



# Potential for Power Plant Stack Exhaust to Disrupt Aircraft Operations

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## ABSTRACT

Power plant siting studies near airports typically include an analysis of the distance, separation, height, configuration and lighting of structures that may influence aircraft takeoffs and landings. However, other operational factors may also pose potential hazards to aircraft. One of these factors is the large volume of high temperature combustion air from stacks that may create localized turbulent updrafts and present a windshear problem to aircraft flying overhead. This paper examines the physics of plume rise from stacks and develops a methodology for determining the vertical velocity component. Development of the methodology notwithstanding, official guidelines do not exist and are needed to allow siting engineers to evaluate their project impacts to determine if a potential safety hazard exists.

## INTRODUCTION

With increased development and power needs, and because airports are typically compatible with industrial uses, power plants and other industrial facilities are increasingly being developed near airports; as a corollary, airports sometimes are seeking to expand operations toward industrial parks. The Federal Aviation Administration (FAA) Standards and Planning Section has promulgated regulations that address requirements for physical obstructions (see Federal Aviation Regulations (FAR) Part 77, *Objects Affecting Navigable Airspace* and Part 101, *Moored Balloons, Kites, Unmanned Rockets And Unmanned Free Balloons*), but has not published guidelines on other potential impacts to aircraft operations, such as hot exhaust plumes from power plant or heavy industrial stacks. Several interviews with FAA personnel indicated that no problems with thermal plumes affecting aircraft had ever been reported. However, when these types of projects are proposed, there are often questions raised by pilots and airport managers concerning the potential for a rapidly rising heat plume to impact aircraft operations by causing air turbulence. The problem is of further concern because these plumes are not generally visible.

Standard plume rise formulas, such as those developed by Briggs<sup>1,2</sup>, apply to bent-over, buoyant plumes in windy conditions, have been verified by field data, and are employed in most EPA dispersion models. They are used to estimate gradual and final plume height from air emission sources as a means to predict downwind ground level concentrations of stack emissions. While plume velocity is not needed in dispersion modeling, these formulas may be used to mathematically derive plume velocity equations. Thus, plume vertical velocity can be predicted as a function of elevation above stack top using stack exhaust parameters and ambient

meteorological conditions. This enables performing a quantitative analysis of the potential plume vertical velocity that an aircraft may encounter.

## EXHAUST PLUME BEHAVIOR

When exiting a stack, a typical combustion plume has vertical impetus due to (1) momentum, by virtue of its stack exit velocity and (2) buoyancy, due to the fact that the exit gas is warmer than the ambient air. Upon exiting the stack, the exhaust plume grows in mass by entraining ambient air, causing the plume's total velocity relative to the ambient wind velocity to decrease. The entrainment of air is caused by self-induced turbulence derived from the plume's initial velocity and buoyancy momentum as well as by atmospheric turbulence. The further the plume travels, the more air it entrains and the slower its velocity becomes relative to the ambient wind velocity<sup>3</sup>. Furthermore, the dominant feature in plume behavior is its buoyancy. Momentum forces are dominant only for the very initial plume portion directly above the stack and quickly dissipate.

Briggs<sup>1,2</sup> developed and refined equations for plumes rise for bent-over, buoyant plumes in windy conditions, which have been verified by field data and are now in common use in most dispersion modeling procedures endorsed by the U.S. EPA. The background and development of these plume rise equations has a long and complex history and will not be addressed in this paper, rather, the basic equations will be presented and used to derive equations that can be solved for plume vertical velocity.

Only plume rise behavior very near the stack top is dominated by momentum forces. Briggs<sup>2</sup> estimates buoyancy forces begin to dominate after approximately 10 seconds after exit. It is assumed that aircraft would not deliberately venture very close to the business end of a large industrial stack, hence, we will focus on equations that consider buoyant forces to be dominant. The well-established and verified "2/3 law" plume rise equation<sup>1,2</sup> for the first and transitional rise stages during all atmospheric conditions (i.e., unstable, neutral, and stable) is:

$$z = 1.6 F^{1/3} x^{2/3} u^{-1} \quad (1)$$

where:

- z = Vertical plume rise above stack exit plane (m)
- F = Briggs' buoyancy flux parameter, m<sup>4</sup>/sec<sup>3</sup>
- x = horizontal distance downwind from stack, m
- u = horizontal wind velocity, m/sec

Briggs' buoyancy flux parameter, F, relates to the buoyancy of the plume at the stack exit, and is defined as:

$$F = \text{Buoyancy force} / \pi \rho_a \quad (2)$$

The buoyancy force is the difference in weight between a parcel of stack gas and the volume of ambient air that it displaces;

$$\text{Buoyancy force} = g(M_a - M_s) = g(\rho_a V_a - \rho_s V_s) \quad (3)$$

where:

- $g$  = acceleration of gravity,  $9.8 \text{ m/sec}^2$   
 $M$  = mass flow rate,  $\text{kg/sec}$   
 subscript a = displaced ambient air  
 subscript s = stack gas  
 $\rho_a$  = density of ambient air, (assume  $01.209 \text{ kg/m}^3$ )  
 $\rho_s$  = density of exhaust gas,  $\text{kg/m}^3$   
 $V$  = volume flow rate,  $\text{m}^3/\text{sec}$

Since  $V_a = V_s$  (ambient air is displaced by stack gases):

$$\text{Buoyancy force} = gV_s(\rho_a - \rho_s) \quad (4)$$

Substituting for Briggs' definition of F (2):

$$F = (gV_s \pi)(1 - \rho_s/\rho_a) \quad (5)$$

A reasonable assumption is that the molecular weight of the stack gas is equal to that of air, therefore, the ideal gas law reduces to (for pressure of exhaust gas = ambient air pressure):

$$\rho_s/\rho_a = T_s/T_a \quad (6)$$

where T is temperature (in °K)

Substituting (6) into (5):

$$F = (gV_s/\pi)(1 - T_s/T_a) \quad (7)$$

or,

$$F = gv_s r^2 (1 - T_s/T_a) \quad (8)$$

where:

- $v_s$  = initial stack gas velocity (m/sec)  
 $r$  = stack inside radius (m)

Equation (1) is for horizontal distances, x, less than the distance to final plume rise ( $x_f$ ), which is the area of interest, since when the plume approaches its final plume rise, its vertical velocity is so small as to be inconsequential.

Since  $x = ut$ , (where t = elapsed time since a parcel of stack gas exits the stack, in seconds) substitute in equation (1) and reduce:

$$z = 1.6 F^{1/3} (ut)^{2/3} u^{-1} = 1.6 F^{1/3} u^{-1/3} t^{2/3} \quad (9)$$

The rate of change of z with respect to time is the plume average vertical velocity (w). Therefore, taking the derivative with respect to time, we obtain:

$$dz/dt = w = (2/3) 1.6 F^{1/3} u^{-1/3} t^{-1/3} = 1.067 F^{1/3} u^{-1/3} t^{-1/3} \quad (10)$$

All of the stack parameters needed to compute F are engineering values and are usually readily available, hence, equation (10) may be used to solve for w as a function of horizontal wind speed, u, and time, t. For any given time, the elevation of the parcel of stack gas above the stack

(z) can be solved for using equation (9). Hence, the plume's vertical velocity and height are solvable and related by t.

Thermal plume characteristics from several types of combustion sources were evaluated using equations (9) and (10), as summarized in Table 1. Graphical representations of predicted plume velocity with respect to height above stack top are presented in Figures 1 – 3 (in each case, the physical stack height must be added to obtain velocity with respect to elevation above ground level (AGL)).

**Table 1: Source Scenarios for Plume Analysis**

Source Type	Stack Parameters			
	Temperature (K)	Diameter (m)	Actual Velocity (m/s)	Stack height (m)
A. Combined Cycle Natural Gas-Fired Combustion Turbine (200MW)	350	5.6	18.1	40
B. Simple Cycle Natural Gas-Fired Combustion Turbine (170MW)	543	6.2	38.0	27
C. Coal Fired - Steam Turbine (600 MW)	447	6.7	25.3	252

## Source Scenarios

### A. Modern Combined Cycle Power Plant

These stack parameters are representative of a typical Class "F" combustion turbine with heat recovery steam generator (HRSG) unit capable of generating approximately 200 MW of electricity. The predicted vertical velocity of the plume is presented as a function of height above the stack in Figure 1 for various horizontal wind speeds. Note that the stack height must be added to the plume rise to obtain the plume centerline height above ground. As indicated by the equation, the lower the horizontal wind speed, the less entrainment and less "bent over" the plume is, resulting in a higher vertical component. Modern combined cycle power plants are thermally efficient, exceeding 55 percent. This means that less heat is discarded up the stack than in conventional thermal plants, which are only 30 – 33% efficient. Therefore, in general, plume velocities associated with combined cycle plants will be less, per heat input, than older, less efficient plants.

### B. Modern Simple Cycle Power Plant

These stack parameters are representative of a typical Class "F" combustion turbine without a HRSG, typically used as "peaking" plants, for providing prompt electrical output on an intermittent basis. Overall output is approximately 170 MW of electricity. The predicted vertical velocity of the plume is presented as a function of height above the stack in Figure 2 for various horizontal wind speeds. As expected, higher vertical plume velocities result at any given height above stack due to the fact that there is no high-efficiency heat recovery process and more energy is contained in the exhaust plume.

Figure 1: Plume Vertical Velocity - 200 MW Combined Cycle Unit

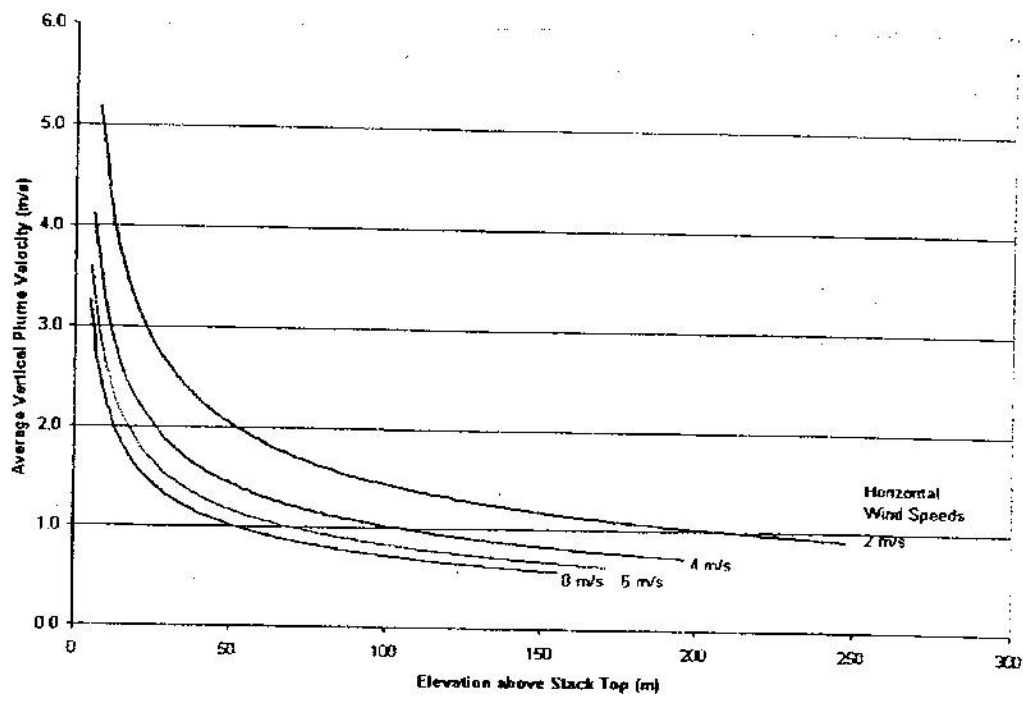
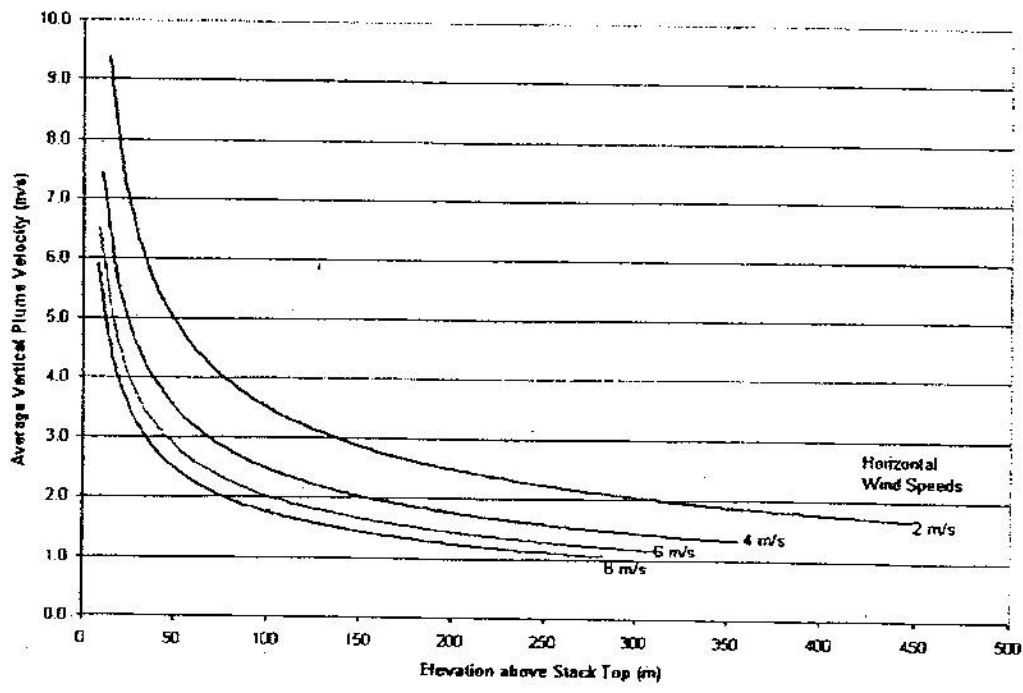


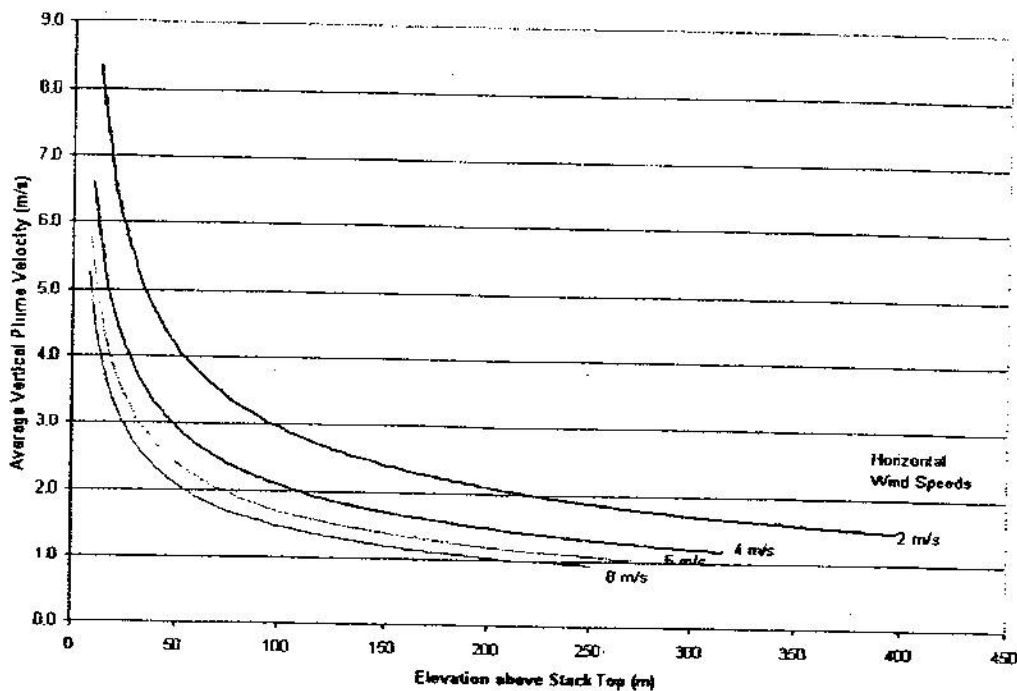
Figure 2: Plume Vertical Velocity - 170 MW Simple Cycle Unit



### C. Coal-Fired Power Plant

Coal-fired power plant stacks serve large boilers, and are often much taller than natural gas fired units in order to more effectively disperse their typically higher levels of air emissions. However, as presented in Table 1, because of the use of heat exchangers ("economizers") to recover much of the waste heat, their exhaust characteristics may not necessarily result in a higher plume rise, or higher plume velocities. The stack data in Table 1 are representative of a typical coal fired unit generating approximately 600 MW of electricity. The predicted vertical velocity of the plume is presented as a function of height above the stack in Figure 3 for various horizontal wind speeds.

Figure 3: Plume Vertical Velocity - 600 MW Coal-Fired Unit



### FIELD DATA

No published field data have been located to correlate these results. In March/April 1995, a confidential study was conducted to investigate the potential effects that plumes from a power station near Kuala Lumpur could have on aircraft operations from a new airport currently being constructed there. The study was funded by the Malaysian Government. The study was organized as a joint program between the Flinders Institute for Atmospheric and Marine Sciences (FLAMS), the National Institute for Water and Atmosphere (NIWA), New Zealand and the Institute for Flight Guidance and Control of the Technical University of Braunschweig (IFGC), Germany. NIWA carried out the numerical modeling of the plume, FLAMS was responsible for carrying out the field measurements, while the IFGC interpreted the model results as well as the FLAMS measurements in terms of large transport aircraft.

A FIAMS Cessna C340A atmospheric research aircraft was used in the collection of plume data. The FIAMS aircraft flew more than 400 traverses through the plumes near Sepang and another power station near Kerteh, for comparison. Unfortunately, the final report remains confidential, and detailed data are not available, however, informal summary data conveyed to the author indicate that, at 136 m above the stack, with horizontal winds of about 3 m/s, average vertical plume velocity is 6 m/s, with a peak of 10 m/s. The plume width is approximately 50 m. No data on the stack exhaust parameters are available, therefore, it is impossible to compare to the predicted value using the method described in this paper.

## CONCLUSION

Using a straightforward, validated equation for bent-over plume rise and taking the time rate of change, the vertical velocity component can be solved for using readily available stack exhaust data. The graphical representation of the results of this procedure demonstrate that for even very hot, large exhaust plumes, vertical velocities do not appear to be high enough to pose a threat to aircraft operations when aircraft maintain prudent distance from the stack mouth. However, further research and study is needed by the FAA or other agency to develop guidelines outlining what plume size and velocity constitutes a safety hazard, and for what type of aircraft. These guidelines would enable power plant siting engineers to evaluate potential sites near airports.

## REFERENCES

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