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STATE OF CALIFORNIA
State Energy Resources
Conservation and Development Commission

In the Matter of:	)	Docket No. 15-AFC-01
	)	**INTERVENORS' SIERRA CLUB LOS PADRES CHAPTER, ENVIRONMENTAL COALITION OF VENTURA COUNTY AND ENVIRONMENTAL DEFENSE CENTER**
APPLICATION FOR CERTIFICATION OF THE PUENTE POWER PROJECT	))	

Exhibit No. 4037

Supplemental Testimony of Dr. H. Andrew Gray

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DECLARATION OF
Dr. H. Andrew Gray

I, **Dr. H. Andrew Gray**, declare as follows:

1. I am an environmental engineer and atmospheric scientist with over 35 years of professional experience performing air quality dispersion modeling and related analyses. I received a Master of Science (MS) and a Ph.D. in Environmental Engineering Science from the California Institute of Technology and have conducted extensive air pollution related research and have developed and worked with atmospheric dispersion models in academic, regulatory and consulting environments.

2. A copy of my professional qualifications and experience is attached and incorporated by reference.

3. I prepared the Closing Testimony of Dr. H. Andrew Gray submitted by intervenors the Los Padres Chapter of the Sierra Club, the Environmental Coalition of Ventura County, and the Environmental Defense Center. The basis for my testimony is set forth in the testimony itself and is incorporated by reference.

4. It is my professional opinion that the prepared testimony is valid and accurate with respect to the issues addressed therein.

5. I am personally familiar with the facts and conclusions related in the testimony and, if called as a witness, could testify competently thereto.

I declare under penalty of perjury that the foregoing is true and correct to the best of my knowledge and belief.

Dated: July 14, 2017 Signed: H Andrew Gray

At: San Rafael, CA

STATE OF CALIFORNIA

Energy Resources Conservation and Development Commission

In the Matter of: APPLICATION FOR CERTIFICATION FOR THE PUENTE POWER PROJECT	Docket No. 15-AFC-01

INTERVENOR SIERRA CLUB, ENVIROMENTAL DEFENSE CENTER, ENVIRONMENTAL COALITION OF VENTURA COUNTY

Exhibit 4037

Supplemental Testimony of Dr. H. Andrew Gray

Summary of Testimony

I am an air quality consultant with over 35 years experience performing air pollution research in academic, regulatory and consulting environments. This testimony describes my assessment of the June 13, 2017 Supplemental Testimony of CEC Staff on Traffic and Transportation issues.[1] Specifically, I reviewed the modeling of the thermal plumes expected to be generated by the proposed GE7HA CTG and the LM6000 CTG alternative designs as part of the Off-Site Alternative described in the Supplemental Testimony, and the imputed impacts to aviation. I concluded that the Staff's analysis over-states the plume impacts to aviation from the alternative designs at the alternative sites, and further conclude that impacts to aviation would not be significant, for the following reasons:

(1) The CEC Supplemental Testimony relies upon the "Spillane Approach" to model aviation impacts. However, the assumption of completely windless conditions assumed by this approach is not just conservative, but completely unrealistic.

- The Spillane Approach will overestimate the critical height in which the threshold vertical velocity of the plume is reached. This over-estimation occurs because the calculations are based on an unrealistic meteorological situation including calm winds

[1] *Staff's Supplemental Testimony Filed in Response to the Committee's March 10, 2017 Order for the Puente Power Project*, California Energy Commission (CEC) (June 23, 2017), TN #218274 ("Supplemental Testimony").

in the entire lower stratosphere (up to unrealistic heights), no shear between the plume the ambient air, and no turbulent mixing. In addition, the approach assumes neutral atmospheric stability which rarely if ever occurs during calm low wind speed conditions.

- If even a very light wind is assumed, the estimate of critical height will be much lower. The predicted critical height using the Spillane Approach is very sensitive to even a small perturbation (non-zero wind) which will dramatically lower the prediction of critical height.
- Using an alternative "textbook" approach with added entrainment to account for light horizontal winds in calm neutral atmosphere reduced the predicted critical height for the the LM6000 CTG (1 Stack) alternative from 512 ft (using the Spillane Approach) to 288 ft (using the alternative).

(2) The CEC Supplemental Testimony omits the Spillane Approach calculations of the plume's temperature as it rises. I conducted these calculations and found that at the height the plume's threshold vertical velocity is reached, the plume is a similar temperature to ambient air and therefore would exert very little force on passing aircraft.

(3) Additionally, the peak plume velocities were **incorrectly** assumed to be twice the estimated average plume velocities.

- The atmospheric equations describing the physics of the plume can be used to compute the plume average velocity, but not the peak (maximum) velocity at the center of the radially spreading plume. A bivariate normal distribution was improperly "imposed" upon the vertical velocity profile in the CEC analysis. Although the observed distribution resembles the shape of a normal distribution, there a few key differences in the mathematical properties of the two distributions that preclude its use.
- To use a bivariate normal distribution to represent the plume's vertical velocity, the velocity at the plume edge must be effectively zero. In the case of a bivariate normal distribution in which the diameter of the plume is assigned to a width of 4σ, the vertical velocity at the plume edge is equal to 13.5% of the maximum velocity, which is not close to zero.
- It can be shown that the width of the normal distribution (4σ) that was included in the "fit" of the velocity profile was chosen arbitrarily. The ratio of the maximum velocity to the average velocity, V_{max}/V_{avg}, was preordained to be equal to 2 by the arbitrary selection of the included width.
- The ratio V_{max}/V_{avg} was incorrectly computed in the "textbook" calculations that purportedly justify the use of the V_{max}/V_{avg} ratio of 2. Applying the correct

calculation methodology, the V_{max}/V_{avg} ratio for a width of 4σ should have been computed to be 2.3 (not 2.0) .

- Because V_{max}/V_{avg} was arbitrarily "preordained" to be 2 (and not correctly computed), CEC's estimated peak vertical velocities using this ratio are largely unreliable.

Considering that (1) the critical heights in the Supplemental Testimony have been overestimated using the Spillane model, which assumes windless conditions which are highly unlikely to actually occur, AND (2) the peak vertical velocities are likely not much higher than the plume average velocities at a height in which the overwhelming majority (more than 80%) of the initial plume velocity has been lost, I concluded that the CEC analysis using the Spillane Approach and the arbitrary doubling to estimate the maximum velocity is grossly overestimating the potential for harm caused by the power plant plumes at the Off-Site Alternative.

Qualifications

I am an environmental engineer and atmospheric scientist with over 35 years of professional experience performing air quality dispersion modeling and related analyses. I received my Bachelor of Science (BS) in Civil Engineering / Engineering and Public Policy from Carnegie-Mellon University in 1979. I received a Master of Science (MS) and a Ph.D. in Environmental Engineering Science from the California Institute of Technology (Caltech). My doctoral thesis was on the control of atmospheric carbon particles. I have developed and worked with atmospheric dispersion models in academic, regulatory and consulting environments. I have expertise in air quality monitoring, statistical analysis, atmospheric physics, atmospheric chemistry, meteorology, particle processes, deposition, numerical methods, computer modeling, air quality control strategy design and environmental public policy. An integral part of my research has involved developing and applying atmospheric dispersion modeling tools to determine the air quality impacts of pollutant sources in the areas surrounding those sources. My experience and qualifications are provided on my Curriculum Vitae attached to this Testimony.

Testimony

For the reasons set forth below, I concluded that the Staff's analysis over-states the plume impacts to aviation at the Off-Site Alternative, and further conclude that impacts to aviation at the Del Norte site would not be significant.

1. The Spillane Approach drastically overestimates the critical height of plume impacts of the alternative project designs by assuming unrealistically windless conditions.

a. *The Spillane Approach equations are based on a calm, neutral environment with no wind, heat transfer, or turbulent mixing.*

The Spillane Approach makes use of a simplified solution to the set of equations that describe the atmospheric physics occurring in and around a buoyant plume (or strictly speaking a buoyant jet, which is a combination of a jet and a plume) in a calm neutral environment. The steady stream of exhaust exiting from a power plant stack rises vertically from the stack opening due to both its momentum and buoyancy. The longitudinal (upwards) momentum of the plume is due to the initial velocity of the air mass and is typically quickly dissipated; however, the vertical force due to buoyancy of the air mass will often transport plumes hundreds of feet vertically.

The Spillane Approach considers equations for (1) the radial growth of the plume (assumed to grow linearly with height in a cone shape, with an angle of 8.9 degrees), (2) the buoyancy flux (which is assumed to remain constant with height), (3) the longitudinal momentum flux (the buoyant force is transferred to upwards momentum), and (4) the heat flux (assumed to be zero, which means that there is no heat transferred between the expanding plume and it surroundings). The buoyant force is what "drives" the plume, just like linear momentum drives a jet.

The Spillane Approach was developed by Dr. Kevin Spillane of Katestone Scientific (Brisbane, Australia) and has been used (by Katestone and others) to assess updraft velocities that might affect aircraft in locations in Australia and the US.[2, 3] Dr. Spillane developed a "top-

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[2] For example, see *Plume Vertical Velocity Assessment of a Proposed Gas-Fired Power Station at Russell City Energy Center*, prepared by Katestone Environmental for Atmospheric Dynamics, Pty Ltd (July 2007). http://www.energy.ca.gov/sitingcases/russellcity_amendment/documents/others/2007-07-11_RCEC_PLUME_ANALYSIS_FINAL.PDF ("RCEC Report"), attached to this expert report as Attachment 1. The RCEC Report describes an assessment of a proposed gas-fired power station at Russell City Energy Center in Northern California. The report also includes an appendix showing how the Spillane Approach was used to evaluate a gas-turbine power station at Oakey, Queensland, Australia.

hat" parameterization of an expanding plume in a "calm neutral environment." The Spillane Approach was adopted from equations developed by Best (2003)[4] which represent a solution of the governing physical atmospheric equations under a set of theoretical extreme conditions including absolute zero horizontal winds.

The Spillane Approach considers a continuously emitted buoyant plume that rises due to the difference in temperature between the plume and the surrounding atmosphere (the upwards force is due to Archimedes Principle). The total upwards force per time due to the plume's buoyancy (the buoyancy flux) is constant, and it is assumed that no energy is transferred between the plume and the surrounding atmosphere (either due to heat transfer or mixing). The method further assumes that there is <u>no</u> shear between the plume and the surrounding atmosphere, and therefore assumes that the velocity at the horizontal edge of the plume is equal to zero.

There is an upwards force on a warm plume due to its buoyancy (temperature difference relative to the atmosphere). Spillane's Approach assumes that there are <u>no</u> additional forces acting upon the plume as it rises through the atmosphere. In fact, the only reason the plume "slows down" at all (the vertical velocity decreases) in Spillane's model is because the plume is spreading out horizontally (using an assumed conic spread with an angle of 8.9 degrees) and in the process entraining air, and therefore becoming heavier (i.e., the plume grows by adding mass to itself, and that higher mass, with the same upwards buoyant momentum, will slow down). If the plume were not spreading (and therefore not gaining mass), Spillane's Approach would assume that the plume would rise at a constant velocity upwards without bound.

Solutions to the system of equations describing the atmosphere (including Spillane's approach) include a relationship in which the vertical velocity (V) is inversely proportional to the cube root of height (z). This creates a "slow" decline in which the vertical velocity never actually goes to zero, as the plume continues to spread out horizontally.

Most notably, the Spillane Approach is based on hypothetical conditions and represents the mathematical solution to the atmospheric equations under non-realistic "ideal" conditions, including (1) horizontal winds that are identically equal to zero in the *entire vertical column* of the atmosphere in which the plume is traversing, (2) zero wind shear between the plume and the atmosphere, (3) zero heat transfer, and (4) no turbulent mixing between the plume and the atmosphere. The entrainment is "minimized" to account for the linearly spreading plume (in a cone at a prescribed angle of 8.9 degrees).

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[3] Atmospheric Dynamics, Inc. (2012). *Plume Vertical Velocity Assessment for the Quail Brush Generation Project (San Diego, CA)* (February 2012). http://www.energy.ca.gov/sitingcases/quailbrush/documents/applicant/2012-03-07_Vertical_Velocity_Plume_Assessment_TN-64030.pdf

[4] Best 2003.

b. The assumption of entirely calm wind conditions under neutral atmospheric stability is unrealistic and unreasonable, especially in the summer.

Although calm neutral conditions can result in a high plume rise, the plume velocity calculations using the Spillane Approach are not just "conservative," they are *unreasonable* – they represent hypothetical conditions that would be highly unlikely to ever occur in the atmosphere. It is one thing to build in a margin of safety, however these calculations represent nearly impossible hypothetical conditions.

In the real world, the atmosphere (at rest) will cause at least some (downward) drag force on the rising plume. Even a neutral calm atmosphere is not completely frictionless. The drag forces will slightly erode the plume edge, causing *some* turbulent mixing, that will lead to increased entrainment of ambient air into the plume. These processes have not just been minimized in the Spillane Approach: they have been set to zero in order to estimate a theoretical extreme case of 'unfettered" plume rise. According to Katestone, "The wind profile is assumed constant with height with no occurrence of wind-shear. In reality, there is a considerable variation with height, especially in light winds."[5]

In examining representative wind data for the Puente site, CEC reported that about 2.7% of the hourly winds have average wind speeds under 0.5 m/s, representing "calm" conditions. The 2.7% of hours that were observed to have low (calm) hourly average wind speed (less than 0.5 m/s) represent hours in which the *ground level* winds were calm. However, the Spillane Approach requires calm conditions (wind speeds near zero) in the entire lower atmosphere, including at heights of hundreds of feet above the ground, where the wind speeds are very rarely calm.

It is unusual to obtain representative wind speed measurements aloft, however prognostic meteorological model predictions can be examined to estimate the likelihood that calm ground level winds extend vertically through the lower atmosphere. Katestone did exactly that for the RCEC site in Northern California and found that "the prognostic meteorological model predictions indicate only two hours per year with calm winds up to a height of 200 meters."[6] Katestone concluded that: "…the scenario of calm winds (i.e. zero m/s) throughout the lower atmosphere is extremely conservative and unlikely to happen in reality."[7] It is particularly unlikely for such calm conditions to exist in the summer, when a facility that provides peaking power like the Puente Project is expected to be running.

[5] RCEC report, pdf pg. 12.
[6] RCEC report, pdf pg 15.
[7] RCEC report, pdf pg 10.

In addition to calm winds, the Spillane approach also assumes a *neutral* atmosphere (in which the buoyancy of the rising plume remains constant regardless of the pressure loss). A neutral atmosphere is not as common as either stable conditions (which typically occur for many hours of the nighttime when the ground is cooler than the air aloft) or unstable conditions (which occur during the day when solar radiation causes heating from below). Neutral conditions only occur when there a perfect balance between the environmental lapse rate and the adiabatic lapse rate. Neutral conditions will generally only occur during dawn and dusk transition periods and during cloudy, windy, well-mixed conditions. Examination of the wind speeds and solar/cloud conditions that are necessary to produce neutral conditions shows that low winds are rarely associated with neutral conditions. The Pasquill Stability Classes that are used to represent atmospheric mixing in many dispersion models are shown in Table 1, below.[8] It can be seen that neutral conditions do not occur when wind speeds are less than 3 m/s. In addition it should be noted that neutral stability conditions (which are really "balanced" conditions) themselves are not "stable", meaning that *any* warming of the lower portion or cooling of the upper portion of a neutral atmosphere will cause the layer to become unstable, and it will then not only permit but will assist, vertical motion. Because such changes are easily brought about, the neutral atmosphere doesn't typically remain neutral for very long (i.e., the balance is "tenuous").

Table 1. Meteorological conditions defining Pasquill stability classes

Surface wind speed		Daytime incoming solar radiation			Night-time cloud cover	
m/s	mph	Strong	Moderate	Slight	>50 %	<50 %
<2	<5	A	A – B	B	E	F
2 – 3	5 – 7	A – B	B	C	E	F
3 – 5	7 – 11	B	B – C	C	D	E
5 – 6	11 – 13	C	C	D	D	D
>6	>13	C	C	D	D	D

c. Adding an assumption of slight winds to the Spillane Approach would lower the predicted critical plume height by 50 to 70 percent.

The computation of the critical height using the Spillane methodology is *very* sensitive to the assumption of zero horizontal winds. Even relatively low level horizontal winds will dramatically lower the predicted critical height, which is defined in the CEC's Supplemental Testimony as the height at which the average plume velocity reduces down to the threshold velocity for impacts to aircraft (set by the CEC at 5.3 m/s).

[8] A: Extremely unstable conditions; B: Moderately unstable conditions; C: Slightly unstable conditions; D: Neutral conditions; E: Slightly stable conditions; F: Moderately stable conditions

In describing the dynamics of a plume during its development, model developer Katestone indicated that

> "…the plume dynamics and trajectories respond to ambient conditions, with much cooler air being entrained into the outer regions of the plume. The momentum and buoyancy of the plume significantly influence its rise as this air mixes into the plume and provides dilution of the exhaust. This dilution is *very sensitive* to ambient wind speed."[9]

Katestone also concluded that "[i]n reality, even light wind speeds can dramatically decrease the predicted plume-averaged vertical velocities so the above [Spillane Approach] results are very conservative indications of adverse conditions."[10] In addition, Katestone reported that "the introduction of realistic wind profiles reduces the height at which the [threshold velocity] is achieved by 50% to 70%."[11]

2. The CEC Supplemental Testimony improperly omits the Spillane Approach calculations on plume temperature, which show that at a plume's critical heights, the minimal temperature difference between the plume and surrounding air make it unlikely to exert significant force on passing aircraft.

The CEC Staff Supplemental Testimony uses the Spillane Approach to estimate the heights at which the plume's average velocity is 5.3 m/s – the "critical height" – for a range of alternative combustion turbine generator (CTG) designs.[12] However, the Testimony omits the Spillane Approach's calculations on the temperature of the plumes at these critical heights. This second step is a key part of the determination of whether the alternative designs will pose a hazard to aircraft: In the case of a buoyant plume, the upwards force is due to the temperature difference between the plume and the ambient air. The temperature of the plume (relative to the surrounding atmosphere) therefore provides a measure of the buoyant force, or *weight*, of the rising plume. By calculating the plume temperatures of the GE7HA CTG and the single stack LM6000 CTG Alternative at the critical heights, I found that the plumes are similar in temperature to the surrounding air, and therefore will not exert substantial buoyant force on a passing aircraft and should pose little hazard.

As an initial matter, it is unclear that updrafts at the CEC's threshold velocity are really a concern to pilots. With regards to the threshold velocity (which was recently revised by CEC from 4.3 to 5.3 m/s), Katestone stated that: "In the absence of the power station, pilots are

[9] RCEC report, pg 8 (emphasis added).
[10] RCEC report, pdf pg 12.
[11] RCEC report, pdf pg 14.
[12] Appendix TT-1 of Supplemental Testimony, June 2017 (pg 39).

probably already experiencing significant updrafts of the order of the 4.3 m/s threshold chosen for the CASA guideline. Vertical velocities in excess of 4.3 m/s are well documented for many regions in Australia and can be expected in California on, for example, hot summer days prior to seabreeze arrival."[13]

a. *Both plume velocity and temperature are relevant to determining hazard, as these factors together determine the force exerted on passing aircraft.*

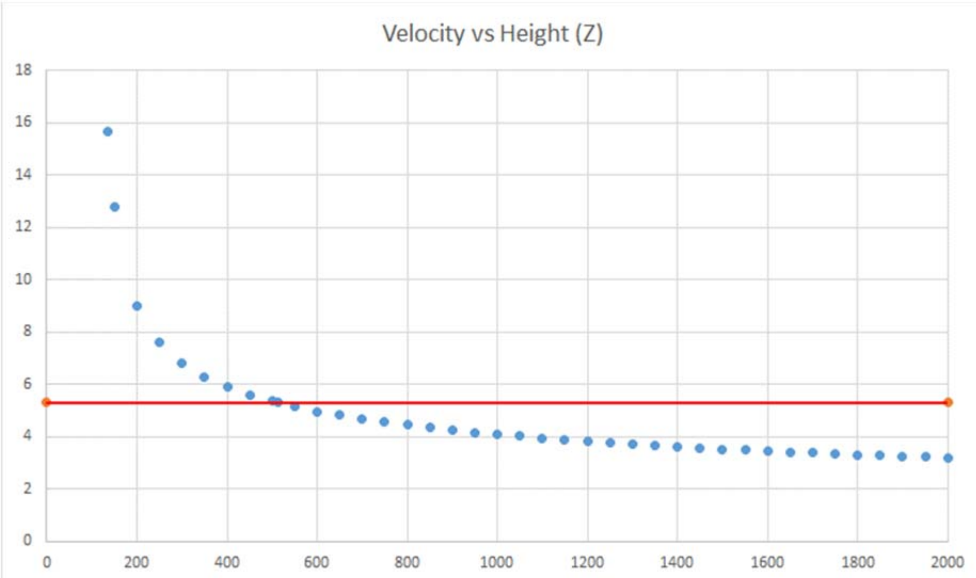
It is not sufficient to only examine the velocity of a rising object (or plume) to determine its potential for creating a physical nuisance if it were to impact an aircraft. After all, it is not just the velocity of a moving object but that combined with its weight that determines the impact (or force due to momentum). Clearly there is a distinct difference between being impacted by a 10 lb brick travelling at 30 mph than a 1-ounce feather travelling at the same velocity. The plume may be moving upwards at 5.3 m/s, but how much *weight* is behind the plume at that height?

To answer this question, I first replicated the CEC Supplemental Testimony's calculations of critical height for each of the alternative facility designs. I set up a spreadsheet to reproduce CECs velocity calculations using the Spillane Approach for the single stack GE7HA CTG and the single stack LM6000 CTG Alternative.[14] I was able to identically re-create their tabulated results for the GE7HA (1 Stack) and the LM6000 (1 Stack), as shown in CEC's Tables 4 and 5.[15] CEC's Table 5 indicates that the average plume velocity for the LM6000 using the Spillane Approach would be 5.36 m/s at 500 ft and 4.97 m/s at a height of 600 ht. Using the Spillane model, I determined that the critical height (at which the vertical velocity equals 5.3. m/s) would be reached at a height of 512 ft.

Figure 1, below, shows the plume average vertical velocity versus height for the LM6000 CTG (1 Stack) Alternative using the Spillane Approach (these results match the results shown in CEC's Table 5). A red line has been placed on Figure 1 at the threshold velocity of 5.3 m/s. The calculations also show that the vertical velocity is computed to be 2.32 m/s at a height of 5000 m, 1.48 at 10,000 m height, 1.46 m/s at 20,000 m, and 1.07 m/s even as high as 50,000 m (with a very wide estimated plume diameter of 5 km). The "unfettered" plume rise that is featured in the Spillane model does not appear to accurately represent the plume's vertical velocity at these very high altitudes.

[13] RCEC report, pdf pg 14.
[14] Table 2, Supplemental Testimony, June 2017 (pg 42).
[15] Table 5, Supplemental Testimony, June 2017 (pg 45).

Figure 1. Average plume vertical velocity (m/s) vs. height (ft) for LM6000 (1 Stack)



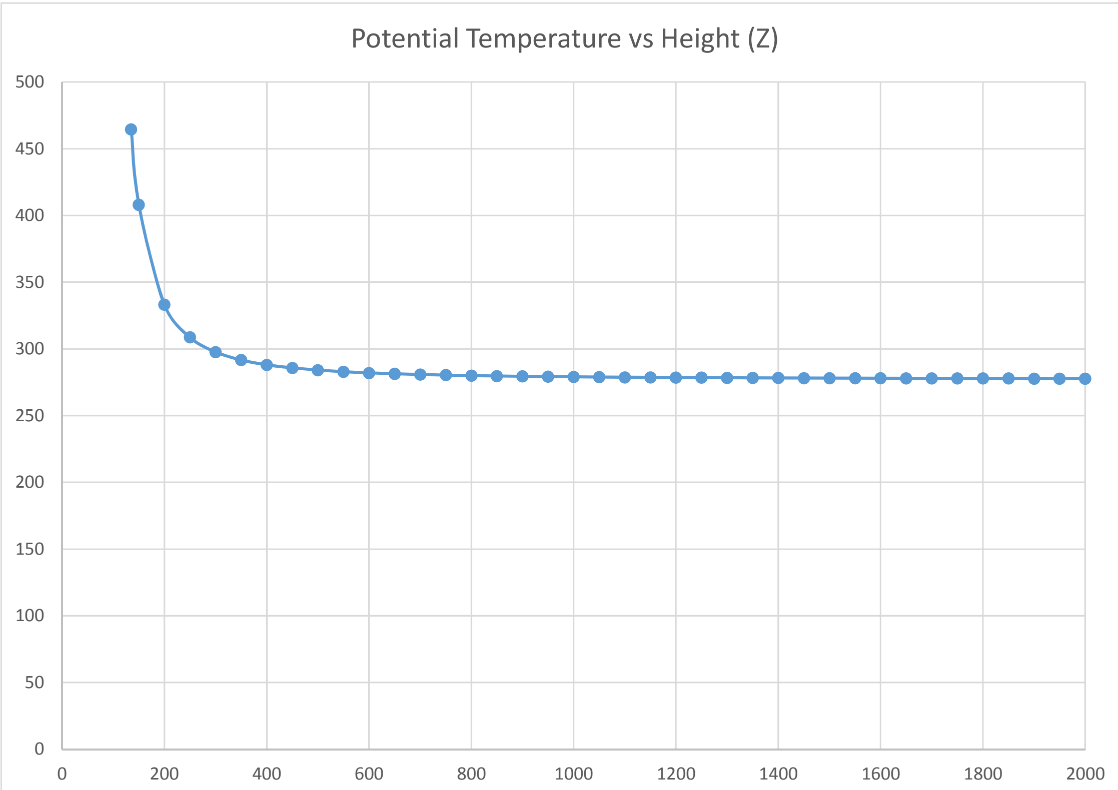
Next, I calculated the plume temperature at those critical heights. The CEC Supplemental Testimony omitted this critical calculation. I used the full set of Spillane Approach equations includes the calculation of the plume average temperature. [16] The results from these calculations indicate that the plume at the critical height is predicted to be very close to ambient air temperature, and therefore will exert very little force on passing aircraft.

In the case of a buoyant plume, the upwards force is due to the temperature difference between the plume and the ambient air. The temperature of the plume (relative to the surrounding atmosphere) therefore provides a measure of the buoyant force, or *weight*, of the rising plume. The temperature of the plume as it leaves the stack for the LM6000 CTG was assumed by CEC to be 868 K. The Spillane Approach assumes that as the plume rises it entrains air due to its radial growth. The entrained air is at a lower temperature than the plume, so the plume's temperature decreases in proportion to the quantity of entrained air: in other words, the plume cools down as it rises and grows.

The average plume temperature can be computed at various heights using the Spillane methodology. Figure 2, below, shows the estimated average potential absolute temperature (K) versus height for the LM6000 CTG unit (1 Stack), using the Spillane Approach.

[16] See for example, Eq. (17) on pdf pg 40 of RCEC report (Spillane Appendix C)

Figure 2. Average plume temperature (K) vs. height (ft) for LM6000 (1 Stack)



At the critical height (512 ft), the modeled diameter of the expanding plume using the Spillane Approach is estimated to be 41 m (135 ft) across, with a predicted average vertical velocity of 5.3 m/s. The average temperature of the expanding plume at that height is predicted by the Spillane model to be 283.8 K (51.2 F), just **6.5 K** degrees warmer than the ambient air (39.4 F). The buoyant force due to such a small temperature difference is extremely weak.

I computed the critical height (the height at which the plume average vertical velocity equals 5.3 m/s) for the GE7HA CTG and the LM6000 CTG (single stack), for each of the three ambient temperature conditions that were evaluated by CEC using the Spillane Approach (see Table 2, below). I used the same ambient temperatures as provided in the CEC Supplemental Testimony, although it is unclear to me why different minimum and maximum temperatures were used for the two alternatives.

I also computed the average plume temperature at each of these critical heights using the Spillane Approach equations for the LM6000 CTG (single stack) Alternative, along with the temperature difference between the plume and the ambient air, as shown in Table 2. For the GE7HA CTG (Table 3), I computed the average plume temperature at a height of 800 feet, the traffic overfly altitude for single- engine aircraft given in Staff's Supplemental Testimony.[17] Finally, Tables 2 and 3 shows the estimated vertical velocity of each plume at a height of 20,000 ft, as estimated by the Spillane equations.

Table 2. Spillane Calculations for the LM6000 CTG (1 Stack)

CTG / Scenario	Critical Height (ft)	Temperature @ Critical Ht. (K)	Temp Difference (K)	Plume Average Velocity (m/s) @ 20,000 ft
LM6000 $T_{ambient}$ = 39.4 F	512.3	283.8	6.5	1.46
$T_{ambient}$ = 59.0 F	503.8	295.1	6.9	1.45
$T_{ambient}$ = 96.0 F	485.4	316.5	7.8	1.43

Table 3. Spillane Calculations for the GE7HA CTG

CTG / Scenario	Critical Height (ft)	Temperature @ 800 ft (K)	Temp Difference (K)	Plume Average Velocity (m/s) @ 20,000 ft
GE7HA $T_{ambient}$ = 38.9 F	2,386.9	289.2	12.2	2.52
$T_{ambient}$ = 59.0 F	2,535.0	267.3	11.9	2.58
$T_{ambient}$ = 82.0 F	2,221.0	303.3	12.4	2.46

As I demonstrate in the section below, the minimal temperature difference between the plume and surrounding air at the critical plume height will, in conjunction with the plume velocity, generate very little upwards buoyant force, supporting my conclusion that both configurations of the Off-Site Alternatives should not significantly impact air traffic.

3. An alternative approach to plume modeling confirms that after accounting for horizontal winds and plume buoyancy, the critical height of the plume will be cut almost in half.

The weak buoyant force at the critical height is further demonstrated by examining an alternative (textbook) approach below, in which the local buoyancy, or reduced gravity, of the plume is estimated in addition to the vertical velocities. The textbook approach also includes horizontal winds to account for horizontal entrainment in a calm neutral environment.

[17] Supplemental Testimony, p. 32.

An alternative mathematical approach that solves the same system of atmospheric equations as the Spillane Approach, but considers entrainment due to horizontal winds, can be found in Chapter 10 ("Plumes and Thermals") in a recent engineering textbook by Roisin.[18] Roisin constructs a solution for the physics of a radially symmetric buoyant plume rising vertically through a homogenous and resting fluid (such as a completely calm and neutral atmosphere), without solving for the details of the turbulent flow that naturally occurs at the boundary of the plume, by assuming that the horizontal entrainment velocity is proportional to the shear flow induced by the plume (i.e., U is proportional to V). Roisin's solution (using dimensional analysis) for a buoyant plume shows that the cross-plume average vertical velocity becomes:

$$\overline{V} = 2.14 \ \frac{F^{1/3}}{z^{1/3}} \qquad \textit{Eq. (1)}$$

where F is the buoyancy flux (m^4/s^3) and z is the height (above the stack).[19]

Roisin's formula (Eq. 1) produces significantly lower plume average vertical velocities than the Spillane Approach due solely to greater horizontal entrainment caused by horizontal winds. Assuming the same initial buoyancy flux that CEC used in their analysis of the LM6000 CTG exhaust using the Spillane approach, but instead using the Roisin model, one would estimate the critical height (at which the vertical velocity equals 5.3 m/s) to be 228 ft above the virtual stack top, at an elevation relative to the ground of **288 ft**, as opposed to 512 ft, as was estimated using the Spillane Approach). While 512 feet was already below the height limit for air traffic, I would expect reductions in critical height of a similar magnitude for other alternative project configurations.

Roisin also computed the local buoyancy (or reduced gravity) of the plume, g', as a function of height:

$$g' = 6.08 \ \frac{F^{2/3}}{z^{5/3}} \qquad \textit{Eq. (2)}$$

The local buoyancy is proportional to the temperature difference between the plume and ambient air. Using Eq. (2) for the LM6000 (1 Stack) alternative at a height of 512 ft, results in g' = 0.14 m/s^2, which is equivalent to just 1.4% of the gravitational force, g (9.8 m/s^2). In other words, the actual upwards buoyant force exerted on the plume would be quite small at this height.

According to the Spillane method, at a height of 512 ft, the LM6000 plume has a vertical velocity of 5.3 m/s, but the expanded plume at that height will only be 6.5 K warmer than the

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[18] Roisin, B.C., 2014. *Environmental Fluid Mechanics*, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755 (March 2014).
[19] The Spillane Approach also has a $z^{-1/3}$ dependency, i.e., V = f($z^{-1/3}$).

surrounding air. And according to the Roisin model (with additional horizontal entrainment), the upwards force due to the relatively small temperature difference at this height would be extremely small, less than 2 percent of the force of gravity.[20]

Using Roisin's equation for the rising plume in a calm neutral environment, which includes light horizontal winds to account for the horizontal entrainment, demonstrates that even a small amount of entrainment (due to horizontal winds) will dramatically lower the estimate of the critical height.

In interpreting the results of the Spillane Approach calculations for Puente, CEC concluded that:

> "The plume average and peak vertical velocities for the Puente and MSG Unit 3 would remain relatively high during calm or very low wind speed conditions. These low wind speed conditions lasting an hour or more occur 2.72 percent of the time. Additionally, shorter periods of dead calm winds, lasting long enough to increase the vertical plume velocities to heights up to peak heights, can also occur during hours with low average wind speeds."[21]

A short period of ground level calm winds is indeed required to achieve the conditions represented by the Spillane Approach, as CEC suggests. However it would also be necessary to have those calm winds extend upwards several hundred feet with almost no interruption whatsoever. Even small horizontal wind perturbations will cause additional entrainment, not to mention some level of turbulent mixing (even the smallest horizontal winds will tend to "erode" the plume edge). In addition, as discussed above, the presence of low wind calm conditions are not likely to occur when the atmosphere is exhibiting neutral stability. It is therefore highly unlikely that the threshold velocity will approach the critical height even with small deviations from the ideal conditions that are represented by the Spillane Approach. For example, the Roisin equations presented above (for a calm neutral atmosphere) suggest that the critical height (at which the velocity equals 5.3 m/s) would be reached at a height of only 228 ft with just a small amount of additional horizontal entrainment considered.

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[20] The effect of such an impact would be like getting hit by a fast rising helium balloon. As stated previously, according to the Spillane model, the plume continues to rise at relatively "high" velocities simply because there are NO external forces acting to slow down the plume other than its own expansion. The *force* behind the rising plume is very low at the critical height.

[21] See pg 4.12-67 of FSA Dec 2016; (pdf pg 1153).

5. CEC Supplemental Testimony Incorrectly Relies on a bivariate normal distribution for the plume vertical velocity.

The Supplemental Testimony is based on the assumption that a critical plume-average velocity of 5.3 would produce the necessary “dangerous” vertical wind speeds of 10.6 m/s. However, I believe this conclusion to be unfounded. CEC Supplemental Testimony assumes that the average plume velocity is exactly half the peak velocity (located at the center of the plume). This notion was apparently based on the flawed assumption that a normal distribution could be used to represent the velocity profile of the plume. However, when “fitting” a normal distribution to the plume velocity, one discovers that only a central *portion* of the normal curve can possibly be included between the edges of the plume. The width of the selected portion of the distribution is completely arbitrary, and therefore so is the computed ratio of the maximum velocity to the average velocity.

The vertical velocity threshold was recently revised by CEC to be 5.3 m/s for the plume average velocity. The actual velocity of concern for aircraft is 10.6 m/s.[22] As CEC staff state: “The altitude at which a plume would have a peak vertical velocity of 10.6 m/s would be the same altitude at which a plume would have an average vertical velocity of half that, 5.3 m/s.”[23] It was therefore assumed that the peak velocity at the "core" of the plume would be equal to exactly two times the average velocity across the plume.

The notion that the peak vertical velocity is **twice** the average velocity appears to be a fairly widespread assumption, despite the fact that it is based on an incorrect application of statistics, as I will explain in detail below. Roisin (2014) presents a mathematical justification for its use which includes the same erroneous statistical interpretation of the normal distribution (and also contains a computational error).[24]

It is unclear how this erroneous notion has propagated. It may have “morphed” from longitudinal velocity measurements at the centerline and near the edge (but inside) of emerging jets. Even if that were the case, such a measured ratio would not at all be applicable to the V_{max}/V_{avg} ratio for a plume (it would be rather difficult to physically measure an average quantity, such as the average velocity across an entire cross-section of a plume). It more likely has come from the idea that a normal distribution can be used to mathematically represent the radial profile of velocities. Observations of longitudinal velocities in jets and plumes have shown a pattern that resembles a Gaussian, or normal distribution. Spillane[25] suggests that the ratio ($V_{max}/V_{avg} = 2$) is warranted due to use of “a Gaussian radial profile” for the vertical

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[22] FSA appendix TT-1pdf pg 1139
[23] FSA pdf pg 1141
[24] Roisin, B.C., 2014. *Environmental Fluid Mechanics*, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire 03755 (March 2014).
[25] Spillane, RCEC report Appendix C, pg C7 (pdf pg 42)

velocity (although he offers no other mathematical justification for its use). Roisin (2014) also claims that (*emphasis* added): "Like for turbulent jets, observations reveal that the Gaussian profile (bell curve) provides a *realistic description* of the…" vertical velocities for expanding plumes."[26]

Although the ratio (V_{max}/V_{avg} = 2) appears to be widely used (even in the Dartmouth College engineering textbook), the use of the normal distribution to approximate the "shape" of the radial cross-section of the velocity profile is NOT appropriate. The observed shape of the velocity profiles for plumes (and jets) is characterized by a peak in the center and values initially dropping off quickly as you move from the center, then dropping more slowly towards the edge of the circular cross-section Although this shape may appear to be similar to a normal distribution, and it may be tempting to use the normal distribution to represent the velocity profile, it is strictly NOT correct to do so. The normal distribution can reasonably accurately represent the center portion of the distribution (near the peak), however the "tails" of the normal distribution DO NOT adequately represent the edges of the velocity profile. The problem becomes apparent when attempting to determine the average value of a quantity that is fit to a normal distribution. As will be demonstrated, the selection of the width of the distribution that is included within the plume's radius is a largely arbitrary choice and therefore can result in almost any ratio for V_{max}/V_{avg} ! (In addition, Roisin made a computation error when computing the value of V_{avg}.)

In Chapter 9 (Jets), Roisin (2014) presents the mathematical justification for the use of the V_{max}/V_{avg} = 2 ratio (used both for jets and plumes in Chapter 10). It is stated that "All cross-sections appear identical, except for a stretching factor, and the velocity profile across the jet exhibits a nearly Gaussian shape (bell curve):…" A bivariate normal (Gaussian) distribution was imposed on the velocity profile V across the plume:

$$V(z,r) = \frac{1}{2\pi\sigma^2}(z)\ \exp(-\frac{r^2}{2\sigma^2}) \qquad \text{Eq. (3)}$$

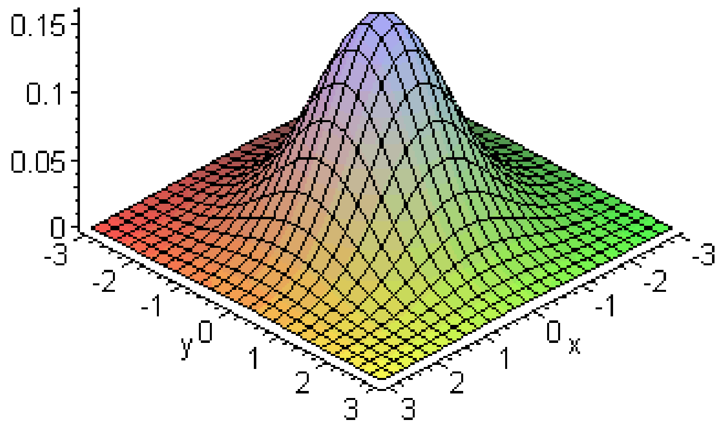
where 2σ represents the radius of the plume, and r is the horizontal distance from the center of the plume. The peak velocity, V_{max}, occurs at the center of the plume, at r=0:

$$V_{max}(z) = V(z,0) = \frac{1}{2\pi\sigma^2}(z) \qquad \text{Eq. (4)}$$

The bivariate normal distribution is illustrated in Figure 3.

[26] Roisin (2014), pg 164.

Figure 3. Standard Bivariate Normal Distribution



For the standard bivariate normal distribution ($\sigma = 1$), $\mathbf{V_{max} = 1/(2\pi) = 0.159}$. As stated above, the vertical velocity V is assumed to follow a standard bivariate normal distribution. The probability density function (pdf) for the standard bivariate normal distribution ($\sigma = 1$) is:

$$f(r) = \frac{1}{2\pi} \exp(-\frac{r^2}{2}) \qquad \text{Eq. (5)}$$

The cumulative density (area) of the standard bivariate normal distribution within a radius of R can be computed as the integral:

$$F(R) = \frac{1}{2\pi} \int_0^R \exp(-\frac{r^2}{2})\, dr \qquad \text{Eq. (6)}$$

The solution to Eq. 6 is:

$$F(R) = 1 - \exp(-\frac{R^2}{2}) \qquad \text{Eq. (7)}$$

To illustrate the "problem" with Roisin's (and CEC's) methodology in which the standard bivariate normal distribution was used to determine the ratio V_{max}/V_{avg}, I have computed the probability density function value (pdf), f, for different distances, R, from the center (see Table 4, below) using Eq. 5. I also computed the cumulative density from the center out to the distance R (using Eq. 7). The average value of f over the circular area is equal to the cumulative density, F(R), divided by the enclosed area.

Table 4. Bivariate Standard Normal Distribution: Function Density (f), Cumulative Density (F), and Average Value (f_{avg})

R (σ)	f(R)	f(R) / f_{max}	F(R)	Enclosed area	Average f value	f_{max}/f_{avg}
0	0.159	1	0	0	**0.159**	1
1	0.097	0.607	0.393	π	0.125	1.27
1.75	0.034	0.216	0.784	3.06π	0.081	1.95
2	0.022	0.135	0.865	4π	0.069	2.31
2.5	0.0070	0.044	0.956	6.25π	0.049	3.27
3	0.0018	0.011	0.989	9π	0.035	4.55
4	0.00005	0.00034	0.99966	16π	0.020	8.00

Roisin assumed that the radius of the plume equals 2σ which he justified based on the following statement: "Since 4σ is the width of the distribution that encompasses 95% of the area under the curve (a traditional and practical measure borrowed from statistics) and since we know it to be the diameter 2R…", the diameter 2R is set equal to 4σ (or R=2σ). This assumption (R=2σ) should have led to the computation of the ratio of V_{max}/V_{avg} = 2.31. The textbook (erroneously) computed the ratio as 2.0 due to the incorrect assumption that the cumulative density F(R) within the circle bound by R=2 equals 1, instead of 0.865.

The statement that "95% of the area under the curve is included in the interval R=0±2σ" is approximately true for a one-dimensional normal distribution. The normal distribution that Roisin has imposed upon the plume's vertical velocity profile is the two-dimensional (bivariate) version, in which the 4σ width (radially from -2σ to +2σ) actually only encompasses 86.5% of the distribution (i.e., F(2) = 0.865). In his calculation of the average velocity, Roisin incorrectly used the cumulative density of the entire distribution, F(∞), which equals 1, rather than the value for F(2). In other words, he integrated f(r) from R=0 to infinity rather than from R=0 to 2, which is the proper way to compute the average value of the velocity across the circular plume top; his integration to infinity incorrectly yields $f_{avg} = 1/4\pi = 0.080$, and therefore (recall that $f_{max} = 1/2\pi$) $f_{max}/f_{avg} = 0.159/0.080 = 2.0$ (exactly).

If Roisin had properly computed the average value using the 2-D bivariate normal distribution from R=0 to R=2 the value of f_{avg} would be 0.069, as shown in Table 4, and the f_{max}/f_{avg} ratio would be 0.159/0.069 = 2.31.

The f_{max}/f_{avg} ratio computed in the Roisin textbook was actually preordained to be 2 (actually 2.31, since it was incorrectly calculated as discussed above) simply by the arbitrary choice of setting the plume width, R, to 2σ.

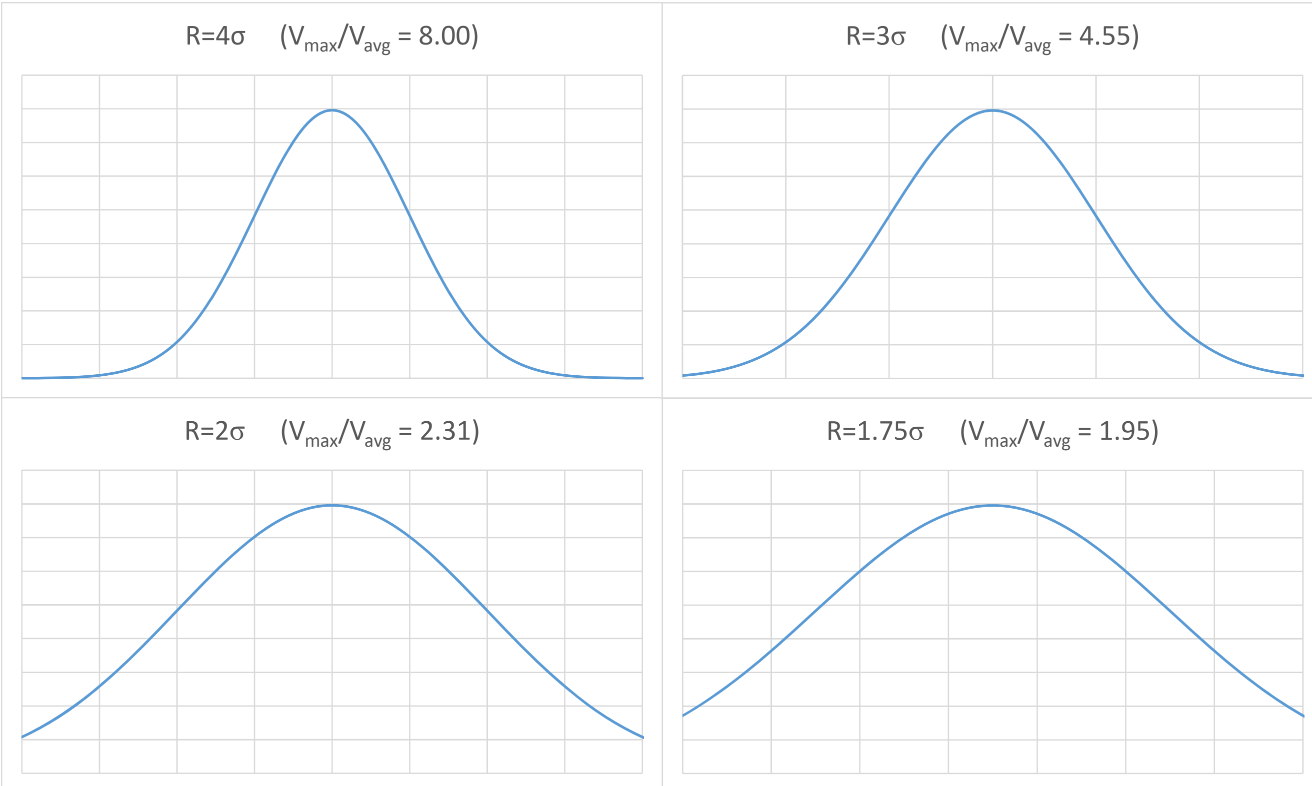
The normal distribution extends laterally to infinity. Therefore, to use the normal distribution to represent plume velocities across the *finite* width of the plume, only a central portion of the distribution can be used. There is no "correct" width of the central portion to include -- *any* width can be reasonably chosen – and this will result in values of V_{max}/V_{avg} ranging from near 1 to infinity.

The problem with this approach – imposing (or fitting) a normal distribution to describe the radial spread of the plume's vertical velocity -- (even if it was corrected so that f_{max}/f_{avg} = 2.3 for R=2) is that the width of the plume was arbitrarily chosen to be R=2σ without proper justification. The stated justification that R=2σ would capture 95% of the distribution is not true for the 2-D bivariate normal distribution. For the 2-D bivariate distribution, R=2σ captures only 86.5% of the distribution (as shown in Table 4), not 95%. Nonetheless, it could be argued that it would be MORE accurate to use R=3 or even R=4, in order to be as "precise" as possible when computing the average velocity (why allow so much error by leaving out 13.5% of the distribution?). If we were to extend the integral to capture **more** of the distribution, it would quickly become apparent that f_{max}/f_{avg} can be as high as we want it to be. (For F=3 the f_{max}/f_{avg} =4.55 and for R=4, f_{max}/f_{avg} = 8!). Likewise, we could choose R=1.75σ for the plume width which would result in a ratio of f_{max}/f_{avg} = 1.95.

Although we might like to use the bivariate normal distribution to be used to represent the velocity profile within a plume, it CANNOT really do so unless the density function actually **goes to zero** at the edge of the plume. For plume width R = 2σ, Table 4 shows that the vertical velocity at the *edge* of the plume (at R=2) is equal to 13.5% of the maximum velocity V_{max} (at the center of the plume). The velocity must be zero (or very nearly zero) at the plume edge, not just a low value (such as 0.135*V_{max}) in order to effectively use the normal distribution to represent the velocity profile. Otherwise, the average V value can be made as low as you want simply by including more of the distribution in the integration (as described above). Unfortunately, the normal distribution never (mathematically) gets close enough to zero.

The problem with trying to "fit" the radial velocity profile to the bivariate normal distribution is further illustrated in Figure 4, which shows the vertical velocity profile across the width of the plume (from edge to edge), "fit" to the cross-section of the bivariate normal distribution. All four curves shown in Figure 4 have the same maximum velocity and each represent *a portion* of the bivariate normal distribution shown in Figure 3. Changing how much of the distribution is allowed to fit between the plume edges (i.e., the choice of σ) dramatically affects the peak to average ratio (as was also shown in Table 4).

Figure 4. Cross-section of Bivariate Normal Distribution "Fit" to Velocity Profile. The choice of σ affects the "shape" of the curve, resulting in different values of V_{max}/V_{avg}.



To use the bivariate normal distribution to represent the velocity profile across the plume, one must select the lateral extent, or width, of the normal distribution to include between the center point and the "edge" of the plume, where the velocity is zero. Figure 4 (and Table 4) shows that, when using the normal distribution to represent the velocity profile, the velocity at the plume edge is NOT zero (even for R=4σ). For example, for R=2σ, the velocity at the plume edge is shown to be 0.135 * the maximum value. The choice of width is completely arbitrary -- Roisin justified setting R=2σ based on the (incorrect) assumption that 2σ would capture 95 percent of the distribution. (For the 2-D bivariate version of the normal distribution, a 2σ radius actually only captures 86.5% of the distribution.) However, that inaccuracy is not the issue! The problem is that one can choose ANY point as the width (for example, 1.75σ, 2σ, 3σ, or 4σ could all be considered to be reasonable choices) -- and one could always argue that including more of the distribution (or almost all of it), would produce a more accurate result -- but including more and more of the distribution actually forces the average value to go down *all the way* to zero! Yes, that is true: the average value of the *complete* normal distribution which extends from negative infinity to positive infinity is actually ZERO! -- which is an uncomfortable mathematical reality when you are trying to use that distribution to fit to actual physical data and are relating the average value to the peak value!

Although the velocity profile may "look like" a normal distribution, the normal distribution **CANNOT** be used to represent the velocity profile (especially when computing a peak to average value ratio). The plume average velocity (and other plume-averaged quantities) can be estimated by the atmospheric equations because it is representing the buoyancy of the entire plume (a fixed quantity, related to the amount of heat, or energy, in the plume, that can be determined at the stack). So a "reasonable" model of the atmospheric physics should be able to predict the plume *average* velocity well, but not necessarily the *maximum* velocity.

As the plume continues to rise in a calm neutral environment, it is likely that the profile of the vertical velocity across the plume will actually be seen to "flatten", so that although it still may resemble a Gaussian profile, it in fact accounts for less width of the profile and therefore the peak value becomes much lower relative to the average (as in the "lower" σ curves in Figure 4). According to the simplistic version of the atmosphere as represented in the Spillane Approach (in which there is no shear at the "edge" of the radially expanding plume), the velocity at the plume edge must be zero, and so there will ALWAYS be a gradient across the plume as the velocity increases from zero at the plume edge to the maximum value at the center. There is no justification for assuming the gradient in such a situation must follow a normal distribution, nor can it accurately do so since the velocity at R=2 for the normal distribution (= $0.135*V_{max}$) is not even close to zero. The more important question is whether the radial profile will remain so "peaked" that the maximum value will always be 2 times the average value (or some other constant ratio), or will the profile flatten so that f_{max}/f_{avg} actually decreases with height (a real-world plume that is slowly losing energy, will eventually exhibit this flattening behavior). In the actual atmosphere, the plume will lose much of its momentum due to actual shearing of the plume edge, which will affect the entire plume by the time a height of hundreds of feet is reached. The result is that the maximum velocity will become only slightly higher than the average velocity (at the limit as the velocity continues to drop, the plume will likely become more horizontally uniform, and f_{max}/f_{avg} will approach 1).

The previous discussion concerning the normal distribution implies that CEC's assumption that a critical plume-average velocity of 5.3 would produce the necessary "dangerous" vertical wind speeds of 10.6 m/s is completely unfounded. Although the maximum velocity will most likely be somewhat higher than the plume average (especially at low heights), it is unclear what the value of V_{max} would actually be at any particular height, including at the critical heights being computed by CEC using the Spillane Approach. As explained above, CEC's assumption of V_{max}/V_{avg}=2 is completely arbitrary, and is the result of choosing a radius R of 2σ when improperly fitting the velocity profile to a bivariate normal distribution (and it was also computed incorrectly).

H. ANDREW GRAY

EDUCATION

Ph.D. environmental engineering science, California Institute of Technology, Pasadena, California, 1986

M.S. environmental engineering science, California Institute of Technology, Pasadena, California, 1980

B.S. civil engineering/engineering and public policy, Carnegie-Mellon University, Pittsburgh, Pennsylvania, 1979

EXPERIENCE

Dr. H. Andrew Gray has been performing research in air pollution for over 35 years, within academic, governmental, and consulting environments. He has made significant contributions in the areas of airborne particles and visibility, including the development and application of computer-based air quality models. His areas of expertise are air pollution control strategy design and evaluation, computer modeling of the atmosphere (including AERMOD, CALPUFF, CAMx, etc.), characterization of ambient air quality and air pollutant source emissions, aerosol monitoring and modeling, visibility analysis, receptor modeling, statistical data analysis, mathematical programming, numerical methods, and analysis of environmental public policy. Dr. Gray is currently an independent contractor focusing on particulate matter and visibility related research issues. Previous Gray Sky Solutions projects include assessment of Clean Air Act and other regulations on visibility in Class I (park and wilderness) areas, development of air pollution control plans and emission inventories for tribal lands, review and development of guidelines for modeling long-range transport impacts using the CALPUFF model, evaluation of particulate air quality impacts associated with diesel exhaust emissions, air quality management plan modeling protocol review, a critical review of Clean Air Mercury Rule (CAMR) documents, and assessment of the regional air quality impacts of power plant emissions. Dr. Gray has performed dispersion modeling studies to determine the impacts associated with mercury emissions in the Chesapeake Bay region, and has evaluated the air quality, visibility and health impacts of numerous electric generating facilities, industrial sources, and container ship traffic. Recently, Dr. Gray worked with a team of researchers to evaluate the health effects due to coal-fired power plant emissions throughout China. Dr. Gray was invited by the Royal Institute of International Affairs to participate in the "Balancing Global Energy Policy Objectives: A High-Level Roundtable" meeting in April 2014.

Before starting Gray Sky Solutions, Dr. Gray was the manager of the PM_{10} and Visibility Program at Systems Applications International (SAI / ICF Inc.). At SAI, Dr. Gray conducted and managed a number of varied air pollution research projects. In the early 1990s, Dr. Gray directed a large (over $1 million) air-quality modeling program to determine the impact of SO_2 emissions from a large coal-fired power plant on Grand Canyon sulfate and visibility levels. He managed projects to develop carbon particle emission data for the Denver area, designed a PM_{10} monitoring and modeling program for the El Paso area, determined the appropriate tradeoffs between direct PM_{10} emissions and emissions of PM_{10} precursors, estimated the visibility effects in federal Class I areas due to the 1990 Clean Air Act Amendments (results of which were incorporated into EPA's 1993 Report to Congress on the expected visibility consequences of the 1990 Clean Air Act Amendments), and provided assistance to EPA Region VIII's tribal air programs. Other projects include emission inventory development for Sacramento and carbon monoxide modeling of Phoenix, Arizona to support federal and regional implementation plans in those regions, systematic evaluation of the Interagency Workgroup on Air Quality Modeling (IWAQM) recommendations for the use of MESOPUFF II, a critical assessment of exposures to particulate diesel exhaust in California, and an evaluation of $PM_{2.5}$ and PM_{10} air quality data in support of EPA's review of the federal particulate matter air quality standards. Later projects included a study of micrometeorology and modeling of low wind speed stable conditions in the San Joaquin Valley (CA), an assessment of the reductions in nationwide ambient particulate nitrate exposures due to mobile source NO_X emission reductions, an evaluation of visibility conditions in the Southern Appalachian Mountains region, a review of cotton ginning emission factors, and a critical review and assessment of the PM_{10} Attainment Demonstration Plan for the San Joaquin Valley. Dr. Gray was a member of the modeling subcommittee of the technical committee of the Grand Canyon Visibility Transport Commission.

Previous to his tenure at SAI, Dr. Gray was responsible for the PM_{10} and visibility programs at the South Coast Air Quality Management District which involved directing monitoring, analysis, and modeling efforts to support the design of air pollution control strategies for the South Coast Air Basin of California. He developed and applied the methodologies for assessing PM_{10} concentrations that were used by the District through numerous subsequent air quality management plan revisions. Dr. Gray authored portions of the 1989 Air Quality Management Plan issued by the District that describe the results of modeling and data analyses used to evaluate particulate matter control strategies. Dr. Gray was instrumental in promoting the development and application of state-of-science models for predicting particulate matter concentrations. His responsibilities included direction and oversight of numerous aerosol-related contracts, including development of the SEQUILIB and SAFER models, construction of an ammonia emission database, and development of sulfate, nitrate and organic chemical mechanisms. In addition, Dr. Gray was responsible for initiating the District's visibility control program.

In research performed at the California Institute of Technology, Dr. Gray studied control of atmospheric fine primary carbon particle concentrations and performed computer programming tasks for acquisition and analysis of real-time experimental data. He designed, constructed, and operated the first long-term fine particle monitoring network in Southern California in the early 1980s. He also developed and applied deterministic models to predict source contributions to fine primary carbon particle concentrations and constructed objective optimization procedures for control strategy design. In research carried out for the Department of Mechanical Engineering at Carnegie-Mellon University, Dr. Gray developed fuel use data for input to an emission simulation model for the northeastern United States.

Specialized Professional Competence

- Air pollution control strategy design
- Atmospheric air quality characterization
- Aerosols and visibility
- Computer modeling and data analysis
- Dispersion modeling for particulate matter and visibility

- Receptor modeling including Chemical Mass Balance (CMB) and factor analysis
- Analysis of environmental public policy

Professional Experience

- Systems Applications International (SAI/ICF)—PM_{10} and visibility program manager—participated in and managed numerous air quality modeling and analysis projects for public and private sector clients, with emphasis on particulate matter and visibility research
- South Coast Air Quality Management District, El Monte, California—air quality specialist—developed and applied air quality modeling analyses to support air pollution control strategy design for the South Coast Air Basin of California
- California Institute of Technology, Pasadena, California—research assistant—Ph.D. candidate in environmental engineering science. Thesis: Control of atmospheric fine primary carbon particle concentrations (thesis advisors: Dr. Glen Cass, Dr. John Seinfeld, and Dr. Richard Flagan)
- California Institute of Technology, Pasadena, California—laboratory assistant—performed computer programming tasks for acquisition and analysis of real-time experimental data
- Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania—research assistant—developed fuel use data for an emissions simulation model for the northeastern United States. Grant from the U.S. Department of Energy for evaluation of national energy policy
- Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pennsylvania—consultant—analyzed structural retrofit design for Ferrari Dino import automobile for United States five mph crash test

HONORS AND AWARDS

Harold Allen Thomas Scholarship Award, Carnegie-Mellon University

University Honors, Carnegie-Mellon University

PROFESSIONAL AFFILIATIONS

Air and Waste Management Association

American Association for Aerosol Research

SELECTED PUBLICATIONS AND PRESENTATIONS

The Deposition of Airborne Mercury within the Chesapeake Bay Region from Coal-fired Power Plant Emission in Pennsylvania, in press (2012)

Peer Review of the Interagency Workgroup On Air Quality Modeling Phase 2 Summary Report And Recommendations For Modeling Long Range Transport Impacts (with others), Report compiled by: John S. Irwin, Air Policy Support Branch, Atmospheric Sciences Modeling Division, U.S. Environmental Protection Agency Research Triangle Park, NC 27711 (1999)

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Attachment 1

Plume Vertical Velocity Assessment of a Proposed Gas-Fired Power Station at Russell City Energy Center

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1. Introduction

Katestone Environmental has been commissioned by Atmospheric Dynamics Pty Ltd to prepare a plume vertical velocity assessment of a proposed gas-fired power station at Russell City Energy Center in California. The proposed power station, called the Russell City Energy Center (RCEC) is to consist of two combined-cycle gas-turbines. The station also includes a bank of nine wet cooling towers.

The assessment presented in this report is based on the guidelines for aviation safety set out by the Australian Civil Aviation Safety Authority (CASA) and presented in "*Guidelines for conducting plume rise assessments (CASA, 2004)"*.

The aim of this assessment is to determine the height at which the average vertical plume velocity emitted from the power station gas-turbines and cooling towers achieves the critical value of 4.3 m/s. Two separate methods have been used to assess the vertical plume velocities:

- Method 1 – Worst case assessment assuming calm winds and neutral atmospheric conditions for the entire length and height of the plume.
- Method 2 – Realistic wind scenario using vertical wind profiles generated by a prognostic weather model for a full year simulation.

2. Local terrain and surrounding land use

RCEC is to be located in an established industrial area between Hayward and the San Francisco Bay Area, California. The area surrounding the RCEC is relatively flat with little significant terrain extending away for a radius of approximately 10 kilometers, and the bay is located approximately 2 kilometers to the west of the proposed power station. The land is relatively flat surrounding the Bay Area, however, further from the coast significant terrain runs from the northwest to southeast. Figure 1 shows images of the area surrounding the RCEC.

The closest airport to the proposed facility is the Hayward Executive Airport. The distance from the site to the closest runway is approximately 2.5 kilometers.

3. Vertical plume velocity guidelines

Since the development of an open-cycle gas turbine power station at the end of a runway in Australia in the mid 1990s, the CASA has taken a keen interest in the siting of industries with discharges to the atmosphere. Potential hazards that could affect the safety of aircraft include tall visible or invisible obstructions. Visible obstructions include structures such as tall stacks or communication towers. Invisible obstructions include vertical industrial exhausts that are of high velocity and buoyancy, such as gas turbines. CASA has issued an Advisory Circular, (CASA 2004) that specifies the requirements and methodologies to be used to assess whether a new industrial plume is likely to have adverse implications for aviation safety. In the absence of any guidance for such activities in California, the CASA guidelines have been used in this assessment.

The general CASA requirement is to determine the height at which the in plume (or plumes) could exceed an average in-plume vertical velocity threshold of 4.3 m/s and to determine the dimensions of the plume in these circumstances. The frequency of in-plume vertical velocities at the lowest height an aircraft may travel over the site, and at other heights are also required. For large plumes that are remote from airports, CASA requires an assessment that determines the size of a hazard zone to alert pilots to the potential hazard.

Advice from Atmospheric Dynamics indicates that the Traffic Pattern Zone extends for one mile (or approximately 1600 meters) from the Hayward Airport runways. The proposed development site is outside the Traffic Pattern Zone. The Pattern Altitude (the altitude at which aircraft are required to fly when circling the runway for landing approach within the Traffic Pattern Zone) are 600 feet (180 meters) and 800 feet (240 meters) for the runways at Hayward Airport.

For this report, the average plume height and downwind distance has been presented. While there are some sections of the plume that may have a vertical velocity higher than that for the average plume height and downwind distance, it has been Katestone Environmental's experience that these peak plume height predictions do not assess aviation safety risk appropriately. Past discussions between Katestone Environmental and CASA have concluded that analysis of the average plume height and downwind distance is appropriate for these assessments. The threshold limit of 4.3 m/s for the average vertical velocity has been used throughout this assessment for the critical plume height calculations.

4. Emission characteristics

A summary of the stack configuration and plume emission characteristics of the proposed RCEC are presented in Table 1.

Table 1: Stack characteristics for the proposed power station.

Parameter	Units	Gas turbines	Cooling Tower
Number of stacks	-	2	9
Location	AMG (mN, mE)	576552.23 4165363.93 576515.65 4165363.93	576424.97 4165459.04 576417.23 4165475.65 576409.48 4165492.27 576401.74 4165508.88 576394.00 4165525.49 576386.26 4165542.10 576378.52 4165558.72 576370.78 4165575.33 576363.04 4165591.94
Stack height	m	44.2	18.3
Stack diameter	m	5.49	9.75
Volume Flow per stack	m^3/s	525	770
Single plume buoyancy flux	m^4/s^3	346	159
Exit velocity	m/s	22.2	10.3
Temperature	°C	82	28.3
Stack separation	m	36.6	18.3

Katestone Environmental

The gas turbines have relatively low buoyancy compared to these from open-cycle gas turbines. The cooling towers have even lower buoyancy due to the lower temperature and exit velocity; the plumes from the cooling towers are also emitted from a much lower height of 18.3 meters compared to 44 meters for the gas-turbines. Due to the close proximity of the plumes to each other, enhancement of the buoyancy can be expected under certain meteorological conditions. This is an important feature that will be taken into account in this assessment.

5. Methodology

In Australia, CASA requires that the proponent of a facility with an exhaust plume that has an average vertical velocity exceeding the limiting value (4.3 m/s at the Obstacle Limitation Surface or at 110 meters above ground level anywhere else) to assess the potential hazard posed by the plume to aircraft operations. Attachment A of CASA's Advisory Circular provides a recommended methodology that adopts TAPM (The Air Pollution Model) to conduct plume rise assessments for single exhaust plumes. The CASA Advisory Circular does not specify a method for dealing with multiple plumes but allows for the use of alternative techniques. Katestone Environmental has developed a method that uses the TAPM vertical winds or a calm wind case to assess the average plume vertical velocity and extent due to two or more plumes.

In this study TAPM (Version 3.0.7) was used to calculate the plume height after discharge from the stack for a full year of meteorological conditions. TAPM does not output the downwind distance of the plume with vertical velocity greater than 4.3 m/s, a parameter that is important for presenting the results in accordance with CASA requirements. Experience has shown that comparable results for plume heights are obtained using an alternative methodology developed by Katestone Environmental. This alternative methodology can be used to calculate plume height, downwind distance of the plume and merged plume characteristics. The Katestone methodology is described in detail in Best et al 2003 (see Appendix B) and has been used with the meteorological data derived from TAPM to calculate the frequency, plume height, plume characteristics and downwind distance of the plume for vertical plume velocities greater than 4.3 m/s. Katestone Environmental has used this methodology throughout Australia and for these projects the methodology has been accepted by CASA.

5.1 Background to Katestone Method

The treatment of aviation safety close to industrial plumes has received relatively little attention in aviation circles in the past, and there is only a small amount of literature on possible problems and approaches. The methodology presented and used in this assessment has been based on well-verified laboratory and theoretical treatments of the rise and spread of a buoyant jet, both into a still ambient environment and into a light crosswind. This treatment (developed by Dr Kevin Spillane) covers in detail the initial dynamics of the plume as it exits the stack and the entrainment of ambient air into the plume as it rises directly above the stack. This method also considers the enhancement of vertical velocities that may occur if the plumes from multiple stacks merge and form a higher buoyancy combined plume.

For a scenario involving the merging of stack plumes, plume growth as influenced by the merging process will involve several stages of development:

(a) In the first stage very close to the stack exit, the high plume momentum will result in a short section in which the conditions at the center of each plume are unaffected by ambient conditions. The potential core in which maximum core velocity and temperature remain constant extends approximately a distance of 6.25 D (D is the stack diameter) above the outlet in calm conditions. At the end of this stage, the plume-average velocity has decreased to half of the exit velocity, with a corresponding increase in effective plume diameter.

(b) In the second stage, the plume dynamics and trajectories respond to ambient conditions, with much cooler air being entrained into the outer regions of the plume. The momentum and buoyancy of the plume significantly influence its rise as this air mixes into the plume and provides dilution of the exhaust. This dilution is very sensitive to ambient wind speed.

(c) In the third stage of plume development, plume rise is due entirely to the buoyancy of the plume and continues until there is an equalization of turbulence conditions within and outside the plume. This final rise is often only achieved at distances over 100 meters downstream of the stack; the effective average vertical velocity is then close to zero.

Note that for the case of the power station operating with two or more units on-line, the adjacent plumes may merge for some wind conditions at an early enough stage that the decay rate of vertical velocities with height may be slower than in the single plume case. Conservative assumptions have been made when considering this merging process.

5.2 Calm wind scenario

5.2.1 Single plume

The equations governing the growth of an isolated plume under calm wind conditions in a neutral environment are given in Appendix C. The analytical solution of the governing equations under these conditions is given by:

$$a = 0.16(z - z_v) \qquad (1)$$

and

$$(Va)^3 = (Va)_o^3 + 0.12F_o\left[(z - z_v)^2 - (6.25D - z_v)^2\right] \qquad (2)$$

Where the subscript 'o' refers to values of the parameters at the outlet and the variables are (See Appendix C for details):

a	plume radius (m)
V	average vertical velocity (m/s)
z	height above stack top (m)
z_v	virtual source height (m)
D	stack diameter (m)
F_o	buoyancy flux evaluated at the outlet (m^4s^{-3})

Characteristics of the plume radius, average vertical velocity and plume potential temperature for an isolated plume are plotted in the figures of Appendix C.

This analytical solution is used in the analysis of the merging of multiple identical plumes.

5.2.2 Two or more identical plumes

Determining the height at which the plumes first touch and when they are considered to be fully merged is the crucial first step to determining the vertical profile of plume radius and thus the vertical velocity of the plume that results from two or more identical plumes merging.

Although it may not be difficult to argue that two identical plumes begin to merge when the radius of the plumes is equal to half the stack separation distance, the height at which the multiple plumes (N) may assume to be fully merged is not so apparent. It has been suggested (Best et al, 2003) that under calm conditions, multiple plumes may be assumed to have fully merged at a height that corresponds to a single plume radius of:

$$\frac{1}{2}S(N-1) \text{ for } N \geq 3. \qquad (3)$$

This expression suggests that three identical plumes will have merged fully at a height that is equivalent to the stack separation distance. An additional radial distance S/2 is assumed to be required for each additional plume greater than three. Assuming that all plumes will be fully merged at a height corresponding to a single plume radius of S regardless of the number of plumes assessed will, result in a conservative estimate for the critical height (i.e the height at which $V_m = 4.3$ m/s). A more accurate estimate of the critical height would require a more accurate representation of the height at which buoyancy enhancement of the plume is applied.

During the three stages of plume growth that are described in Section 5.1 the assumed characteristics of plume growth are as indicated in Figure 2.

The methodology applied in the current study for the calm wind scenarios has assumed a fully merged height corresponding to a single plume radius of S for the gas-turbine scenario involving two plumes, and a height corresponding to a single plume radius of (3) for the nine cooling towers scenario.

See Appendix D for details of the methodology involving the merging of multiple, identical plumes.

5.3 Non-calm wind scenario

The governing differential equations that are outlined in detail in Best et al (2003) have been solved for merged plume characteristics as a function of height above the stack. These equations are a generalization of the equations presented in Appendix C and Appendix D for the calm winds case and are based on the same fundamental assumptions.

The non-calm wind scenario incorporates:

(a) Wind speed variations with height as predicted by TAPM for each vertical level included in the TAPM model.

(b) An assumption that merging of the plumes will be completed at a height corresponding to a single plume radius equal to the stack separation distance. This is a reasonable assumption for the case of two identical plumes (gas-turbine scenario). For the scenario involving nine cooling towers, the assumption that the plumes will have fully merged by a height corresponding to a single plume radius of S regardless of the number of plumes (as opposed to for example, 4S proposed in Best et al (2003), for calm wind conditions), will result in a conservative estimate for the average vertical velocity of the merged plumes.

Similar to the calm-wind case, a more accurate estimate of the critical height would require a more accurate representation of the height at which buoyancy enhancement of the plume is applied under non-calm conditions. It is plausible that this height would depend on wind speed.

6. Meteorology

The RCEC is located approximately 10 kilometers from the nearest meteorological monitoring station. For this assessment, meteorological data for the dispersion modelling was generated using the TAPM meteorological model for the year 1994. A comparison of meteorological data that was generated using TAPM (without data assimilation) with data from the Union City Meteorology Station, suggested that the TAPM meteorology did not adequately represent actual conditions (see verification presented in Appendix A). Consequently, the wind speed and direction data collected from the Union City Meteorological Station were integrated into the TAPM modelling to produce more representative conditions. The use of this model is described further in Appendix A.

The seasonal, diurnal and all hours wind roses for the RCEC site are presented in Figure 3. The wind roses show that the site is dominated by winds from the west-northwesterly sector particularly from midday to 6pm and in autumn and winter.

The most important meteorological conditions that could results in significant plume rise and potentially high vertical velocities at significant elevation are calm or light winds from ground level throughout the lower atmosphere.

Figure 4 presents the frequency distribution of wind speed observed and predicted at the Union City Meteorological Station. It can be seen that the model predicted a higher frequency of light winds at both 10 meters and 25 meters above ground level compared to the observations that are recorded at 20 meters. An analysis of the vertical wind profiles that were simulated using TAPM indicates that for only two hours out of a possible 8760 the winds at the RCEC location less than 0.5 m/s up to a height of 200 meters. Similarly, winds that are less than 1 m/s are predicted to occur up to a height of 300 meters on 19 hours; these occurring mostly between 6-8 am from the end of September to the end of March.

This again indicates that the scenario of calm winds (i.e. zero m/s) throughout the lower atmosphere is extremely conservative and unlikely to happen in reality.

7. Results

7.1 Worst-case calm wind scenario

An assessment assuming calm winds for the entire length and height of the plume is presented here to represent the absolute worst-case. Results of the height at which the average vertical velocity is reduced below the critical velocity of 4.3 m/s for the single and multiple plumes for the cooling towers and gas-turbines are presented in Table 2. The stack and plume characteristics used in the analysis are those presented in Table 1.

Table 2: Summary of height vertical velocity is reduced to 4.3 m/s for single and multiple plumes for worst-case calm wind scenario

Scenario	Height at which average vertical plume velocity is less than 4.3 m/s (meters above ground level)	
	Gas turbine	Cooling towers
Single plume	198	105
Merged plumes	285	315

Presented in Table 3 is the estimated horizontal extent of the plume at the height when the average vertical velocity of the plume falls below the critical value of 4.3 m/s. The plume width is estimated at 89 meters in diameter for the two gas turbines scenario and 158 meters in diameter for the nine cooling towers.

Table 3: Extent of plume at height critical plume velocity is achieved for calm wind scenario

Scenario	Horizontal extent of plume (meters)	
	Gas turbine	Cooling towers
Single plume	75	94
Merged plumes	89	158

The estimated vertical plume velocities at the heights of 180 meters and 240 meters (heights at which aircraft may circle the airport) are presented in Table 4. Figure 5 presents a vertical profile of predicted average vertical velocities for both calm and merged plume cases. It can be seen from this figure that once the plumes are fully merged the decrease in vertical velocity is linear and is a consequence of the assumption that the buoyancy flux is conserved.

Table 4: Average vertical velocity at various heights for calm wind scenario

Scenario	Average vertical velocity (m/s)	
	180 meters above ground level	240 meters above ground level
Single Gas Turbine Plume	4.5	3.8
Single Cooling Tower Plume	3.2	2.9
Two Gas Turbine Plumes Merged	4.7	4.4
Nine Cooling Tower Plumes Merged	4.8	4.6

At the lowest height that planes are likely to circle the Hayward Airport (180 meters) the average vertical velocity for all scenarios under worst-case calm wind conditions is estimated to be 4.8 m/s, approximately 10% higher than the 4.3 m/s threshold value.

In reality, wind speed and direction can vary dramatically with height, especially in a coastal environment and the above results are very conservative indications of adverse conditions. The important factor for a given location is the appropriateness of available information for estimating true wind and temperature profiles throughout a typical year. Theoretical predictions, as shown in Table 2 and Table 3, are likely to overestimate the expected vertical velocities, for the following reasons:

- The wind profile is assumed constant with height with no occurrence of wind-shear. In reality, there is a considerable variation with height, especially in light winds;
- Wind direction is assumed to be parallel with the line of stacks resulting in the maximum enhancement and merging of the plumes; and
- Worst-case scenarios are for very light-wind, near-neutral atmospheric conditions with maximum loading.

Section 7.2 details a more realistic approach to estimating the average in-plume vertical velocity profiles using vertical profiles of meteorological data generated by a prognostic wind-field model for an entire year and estimates the frequency of occurrence of the height at which the plume achieves the critical vertical velocity of 4.3 m/s.

7.2 Realistic wind scenario

A one-year meteorological simulation has been prepared using the TAPM model utilising synoptic data for the year 1994 to quantify:

(a) The critical plume height. The critical plume height is the height at which the vertical velocity of the plume falls below 4.3 m/s; and
(b) How frequently critical plume heights of various magnitudes are likely to occur.

Results for the proposed RCEC for full load operations are presented in Table 5. This table includes the results of the TAPM methodology for the single plumes as well as the results obtained using the Katestone methodology for both the single and merged plume scenarios. Good agreement is evident between the two methodologies.

The results in Table 5 show that the critical plume heights are predicted to be below 175 meters for 99.95% of the time for the two gas turbine plumes, and below 93 meters for the nine cooling tower plumes. Frequency plots are also presented in Figure 6.

Figure 7 shows the calculated critical plume height for full load operations versus time of day for the two gas-turbine exhaust plumes from the RCEC.

Table 5: Critical plume height for the proposed RCEC (Gas Turbine (GT) and Cooling Tower (CT)) and the proportion of the simulation year that the critical height is exceeded for a single and merged plume.

Percent of time (%)	TAPM results		Katestone methodology results		Katestone methodology results	
	Single GT	Single CT	Single GT	Single CT	Two merged GT	Nine merged CT
90	59	29	64	24	64	28
80	59	29	68	26	68	31
70	60	30	71	28	72	34
60	65	30	75	31	76	37
50	66	31	80	33	80	42
40	67	35	86	36	86	47
30	72	35	92	39	92	53
20	78	36	101	44	101	58
10	100	41	116	51	116	64
9	100	41	118	53	118	65
8	101	42	120	54	120	66
7	102	42	122	56	122	67
6	103	42	125	58	125	69
5	104	42	128	60	128	70
4	105	43	132	62	132	73
3	107	47	136	65	136	76
2	111	48	141	67	142	80
1	132	49	149	70	150	84
0.5	134	68	155	71	156	87
0.3	136	68	158	71	159	89
0.2	152	69	161	72	161	90
0.1	157	69	164	72	167	92
0.05	160	70	165	72	175	93

The plume extent is calculated as the sum of the plume radius and downwind distance. In Table 6 the plume extents are shown for various heights above ground level for the two merged plume scenarios. For example for a height of 150 meters, the vertical velocity of the plume falls below 4.3 m/s at a maximum downwind distance from the stack of 35 meters. On average, for a height of 150 meters the vertical velocity falls below 4.3 m/s at a downwind distance of 26 meters.

Table 6 shows that the vertical velocity of the plume is likely to be below 4.3 m/s under all meteorological conditions at a distance of up to 84 meters from the stack of the RCEC.

Table 6: Predicted plume extent (plume radius + distance downwind in meters) where the average vertical velocity exceeds the 4.3 m/s threshold for various heights, using Katestone methodology for the RCEC for the TAPM simulation year 1994.

Plume extent	Height (meters)				
	75	**100**	**125**	**150**	**175**
Gas turbines					
Maximum	25	28	28	35	31
Average	14	18	22	26	31
Minimum	5	7	14	21	31
Cooling towers					
Maximum	84	73	NA	NA	NA
Average	32	39	NA	NA	NA
Minimum	20	36	NA	NA	NA

7.3 Interpretation of results

In any evaluation of the results given above there are several aspects that are of relevance:

(a) The response of an aircraft to enhanced vertical velocities and the distance over which they are likely to be experienced should be considered. At heights of 175 meters above ground level the plume will be relatively narrow, typically 32 meters in radius depending on wind conditions.

(b) In the absence of the power station, pilots are probably already experiencing significant updrafts of the order of the 4.3 m/s threshold chosen for the CASA guideline. Vertical velocities in excess of 4.3 m/s are well documented for many regions in Australia and can be expected in California on, for example, hot summer days prior to seabreeze arrival.

During the abstract case of uniform calm wind conditions throughout the lower atmosphere, the average vertical velocity within the plume is not predicted to be below the CASA threshold until 285-315 meters above ground-level for the worst case operating scenario of all units operating at peak load. The height at which the guideline is achieved is significantly reduced for greater wind speeds, with peak values of 95 meters above ground-level for cooling tower plumes and 176 meters above ground-level for gas turbine plumes.

Assuming a uniform wind profile is extremely conservative and as presented in Table 5, the introduction of realistic wind profiles reduces the height at which the guidelines is achieved by 50% to 70%.

8. Conclusions

An aviation safety assessment has been conducted in accordance with the Australian Civil Aviation and Safety Authority (CASA) requirements for the proposed Russell City Energy Center.

The assessment has shown the following important characteristics:

- The power station is situated at a distance of approximately 2.5 kilometers to the southwest of Hayward Executive Airport.

- The power station is located outside the Traffic Pattern Zone for Hayward Executive Airport.

- For the unrealistic scenario of calm winds throughout the lower atmosphere, the average plume vertical velocity is estimated to achieve 4.3 m/s at a height of 285 meters above ground level for the merged gas turbine plumes and 315 meters above ground level for the merged cooling tower plumes.

- As no vertical wind speed measurements are available for the site, inspection of the prognostic meteorological model predictions indicates only two hours per year with calm winds to a height of 200 meters.

- For realistic wind scenarios the average plume vertical velocities are unlikely to exceed the critical threshold of 4.3 m/s above a height of 176 meters and at a maximum distance of 84 meters from the power station.

9. References

Best P, Jackson L, Killip C, Kanowski M and Spillane K (2003), "Aviation Safety and Buoyant Plumes", Clean Air Conference, Newcastle, New South Wales, Australia.

CASA (2004), "Guidelines for conducting plume rise assessments" – Civil Aviation Safety Authority, Publication AC 139-05(0), June 2004.

TAPM (2006) Version 3.0.7 developed by the CSIRO (www.dar.csiro.au/TAPM).

Figure 1: Location of Russell City Energy Center Power Station

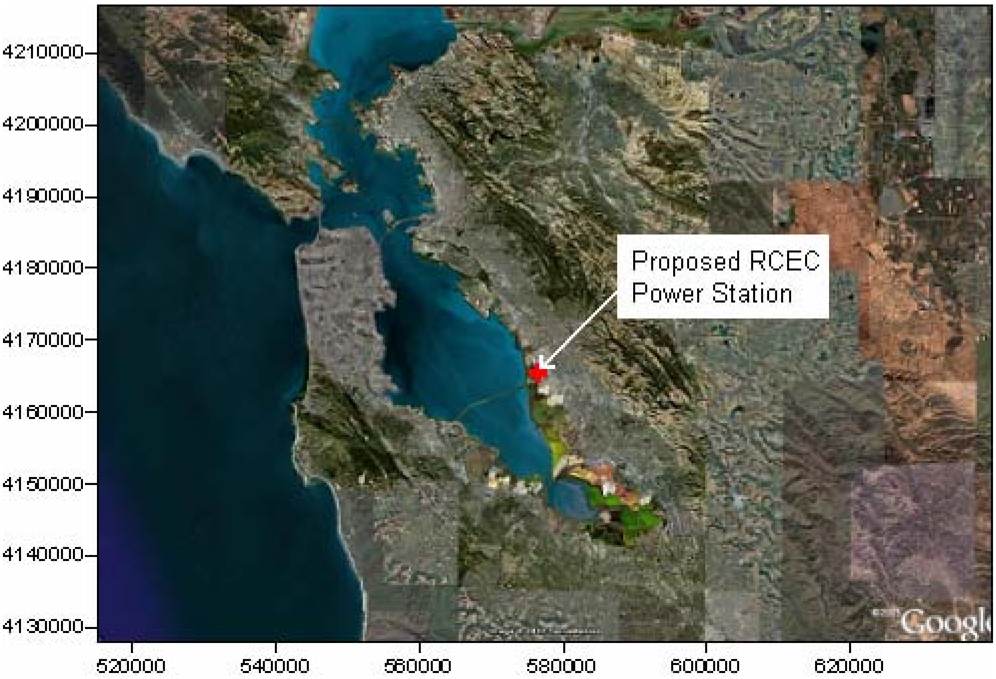


Figure 2: Description of the three phases of plume merging from multiple stacks.

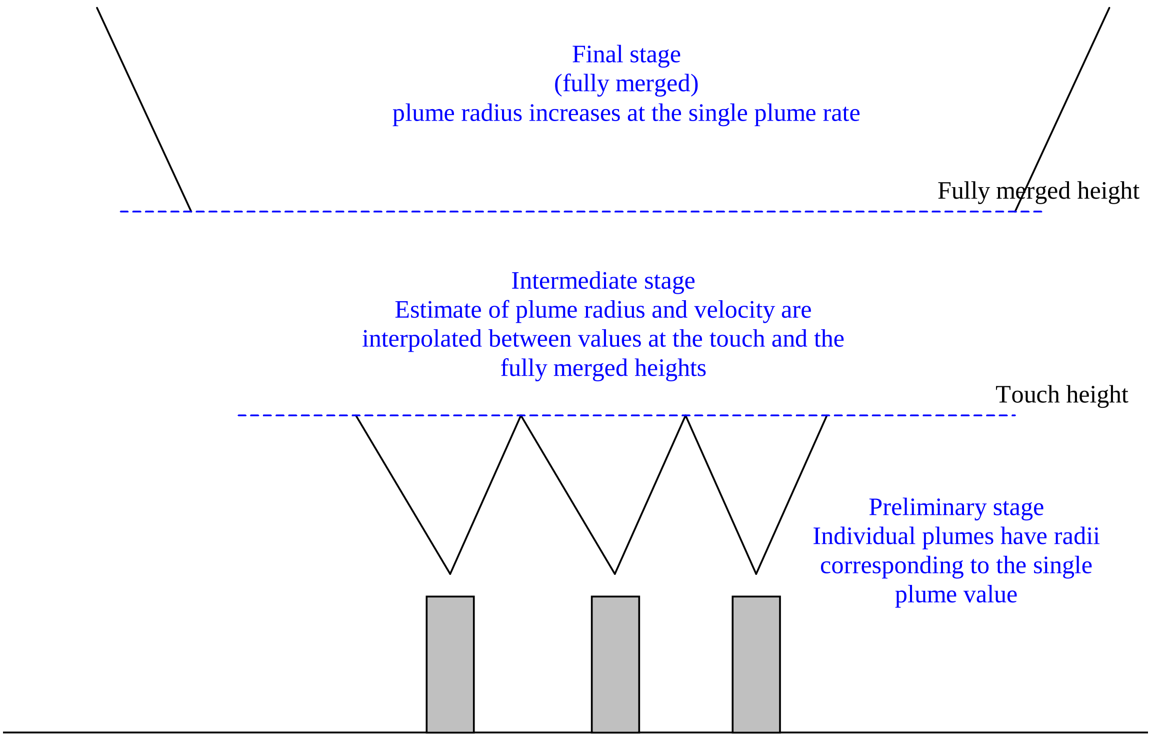
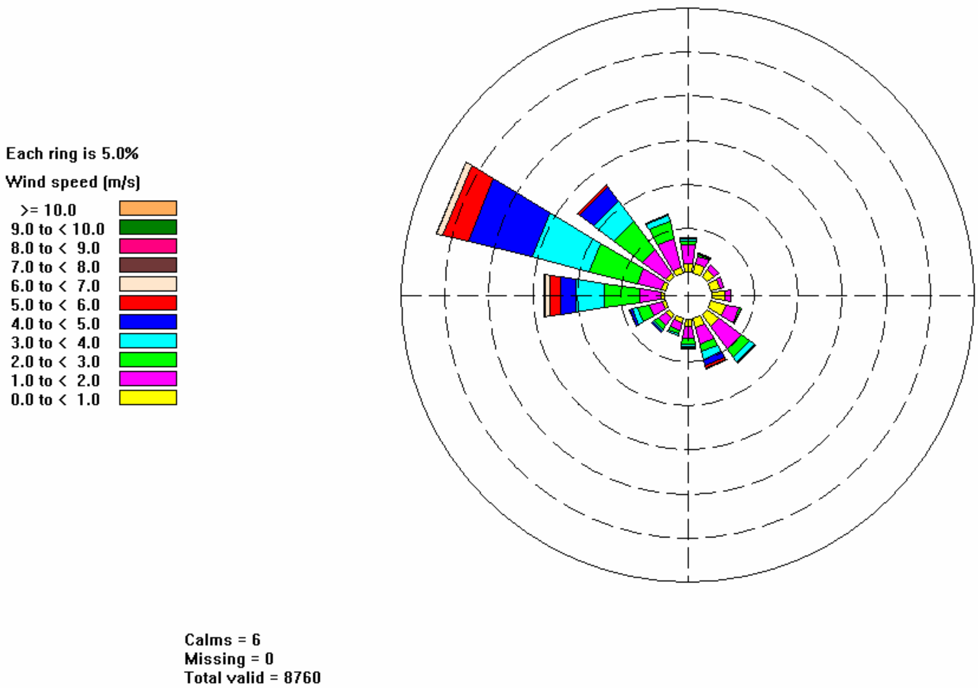


Figure 3: Wind roses as predicted by TAPM for 1994 for the RCEC site for (a) all hours, (b) diurnal variation.

(a)



(b)

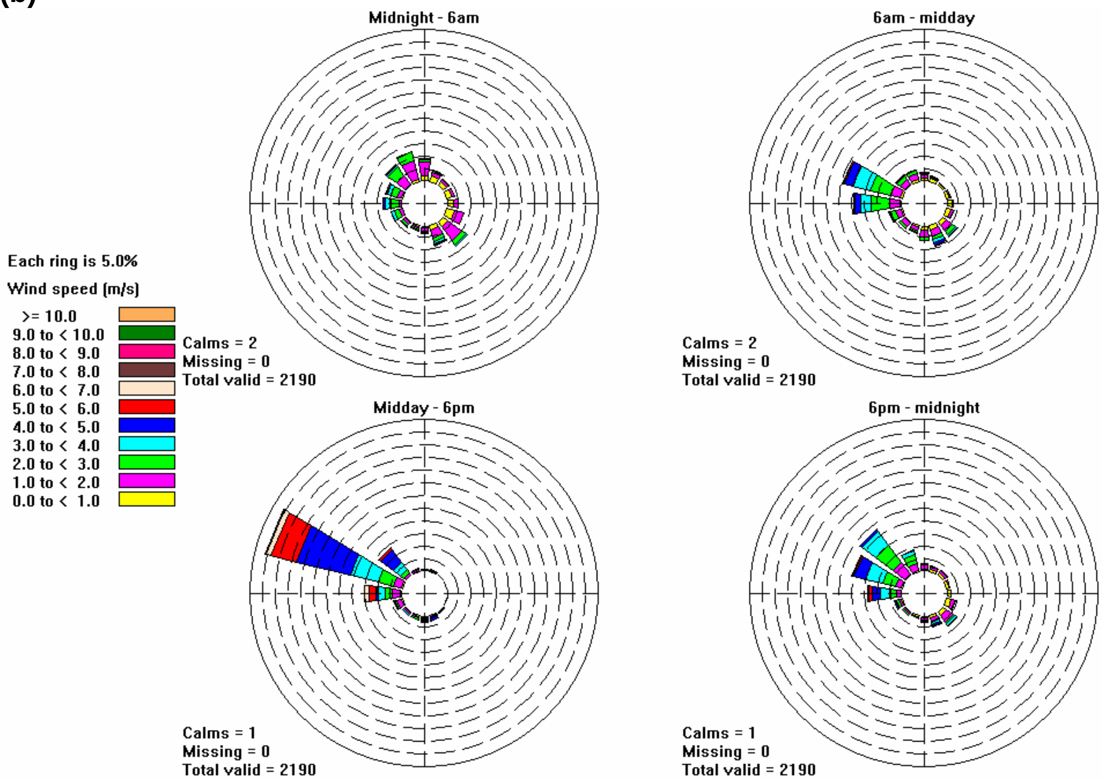


Figure 4: Comparison of frequency of wind speed between TAPM predictions and Observations at Union City Meteorological Station

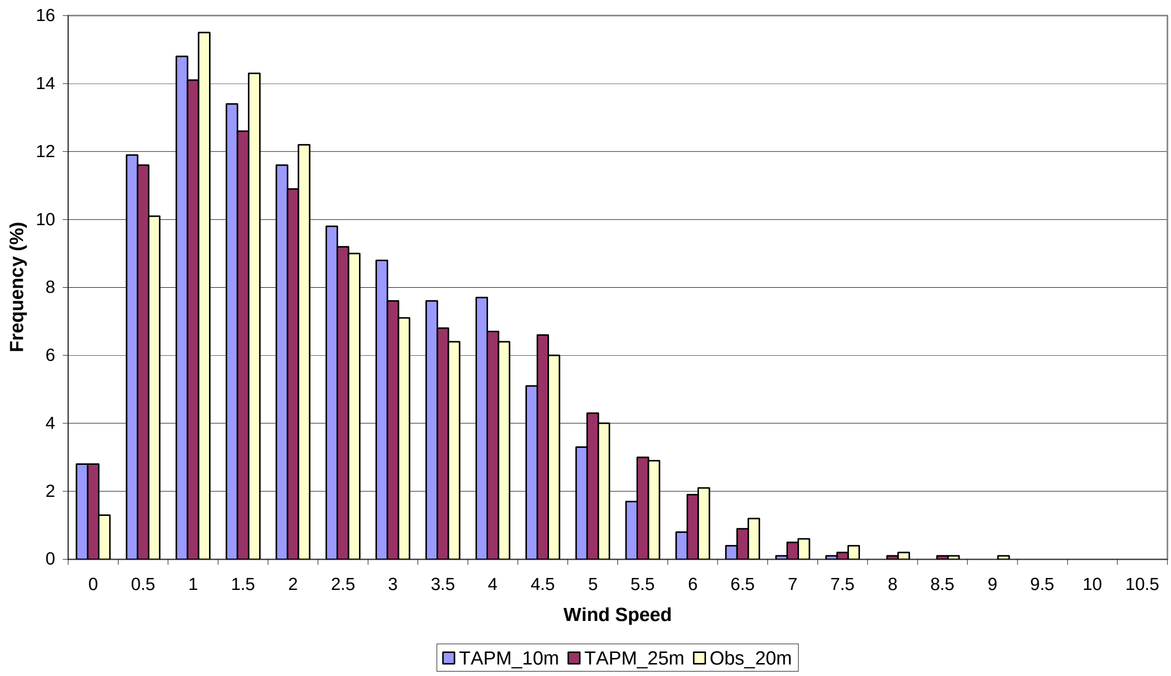


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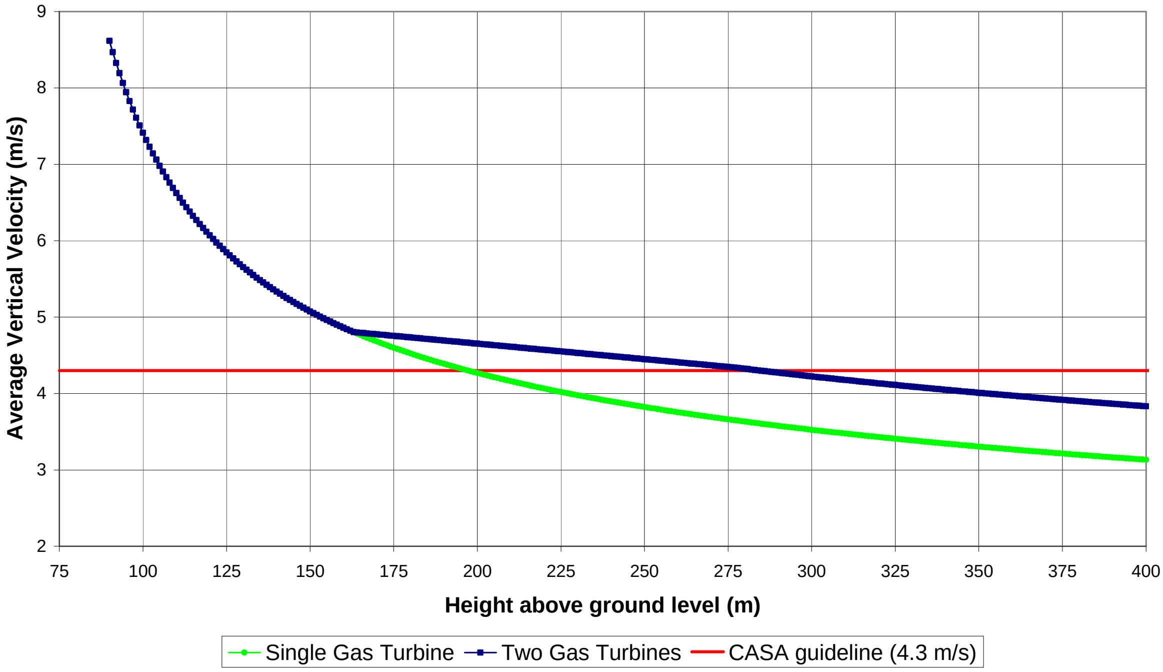
Figure 5: Predicted average vertical plume velocity with height for worst-case calm wind conditions and neutral stability for all heights for (a) gas turbines and (b) cooling towers

(a)



(b)

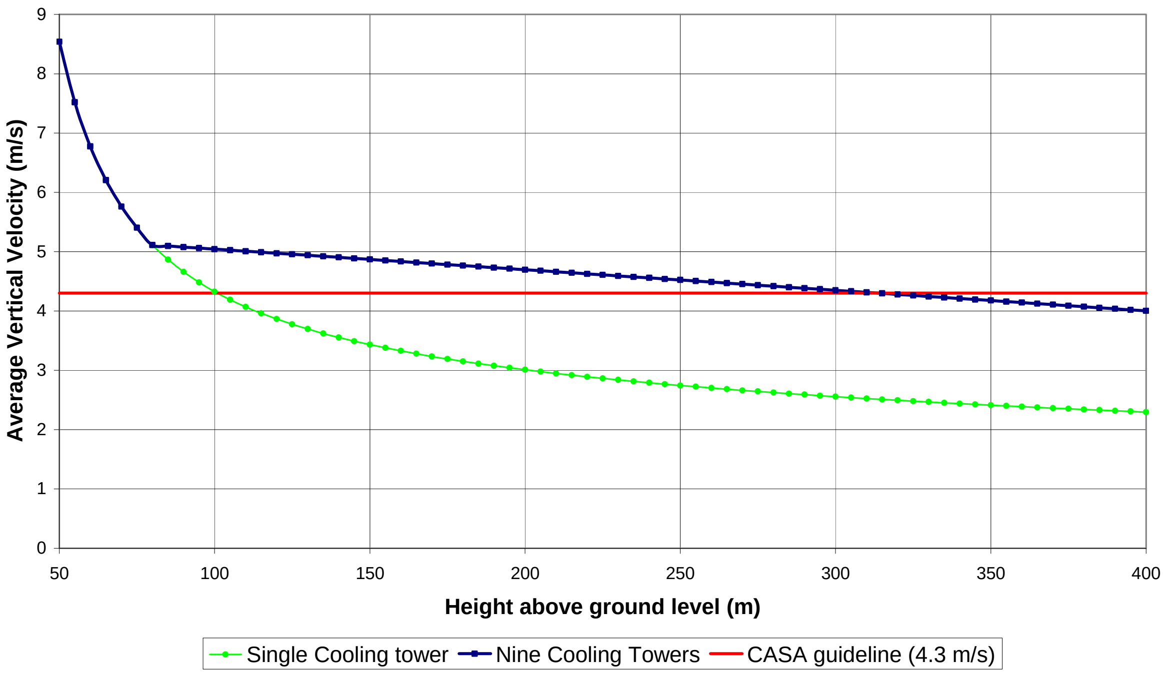


Figure 6: Frequency distribution of critical plume height (meters) for merged plumes for gas turbines (red) and cooling towers (blue) using the Katestone Method and TAPM meteorology for one year

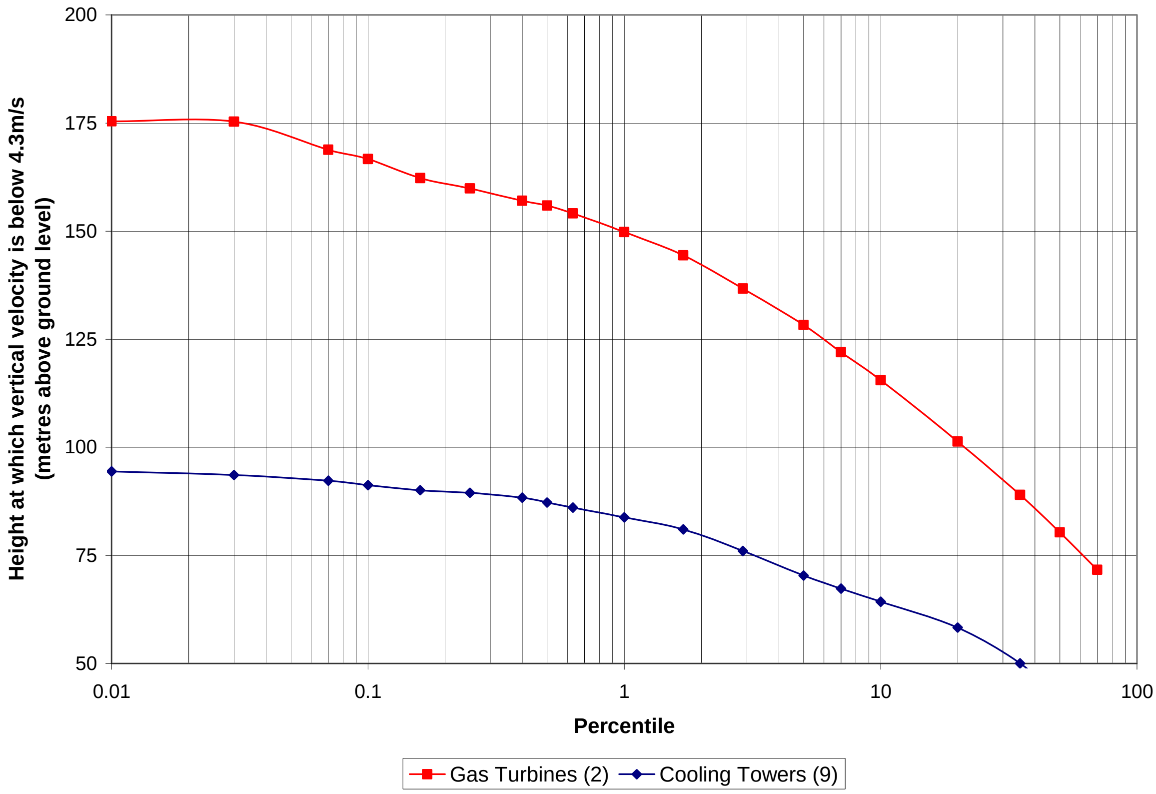
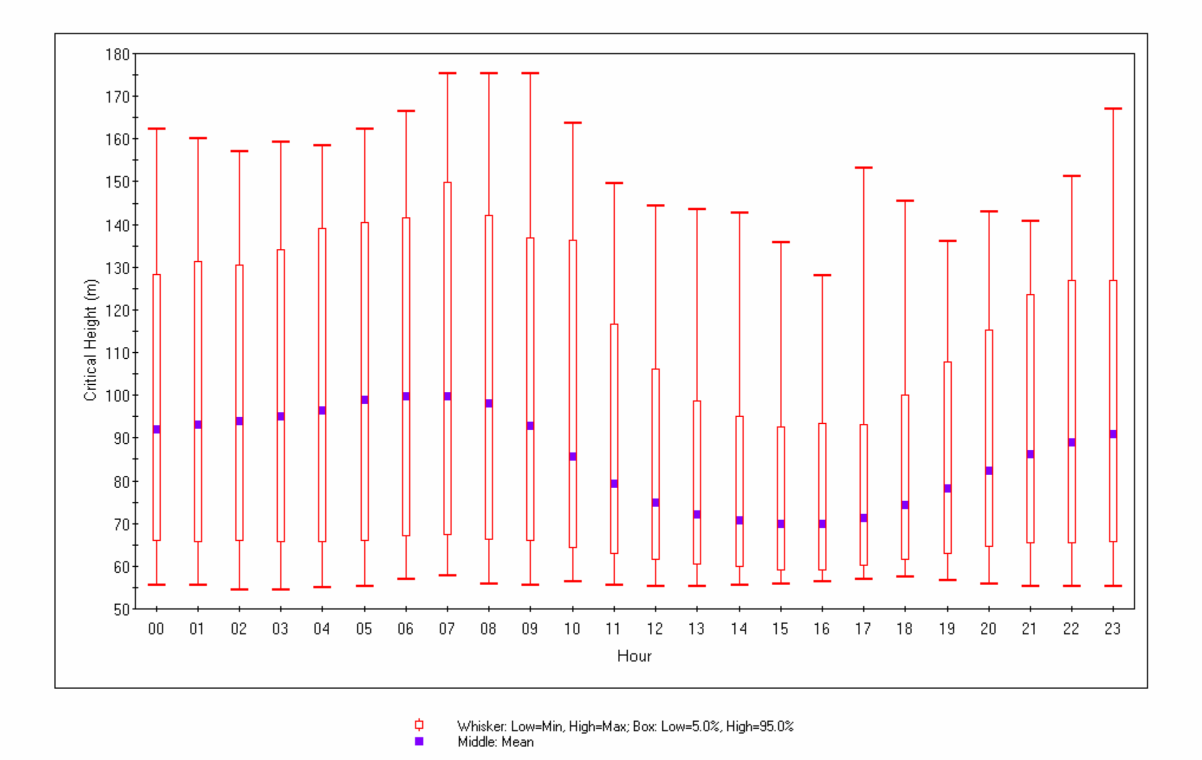


Figure 7: Box and whisker plot of the critical plume height (meters) versus hour of day for the merged plume results for the two gas turbine units.



APPENDIX A
TAPM

A1.1 Methodology

The prognostic meteorological model, TAPM (The Air Pollution Model) Version 3.0.7, was developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) and has been validated by the CSIRO, Katestone Environmental and others for many locations in Australia, in southeast Asia and in North America (see www.dar.csiro.au/TAPM for more details on the model and validation results from the CSIRO). Katestone Environmental has used the TAPM model throughout Australia as well as in parts of New Caledonia, Bangladesh and Vietnam. This model generally has performed well for simulating winds in a region. TAPM has proven to be a useful model for simulating meteorology in locations where detailed monitoring data is unavailable.

TAPM is a prognostic meteorological model which predicts the flows important to regional and local scale meteorology, such as sea breezes and terrain-induced flows from the larger-scale meteorology provided by the synoptic analyses. TAPM solves the fundamental fluid dynamics equations to predict meteorology at a mesoscale (20 kilometers to 200 kilometers) and at a local scale (down to a few hundred meters). TAPM includes parameterizations of cloud/rain micro-physical processes, urban/vegetation canopy and soil, and radiative fluxes.

TAPM requires synoptic meteorological information for the study region as input into the model. This information is generated by a global model similar to the large scale models used to forecast the weather. This assessment used the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996) on horizontal wind components, temperature and moisture, to obtain the required synoptic fields for the model. These data have a horizontal resolution of 2.5º and a temporal resolution of 6 h, while the vertical levels are in a pressure coordinate system with the lowest five levels being 1000, 925, 850, 700 and 600 hPa. TAPM uses this synoptic information, along with specific details of the location such as surrounding terrain, landuse, soil moisture content and soil type to simulate the likely meteorology of a region as well as at a specific location.

The TAPM was configured with data assimilation from the Union City monitoring station located within the modelling domain (Section 6). This method was used to ensure representative local meteorological conditions existed within the model. The proposed power station has been assessed for an operational load of 100% for the full year 1994.

TAPM was setup as follows:

- 30 x 30 grid point domain with an outer grid of 30 kilometers and nesting grids of 10 kilometers, 3 kilometers and 1 kilometer (with a 1 kilometer grid for the stack dispersion modelling);
- 25 vertical levels;
- Grid centered over the RCEC site centered (latitude 37° 38’, longitude -122°-8’);
- The TAPM defaults for sea surface temperature;
- Default options selected for advanced meteorological inputs; and
- The synoptic data used in the simulation is for the year 1994.
- Default vegetation information.

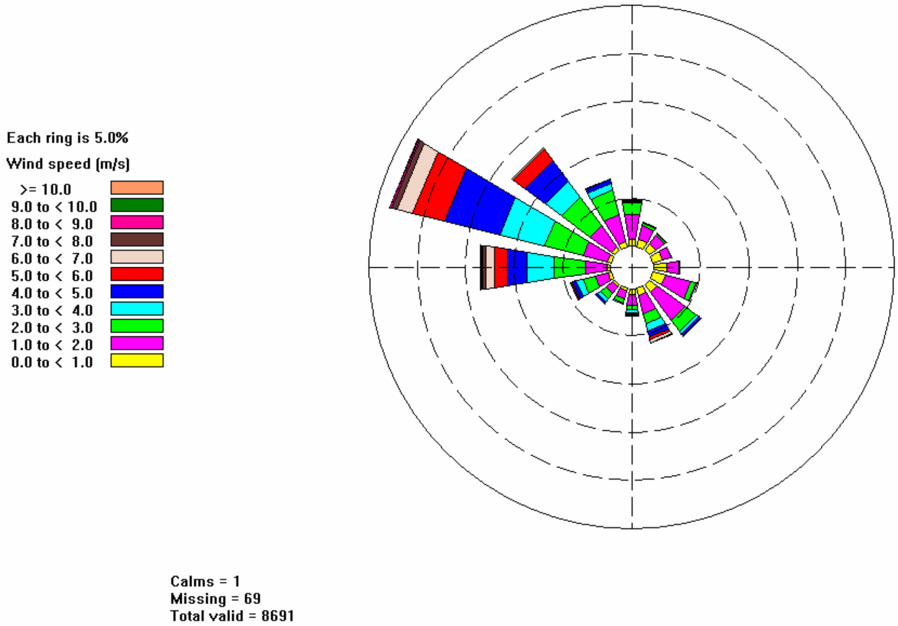
The TAPM land-use at a 1 kilometer resolution was mainly defined as urban, low sparse shrubland to tall mid-dense shrubland. A significant portion was also water. The soils were defined as sandy clay loam and water within the domain, consistent with TAPM defaults.
The Russell City Energy Center Power Station was modelled in Lagrangian mode. Although more computationally intense, the Lagrangian mode is important for assessing near field impacts and assessing aviation safety.

A1.2 Verification of winds

To determine the suitability of the meteorological data generated by TAPM, an evaluation of the predicted and measured winds was conducted for the Union City meteorological station (nearest monitoring station with representative data for 1994). Wind roses are presented in Figure A1 that compare the measured and predicted wind speeds and wind directions at Union City, without data assimilation. The wind roses show that TAPM simulates the winds quote well, but predicts winds slightly more westerly than observations, once local observations are assimilated the predictions are satisfactory (Figure A2).

Figure A1: Wind rose for all hours for (a) the Union city monitoring station and (b) TAPM predicted at the Union city monitoring location for the year 1994 (no data assimilation included).

(a) Measured



(b) TAPM

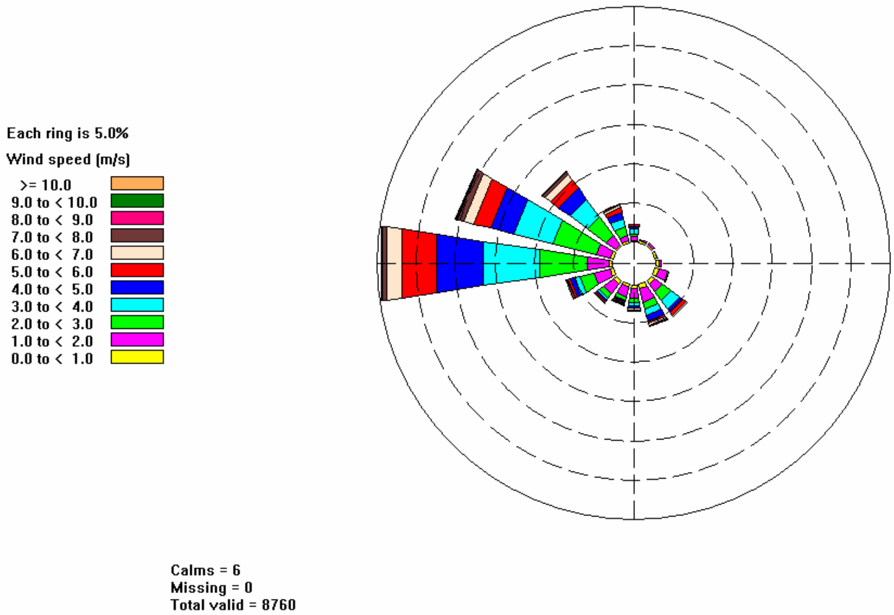
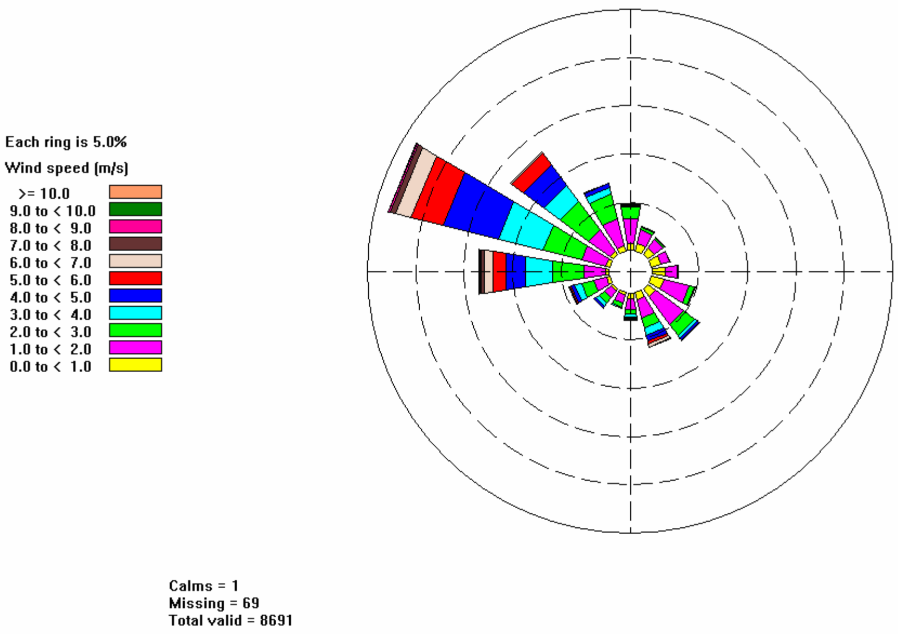


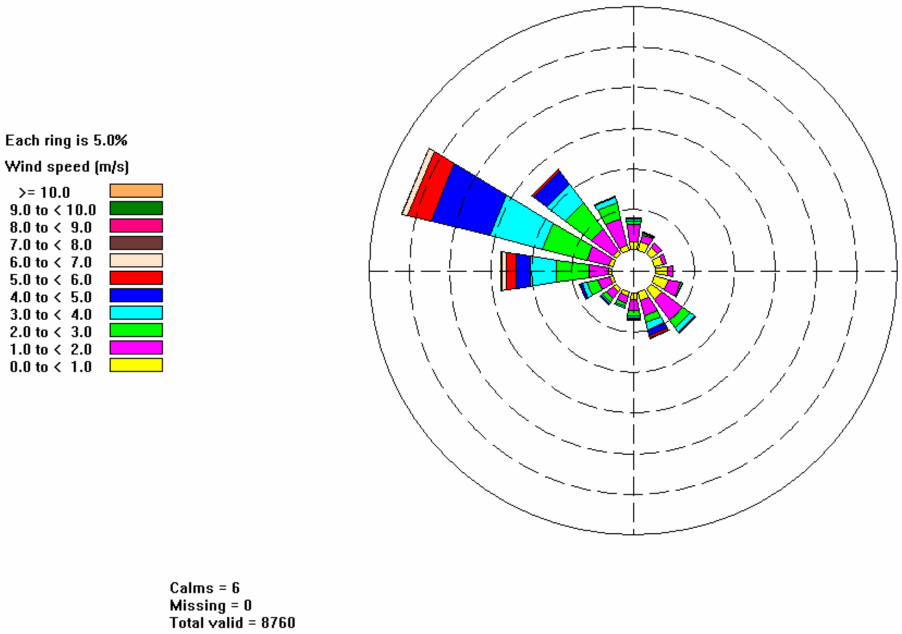
Figure A2: Wind rose for (a) all hours and (b) diurnal for (i) the Union city monitoring station and (ii) TAPM predicted at the Union city monitoring location for the year 1994, following the assimilation union city data.

(a)

(i) Measured



(ii) TAPM



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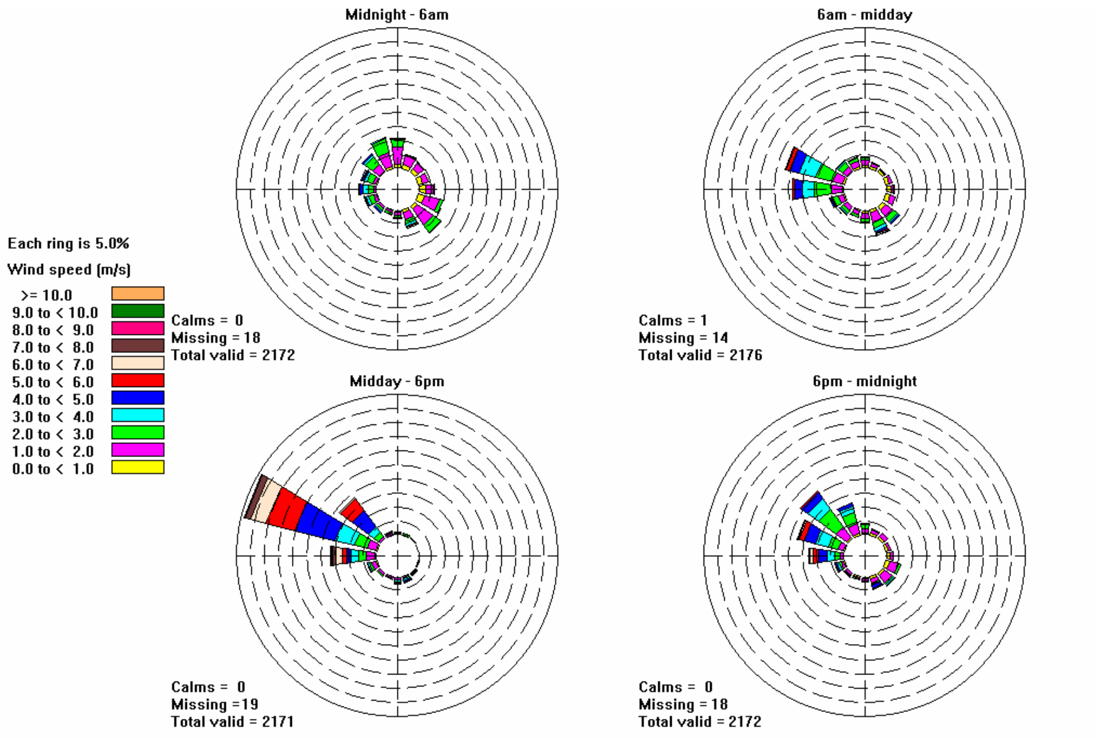
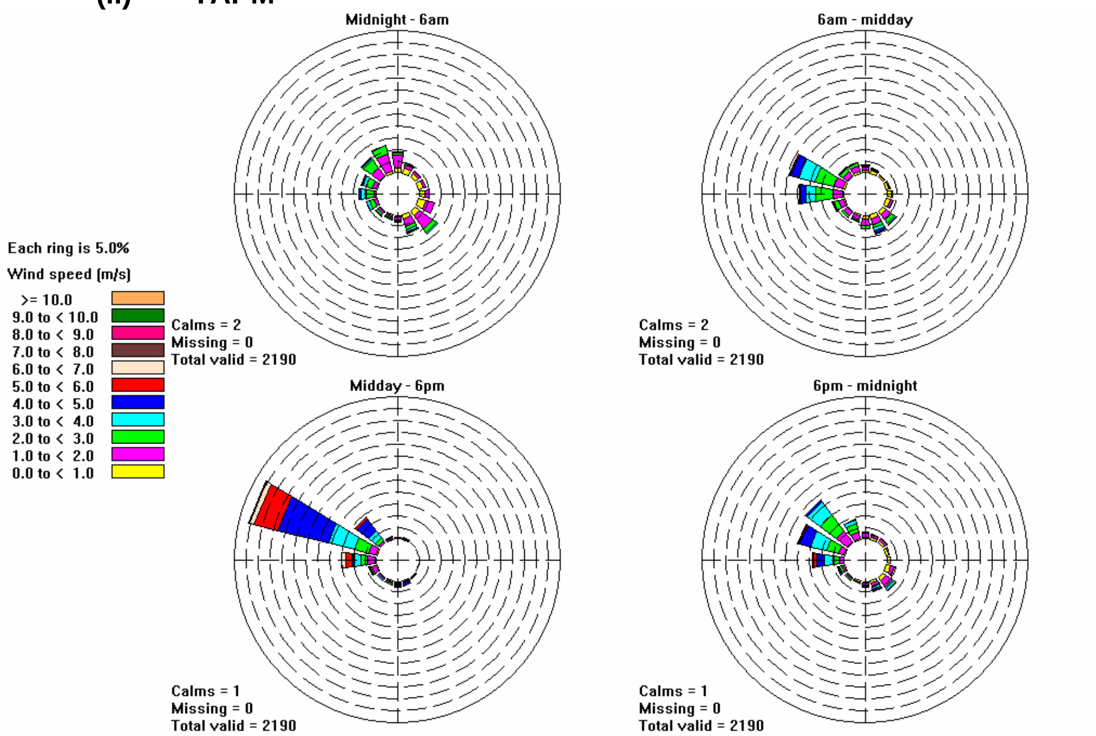
(b)

(i) Measured



(ii) TAPM



APPENDIX B

Clean Air Conference, Newcastle, New South Wales, Australia, 2003

AVIATION SAFETY AND BUOYANT PLUMES

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Summary

Very buoyant plumes generally experience good dispersion but can, in some circumstances, affect aviation safety. Large in-plume vertical velocities can occur in calm conditions with minimal wind shear. Recent civil aviation guidelines seek to restrict the horizontal or vertical extent where average in-plume vertical velocities exceed a threshold that can threaten aircraft performance or structural stability. Key plume calculation procedures require adequate predictions or measurements of vertical profiles of wind and turbulence parameters. The TAPM scheme proves useful but requires additional features for complex source geometry. A hybrid approach overcomes most of these limitations, whilst treating the initial plume development in more detail. Design issues for typical stack configurations are discussed.

Keywords: Plume velocities, stacks, cooling towers, flares, safety

1. Introduction

Over the past 25 years, considerable laboratory, field and theoretical work has been undertaken on the dispersion of very buoyant plumes from industrial sources. Such sources have traditionally included single or multi-flue stacks for major power stations, cooling towers and gas turbine generating plants where large volume flows, together with high exit temperatures, produce some of the highest buoyancy fluxes for normal power station configurations. With the increasing emphasis on gas and similar alternatives for power generation and the recent consideration of stack-in-tower configurations for locations where dry cooling is preferred, highly buoyant plumes are becoming the rule. In addition, industrial flares or unintended releases from pressurised pipelines can yield plumes with large momentum and/or buoyancy fluxes and may have structures approximating line or area sources. Recent dispersion analyses (Weil et al 2001) have shown that very buoyant plumes can readily interact with the overlying inversion and have plume spread dominated by buoyancy for most of the near-field. Plume rise and spread descriptions may need to be revisited.

High buoyancy plumes can, however, give rise to other problems that may require addressing in environmental impact assessments. High buoyancy plumes rise quickly and have significant in-plume vertical velocities. Should the facility be close to local airfields or aviation transport routes, any aircraft encountering the buoyant plumes may experience sufficient vertical uplift and turbulence to cause some temporary disruption to the manoeuvrability of aircraft, especially light commercial (rather than jet) aircraft.

There are no publicly-available field studies that document the decline of in-plume velocities with plume travel time for a variety of conditions necessary to produce validated modelling schemes. Various experimental and theoretical work was conducted around open-cycle and combined-cycle gas turbines at Kuala Lumpur, with field measurements taken for stack-top windspeeds in the range 2-8 m/s (but not for calm conditions). The Cessna aircraft used (Flinders Institute for Atmospheric and Marine Sciences) was fitted out to measure turbulence and air quality parameters as well as aircraft variables. The unpublished results showed a strong decrease of in-plume vertical velocities with windspeed and height, core vertical velocities a factor of approximately 2 greater than plume-averaged values and significant influences on aircraft handling for near-instantaneous (~ 1 sec) exposures to strong plume velocities, especially if encountered by surprise.

The importance of vertical motion in causing aviation problems is better documented by the number of light aircraft incidents reported during strong convection in Australia (Spillane and Hess 1988). During extreme events, naturally-occurring vertical velocities can reach 8 m/s.

The current studies were conducted for an environmental impact assessment of a 700 MW open cycle gas-fired turbine near an army aviation centre at Oakey in southern Queensland. Previous studies by Spillane (1980) on moist plumes were adapted to treat buoyant plumes from closely located sources in calm and low windspeed neutral conditions (Katestone

Scientific 1997). At the time, there was no model recommended by the Civil Aviation Safety Authority of Australia (CASA) and, indeed, very little guidance internationally as to the manner in which available velocity thresholds should be interpreted. Representations were made and generally accepted that the threshold vertical velocity of 4.3 m/s recommended by Australia and New Zealand authorities should be viewed as a plume-average rather than plume centreline criterion.

Critical (but extreme) aviation conditions are expected to be very light winds and neutral stability to heights of 500 m or more. For most assessment sites, there is unlikely to be a substantial database of near-surface and upper-level wind and temperature information to estimate the frequency of occurrence of such rare cases. Recognising this, CASA recently recommended the use of the CSIRO TAPM model for producing long-term databases of such profiles at any location within Australia and for providing a publicly-available method of calculating plume vertical velocities in the near-field of a single plume source (CASA 2003). The TAPM treatment of plume rise (Hurley and Manins 1995) uses coupled non-linear first-order differential equations for the plume volume G, buoyancy F and momentum M fluxes that are generalisations of the original Briggs (1975) plume rise formulation, based on the work of Glendening et al (1984) for stable atmospheres with complex structures. The TAPM scheme does not include any influence of source-altered flow fields or moisture content. It is also strictly valid only for single sources, with multiple sources being treated only via use of a plume enhancement factor, a relatively coarse device for describing near-field plume dynamics. For cooling tower sources, moisture emissions, the confluence of adjacent plumes and the influence of suction occurring due to tower bypass flow can be important (Rezacova and Sokol, 2000). This paper restricts attention to essentially dry plumes with no interactions with distorted flow fields.

Aviation safety risk assessments require the evaluation of concurrence of adverse vertical velocities with the presence of aircraft in the vicinity of the plume and a spectrum of aircraft types and pilot skill. Ideally, a generalised scheme should facilitate the prediction of likely pilot response to such events but publicly-available schemes are not yet available. As for many air quality problems, the main difficulties are assessing the relevance of traditional techniques to the forecasting of extreme conditions and determining the reliability of such assessments based on existing knowledge.

The present paper outlines the available plume calculation methodologies for the Spillane and TAPM approaches, addresses the modifications necessary for multiple sources and assesses the utility of the various schemes for dispersion and meteorological modelling in providing initial and detailed assessments. The high buoyancy of the plumes diminishes the utility of various design alternatives such as increasing stack separation, reducing exit velocity and changing the orientation of discharge. Practical measures are discussed.

2. General considerations

For the generic stack problem, we choose the case of multiple but identical sources of high initial exit velocity and temperature but low enough water vapour content to neglect latent heat considerations. In light winds, influences of the aerodynamic wakes or other effects of stack or cooling tower structures can be neglected. The initial stage (exit conditions) is assumed to be a plume emanating from a stack of height h_s and diameter D, with plume exit velocity either uniform over the cross-section (with a value V_{exit}) or, more likely, a non-uniform velocity profile with plume average velocity V_{exit}. The exit virtual potential temperature θ_s, volume flow $\pi D^2 V_{exit}/4$ and initial buoyancy flux $F_o = gV_{exit} D^2 (1 - \theta_a/\theta_s) / 4$ are readily calculated, with θ_a denoting ambient conditions. The ambient airspeed at stack top is denoted u_e with $K_o = V_{exit}/u_e$ being the initial plume to ambient velocity ratio.

An outline is given in the following sections of the Spillane and TAPM plume dynamics modules for single plumes (retaining their respective notations). The physical interpretation of the processes is outlined in Section 3 with the additional considerations needed for multiple plumes.

2.1 Spillane methodology

The plume radius a, orientation ϕ and velocity V are followed along the plume trajectory. Five equations are solved numerically for the normalised vertical velocity $K = V/u_e$:

Radial growth of a forced-plume bending in a wind:

$$\frac{da}{ds} = \beta_n \cos\phi / K + \beta_e \left| 1 - \frac{\sin\phi}{K} \right| \quad (1)$$

Rate of entrainment, E, into the plume:

$$2E / V = \left(\frac{da}{ds} + (\lambda^2 \cos\phi) / 2F_r^2\right) / (1 - \sin\phi / 2K) \quad (2)$$

Momentum flux, Va, (longitudinal)

$$\frac{d(Va)}{ds} = 2E - V\frac{da}{ds} \quad (3)$$

Trajectory curvature; transverse momentum flux

$$\frac{d\phi}{ds} = \left(2\, Ea\, u_e \cos\phi - (F \sin\phi) / 2.25V\right) / (Va)^2 \quad (4)$$

Flux of heat:

$$\frac{d\left(Va^2 \Delta\theta / \theta\right)}{ds} = 0, \text{ in a neutral environment} \quad (5)$$

where the notation is as follows:

a = plume top-hat radius;
s = distance along plume trajectory;
ϕ = angle of plume centre line to vertical ;
K = V/u_e;
V = plume-averaged speed.
β_n = 0.40; β_e = 0.16; λ = 1.11;
F_r^2 = Froude No = $V^2/(ag\Delta\theta/\theta)$
F = flux of buoyancy = $\lambda^2 a^2 Vg\ \Delta\theta/\theta$; $\Delta\theta = \theta_p - \theta_e$ and suffices p and e for plume and environment.
θ = virtual potential temperature.

Initial conditions for ϕ, V, a and z are set for the end of the momentum rise stage (for a single plume) or at the end of the merged plume stage (for multiple plumes). An along-plume distance step of Δs = 20 m is used, and the appropriate value of $u_e(z)$ adopted for non-uniform profiles.

For the case of calm conditions, analytic solutions are possible, one for the product Va at any height, the other a linear increase of a = 0.16 (z - z_v) where the virtual source height (above stacktop) z_v = 6.25 D [1 - $(\theta_e / \theta_s)^{1/2}$]. For z > 6.25 D > z_v we have:

$$(Va)^3 = (Va)_o^3 + 0.12\,F_o\left[(z-z_v)^2 - (6.25D - z_v)^2\right]$$
$$where\ (Va)_o = V_{exit}\,D/2\left(\theta_e/\theta_s\right)^{1/2} \tag{6}$$

2.2 CSIRO TAPM methodology

The TAPM mean plume rise estimation takes the Glendening et al (1984) approach but assumes that the horizontal plume velocity instantaneously takes up the ambient horizontal velocity at stack height. Cartesian co-ordinates are adopted. The differential equation for plume volume flux G:

$$\frac{dG}{dt} = 2R\ w_p\left(\alpha\,w_p + \beta\,u_e\right) \tag{7}$$

neglects a third term due to ambient turbulence entrainment. $w_p = \frac{dz_p}{dt}$ is the plume vertical velocity, α = 0.1 and β = 0.6 are vertical and bent-over entrainment coefficients and R is the plume radius. For the buoyancy flux F, it assumes:

$$\frac{dF}{dt} = -\frac{sM}{u_p}\left(A\,u_a + w_p\right) \tag{8}$$

where $s^2 = \frac{g}{\theta_a}\frac{\partial\theta_a}{\partial z}$ gives the ambient buoyancy frequency (s = 0 in neutral conditions), $u_p^2 = u_e^2 + w_p^2$, A = 1/2.25 and M is determined by $\frac{dM}{dt}$ = F (= F_o in neutral conditions). By definition,

$$G = \frac{\theta_e}{\theta_p}u_p\,R^2,\ F = gu_p\,R^2\frac{\Delta\theta}{\theta_p},\ u_pR^2 = G + F/g,$$

$$w_p = M/G \tag{9}$$

Initial conditions are set with G, F and M evaluated with $w_p = V_{exit}$, R = R_s = D/2 but with the initial integration having

$$R = R_o = R_s\left(V_{exit}/\left(u_a^2 + V_{exit}^2\right)^{1/2}\right)^{1/2} \tag{10}$$

The plume rise height is terminated when F = 0 and plume and ambient dissipation rates are equal. The plume dimensions are based on R = 0.4 (z - h_s) or equivalent prescriptions.

3. Treatment of multiple plumes

For N multiple, identical sources with stack separation d, Table 1 summarises the expected multi-stage plume development as well as Figure 1. The first stage is the rapid (almost vertical) rise of the individual plumes due to their momentum. The external surface of the plume entrains air as it rises (and the vertical velocities are reduced). The end of the momentum-dominated phase occurs when this entrainment reaches the plume core, the plume centreline has a vertical velocity equal to V_{exit} and the velocity profile will be essentially Gaussian. The peak (core) vertical velocity is therefore V_{exit} but the plume average value is 0.5 V_{exit}. Conservation of momentum therefore requires the plume width to have effectively doubled from its initial value a_o.

In this first phase, the plume travels a height of 6.25 D in calm conditions and 0.4 $K_o a_o$ for K_o reasonably large (based on laboratory experiments). Davidson (1994) has also shown that an analytic form for plume rise in a uniform wind has an initial component of 6.2 D exp (-3.3/K_o).

In the second stage, the plume dynamics and trajectories respond to ambient conditions, with much cooler air being entrained into the stack plume. The buoyancy of the plumes has significant influences on the rise as this air mixes into the plume and provides dilution of the exhaust. This dilution is very sensitive to ambient wind speed. For multiple plumes from closely-spaced stacks, this leads almost immediately to a height at which two plumes first touch each other (and plume merging commences) when the effective plume radius is equal to half the stack separation (this is exact in calm winds and approximately correct for light winds). Total merging is assumed to occur when the single plume radius equals stack separation. Conservation of buoyancy flux and Froude number (a reasonable assumption for coherent plumes) leads to a conclusion that the plume radius and vertical velocity will be increased overall by a factor of $2^{0.25}$ = 1.189 by the merging of 2 adjacent plumes.

For more than two stacks, the situation is more complex. In calm conditions, the combined plumes from pairs of stacks will coalesce shortly after to form a coherent plume, assumed to be complete before the single plume radius, a^{sp}, is ½ d (N-1) At this height, the combined plume velocity V_m and radius a_m are $N^{0.25}$

greater than for a single plume. For non-calm conditions, a simplified treatment shows that total merging is likely to occur soon after the merging of two adjacent plumes, for winds at right angles to the line of separation of the stack. For winds at smaller angles ω to the line of stacks, the process is more sequential and the effective stack separation can be reduced by a factor proportional to cos ω.

In the third stage of plume development, plume rise is due entirely to the buoyancy of the (merged) plume and continues until there is an equalisation of turbulent conditions within and outside the plume. The effective average vertical velocity is then close to zero. The third stage of plume development can then be treated as that of a single merged plume (with different initial conditions for a, V and ϕ) passing through different atmospheric layers with varying horizontal velocity u_e. The Katestone software uses a simple successive substitution method to determine a, E (the entrainment), V and ϕ in that order. These equations are valid up to a critical value of ϕ_c ($\phi_c < \pi/2$) at which either the assumptions become invalid or plume rise should be effectively terminated.

These equations can be used in the second stage prior to plume touching and in the third stage once merging has been completed. Plume height is calculated by aggregating $\Delta s \cos \phi$, centreline displacement by aggregating $\Delta s \sin \phi$. For each Δs, the appropriate ambient windspeed is determined by linear interpolation (or power law curve fitting of available meteorological profile measurements or predictions).

A fourth stage can occur if the coherent plume reaches the base of the overlying inversion (height Z_i). Some of the plume will punch through the inversion base, albeit with reduced vertical velocity. The remainder will be effectively trapped within the inversion layer with essentially zero vertical velocity. Weil et al (2001) show that the penetration in convective conditions depends on $F_*^{2/3}$ where $F_*=F/(u_e w_*^2 Z_i)$ and w_* is the convective velocity scale. There is as yet little guidance on plume dimensions and vertical velocity for the penetrative component.

Table 1: Key parameters for the various stages of development for merging plumes.

Stage	Average plume velocity		Plume width	Plume height	Plume angle	Comments
	Vertical	Horizontal				
Stack exit	V_{exit}	0	a_o	h_s	0^o	
End of jet phase	$0.5\ V_{exit}$	$u_e(z) + V \sin \phi_o$	$2a_o$	$h_s + z_o$	ϕ_o	$z_o = K_o a_o < 6.25D$
Plumes first touch	$V_t \cos \phi_t$	$u_e(z) + V_t \sin \phi_t$	a_t	z_t	ϕ_t	$V_t < 0.5\ V_{exit}$
End of plume merging	$V_m \cos \phi_m$	$u_e(z) + V_m \sin \phi_m$	a_m	z_m	ϕ_m	$a_m \approx N^{1/4} a^{sp}$ $V_m \approx N^{1/4} V^{sp}$
Coherent merged plume	$V \cos \phi$	$u_e(z) + V \sin \phi$	a	z	ϕ	$V < V_m$ $a > a_m$
Maximum plume rise	0	$u_e(z) + V \sin \phi$	a_c	z_c	ϕ_c	$\phi_c < 90^o$
Inversion interaction	Low	Shear-affected	Enhanced	$> Z_i$	Variable	(Weil et al 2001)

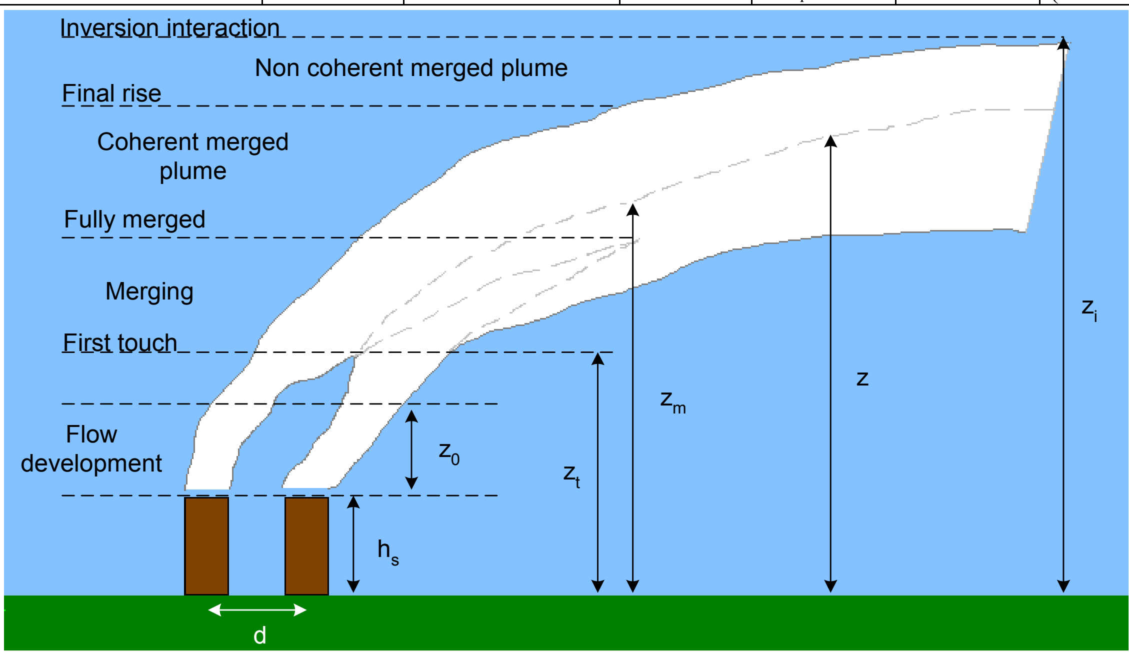

Figure 1: Schematic of plumes merging.

4. Illustrative examples

The simplest cases assume identical sources with stack separation d operating in a neutral and unbounded atmosphere with uniform conditions. For the Spillane approach, Table 2 gives the resulting plume-average vertical velocities for the cases with V_{exit} = 38.9 m/s, h_s = 35 m, F = 2300 m^4/s^3 and N = 1 and separately N = 2 with d = 25 m.

The heights experiencing threshold exceedances are dramatically reduced going from calm to light winds. The TAPM approach for single plumes gives similar results if some allowance is made for an initial displacement offset z_0 (Figure 2).

Table 2: Plume average vertical velocities (m/s) for uniform calm and light wind conditions in a neutral atmosphere

Height	Calm		u_e = 1.5 m/s		u_e = 3 m/s	
	Single	Double	Single	Double	Single	Double
100	12.2	12.2	9.0	9.3	6.9	8.3
200	7.8	9.2	5.5	7.0	3.6	5.1
300	6.5	8.0	4.4	5.8	2.6	3.9
500	5.3	6.6	3.2	4.5		2.8
700	4.8	6.0	2.6	3.7		2.2
1000	4.1	5.2				

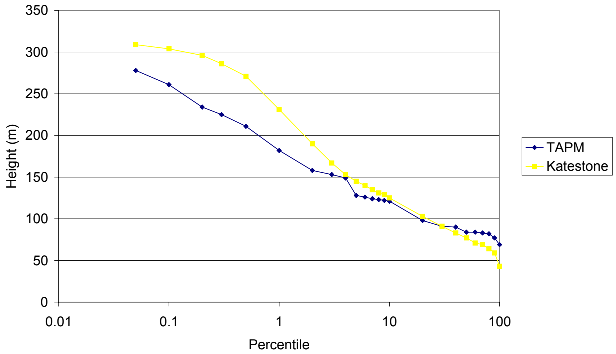

Figure 2: Comparison of methodologies for plume height calculations for a 5 year period.

5. Meteorological modelling

Meteorological inputs are critical for a reasonable treatment of risk, especially for near-calm conditions at stack-top and above. Unfortunately, it is these very conditions under which near-surface measurements (together with stability-dependent profile laws) or TAPM-like prediction methodologies are likely to be poor indicators of actual conditions, at least for inland sites (Jackson et al 2003). Presumably this quandary lead CASA to recommend the TAPM approach. If measurements are available from a nearby 30-100 m tower, we would recommend their use unless TAPM results are carefully tuned to the appropriate surface conditions.

Recent project work near Williamtown Airport gave a comparison of five years of hourly TAPM results with available balloon and 30 m tower measurements. The main conclusions were:

- Moderate interannual variability in the actual and predicted occurrence of light winds at 30 m and above.
- TAPM tends to underpredict the frequency of occurrence of very light winds (< 1 m/s) compared to tower observations (typically 1.2 - 3.5% compared to 5.7 - 14.9%).
- For available balloon profiles, TAPM overpredicted the frequency of very light winds at 600 m and 900 m agl.
- Very few measurements are available in the crucial 100-500 m height range.

6. Synthetic approaches

The Spillane approach has been adapted to take in the TAPM wind profile conditions. Figure 3 compares the cumulative probability distributions for critical heights (where the in-plume average velocity drops below 4.3 m/s) obtained by using either the TAPM wind predictions or the interpolated measured winds, for the case of two 35 m high, 54 m separated combined-cycle units of total capacity over 800 MW. Close agreement is obtained.

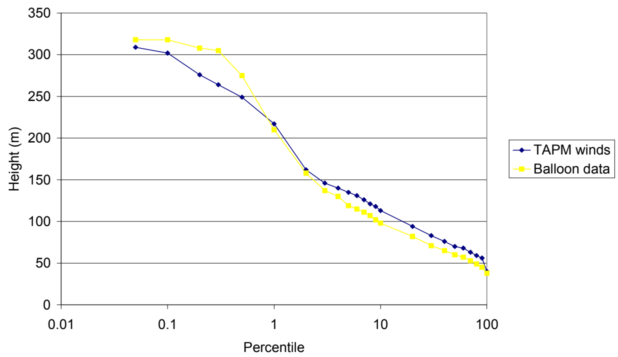

Figure 3: Comparison of Spillane plume height calculations for TAPM - generated and measured winds.

7. Design options

Decreasing the exit velocity will reduce the initial flow development length but plume buoyancy is the key factor in the magnitude of the vertical velocity. Similarly any reduction in stack height gives little benefit to aviation safety concerns and may risk poor plume dispersion in high-wind conditions (due to building wake influences). Increasing the stack separation does delay the time when plumes merge but with little overall practical benefit (Figure 4). Horizontally-pointing stack exits will reduce initial momentum but again buoyancy is dominant.

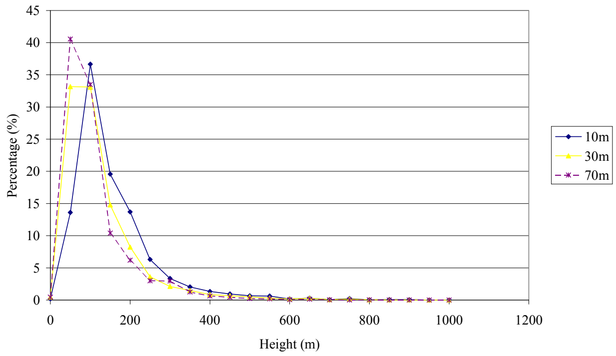

Figure 4: Frequency of critical height for varying stack configurations.

The reduction of plume buoyancy by using heat recovery results in a very significant reduction of critical heights but open-cycle operation usually has to be considered in any risk assessment. For critical cases, it appears better to take advantage of the relatively small zone of influence on vertical velocities and the usual requirement of CASA to identify stack locations for low-flying aircraft. A notice to aircrew together with real-time indication of site operations may be effective in most situations.

8. Conclusions

Methodologies now exist for major point sources and point to the dominating role of initial plume buoyancy. Detailed measurements are required for light-wind conditions and are readily taken by experienced research aircrews. TAPM methodologies are reasonable for single plumes but inappropriate for multiple plumes. For key sites, remote sensing equipment is required to gather reliable wind statistics in the critical 100-500 m range. Theoretical advances are needed to treat inversion penetration in very light-wind conditions and to extend the methods to moist plumes and different source geometries.

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APPENDIX C

The evaluation of maximum updraft speeds for calm conditions at various heights in the plume from a gas-turbine power station at Oakey, Queensland, Australia

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C1.1 Introduction

This report evaluates the core velocity of a forced-plume discharged vertically from a gas-turbine power station in a calm neutral environment. It is in such an environment that maximum (relative) updrafts occur and such updrafts are of interest to aircraft that may traverse the plume core.

The forced-plume model adopted here is based on the review of literature and experimental observations outlined in Spillane (1980). The so-called top-hat profile of a plume with Gaussian distributed properties is used herein. Such top-hat profiles assume that cross-sectional area integrals can be expressed as averaged values $\overline{C}$ over a cross-section of equivalent circular radius, b, and also that the integral of products can be treated as the product of averaged quantities. For a Gaussian profile of a property with standard deviation σ (i.e. a decay from a core value of C_{MAX} proportional to exp $(-r^2/2\sigma^2)$ in any radial r direction), we have that

The equivalent radius is

$$b = 2\sigma \qquad (1)$$

The maximum value is

$$C_{MAX} = 2\overline{C} \qquad (2)$$

and the transverse gradient of the property is closely given by

$$C_{MAX} / b = 2\overline{C} / b \qquad (3)$$

C1.2 Method (model):

In a calm neutral (uniform) atmosphere the jet-plume integral equations in top-hat parameterisation are;

Radius growth: $$\frac{da}{dz} = \beta = 2\alpha - \frac{\lambda^2}{2F_r^2} \qquad (4)$$

Flux of buoyancy: $$\frac{dF}{dz} = 0 \rightarrow F = F_o \qquad \text{(i.e. } F \neq F(z)\text{)} \qquad (5)$$

Momentum flux: $$\frac{d(Va)^2}{dz} = \frac{Fa}{Va} = \frac{F_o a}{Va} \qquad \text{(using (5))} \qquad (6)$$

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Flux of heat: $$\frac{d}{dz}(Va^2\lambda^2\Delta\theta/\theta_E)=0 \qquad (7)$$

wherein, after Morton (1965),

$\rho b^2 = \rho_e a^2$, i.e. $$b = a\left(\frac{\theta_p}{\theta_E}\right)^{1/2} \qquad (7b)$$

where

θ_E = virtual potential temperature of environment (in ^oK)

θ_p = virtual potential temperature of plume.

$\Delta\ \theta_E = (\theta_p - \theta_E)$

Now the buoyancy is given by

$$F = V\lambda^2 a^2 g\,\frac{\Delta\theta}{\theta_E}\ , \qquad (7c)$$

where V is the velocity in the plume at height z. Using that at the outlet (with diameter D)

$$a = a_o = \left(\frac{D}{2}\right)\left(\frac{\theta_{Eo}}{\theta_{p_o}}\right)^{1/2}$$

and that:

$\lambda \approx 1.11\lambda$ for an established Gaussian profile

with

$\lambda = \lambda_o \approx 1.0$ at the outlet,

the buoyancy at the outlet may be calculated using

$$F = F_o = V\lambda_o^2 a_o^2 g\,\frac{(\Delta\theta)_o}{\theta_{Eo}} = V(1)^2\left[\left(\frac{D}{2}\right)\left(\frac{\theta_{E_o}}{\theta_{p_o}}\right)^{1/2}\right]^2 g\,\frac{(\Delta\theta)_o}{\theta_{Eo}} = Vg\,\frac{D^2}{4}\frac{(\Delta\theta)_o}{\theta_{po}}$$

or

$$F_o = Vg\,\frac{D^2}{4}\frac{(\Delta\theta)_o}{\theta_{po}} \qquad (7d)$$

Finally, the Froude number (Fr^2) is defined by

$$Fr^2 = \frac{V^2}{(ag\Delta\theta/\theta_E)}$$

which for a non-buoyant $(\Delta\theta = 0)$ jet is infinite.

From Schlicting (1955), Ricou and Spalding (1961), Hill (1972), Turner (1973) and Briggs (1975), a jet in a calm neutral atmosphere has a radius growth of:-

$$\frac{da}{dz} = \frac{db}{dz} = 2\,\alpha = 0.16,\ (\alpha = 0.08) \qquad (8)$$

After Schmidt (1941), Rouse et al (1952), Morton et al (1956), Turner (1973) and Briggs (1975), a plume in a calm neutral atmosphere has a radius growth of:

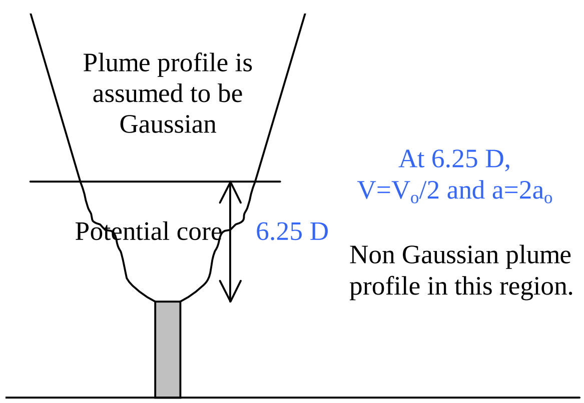
$$\frac{da}{dz} \approx \frac{db}{dz} = 6\alpha\ /\ 5 = 0.15,\ (\alpha\ = 0.125) \qquad (9)$$

We note from the transformation (8) above that $\frac{da}{dz}$ is (slightly) greater than $\frac{db}{dz}$ for plumes and, as noted by Scorer (1959) and Abrahams (1963, 1965), $\frac{da}{dz}$ for a plume is almost indiscernible from that of the jet. It follows the best practical relationship is:

$$\frac{da}{dz} = 0.16 \qquad (10)$$

for both forced plumes and jets.

However, near the outlet the radial profiles are not Gaussian. A potential core, in which the maximum core velocity and temperature remain constant, extends approximately 6.25 times the outlet diameter, D, above the outlet (see Forstall and Shapiro (1950), Pratte and Baines (1967)).



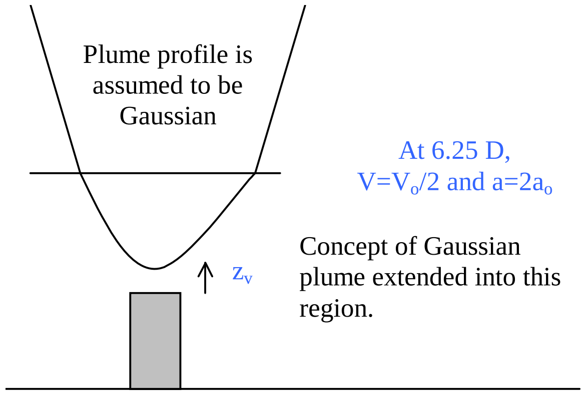
In this potential core zone the flux of momentum of jet-plume is approximately constant. Adopting a Gaussian profile with its core maximum = V_o at 6.25 D above the outlet, the average plume velocity is given by:

$$V = \frac{V_o}{2} \qquad \text{(at } z = 6.25D\text{)} \qquad (11)$$

and

$$a = 2a_o = D\left(\frac{\theta_E}{\theta_{P_o}}\right)^{1/2} \qquad \text{(at } z = 6.25D\text{)} \qquad (12)$$

It is convenient to introduce the concept of a 'virtual' plume point source which is located at a height z_v above the stack. The origin of the 'virtual' source is determined by extending the Gaussian profile below the height of 6.25 D to its origin i.e. z_v.



The "virtual" point source of a forced-plume, from (12) and (9), is thus located at a height above the outlet of:

$$z_v = 6.25D\left(1 - \left(\frac{\theta_E}{\theta_{p_o}}\right)^{1/2}\right) \tag{13}$$

Note that from (10) this implies that the variation of the radius of the plume with height is given by:

$$a = 0.16(z - z_v) \qquad \text{(for } z \geq 6.25D\text{)} \tag{14}$$

For a neutral environment, i.e. one for which

$$\left(\frac{d\theta_E}{dz}\right) = 0 \qquad \text{or} \qquad \theta_E = \text{constant} = \theta_{Eo}$$

the solution of (5) that satisfies (11) and (12) with plume radius 'a' given by (14) is:

$$(Va)^3 = (Va)_o^3 + 0.12F_o\left[(z - z_v)^2 - (6.25D - z_v)^2\right] \qquad \text{(For } z \geq 6.25D\text{)} \tag{15}$$

Conservation of heat flux equation (i.e. equation 7) yields:

$$Va^2\lambda^2\frac{\Delta\theta}{\theta_E} = \text{constant} = V_o a_o^2 \lambda_o^2 \left(\frac{(\Delta\theta)_o}{\theta_{Eo}}\right)$$

and since $\lambda_o^2 \approx 1.0$, with $a_o = \left(\frac{D}{2}\right)\left(\frac{\theta_{Eo}}{\theta_{p_o}}\right)^{1/2}$ this may be written:

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$$Va^2\lambda^2\frac{\Delta\theta}{\theta_E} = V_o\left(\frac{D^2}{4}\right)\frac{(\Delta\theta)_o}{\theta_{p_o}} \tag{16}$$

This may be rewritten for the plume potential temperature as a function of height as:

$$\theta_p(z) = \theta_E\left[1 + \left(\frac{\theta_{po} - \theta_E}{\theta_{po}}\right)\left(\frac{(V_o D^2)}{4(Va^2\lambda^2)}\right)\right] \tag{17}$$

The product (Va^2) is evaluated from (15) with (14) and (13).

C1.3 Summary of equations for a(z), V(z) and θ_p (z).

At height z above the outlet and $z \geq 6.25D \geq z_v$;

$$a = 0.16(z - z_v)$$

$$(Va)^3 = (Va)_o^3 + 0.12F_o\left[(z - z_v)^2 - (6.25D - z_v)^2\right]$$

$$\theta_p(z) = \theta_E\left[1 + \left(\frac{\theta_{po} - \theta_E}{\theta_{po}}\right)\left(\frac{(V_o D^2)}{4(Va^2\lambda^2)}\right)\right]$$

where

$$z_v = 6.25D\left(1 - \left(\frac{\theta_E}{\theta_{p_o}}\right)^{1/2}\right)$$

$$F_o = Vg\frac{D^2}{4}\frac{(\Delta\theta)_o}{\theta_{p_o}}$$

$$a_o = \left(\frac{D}{2}\right)\left(\frac{\theta_{Eo}}{\theta_{p_o}}\right)^{1/2}$$

$$(Va)_o = V_o a_o = V_o\left(\frac{D}{2}\right)\left(\frac{\theta_{Eo}}{\theta_{p_o}}\right)^{1/2} \tag{18}$$

C1.4 Sample solution flow chart

INPUT VARIABLES →

Stack height (**H**)
Stack diameter (**D**)
Exit velocity (**V_o**)
Plume Temp (K) (**θ_{Po}**)
Ambient Temp (K) (**θ_E**)

Calculate initial parameters

↓

Height above stack of virtual point source (**z_v**)
Initial buoyancy (**F_o**)
Calculate the initial value of **$((Va)_o)^3$**

↓

Determine the starting height for calculations i.e. (**6.25D**)

↓

Calculate the plume radius (**a**) at all heights greater than 6.25D using

$$a = 0.16(z - z_v)$$

↓

Calculate the velocity (**V**) at all heights greater than 6.25D using

$$V = \frac{1}{a}\left[(Va)_o^3 + 0.12F_o\left[(z - z_v)^2 - (6.25D - z_v)^2\right]\right]^{1/3}$$

↓

(If required) calculate the plume potential temperature profile (**θ_p**) at all heights greater than 6.25D using

$$\theta_p(z) = \theta_E\left[1 + \left(\frac{\theta_{po} - \theta_E}{\theta_{po}}\right)\left(\frac{(V_o D^2)}{4(Va^2\lambda^2)}\right)\right]$$

C1.5 Example: Calculations for Oakey Power Station

Evaluations of V, a and θ_p at 100 m intervals are presented below for the Oakey Power Station with unit characteristics:

Stack height $Z_o = 35$ m

Stack diameter D = 6.2 m

Exit velocity, full load $V_o = 38.9$ ms^{-1}

Exit Temperature $\theta_{po} = 835$ ^{o}K

Buoyancy Flux $F_o = 2300$ m^4 s^{-3}

Environmental virtual potential temperature, $\theta_E = 300$ ^{o} K (independent of height for a neutral atmosphere).

It follows that $(Va)_o = 72.28$ m^2 s^{-1} and

$z_v = 15.52$ m above outlet.

Height of potential core is 6.25D = 38.8 m above the outlet.

Minimum starting height above ground level for calculations is (38.8+35 = 73.8 m)

Presented in Table 1 and plotted in Figure 1 through Figure 3 are the results for the plume radius, average vertical velocity, and plume potential temperature as a function of height for the Oakey power station.

Conclusions

It is concluded that in the (rare) event of a calm uniform and neutral atmosphere (the situation most favourable to the rise of the vertically forced buoyant plume discharged from the outlet of a unit stack of the Oakey power station), a plume will extend above 1000 m with vertical velocities averaged across the plume area equal to 4.14 ms^{-1}, over a plume width of approximately 300 m. In a Gaussian radial profile with an average vertical velocity of 4.14 ms^{-1}, the core maximum is close to 8.3 ms^{-1}.

Table C1: Calculations at various heights above ground.

Height above ground (m)	Plume radius (m)	Plume average vertical velocity (m/s)	Plume potential temperature (K)
100	7.92	12.26	375.93
125	11.92	10.18	340.35
150	15.92	9.07	325.39
175	19.92	8.34	317.63
200	23.92	7.81	313.06
225	27.92	7.39	310.13
250	31.92	7.05	308.12
275	35.92	6.77	306.68
300	39.92	6.53	305.60
325	43.92	6.32	304.78
350	47.92	6.14	304.14
375	51.92	5.97	303.62
400	55.92	5.83	303.20
425	59.92	5.69	302.85
450	63.92	5.57	302.56
475	67.92	5.46	302.32
500	71.92	5.35	302.11
525	75.92	5.26	301.93
550	79.92	5.17	301.77
575	83.92	5.08	301.63
600	87.92	5.00	301.51
625	91.92	4.93	301.40
650	95.92	4.86	301.30
675	99.92	4.79	301.22
700	103.92	4.73	301.14
725	107.92	4.67	301.07
750	111.92	4.62	301.01
775	115.92	4.56	300.95
800	119.92	4.51	300.90
825	123.92	4.46	300.85
850	127.92	4.41	300.81
875	131.92	4.37	300.77
900	135.92	4.32	300.73
925	139.92	4.28	300.70
950	143.92	4.24	300.66
975	147.92	4.20	300.63
1000	151.92	4.17	300.61

Figure C1: Plume radius as a function of the height above the ground.

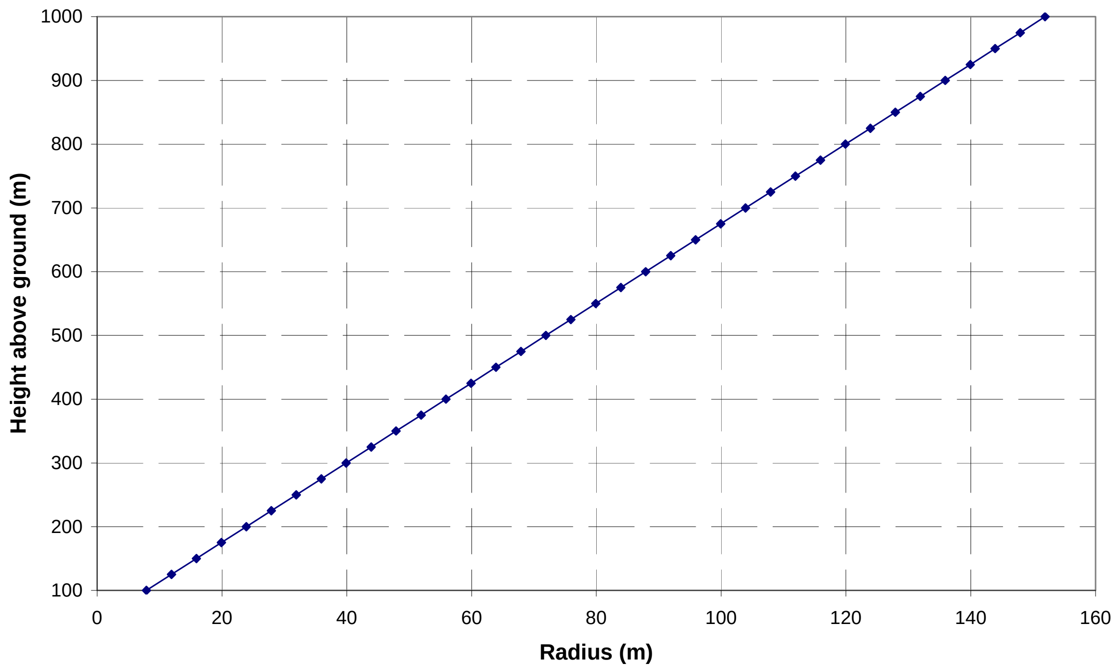


Figure C2: Plume average vertical velocity as a function of the height above the ground. (A vertical velocity of 4.3 m/s is also highlighted in the figure.)

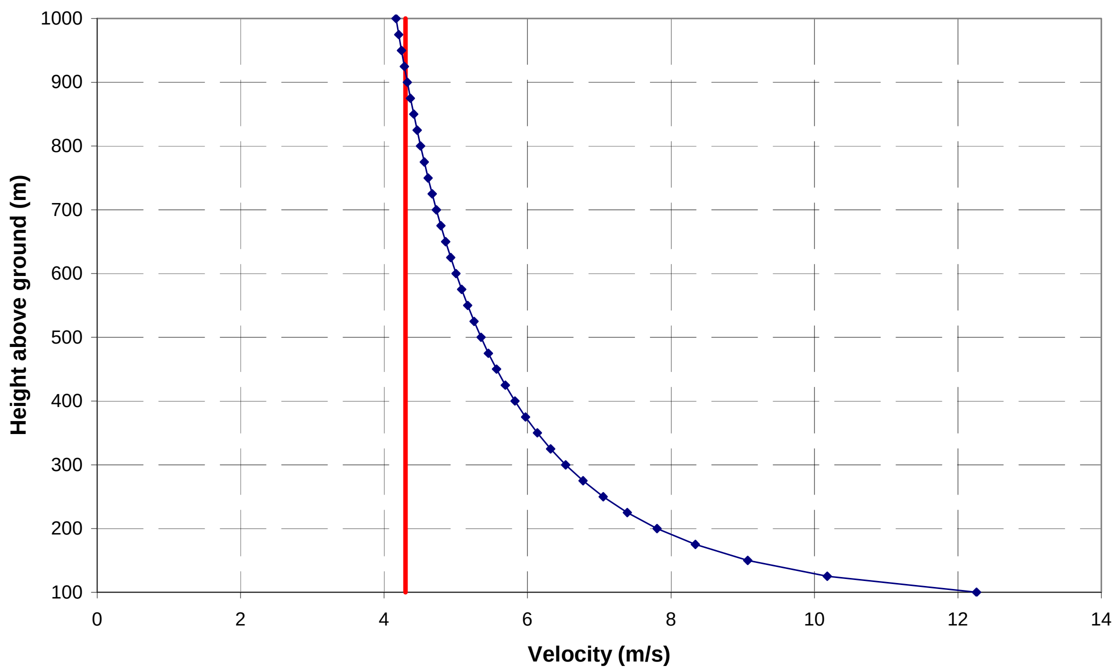
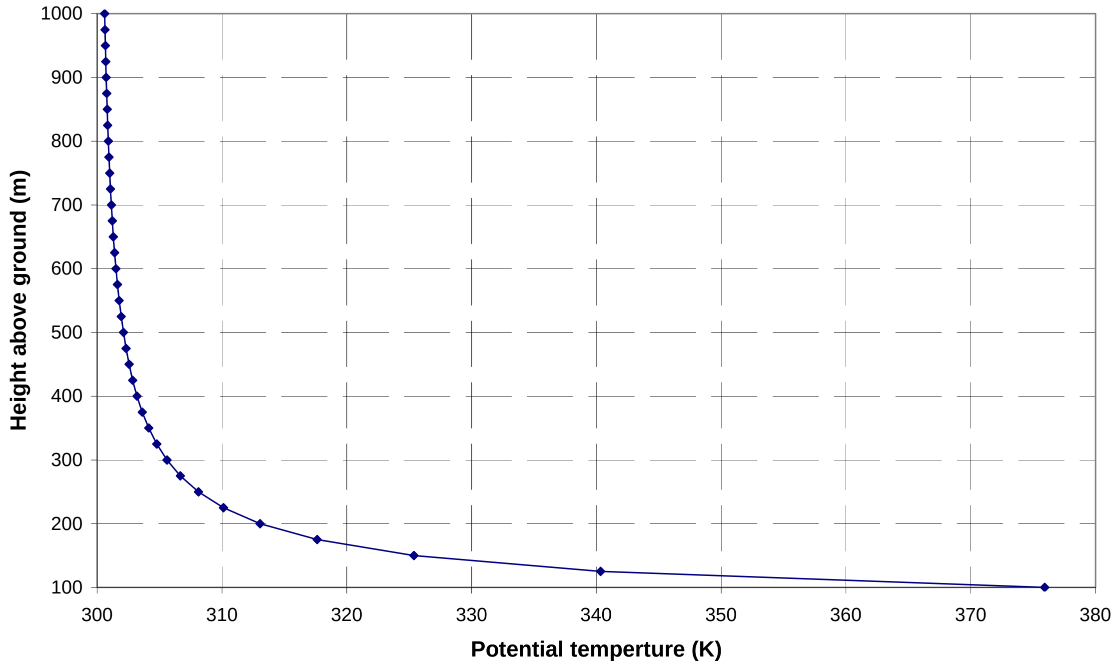


Figure C3: Plume potential temperature as a function of the height above the ground.



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Appendix D

The evaluation of updraft speeds at various heights in the merged plume from two gas-turbine power units at Oakey, Queensland in a calm neutral environment.

D1.1 Introduction

This appendix extends the previous examination given in Appendix B of a single plume to embrace the situation where two identical units are operating in close proximity and their plumes merge to form a single larger plume in which the flux of buoyancy is twice that in an individual plume.

The forced-plume model adopted here has been detailed in Appendix 1 and is based on that review of literature and experiments discussed in Spillane (1980). The so-called "top-hat" parameterisation of a plume with Gaussian distributed properties in a calm neutral environment leads to the jet-plume (integral) equations;

Radius growth: $$\frac{da}{dz}=\beta=2\alpha-\frac{\lambda^2}{2F_r^2} \qquad (1)$$

Flux of buoyancy: $$\frac{dF}{dz}=0 \rightarrow F=F_o \qquad \text{(i.e. } F \neq F(z)\text{)} \qquad (2)$$

Momentum flux: $$\frac{d(Va)^2}{dz}=\frac{Fa}{Va}=\frac{F_o a}{Va} \qquad \text{(using (5))} \qquad (3)$$

Flux of heat: $$\frac{d}{dz}(Va^2\lambda^2\Delta\theta/\theta_E)=0 \qquad (4)$$

All above symbols are as defined in Appendix 1. As discussed in Appendix 1, $\frac{da}{dz}=0.16$ is the best practical relationship of both plumes and jets and the virtual point source of the forced-plume from a single unit, of outlet diameter D, is located at a height above the outlet of:

$$z_v = 6.25D\left(1-\left(\frac{\theta_E}{\theta_{p_o}}\right)^{1/2}\right) \qquad (5)$$

In summary the equations for a single plume's radius (a), average vertical velocity (V) and potential temperature (θ_p) at a height z above the outlet, (valid for z $\geq$ 6.25 D, the core height), are:

$$(Va)^3 = (Va)_o^3 + 0.12F_o\left[(z-z_v)^2-(6.25D-z_v)^2\right] \qquad (6)$$

$$a = 0.16(z-z_v) \qquad (7)$$

$$\theta_p(z)=\theta_E\left[1+\left(\frac{\theta_{po}-\theta_E}{\theta_{po}}\right)\left(\frac{(V_oD^2)}{4(Va^2\lambda^2)}\right)\right] \qquad (8)$$

D1.2 Merging of identical plumes

Equation 1 is based on Morton et al (1956) with the integral-plumes entrainment velocity proportional to the plume's top-hat velocity, in combination with the momentum flux equation (2), and the plume Froude number, F_r^2, defined by

$$Fr^2 = \frac{V^2}{\left(ag\Delta\theta/\theta_E\right)} \qquad (9)$$

We note that, for a forced plume, while constant radial growth is adopted above the potential-core, the classical plume behavior consistent also with constant radial growth, is given by:

$$\frac{da}{dz} = \beta = \frac{6\alpha}{5} \qquad (10)$$

This is only attained when the Froude Number becomes constant with height; i.e. from equation (1);

$$Fr^2 = \frac{5\lambda^2}{8\alpha} \qquad (11)$$

For λ = 1.11, β = 0.16 or α = 0.133, F_r^2 = 5.78 while for α = 0.125, β = 0.15, F_r^2 = 6.16.

As we have adopted the practical value of β = 0.16, F_r^2 will be 5.78 and constant with height. The relationship $F_r^2/\lambda^2 = 5/8\alpha$ throughout a point-source plume with boundary conditions of zero momentum and mass flux can be seen directly from the classical solutions (given by set 6.16, p172, of Turner's 1973 text).

For our purposes it is convenient to note, from equation 9, that in a neutral environment

$$Fr^2F_o = \lambda^2\left(V^3a\right) \text{ (?)} \qquad (12)$$

Thus V^3a becomes constant above that level where the Froude number of the forced plume falls to its constant buoyancy-dominated value (i.e. approximately 5.78).

Assumptions and consequences: The merging of two plumes

Note that the subscript m refers to the merged plume, the subscript s to results for the single plume as outlined in appendix 1.

- The two plumes initially 'touch' at a height (z_{touch}) when the radius of the single plume is equal to half the separation distance, i.e. $a_s = d/2$.

- The plumes have finished merging at a height (z_{full}) corresponding to when the single plume radius is equal to the separation distance, i.e $a_s = d$.

- The flux of buoyancy is conserved when plumes merge. Thus when (z_{full}) we have that $F_m = 2F_s = 2F_o$. According to (12), this may also be written:

$$V_m^3 a_m = 2\left(V_s^3 a_s\right)\Big|_{z=z_{full}} = 2V_{full}^3 a_{full} \qquad (13)$$

- Momentum flux is conserved at the height where merging is assumed to be complete (i.e. at (z_{full})), i.e.

$$(Va)_m^2 = 2(Va)_s^2\Big|_{z=z_{full}}$$

or

$$V_m^2 a_m^2 = 2V_{full}^2 a_{full}^2 \qquad (14)$$

where

$$V_{full} = V_s\Big|_{z=z_{full}} \quad \text{and} \quad a_{full} = a_s\Big|_{z=z_{full}}$$

- Combining equations (13) and (14) we find that at a height of $z = z_{full}$:

$$a_m = 2^{1/4} a_{full} \quad \text{and} \quad V_m = 2^{1/4} V_{full} \qquad (15)$$

- Above this height, it is assumed that the plume behaves as a single plume and therefore that the radius of the merged plume is given by

$$a_m = (2^{1/4} a_{full}) + 0.16(z - z_{full}) \qquad \text{for } z \geq z_{full} \qquad (16)$$

- Above $z = z_{full}$ the average vertical velocity of the merged plume may be found using:

$$V_m = \left[\frac{\left(2V_{full}^3 a_{full}\right)}{a_m}\right]^{1/3} \qquad (17)$$

- As the flux of buoyancy is conserved, the following relationships hold

$$F_m = \left[V_m a_m^2 \lambda^2 g \frac{\Delta\theta_m}{\theta_E}\right] = 2\left[Va^2 \lambda^2 g \frac{\Delta\theta}{\theta}\right]$$

and substituting for V_m and a_m from (15) gives

$$\Delta\theta_m = 2^{1/4}\,\Delta\theta \quad . \qquad (18)$$

D1.3 Sample solution flow chart: 2 plumes

INPUT VARIABLES →

Stack height (**H**)
Stack diameter (**D**)
Exit velocity (**V_o**)
Plume Temp (K) (**θ_{Po}**)
Ambient Temp (K) (**θ_E**)
Stack separation distance (**d**)

↓

Calculate initial parameters →

Height above stack of virtual point source (**z_v**)
Initial buoyancy (**F_o**)
Calculate the initial value of **$((Va)_o)^3$**

↓

Calculate the single plume vertical profile for plume radius, vertical velocity, as well as the parameter **V^3a** at each height. See appendix 1 for details.

↓

Determine the value of **z_{touch}** which is the height at which the single plume radius is **$a_s=d/2=a_{touch}$**
Determine the value of **z_{full}** which is the height at which the single plume radius is **$a_s=d=a_{full}$**.
Determine the value of **V_{full}** which is the value of **V_s** at the height when is **a_{touch}**.

↓

Determine the value of the merged plume radius **a_m** at **z_{full}**, i.e. **$a_m=2^{1/4}a_{full}$**
Determine the value of the merged plume average velocity **V_m** at **z_{full}**, i.e. **$V_m=2^{1/4}V_{full}$**

↓

Calculate the plume radius (**a_m**) at all heights greater than **z_{full}** using

$$a_m = (2^{1/4}a_{full}) + 0.16(z - z_{full})$$

↓

Calculate the average vertical velocity of the merged plume (**V_m**) at all heights greater than **z_{full}** using

$$V_m = \left[\frac{\left(2V_{full}^3 a_{full}\right)}{a_m}\right]^{1/3} = \left[\frac{\left(2F_o\right)}{a_m}\right]^{1/3}$$

Note: for values of the merge plume radius and average vertical velocity at heights between $z = z_{touch}$ and $z = z_{full}$, use linear interpolation between the values of the parameters at these two heights.

D1.4 Example: Calculations for Oakey Power Station

Recall from Appendix 1 the characteristics of the Oakey power station:

Stack height	Z_o = 35 m
Stack diameter	D = 6.2 m
Exit velocity, full load	V_o = 38.9 ms^{-1}
Exit temperature	θ_{po} = 835 ^{o}K
Buoyancy Flux	F_o = 2300 m^4 s^{-3}

Environmental virtual potential temperature, θ_E = 300 ^{o}K (independent of height for a neutral atmosphere).

It follows that $(Va)_o$ = 72.28 m^2 s^{-1} and

z_v = 15.52 m above outlet.

Height of potential core is 6.25D = 38.8 m above the outlet.

Minimum starting height above ground level for calculations is (38.8+35 = 73.8 m)

Now, assume that there are two stacks separated by a distance of 25 m. Then it follows that:
a_{touch} = 12.5 m and a_{full} = 25.0 m

Solution:

- For $z < z_{touch}$, there is no overlap of the plumes and therefore the value of the plume radius, velocity etc, correspond to the single plume solution, i.e.

  $$a = a_s = 0.16(z - 15.52)$$

  and

  $$V = V_s = \frac{1}{a}\left[(72.28)^3 + 0.12(2300)\left[(z-15.52)^2 - (38.8-15.52)^2\right]\right]^{1/3}$$

- For $z = z_{touch}$ we have that

  $$a = a_{touch} = 12.5 \text{ and } z = z_{touch} = \left[15.52 + \left(\frac{12.5}{0.16}\right)\right] = 93.64 \text{ m}$$

  giving

  $$V = V_{touch} = \frac{1}{12.5}\left[(72.28)^3 + 0.12(2300)\left[(93.64-15.52)^2 - (38.8-15.52)^2\right]\right]^{1/3}$$

  or $V_{touch} = 9.93$ m/s

- For $z = z_{full}$, the single plume radius is

  $$a_{full} = 25.0 \text{ and } z = z_{full} = \left[15.52 + \left(\frac{25}{0.16}\right)\right] = 171.8 \text{ m}$$

Giving

$$V_{full} = \frac{1}{25.0}\left[(72.28)^3 + 0.12(2300)\left[(171.8-15.52)^2 - (38.8-15.52)^2\right]\right]^{1/3}$$

or $V_{full} = 7.64$ m/s

Giving a value for $V_{full}^3 a_{full} = (7.64)^3(25) = 11{,}149$.

The merge plume radius and vertical velocity are therefore given by:

$$a = a_m = 2^{1/4} a_{full} = 29.7 \text{ m}$$

and

$$V = V_m = 2^{1/4} V_{full} = 9.1 \text{ m/s}$$

- Above $z > z_{full}$, the plumes are assumed to be fully merged and the value of the merge plume radius and vertical velocity are given by

$$a = a_m = 29.7 + 0.16(z - 171.8)$$

and

$$V = V_m = \left[\frac{11{,}149}{(29.7 + 0.16(z - 171.8))}\right]^{1/3}$$

- For values of z between $z = z_{touch}$ and $z = z_{full}$, linear interpolation can be used to calculate the value of the (partially) merged plume radius and vertical velocity, i.e. between $a = 12.5$ m and $a = 29.7$ m as well as $V = 9.93$ m/s and $V = 9.1$ m/s.
- Note that for this example, the critical velocity of 4.3 m/s occurs at a height that is greater than 171.8 m above the stack height. Therefore to find the height above the stack that corresponds to the critical value of the vertical velocity we use the equations for $z > z_{full}$ and solve for $V_m = 4.3$ m/s.

$$z_{critical} = \frac{1}{0.16}\left[\frac{11{,}502}{(4.3)^3} - 29.7\right] + 171.8 = 890.3 \text{ m}$$

above the stack, or 925 m above the ground. At this height the plume radius is:

$$a_{critical} = 29.7 + 0.16(890.3 - 171.8) = 144.7 \text{ m}$$

D1.5 Possible extension to N identical plumes

The model for outlined in the previous sections could be extended to include multiple plumes by applying the same assumptions of buoyancy flux conservation and momentum flux conservation at the height at which the plumes are assumed to be fully merged. In this case, however, we would have that at $z = z_{full}$, the merged plume radius would be given by $a_m = N^{1/4} a_{full}$ and the merged plume vertical velocity would be given by $V_m = N^{1/4} V_{full}$ where N is the number of identical stacks and a_{full} and V_{full} correspond to the value of the single plume radius and vertical velocity at z_{full} .

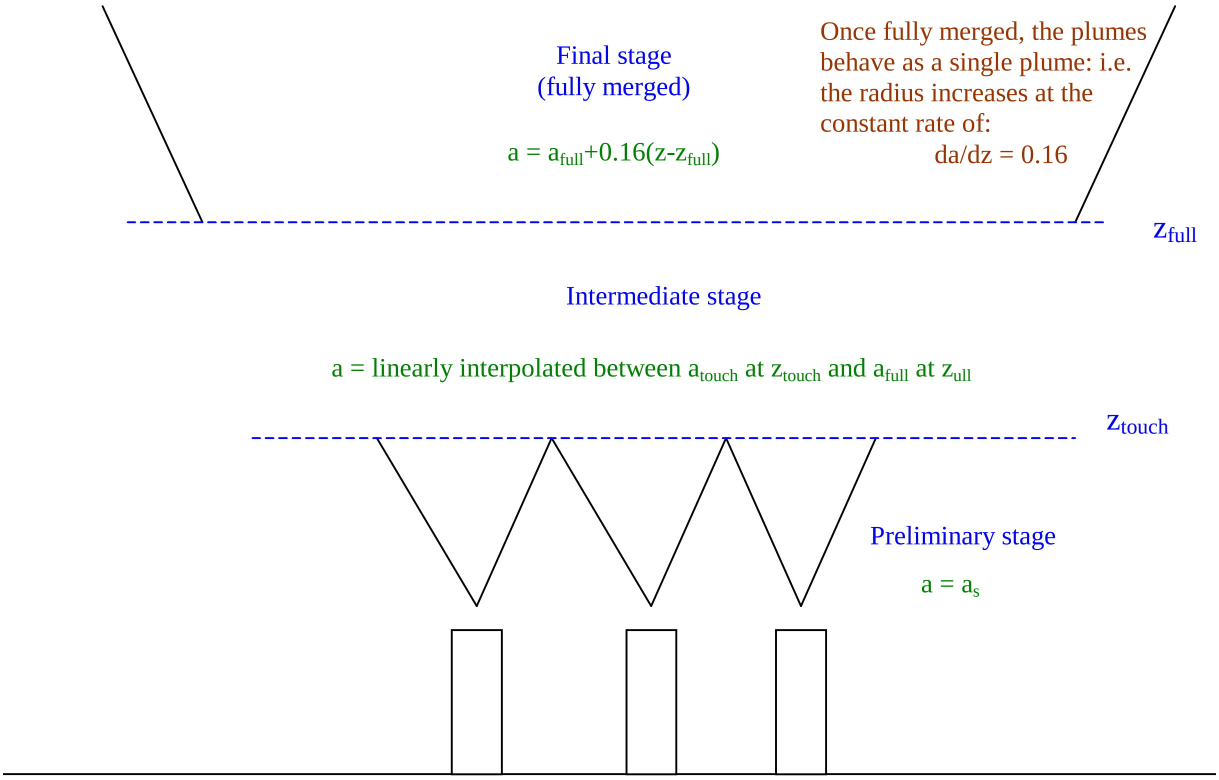
Although it may not be difficult to argue that the value of z_{touch} corresponds to $a_s = d/2$ (where d is the stack separation distance), the height at which the multiple plumes may assume to be fully merged is not so apparent.

It has been suggested (Katestone, 2003) that multiple plumes may be assumed to have fully merged at a height that corresponds to a single plume radius of $\frac{1}{2}d(N-1)$ for $N \geq 3$. This expression suggests that 3 identical plumes will have fully merged before $a_s = D$, with the required radial distance increasing at a rate of d/2 for each additional stack.

Assuming that all plumes will be fully merged by the time $a_s = D$ regardless of the number of plumes assessed will result in a conservative estimate for the critical height (i.e the height at which $V_m = 4.3$ m/s).

A more realistic estimate of the critical height would require a more accurate estimate of the height at which buoyancy enhancement of the plume as they merge is applied i.e. z_{full} .

During the three stages of plume growth the equations for the radius of the plume are as indicated in the figure in green.



D1.6 Turbulence parameters of a plume

In a vertical plume the rate of dissipation of turbulent kinetic energy, ε_p, per unit volume is;

$$\varepsilon_p = A\, F_o V / Va^2 \approx 0.8\, F_o / a \qquad (17)$$

where A = 0.8 is based on heat convection studies in the atmospheric boundary layer.

The formulation of eddy diffusivity by Pasquill (1974. p.84) employs the empirical relation:

$$\sigma_w^3 = 0.3 \varepsilon \lambda_m \qquad (18)$$

when λ_m is the wavelength of maximum energy in the power spectrum of w variance while λ_m in (18) has been determined by observations in the boundary layer. The empirical relationship is here applied to the buoyant plume space with λ_m limited by plume width. Assuming that the spectral distribution of the variance of vertical fluctuations has a peak with λ = a, or that the spectral energy decreases rapidly for λ < a we obtain an upper-bound to an estimate of $\sigma_{w,p}$ of;

$$\begin{aligned} &\sigma_{w,p}^3 = 0.24\ \mathrm{F_o} / \mathrm{a}. \\ &\text{As } \mathrm{V}^3 = \mathrm{F_r^2 F_o} / \mathrm{a} \text{ and } \mathrm{F_r^2} = 5.8, \text{ it follows that } (\sigma_w / \mathrm{V})_p = 0.35. \end{aligned} \qquad (19)$$

While the plume average structure has a top-hat profile average of V and a mean Gaussian distribution with a core average = 2V the traverse of the plume in aeronautical terms could be considered an encounter with C.A.T. over a distance of 2a, in which the r.m.s. vertical velocity is 0.35 V and in the power spectrum energy decreases strongly at λ < a. (It is noted our postulated intensity of turbulence in the confines of the plume is close to the practical operational guide of $\sigma_v / \overline{V} = 0.3$ for surface wind, in a neutral atmosphere where mixing (isotopic) is determined by the mechanics of flow).

It follows that a mean plume velocity of 4.3 m/s may be considered to have imposed spatial variations with a r.m.s. of 4.3 x 0.35 = 1.5 m/s, entirely consistent with a peak (core) gust of say, V + 3 σ = 2 V = 8.6 m/s and, at the boundary, a mean flow of v -3 $\sigma \approx$ 0.