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RB INYOKERN DATA CENTER

Application for Small Power Plant Exemption (SPPE)

Inyokern, Kern County, California

Docket Number - 26-SPPE-01

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- E.4 - Thermal Plume Analysis

RB Inyokern Data Center

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January 2026

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Thermal Plume Analysis

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Prepared for:

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Construction, Inc.
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List of Acronyms and Abbreviations

CASA	Australian Government Civil Aviation Safety Authority
CCR	California Code of Regulations
CEC	California Energy Commission
DEF	Diesel Exhaust Fluid
DPF	Diesel Particulate Filter
°F	Degrees Fahrenheit
FAA	U.S. Federal Aviation Administration
ft	Foot
°K	Degrees Kelvin
m	Meter
m/s	Meters per Second
m/s ²	Meters per Second Squared
MW	Megawatt
NCDC	National Climatic Data Center
RBIDC	RB Inyokern Data Center
s	Second
SCR	Selective Catalytic Reduction
SPPE	Small Power Plant Exemption

Thermal Plume Analysis

1.0 INTRODUCTION

Yorke Engineering LLC prepared this thermal plume analysis for Valley Wide Engineering & Construction, Inc., in conjunction with R&L Capital, Inc. who is proposing the RB Inyokern Data Center (RBIDC), a 99-megawatt (MW) data center located in Inyokern, CA. The RBIDC will be electrically interconnected to the regional transmission grid, but it will also have redundant electrical capacity to operate independently in the event the primary power supply is interrupted.

The facility will include forty (40) 3-MW Caterpillar diesel-fired generators equipped with selective catalytic reduction (SCR) systems, diesel exhaust fluid (DEF), and diesel particulate filters (DPFs) to comply with Tier 3 emissions standards. Under typical backup operation, when all generators are active, the maximum load on each generator will be designed to be 80% of peak capacity.

Hybrid cooling towers and water-cooled chillers will be used to remove heat generated in the data center. There are two (2) four-cell cooling towers proposed and twenty-eight (28) 24-cell chillers.

As the project proposes 99 MW of backup thermal power, the project's environmental impacts will be reviewed by the California Energy Commission (CEC) through a Small Power Plant Exemption (SPPE) application.

The project will be located 0.9 miles from the Inyokern Airport, as shown in Figure 1-1. The CEC requires SPPE applications to include an analysis of the thermal plumes and potential interference with nearby airports if there is an airport within 4 miles of the facility. Figures 1-2 and 1-3 show the proposed layout for the site.

This thermal plume analysis will determine if project plumes would cause unacceptable turbulent conditions for light aircraft at the nearby airport.

Figure 1-1: Facility Location and Proximity to Inyokern Airport

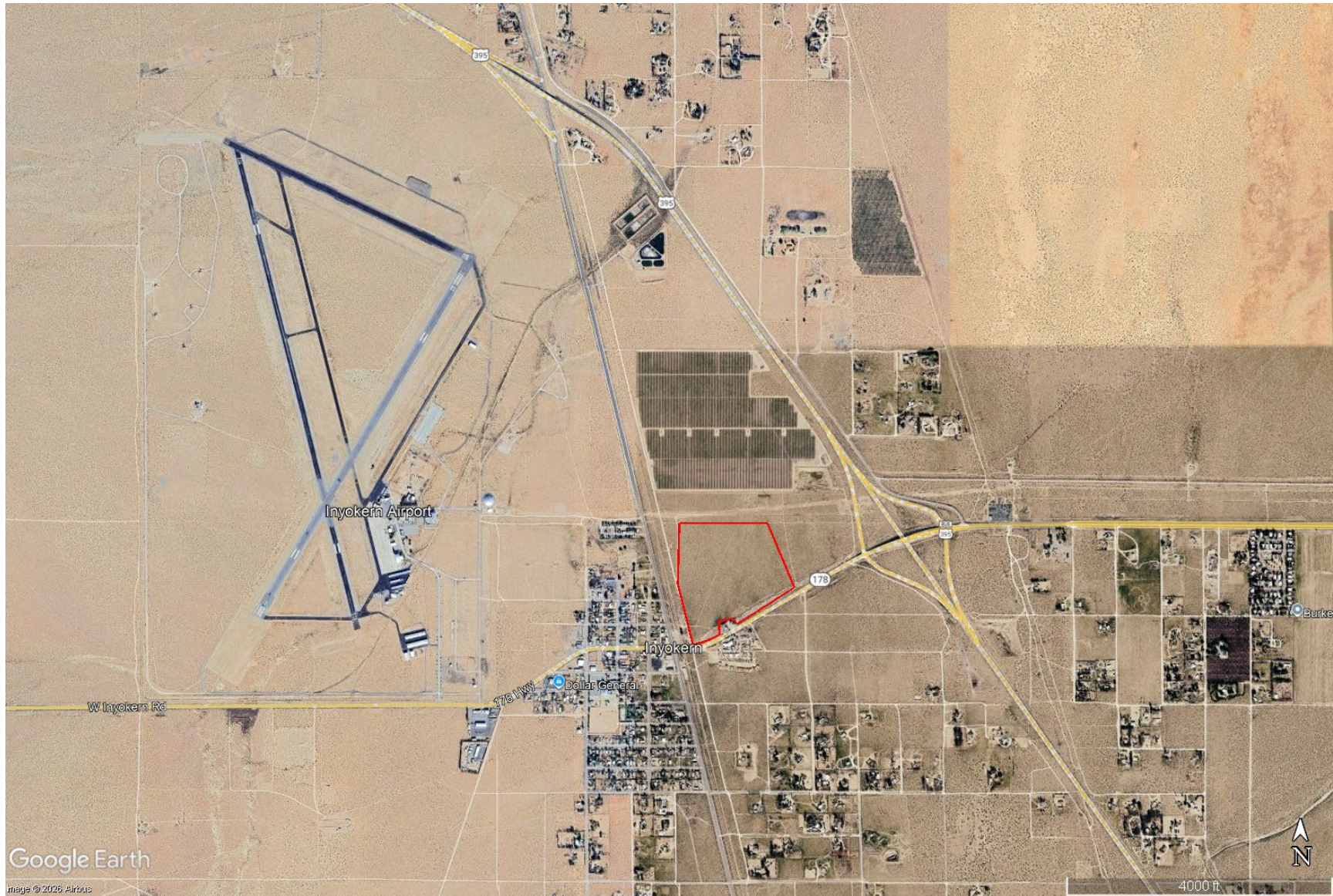


Figure 1-2: Proposed Facility Layout

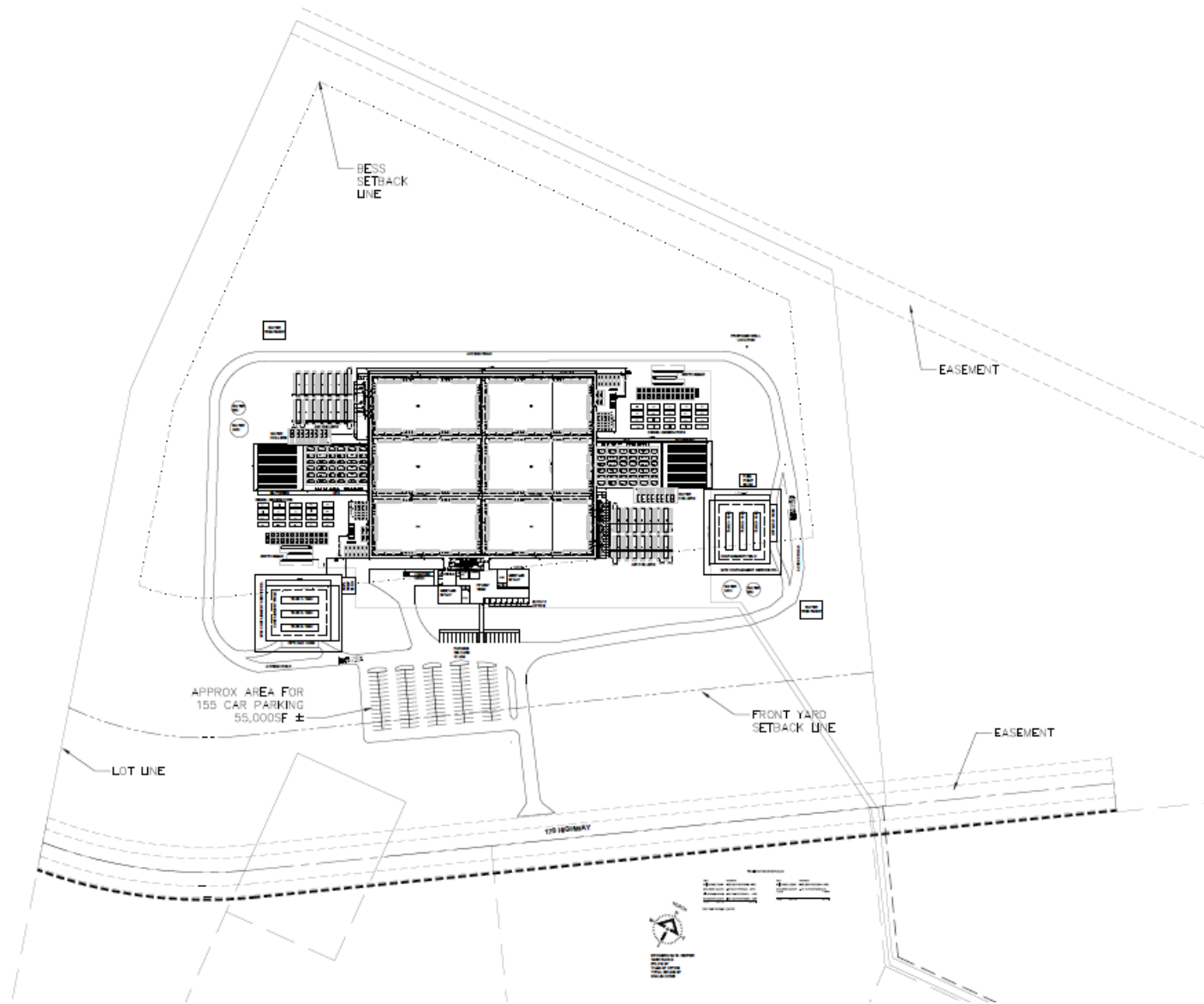
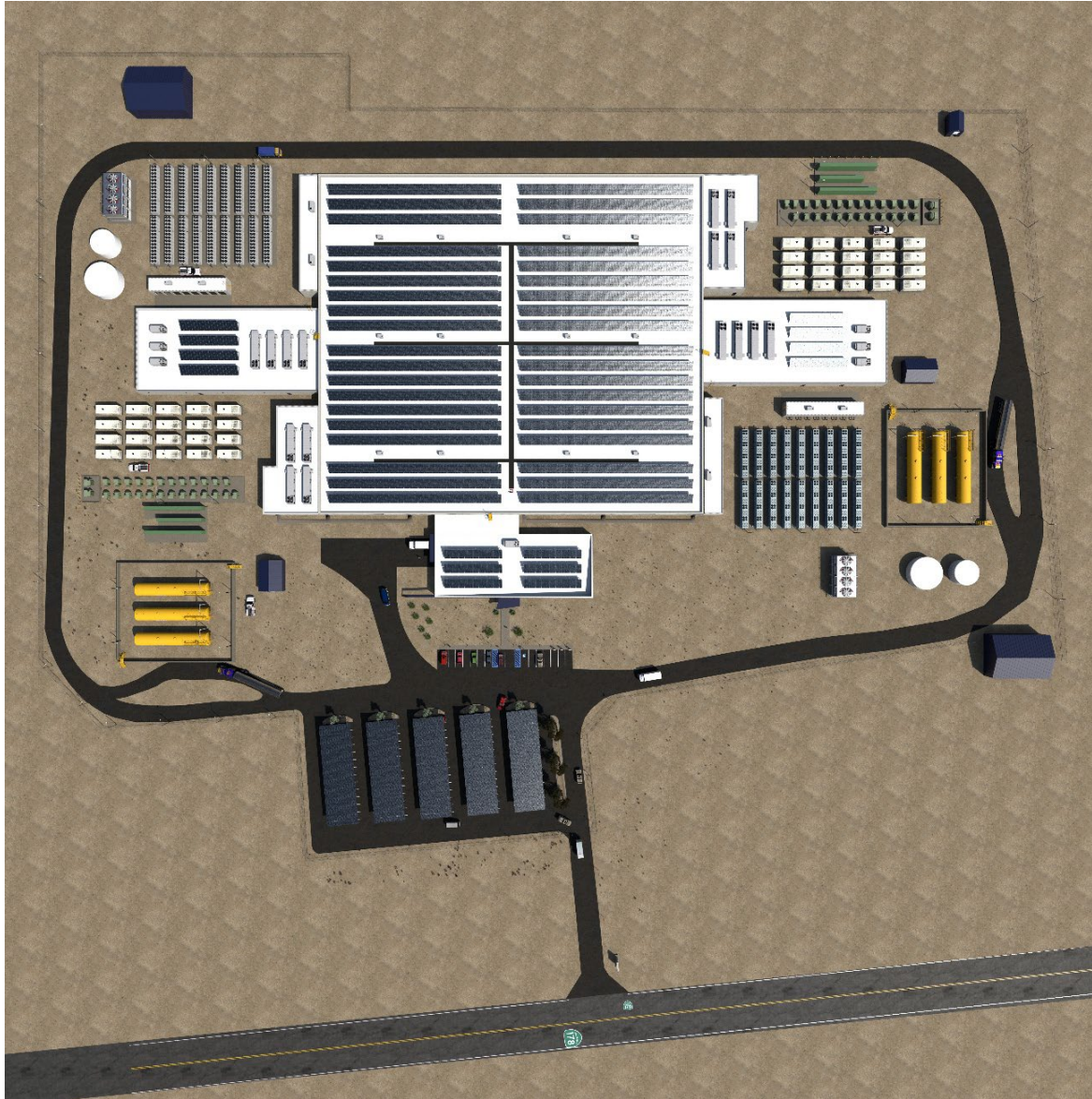


Figure 1-3: Rendering of Proposed Facility Layout



2.0 THERMAL PLUME ANALYSIS METHODOLOGY

The initial phase of plume rise is based on momentum flux, which is primarily dependent on the speed of the stack exhaust flow. The second phase of plume rise is dominated by buoyancy flux, which is primarily dependent on the stack exhaust and ambient temperatures. When the atmosphere is stable and winds are calm, the plume will rise vertically through the momentum phase swiftly. In the second phase, buoyancy flux is reduced with height as cooler ambient air is mixed into the plume. In all but stable, low-wind conditions, buoyancy flux will be reduced rapidly due to ambient winds.

The following analysis uses the Spillane methodology, outlined in a paper by Peter Best titled “Aviation Safety and Buoyant Plumes” (Best 2003), to calculate the height at which the vertical plume velocity drops below the CEC threshold for single plumes and multiple merged plumes. The analysis is limited to calm wind conditions, which are the worst-case wind conditions.

The Spillane methodology analyzes the momentum-phase parameters, followed by using the Spillane methodology to determine buoyant single-plume parameters, and then buoyant merged-plume parameters, if applicable. Momentum and buoyancy fluxes are based on standard atmospheric parameterization developed by Gary Briggs and outlined in “Handbook on Atmospheric Diffusion” (Hanna 1982). Briggs describes the distribution of temperature, speed, or other parameters across the plume as assumed to have a “top-hat” form or Gaussian distribution, such that the parameters can be expressed as the average values across a cross-section of two standard deviations. The Spillane method calculates these plume average parameters.

At this facility, there are multiple stacks located close to each other that have the potential for the plumes to combine and effectively create a larger, merged plume. Spillane developed a method to parameterize these merged plumes.

To ensure the maximum height at which the plume vertical velocity drops below the CEC threshold, the analysis was conducted for the maximum and minimum ambient temperatures recorded in Inyokern. The analysis was conducted for two ambient temperatures from the Inyokern meteorological station: the minimum mean daily temperature of 31 degrees Fahrenheit (°F) and the maximum mean daily temperature of 102°F from the National Climatic Data Center (NCDC) Climate Normals for 1981-2010.

2.1 CEC Significance Threshold

The CEC staff have determined that project plumes would cause unacceptable turbulent conditions for light aircraft if the average vertical velocity across the plume was 5.3 meters per second (m/s) or greater (CEC 2016). This threshold is based on guidance from the Australian Government Civil Aviation Safety Authority (CASA) and the U.S. Federal Aviation Administration (FAA). Therefore, the significance threshold for average vertical velocity across the plume is:

$$V_{\text{crit}} = 5.3 \text{ m/s}$$

The thermal plume analysis will calculate the height of the plume where the vertical velocity drops below this threshold.

2.2 Single Plume

Momentum Phase

The Best paper outlines the calculations to determine the momentum-phase plume parameters; this phase is also referred to as the jet phase. The momentum phase is parameterized by:

$$z_{\text{jet}} = 6.25D = \text{Height Above Stack (m)}$$

$$V_{\text{jet}} = 0.5V_{\text{exit}} = \text{Plume Average Vertical Velocity (m/s)}$$

$$a_{\text{jet}} = D = \text{Plume Top-Hat Radius at Top of Momentum Phase (m)}$$

Where:

$$D = \text{Stack Diameter (m)}$$

$$V_{\text{exit}} = \text{Stack Exit Velocity (m/s)}$$

Spillane/Buoyancy Phase

For calm conditions, plume parameters above the momentum phase are calculated using the Spillane methodology, as outlined in the Best paper, using the following:

$$z_v = 6.25D[1 - (\theta_e/\theta_s)^{1/2}] = \text{Virtual Source Height Above Stack (m)}$$

$$a = 0.16(z - z_v) = \text{Plume Top-Hat Radius (m)}$$

$$V = \{(Va)_o^3 + 0.12F_o [(z - z_v)^2 - (6.25D - z_v)^2]\}^{(1/3)} / a = \text{Vertical Velocity (m/s)}$$

Where:

$$\theta_a = \theta_e = \text{Ambient Temperature (}^\circ\text{K)}$$

$$\theta_s = \text{Stack Temperature (}^\circ\text{K)}$$

$$F_o = gV_{\text{exit}}D^2(1 - \theta_s/\theta_a)/4 = \text{Initial Stack Buoyancy Flux (m}^4\text{/s}^3)$$

$$g = \text{Gravity Constant} = 9.8 \text{ m/s}^2$$

The plume radius and vertical velocity equations are solved iteratively for various heights (z) that are above the momentum rise phase where $z > 6.25D$.

2.3 Multiple Plumes

The single-plume calculations are conducted to determine the momentum phase and the single-plume parameters until the plumes merge. As the individual plumes rise, they will initially touch, then ultimately combine to create a larger, merged plume.

The parameters for the radius and height at which the plumes first touch (a_{touch} and z_{touch}) and initially combine (a_{comb} and z_{comb}) are calculated as follows:

$$a_{\text{touch}} = d/2 = \text{Plume Top-Hat Radius Where Plumes Initially Touch (m)}$$

$$z_{\text{touch}} = a_{\text{touch}}/0.16 + z_v = \text{Height Above Stack Where Plumes Initially Touch (m)}$$

$$a_{\text{comb}} = d \text{ (if } N \leq 2)$$

$$= d/2(N-1) \text{ (if } N > 2)$$

$$= \text{Plume Top-Hat Radius Where Plumes Initially Combine (m)}$$

$$z_{\text{comb}} = a_{\text{comb}}/0.16 + z_v = \text{Height Above Stack Where Plumes Initially Combine (m)}$$

Where:

$$d = \text{Distance Between Stacks (m)}$$

$$N = \text{Number of Stacks}$$

Once the plumes have fully merged, the merged-plume parameters are calculated iteratively for various heights (z) based on the single-stack parameters [radius (a) and velocity (V) at height (z)] times the factor $N^{0.25}$.

$$a_{\text{merge}} = a \times N^{0.25} = \text{Merged-Plume Top-Hat Radius (m)}$$

$$V_{\text{merge}} = V \times N^{0.25} = \text{Merged-Plume Vertical Velocity (m/s)}$$

3.0 THERMAL PLUME ANALYSIS

3.1 Diesel Engine Generators

The facility is laid out with the building in between two equal groups of equipment, as shown in Figure 1-2. The 40 diesel generators will be located in two groups of 20 on either side of the building. They will be laid out in a grid of five (east-west) by four (north-south) engines, with approximately 13.4 feet between the engine stacks in the east-west configuration. Since the Spillane method for merged plumes is limited to combining plumes aligned in a row, but not two dimensionally, the larger configuration of five stacks was analyzed using the multiple-plume methodology.

The stack parameter data used in the analysis, along with the detailed calculations and results, are presented in Appendix A. The height to the critical velocity for each case and source is presented in Table 3-1.

The maximum temperature analysis indicates that the momentum phase ends just 1.9 m above the stack (18.2 feet aboveground), after which the plumes become buoyancy-dominated. For individual generator plumes, the critical vertical velocity is reached at 77.7 feet above ground. For merged plumes, the maximum height at which V_{crit} is reached is 119.7 feet aboveground, even though full plume merging does not occur until 181.7 feet. By that height, the vertical velocity is already well below V_{crit} . Results for the minimum-ambient-temperature scenario follow the same pattern, with slightly lower heights.

Table 3-1: Height to Critical Velocity Results

Source	Number of Units Modeled Together	Number of Cells/Unit	Maximum Height Aboveground of Critical Velocity (ft)	
			Minimum Ambient Temperature Case	Maximum Ambient Temperature Case
Diesel Emergency Engines	5	1	116.3	119.7
Series 3000 Cooling Tower	1	4	125.5	125.5
508T Air-Cooled Screw Chillers	7	24	201.7	152.2

Notes:

- CEC critical velocity threshold is 5.3 m/s.
- Two ambient temperatures were assessed to identify the potential range of vertical heights to critical velocity.
- Maximum temperatures for the chillers and cooling tower are limited based on the Spillane equations and the stack exhaust temperature.
- Maximum height to V_{crit} is reported for merged plumes, even if the plumes are not fully merged.

3.2 Cooling Towers

There are two cooling towers proposed for the facility. They are located on either side of the building. Each cooling tower has four cells spaced less than a foot apart. Due to this close proximity of the cells, each cooling tower was treated as a single stack. The cooling tower locations are shown in Figure 1-3 next to the water tanks. The effective stack diameter from combining all cells was calculated as input. The single-plume methodology was used for the cooling tower.

The stack parameter data used in the analysis, along with the detailed calculations and results, are presented in Appendix A. The height to the critical velocity for each case is presented in Table 3-1.

The analysis shows that the top of the momentum phase occurs 45 m above the stack or 164.8 feet aboveground. After that point, the plumes are buoyancy-dominated. Solving for V_{crit} for buoyant plumes estimates a height within the momentum phase; thus, the associated buoyant-plume parameters are ignored.

The analysis determined the maximum height to V_{crit} for the single plume occurred within the momentum phase at 125.5 feet above ground, which is the same for both temperature cases.

3.3 Chillers

There are 28 chiller units proposed for the facility. They are located in two groups of 14 on either side of the building. They will be laid out in a grid of seven (east-west) by two (north-south), with approximately 16 feet between the chillers in the east-west configuration. Since the Spillane method for merged plumes is limited to combining plumes aligned in a row, but not two dimensionally, the larger configuration of seven units was analyzed using the multiple-plume methodology. Each chiller has 24 cells; thus, an effective stack diameter from combining all cells was calculated.

The stack parameter data used in the analysis, along with the detailed calculations and results, are presented in Appendix A. The height to the critical velocity for each temperature case is presented in Table 3-1. The maximum ambient temperature was set to the chiller exhaust temperature to ensure appropriate buoyant-plume height calculations.

The minimum-temperature analysis indicates that the momentum phase extends to 23.3 m above the stack (84.8 feet aboveground). The plumes are estimated to first touch at 63 feet above ground. Because this height lies within the momentum-dominated region, the corresponding buoyant-plume parameters are not applied.

Above the momentum phase, the plumes transition to buoyancy dominance. The critical velocity for an individual plume is reached at 99.5 feet above ground. For merged plumes, the maximum height at which V_{crit} is reached is 201.7 feet aboveground in the minimum temperature case, even though full merging occurs at a higher elevation. Results for the maximum ambient temperature scenario follow the same pattern.

4.0 CEC TRANSPORTATION ANALYSIS

To meet the SPPE requirements outlined in California Code of Regulations (CCR) Title 20, Division 2, Chapter 5, Appendix B (g)(5)(B) (CCR 2026), the transportation analysis needs to include the following:

- (i) A map at a scale of 1:24,000 that displays the airport or airstrip runway configuration, the airport influence area including all safety zones, and the proposed power plant site and related facilities;
- (ii) A thermal plume analysis that describes the plume's velocity;
- (iii) A discussion of the project's conformance with applicable Airport Land Use Compatibility Plan policies; and
- (iv) Copies of FAA Form 7460-1, Notice of Proposed Construction or Alteration, that were submitted or approved for any project component requiring notice.

Figure 1-1, although not to a scale of 1:24,000, displays the airport configuration relative to the RBIDC project site. The RBIDC project site does not line up with any of the takeoff or landing pathways for the airport.

Figure 4-1 shows the airport influence areas including safety zones, and that the RBIDC project site is located in Zone C of the Kern County Airport Land Use Compatibility Plan (County of Kern 2011). Zone C is the outer boundary of the Common Traffic Pattern Zone, an area where aircraft are commonly below 1,000 feet above ground. The project does not require a variance from County height limits and does not require FAA review; thus, the project conforms with applicable Airport Land Use Compatibility Plan policies.

The FAA Form 7460-1, Notice of Proposed Construction or Alteration is not required for this project, since there are no structures taller than 200 feet. Additionally, the closest takeoff/landing portion of a runway is 5,000 feet; thus, all structures must be below a 25-to-1 rise, and since all structures are less than 200 feet, this requirement is met. Lastly, the thermal plume analysis demonstrates the RBIDC project will have a less than significant impact on aircraft in the region.

5.0 CONCLUSIONS

The thermal plume analysis determined that in calm atmospheric conditions, the maximum height to V_{crit} was approximately 200 feet above ground. As calm conditions occur infrequently, the height to V_{crit} was conservatively estimated. This is a level at which no aircraft is expected to be flying over the project; thus, the thermal plumes from the RBIDC project will have a less than significant impact on aircraft in the region.

6.0 REFERENCES

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APPENDIX A – THERMAL PLUME CALCULATIONS

Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Diesel Engines
Thermal Plume Vertical Velocity Analysis - Multiple Plumes

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	272.59	Kelvin	31	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_j/d_p=0$ or $\theta_a=\theta_j$)						
Stack Exhaust Parameters						
Metric	Units	Imperial	Units	Notes	Equation	
Stack Height above ground h_s	3.64	meters	11.94	feet		
Stack Diameter D	0.30	meters	1.00	feet		
Stack Area	0.07	m ²	0.79	feet ²		$A = \pi(D/2)^2$
Volumetric Flow Q	11.31	m ³ /s	23,971	acfm		$A = \pi(D/2)^2 V_{exit}$
Stack Velocity V_{exit}	155.06	m/s	508.8	ft/s		$V_{exit} = Q/A$
Stack Potential Temp θ_s	757	Kelvin	903	F		
Initial Stack Buoyancy Flux F_b	22.61	m ³ /s ³			Section 2	$F_b = g V_{exit} D^3 (1 - \theta_a/\theta_s)/4$
No. of Stacks N	5				Section 3	Multiple Stack Multiplication Factor ($N^{0.25}$)
Distance between Stacks d	4.08	meters	13.40	feet	Section 3	
Stack parameters provided by Valley Wide						
Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	1.90	meters	6.3	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	77.53	m/s	254.4	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{exit}$
Plume radius a_{jet}	0.30	meters	1.0	feet	Section 3	$a_{jet} = D$
Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	0.76	meters	2.5	feet	Section 2.1	$6.25D[1 - (\theta_a/\theta_s)^{1/2}]$
Product $(Va)_v$	14.18	m ³ /s			Section 2.1	$V_{exit} D / (2(\theta_a/\theta_s)^{1/2})$
where: $(\theta_a/\theta_s)^{1/2} = (\theta_a/\theta_s)^{1/2} =$	0.6001	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$[(Va)_v^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s			plume-averaged vertical velocity	
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for z_{crit} only if $z > z_{jet}$	
where: $a = 1, c = 0$, and $b = -(0.12F_b)/(V_{crit}^3 * 0.16)^3$	-4.448549321					
and $d = (0.12F_b(6.25D-z_v) - (Va)_v^3)/(V_{crit}^3 * 0.16)^3$	-4669.483422					
$x=(z-z_v)$	18.336				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	19.10	meters	62.7	feet	$z_{crit} > z_{jet}$	$x + z_v$
Calculate the Merged Plume Parameters using the Spillane Methodology						
Height above Stack z_{touch}	13.52	meters	44.4	feet	Section 3 - height where the plumes initially touch	$a_{touch}/0.16+z_v$
Plume Top-Hat Radius a_{touch}	2.04	meters	6.7	feet	Section 3	$d/2$
Vertical Velocity V_{touch}	7.28	m/s	23.9	ft/s	Section 3	$[(Va)_v^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Height above Stack z_{comb}	51.81	meters	170.0	feet	Section 3 - height where the plumes fully combine	$a_{touch}/0.16+z_v$
Plume Top-Hat Radius a_{comb}	8.17	meters	26.8	feet	Section 3	if $N \leq 2$ then d else $d/(N-1)$
Vertical Velocity V_{comb}	2.63	m/s	8.6	ft/s	Section 3	$[(Va)_v^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Merged plumes parameters						
Height above Stack z_{merge}	51.81	meters	170.0	feet	Section 3	merged plumes start at z_{comb} height
Plume Top-Hat Radius a_{merge}	12.21	meters	40.1	feet	Section 3	$a \times N^{0.25}$
Vertical Velocity V_{merge}	3.93	m/s	12.9	ft/s	Section 3	$V \times N^{0.25}$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	3.544	m/s			plume-averaged vertical velocity	$5.3 \text{ m/s} / N^{0.25}$
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for z_{crit} only if $z > z_{jet}$	
where: $a = 1, c = 0$, and $b = -(0.12F_b)/(V_{crit}^3 * 0.16)^3$	-14.87462115					
and $d = (0.12F_b(6.25D-z_v) - (Va)_v^3)/(V_{crit}^3 * 0.16)^3$	156.1335884					
$x=(z-z_v)$	31.059				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	31.82	meters	104.4	feet	$z_{crit} > z_{jet}$	Note: Plumes not fully merged at this height

Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method	Merged Plume Radius (m) $a \times N^{0.25}$	Merged Plume Vertical Velocity (m/s) $V \times N^{0.25}$
11.9	3.64	0.0	0.15	155.06	Stack tip	Actual Stack Parameters	-	-
15.2	4.64	1.0	0.23	114.36	Momentum	Parameters linearly interpolated to z_{jet}	-	-
18.2	5.54	1.9	0.30	77.53	Top of Momentum (Jet)	End of Momentum Rise Height	-	-
56.3	17.16	13.5	2.04	7.28	Plumes Touch Height Buoyancy Dominated	Spillane	-	-
74.6	22.74	19.1	2.93	5.30	Height where $V_{crit}=5.3 \text{ m/s}$ Single Plume Buoyancy Dominated	Spillane	-	-
94.0	28.64	25.0	3.88	4.24	Buoyancy Dominated	Spillane	-	-
116.3	35.46	31.8	4.97	3.54	Height where $V_{crit}=5.3 \text{ m/s}$ for merged plume Buoyancy Dominated	Spillane	7.43	5.30
181.9	55.45	51.8	8.17	2.63	Merged Plume Height Buoyancy Dominated	Spillane	12.21	3.93
340.0	103.64	100.0	15.88	1.95	Buoyancy Dominated	Spillane	23.74	2.91
504.1	153.64	150.0	23.88	1.67	Buoyancy Dominated	Spillane	35.71	2.50
668.1	203.64	200.0	31.88	1.51	Buoyancy Dominated	Spillane	47.67	2.25
832.1	253.64	250.0	39.88	1.39	Buoyancy Dominated	Spillane	59.63	2.08
996.2	303.64	300.0	47.88	1.31	Buoyancy Dominated	Spillane	71.59	1.96
1160.2	353.64	350.0	55.88	1.24	Buoyancy Dominated	Spillane	83.56	1.86
1324.3	403.64	400.0	63.88	1.19	Buoyancy Dominated	Spillane	95.52	1.77
1632.4	503.64	500.0	79.88	1.10	Buoyancy Dominated	Spillane	119.45	1.65
2144.5	653.64	650.0	103.88	1.01	Buoyancy Dominated	Spillane	155.33	1.51
2308.5	703.64	700.0	111.88	0.98	Buoyancy Dominated	Spillane	167.30	1.47
2472.6	753.64	750.0	119.88	0.96	Buoyancy Dominated	Spillane	179.26	1.44
2636.6	803.64	800.0	127.88	0.94	Buoyancy Dominated	Spillane	191.22	1.41
2964.7	903.64	900.0	143.88	0.90	Buoyancy Dominated	Spillane	215.15	1.35
3292.8	1003.64	1000.0	159.88	0.87	Buoyancy Dominated	Spillane	239.07	1.30

Reference:
Spillane Method:

Best, P. et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katestone Environmental, Toowoong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
CEC critical vertical velocity threshold V_{crit} :
California Energy Commission, "County of Ventura, Department of Airports Comments: P3 Incompatible with Oxnard Airport," Puente Power Project, Docket 15-AFC-01, TN# 213674, 9/15/2016.

Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Diesel Engines
Thermal Plume Vertical Velocity Analysis - Multiple Plumes

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	312.04	Kelvin	102	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_j/d_i=0$ or $\theta_a=\theta_j$)						
Stack Exhaust Parameters						
Metric	Units	Imperial	Units	Notes	Equation	
Stack Height above ground h_s	3.64	meters	11.94	feet		
Stack Diameter D	0.30	meters	1.00	feet		
Stack Area	0.07	m ²	0.79	feet ²		$A = \pi(D/2)^2$
Volumetric Flow Q	11.31	m ³ /s	23,971	acfm		$A = \pi(D/2)^2$
Stack Velocity V_{stack}	155.06	m/s	508.8	ft/s		$V_{stack} = Q/A$
Stack Potential Temp θ_s	757	Kelvin	903	F		
Initial Stack Buoyancy Flux F_b	20.77	m ³ /s ³			Section 2	$F_b = g V_{stack} D^3 (1 - \theta_a/\theta_s)/4$
No. of Stacks N	5					
Distance between Stacks d	4.08	meters	13.40	feet	Section 3	Multiple Stack Multiplication Factor ($N^{0.25}$)
Stack parameters provided by Valley Wide						
Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	1.90	meters	6.3	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	77.53	m/s	254.4	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{stack}$
Plume radius a_{jet}	0.30	meters	1.0	feet	Section 3	$a_{jet} = D$
Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	0.68	meters	2.2	feet	Section 2.1	$6.25D[1 - (\theta_a/\theta_s)^{1/2}]$
Product $(Va)_j$	15.17	m ³ /s			Section 2.1	$V_{stack} D / (2(\theta_a/\theta_s)^{1/2})$
where: $(\theta_a/\theta_s)^{1/2} = (\theta_a/\theta_s)^{1/2} =$	0.6420	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$[(Va)_j^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s			plume-averaged vertical velocity	
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for z_{crit} only if $z > z_{jet}$	
where: $a = 1, c = 0$, and $b = -(0.12F_b)/(V_{crit}^3 * 0.16)^3$	-4.086339456					
and $d = (0.12F_b(6.25D-z_v) - (Va)_j^3)/(V_{crit}^3 * 0.16)^3$	-5719.8268					
$x=(z-z_v)$	19.355				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	20.04	meters	65.7	feet	$z_{crit} > z_{jet}$	$x + z_v$
Calculate the Merged Plume Parameters using the Spillane Methodology						
Height above Stack z_{touch}	13.44	meters	44.1	feet	Section 3 - height where the plumes initially touch	$a_{touch}/0.16+z_v$
Plume Top-Hat Radius a_{touch}	2.04	meters	6.7	feet	Section 3	$d/2$
Vertical Velocity V_{touch}	7.70	m/s	25.3	ft/s	Section 3	$[(Va)_j^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Height above Stack z_{comb}	51.73	meters	169.7	feet	Section 3 - height where the plumes fully combine	$a_{comb}/0.16+z_v$
Plume Top-Hat Radius a_{comb}	8.17	meters	26.8	feet	Section 3	if $N \geq 2$ then d else $d/(N-1)$
Vertical Velocity V_{comb}	2.64	m/s	8.6	ft/s	Section 3	$[(Va)_j^3 + 0.12F_b [(z-z_v)^3 - (6.25D-z_v)^3]]^{1/3} / a$
Merged plumes parameters						
Height above Stack z_{merge}	51.73	meters	169.7	feet	Section 3	merged plumes start at z_{comb} height
Plume Top-Hat Radius a_{merge}	12.21	meters	40.1	feet	Section 3	$a \times N^{0.25}$
Vertical Velocity V_{merge}	3.94	m/s	12.9	ft/s	Section 3	$V \times N^{0.25}$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	3.544	m/s			plume-averaged vertical velocity	$5.3 \text{ m/s} / N^{0.25}$
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for z_{crit} only if $z > z_{jet}$	
where: $a = 1, c = 0$, and $b = -(0.12F_b)/(V_{crit}^3 * 0.16)^3$	-13.66349947					
and $d = (0.12F_b(6.25D-z_v) - (Va)_j^3)/(V_{crit}^3 * 0.16)^3$	-191.2539359					
$x=(z-z_v)$	32.158				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	32.84	meters	107.7	feet	$z_{crit} > z_{jet}$	Note: Plumes not fully merged at this height

Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method	Merged Plume Radius (m) $a \times N^{0.25}$	Merged Plume Vertical Velocity (m/s) $V \times N^{0.25}$
11.9	3.64	0.0	0.15	155.06	Stack tip	Actual Stack Parameters	-	-
15.2	4.64	1.0	0.23	114.36	Momentum	Parameters linearly interpolated to z_{jet}	-	-
18.2	5.54	1.9	0.30	77.53	Top of Momentum (Jet)	End of Momentum Rise Height	-	-
56.0	17.08	13.4	2.04	7.70	Plumes Touch Height	Spillane	-	-
77.7	23.68	20.0	3.10	5.30	Buoyancy Dominated	Spillane	-	-
94.0	28.64	25.0	3.89	4.38	Height where $V_{crit}=5.3 \text{ m/s}$ Single Plume	Spillane	-	-
119.7	36.48	32.8	5.15	3.54	Buoyancy Dominated	Spillane	7.69	5.30
181.7	55.37	51.7	8.17	2.64	Height where $V_{crit}=5.3 \text{ m/s}$ for merged plume	Spillane	12.21	3.94
340.0	103.64	100.0	15.89	1.91	Buoyancy Dominated	Spillane	23.76	2.86
504.1	153.64	150.0	23.89	1.63	Buoyancy Dominated	Spillane	35.73	2.44
668.1	203.64	200.0	31.89	1.47	Buoyancy Dominated	Spillane	47.69	2.19
832.1	253.64	250.0	39.89	1.36	Buoyancy Dominated	Spillane	59.65	2.03
996.2	303.64	300.0	47.89	1.27	Buoyancy Dominated	Spillane	71.61	1.90
1160.2	353.64	350.0	55.89	1.21	Buoyancy Dominated	Spillane	83.58	1.81
1324.3	403.64	400.0	63.89	1.15	Buoyancy Dominated	Spillane	95.54	1.73
1652.4	503.64	500.0	79.89	1.07	Buoyancy Dominated	Spillane	119.46	1.60
2144.5	653.64	650.0	103.89	0.98	Buoyancy Dominated	Spillane	155.35	1.46
2308.5	703.64	700.0	111.89	0.96	Buoyancy Dominated	Spillane	167.32	1.43
2472.6	753.64	750.0	119.89	0.93	Buoyancy Dominated	Spillane	179.28	1.40
2636.6	803.64	800.0	127.89	0.91	Buoyancy Dominated	Spillane	191.24	1.37
2964.7	903.64	900.0	143.89	0.88	Buoyancy Dominated	Spillane	215.17	1.31
3292.8	1003.64	1000.0	159.89	0.85	Buoyancy Dominated	Spillane	239.09	1.27

Reference:
Spillane Method:

Best, P. et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katestone Environmental, Toowoong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
CEC critical vertical velocity threshold V_{crit} :
California Energy Commission, "County of Ventura, Department of Airports Comments: P3 Incompatible with Oxnard Airport," Puente Power Project, Docket 15-AFC-01, TN# 213674, 9/15/2016.

**Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Cooling Tower
Thermal Plume Vertical Velocity Analysis - Single Plume**

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	272.59	Kelvin	31	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_a/d_s=0$ or $\theta_a=\theta_s$)						
Stack Exhaust Parameters						
Stack Height above ground h_s	Metric	Units	Imperial	Units	Notes	Equation
Stack Height above ground h_s	5.24	meters	17.2	feet		
Cell Stack Diameter D_{cell}	3.60	meters	11.81	feet		
Number of cells per tower N_{cell}	4					
Effective Stack Diameter D	7.20	meters	23.62	feet		$=D_{cell} \times \sqrt{N_{cell}}$
Stack Area	40.70	m ²	438.18	feet ²		$A = \pi(D/2)^2$
Volumetric Flow Q	340.60	m ³ /s	721,691	acfm	total tower flow rate	$A = \pi(D/2)^2$
Stack Velocity V_{exit}	8.37	m/s	27.5	ft/s		$V_{exit} = Q/A$
Stack Potential Temp θ_s	303	Kelvin	85	F		
Initial Stack Buoyancy Flux F_0	105.44	m ³ /s ³			Section 2	$F_0 = gV_{exit}D^3(1-\theta_s/\theta_a)/4$

Stack parameters provided by Valley Wide

Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	44.99	meters	147.6	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	4.18	m/s	13.7	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{exit}$
Plume radius a_{jet}	7.20	meters	23.6	feet	Section 3	$a_{jet} = D$

Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	2.29	meters	7.5	feet	Section 2.1	$6.25D[1-(\theta_s/\theta_a)^{1/2}]$
Product $(Va)_0$	28.59	m ² /s			Section 2.1	$V_{exit}D/2(\theta_s/\theta_a)^{1/2}$
where: $(\theta_s/\theta_a)^{1/2} = (\theta_s/\theta_a)^{1/2} =$	0.9491	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$\{(Va)_0^3 + 0.12F_0 [(z-z_v)^2 - (6.25D-z_v)^2]\}^{1/3} / a$

Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s			plume-averaged vertical velocity	
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for Z_{crit} only if $> z_{jet}$	
where: $a = 1$, $c = 0$, and $b = -(0.12F_0)/(V_{crit}^2 * 0.16^2) =$	-20.74999812					
and $d = [0.12F_0(6.25D-z_v) - (Va)_0^2]/(V_{crit}^2 * 0.16^2) =$	-470.7564074					
$x=(z-z_v)$	21.746				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	24.03	meters	78.9	feet	Spillane height calculated to be within Momentum Jet	$x + z_v$

Plume Parameters						
Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method
17.2	5.24	0.0	3.60	8.37	Stack tip	Actual Stack Parameters
50.0	15.24	10.0	4.40	7.44	Momentum	Parameters linearly interpolated to z_{jet}
125.5	38.24	33.0	6.24	5.30	Momentum	Parameters linearly interpolated to z_{jet}
164.8	50.24	45.0	7.20	4.18	Top of Momentum (Jet)	End of Momentum Rise Height
181.2	55.24	50.0	7.63	4.03	Buoyancy Dominated	Spillane
345.3	105.24	100.0	15.63	3.16	Buoyancy Dominated	Spillane
509.3	155.24	150.0	23.63	2.76	Buoyancy Dominated	Spillane
673.4	205.24	200.0	31.63	2.50	Buoyancy Dominated	Spillane
837.4	255.24	250.0	39.63	2.32	Buoyancy Dominated	Spillane
1001.5	305.24	300.0	47.63	2.18	Buoyancy Dominated	Spillane
1165.5	355.24	350.0	55.63	2.07	Buoyancy Dominated	Spillane
1329.5	405.24	400.0	63.63	1.98	Buoyancy Dominated	Spillane
1657.6	505.24	500.0	79.63	1.84	Buoyancy Dominated	Spillane
2149.7	655.24	650.0	103.63	1.68	Buoyancy Dominated	Spillane
2313.8	705.24	700.0	111.63	1.64	Buoyancy Dominated	Spillane
2477.8	755.24	750.0	119.63	1.60	Buoyancy Dominated	Spillane
2641.9	805.24	800.0	127.63	1.57	Buoyancy Dominated	Spillane
2970.0	905.24	900.0	143.63	1.51	Buoyancy Dominated	Spillane
3298.0	1005.24	1000.0	159.63	1.46	Buoyancy Dominated	Spillane

Reference:
Spillane Method:

Best, P. et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katestone Environmental, Toowong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
CEC critical vertical velocity threshold V_{crit} :

California Energy Commission, "County of Ventura, Department of Airports Comments: P3 Incompatible with
Oxnard Airport," Puente Power Project, Docket 15-AFC-01, TN# 213674, 9/15/2016.

**Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Cooling Tower
Thermal Plume Vertical Velocity Analysis - Single Plume**

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	302.59	Kelvin	85	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_a/d_s=0$ or $\theta_a=\theta_s$)						
Stack Exhaust Parameters						
Stack Height above ground h_s	Metric	Units	Imperial	Units	Notes	Equation
Stack Height above ground h_s	5.24	meters	17.2	feet		
Cell Stack Diameter D_{cell}	3.60	meters	11.81	feet		
Number of cells per tower N_{cell}	4					
Effective Stack Diameter D	7.20	meters	23.62	feet		$=D_{cell} \times \sqrt{N_{cell}}$
Stack Area	40.70	m ²	438.18	feet ²		$A = \text{PI}() \times (D/2)^2$
Volumetric Flow Q	340.60	m ³ /s	721,691	acfm	total tower flow rate	$A = \pi(D/2)^2$
Stack Velocity V_{exit}	8.37	m/s	27.5	ft/s		$V_{exit} = Q/A$
Stack Potential Temp θ_s	303	Kelvin	85	F		
Initial Stack Buoyancy Flux F_0	0.00	m ³ /s ³			Section 2	$F_0 = gV_{exit}D^3(1-\theta_s/\theta_a)/4$

Stack parameters provided by Valley Wide

Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	44.99	meters	147.6	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	4.18	m/s	13.7	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{exit}$
Plume radius a_{jet}	7.20	meters	23.6	feet	Section 3	$a_{jet} = D$

Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	0.00	meters	0.0	feet	Section 2.1	$6.25D[1-(\theta_s/\theta_a)^{1/2}]$
Product $(Va)_0$	30.12	m ² /s			Section 2.1	$V_{exit}D/2(\theta_s/\theta_a)^{1/2}$
where: $(\theta_s/\theta_a)^{1/2} = (\theta_s/\theta_a)^{1/2} =$	1.0000	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$\{(Va)_0^3 + 0.12F_0 [(z-z_v)^2 - (6.25D-z_v)^2]^{1/3}\} / a$

Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s			plume-averaged vertical velocity	
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$					Solve for z_{crit} only if $> z_{jet}$	
where: $a = 1$, $c = 0$, and $b = -(0.12F_0)/(V_{crit}^2 * 0.16^3) =$	0					
and $d = [0.12F_0(6.25D-z_v) - (Va)_0^3]/(V_{crit}^2 * 0.16^3) =$	-44809.14149					
$x=(z-z_v)$	35.519				solve using	CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	35.52	meters	116.5	feet	Spillane height calculated to be within Momentum Jet	$x + z_v$

Plume Parameters						
Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method
17.2	5.24	0.0	3.60	8.37	Stack tip	Actual Stack Parameters
50.0	15.24	10.0	4.40	7.44	Momentum	Parameters linearly interpolated to z_{jet}
125.5	38.24	33.0	6.24	5.30	Momentum	Parameters linearly interpolated to z_{jet}
164.8	50.24	45.0	7.20	4.18	Top of Momentum (Jet)	End of Momentum Rise Height
181.2	55.24	50.0	8.00	3.76	Buoyancy Dominated	Spillane
345.3	105.24	100.0	16.00	1.88	Buoyancy Dominated	Spillane
509.3	155.24	150.0	24.00	1.25	Buoyancy Dominated	Spillane
673.4	205.24	200.0	32.00	0.94	Buoyancy Dominated	Spillane
837.4	255.24	250.0	40.00	0.75	Buoyancy Dominated	Spillane
1001.5	305.24	300.0	48.00	0.63	Buoyancy Dominated	Spillane
1165.5	355.24	350.0	56.00	0.54	Buoyancy Dominated	Spillane
1329.5	405.24	400.0	64.00	0.47	Buoyancy Dominated	Spillane
1657.6	505.24	500.0	80.00	0.38	Buoyancy Dominated	Spillane
2149.7	655.24	650.0	104.00	0.29	Buoyancy Dominated	Spillane
2313.8	705.24	700.0	112.00	0.27	Buoyancy Dominated	Spillane
2477.8	755.24	750.0	120.00	0.25	Buoyancy Dominated	Spillane
2641.9	805.24	800.0	128.00	0.24	Buoyancy Dominated	Spillane
2970.0	905.24	900.0	144.00	0.21	Buoyancy Dominated	Spillane
3298.0	1005.24	1000.0	160.00	0.19	Buoyancy Dominated	Spillane

Reference:
Spillane Method:

Best, P. et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katestone Environmental, Toowong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
CEC critical vertical velocity threshold V_{crit} :

California Energy Commission, "County of Ventura, Department of Airports Comments: P3 Incompatible with
Oxnard Airport," Puente Power Project, Docket 15-AFC-01, TN# 213674, 9/15/2016.

Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Chillers
Thermal Plume Vertical Velocity Analysis - Multiple Plumes

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	272.59	Kelvin	31	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_j/d_p=0$ or $\theta_a=\theta_j$)						
Stack Exhaust Parameters						
	Metric	Units	Imperial	Units	Notes	Equation
Stack Height above ground h_s	2.51	meters	8.25	feet		
Cell Stack Diameter D_{cell}	0.76	meters	2.50	feet		
Number of cells per tower N_{cell}	24					
Effective Stack Diameter D	3.73	meters	12.25	feet		$=D_{cell} \times \sqrt{N_{cell}}$
Stack Area	10.94	m ²	117.81	feet ²		$A = \pi(D/2)^2$
Volumetric Flow Q	134.12	m ³ /s	284,177	acfm	total tower flow rate	$A = \pi(D/2)^2$
Stack Velocity V_{stack}	12.26	m/s	40.2	ft/s		$V_{stack} = Q/A$
Stack Potential Temp θ_s	310	Kelvin	98	F		
Initial Stack Buoyancy Flux F_{s0}	50.32	m ³ /s ³			Section 2	$F_{s0} = gV_{stack}D^3(1-\theta_s/\theta_a)/4$
No. of Stacks N	7					
Distance between Stacks d	1.63	meters	16.00	feet	Section 3	Multiple Stack Multiplication Factor ($N^{0.25}$)

Stack parameters provided by Valley Wide						
Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	23.33	meters	76.5	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	6.13	m/s	20.1	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{stack}$
Plume radius a_{jet}	3.73	meters	12.2	feet	Section 3	$a_{jet} = D$

Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	1.45	meters	4.7	feet	Section 2.1	$6.25D[1-(\theta_s/\theta_a)^{1/2}]$
Product $(Va)_s$	21.46	m ³ /s			Section 2.1	$V_{stack}D/2(\theta_s/\theta_a)^{1/2}$
where: $(\theta_s/\theta_a)^{1/2} = (\theta_s/\theta_a)^{1/2} =$	0.9380	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$([Va]_s^3 + 0.12F_s [(z-z_v)^3 - (6.25D-z_v)^3])^{1/3} / a$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s				plume-averaged vertical velocity
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$	Solved Iteratively Below					Solve for z_{crit} only if $z > z_{jet}$
where: $a = 1$, $c = 0$, and $b = -(0.12F_s)/(V_{crit}^2 + 0.16)^{1/3}$	-9.901315826					
and $d = [0.12F_s(6.25D-z_v)^3 - (Va)_s^3]/(V_{crit}^2 + 0.16)^{1/3}$	-11453.92676					
$x=(z-z_v)$	26.371					solve using CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	27.82	meters	91.3	feet		$z_{crit} > z_{jet}$

Calculate the Merged Plume Parameters using the Spillane Methodology						
Height above Stack z_{touch}	16.69	meters	54.7	feet	Section 3 - height where the plumes initially touch	$a_{touch}/0.16+z_v$
Plume Top-Hat Radius a_{touch}	2.44	meters	8.0	feet	Section 3	$d/2$
Vertical Velocity V_{touch}	8.33	m/s	27.3	ft/s	Section 3	$([Va]_s^3 + 0.12F_s [(z-z_v)^3 - (6.25D-z_v)^3])^{1/3} / a$
Height above Stack z_{comb}	92.88	meters	304.7	feet	Section 3 - height where the plumes fully combine	$a_{comb}/0.16+z_v$
Plume Top-Hat Radius a_{comb}	14.63	meters	48.0	feet	Section 3	if $N \geq 2$ then d else $d/2(N-1)$
Vertical Velocity V_{comb}	2.64	m/s	8.7	ft/s	Section 3	$([Va]_s^3 + 0.12F_s [(z-z_v)^3 - (6.25D-z_v)^3])^{1/3} / a$
Merged plumes parameters						
Height above Stack z_{merge}	92.88	meters	304.7	feet	Section 3	merged plumes start at z_{comb} height
Plume Top-Hat Radius a_{merge}	23.80	meters	78.1	feet	Section 3	$a \times N^{0.25}$
Vertical Velocity V_{merge}	4.29	m/s	14.1	ft/s	Section 3	$V \times N^{0.25}$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	3.258	m/s				plume-averaged vertical velocity
Solve for $V=V_{crit}$ using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$	Solved Iteratively Below					Solve for z_{crit} only if $z > z_{jet}$
where: $a = 1$, $c = 0$, and $b = -(0.12F_s)/(V_{crit}^2 + 0.16)^{1/3}$	-42.61048168					
and $d = [0.12F_s(6.25D-z_v)^3 - (Va)_s^3]/(V_{crit}^2 + 0.16)^{1/3}$	-49299.16934					
$x=(z-z_v)$	57.513					solve using CUBIC EQUATION CALCULATOR
Height above Stack z_{crit}	58.96	meters	193.4	feet		Note: Plumes not fully merged at this height

Plume Parameters								
Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method	Merged Plume Radius (m) $a \times N^{0.25}$	Merged Plume Vertical Velocity (m/s) $V \times N^{0.25}$
8.2	2.51	0.0	1.87	12.26	Stack tip	Actual Stack Parameters	-	-
41.1	12.51	10.0	2.67	9.63	Momentum	Parameters linearly interpolated to z_{jet}	-	-
57.5	17.51	15.0	3.07	8.32	Momentum	Parameters linearly interpolated to z_{jet}	-	-
84.8	25.84	23.3	3.73	6.13	Top of Momentum (jet)	End of Momentum Rise Height	-	-
99.5	30.33	27.8	4.22	5.30	Height where $V_{crit}=5.3$ m/s Single Plume Buoyancy Dominated	Spillane	-	-
201.7	61.47	59.0	9.20	3.26	Height where $V_{crit}=5.3$ m/s for merged plume Buoyancy Dominated	Spillane	14.97	5.30
313.0	95.40	92.9	14.63	2.64	Buoyancy Dominated	Spillane	23.80	4.29
336.3	102.51	100.0	15.77	2.56	Buoyancy Dominated	Spillane	25.65	4.16
500.4	152.51	150.0	23.77	2.19	Buoyancy Dominated	Spillane	38.66	3.56
664.4	202.51	200.0	31.77	1.97	Buoyancy Dominated	Spillane	51.67	3.20
828.5	252.51	250.0	39.77	1.82	Buoyancy Dominated	Spillane	64.69	2.96
992.5	302.51	300.0	47.77	1.71	Buoyancy Dominated	Spillane	77.70	2.78
1156.5	352.51	350.0	55.77	1.62	Buoyancy Dominated	Spillane	90.71	2.64
1320.6	402.51	400.0	63.77	1.55	Buoyancy Dominated	Spillane	103.72	2.52
1648.7	500.51	500.0	79.77	1.44	Buoyancy Dominated	Spillane	129.75	2.34
2140.8	652.51	650.0	103.77	1.32	Buoyancy Dominated	Spillane	168.79	2.14
2304.8	702.51	700.0	111.77	1.28	Buoyancy Dominated	Spillane	181.80	2.09
2468.9	752.51	750.0	119.77	1.25	Buoyancy Dominated	Spillane	194.81	2.04
2632.9	802.51	800.0	127.77	1.23	Buoyancy Dominated	Spillane	207.83	2.00
2961.0	902.51	900.0	143.77	1.18	Buoyancy Dominated	Spillane	233.85	1.92
3289.1	1002.51	1000.0	159.77	1.14	Buoyancy Dominated	Spillane	259.88	1.85

Reference:
Spillane Method:

Best, P., et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katesone Environmental, Toowoong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
CEC critical vertical velocity threshold V_{crit} :
California Energy Commission, "County of Ventura, Department of Airports Comments: P3 Incompatible with Oxnard Airport," Puente Power Project, Docket 15-AFC-01, TN# 213674, 9/15/2016.

Valley Wide Construction - Inyokern Data Center Thermal Plume Modeling - Chillers
Thermal Plume Vertical Velocity Analysis - Multiple Plumes

Input Parameters						
Ambient Conditions	Metric	Units	Imperial	Units	Notes	Equation
Ambient Temp θ_a	309.82	Kelvin	98	F		
Gravity g	9.81	m/s ²				
Assume calm wind conditions						
Assume neutral conditions ($d_j/d_p=0$ or $\theta_a=\theta_j$)						
Stack Exhaust Parameters						
	Metric	Units	Imperial	Units	Notes	Equation
Stack Height above ground h_s	2.51	meters	8.25	feet		
Cell Stack Diameter D_{cell}	0.76	meters	2.50	feet		
Number of cells per tower N_{cell}	24					
Effective Stack Diameter D	3.73	meters	12.25	feet		$=D_{cell} \times \sqrt{N_{cell}}$
Stack Area	10.94	m ²	117.81	feet ²		$A = \pi(D/2)^2$
Volumetric Flow Q	134.12	m ³ /s	284,177	acfm	total tower flow rate	$A = \pi(D/2)^2$
Stack Velocity V_{stack}	12.26	m/s	40.2	ft/s		$V_{stack} = Q/A$
Stack Potential Temp θ_s	310	Kelvin	98	F		
Initial Stack Buoyancy Flux F_{s0}	0.00	m ³ /s ³			Section 2	$F_{s0} = gV_{stack}D^3(1-\theta_s/\theta_a)/4$
No. of Stacks N	7					
Distance between Stacks d	1.63	meters	16.00	feet	Section 3	Multiple Stack Multiplication Factor ($N^{0.25}$)

Stack parameters provided by Valley Wide

Calculate the Momentum Phase Plume Parameters						
Height above Stack z_{jet}	23.33	meters	76.5	feet	Plume rise in calm conditions - Section 2.1	$z_{jet} = 6.25D$
Plume Average Vertical Velocity V_{jet}	6.13	m/s	20.1	ft/s	Spillane calm-wind assumption - Section 3	$V_{jet} = 0.5V_{stack}$
Plume radius a_{jet}	3.73	meters	12.2	feet	Section 3	$a_{jet} = D$

Calculate the Single Plume Parameters using the Spillane Methodology above the Momentum Phase						
Virtual Source Height above stack z_v	0.00	meters	0.0	feet	Section 2.1	$6.25D(1-(\theta_s/\theta_a)^{1/2})$
Product $(Va)_s$	22.87	m ³ /s			Section 2.1	$V_{stack}D/2(\theta_s/\theta_a)^{1/2}$
where: $(\theta_s/\theta_a)^{1/2} = (\theta_s/\theta_a)^{1/2} =$	1.0000	unitless				
Plume Top-Hat Radius a	Solved Iteratively Below				Section 2.1	$0.16(z-z_v)$
Vertical Velocity V	Solved Iteratively Below				Section 2.1	$(\frac{F_{s0}}{V^2})^{0.5} + 0.12F_s [(z-z_v)^2 - (6.25D-z_v)^2]^{0.75} / a$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	5.3	m/s				plume-averaged vertical velocity
Solve for V in V_{crit} using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$						
where: $a = 1$, $c = 0$, and $b = -(0.12F_s)/(V_{crit}^2 + 0.16)^{0.75}$						Solve for z_{crit} only if $z > z_{jet}$
and $d = [0.12F_s(6.25D-z_v)^2 - (Va)_s] / (V_{crit}^2 + 0.16)^{0.75}$						
$x=(z-z_v)$	26.973					
Height above Stack z_{crit}	26.97	meters	88.5	feet		solve using CUBIC EQUATION CALCULATOR

Calculate the Merged Plume Parameters using the Spillane Methodology						
Height above Stack z_{touch}	15.24	meters	50.0	feet	Section 3 - height where the plumes initially touch	$a_{touch}/0.16+z_v$
Plume Top-Hat Radius a_{touch}	2.44	meters	8.0	feet	Section 3	$d/2$
Vertical Velocity V_{touch}	9.38	m/s	30.8	ft/s	Section 3	$(\frac{F_{s0}}{V^2})^{0.5} + 0.12F_s [(z-z_v)^2 - (6.25D-z_v)^2]^{0.75} / a$
Height above Stack z_{comb}	91.44	meters	300.0	feet	Section 3 - height where the plumes fully combine	$a_{comb}/0.16+z_v$
Plume Top-Hat Radius a_{comb}	14.63	meters	48.0	feet	Section 3	if $N \geq 2$ then d else $d/2(N-1)$
Vertical Velocity V_{comb}	1.56	m/s	5.1	ft/s	Section 3	$(\frac{F_{s0}}{V^2})^{0.5} + 0.12F_s [(z-z_v)^2 - (6.25D-z_v)^2]^{0.75} / a$

Merged plumes parameters						
Height above Stack z_{merge}	91.44	meters	300.0	feet	Section 3	merged plumes start at z_{comb} height
Plume Top-Hat Radius a_{merge}	23.80	meters	78.1	feet	Section 3	$a \times N^{0.25}$
Vertical Velocity V_{merge}	2.54	m/s	8.3	ft/s	Section 3	$V \times N^{0.25}$
Solve for Height of CEC critical vertical velocity threshold V_{crit}	3.258	m/s				plume-averaged vertical velocity $5.3 \text{ m/s} / N^{0.25}$
Solve for V in V_{crit} using the cubic equation $ax^3 + bx^2 + cx + d = 0$, where $x=(z-z_v)$						
where: $a = 1$, $c = 0$, and $b = -(0.12F_s)/(V_{crit}^2 + 0.16)^{0.75}$						Solve for z_{crit} only if $z > z_{jet}$
and $d = [0.12F_s(6.25D-z_v)^2 - (Va)_s] / (V_{crit}^2 + 0.16)^{0.75}$						
$x=(z-z_v)$	43.873					
Height above Stack z_{crit}	43.87	meters	143.9	feet		solve using CUBIC EQUATION CALCULATOR

Height above ground (ft)	Height above ground (m)	Height above stack (m)	a = Single Plume Radius (m)	V = Single Plume Vertical Velocity (m/s)	Phase	Calculation Method	Merged Plume Radius (m) $a \times N^{0.25}$	Merged Plume Vertical Velocity (m/s) $V \times N^{0.25}$
8.2	2.51	0.0	1.87	12.26	Stack tip	Actual Stack Parameters	-	-
41.1	12.51	10.0	2.67	9.63	Momentum	Parameters linearly interpolated to z_{jet}	-	-
57.5	17.51	15.0	3.07	8.32	Momentum	Parameters linearly interpolated to z_{jet}	-	-
84.8	25.84	23.3	3.73	6.13	Top of Momentum (jet)	End of Momentum Rise Height	-	-
96.7	29.49	27.0	4.32	5.30	Height where $V_{crit}=5.3 \text{ m/s}$ Single Plume Buoyancy Dominated	Spillane	-	-
152.2	46.39	43.9	7.02	3.26	Height where $V_{crit}=5.3 \text{ m/s}$ for merged plume Buoyancy Dominated	Spillane	11.42	5.30
308.2	93.95	91.4	14.63	1.56	Buoyancy Dominated	Spillane	23.80	2.54
336.3	102.51	100.0	16.00	1.43	Buoyancy Dominated	Spillane	26.03	2.33
500.4	152.51	150.0	24.00	0.95	Buoyancy Dominated	Spillane	39.04	1.55
664.4	202.51	200.0	32.00	0.71	Buoyancy Dominated	Spillane	52.05	1.16
828.5	252.51	250.0	40.00	0.57	Buoyancy Dominated	Spillane	65.06	0.93
992.5	302.51	300.0	48.00	0.48	Buoyancy Dominated	Spillane	78.08	0.78
1156.5	352.51	350.0	56.00	0.41	Buoyancy Dominated	Spillane	91.09	0.66
1320.6	402.51	400.0	64.00	0.36	Buoyancy Dominated	Spillane	104.10	0.58
1648.7	502.51	500.0	80.00	0.29	Buoyancy Dominated	Spillane	130.13	0.47
2140.8	652.51	650.0	104.00	0.22	Buoyancy Dominated	Spillane	169.16	0.36
2304.8	702.51	700.0	112.00	0.20	Buoyancy Dominated	Spillane	182.18	0.33
2468.9	752.51	750.0	120.00	0.19	Buoyancy Dominated	Spillane	195.19	0.31
2632.9	802.51	800.0	128.00	0.18	Buoyancy Dominated	Spillane	208.20	0.29
2961.0	902.51	900.0	144.00	0.16	Buoyancy Dominated	Spillane	234.23	0.26
3289.1	1002.51	1000.0	160.00	0.14	Buoyancy Dominated	Spillane	260.25	0.23

Reference:
Spillane Method:

Best, P., et al. 2003. Aviation Safety and Buoyant Plumes. Presented at the Clean Air Conference, Newcastle, New South Wales, Australia. By Peter Best, Lena Jackson, Mark Kanowski of Katesone Environmental, Toowoong, Queensland, Australia and Kevin Spillane of Bendigo, Victoria, Australia
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