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Estimation of Viable Airborne Microbes Downwind from a Point Source

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Modification of the Pasquill atmospheric diffusion equations for estimating viable microbial airborne cell concentrations downwind from a continuous point source is presented. A graphical method is given to estimate the ground level cell concentration given (i) microbial death rate, (ii) mean wind speed, (iii) atmospheric stability class, (iv) downwind sample distance from the source, and (v) source height.

Microorganisms may be introduced into the atmosphere from various sources, transmitted downwind via the airstream, and finally deposited on some surface (B. Lighthart, A. B. Akers, and J. C. Spendlove, in press). The airborne microorganisms may originate from human sources and activities, such as dust generated by urban and rural vehicles (J. W. Roberts, M. S. thesis, Univ. of Washington, Seattle, 1973), manufacturing processes, and construction. Microbial aerosols may be produced also from solid waste and sewage treatment plants (26; C. R. Albright, M. S. thesis, Univ. of Florida, Gainesville, 1958; B. Lighthart, Ph.D. thesis, Univ. of Washington, Seattle, 1967), talking, coughing, sneezing (3), and skin shedding.

Nonhuman sources of airborne microbes may be aquatic, such as bubble bursting of microbial-laden surface films of rivers, lakes, and oceans or from spray generated by breaking waves (20, 28) and rainwater splashes (2, 27), or terrestrial sources, such as dislodgement from vegetation or soil as a result of wind action or thermal convection (10-12). A new and potentially significant source of airborne microbes could be those originating from huge air draft cooling towers associated with nuclear and fossil-fueled power plants. The source of microorganisms is the water being used as the liquid coolant in the towers.

While airborne, microbial death is a function of many factors, including cellular physiological differences (1), relative humidity (9, 15), temperature (8), oxygen concentration (4, 16), light (22), and air pollutants (7, 17, 19, 23). Depending upon the quality and quantity of these factors, the death rate (see reference 6 for definition) may increase or decrease (e.g., 17).

Deposition of airborne bacteria may be by gravitational fallout, wind impaction of particles onto surfaces, and other mechanisms (13, 14).

It is the purpose of this communication to present a relatively simple graphical method to estimate the potential concentration of viable microorganisms at ground level downwind from a continuous point source given: (i) microbial death rate, (ii) wind speed, (iii) atmospheric stability class, (iv) source height, and (v) microbial source concentration.

METHODS

Microbial diffusion model. The downwind concentration of viable microbes may be estimated by using a modified Pasquill inert particle dispersion model (21, 24). The inert particle dispersion model is an empirical model, based on many observations of the dispersion of tracers in the atmosphere. For this reason we used it as the basis of our calculations of the numbers of microbes downwind from a source. We can use this model if we know: (i) the initial concentration of cells at the injection site, (ii) the death rate of the microorganisms in the ambient atmospheric after injection, and (iii) the meteorological conditions (i.e., wind velocity and diffusion factors) about the injection site.

The microbial death rate (λ) in the "real world" atmosphere is a dynamic function of many biological and environmental variables and, to our knowledge, has not been measured. Laboratory measurements of the death rate of airborne microbes as a time function of several variables (see B. Lighthart, C. Mason, G. Vali, and R. Edmonds, *in* R. L. Edmonds (ed.), *Ecological Systems Approaches to Aerobiology*, in press, for a description of these variables) have been made under steady-state and, to a limited extent, dynamic environmental conditions (15). Because of the lack of data describing death rates in the natural environment, it is assumed for the purposes of this communication that laboratory-

measured values will at least roughly approximate mean death rates in the dynamically changing atmosphere. Laboratory measurements vary from very rapid death rates for sensitive cells in hostile environmental conditions, e.g., $\lambda = 10^{-4}$/s, to moderate death rates, e.g., $\lambda = 10^{-1}$/s, to negligible rates for certain endospores (see Table 1). In any event, they are the only measurements we have and must suffice for the moment.

Atmospheric dispersion of inert materials [$\chi(x,y,z:H)$] from a point source, given the source height (H) and meteorological conditions (see Table 2 for categories of weather conditions [24]), may be predicted by Pasquill's models:

$$\chi(x,y,z:H) = Q/(2\Pi(\sigma_y\sigma_z)\bar{U}) \times \mathrm{EXP}[-0.5(Y/\sigma_y)^2] \times \{\mathrm{EXP}[-0.5((Z - H)/\sigma_y)^2] + [-0.5((Z + H)/\sigma_z)^2]\} \quad (1)$$

where χ is number of particles per cubic meter, Q is number of particles emitted from the source per second, $\bar{U}$ is mean air speed in meters per second, and σ_y, σ_z are the diffusion factors in the y and z plans and are functions of meteorological conditions and downwind distance from the source. The source height (H) and x, y, and z are coordinates, all in meters.

BD modification of dispersion model. The maximum number of viable particles remaining in the atmosphere after some time (t) depends upon atmospheric and cellular conditions. Knowing the biological death (BD) constant (λ) under various specific conditions, we may modify equation 1 to account for these factors by letting

$$\chi(x,y,z:H)_{BD} = \chi(x,y,z:H)\mathrm{EXP}(-\lambda\bar{t}) \quad (2)$$

where $\chi(x,y,z:H)_{BD}$ is the concentration with a death rate, $\bar{t}$ is the average time in seconds for transit of the bacteria, and λ is the microbial death constant

TABLE 1. *Some reported death rate constants[a] of certain airborne bacteria at the indicated relative humidities and temperatures*

Organism	% Relative humidity	Death rate constant		
		Temp (C)	λ (s^{-1})	Source
Serratia marcesens 8UK	1.2–3.4	15	7.5×10^{-2}	Ref. 17
	23.4–26.5	15	8.1×10^{-2}	Ref. 17
	45.0–51.5	15	2.4×10^{-1}	Ref. 17
	73.0–75.5	15	1.3×10^{-1}	Ref. 17
	88.0–96.0	15	1.1×10^{-1}	Ref. 17
Sarcina lutea	1.2–3.4	15	4.6×10^{-2}	Ref. 17
	23.4–25.5	15	1.1×10^{-2}	Ref. 17
	45.0–51.5	15	5.5×10^{-3}	Ref. 17
	73.0–75.5	15	5.5×10^{-3}	Ref. 17
	88.0–96.0	15	5.8×10^{-4}	Ref. 17
Pasturella tularensis LVS	90	26.8	2.4×10^{-3}	Ref. 5
	80	26.8	5.5×10^{-4}	Ref. 5
	0	26.8	7.1×10^{-2}	Ref. 5

[a] Data include aerosols up to 1 h old.

TABLE 2. *Relation of turbulence types to meteorological conditions (from reference 24)[a]*

Surface wind speed (m/s)	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or ≥4/8 cloudiness[b]	≤3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

[a] A, Extremely unstable conditions; B, moderately unstable conditions; C, slightly unstable conditions; D, neutral conditions applicable to heavy overcast, day or night; E, slightly stable conditions; F, moderately stable conditions.

[b] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

(per second) experimentally determined for the particular atmospheric conditions. We may approximate $\bar{t}$ by $x/\bar{U}$. Thus equation 2 becomes

$$\chi(x,y,z:H)_{BD} = \chi(x,y,z:H)\mathrm{EXP}(-\lambda x/\bar{U}) \quad (3)$$

where $\chi(x,y,z:H)_{BD}$ is the concentration of microorganisms per cubic meter with the microbial death constant included. Figure 1 shows examples of computed viable cell concentrations downwind from a continuous point source for the given conditions.

Knowing the microbial death constants, atmospheric conditions, σ_y, and σ_z, we may apply this model to give the concentration of microorganisms as a function of the distance (x) from the source with some effective height (H). If the death rates change with time, equation 2 can be modified to account for this change. For example, let λ_1 be the first death rate until time t_1, and let λ_2 be for times greater than t_1. Then

$$\chi(x,y,z:H)_{BD} = \chi(x,y,z:H)\mathrm{EXP}(-\lambda_1 t) \text{ for } t \le t_1 \quad (4)$$

Since the mean distance traveled in time t is

$$x = \bar{U}t \quad (5)$$

then

$$\chi(x,y,z:H)_{BD} = \chi(x,y,z:H)\mathrm{EXP}(-\lambda_1 x/\bar{U}) \quad (6)$$

for $x < x_1$ (where $x_1 = \bar{U}t_1$), and

$$\chi(x,y,z:H)_{BD} = \chi(x,y,z:H)\mathrm{EXP}(-\lambda_1 x_1/\bar{U}) \cdot \mathrm{EXP}[-\lambda_1(x-x_1)/\bar{U}] \quad (7)$$

for $x < x_1$ (see reference 18 for further details).

Using equation 1, and letting $y = 0$ and $z = 0$, equation 3 may be rewritten

$$\frac{\chi}{Q} \cdot \frac{\bar{U}}{\mathrm{EXP}(-\lambda x/\bar{U})} = \frac{1}{2\Pi\sigma_y\sigma_z} \cdot \mathrm{EXP}\left[-\left(\frac{H^2}{2\sigma^2 z}\right)\right] \equiv g \quad (8)$$

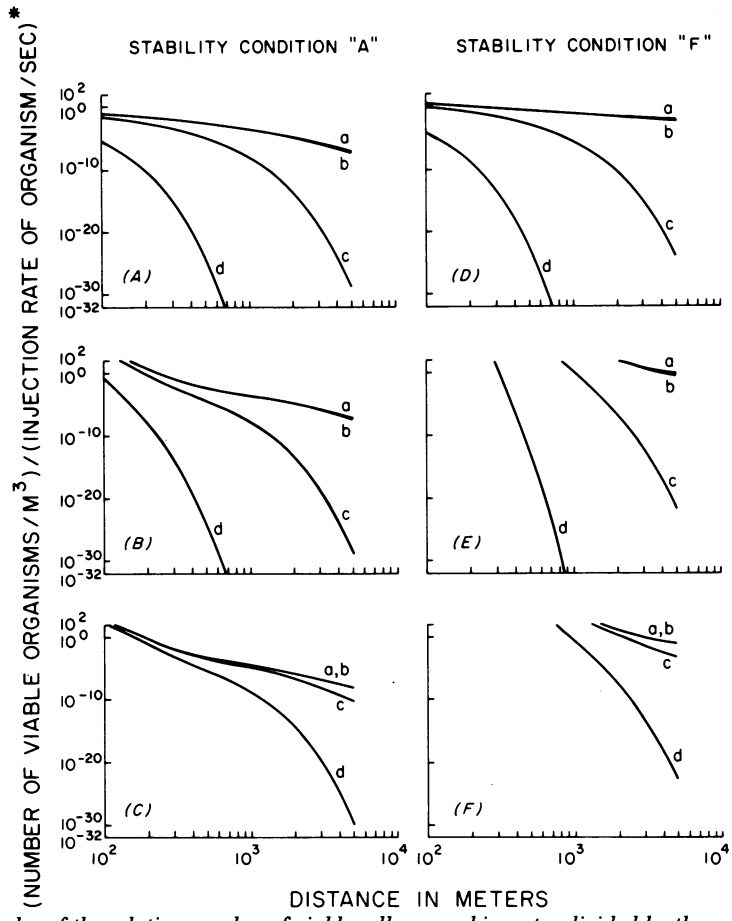

FIG. 1. *Examples of the relative number of viable cells per cubic meter divided by the number per second injected into the atmosphere downwind from a continuous point source (using equation 2) at a sample height of 2 m and a microbial death rate of 0 (a), 10^{-1} (b), 10^{-2} (c), and 10^{-3} (d) per s for stability classes "A" and "F." (A) and (D) Source height, 0 m; mean air speed, 1 m/s. (B) and (E) Source height, 200 m; mean air speed, 1 m/s. (C) and (F) Source height, 200 m; mean air speed, 10 m/s. *Percentage of viable organisms.*

Once this function is evaluated for a certain source height, stability class, wind speed, and distance, one can use any death rate to evaluate the ratio of the concentration, χ, to source strength Q. For convenience, g versus x for several source heights are shown in Fig. 2 for the stability classes defined in reference 24. With these figures, the user can estimate the viable microbial concentration downwind at a distance from a source of height H and strength Q and for a given stability class and death rate λ.

EXAMPLE AND DISCUSSION

The question asked was how many viable microorganisms at ground level (i.e., sample height = 0) are there per cubic meter downwind some distance (x in meters) from a continous point source, given an emission source strength of Q bacteria per second? One must first know or estimate (i) the microbial death constant (λ in seconds) under the prevailing atmospheric conditions, (ii) the mean wind speed ($\bar{U}$ in meters per second), (iii) the meters downwind from the source, (iv) the atmospheric stability class (Table 2), and (v) the source height (H in meters). With this data one can use equation 8 with the appropriate values of σ_y and σ_z, or, alternatively, one can use Fig. 2, which is based on equation 8, to evaluate g.

For example, a hypothetical 200-m-high point source (H) might have an emission rate, Q, of 10^{10} bacteria/s in particles assumed to be distributed about a 10-μm diameter (Lighthart et al., in press). Assuming that these viable particles were dispersed from the source into a class "A" stability atmosphere with winds of 10 m/s, using our calculations, one might expect that viable bacteria having a mean death rate (λ) of 10^{-1}/s (e.g., see Table 1) would be found at

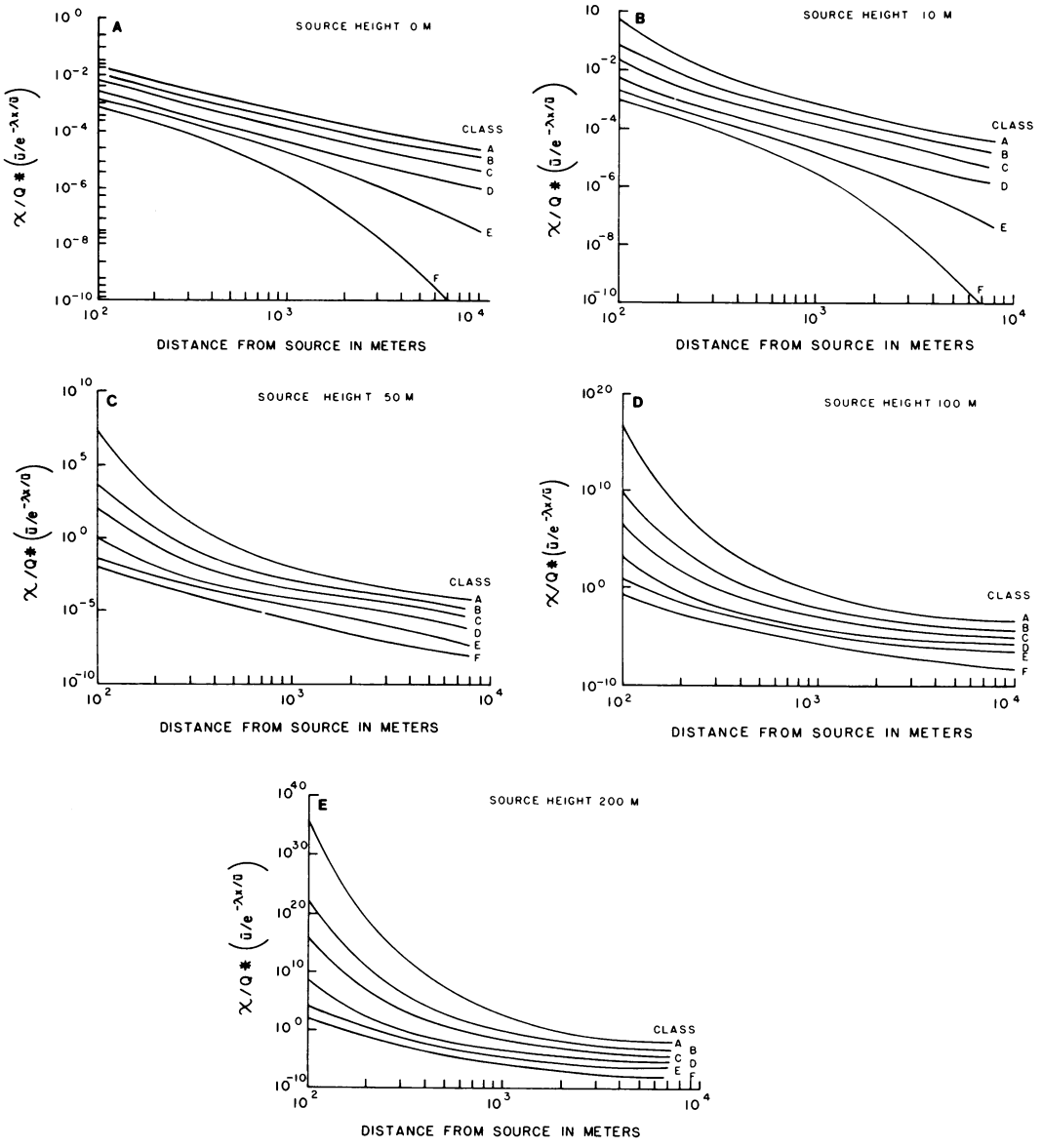

FIG. 2. *Function* $\chi/Q \times (\bar{U}/e^{-\lambda x/\bar{U}})$ *versus distance from the source in meters for the indicated stability classes and several source heights.* χ *is the downwind concentration of viable bacteria per cubic meter,* Q *is the injection rate of live bacteria (number per second), and* $\bar{U}$ *is the mean wind velocity in meters per second,* x *the downwind distance (meters), and* λ *the microbial death rate (number per second).*

a concentration of 1.4×10^4 viable bacteria/liter in the ground level atmosphere 1,000 m downwind from the source. That is, from Fig. 2, g is found to be 316/m^2; solving for $\chi = (Q/\bar{U}) \times g$ [EXP$(-\lambda x/\bar{U})$] = (10^{10} bacteria/s)/10 m per s $\times$ 316/m^2 $\times$ [EXP$(-10^{-1}$/s $\times$ 10^3 m/10 m per s)] = 1.4×10^7 bacteria/m^3. It is also estimated that a person with a 0.5-liter lung tidal-volume breathing rate of 12 cycles/min would inhale 8.4 $\times$ 10^4 bacteria/min at this same location (25). This estimate is significant even if the diffusion model is in error by a factor of 10. In this example, the pathogenic and allergenic potential of the phenomena remains problematical.

Albeit the flavor of this technique of estimating viable airborne cells is quantitative, it is anticipated that present and future research in the areas of atmospheric turbulence and model

development, microbial death mechanisms, atmospheric injection phenomena, and particle sizing of airborne microorganisms will result in more precise estimates of airborne microbial loads downwind from sources.

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LITERATURE CITED

1. **Anderson, J. D., and C. S. Cox.** 1967. Microbial survival. *In* Airborne microbes. Proceedings of the 17th symposium. Society for General Microbiology, Cambridge.
2. **Blanchard, D. C., and L. Syzdek.** 1970. Mechanism for the water-to-air transfer and concentration of bacteria. Science 170:626-628.
3. **Buchbinder, L., M. Solowey, and M. Solotorovsky.** 1945. Comparative quantitative studies of bacteria in air of enclosed places. Air Pollution Survey of New York, Part I. Heat. Piping Air Cond., p. 389-397.
4. **Cox, C. S.** 1967. The toxic effect of oxygen upon the aerosol survival of *Escherichia coli* B. J. Gen. Microbiol. 49:115-117.
5. **Cox, C. S., and L. J. Goldberg.** 1972. Aerosol survival of *Pasteurella tularensis* and the influence of relative humidity. Appl. Microbiol. 23:1-3.
6. **Dimmick, R. L., and A. B. Akers (ed.).** 1969. An introduction of experimental aerobiology. Wiley-Interscience, John Wiley & Sons, New York.
7. **Druett, H., and K. May.** 1969. The open air factor. New Sci., p. 579-581.
8. **Ehrlich, R., and S. Miller.** 1973. Survival of airborne *Pasturella tularensis* at different atmospheric temperatures. Appl. Microbiol. 25:369-372.
9. **Ehrlich, R., S. Miller, and R. L. Walker.** 1970. Effects of atmospheric humidity and temperature on the survival of airborne *Flavobacterium*. Appl. Microbiol. 20:884-887.
10. **Fulton, J. D.** 1966. Microorganisms of the upper atmosphere. III. Relationship between altitude and micropopulation. Appl. Microbiol. 14:237-240.
11. **Fulton, J. D.** 1966. Microorganisms of the upper atmosphere. V. Relationship between frontal activity and the micropopulation at altitude. Appl. Microbiol. 14:245-250.
12. **Fulton, J. D., and R. B. Mitchell.** 1966. Microorganisms of the upper atmosphere. II. Microorganisms in two types of air masses at 690 meters over a city. Appl. Microbiol. 14:232-236.
13. **Gregory, P. H.** 1973. The microbiology of the atmosphere. John Wiley & Sons, New York.
14. **Gregory, P. H., and J. L. Monteith.** 1967. Airborne microbes. Proceedings of the 17th symposium. Society for General Microbiology, Cambridge.
15. **Hatch, M. T., and R. L. Dimmick.** 1966. Physiological responses of airborne bacteria to shift in relative humidity. Bacteriol. Rev. 30:597-602.
16. **Hess, G. E.** 1965. Effects of oxygen on aerosolized *Serratia marcescens*. Appl. Microbiol. 13:781-787.
17. **Lighthart, B.** 1973. Survival of airborne bacteria in a high urban concentration of carbon monoxide. Appl. Microbiol. 25:86-91.
18. **Lighthart, B., and A. S. Frisch.** 1973. A model to evaluate the airborne bacterial concentration from a continuous source, 139-149. *In* R. L. Edmonds and W. S. Benninghoff (ed.), Proc. of workshop/conference ecological systems approaches to aerobiology. II. Development and demonstration, and evaluation of models. US/IBP Aerobiology Program Handbook no. 3. University of Michigan, Ann Arbor.
19. **Lighthart, B., V. E. Hiatt, and A. T. Rossano, Jr.** 1971. The survival of airborne *Serratia marcescens* in urban concentrations of sulfur dioxide. J. Air Pollut. Control Assoc. 21:639-642.
20. **Parker, B., and G. Barsom.** 1970. Biological and chemical significance of surface microlayers in aquatic ecosystems. Bioscience 20:87-93.
21. **Pasquill, F.** 1962. Atmospheric diffusion. D. van Nostrand Co., Ltd, London.
22. **Riley, R. L., and J. E. Kaufman.** 1972. Effect of relative humidity on the inactivation of airborne *Serratia marcescens* by ultraviolet radiation. Appl. Microbiol. 23:1113-1120.
23. **Serat, W. F.** 1969. Approaches to the bioassay of airborne pollution, p. 123-125. *In* R. L. Dimmick and A. B. Akers (ed.), An introduction to experimental aerobiology. Wiley-Interscience, John Wiley & Sons, New York.
24. **Slade, D. H. (ed.).** 1968. Meteorology and atomic energy, 1968. U.S. Atomic Energy Commission, Publication no. TID-24190, Washington, D. C.
25. **Sodeman, W. A.** 1961. Pathogenic physiology. W. B. Saunders Co., Philadelphia.
26. **Spendlove, J. C.** 1974. Industrial, agricultural and municipal microbial aerosol problems. Dev. Ind. Microbiol. 15:20-27.
27. **Woodcock, A. H.** 1955. Bursting bubbles and air pollution. J. Hyg. 42:339-353.
28. **Zobell, C. E.** 1946. Marine microbiology. Chronica Botanica Co., Waltham, Mass.