Review of LIFTOFF Model as AECOM has Implemented into AERMOD

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Prepared for AECOM
Report P210

6 February 2022

Summary of Conclusions:

1) The liftoff theory and equations developed by Briggs (1973) and Hanna, Briggs and Chang (1998) apply only to buoyant plumes whose bottoms are on the ground. Therefore, the AECOM-developed LIFTOFF model option in AERMOD should also be used only for ground-based plumes.
2) Regarding the Alcoa Massena AERMOD runs carried out by AECOM, using several alternate alpha options of modules, I conclude that is important to account for the fact that the fugitive heat emissions are causing the local stability to remain neutral during the night. This correction will help reduce the significant overpredictions by the default AERMOD model.

Introduction.

This document reviews the LIFTOFF model that AECOM has implemented into AERMOD (AECOM 2021a). The revised AERMOD model is being used for predicting concentrations from stack emissions at the Alcoa Massena aluminum smelter, in an attempt to correct significant overpredictions by the default AERMOD model. The EPA has provided critical comments on the approach and AECOM (2021b) has responded in detail to each EPA comment.

I was lead author on the journal article where a liftoff model was proposed for ground-based buoyant plumes (Hanna, Briggs, and Chang, 1998). My coauthor, Gary Briggs, was the primary developer of the liftoff model equations (Briggs, 1973) and wrote the various justifications of the model in the 1998 paper. Unfortunately, he passed away about ten years ago.

The key technical question is whether Briggs' liftoff model, developed for initially ground-based plumes, is applicable to plumes whose bottoms do not initially touch the ground.

Another important question concerns other AERMOD options, in addition to LIFTOFF, being evaluated by AECOM (2021a). These options include i) use of recent building downwash improvements that EPA has issued as "alpha options" in AERMOD version 21112 (see USEPA, 2022); ii) use of low-wind performance improvements that EPA is exploring, and iii) accounting for the additional buoyancy due to fugitive heat releases from the building

Original liftoff model development.

In the 1960s through the 1990s, Gary Briggs was considered one of the top international experts on plume rise in the atmosphere. His 1969 book, entitled “Plume Rise”, presented a basic science approach that harmonized the various approaches in use at the time, and used extensive field and laboratory observations to validate his formulas. He subsequently wrote reports and book chapters describing the formulas and giving the technical (basic science) rationale (see Briggs 1974, 1975, 1984). Through that period, he was employed at NOAA and EPA air modeling research groups.

Although, in 1969, the initial scenario of importance was a momentum jet and/or buoyant plume from a single stack, Briggs later developed formulas for plumes from area sources, from multiple single stacks, from a line of stacks, and for moist plumes (such as a cooling tower). Many of these formulas are still in use in operational dispersion models.

In the early 1970’s, Briggs (1973) turned his attention to buoyant plumes that were initially ground-based, such as a forest fire. As anyone knows who has observed a campfire, when the fire is burning strongly and the winds are light, the smoke plume rises up. But when winds are moderate or strong, the smoke plume blows along the ground. There is no ambient air entrainment for the part of the plume touching the ground. This is more likely to occur if the buoyancy of the plume is less. Briggs suggested a dimensionless liftoff parameter, L_p, representing the ratio of the inward velocity at the plume base due to buoyancy forces to the outward mixing velocity due to the ambient turbulence:

$$L_p = (gH(\rho_a - \rho_p)/\rho_a)/u*^2 \qquad (1)$$

where g is the acceleration of gravity (9.8 m/s^2), H is the cloud depth, u* is the friction velocity (roughly equal to 10% of the wind speed), ρ_a is ambient air density and ρ_p is initial plume density (in g/m^3). The denominator, $u*^2$, is proportional to the ambient turbulent kinetic energy.

Briggs (1973) suggested, based on comparisons with field and laboratory data, that plumes would “lift-off” the ground if $L_p > 20$, which is stated to have an uncertainty of at least a factor of two.

The numerator in eq. (1) was derived by assuming that the inward velocity at the plume base due to buoyancy forces is determined by the initial buoyancy flux F_o that he defines (Briggs, 1969) as:

$$F_o = V_o g(\rho_a - \rho_p)/\rho_a, \qquad (2)$$

which has dimensions m^4/s^3. V_o is the initial volume flux (m^{3}s) in the plume. However, for ground-based plumes, which have “bent over” and are travelling horizontally, V_o = UWH, where U is mean wind speed across the depth of the plume, W is plume width, and H is plume depth. Thus, L_p in eq. (1) can be expressed as a function of F_o:

$$L_p = F_o/(WUu^{*2}) \tag{3}$$

The term F_o/Uu^{*2}, which has units of m, also appears in Briggs' equation for final plume rise Δh of buoyant stack plumes in nearly neutral conditions:

$$\Delta h = 1.54\ (F_o/Uu^{*2})^{2/3}\ h_s^{1/3} \tag{4}$$

Stack height, h_s, appears in this equation because the denominator of the formula uses the turbulent dissipation rate ε, which is proportional to u^{*3}/z, and height z is assumed to be h_s.

Extension of liftoff model by Hanna, Briggs, and Chang (1998). The 1973 Briggs paper focused on the liftoff parameter L_p, discussed above. The Hanna, Briggs, and Chang (1998) paper extended this concept for use in calculating ground level concentrations for a buoyant plume that has not lifted off the ground. The specific scenario of interest was an accidental release of UF_6 (Hanna, Chang and Zhang, 1997) from a large industrial building, but the method would also apply to any ground-based buoyant plume. The new method involved definition of a dimensionless buoyancy flux:

$$F^{**} = F/(U^3W) \tag{5}$$

where F is the buoyancy flux defined in eq. (2). However, local values of plume volume flux and density are used, and therefore F is treated as a local parameter (to account for possible changes in buoyancy due to chemical reactions and other processes). Thus, eq. (5) says that lift-off is inhibited for broad flat plumes (large W). If the common approximation is made that $u^* = 0.1U$, then L_p in eq. (1) equals $300F^{**}$.

In our 1998 paper, Briggs used extensive wind tunnel observations by Hall et al. (1986 and 1995) to develop an analytical expression for how ground-level concentration at any given downwind distance, x, varied as F^{**} increased. Non-dimensional observed concentrations were plotted against F^{**} for various dimensionless downwind distances, x/H_b, where H_b is the building height. The wind tunnel experiments used broad flat buildings (such as warehouses) and buoyant sources broadly distributed on the building lee wall or the roof. In all cases analyzed, the plume was initially ground-based. This includes plumes released from vents on the building roof and entrained into the recirculating wake behind the building, as long as the base of the entrained plume is at ground level. Effective full scale downwind distances of 60 m, 600 m, and 2000 m were studied in the wind tunnel. The physical concept is that, although the plume base remained at ground level, the rest of the plume was stretched vertically by the buoyancy force, resulting in a decrease in ground level concentration as F^* increased. The following equation was proposed for the ratio of the ground level concentration, C, at any value of F^{**} to the ground level concentration in the absence of any buoyancy flux (i.e., $F^{**} = 0$):

$$C(\text{for } F^{**}>0)/C(\text{for } F^{**}=0) = \exp\ (-6F^{**0.4}) \tag{6}$$

AECOM interpretation of Hanna, Briggs, and Chang (1998) liftoff formulas.

Based on the liftoff formulas in Hanna, Briggs and Chang (1998), Robert Paine and others at AECOM wrote software named LIFTOFF (Paine et al. 2016, AECOM 2021a and b, Kieldsing 2021) and incorporated the software as an option in the EPA's AERMOD model (EPA 2003, Cimorelli et al. 2005). The LIFTOFF software does follow the equations in Hanna, Briggs, and Chang (1998).

It is my opinion that LIFTOFF is appropriate for buoyant plumes whose bases are on the ground. However, the LIFTOFF software is said in the AECOM documents to be valid also for plumes whose bases are above the ground. This interpretation is not consistent with Briggs' guidance. The standard plume rise formulas are sufficient for plumes whose bases are not at the ground, including scenarios where downwash occurs into the building's wake. Formulas already exist (e.g., PRIME, Schulman et al, 2000) for accounting for these scenarios. Petersen (2015) reviews building downwash model status and needs.

An error due to double counting of plume buoyancy effects may occur if both the standard plume rise formulas and LIFTOFF are applied. It is not by random chance that both the liftoff formula and the buoyant plume final rise formula include a term F_o/U^3.

Comments on other possible modifications to AERMOD based on EPA's alpha modifications, as well as suggestions by Paine et al. (2016) and Petersen and Paumier (2021) and implemented by AECOM (2021a and b) and Kieldsing (2021).

AECOM has tested several modifications to AERMOD to assure that the predicted concentrations are as close as possible to the observed concentrations for the Alcoa Massena scenario and other industrial plants. The modifications include:

1) incorporation of the liftoff formulas
2) use of recent downwash improvements that EPA has issued as "alpha options" in AERMOD version 21112 (see USEPA, 2022)
3) consideration of low-wind performance improvements that EPA is already exploring.
4) accounting for the additional buoyancy due to fugitive heat releases from the building

When this suite of modifications is used, the AERMOD performance improves. However, it is difficult to determine which of the improvements is contributing the most to the improved performance. It would require costly additional experiments to evaluate specific modules.

The modification to account for fugitive heat releases holds promise. The current AERMOD model and PRIME downwash model neglect the effects of fugitive heat releases around the building, which will lead to underpredictions of plume rise and hence overprediction biases in concentration. The fugitive heat releases are spread across the broad building roof, and are about the same magnitude (a few hundred watts/m^2) as the natural daytime sensible heat flux due to solar warming of the ground surface. Therefore, stable boundary conditions do not occur at night over and around the building, and the effective stability is neutral or slightly unstable. In order to accommodate the effects of fugitive heat releases at night, a neutral temperature lapse rate could be assumed in the vicinity of the sources affected by the fugitive heat releases.

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