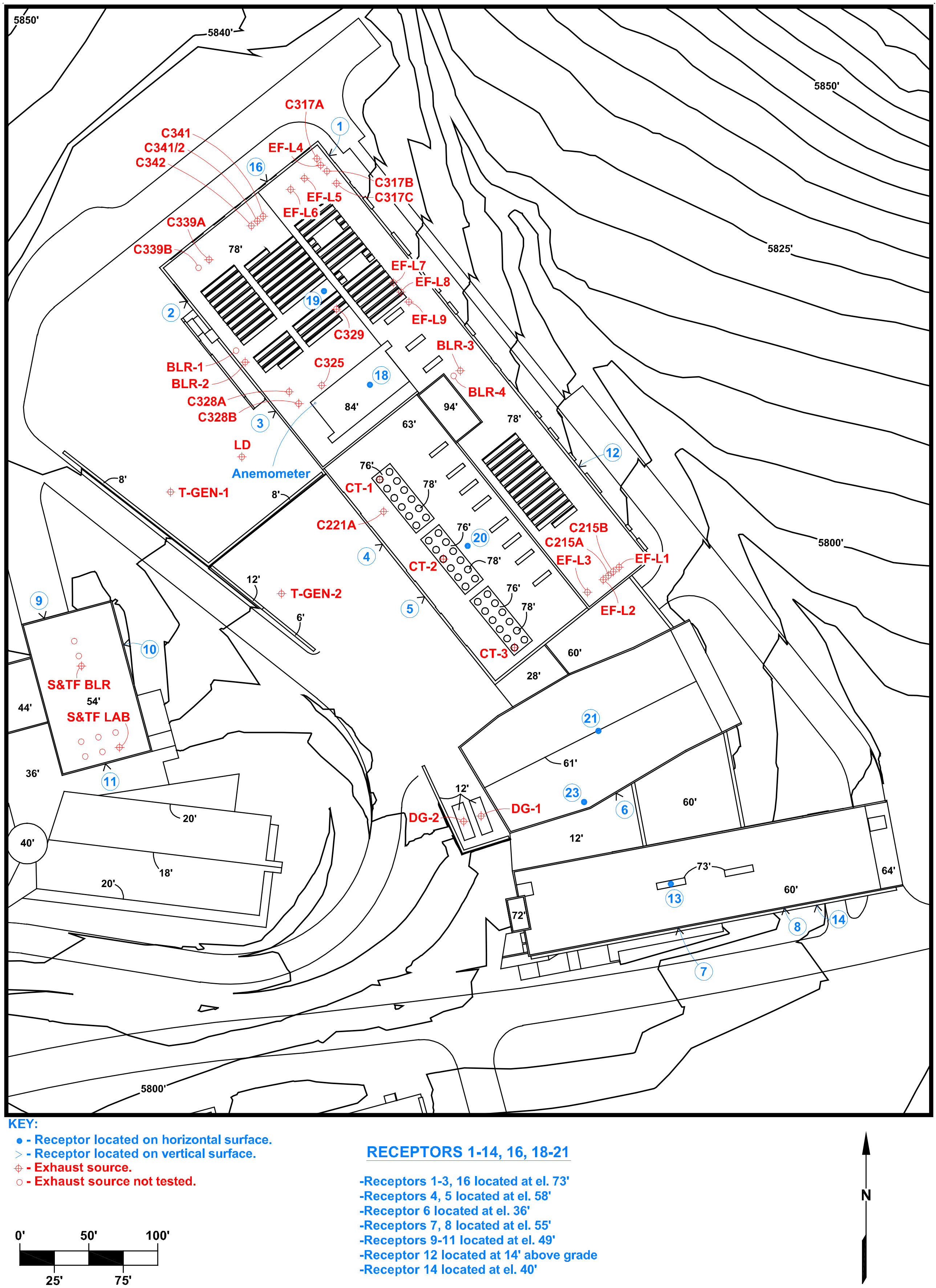


Figure 2. Plan views of the area modeled: b) close up of the NREL ESIF with tier heights and source and receptor locations.

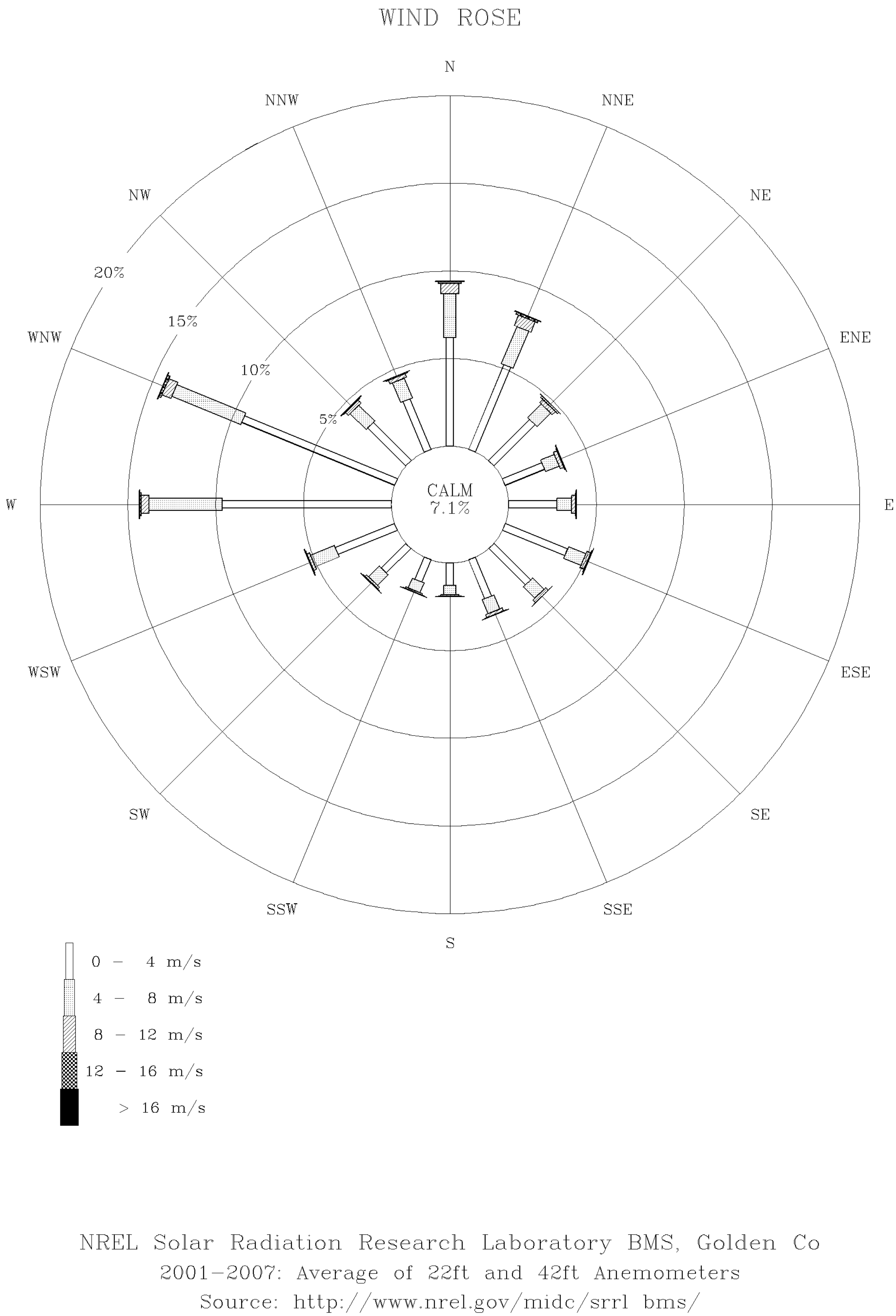
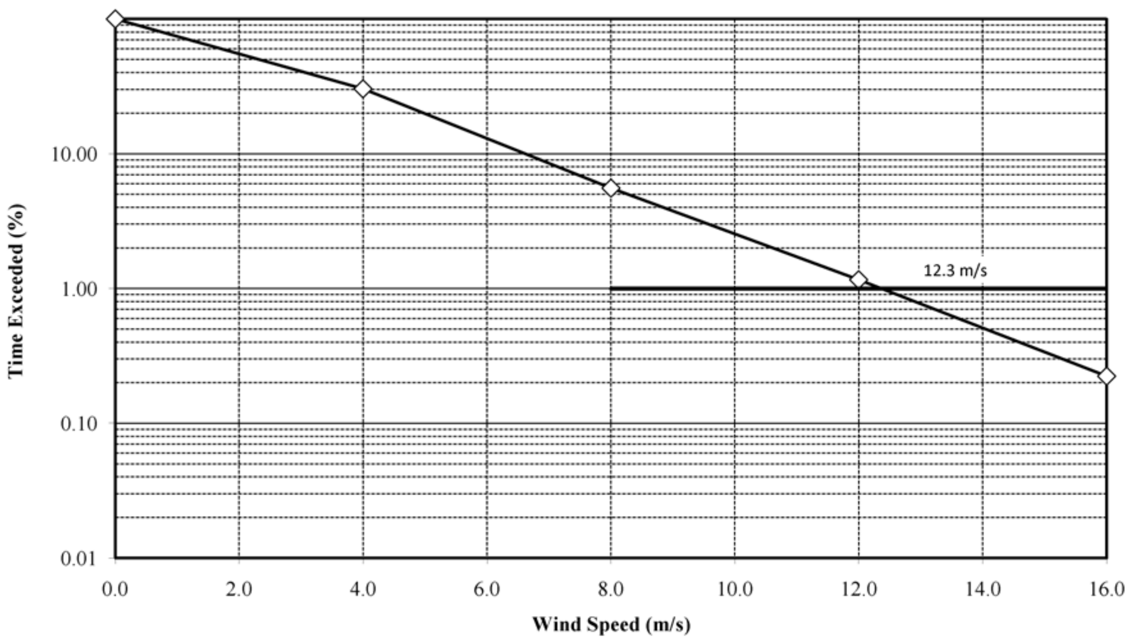


Figure 3. Wind rose for the NREL SRRL BMS anemometer.

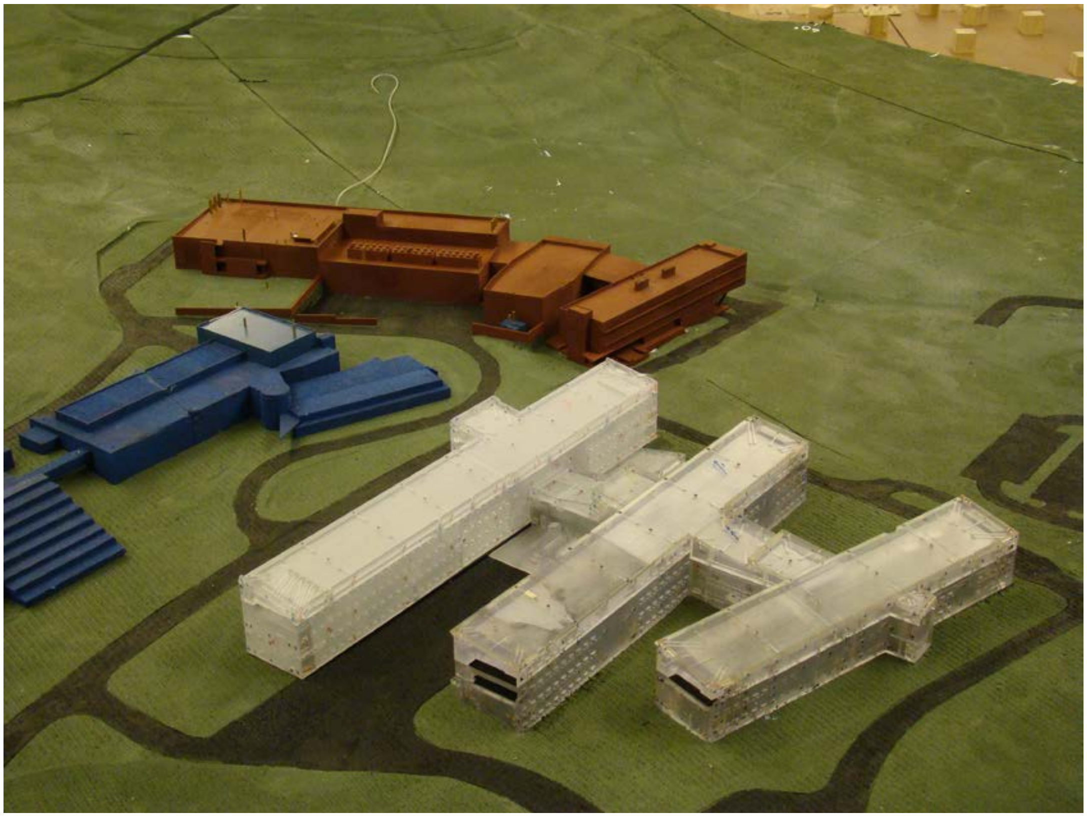
1% Wind Speed Analysis
NREL Solar Radiation Research Laboratory BMS, Golden Co
2001-2007: Average of 22ft and 42ft Anemometers



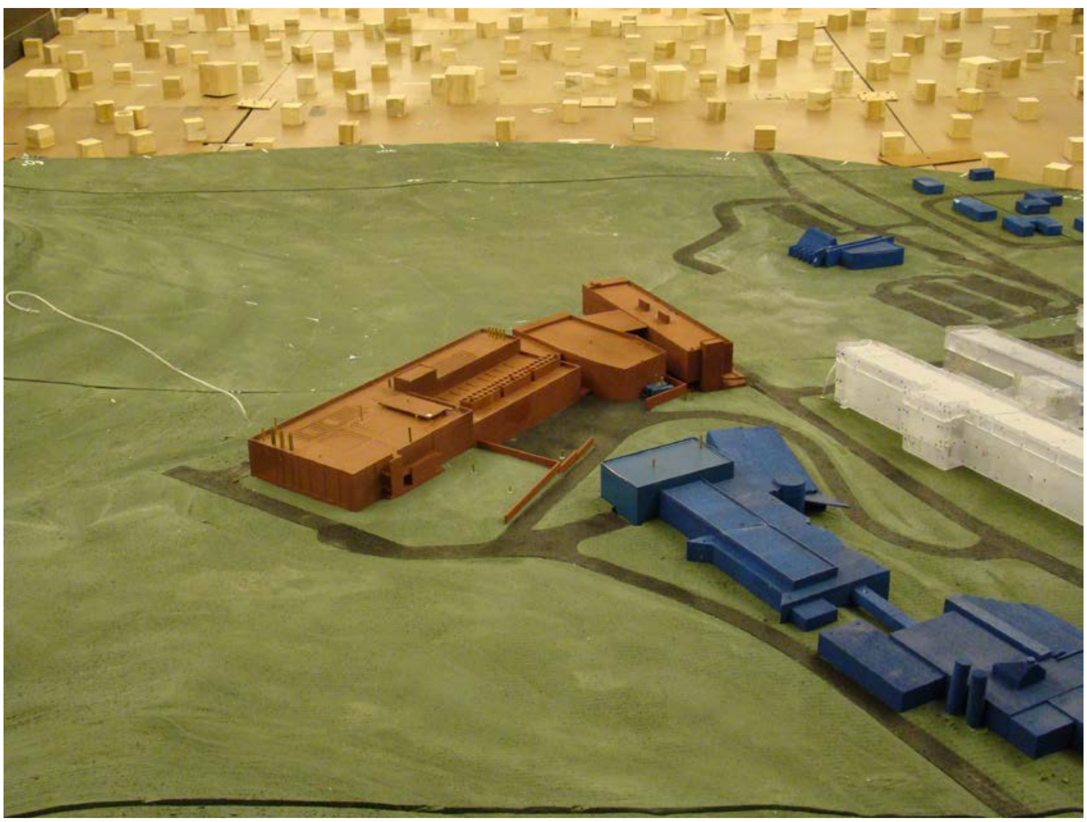
Joint Probability Distribution of Wind Speed and Wind Direction at the NREL Solar Radiation Research Laboratory BMS, Golden Co Anemometer

Category: Maximum Wind Speed (m/s):	1 4.0	2 8.0	3 12.0	4 16.0	5 >16	Totals by Direction (%)
N	6.183	2.501	0.567	0.127	0.028	**9.406**
NNE	5.211	2.280	0.635	0.122	0.033	**8.281**
NE	3.305	1.101	0.264	0.087	0.018	**4.776**
ENE	2.413	0.850	0.203	0.057	0.008	**3.531**
E	2.776	0.831	0.207	0.045	0.006	**3.866**
ESE	3.826	1.052	0.265	0.036	0.002	**5.180**
SE	2.948	0.912	0.203	0.029	0.002	**4.092**
SSE	2.383	0.878	0.171	0.027	0.002	**3.461**
S	1.283	0.533	0.087	0.018	0.005	**1.926**
SSW	1.366	0.611	0.090	0.025	0.009	**2.100**
SW	1.990	0.878	0.120	0.021	0.007	**3.017**
WSW	3.617	1.475	0.170	0.029	0.010	**5.301**
W	9.619	4.176	0.452	0.087	0.022	**14.355**
WNW	9.403	4.246	0.546	0.126	0.038	**14.360**
NW	3.064	1.274	0.223	0.049	0.019	**4.629**
NNW	3.104	1.214	0.209	0.057	0.015	**4.599**
Calm	7.120					
Totals by Category (%):	**69.611**	**24.811**	**4.412**	**0.941**	**0.224**	**100**
Time Exceeded (%):	**30.388**	**5.577**	**1.165**	**0.224**	**0.000**	

Figure 4. Percent time indicated wind speed is exceeded at the NREL SRRL BMS anemometer.

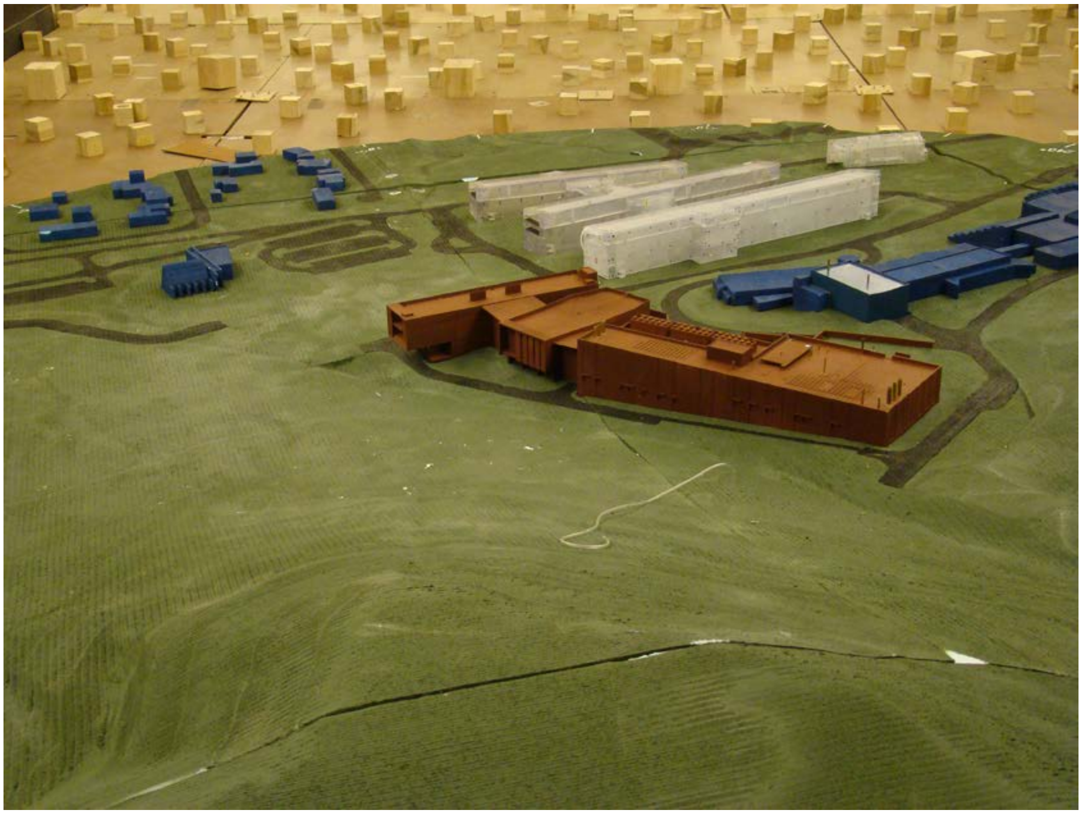


a)



b)

Figure 5. Photographs of the model in the wind tunnel: a) View from the southwest; b) View from the northwest.

c) 

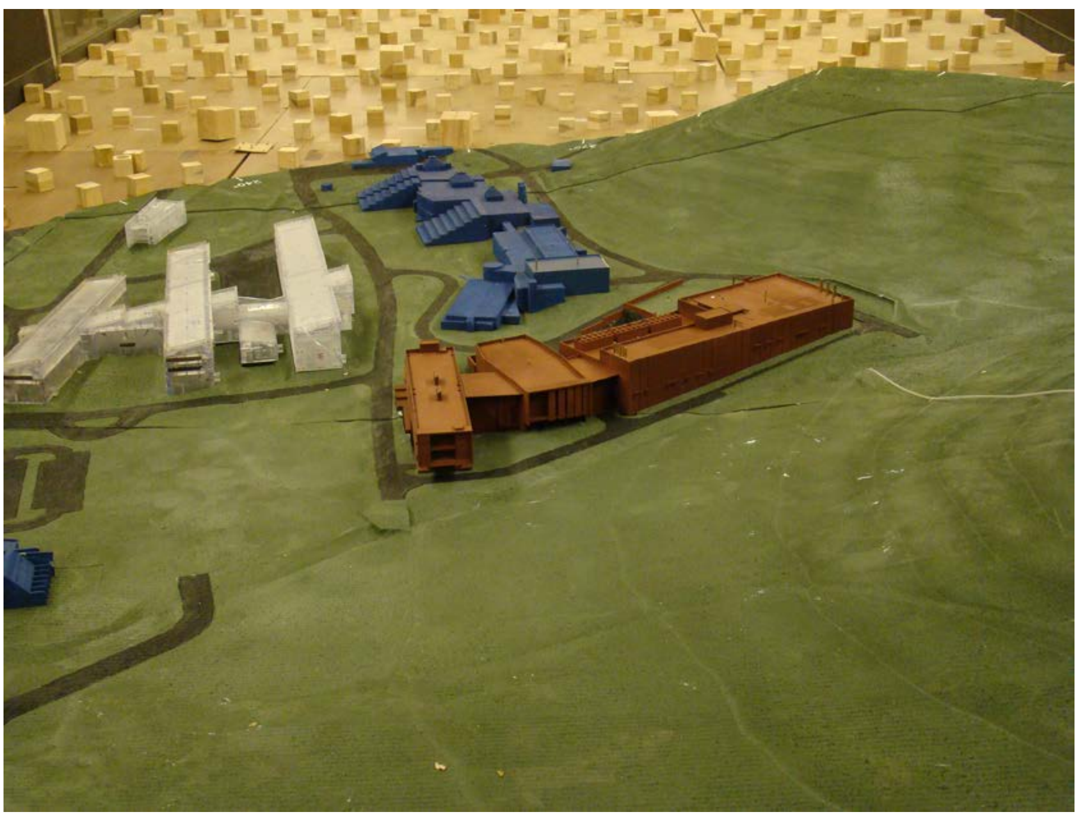
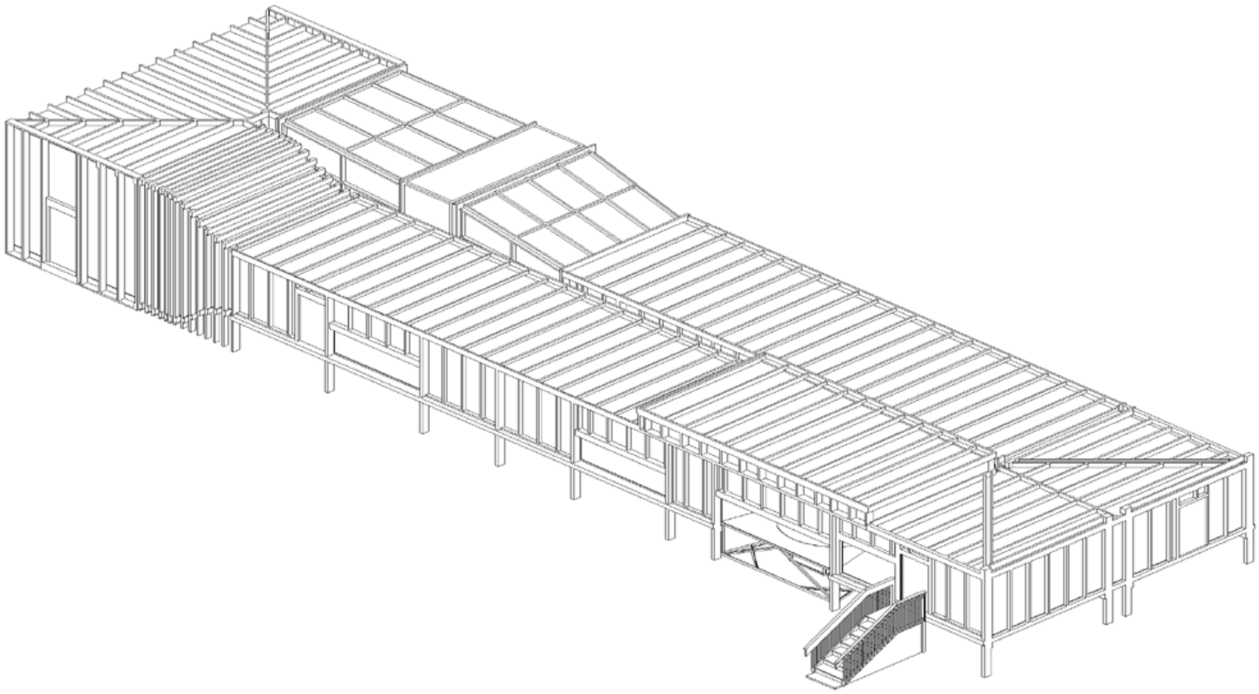
d) 

Figure 5. Photographs of the model in the wind tunnel: c) View from the northeast; d) View from the east.



CPP's Closed-Circuit Wind Tunnel

Figure 6. Schematic of the wind tunnel used for testing and photograph of the wind-tunnel configuration. Note spires and trip at entrance to test section, and roughness elements on approach fetch to develop a turbulent boundary-layer flow.

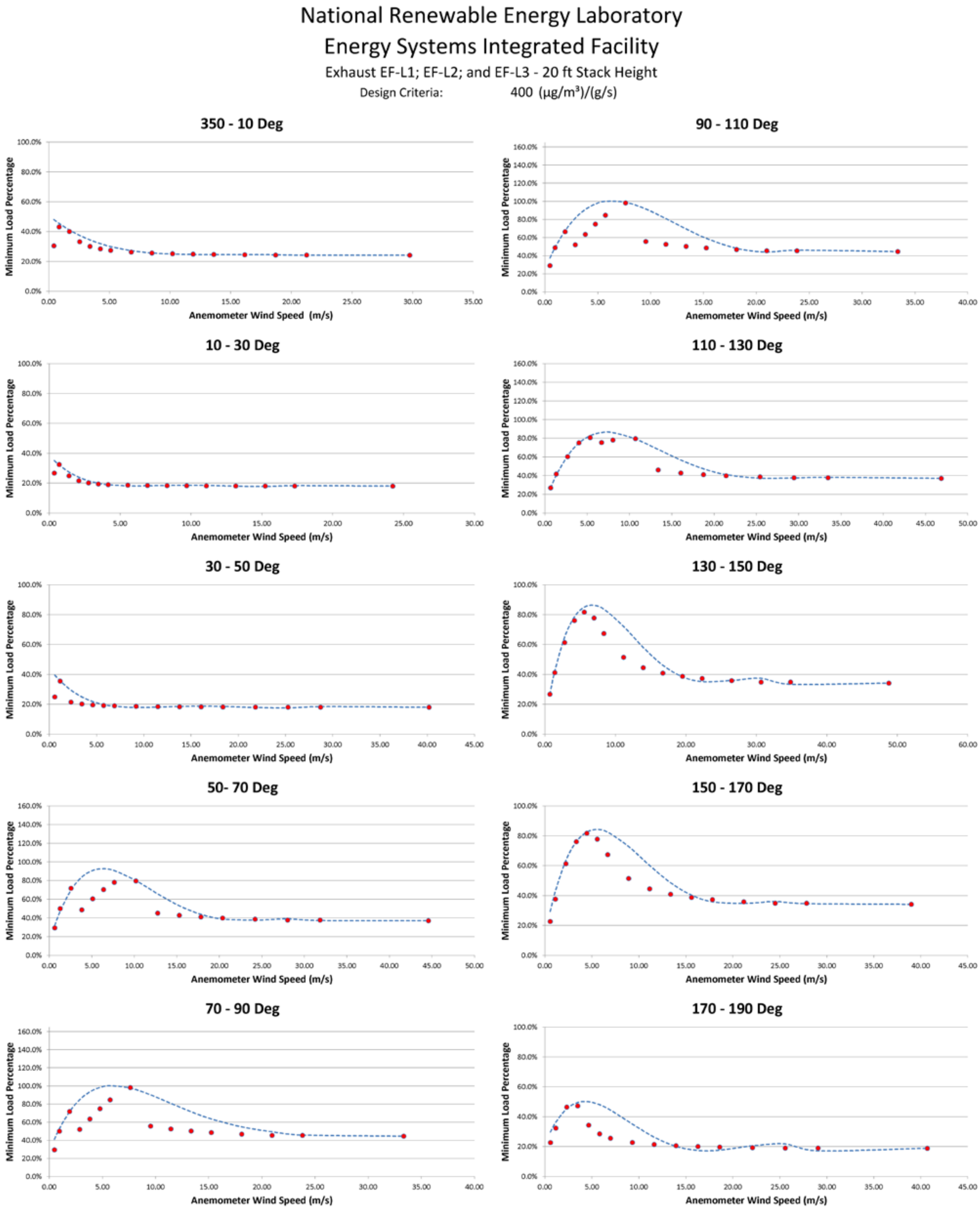


Figure 7. Plots of Minimum Flow Rate versus Wind Speed and Wind Direction: a) 20 ft tall EF-L1,2,3 (350 to 190 degrees).

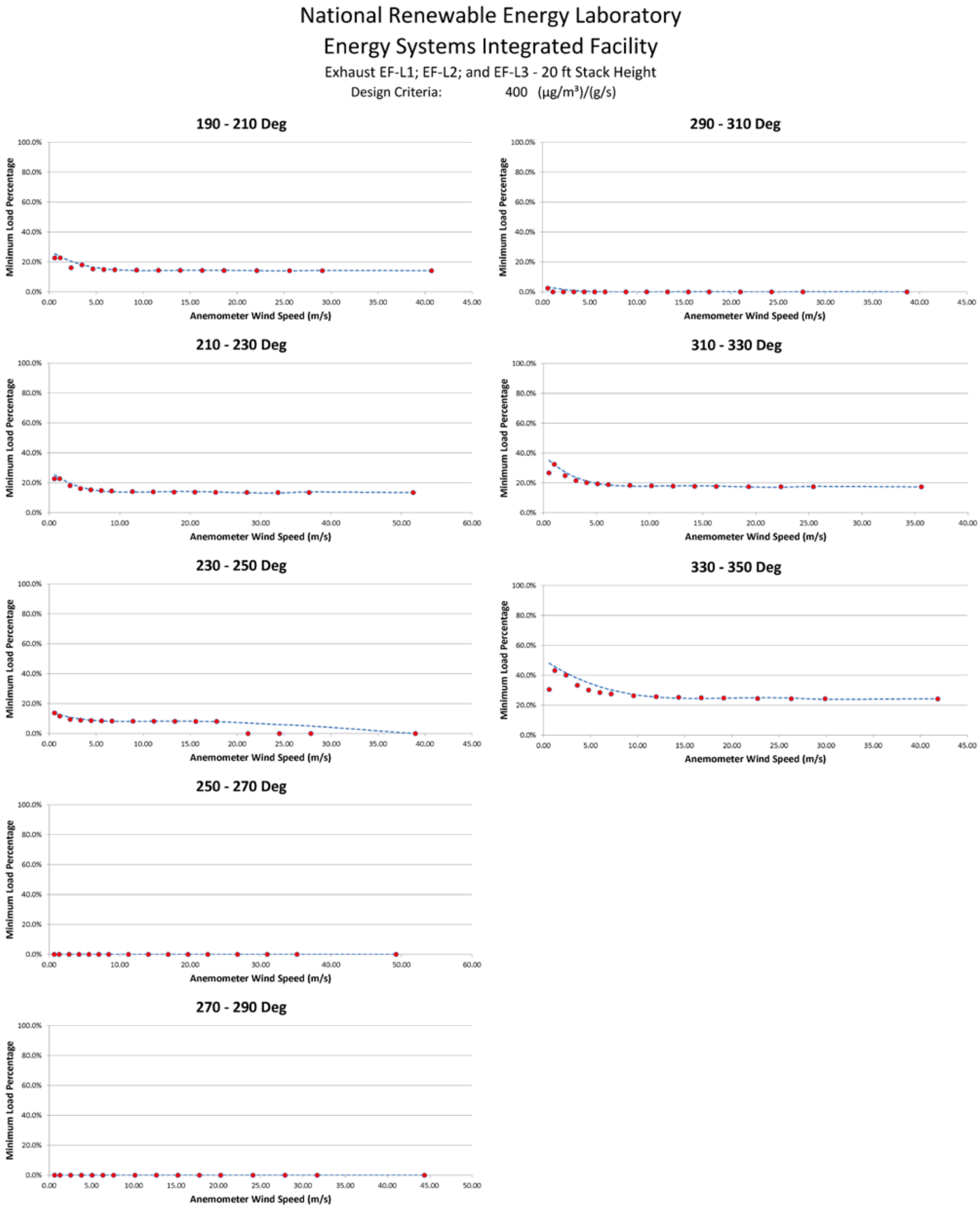


Figure 7. Plots of Minimum Flow Rate versus Wind Speed and Wind Direction: b) 20ft tall EF-L1,2,3 (190 to 350 degrees).

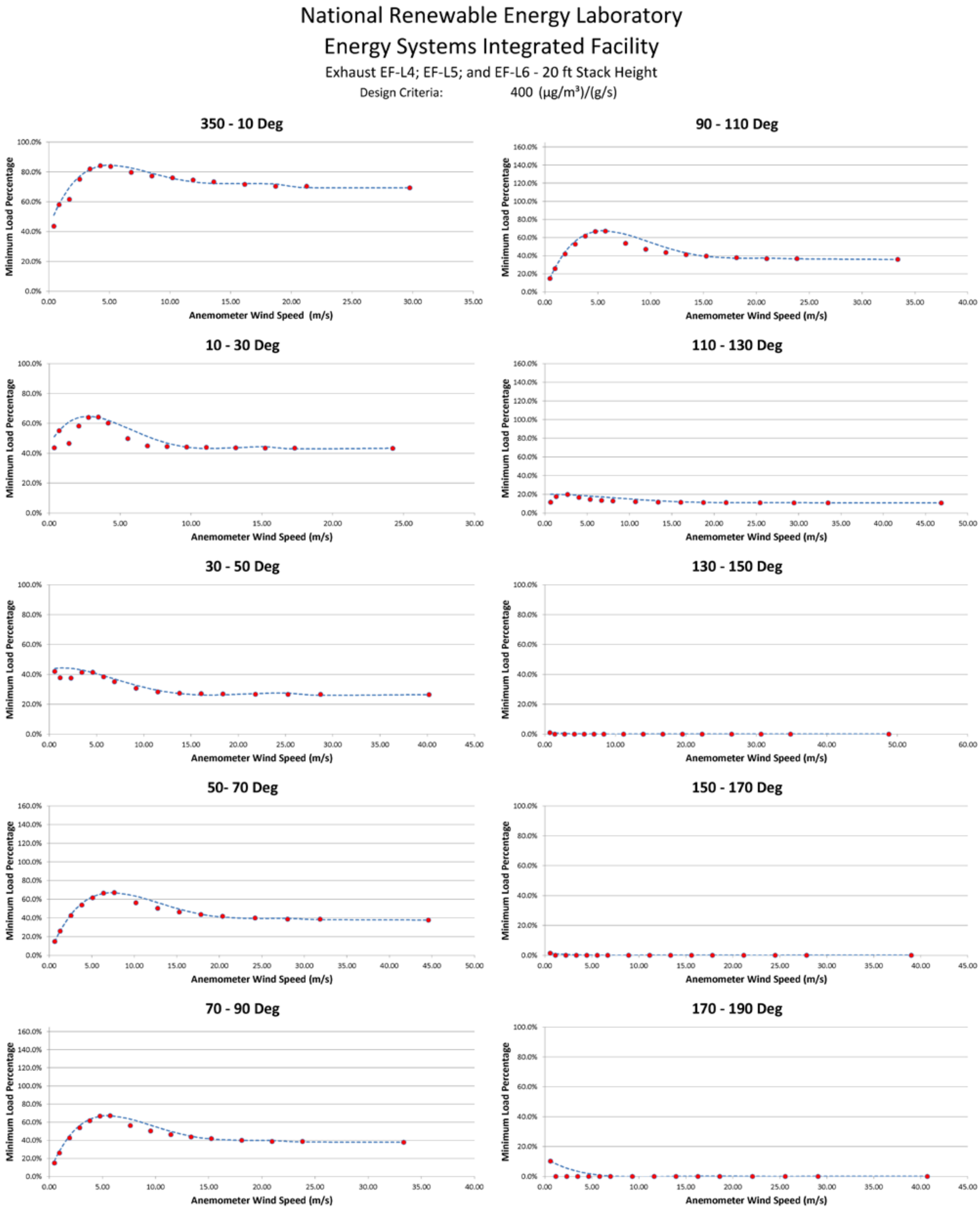


Figure 7. Plots of Minimum Flow Rate versus Wind Speed and Wind Direction: c) 20 ft tall EF-L4,5,6 (350 to 190 degrees).

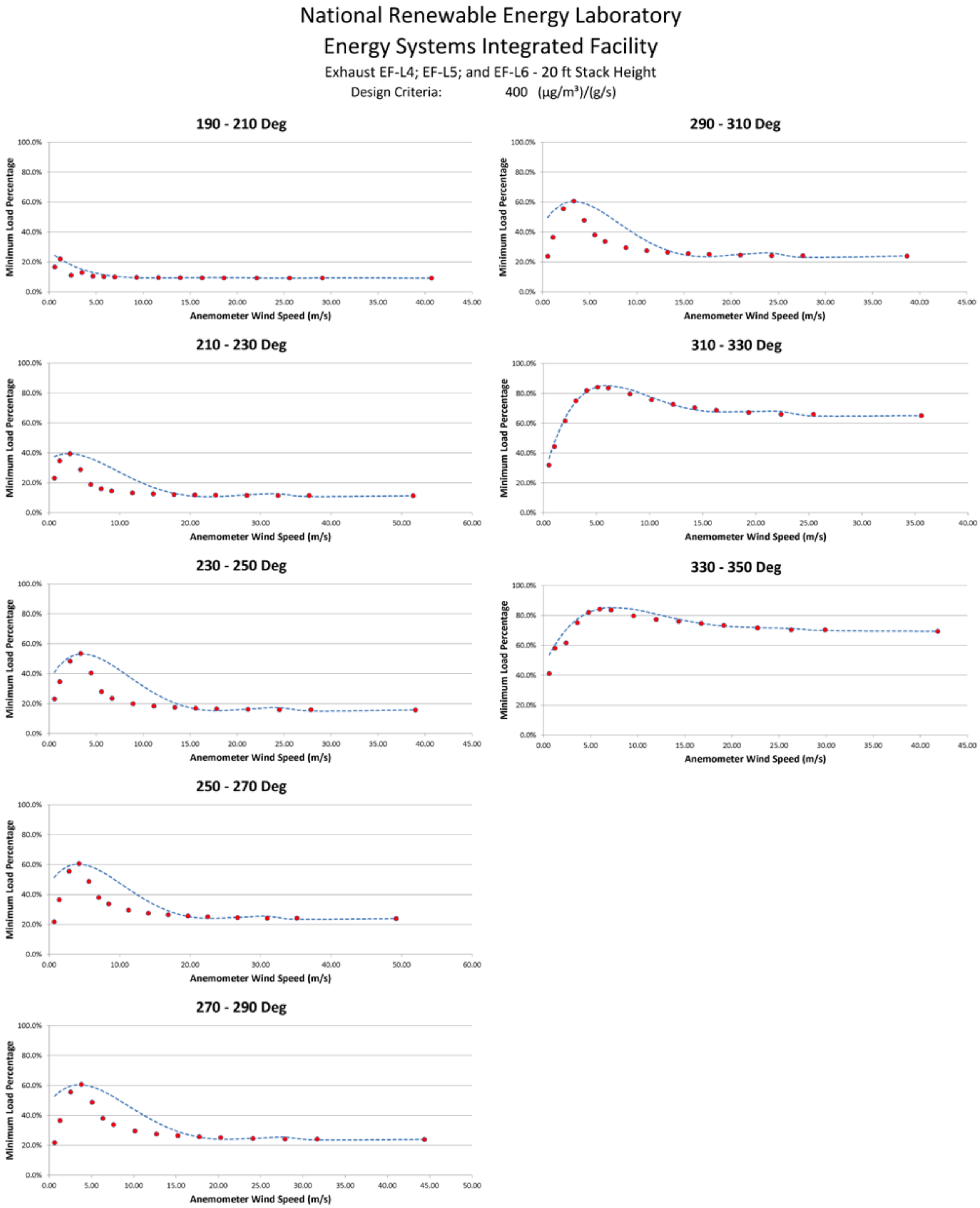


Figure 7. Plots of Minimum Flow Rate versus Wind Speed and Wind Direction: d) 20 ft tall EF-L4,5,6 (190 to 350 degrees).

TABLES

Table 1
Full-scale Exhaust and Modeling Information

Source Description	Source ID	Initial Source Height Above Base (ft)	Exit Diameter (in)	Exit Temp. (^oF)	Design Volume Flow Rate (cfm)	Design Exit Velocity (fpm)	Source Base Height Above Grade (ft)	Comment
NREL ESIF								
Level 2 General Lab Exhaust	EF-L1	20.0	28.0	70.0	13,520	3,161	78.0	Main Roof
Level 2 General Lab Exhaust	EF-L2	20.0	28.0	70.0	13,520	3,161	78.0	Main Roof
Level 2 General Lab Exhaust	EF-L3	20.0	28.0	70.0	13,520	3,161	78.0	Main Roof
Level 3 General Lab Exhaust	EF-L4	20.0	30.0	70.0	14,000	2,852	78.0	Main Roof
Level 3 General Lab Exhaust	EF-L5	20.0	30.0	70.0	14,000	2,852	78.0	Main Roof
Level 3 General Lab Exhaust	EF-L6	20.0	30.0	70.0	14,000	2,852	78.0	Main Roof
Central HEPA System Fume Hoods	EF-L7	20.0	22.0	70.0	8,320	3,153	78.0	Main Roof
Central HEPA System Fume Hoods	EF-L8	20.0	22.0	70.0	8,320	3,153	78.0	Main Roof
Central HEPA System Fume Hoods	EF-L9	20.0	22.0	70.0	8,320	3,153	78.0	Main Roof
400 hp Diesel Truck at Loading Dock	LD	10.0	6.0	300.0	200	1,019	0.0	Local Grade
900 kW Diesel Generator	DG-1	13.0	13.2	866.0	6,950	7,313	0.0	Local Grade
900 kW Diesel Generator	DG-2	13.0	13.2	866.0	6,950	7,313	0.0	Local Grade
Tailpipe Exhaust[1]	C221A	20.0	16.0	70.0	2,400	1,719	63.0	Lower Roof
Tailpipe/Generator Exhaust[1]	C328A	20.0	12.0	70.0	2,400	3,056	78.0	Main Roof
Perchloric Hood	C329	20.0	10.0	70.0	910	1,668	78.0	Main Roof
500 kW Test Diesel Generator	T-Gen-1	10.0	10.0	935.0	4,291	7,867	0.0	Local Grade
500 kW Test Diesel Generator	T-Gen-2	10.0	10.0	935.0	4,291	7,867	0.0	Local Grade
additional sources (not tested in the wind tunnel)								
H2 Vent	C339A	15.0	26.0	70.0	4,700	1,275	78.0	Main Roof
Smoke Removal Exhaust	C317A,B	15.0	22.0	70.0	7,000	2,652	78.0	Main Roof
Tailpipe/Generator Exhaust	C317C	15.0	10.0	70.0	1,200	2,200	78.0	Main Roof
H2 Vent	C341/C342	15.0	8.0	70.0	1,000	2,865	78.0	Main Roof
Scavange Exhaust	C328B	15.0	8.0	70.0	1,000	2,865	78.0	Main Roof
Tailpipe Exhaust	C325	15.0	10.0	70.0	1,200	2,200	78.0	Main Roof
Welding Hoods (future)	C215A	10.0	10.0	70.0	1,500	2,750	78.0	Main Roof
Paint Spray Booth (future)	C215B	10.0	12.0	70.0	2,000	2,546	78.0	Main Roof
(750 MBH) Boiler	BLR-1,2	10.0	12.0	932.0	1,000	1,273	78.0	Main Roof
(750 MBH) Boiler (future)	BLR-3,4	10.0	12.0	932.0	1,000	1,273	78.0	Main Roof
Delta Cooling Tower (6 cells with 2 fans each)	CT-1	15.5	67.0	67.0	35,000	1,430	63.0	Lower Roof
Delta Cooling Tower (6 cells with 2 fans each)	CT-2	15.5	67.0	67.0	35,000	1,430	63.0	Lower Roof
Delta Cooling Tower (6 cells with 2 fans each)	CT-3	15.5	67.0	67.0	35,000	1,430	63.0	Lower Roof
S&TF								
Lab Exhaust	S&TF Lab	15.0	32.0	70.0	16,500	2,954	54.0	Penthouse

1) After wind tunnel modeling was completed, the operating flows and exit velocities have been revised.

Site Parameters:

Scale Reduction:	240	
Grade Elevation (m):	1,777.7	5831 ft msl
Typical Building Height (m):	23.8	
Ambient Temperature (^oK):	294.3	Assumed Equal to Indoor Temperature
Anemometer Height (m):	10.00	NREL SRRL BMS
Anemometer Surface Roughness (m):	0.13	NREL SRRL BMS
Site Anemometer Height (m):	10.00	
Site Surface Roughness (m):	0.20	
1 Percent Wind Speed (m/s):	12.3	NREL SRRL BMS (Period of Record: 2001 to 2007)

Table 2
Receptor Descriptions

Receptor Number	Receptor Identification
1	ESIF East Sidewall (Equipment Intake)
2	ESIF West Sidewall
3	ESIF West Sidewall (Equipment Intake)
4	ESIF West Sidewall (Equipment Intake)
5	ESIF West Sidewall (Equipment Intake)
6	Data Center Sidewall (original location not used)
7	Office Window (Natural Ventilation)
8	Office Window (Natural Ventilation)
9	S&TF North
10	S&TF East
11	S&TF West
12	ESIF East Sidewall
13	Office Roof Natural Ventilation Relief
14	Office South Sidewall
15	Residential
16	ESIF North Sidewall
17	Hiking Trail
18	Test Area
19	High Roof
20	Low Roof
21	Data Center Roof (alternative location)
22	RSF Roof
23	Data Center Roof (revised location in lieu of Rec. 6)

Table 3
Summary of Normalized Concentration Design Criteria

Source Type	Design Criteria Type	Design Criteria (µg/m³) / (g/s)	Basis for Design Criteria
NREL ESIF			
Laboratory Exhaust	Health/Odor	400	ASHRAE (2007) example criterion for an accidental spill in a fume hood
Central HEPA System Fume Hoods	Health/Odor	400	ASHRAE (2007) example criterion for an accidental spill in a fume hood
400 hp Diesel Truck at Loading Dock	Health	68,429	Health limit associated with NO2 emissions
	Odor	5,293	1:2000 odor dilution threshold for diesel exhaust
900 kW Diesel Generator (one unit operating)	Health (NIOSH)	1,768	Health limit associated with NO2 emissions
	Health (OSHA)	8,838	Health limit associated with NO2 emissions
	EPA NAAQS	185	National Ambient Air Quality Standard for NO2
	Odor	152	1:2000 odor dilution threshold for diesel exhaust
	Odor (filtered)	762	1:400 odor dilution threshold for filtered diesel exhaust (80% efficient)
900 kW Diesel Generators (two units operating)	Health (NIOSH)	884	Health limit associated with NO2 emissions
	Health (OSHA)	4,419	Health limit associated with NO2 emissions
	EPA NAAQS	92	National Ambient Air Quality Standard for NO2
	Odor	76	1:2000 odor dilution threshold for diesel exhaust
	Odor (filtered)	381	1:400 odor dilution threshold for filtered diesel exhaust (80% efficient)
Tailpipe Exhaust (C221A)	Health (NIOSH)	1,702	Health limit for NO2 associated an NOx emission rate of 1.41 g/s
	Odor	441	1:2000 odor dilution threshold for diesel exhaust
Tailpipe Exhaust (C328A)	Health (NIOSH)	723	Health limit for NO2 associated an NOx emission rate of 3.32 g/s
	Odor	247	1:2000 odor dilution threshold for diesel exhaust
500 kW Test Diesel Generator	Health (NIOSH)	1,455	Health limit for NO2 associated an NOx emission rate of 1.65 g/s
	Odor	247	1:2000 odor dilution threshold for diesel exhaust
	Odor (filtered)	1,234	1:400 odor dilution threshold for filtered diesel exhaust
Perchloric Hood	Health/Odor	1,500	ANSI/AIHA Z9.5 "as installed" fume hood containment criterion
	Health/Odor	400	ASHRAE (2007) example criterion for an accidental spill in a fume hood
S&TF			
General Lab Exhaust	Health	54	Health criterion based on release of 1.5 ppm arsine
	Health/Odor	400	ASHRAE (2007) example criterion for an accidental spill in a fume hood

Note:
See Section 2 for detailed discussion.

Table 4
Test Plan, Normalized Concentration Results
and Percent Time the Design Criteria may be Exceeded For Each Source/Receptor Combination Evaluated

Run No.	Source ID	Stack Height Above Base (ft)	Receptor Identification	Wind Direction (Deg.)	Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (µg/m³)/(g/s)	(2) Design Criteria (µg/m³)/(g/s)	(3) Design Criteria Achieved?	(4) Percent Time Design Criteria May Be Exceeded
NREL ESIF									
previously tested in March 2011 and post processed with updated flow and velocity									
Level 2 General Lab Exhaust									
(13000 cfm @ 3040 fpm)							ASHRAE		
101	EF-L2	20.0*	2 - ESIF West Sidewall	115	2.9	179	400	Yes	-
102	EF-L2	20.0*	6 - Data Center Sidewall (original location no	0	2.9	90	400	Yes	-
103	EF-L2	20.0*	8 - Office Window (Natural Ventilation)	25	3.8	64	400	Yes	-
105	EF-L2	20.0*	12 - ESIF East Sidewall	210	3.6	90	400	Yes	-
106	EF-L2	20.0*	13 - Office Roof Natural Ventilation Relief	350	2.9	154	400	Yes	-
107	EF-L2	20.0*	15 - Residential	350	1.2	71	400	Yes	-
108	EF-L2	20.0*	16 - ESIF North Sidewall	105	2.9	135	400	Yes	-
222	EF-L2	20.0**	17 - Hiking Trail	200	1.5	100	400	Yes	-
223	EF-L2	20.0**	18 - Test Area	135	6.4	189	400	Yes	-
226	EF-L2	20.0**	22 - RSF Roof	15	1.2	113	400	Yes	-
231	EF-L2	20.0	20 - Low Roof	95	8.5	336	400	Yes	-
232	EF-L2	20.0	10 - S&TF East	75	3.6	240	400	Yes	-
233	EF-L2	20.0	19 - High Roof	140	6.4	250	400	Yes	-
* tested at 10 ft, results are conservative for 20 ft stack height									
** tested at 15 ft, results are conservative for 20 ft stack height									
confirmation tests							ASHRAE		
161	EF-L1	20.0*	10 - S&TF East	75	2.9	288	400	Yes	-
162	EF-L1	20.0*	19 - High Roof	135	5.0	312	400	Yes	-
163	EF-L1	20.0	20 - Low Roof	90	8.8	390	400	Yes	-
* tested at 15 ft, results are conservative for 20 ft stack height									
sensitivity tests with updated location, flow and velocity							ASHRAE		
601	EF-L3	20.0	10 - S&TF East	75	4.0	191	400	Yes	-
602	EF-L3	20.0	18 - Test Area	150	5.3	177	400	Yes	-
603	EF-L3	20.0	19 - High Roof	150	5.3	281	400	Yes	-
604	EF-L3	20.0	20 - Low Roof	90	9.3	249	400	Yes	-
previously tested in March 2011 and post processed with updated flow and velocity									
Level 3 General Lab Exhaust									
(14000 cfm @ 2852 fpm)							ASHRAE		
201	EF-L6	20.0	1 - ESIF East Sidewall (Equipment Intake)	215	8.3	54	400	Yes	-
202	EF-L6	20.0	2 - ESIF West Sidewall	20	3.5	147	400	Yes	-
203	EF-L6	20.0	3 - ESIF West Sidewall (Equipment Intake)	340	1.4	121	400	Yes	-
204	EF-L6	20.0	8 - Office Window (Natural Ventilation)	340	1.4	55	400	Yes	-
205	EF-L6	20.0	10 - S&TF East	15	1.4	170	400	Yes	-
206	EF-L6	20.0	12 - ESIF East Sidewall	280	4.6	237	400	Yes	-
207	EF-L6	20.0	13 - Office Roof Natural Ventilation Relief	340	1.9	107	400	Yes	-
208	EF-L6	20.0	15 - Residential	350	1.1	83	400	Yes	-
209	EF-L6	20.0	16 - ESIF North Sidewall	80	8.3	268	400	Yes	-
210	EF-L6	20.0	17 - Hiking Trail	230	3.5	147	400	Yes	-
211	EF-L6	20.0	18 - Test Area	340	6.2	299	400	Yes	-
212	EF-L6	20.0	19 - High Roof	340	6.2	223	400	Yes	-
213	EF-L6	20.0	20 - Low Roof	335	3.5	227	400	Yes	-
confirmation tests							ASHRAE		
261	EF-L5	20.0	12 - ESIF East Sidewall	280	4.6	223	400	Yes	-
262	EF-L5	20.0	16 - ESIF North Sidewall	75	8.3	252	400	Yes	-
263	EF-L5	20.0	18 - Test Area	355	1.9	215	400	Yes	-

Table 4
Test Plan, Normalized Concentration Results
and Percent Time the Design Criteria may be Exceeded For Each Source/Receptor Combination Evaluated

Run No.	Source ID	Stack Height Above Base (ft)	Receptor Identification	Wind Direction (Deg.)	Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (µg/m³)/(g/s)	(2) Design Criteria (µg/m³)/(g/s)		(3) Design Criteria Achieved?		(4) Percent Time Design Criteria May Be Exceeded	
sensitivity tests with updated location, flow and velocity							ASHRAE					
611	EF-L4	20.0	12 - ESIF East Sidewall	275	5.3	219	400		Yes		-	
612	EF-L4	20.0	16 - ESIF North Sidewall	75	9.3	192	400		Yes		-	
613	EF-L4	20.0	18 - Test Area	345	7.0	260	400		Yes		-	
614	EF-L4	20.0	19 - High Roof	0	7.0	259	400		Yes		-	
Central HEPA System Fume Hoods												
tested at 8000 cfm/3031 fpm and post processed for 8320 cfm/3153 fpm												
(8320 cfm @ 3153 fpm)							ASHRAE					
501	EF-L8	20.0	2 - ESIF West Sidewall	70	5.3	197	400		Yes		-	
502	EF-L8	20.0	8 - Office Window (Natural Ventilation)	345	1.0	98	400		Yes		-	
503	EF-L8	20.0	10 - S&TF East	40	1.7	266	400		Yes		-	
504	EF-L8	20.0	12 - ESIF East Sidewall	220	3.1	128	400		Yes		-	
505	EF-L8	20.0	13 - Office Roof Natural Ventilation Relief	345	1.0	205	400		Yes		-	
506	EF-L8	20.0	15 - Residential	350	1.0	97	400		Yes		-	
507	EF-L8	20.0	16 - ESIF North Sidewall	85	4.0	72	400		Yes		-	
508	EF-L8	20.0	17 - Hiking Trail	220	1.3	187	400		Yes		-	
509	EF-L8	20.0	18 - Test Area	15	4.0	350	400		Yes		-	
510	EF-L8	20.0	19 - High Roof	80	16.2	285	400		Yes		-	
511	EF-L8	20.0	20 - Low Roof	345	4.0	248	400		Yes		-	
512	EF-L8	20.0	22 - RSF Roof	5	1.0	179	400		Yes		-	
513	EF-L8	20.0	23 - Data Center Roof (revised location in lieu	345	1.0	250	400		Yes		-	
confirmation tests							ASHRAE					
521	EF-L7	20.0	10 - S&TF East	40	3.1	266	400		Yes		-	
522	EF-L7	20.0	18 - Test Area	15	5.3	400	400		Yes		-	
523	EF-L7	20.0	19 - High Roof	65	21.4	302	400		Yes		-	
confirmation tests							ASHRAE					
541	EF-L9	20.0	10 - S&TF East	40	2.3	343	400		Yes		-	
542	EF-L9	20.0	18 - Test Area	5	5.3	297	400		Yes		-	
543	EF-L9	20.0	19 - High Roof	85	7.0	310	400		Yes		-	
Perchloric Hood								ASHRAE				
(670 cfm @ 1919 fpm)							'as installed'	(future conversion)				
302	C329	20.0*	12 - ESIF East Sidewall	230	1.3	552	1,500	400	Yes	No	-	0.98%
303	C329	20.0*	16 - ESIF North Sidewall	90	1.0	360	1,500	400	Yes	Yes	-	-
305	C329	20.0	2 - ESIF West Sidewall	70	1.7	995	1,500	400	Yes	No	-	4.19%
306	C329	20.0	18 - Test Area	335	5.3	993	1,500	400	Yes	No	-	4.68%
* tested at 15 ft, results are conservative for 20 ft stack height												
Tailpipe Exhaust1												
After wind tunnel modeling was completed, the operating flows and exit velocities have been revised. Results are displayed for reference only.							Health					
(2400 cfm @ 1719 fpm)							(NIOSH)	Odor				
311	C221A	20.0	4 - ESIF West Sidewall (Equipment Intake)	55	1.7	895	1,702	441	Yes	No	-	7.58%
322	C221Aest*	20.0*	18 - Test Area	200	7.0	1,695	1,702	441	Yes	No	-	less than 2.5%
* C221A was not tested at Receptor 18 (Test Area). The maximum impact was estimated based on testing at a different stack location and stack height. The results are likely conservative.												
Tailpipe/Generator Exhaust1												
After wind tunnel modeling was completed, the operating flows and exit velocities have been revised. Results are displayed for reference only.							Health					
(2400 cfm @ 3056 fpm)							(NIOSH)	Odor				
332	C328A	20.0*	3 - ESIF West Sidewall (Equipment Intake)	75	2.3	410	723	441	Yes	Yes	-	-
333	C328A	20.0*	16 - ESIF North Sidewall	165	2.3	287	723	441	Yes	Yes	-	-
335	C328A	20.0	2 - ESIF West Sidewall	105	4.0	266	723	441	Yes	Yes	-	-
336	C328A	20.0	18 - Test Area	270	9.3	722	723	441	Yes	No	-	3.98%
* tested at 15 ft, results are conservative for 20 ft stack height												

Table 4
Test Plan, Normalized Concentration Results
and Percent Time the Design Criteria may be Exceeded For Each Source/Receptor Combination Evaluated

Run No.	Source ID	Stack Height Above Base (ft)	Receptor Identification	Wind Direction (Deg.)	Wind Speed (m/s)	(1) Max Normalized WT-Measured Concentration (µg/m³)/(g/s)	(2) Design Criteria (µg/m³)/(g/s)			(3) Design Criteria Achieved?			(4) Percent Time Design Criteria May Be Exceeded		
900 kW Diesel Generator															
(6950 cfm @ 7313 fpm)							Health		Odor						
single unit operating							(NIOSH)	Odor	(filtered)						
341	DG-1	13.0	5 - ESIF West Sidewall (Equipment Intake)	180	3.1	1,230	1,768	152	762	Yes	No	No	-	19.41%	1.24%
342	DG-1	13.0	6 - Data Center Sidewall (original location no	310	5.3	774	1,768	152	762	Yes	No	No	-	31.92%	0.58%
343	DG-1	13.0	7 - Office Window (Natural Ventilation)	295	3.1	229	1,768	152	762	Yes	No	Yes	-	13.85%	-
344	DG-1	13.0	10 - S&TF East	115	1.0	1,058	1,768	152	762	Yes	No	No	-	7.60%	0.84%
342	DG-1	13.0	6 - Data Center Sidewall (original location no	310	5.3	774	1,768	152	381	Yes	No	No	-	31.92%	17.17%
							EPA NAAQS (5)	Odor	Odor (filtered)						
346	DG-1	13.0	15 - Residential	350	1.3	181	185	152	762	Yes	No	Yes	-	2.35%	-
							Health		Odor						
two units operating (future operating scenario, occurs only withloss of power)							(NIOSH)	Odor	(filtered)						
341	DG-1	13.0	5* - ESIF West Sidewall (Equipment Intake)	180	3.1	1,230	884	76	381	No	No	No	0.87%	38.28%	9.05%
342	DG-1	13.0	6* - Data Center Sidewall	310	5.3	774	884	76	381	Yes	No	No	-	38.97%	17.17%
343	DG-1	13.0	7 - Office Window (Natural Ventilation)	295	3.1	229	884	76	381	Yes	No	Yes	-	21.89%	-
344	DG-1	13.0	10 - S&TF East	115	1.0	1,058	884	76	381	No	No	No	0.45%	10.51%	2.76%
* The ESIF West Sidewall and the Data Center intakes will not be operating during loss of power at the site.															
							EPA NAAQS (5)	Odor	Odor (filtered)						
346	DG-1	13.0	15 - Residential	350	1.3	181	92	76	381	No	No	Yes	7.22%	9.60%	-
500 kW Test Diesel Generator							Health								
(4291 cfm @ 7867 fpm)							(NIOSH)	Odor							
381	T-Gen-1	10.0	2 - ESIF West Sidewall	185	2.3	891	1,455	247		Yes	No		-	2.53%	
382	T-Gen-1	10.0	3 - ESIF West Sidewall (Equipment Intake)	240	2.3	1,260	1,455	247		Yes	No		-	7.77%	
383	T-Gen-1	10.0	10 - S&TF East	15	1.3	1,153	1,455	247		Yes	No		-	9.03%	
500 kW Test Diesel Generator							Health								
(4291 cfm @ 7867 fpm)							(NIOSH)	Odor							
401	T-Gen-2	10.0	4 - ESIF West Sidewall (Equipment Intake)	50	4.0	1,373	1,455	247		Yes	No		-	20.16%	
402	T-Gen-2	10.0	10 - S&TF East	70	1.0	1,450	1,455	247		Yes	No		-	5.68%	
S&TF															
Lab Exhaust							Health								
(16500 cfm @ 2954 fpm)							(Arsine)	ASHRAE							
421	S&TF Lab	15.0	2 - ESIF West Sidewall	195	3.1	245	54	400		No	Yes		2.37%	-	

Notes:

1) The maximum normalized concentration (C/m) measured in the wind tunnel for the specific source/receptor pair.
2) The maximum acceptable C/m for each specific source, based on criteria discussed in Section 2.
3) "Yes" if (1) < (2) or "No" if (1) > (2).
4) Percentage of time for which the prescribed emission scenario may produce concentrations greater than (2), based on a curve fit to all data collected for the specific source/receptor pair and the local wind frequency distribution.
5) US EPA National Ambient Air Quality Standard for NO_2. No statistical analysis for the 99th percentile was conducted. The results are therefore conservative.

Table 5a
Minimum Fan Load Percentages vs. Wind Speed and Wind Direction

National Renewable Energy Laboratory
Energy Systems Integrated Facility

Exhaust EF-L1; EF-L2; and EF-L3 - 20 ft Stack Height

Full Load Volume Flow Rate: 13,520 cfm
Design Criteria: 400 (μg/m³)/(g/s) Exit Velocity: 3,161 fpm

Wind Direction		Anemometer Wind Speed*														
Min	Max	< 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
350	10	54%	45%	40%	36%	33%	30%	28%	27%	26%	25%	25%	25%	25%	25%	25%
10	30	54%	30%	24%	21%	19%	18%	18%	18%	18%	19%	19%	18%	18%	18%	18%
30	50	54%	37%	31%	26%	23%	21%	20%	19%	18%	18%	18%	18%	18%	18%	19%
50	70	54%	41%	61%	76%	85%	91%	93%	92%	90%	86%	81%	76%	70%	64%	59%
70	90	54%	54%	73%	86%	95%	99%	100%	99%	96%	93%	88%	83%	78%	73%	69%
90	110	54%	50%	69%	83%	92%	98%	100%	100%	98%	94%	89%	84%	78%	72%	66%
110	130	54%	34%	52%	65%	75%	81%	85%	86%	86%	84%	82%	78%	74%	70%	65%
130	150	54%	34%	53%	68%	77%	83%	86%	86%	85%	82%	78%	73%	68%	63%	58%
150	170	54%	41%	60%	73%	81%	84%	84%	81%	77%	72%	67%	61%	55%	50%	46%
170	190	54%	35%	43%	48%	50%	50%	48%	44%	40%	36%	32%	28%	25%	22%	20%
190	210	54%	24%	21%	19%	17%	16%	15%	15%	14%	14%	14%	14%	14%	14%	14%
210	230	54%	25%	22%	20%	18%	16%	15%	15%	14%	14%	14%	14%	14%	14%	14%
230	250	54%	13%	11%	10%	9%	9%	8%	8%	8%	8%	8%	8%	8%	8%	8%
250	270	54%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
270	290	54%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
290	310	54%	3%	2%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
310	330	54%	32%	27%	24%	21%	20%	19%	18%	18%	18%	18%	18%	18%	18%	18%
330	350	54%	47%	43%	40%	37%	34%	32%	31%	29%	28%	27%	26%	25%	25%	25%

*U = Local anemometer wind speed

Table 5b
Minimum Fan Load Percentages vs. Wind Speed and Wind Direction

National Renewable Energy Laboratory
Energy Systems Integrated Facility

Exhaust EF-L4; EF-L5; and EF-L6 - 20 ft Stack Height

Full Load Volume Flow Rate: 14,000 cfm
Design Criteria: 400 (μg/m³)/(g/s) Exit Velocity: 2,852 fpm

Wind Direction		Anemometer Wind Speed*														
Min	Max	< 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
350	10	61%	61%	73%	80%	83%	84%	84%	82%	80%	78%	76%	74%	73%	73%	72%
10	30	61%	58%	64%	65%	63%	59%	55%	51%	48%	45%	44%	43%	43%	44%	44%
30	50	61%	44%	44%	43%	42%	41%	39%	37%	35%	33%	31%	30%	29%	28%	27%
50	70	61%	21%	37%	49%	57%	62%	66%	67%	67%	66%	64%	61%	59%	56%	53%
70	90	61%	29%	46%	58%	64%	67%	67%	65%	62%	59%	55%	51%	48%	45%	43%
90	110	61%	28%	46%	57%	64%	67%	67%	65%	62%	59%	55%	51%	47%	44%	41%
110	130	61%	20%	20%	19%	19%	18%	18%	17%	16%	16%	15%	14%	14%	13%	13%
130	150	61%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
150	170	61%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
170	190	61%	9%	6%	4%	3%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
190	210	61%	23%	19%	16%	14%	12%	11%	10%	10%	10%	9%	9%	9%	9%	9%
210	230	61%	38%	39%	40%	39%	38%	36%	34%	32%	29%	27%	25%	22%	20%	18%
230	250	61%	45%	50%	53%	53%	51%	48%	44%	40%	36%	32%	28%	24%	21%	19%
250	270	61%	53%	57%	60%	60%	60%	59%	56%	54%	51%	48%	44%	41%	38%	36%
270	290	61%	55%	59%	60%	60%	59%	57%	54%	51%	48%	44%	41%	37%	34%	32%
290	310	61%	53%	58%	60%	60%	58%	55%	51%	46%	42%	38%	34%	31%	28%	26%
310	330	61%	47%	63%	74%	81%	84%	85%	85%	83%	81%	78%	75%	73%	71%	69%
330	350	61%	58%	67%	74%	79%	83%	84%	85%	85%	85%	84%	82%	81%	79%	78%

*U = Local anemometer wind speed

Table 6a
Load Percentage Coefficients for Specific Wind Speeds and Wind Directions

National Renewable Energy Laboratory

Energy Systems Integrated Facility

Exhaust EF-L1; EF-L2; and EF-L3 - 20 ft Stack Height

Full Load Volume Flow Rate: 13,520 cfm

Design Criteria: 400 (μg/m³)/(g/s) Exit Velocity: 3,161 fpm

Wind Direction		Load Percentage Coefficients $aU^5+bU^4+cU^3+dU^2+eU+f$ *					
Min	Max	a	b	c	d	e	f
350	10	-4.46E-08	6.10E-06	-2.95E-04	6.52E-03	-6.71E-02	5.09E-01
10	30	-1.08E-06	7.13E-05	-1.75E-03	1.99E-02	-1.04E-01	3.85E-01
30	50	-1.25E-07	1.35E-05	-5.40E-04	9.96E-03	-8.40E-02	4.41E-01
50	70	3.72E-07	-4.58E-05	2.07E-03	-4.10E-02	3.12E-01	1.38E-01
70	90	6.20E-07	-6.32E-05	2.45E-03	-4.34E-02	3.06E-01	2.75E-01
90	110	9.90E-08	-2.48E-05	1.51E-03	-3.50E-02	2.87E-01	2.46E-01
110	130	1.85E-07	-2.55E-05	1.30E-03	-2.93E-02	2.58E-01	1.10E-01
130	150	2.79E-07	-3.66E-05	1.74E-03	-3.64E-02	2.93E-01	8.09E-02
150	170	6.50E-07	-7.01E-05	2.77E-03	-4.81E-02	3.21E-01	1.30E-01
170	190	4.86E-07	-5.04E-05	1.87E-03	-2.93E-02	1.62E-01	2.13E-01
190	210	-5.09E-08	5.66E-06	-2.35E-04	4.52E-03	-4.04E-02	2.77E-01
210	230	-2.38E-08	3.23E-06	-1.61E-04	3.65E-03	-3.77E-02	2.80E-01
230	250	-4.07E-08	4.36E-06	-1.73E-04	3.05E-03	-2.39E-02	1.49E-01
250	270	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
270	290	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
290	310	-1.97E-08	2.12E-06	-8.51E-05	1.58E-03	-1.33E-02	3.94E-02
310	330	-1.71E-07	1.64E-05	-5.85E-04	9.63E-03	-7.35E-02	3.87E-01
330	350	1.41E-08	-6.33E-07	-3.15E-05	2.26E-03	-4.28E-02	5.06E-01

*U = Local anemometer wind speed

Table 6b
Load Percentage Coefficients for Specific Wind Speeds and Wind Directions

National Renewable Energy Laboratory

Energy Systems Integrated Facility

Exhaust EF-L4; EF-L5; and EF-L6 - 20 ft Stack Height

		Full Load Volume Flow Rate:	14,000	cfm
Design Criteria:	400 (µg/m³)/(g/s)	Exit Velocity:	2,852	fpm

Wind Direction		Load Percentage Coefficients $aU^5+bU^4+cU^3+dU^2+eU+f$ *					
Min	Max	a	b	c	d	e	f
350	10	1.24E-06	-9.94E-05	2.93E-03	-3.90E-02	2.17E-01	4.26E-01
10	30	3.18E-06	-2.04E-04	4.71E-03	-4.66E-02	1.65E-01	4.59E-01
30	50	1.36E-07	-1.35E-05	4.61E-04	-6.10E-03	1.51E-02	4.33E-01
50	70	2.24E-07	-2.80E-05	1.29E-03	-2.69E-02	2.27E-01	1.31E-02
70	90	9.31E-07	-8.68E-05	3.00E-03	-4.64E-02	2.93E-01	4.21E-02
90	110	8.87E-07	-8.44E-05	2.98E-03	-4.71E-02	3.01E-01	1.90E-02
110	130	1.64E-08	-1.96E-06	8.10E-05	-1.25E-03	1.23E-03	2.00E-01
130	150	-3.87E-09	4.92E-07	-2.29E-05	4.79E-04	-4.40E-03	1.36E-02
150	170	-1.64E-08	1.66E-06	-6.10E-05	1.01E-03	-7.27E-03	1.76E-02
170	190	-4.20E-08	4.79E-06	-2.05E-04	4.07E-03	-3.72E-02	1.22E-01
190	210	-5.10E-08	5.88E-06	-2.55E-04	5.21E-03	-4.97E-02	2.71E-01
210	230	6.54E-08	-8.50E-06	3.87E-04	-6.99E-03	3.05E-02	3.57E-01
230	250	4.36E-07	-4.42E-05	1.60E-03	-2.43E-02	1.19E-01	3.52E-01
250	270	1.16E-07	-1.48E-05	6.76E-04	-1.28E-02	7.52E-02	4.68E-01
270	290	1.83E-07	-2.12E-05	8.74E-04	-1.49E-02	7.65E-02	4.85E-01
290	310	4.64E-07	-4.61E-05	1.63E-03	-2.39E-02	1.11E-01	4.44E-01
310	330	7.39E-07	-7.10E-05	2.51E-03	-4.00E-02	2.66E-01	2.40E-01
330	350	1.67E-07	-1.95E-05	8.49E-04	-1.67E-02	1.38E-01	4.59E-01

*U = Local anemometer wind speed

Table 7
Normalized Health Limits and Odor Thresholds
Listed in Order of Toxicity and Volatility

		1 min Lecture Bottle Release / 1 Liter Spill Health Limit (μg/m^3)/(g/s)		Odor Threshold (μg/m^3)/(g/s)		Limiting Value Per 1 Liter Spill or 1 min Release	Max Volume (mL) for Liquid Max Release Rate (g/s) for Gas					
							ASHRAE		"as mfg"		"as inst"	
Substance	**CAS#**	**Gas**	**Liquid**	**Gas**	**Liquid**	**(μg/m^3)/(g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**
Arsine	7784-42-1	0.3		3888.4		0.3	-	0.005	-	0.003	-	0.001
Methyl mercaptan	74-93-1	264.3		0.3		0.3	-	0.003	-	0.001	-	0.001
Ethyl mercaptan	75-08-1		437.2		0.3	0.3	0.7	-	0.4	-	0.2	-
Ethyl acrylate	140-88-5		193981.8		3.1	3.1	7.8	-	4.2	-	2.1	-
Hydrogen sulfide	7783-06-4	3964.8		3.5		3.5	-	0.03	-	0.02	-	0.01
Nickel carbonyl (as Ni)	13463-39-3		3.6		360.5	3.6	9.0	-	4.8	-	2.4	-
Perchloromethyl mercaptan	594-42-3		1741.8		5.7	5.7	14	-	7.6	-	3.8	-
Sulfur pentafluoride	5714-22-7		6.5			6.5	16	-	8.6	-	4.3	-
Chromyl chloride	14977-61-8		6.9			6.9	17	-	9.2	-	4.6	-
Chlorine trifluoride	7790-91-2	10.0				10.0	-	1.0	-	0.5	-	0.3
Butyl mercaptan	109-79-5		5263.3		10.8	10.8	27	-	14	-	7.2	-
Osmium tetroxide	20816-12-0		15.5			15.5	39	-	21	-	10	-
Picric acid	88-89-1				20.1	20.1	50	-	27	-	13	-
Pentaborane	19624-22-7		21.9		1828.7	21.9	55	-	29	-	15	-
Chlorine	7782-50-5	191.6		30.6		30.6	-	0.6	-	0.3	-	0.2
Acetaldehyde	75-07-0	3737845.4	12758.3	10017.4	34.1	34.1	85	0.001	46	0.001	23	0.0003
Hydrogen selenide	7783-07-5	126.9		36.6		36.6	-	0.3	-	0.2	-	0.1
Chloromethyl ether(bis-)	542-88-1		37.7			37.7	94	-	50	-	25	-
Hydrogen fluoride	7664-39-3	607.9	1396.8		40.5	40.5	101	0.4	54	0.2	27	0.1
Isopropyl ether	108-20-3		986753.6		53.8	53.8	135	-	72	-	36	-
Methyl isocyanate	624-83-9		65.5			65.5	164	-	87	-	44	-
Diethylamine	109-89-7		29597.6		104.0	104.0	260	-	139	-	69	-
Phosgene	75-44-5	105.7		373.8		105.7	-	2.0	-	1.1	-	0.5
Amyl acetate(sec-)	626-38-0		19750987.8		108.4	108.4	271	-	145	-	72	-
Tungsten hexafluoride	7783-82-6	132.2	409.0			132.2	1,022	25.0	545	13.3	273	6.7
Dimethylhydrazine(1,1-)	57-14-7		146.8		22079.3	146.8	367	-	196	-	98	-
Isopropylamine	75-31-0		8149.5		172.0	172.0	430	-	229	-	115	-
Cresol (all isomers)	1319-77-3		2559512.3		226.1	226.1	565	-	301	-	151	-
Diborane	19287-45-7	240.3		2265.5		240.3	-	0.8	-	0.4	-	0.2
Phosphine	7803-51-2	264.3		685.7		264.3	-	2.5	-	1.3	-	0.7
Nitrogen dioxide	10102-44-0	297.5		739.2		297.5	-	4.5	-	2.4	-	1.2
Ethylamine	75-04-7	16560.0		298.2		298.2	-	1.2	-	0.7	-	0.3
Carbon disulfide	75-15-0		12253.0		306.0	306.0	765	-	408	-	204	-
Methyl hydrazine	60-34-4		320.4		12139.2	320.4	801	-	427	-	214	-
Bromine pentafluoride	7789-30-2		335.7			335.7	839	-	448	-	224	-
Tetramethyl lead (as Pb)	75-74-1		337.8			337.8	845	-	451	-	225	-
Butadiene	106-99-0	4652.0		350.2		350.2	-	2.5	-	1.3	-	0.7
Butylamine	109-73-9		23069.0		367.6	367.6	919	-	490	-	245	-
ASHRAE Criterion 400 (μg/m^3)/(g/s)												
Bromine	7726-95-6		436.6		953.5	436.6			582	-	291	-
Dimethylamine	124-40-3	9118.9		479.8		479.8			-	1.9	-	1.0
Ethyl ether	60-29-7		430364.0		487.9	487.9			651	-	325	-
Acrolein	107-02-8		540.7		3229.6	540.7			721	-	360	-
Morpholine	110-91-8		1854740.4		690.8	690.8			921	-	461	-
Diisopropylamine	108-18-9		78187.2		699.7	699.7			933	-	467	-
Tetranitromethane	509-14-8		706.5			706.5			942	-	471	-
Mesityl oxide	141-79-7		1044501.9		711.7	711.7			949	-	475	-
ANSI/AIHA Z9.5 "as manufactured" Criterion 750 (μg/m^3)/(g/s)												
Fluorine	7782-41-4	819.4		1585.9		819.4					-	2.1
Hydrogen bromide	10035-10-6	1308.4	53793.6	881.1	36224.8	881.1					24,150	4.4
Sulfur dioxide	7446-09-5	1718.1		933.6		933.6					-	4.7
Nitric oxide	10102-43-9	129285.6		944.2		944.2					-	0.4
Boron trifluoride	7637-07-2	986.8		1585.9		986.8					-	1.9
Germane tetrahydride	7785-65-2	1080.0				1,080.0					-	1.2
Hydrazine	302-01-2		1153.9		139411.6	1,153.9					769	-
Methyl methracrylate	80-62-6		2835791.4		1232.5	1,232.5					822	-
Ethylene oxide	75-21-8	1321.6		199823.8		1,321.6					-	3.3
Dibromo-3-chloropropane(1,2-)	96-12-8		1420.4		8158.6	1,420.4					947	-
ANSI/AIHA Z9.5 "as installed" Criterion 1500 (μg/m^3)/(g/s)												
Propyl acetate(n-)	109-60-4		2348473.6		1695.5	1,695.5						
Triethylamine	121-44-8		34967.1		1744.4	1,744.4						
Tributyl phosphate	126-73-8		1801.5			1,801.5						
Xylidine	1300-73-8		571244.3		1828.0	1,828.0						
Hydrogen chloride	7647-01-0	1850.2	4440.7		11749.0	1,850.2						
Phosphorus trichloride	7719-12-2		1881.2			1,881.2						
Iron carbonyl	13463-40-6		1883.9			1,883.9						
Fluroxene	406-90-6		1985.8			1,985.8						
Chloroprene(beta-)	126-99-8		1997.4			1,997.4						
Methylamine	74-89-5	6696.0		2102.6		2,102.6						
Cumene	98-82-8		11289536.2		2411.4	2,411.4						
Dichloropropane (-1,2)	78-87-5		1037501.0		2449.1	2,449.1						
Allyl chloride	107-05-1		2454.3		4206.5	2,454.3						
Methyl (n-amyl) ketone	110-43-0		18834454.7		2532.8	2,532.8						
Acetic acid	64-19-7		516651.6		2534.8	2,534.8						
Halothane	151-67-7		2635.8			2,635.8						
Enflurane	13838-16-9		3293.8			3,293.8						
Chloroacetaldehyde	107-20-0		3527.9		3527.9	3,527.9						
Ethylenimine	151-56-4		3534.0		5354.6	3,534.0						
Nitrogen trifluoride	7783-54-2	3832.6				3,832.6						
Amyl acetate(n-)	628-63-7		22333809.3		3918.6	3,918.6						
Thionyl chloride	7719-09-7		3959.5			3,959.5						

Table 7
Normalized Health Limits and Odor Thresholds
Listed in Order of Toxicity and Volatility

		1 min Lecture Bottle Release / 1 Liter Spill				Limiting Value	Max Volume (mL) for Liquid Max Release Rate (g/s) for Gas					
		Health Limit (µg/m³)/(g/s)		Odor Threshold (µg/m³)/(g/s)		Per 1 Liter Spill or 1 min Release	ASHRAE		"as mfg"		"as inst"	
Substance	**CAS#**	**Gas**	**Liquid**	**Gas**	**Liquid**	**(µg/m³)/(g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**
Ethylene dibromide	106-93-4		4094.1		314424.5	4,094.1						
Nitric acid	7697-37-2		30526.8		4180.1	4,180.1						
Chloroform	67-66-3		4725.8		452145.7	4,725.8						
Methyl iodide	74-88-4		4879.1			4,879.1						
Benzene	71-43-2		5043.1		306454.3	5,043.1						
Ethylmorpholine(n-)	100-74-3		921528.1		5337.8	5,337.8						
Methyl chloride	74-87-3	54713.7		5550.7		5,550.7						
Chloropicrin	76-06-2		5643.2		18204.3	5,643.2						
Phosphorus oxychloride	10025-87-3		6249.0			6,249.0						
Methyl bromide	74-83-9	7048.5		49840.1		7,048.5						
Boron tribromide	10294-33-4		7056.9			7,056.9						
Acrylonitrile	107-13-1		45032.8		7263.4	7,263.4						
Formic acid	64-18-6		108940.9		7478.1	7,478.1						
Acetone cyanohydrin	75-86-5		7612.4			7,612.4						
Butyl acetate(n-)	123-86-4		5031407.0		7787.0	7,787.0						
Cyanogen	460-19-5	7929.5				7,929.5						
Carbon tetrachloride	56-23-5		8310.7		1043413.1	8,310.7						
Ammonia	7664-41-7	8458.1			12940.2	8,458.1						
Trimethylamine	75-50-3	9515.4				9,515.4						
Acetylene	74-86-2	39781.2		9731.1		9,731.1						
Styrene, monomer	100-42-5		7530337.5		10550.1	10,550.1						
Dichloroethylene(1,2-)	540-59-0		1015984.0		11039.8	11,039.8						
Ethylene dichloride	107-06-2		11655.7		153070.2	11,655.7						
Silane	7803-62-5	11880.0				11,880.0						
Pyridine	110-86-1		262584.6		12434.0	12,434.0						
Hydrogen cyanide	74-90-8	29610.5		12562.7		12,562.7						
Dioxane	123-91-1		13007.4		155912.3	13,007.4						
Sulfur monochloride	10025-67-9		13018.0			13,018.0						
Acetic anhydride	108-24-7		452071.9		13187.6	13,187.6						
Nitrobenzene	98-95-3		1124854.7		13941.2	13,941.2						
Ethyl bromide	74-96-4		13974.0		188437.2	13,974.0						
Benzyl chloride	100-44-7		364585.6		15448.3	15,448.3						
Chloroacetone	78-95-5		15801.3			15,801.3						
Vinyl acetate	108-05-4		17890.1			17,890.1						
Methyl cellosolve	109-86-4		18195.7		150715.2	18,195.7						
Pentyl mercaptan	110-66-7		18420.2			18,420.2						
Methoxyflurane	76-38-0		18882.2			18,882.2						
Propylenimine	75-55-8		20353.0			20,353.0						
Dichloromonofluoromethane	75-43-4	21145.4				21,145.4						
Methylacrylonitrile	126-98-7		22776.0			22,776.0						
Acrylic acid	79-10-7		26387.9			26,387.9						
Glutaraldehyde	111-30-8		28404.0			28,404.0						
Phenyl mercaptan	108-98-5		29971.8			29,971.8						
Toluene	108-88-3		2806478.0		30143.0	30,143.0						
Dichoropropene(1,3-)	542-75-6		32077.9			32,077.9						
Tetraethyl lead (as Pb)	78-00-2		32102.7			32,102.7						
Dichloroethylene(1,1-)	75-35-4		33866.1			33,866.1						
Propargyl alcohol	107-19-7		34105.8			34,105.8						
Methyl acrylate	96-33-3		34639.1		115463.5	34,639.1						
Diisobutyl ketone	108-83-8		14109694.0		35938.2	35,938.2						
Nitrous oxide	10024-97-2	36475.8				36,475.8						
Isopropyl acetate	108-21-4		2774295.8		36781.7	36,781.7						
Allyl alcohol	107-18-6		88789.5		37678.8	37,678.8						
Propylene oxide	75-56-9		51415.0		38102.2	38,102.2						
Chlorobenzene	108-90-7		942806.8		40818.7	40,818.7						
Pentane(n-)	109-66-0		575358.5		44977.8	44,977.8						
Butyl alcohol(sec-)	78-92-2		2361811.2		50238.4	50,238.4						
Phenylhydrazine	100-63-0		51237.6			51,237.6						
Dichlorobenzene(o-)	95-50-1		18839403.8		52750.3	52,750.3						
Hexyl acetate(sec-)	108-84-9		18885130.5		57258.9	57,258.9						
Methyl cellosolve acetate	110-49-6		58623.9		62170.0	58,623.9						
Cyclohexanol	108-93-0		55277292.6		60286.1	60,286.1						
Furfural	98-01-1		2276607.7		66551.9	66,551.9						
Ethylene chlorohydrin	107-07-3		68804.8			68,804.8						
Butyl alcohol(n-)	71-36-3		3114476.3		75357.6	75,357.6						
Ethyl alcohol	64-17-5		25364403.4		83730.7	83,730.7						
Acetone	67-64-1		1421616.4		87822.8	87,822.8						
Tetrahydrofuran	109-99-9		712921.0		88488.1	88,488.1						
Ethyl acetate	141-78-6		5947095.3		91651.2	91,651.2						
Sulfuric acid	7664-93-9		282303.0		94101.0	94,101.0						
Propyl alcohol(n-)	71-23-8		4490946.1		95094.1	95,094.1						
Diacetone alcohol	123-42-2		56722494.1		101732.8	101,732.8						
Chlorodiphenyl (42% chlorine)	53469-21-9		107340.8			107,340.8						
Diethylaminoethanol(2-)	100-37-8		108021.2			108,021.2						
Bromoform	75-25-2		109548.7		38707224.4	109,548.7						
Formaldehyde (Formalin)	50-00-0		113852.8		3198485.0	113,852.8						
Crotonaldehyde	4170-30-3		118518.9			118,518.9						
Methyl formate	107-31-3		118748.9		1583143.2	118,748.9						
Ethylene glycol dinitrate	628-96-6		121384.7			121,384.7						
Benzoyl chloride	98-88-4		122558.9			122,558.9						
Tetrachloroethane(1,1,2,2-)	79-34-5		126456.3		305617.0	126,456.3						

Table 7
Normalized Health Limits and Odor Thresholds
Listed in Order of Toxicity and Volatility

		1 min Lecture Bottle Release / 1 Liter Spill				Limiting Value	Max Volume (mL) for Liquid Max Release Rate (g/s) for Gas					
		Health Limit ($\mu g/m^3$)/(g/s)		Odor Threshold ($\mu g/m^3$)/(g/s)		Per 1 Liter Spill or 1 min Release	ASHRAE		"as mfg"		"as inst"	
Substance	CAS#	Gas	Liquid	Gas	Liquid	($\mu g/m^3$)/(g/s)	liquid (mL)	gas (g/s)	liquid (mL)	gas (g/s)	liquid (mL)	gas (g/s)
Ethoxyethanol(2-)	110-80-5		138315.9			138,315.9						
Methylene chloride	75-09-2		162165.3		172246.0	162,165.3						
Vinyl chloride	75-01-4	166292.6				166,292.6						
Epichlorohydrin	106-89-8		175030.2		485521.1	175,030.2						
Isophorone	78-59-1		4675771.0		178974.3	178,974.3						
Methyl (tert-) butyl ether	1634-04-4		188822.2			188,822.2						
Phenyl ether (vapor)	101-84-8		37966601.1		189833.0	189,833.0						
Propiolactone(beta-)	57-57-8		192052.2			192,052.2						
Propionitrile	107-12-0		193133.2			193,133.2						
Ethyl chloride	75-00-3	209339.2				209,339.2						
Cyclopentadiene	542-92-7		215964.0			215,964.0						
Hydrogen peroxide	7722-84-1		228067.6			228,067.6						
Carbon monoxide	630-08-0	238655.8				238,655.8						
Dichloroethane(1,1-)	75-34-3		486498.4		243401.2	243,401.2						
Chloropentafluoroethane (Freon 115)	76-15-3	250572.7				250,572.7						
Dichloro-1-nitro-ethane(1,1-)	594-72-9		256603.4			256,603.4						
Hexanone(2-)	591-78-6		276386.5			276,386.5						
Ethoxyethyl acetate(2-)	111-15-9		282804.8			282,804.8						
Acetonitrile	75-05-8		310756.3		5987317.4	310,756.3						
Butyronitrile (n-)	109-74-0		339121.9			339,121.9						
Methyl aniline	100-61-8		345095.6			345,095.6						
Methyl aniline	100-61-8		345095.6			345,095.6						
Ethylenediamine	107-15-3		1047266.8		369441.0	369,441.0						
Chloro-1-nitropropane(1-)	600-25-9		373434.8			373,434.8						
Hexane(n-)	110-54-3		376962.9			376,962.9						
Methyl acetate	79-20-9		545123.4		392033.8	392,033.8						
Methyl alcohol	67-56-1		1015906.5		409552.3	409,552.3						
Dibutyl phosphate	107-66-4		439167.8			439,167.8						
Isopropyl alcohol	67-63-0		5701786.0		490966.3	490,966.3						
Trichloroethane(1,1,2-)	79-00-5		491685.7			491,685.7						
Trichloroethylene	79-01-6		650450.4		532700.4	532,700.4						
Propionic acid	79-09-4		539492.0			539,492.0						
Ethyl formate	109-94-4		560605.7			560,605.7						
Methyl styrene(alpha-)	98-83-9		18743772.3		604468.5	604,468.5						
Isoamyl alcohol	123-51-3		1682089.6		608843.9	608,843.9						
Methyl isobutyl carbinol	108-11-2		4967925.0		614098.1	614,098.1						
Butyl glycidl ether(n-)	2426-08-6		709009.8			709,009.8						
Toluene-2,4-diisocyanate	584-84-9		741896.2		39223103.4	741,896.2						
Ethyl benzene	100-41-4		4719962.5		756237.1	756,237.1						
Cyclohexylamine	108-91-8		799247.4			799,247.4						
Nitromethane	75-52-5		810712.0		1351186.7	810,712.0						
Propyl nitrate(n-)	627-13-4		829539.2		1024724.9	829,539.2						
Xylenes (o-,m-,p-isomers)	1330-20-7		6287488.4		837306.8	837,306.8						
Nitropropane(2-)	79-46-9		860728.0		1069470.7	860,728.0						
Phenol	108-95-2				885452.0	885,452.0						
Chlorobromomethane	74-97-5		1404492.8		936328.6	936,328.6						
Nicotine	54-11-5		1067121.0			1,067,121.0						
Dimethyl sulfate	77-78-1		1098093.7			1,098,093.7						
Anisidine (o-,p-isomers)	29191-52-4		1123941.7			1,123,941.7						
Trichloropropane(1,2,3-)	96-18-4		1127296.8			1,127,296.8						
Valeraldehyde (n-)	110-62-3		1260714.0			1,260,714.0						
Tetrachloroethylene	127-18-4		2724214.1		1264931.4	1,264,931.4						
Butyl acrylate (n-)	141-32-2		1304542.1			1,304,542.1						
Methyl chloroform	71-55-6		1314804.0		1469473.5	1,314,804.0						
Cyclohexanone	108-94-1		5640310.3		1318758.3	1,318,758.3						
Butyl alcohol(tert-)	75-65-0		1334775.6		8612298.9	1,334,775.6						
Ethyl silicate	78-10-4		11300929.0		1356437.1	1,356,437.1						
Butoxyethanol	111-76-2		1408165.6			1,408,165.6						
Butoxyethanol	111-76-2		1408165.6			1,408,165.6						
Chlorodiphenyl (54% chlorine)	11097-69-1		1415844.8			1,415,844.8						
Aniline	62-53-3		3767880.8		1507152.3	1,507,152.3						
Difluorodibromomethane	75-61-6	1544400.0				1,544,400.0						
Butanone(2-)	78-93-3		1595926.5			1,595,926.5						
Trichloro-1,2,2,-trifluoroethane(1,1,2-)	76-13-1		1641997.1			1,641,997.1						
Hexone	108-10-1		1727415.4			1,727,415.4						
Allyl glycidyl ether	106-92-3		1778360.5		1778360.5	1,778,360.5						
Toluidine(m-)	108-44-1		1894484.8			1,894,484.8						
Isopropyl glycidyl ether	4016-14-2		2118487.2		12710923.0	2,118,487.2						
Cyclohexene	110-83-8		2126738.4			2,126,738.4						
Heptane(n-)	142-82-5		4145796.9		2166531.4	2,166,531.4						
Diglycidyl ether	2238-07-5		2205808.3		19694717.2	2,205,808.3						
Nitrotoluene, m-isomer	99-08-1		2221977.8			2,221,977.8						
Nitrotoluene, o-isomer	88-72-2		2221977.8			2,221,977.8						
Nitrotoluene, p-isomer	#N/A		2221977.8			2,221,977.8						
Propane	74-98-6	2283700.4		3404339.6		2,283,700.4						
Trichlorobenzene(1,2,4-)	120-82-1		2358828.7			2,358,828.7						
Glycidol	556-52-5		2533107.4			2,533,107.4						
Dichlorodifluoromethane	75-71-8	2616740.1				2,616,740.1						
Cyclopentane	287-92-3		2654330.2			2,654,330.2						
Butyltoluene(p-tert-)	98-51-1		10671004.2		2667751.0	2,667,751.0						
Dimethylformamide	68-12-2		2841373.8		9471246.1	2,841,373.8						

Table 7
Normalized Health Limits and Odor Thresholds
Listed in Order of Toxicity and Volatility

		1 min Lecture Bottle Release / 1 Liter Spill				Limiting Value	Max Volume (mL) for Liquid Max Release Rate (g/s) for Gas					
		Health Limit (µg/m³)/(g/s)		Odor Threshold (µg/m³)/(g/s)		Per 1 Liter Spill or 1 min Release	ASHRAE		"as mfg"		"as inst"	
Substance	**CAS#**	**Gas**	**Liquid**	**Gas**	**Liquid**	**(µg/m³)/(g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**	**liquid (mL)**	**gas (g/s)**
Ethanolamine	141-43-5		5665696.3		2848872.7	2,848,872.7						
Cyclohexane	110-82-7		3456874.0		2998925.5	2,998,925.5						
Furfuryl alcohol	98-00-0		5646059.9		3014304.6	3,014,304.6						
Bromotrifluoromethane	75-63-8	3018171.8				3,018,171.8						
Methylal	109-87-5		3418594.5			3,418,594.5						
Nitropropane(1-)	108-03-2		3496707.5		6593791.3	3,496,707.5						
Phosdrin	7786-34-7		3705699.0			3,705,699.0						
Dimethylaniline	121-69-7		3808295.3			3,808,295.3						
Mercury vapor	7439-97-6		3834873.7			3,834,873.7						
Indene	95-13-6		4297333.0			4,297,333.0						
Butyl acetate(tert-)	540-88-5		4354102.2			4,354,102.2						
Methylcyclohexane	108-87-2		10493600.6		4372333.6	4,372,333.6						
Pyrethrum	8003-34-7		4381949.9			4,381,949.9						
Methacrylic acid	79-41-4		4508313.1			4,508,313.1						
Sulfur hexafluoride	2552-62-4	4733920.7				4,733,920.7						
Nitroethane	79-24-3		7075594.7		4763158.2	4,763,158.2						
Ethyl amyl ketone	541-85-5		5113934.8			5,113,934.8						
Dichloroethylether	111-44-4		5348809.7		40660928.1	5,348,809.7						
Dimethyl acetamide	127-19-5		5564221.2		8605675.6	5,564,221.2						
Octane	111-65-9		14146049.7		5651821.1	5,651,821.1						
Dipropyl ketone	123-19-3		5660249.3			5,660,249.3						
Pentanone(2-)	107-87-9		5903587.6			5,903,587.6						
Isobutyl alcohol	78-83-1		6228952.7			6,228,952.7						
Hexylene glycol	107-41-5		6713476.7			6,713,476.7						
Kerosene	8008-20-6		6923480.9			6,923,480.9						
Toluidine(o-)	95-53-4		7577939.3			7,577,939.3						
Phorate	298-02-2		8453578.6			8,453,578.6						
Diethyl ketone	96-22-0		8461272.1			8,461,272.1						
Dichlorvos	62-73-7		9398390.4			9,398,390.4						
Phosphoric acid	7664-38-2		9419701.9			9,419,701.9						
Butyl acetate(sec-)	105-46-4		9433888.2			9,433,888.2						
Tetraethyl pyrophosphate	107-49-3		9549628.8			9,549,628.8						
Formamide	75-12-7		10257008.7			10,257,008.7						
Chlorotoluene(o-)	95-49-8		10483768.8			10,483,768.8						
Ethylene glycol	107-21-1		10635147.3			10,635,147.3						
Turpentine	8006-64-2		22643855.2		10751210.0	10,751,210.0						
Dichlorotetrafluorethane	76-14-2	12582000.0				12,582,000.0						
Isobutyl acetate	110-19-0		12833143.5			12,833,143.5						
Fluorotrichloromethane	75-69-4	13440000.0				13,440,000.0						
Nitroglycerin	55-63-0		13549549.2			13,549,549.2						
Ethyl butyl ketone	106-35-4		13943963.3			13,943,963.3						
Phenyl ether-bi-phenyl mix (vapor)	8004-13-5		14597700.7			14,597,700.7						
Vinyl toluene	25013-15-4		37721841.7		18743772.3	18,743,772.3						
Naphtha (coal tar)	8030-30-6		20141035.3			20,141,035.3						
Di-sec octyl phthalate	117-81-7		23639712.8			23,639,712.8						
Triethanolamine	102-71-6		26552179.8			26,552,179.8						
Isoamyl acetate	123-92-2		27917261.7			27,917,261.7						
Methylcyclohexanone(o-)	583-60-8		28302762.1			28,302,762.1						
Methylcyclohexanol	25639-42-3		28372934.0		94980619.4	28,372,934.0						
Dichrotophos	141-66-2		29212999.5			29,212,999.5						
Sulfotep	3689-24-5		33727832.9			33,727,832.9						
Phenyl glycidyl ether	122-60-1		36900631.0			36,900,631.0						
Dibutylphthalate	84-74-2		49755522.0			49,755,522.0						
Acetylene tetrabromide	79-27-6		56076790.6			56,076,790.6						
Disulfoton	298-04-4		56151507.6			56,151,507.6						
Acetophenone	98-86-2		56541760.6			56,541,760.6						
Stoddard solvent	8052-41-3		57695674.1			57,695,674.1						
Diazinon	333-41-5		65070309.1			65,070,309.1						
Dimethylphthalate	131-11-3		71302583.9			71,302,583.9						
Dibrom	300-76-5		109031195.2			109,031,195.2						
Parathion	56-38-2		118837639.8		377111443.5	118,837,639.8						
Dipropylene glycol methyl ether	34590-94-8		140151435.1		174799550.8	140,151,435.1						
Triorthocresyl phosphate	78-30-8		375867583.7			375,867,583.7						
Fenthion	55-38-9		569248172.0			569,248,172.0						
Chlorinated diphenyl oxide	55720-99-5		612318112.0			612,318,112.0						
Thioglycolic acid	68-11-1		1142637454.6			1,142,637,454.6						
Malathion	121-75-5		20954845316.1		9429680392.2	9,429,680,392.2						
Ethion	563-12-2		19231891367.9			19,231,891,367.9						

NOTE: See CPP internal document "Simulation and Analysis Techniques for Air Quality Assessments," April 2010 for a description on how an HL is computed from the OEL.

Table 8
Normalized Health Limits and Odor Thresholds
For the Combustion Sources

Health Limits and Odor Thresholds

	Health ($\mu g/m^3$) TWA	Health ($\mu g/m^3$) STEL	Odor ($\mu g/m^3$)
Diesel Exhaust (dilution):			2,000
CO - ACGIH[1]		229,000	#N/A
NO - NIOSH[1]	30,000	90,000	657
NO_2 - NIOSH[1]		1,800	4,472
NO_2 - OSHA[1]		9,000	4,472
NO_2 - EPA[1]		188	4,472
SO_2 - ACGIH[1]		13,000	3,832
SO_2 - EPA[1]		197	3,832
PM_{10} (Inhalable) OSHA[1]	15,000	45,000	#N/A
$PM_{2.5}$ (Respirable) EPA[1]		88	#N/A
$PM_{2.5}$ (Respirable) OSHA[1]	5,000	15,000	#N/A

Emissions Data	**900kW Diesel Generator (EPA Tier 2)**	**900kW Diesel Generators (combined)**	**400 hp Diesel Truck[3]**
	Cummins QST30-G5 NR2 (2)	**Cummins QST30-G5 NR2 (2)**	**Post 1985**
Stack Letter	AU	AUx2	AT
StackID	900 kW Diesel Generator	900 kW Diesel Generator	Diesel Truck at Loading Dock
Output Data:			
Rated Engine Power Output (kW):	900.00	1,800.00	
Mass Emission Rate (g/s):	1,599.75	3,199.51	80.34
Mass Emission Rate (lb/hr):	12,696.73	25,393.46	637.60
Volume Flow (m^3/s):	3.28	6.57	0.09
Emission Factors:			
CO (g/kWhr-DG; lb/MMBTU - Boiler):	0.78		
NO_x (g/kWhr-DG; lb/MMBTU - Boiler):	5.43		
SO_2 (g/kWhr-DG; lb/MMBTU - Boiler):	0.13		
PM_{10} (g/kWhr-DG; lb/MMBTU - Boiler):	0.148		
$PM_{2.5}$ (g/kWhr-DG; lb/MMBTU - Boiler):	0.148		
Emission Rates:			
CO (g/s):	0.19	0.39	0.011
NO_x (g/s):	1.36	1.53	0.004
NO (g/s):	0.34	0.68	0.001
NO_2 (g/s):	1.02	2.04	0.003
SO_2 (g/s):	0.03	0.07	#N/A
PM_{10} (g/s):	0.04	0.07	#N/A
$PM_{2.5}$ (g/s):	0.04	0.07	#N/A
Normalized Health Limits and Odor Thresholds			
Health Limits			
CO ($\mu g/m^3$)/(g/s):	1,177,378	588,689	20,507,462.69
NO ($\mu g/m^3$)/(g/s):	265,145	132,572	98,181,818.18
NIOSH - NO_2 ($\mu g/m^3$)/(g/s):	1,768	884	654,545.45
OSHA - NO_2 ($\mu g/m^3$)/(g/s):	8,838	4,419	3,272,727.27
EPA - NO_2 ($\mu g/m^3$)/(g/s):	185	92	68,429
ACGIH - SO_2 ($\mu g/m^3$)/(g/s):	387,770	193,885	#N/A
EPA - SO_2 ($\mu g/m^3$)/(g/s):	5,862	2,931	#N/A
PM_{10} ($\mu g/m^3$)/(g/s):	1,220,339	610,169	#N/A
EPA - $PM_{2.5}$ ($\mu g/m^3$)/(g/s):	2,373	1,186	#N/A
OSHA - $PM_{2.5}$ ($\mu g/m^3$)/(g/s):	406,780	203,390	#N/A
Health Design Criteria ($\mu g/m^3$)/(g/s):	**185**	**92**	**68,429**
Odor Thresholds			
Combined Exhaust ($\mu g/m^3$)/(g/s):	152	76	5,293.13
CO ($\mu g/m^3$)/(g/s):	#N/A	#N/A	#N/A
NO ($\mu g/m^3$)/(g/s):	1,936	968	716,727.27
NO_2 ($\mu g/m^3$)/(g/s):	4,392	2,196	1,626,181.82
SO_2 ($\mu g/m^3$)/(g/s):	114,303	57,151	#N/A
PM_{10} ($\mu g/m^3$)/(g/s):	#N/A	#N/A	#N/A
$PM_{2.5}$ ($\mu g/m^3$)/(g/s):	#N/A	#N/A	#N/A
Odor Design Criteria ($\mu g/m^3$)/(g/s):	**152**	**76**	**5,293**

Notes:
1) Only applies to Health Limits, Odor Thresholds are referenced in the report text.
2) Emission factors for Cummins QST30-G5 NR2 engine provided by client.
3) Emission rates from AP 42 Volume II, Mobile Sources, Table 1.7.3 (EPA, 1985).

Table 8
Normalized Health Limits and Odor Thresholds
For the Combustion Sources

Health Limits and Odor Thresholds

	Health (µg/m³) TWA	Health (µg/m³) STEL	Odor (µg/m³)
Diesel Exhaust (dilution):			2,000
CO - ACGIH[1]		229,000	#N/A
NO - NIOSH[1]	30,000	90,000	657
NO_2 - NIOSH[1]		1,800	4,472
NO_2 - OSHA[1]		9,000	4,472
NO_2 - EPA[1]		188	4,472
SO_2 - ACGIH[1]		13,000	3,832
SO_2 - EPA[1]		197	3,832
PM_{10} (Inhalable) OSHA[1]	15,000	45,000	#N/A
$PM_{2.5}$ (Respirable) EPA[1]		88	#N/A
$PM_{2.5}$ (Respirable) OSHA[1]	5,000	15,000	#N/A

Emissions Data

	Tailpipe Exhaust	Tailpipe Exhaust	500 kW Test Generator
	C221A	C328A	T-Gen-1,2
Stack Letter	AC	AI	CF
StackID	Tailpipe Exhaust	Tailpipe/Generator Exhaust	500 kW Test Diesel Generator
Output Data:			
Rated Engine Power Output (kW):			500.00
Mass Emission Rate (g/s):	1,382.64	1,382.64	938.77
Mass Emission Rate (lb/hr):	10,973.58	10,973.58	7,450.74
Volume Flow (m^3/s):	1.13	1.13	2.03
Emission Factors:			
CO (g/kWhr-DG; lb/MMBTU - Boiler):			
NO_x (g/kWhr-DG; lb/MMBTU - Boiler):			
SO_2 (g/kWhr-DG; lb/MMBTU - Boiler):			
PM_{10} (g/kWhr-DG; lb/MMBTU - Boiler):			
$PM_{2.5}$ (g/kWhr-DG; lb/MMBTU - Boiler):			
Emission Rates:			
CO (g/s):	#N/A	#N/A	#N/A
NO_x (g/s):	1.41	3.32	1.65
NO (g/s):	0.35	0.83	0.413
NO_2 (g/s):	1.06	2.49	1.238
SO_2 (g/s):	#N/A	#N/A	#N/A
PM_{10} (g/s):	#N/A	#N/A	#N/A
$PM_{2.5}$ (g/s):	#N/A	#N/A	#N/A

Normalized Health Limits and Odor Thresholds

Health Limits			
CO (µg/m³)/(g/s):	#N/A	#N/A	#N/A
NO (µg/m³)/(g/s):	255,319	108,434	218,182
NIOSH - NO_2 (µg/m³)/(g/s):	1,702	723	1,455
OSHA - NO_2 (µg/m³)/(g/s):	8,511	3,614	7,273
EPA - NO_2 (µg/m³)/(g/s):	178	76	152
ACGIH - SO_2 (µg/m³)/(g/s):	#N/A	#N/A	#N/A
EPA - SO_2 (µg/m³)/(g/s):	#N/A	#N/A	#N/A
PM_{10} (µg/m³)/(g/s):	#N/A	#N/A	#N/A
EPA - $PM_{2.5}$ (µg/m³)/(g/s):	#N/A	#N/A	#N/A
OSHA - $PM_{2.5}$ (µg/m³)/(g/s):	#N/A	#N/A	#N/A
Health Design Criteria (µg/m³)/(g/s):	**1,702**	**723**	**1,455**
Odor Thresholds			
Combined Exhaust (µg/m³)/(g/s):	441	441	247
CO (µg/m³)/(g/s):	#N/A	#N/A	#N/A
NO (µg/m³)/(g/s):	1,864	792	1,593
NO_2 (µg/m³)/(g/s):	4,229	1,796	3,614
SO_2 (µg/m³)/(g/s):	#N/A	#N/A	#N/A
PM_{10} (µg/m³)/(g/s):	#N/A	#N/A	#N/A
$PM_{2.5}$ (µg/m³)/(g/s):	#N/A	#N/A	#N/A
Odor Design Criteria (µg/m³)/(g/s):	**441**	**441**	**247**

Notes:
1) Only applies to Health Limits, Odor Thresholds are referenced i
2) Emission factors for Cummins QST30-G5 NR2 engine providec
3) Emission rates from AP 42 Volume II, Mobile Sources, Table 1