

Wind Tunnel Modeling of Radiator and Engine Exhaust Temperature Increases at Air Intake For Nuclear Power Plant

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ABSTRACT

The performance specification for the proper operation of a diesel generator at an existing nuclear facility requires that the temperature at the engine intake be less than 95EF. Field measurements at the site showed that the engine and radiator exhausts were causing a 15EF temperature increase relative to ambient temperature which was causing the performance of the system to be impaired during high temperature days. This increase was thought to be caused by the re-entrainment of the radiator and/or engine exhaust plumes. In order to correct the problem, various modifications to the existing design were proposed which ranged from simple air deflectors near the intake to increased stack heights and increased upward momentum of the radiator and engine exhausts. To determine the optimum design solution, a 1:180 scale model of the nuclear facility was constructed, including operating air intakes and exhausts. The model was placed in an atmospheric boundary layer wind tunnel and multiple wind conditions were simulated. The temperature increase (or exhaust dilution) at the intake was measured for the existing configuration and for various design alternatives. The goal was to find the least expensive alternative that would produce no more than a 2EF temperature increase. The final solution was to increase the upward momentum of the radiator exhaust and leave the engine exhaust unmodified. A validation test was conducted to determine how well the wind tunnel could match the observed temperature increases measured in the field. The wind tunnel results gave a temperature increase that was within 10% of that observed in the field. This validation test provided the necessary confidence that the modification would work after construction was completed.

This paper describes the methods used to evaluate the various design alternatives through wind tunnel modeling. In particular, the method for using tracer gas dispersion measurements to estimate temperature increases is documented.

INTRODUCTION

This paper describes the wind tunnel modeling conducted to predict temperature increases at the radiator air intake due to thermal emissions from the radiator and engine exhausts associated with an Emergency Diesel Generator (EDG). Past field tests documented that the air coming into the EDG intake was 10 to 15EF higher than ambient temperature. The source of the excess temperature was thought to be the EDG radiator and engine exhausts. The excess temperature affects the supply air temperature to the radiator, the engine room, control room ventilation air, and the engine combustion air. This increased temperature can cause various design basis conditions to be exceeded. Various

modifications to the EDG were considered to reduce the intake temperature. Some of these modifications included: various deflector arrangements, vertically directed radiator exhaust, and taller stacks for the engine.

The purpose of the wind tunnel study was to simulate various EDG design modifications in an atmospheric boundary layer wind tunnel and determine the temperature difference between the EDG air inlet and ambient air. For this evaluation, the design basis, or design goal, was set at 100EF. Hence, the goal of this study was to find a design alternative that would minimize the number of hours per year that 100EF is exceeded. Currently, with a 10 to 15E F temperature increase due to the existing radiator and engine exhaust configuration, the design basis temperature is exceeded many hours per year. A secondary objective of the wind tunnel study was to document the existing EDG situation and compare wind tunnel determined temperature differences with values observed at the site.

SCOPE OF WORK

Description of the Site

The nuclear power plant is located on the Gulf of Mexico, 70 miles north of Tampa, Florida. The topography in the area around the site is extremely flat and featureless with primarily agricultural land use. The subtropical marine climate of the site region is characterized by diurnal wind shifts from the Gulf of Mexico and frequent nocturnal inversions. Table 1 provides information on the temperature and wind direction occurrences.

Figure 1 shows the area modeled for the present study. The radius of the area represented by the physical model is approximately 1000 ft. The EDG is near the center of the model. Figure 2 is a closeup plan and elevation view of the EDG showing the existing and modified design configurations.

Exhausts and Intakes Studied

Four sources of thermal emissions were investigated in the present study: 1) emissions from the two radiator exhausts (Side A and Side B); and 2) emissions from the two engine exhausts (Side A and Side B). The impact of the thermal emissions was measured at the two intakes for the EDG. Most of the testing was conducted using parameters for a 3500 kW EDG. A set of tests was also conducted using conditions during a field test (i.e., 2700 kW). Table 2 lists the source parameters, such as volume flow rate, exit diameter, exit velocity, and exit temperature as well as characteristic parameters for the air intake.

METHODOLOGY

In this study, concentrations and temperatures due to radiator and engine exhaust were predicted with wind tunnel (physical) modeling. Wind tunnel modeling is well-suited for predicting the air flow patterns around building configurations. Wind tunnel modeling is much like conducting a field experiment. Concentrations due to tracer gases released from the sources are measured at the points of interest. The only difference is that the concentrations are measured over a scale model of the facility in a wind tunnel that simulates the wind flow over the buildings.

Establishment of the Wind Tunnel Modeling Similarity Criteria

An accurate simulation of the boundary-layer winds and source emissions is an essential prerequisite to any wind tunnel study of diffusion. The similarity requirements can be obtained from dimensional arguments derived from the equations governing fluid motion^{1,2}.

All testing was performed with neutral stability ($Ri = 0$). Meroney³ cites a Colorado State University report which determined that the effect of atmospheric stability on dispersion within five building heights of a building complex is relatively small due to the dominance of mechanical turbulence generated within the building complex.

For buoyant sources, the ideal modeling situation is to simultaneously match the stack exit Froude number, momentum ratio and density ratio. Achieving such a match requires that the wind speed in the tunnel be equal to the full scale wind speed divided by the square root of the length scale. For the 1:180 length scale of this study, the wind speed ratio would be approximately 1:13, meaning the tunnel speeds would be 13 times lower than the full scale wind speeds. Such a low tunnel speed would produce low Reynolds numbers and is operationally difficult to achieve. Hence, Froude number scaling was not used. For this evaluation, the radiator exhaust is nearly at ambient temperature so Froude number effects are small and it's exclusion is not an issue. For the engine exhaust, Froude number effects may be significant farther downwind but the initial phase of plume rise is primarily dominated by momentum. In any case, the exclusion of Froude number similarity will result in lower plume rise which in turn will result in higher predicted temperatures at the intake. Hence, the results of the study will be conservative.

Model Construction and Installation

The nuclear power plant structures and nearby terrain within a radius of approximately 1000 ft were constructed at a 1:180 scale ratio, which is equivalent to 1 model inch equaling 15 ft in full-scale. The physical model plan view is depicted in Figure 1. The main Unit #3 buildings were constructed from plexiglass, and Units #1& #2, the smaller structures and the office buildings were made from styrofoam.

The physical model was installed onto a rotating turntable used to facilitate changes of wind direction. The approach conditions were established with appropriate roughness elements and flow trips in the approach test section of the wind tunnel. The release sources and measurement locations were then installed onto the model.

The existing EDG radiator and engine exhausts were modeled as shown in Figure 2 along with the EDG air intakes. It should be noted that the radiator intakes were made operational and were operating at the properly scaled flows during all tests.

Data Collection

The quantitative concentration data was collected in a series of wind tunnel tests as summarized in Table 3. Each concentration test consisted of measurements of concentration over a series of wind directions and wind speeds for the particular source/receptor combinations listed in the table.

The air intake measurement locations on the physical model were connected via a sample tube connected to a Flame Ionization Detector (FID) located outside of the tunnel. A second sampling tube,

placed upwind of the model, was also connected to the FID so that the background concentration could be subtracted from all measurements. The voltage signal from the FID, which is linearly proportional to the concentration of tracer gas present in the sample, was monitored from a PC based data acquisition system and converted to full-scale concentrations in near real-time.

Data Reduction

The collected raw voltage data was reduced to produce full scale (real-world) normalized concentrations, dilutions and temperature differences at the radiator intake. The concentration data reduction calculation consists of two steps: computation of the tunnel tracer gas concentrations from the raw voltage data, and scaling the model concentrations to full scale values. Dilution values (D) were then calculated from the normalized concentration as the reciprocal of the product of the normalized concentration and volume flow rate. The final step in the process was to compute a temperature increase from the exhaust dilution value using the following equation:

$$T_i - T_a = \frac{1}{D} \left[\frac{(C_{p_s} T_s + C_{p_a} T_a)}{C_{p_i}} \right]$$

where the subscript i denotes the intake location.

To prove that temperature difference can be computed from exhaust dilution, consider the energy equation for an incompressible fluid with negligible dissipation.

$$\dot{m} C_p \frac{dT}{dt} = k A^2 T$$

Now, non-dimensionalize the equation by letting

$$T^* = \frac{C_p T + C_{p_a} T_a}{C_{p_s} T_s + C_{p_a} T_a}; \quad u_i^* = \frac{u_i}{U_R}; \quad x_i^* = \frac{x_i}{L}; \quad \text{and} \quad t^* = \frac{t U_R}{L}$$

substituting gives:

$$\frac{dT^*}{dt^*} = \frac{k}{\dot{m} C_p U_R L} A^2 T^* = \frac{1}{P Re} A^2 T^*$$

where:

$$Re = \frac{U_R L}{\nu} \quad \text{(Reynolds Number)}$$

$$Pr = \frac{\mu C_p}{k} \quad \text{(Prandtl Number)}$$

The diffusion equation can be written in this form:

$$\frac{dC^*}{dt} = \frac{1}{Re Sc} \nabla^2 C^*$$

where Sc is the Schmidt number, ρ/μ , and C^* is normalized concentration or the inverse of dilution.

For flows with a sufficiently high Reynolds number, the solutions for T^* and C^* will be identical. Hence C^* and T^* values are interchangeable. For this study C^* (1/D) is measured in the wind tunnel. The C^* or D result was then used to compute temperature difference. It should be noted that the specific heats were assumed equal and hence canceled from the above equation.

RESULTS

General

The concentration measurement test plan is shown in Table 3. Each line of the plan consists of one run in which concentrations at one of the EDG intakes were measured for several wind directions and wind speeds due to one thermal source (radiator or engine). Run 1 was conducted to replicate the conditions during the June 4, 1997 field experiment. The next eight runs, Runs 2 - 9, were conducted to document the temperature increase at the intakes due to the existing radiator configuration with a 3500 kW rating. Runs 10 - 17 were conducted to document the temperature increases for the modified configuration.

The measured C/m values were converted to temperature increase as described above. A summary of the overall maximum C/m and temperature increase values for all tests is provided in Table 3.

Field Verification Tests

Field verification tests were performed to provide confidence that the wind tunnel simulations can adequately replicate the full-scale conditions. The verification tests were conducted by replicating the operating conditions at the nuclear power plant site during the evening of June 04, 1997 for the hours from 21:30 to 24:00. If the differential between the ambient temperature and the temperature at the Side A air intake obtained from the wind tunnel measurements matched (to within approximately +/- 10%) the values measured at the site, confidence can be gained that the wind tunnel simulations adequately replicate the full-scale conditions. This, in turn, will validate the tests conducted to evaluate the existing and modified designs for the radiator exhaust.

The field conditions at the site were obtained from various sources. Meteorological conditions (wind speed, wind direction and ambient temperature) were obtained from the on-site 33 ft anemometer. During the hours from 21:30 to 24:00 of June 04, 1997, the wind speed varied from 1.9 m/s to 4.2 m/s, the wind direction varied from 48.7 degrees to 69.9 degrees, and the ambient temperature varied from 70.9E F to 71.5E F.

Source parameters for the radiator were obtained from the radiator fan airflow test data and EDG

radiator room temperature test data for June 04, 1997. The data included wind speed and temperature measurements obtained at the east and west intakes to the Side A radiator, with the diesel generator operating at 2700 kW. The average exhaust temperature from the radiator during the hours from 21:30 to 24:00 was 150.3EF. The source parameters are further summarized in Table 2.

Run 1 represents the wind tunnel simulation of the field conditions. During the testing, concentrations (and hence temperature differences) were measured for wind speeds ranging from 2 to 5 m/s in 1 m/s increments and wind directions ranging from 50 to 90 degrees in 10 degree increments. This data set was used to estimate the concentrations as a function of time during the field experiment. For comparison purposes, the field data conditions were specified by rounding off to the nearest 1 m/s for wind speed and to the nearest 10 degrees for wind direction. For example, a field condition with a 1.929 m/s wind speed and 48.7 degree wind direction was compared to a wind tunnel simulation with a 2.0 m/s wind speed and 50 degree wind direction.

A graphical representation of the wind tunnel results and field measurements is shown in Figure 3. The figure shows the temperature difference versus time of day for the two databases. Once the radiator intake temperature stabilized, at approximately 10:00 p.m., the figure shows that the wind tunnel results correspond to the field test data to within approximately 1EF, or within 10% of the field temperature difference. The figure shows that the field temperature differential is consistently higher than the wind tunnel results. The higher field temperature differential can be explained since the wind tunnel results only include the temperature increase due to the radiator exhaust at the air intake. The wind tunnel results do not include any additional temperature increase at the air intake due to the engine exhaust.

In summary, the results of the field verification tests indicate that wind tunnel simulations can replicate the full-scale conditions within the normal uncertainty assumed for wind tunnel simulations, that is to within +/- 10%. This information provides confidence that the temperature increases predicted for the existing and modified radiator and engine exhaust design are reliable.

Tests of Existing Configuration

Testing was conducted for the existing configuration to estimate the number of hours that 100E F is exceeded per year. The annual analysis was carried out to give some indication of the overall magnitude of the temperature increase problem. For this testing, the simulated operating conditions for the EGD are listed in Table 2. The tests that were carried out are summarized in Table 3 (Runs 2 - 9). The wind statistics and temperature information that was used in the analysis is provided in Tables 1. The results of the testing are provided in Tables 3 and 4. Table 4 shows the number of hours that 95, 100 and 105E F are predicted to be exceeded for the entire year.

The estimates in Table 4 were computed using the temperature and wind statistics provided in Tables 1 along with the wind tunnel estimated temperature differences versus wind direction and wind speed. The estimated hours specific temperatures are exceeded were obtained as described below. First, a Weibull probability distribution was fit to the wind distribution. This distribution allows for the calculation of the percent time the wind blows in a particular wind direction and wind speed sector. The Weibull distribution is described below.

$$P (>U) = A \times EXP\left(-\left(\frac{U}{c}\right)^k\right)$$

where:

U = wind speed, (m/s);
 A, c, k = curve fit coefficients.

The A constant in the above equation is equal to the percent time a particular wind direction occurs. (Note: calms were distributed equally by wind direction.) This constant was modified using the information in Table 1 to account for the percent time a certain temperature range (i.e., 82 to 88E F for example) is exceeded for each particular wind direction. The temperature probability factor, $P(T)$, is then multiplied by A to obtain a modified A for use in determining the number of hours the temperature is in a certain range for a specific wind speed and direction category. For each wind direction, the hours that the specified temperature is exceeded are calculated and then summed over all wind directions. The hours for each temperature range were added and the final results are presented in Table 4.

The overall maximum expected temperature was determined in a different manner. The weather records at Tampa International Airport were reviewed to find the maximum expected temperature during the winter months. This annual maximum temperature was found to be 99E F. To obtain a maximum expected intake temperature, the maximum predicted temperature increase from the wind tunnel test for each EDG scenario was simply added to the maximum ambient temperature.

Table 4 shows that the annual overall maximum expected temperatures is 113E F at intake B when all units are operating. For this same scenario, temperatures between 100 and 113E F are predicted to occur for 740 hours during the year. With only one unit operating, the overall maximum expected temperature is 112E F. Temperatures between 100 and 112E F are predicted to occur 532 hours per year. These results demonstrate that temperatures in excess of 100E F will occur a significant fraction of the time during the year and points out the need for a design modification.

Tests of The Modified Design

Testing was conducted for the modified design configuration to estimate the number of hours that 100E F is exceeded per year. This analysis was carried out to document that the modified design is acceptable. The tests that were carried out are summarized in Table 3.

Table 5 shows the number of hours that 95, 100 and 105E F are predicted to be exceeded on an annual basis. The estimates in Tables 5 were computed using the temperature and wind statistics along with the wind tunnel estimated temperature differences versus wind direction and wind speed. Table 5 shows that the overall maximum expected temperature on an annual basis is 104E F at Radiator B when all units are operating. For this same scenario, temperatures between 100 and 104E F are predicted to occur 7 hours per year. With only one unit operating, the overall maximum expected temperature is 102E F. Temperatures between 100 and 102E F are predicted to occur only 5 hours per year.

In summary, it appears that the modified design is adequate to limit temperatures in excess of 100 E F to no more than 7 hours per year, or less than 0.1% of the time. The overall maximum temperature is predicted to be to 104E F.

REFERENCES

1. Cermak, J.E., "Applications of Fluid Mechanics to Wind Engineering," *Journal Fluids Engineering*, Vol. 97, p. 9, 1975.
2. EPA, "Guideline for Use of Fluid Modeling of Atmospheric Diffusion," EPA Office of Air Quality, Planning and Standards, Research Triangle Park, NC, EPA-600/8-81-009, April 1981.
3. Meroney, R.N., "Bluff Body Aerodynamics Influence on Transport and Diffusion," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 33, p. 21, 1990.

Figure 1. Plan view of the turntable model

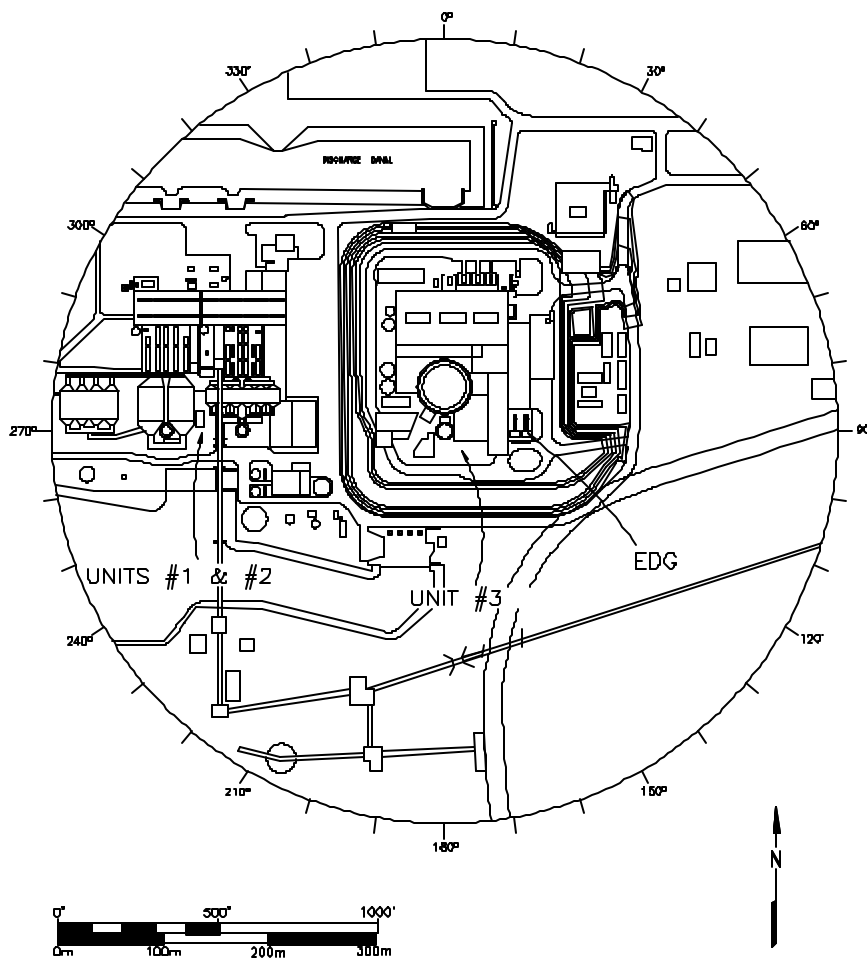


Figure 2. Plan and elevation views of the EDG

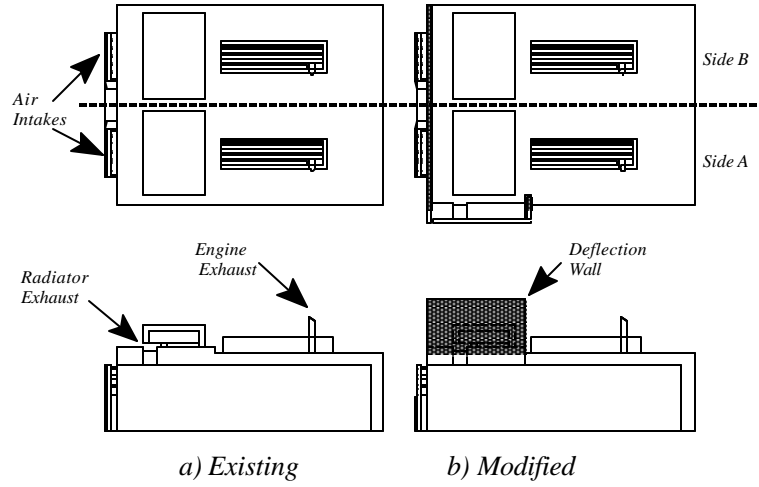


Figure 3. Comparison of field and wind tunnel temperature measurements

Field Verification Tests

June 4, 1997

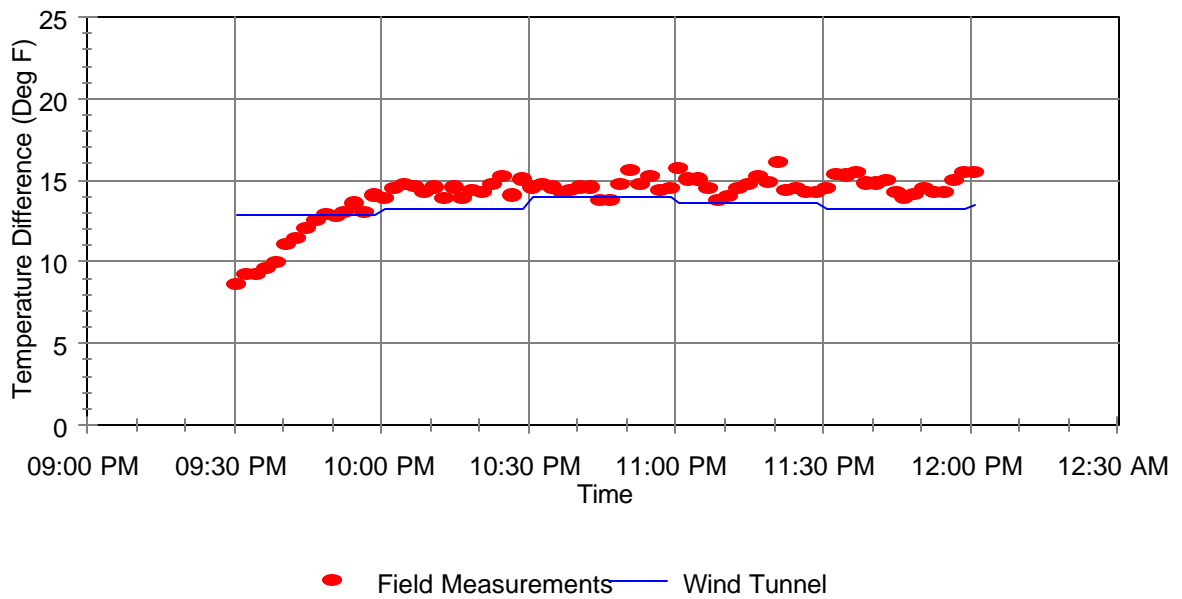


Table 1
Temperature and Wind Direction Occurrences (Hours)
At Tampa International Airport - 10 Years of Record

Wind Direction Category								
	NNW&N	NNE&NE	ENE&E	ESE&SE	SSE&S	SSW&SW	WSW&W	WNW&NW
<i>Hours</i>								
>= 97	0	1	0	0	0	0	1	0
>= 92	48	46	73	52	57	101	285	62
>= 87	388	434	803	485	589	854	2,266	608
>= 82	760	750	1,743	1,216	1,155	1,196	2,108	1,034
Total Hours	9,293	11,835	18,849	10,695	8,065	6,312	9,293	7,276
<i>Fraction of Hours</i>								
>= 97	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
>= 92	0.005	0.004	0.004	0.005	0.007	0.016	0.031	0.009
>= 87	0.042	0.037	0.043	0.045	0.073	0.135	0.244	0.084
>= 82	0.082	0.063	0.092	0.114	0.143	0.189	0.227	0.142
Total Fraction	0.129	0.104	0.139	0.164	0.223	0.341	0.501	0.234

Table 2
Full Scale Parameters for Radiator Exhausts, Engine Exhausts and Air Intakes

Source Description	Stack Height (m)	Exit Diameter (m)	Exit Area (m ²)	Ambient Temp. (K)	Exit Temp. (K)	Volume Flow Rate (m ³ /s)	Exit Velocity (m/s)
3500 kW Radiator Exhaust	8.2	2.60	5.3	308.2	337.0	104.14	19.55
3500 kW Engine Exhaust	12.2	0.56	0.2	308.2	588.7	14.69	59.88
3500 kW Air Intake Scenario	4.6	3.72	10.9	308.2	308.2	103.57	9.51
2700 kW Radiator Exhaust	8.2	2.60	5.3	294.3	338.9	73.05	13.71
2700 kW Air Intake Scenario	4.6	3.72	10.9	294.3	294.3	69.92	6.42

Site Parameters:

Scale Reduction: 180	Anemometer Surface Roughness: 0.1 m
Base Elevation: 0 m	Site Anemometer Height: 10.0 m
Ambient Temp: Varies	Site Surface Roughness: 0.1 m

Anemometer Height: 10.0 m

Table 3
Listing of Maximum Concentrations and Maximum Temperature Differences

Run Number	Side(s) Operating	Measurement Side	Critical ¹⁾ Wind Direction (Deg.)	Critical ¹⁾ Wind Speed (m/s)	Maximum Normalized Concentration -C/Q (Fg/m^3)/(g/s)	C _o /C Dilution (-)	Temperature Difference (T _i - T _a) (Deg. F)
<i>2700 kW Field Verification Tests</i>							
1	A	A	50	3.0	2,355	5.8	13.81
<i>3500 kW Radiator Exhaust - Existing Configuration</i>							
2	A	A	270	2.0	1,875	5.4	12.64
3	B	B	337.5	2.0	1,945	5.2	13.12
4	A & B	A	315	3.0	796	6.3	10.74
5	A & B	B	112.5	2.0	1,003	5.0	13.53
<i>3500 kW Engine Exhaust - Existing Configuration</i>							
6	A	A	337.5	9.0	91	752.9	0.69
7	B	B	67.5	11.0	218	314.3	1.65
8	A & B	A	337.5	7.0	76	450.7	1.15
9	A & B	B	67.5	11.0	161	212.8	2.43
<i>3500 kW Radiator Exhaust - Modified Configuration</i>							
10	A	A		11.0	475	21.2	3.20
11	B	B	67.5	3.0	473	21.3	3.19
12	A & B	A		7.0	231	21.8	3.12
13	A & B	B	67.5	9.0	317	15.9	4.28
<i>3500 kW Engine Exhaust - Modified Configuration</i>							
14	A	A	325	5.0	130	527.0	0.98
15	B	B	80	11.0	107	640.3	0.81
16	A & B	A	325	5.0	126	271.9	1.91
17	A & B	B	80	7.0	90	380.6	1.36

1) Wind direction and wind speed where maximum concentration occurred.

Table 4
Number of Hours 95, 100, and 105 EF Exceeded Per Year
For the Existing EDG Configuration

Units Operating	Intakes Operating	Measurement Side	Hours 95 EF Exceeded per Year	Hours 100EF Exceeded per Year	Hours 105EF Exceeded per Year	Maximum Probable Intake Temperature
RE-A, EE-A	A	A	1316.7	435.5	25.1	112
RE-B, EE-B	B	B	1351.9	531.5	43.2	112
RE-A&B, and EE-A&B	A&B	A	1428.7	499.4	43.7	111
RE-A&B, and EE-A&B	A&B	B	1506.0	740.0	87.4	113

Table 5
Number of Hours 95, 100, and 105 EF Exceeded Per Year
For the Modified EDG Configuration

Units Operating	Intakes Operating	Measurement Side	Hours 95EF Exceeded per Year	Hours 100EF Exceeded per Year	Hours 105EF Exceeded per Year	Maximum Probable Intake Temperature
RE-A, EE-A	A	A	80.5	0.2	0.0	102
RE-B, EE-B	B	B	135.0	5.3	0.0	102
RE-A&B, and EE-A&B	A&B	A	94.4	0.2	0.0	102
RE-A&B, and EE-A&B	A&B	B	144.3	6.6	0.0	104