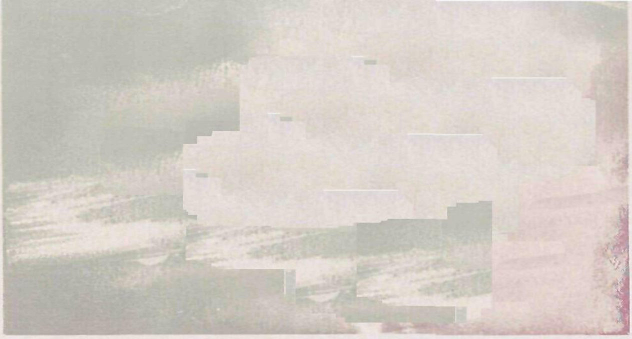

POTENTIAL DISPERSION OF PLUMES FROM LARGE POWER PLANTS

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service

POTENTIAL DISPERSION OF PLUMES FROM LARGE POWER PLANTS

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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
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ABSTRACT

Expected ground-level concentrations resulting from emissions from large power plants are discussed for three meteorological situations considered to be most likely to result in significant air pollution concentrations. These situations are (1) high wind; (2) inversion breakup; and (3) limited mixing layer with a light wind. Effects of increasing stack height are discussed for each situation. Numerical examples based on calculations included as an appendix are shown.

POTENTIAL DISPERSION OF PLUMES FROM LARGE POWER PLANTS

Dispersion of effluent from large power-generating plants must be considered on the basis of individual plants. Although diffusion formulae for comparatively small sources have been at least partially checked against actual dispersion, similar extrapolations from existing data probably cannot be applied to estimates of pollutant emissions from plants in the range of 1000- to 5000-megawatts capacity. Plants of such sizes emit heat at a rate equivalent to the net heating by the sun over an area many hundreds or thousands of meters in diameter; it is evident that such a source will set up its own circulation pattern in the air, at least in the immediate vicinity of the plant. Most of the time the effluent plume will rise far above the ground, and its only influence on air quality will be to increase the surface concentrations of pollutants in the air mass downwind by some rather small amount. If significant background pollution levels exist, however, even a small addition to the background concentration could introduce a pollution problem.

It is assumed that any new plant will be designed to meet two engineering criteria to prevent pollution in the immediate vicinity of the plant. First, the stacks will be tall enough to prevent aerodynamic downwash caused by large obstacles to the air flow. This criterion can be met by following the "2-1/2" rule, which states that a stack should be at least 2-1/2 times the height of any nearby obstacles to the flow. Because a large power plant requires a large building, the minimum stack height imposed by this criterion alone will be several hundred feet. Second, the exit speed of gases from the stack and design of the chimney top should be adequate to prevent entrainment of effluent into the turbulent wake of the stack. Generally, an exit speed in excess of the wind speed will minimize this problem. Since both criteria evolve from aerodynamic considerations, the adequacy of the plant design can be tested by wind-tunnel models.

If it is assumed that these engineering criteria are met, then estimating potential pollution from large plants narrows to a consideration of relatively infrequent weather conditions (conditions that do occur, however) that can bring about ground-level fumigations: high winds, inversion breakup, and a limited mixing layer with light winds. The frequency of these adverse conditions will determine the magnitude and frequency of the potential pollution.

The following discussion of these three types of fumigation is illustrated numerically in Figures 1 through 3. The calculations on which these figures are based are included as an appendix. The models of plume dispersion used were based on the experience of and data collected by TVA personnel (Gartrell et al. 1964), as well as on the author's personal observation of the behavior of plumes from large heat sources. These models were first used in conjunction with climatological data of the Oak Ridge, Tennessee, area (Holland, 1953) as an informal cross-check on calculations then being made by TVA personnel to determine the stack height required for a proposed new generating plant (Thomas et al., 1963). The conclusions regarding required stack height were the same for both methods of calculation. The exact assumptions used to obtain the numerical values shown by the figures are not critical in this discussion; the principal purpose here is to suggest the meteorological factors that influence dispersion and should be considered in location and design of large power plants.

HIGH-WIND FUMIGATION (Figure 1)

High-wind fumigation occurs when the dilution of effluent by motions in the air--longitudinal dilution due directly to wind speed, and transverse dilution by eddies, the magnitude of which is a function of wind speed--is sufficient to overcome the tendency for a heated plume to accelerate upward as the result of buoyancy forces. With sufficiently rapid dilution, the plume continuously decelerates vertically, and an effective plume rise can be computed. The larger the source, the greater the wind speed necessary to cause this vertical deceleration throughout the entire plume volume. Although a precise relationship between plant

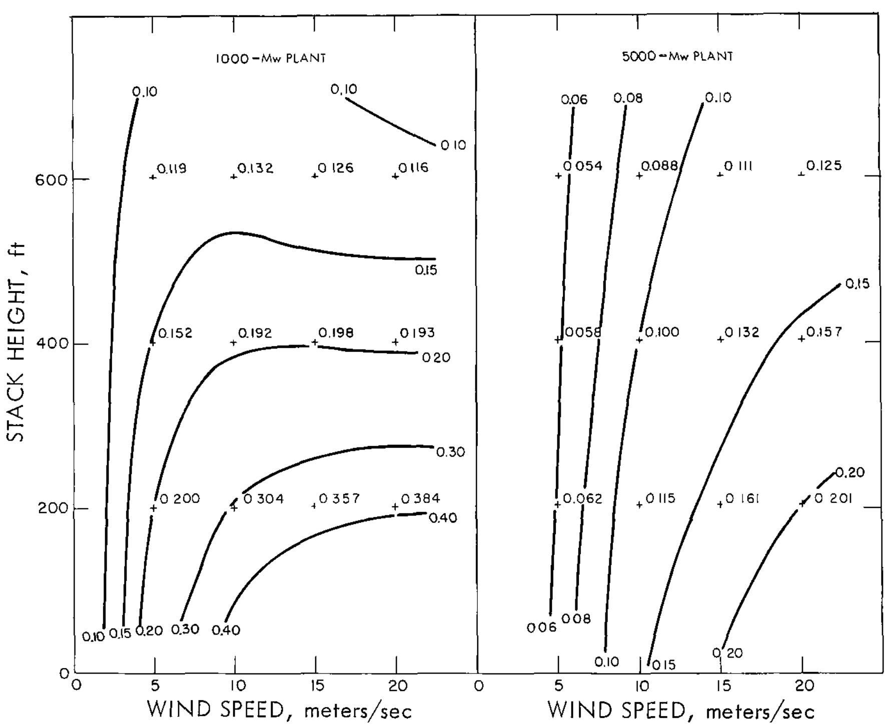


Figure 1. Estimated ground-level SO_2 concentrations (ppm) in high-wind, neutral stability conditions. (Sulfur content of coal is assumed to be 1%; for other sulfur contents, value would be changed proportionately. Values represent 1/2 hour averages. To approximate 3-minute average, multiply by 2.5; to approximate 2-hour average, multiply by 0.5.)

capacity and this "critical" wind speed is not known, it is probable that the critical speed for a 1000-Mw plant would be about 25 mph (13 meters/sec), and for a 5000-Mw plant, about 40 mph (20 meters/sec), if all emissions are assumed to come from a single stack. At wind speeds less than critical, an increasing proportion of the plume should rise at a rate determined principally by buoyancy forces; the dilution of this part of the plume is determined by its upward motion as much as by ambient turbulence. Plume rise with such a divergent plume is difficult to define, and the concept of a coherent plume should probably be discarded in favor of a formulation in which the stabilized portion of the plume is considered, rather than the rising portion. The particular formulations for "plume rise" and plume dispersion were selected only because they are widely used; the numerical results probably do show reasonable trends, even though they should be valid, if at all, only for wind speeds in excess of "critical." The implication is that for plants of large enough capacity, the concentrations in a high-wind fumigation probably depend only on stack height and emission conditions, and thus maximum concentrations from a 5000-Mw plant would be only slightly above those from a 1000-Mw plant (with all emissions from a single stack).

INVERSION-BREAKUP FUMIGATION (Figure 2)

Although inversion-breakup fumigation is likely to produce the highest concentrations at ground level, the area fumigated is likely to be a long, narrow ribbon-like formation with its closest point a number of miles away; therefore, the chances of detecting fumigations of this type are very slight unless the same area is fumigated repeatedly because of topographic restraints. This type of fumigation occurs when effluent is emitted into a stable layer so that the plume moves off as an elevated flat ribbon. A surface-based mixing layer subsequently develops, builds up to include the plume, and stirs the effluent down to ground level. The resultant ground-level concentration is inversely proportional to plume height, horizontal spread, and wind speed at plume height. The plume rise above the top of the stack is determined by the wind speed and the degree of stability in the inversion layer. Since wind speed generally increases through this layer while intensity of the inversion decreases, these factors tend to counteract each other so that plume rise is not strongly dependent on stack height; thus increasing the stack height increases height of the plume above the ground by a like amount. With a taller stack, the plume is likely to be transported away by a stronger flow, and the horizontal spread of the plume will be greater because a longer time is required for the mixing layer to develop to plume height. Thus, tall stacks are fully as important for minimizing this kind of fumigation as for a high-wind fumigation. In addition, since the plume from a sufficiently tall stack may rise above the top of a nocturnal inversion, the frequency of inversion-breakup fumigations is reduced with taller stacks. Under inversion conditions an increase of plant size will result in a proportionately smaller increase of plume rise than under high-wind conditions; thus, the maximum concentrations should increase as plant capacity is increased, but at a less than linear rate.

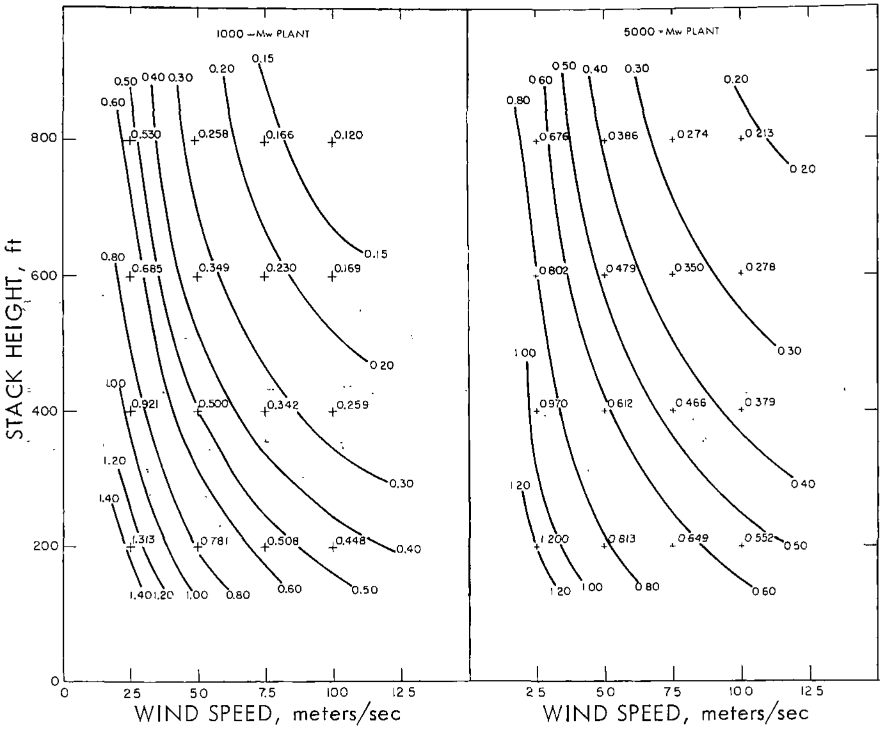


Figure 2. Estimated ground-level SO_2 concentrations (ppm) in inversion-breakup fumigation. (Sulfur content of coal is assumed to be 1%; for other sulfur contents, values would be changed proportionately. Values represent 1/2- to 1-hour averages.)

FUMIGATION IN A LIMITED MIXING LAYER WITH LIGHT WINDS (Figure 3)

Fumigation in a limited mixing layer with light winds occurs when effluent is contained within too small a mixing volume. Under these circumstances, the plume will rise to the top of the surface-based mixing layer (up to the base of the inversion), which may be up to thousands of feet deep, and then diffuse and subside to ground level at a rate determined by the rate of convective overturning brought about by solar heating of the ground. Stack height has essentially no effect on fumigations of this kind. The ground-level concentration after some time will be given by emission rate divided by the product of mixing height, mean wind speed, and cross-wind spread. The time after which such a computation becomes meaningful is that required for the effluent to mix and subside to ground level. With a relatively small plant, this subsidence begins almost immediately after the plume has risen to the top of the mixing layer; with increasing plant size, a greater fraction of the plume will still be warmer and therefore less dense than the air through which it rose, and thus will stabilize at some short distance above the mixing

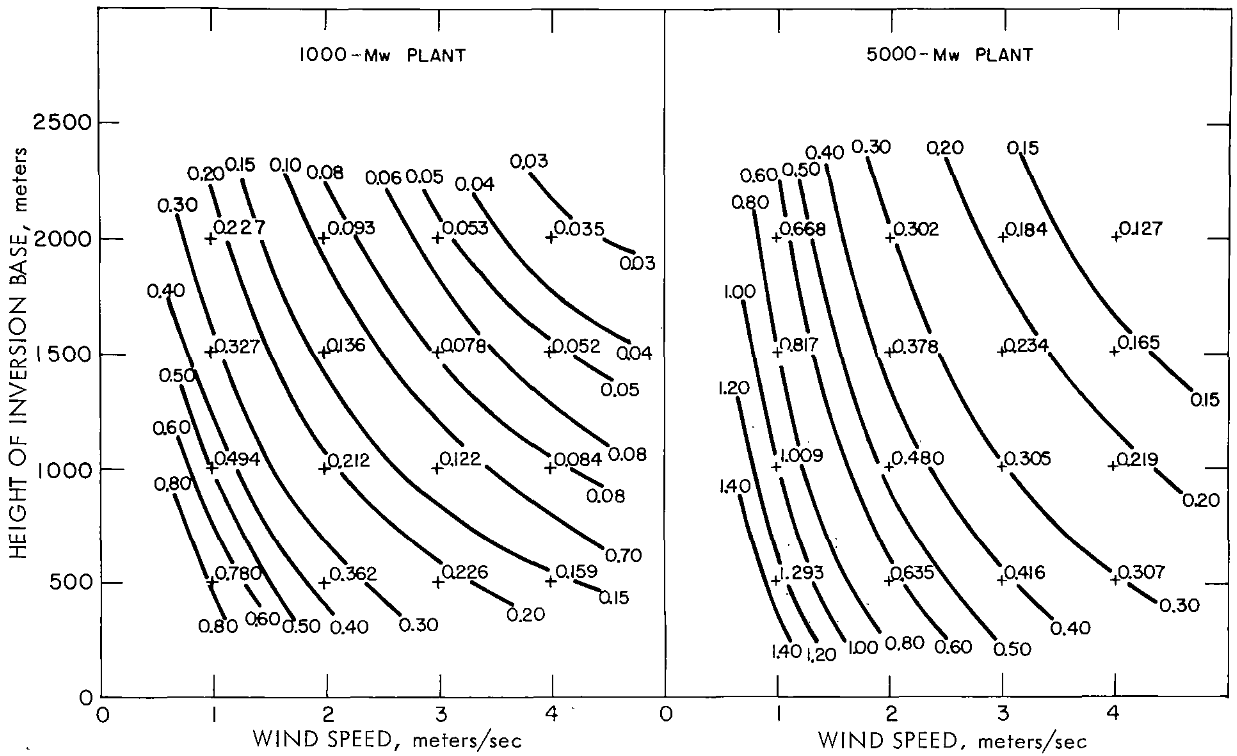


Figure 3. Estimated ground-level SO_2 concentrations (ppm) in light-wind, limited-mixing-depth conditions. (Sulfur content of coal is assumed to be 1%; for other sulfur contents, values would be changed proportionately. Values represent 1/2- to 1-hour averages. To approximate 3-minute average, multiply by 1.75; to approximate 2- to 3-hour average, multiply by 0.75.)

layer or within the capping stable layer. The plume will be released into the mixing layer as that layer develops greater depth, thus introducing a time-delay factor, which increases with increasing plant size. In consequence, the maximum ground-level concentration with this kind of fumigation increases with plant size at a less than linear rate, but the area fumigated increases in direct proportion to plant size.

The experience of the TVA with their many steam-generating plants illustrates some of these situations. As plants of increasingly larger capacity have been built, with correspondingly taller stacks, the fumigations have shifted from the high-wind type, with which many people are most familiar, to the light-wind type. Although tall stacks can be built to minimize the high-wind and inversion-breakup fumigations, the total pollution discharge of the larger plants becomes a problem when the limited capacity of the mixing layer prevents adequate dilution. Thus, the other element that determines concentrations, the pollutant source strength, must be controlled if such large plants are to be built in parts of the country where this type of fumigation occurs with any appreciable frequency. Although conditions of this type are most frequent in Southern California, no section of the country can consider itself immune from such problems if the pollution sources are present.

LOCAL EFFECTS

Local factors may exert some influence on each of these types of fumigation. Since large power plants are built adjacent to sources of cooling water, there are invariably some topographic complications that must be considered. With both high-wind and inversion-breakup fumigations, the more elevated points in the areas affected will experience higher concentrations than would be found over flat terrain. For the high-wind fumigation comparatively large-scale topographic features, such as a small mountain upwind or an extensive water surface downwind, can create a mean downflow that lowers the plume as it moves downwind. For the inversion-breakup fumigation, large-scale channelling such as found with the Trail, B.C., smelter (Hewson and Gill, 1944) may confine the plume to a selected path and lead to repeated local fumigations. In other areas a stable layer may flow over a much warmer region, e.g., from water to land in the summer or from the outskirts of a large city over the city itself, and lead to an inversion-breakup fumigation because of a spatial transition of the flow. For the light-wind fumigation a large, cool surface, such as a lake, will always be a favored region for subsidence, so that the downwind shore may experience more frequent and severe fumigations than any surrounding areas.

The dispersion potential for a large power plant must be calculated from a consideration of the locale into which the plant is to be fitted, and thus the details of location and design must be treated individually. Meteorological control of plant operations may be required when potential pollution cannot be minimized by any other methods.

APPENDIX

Formulae and Numerical Values Used in Calculating Maximum Ground-Level Concentrations

(All symbols and numerical values are listed and defined in Table A1.)

Atmospheric pressure of 1000 mb and temperature of 15°C were assumed for all calculations. The emission rate of heat to the atmosphere was assumed to be 15 percent of the plant generating capacity, with an emission temperature of 140°C and a stack efflux speed of 20 meters per second. From mass continuity with these assumptions, the stack diameter for a 1000-Mw plant is 9.565 meters. With an assumed coal consumption rate of 383 tons per hour for a 1000-Mw plant, with full conversion of the sulfur to SO_2 and its emission to the atmosphere, the SO_2 emission rate is 1.932×10^3 p grams per second. For a 5000-Mw plant, the heat and SO_2 emission rates were multiplied by 5, and the stack diameter by $5^{1/2}$ 2.236. All calculations were for p 1 percent; the concentrations shown in Figures 1, 2, and 3 should be multiplied by p for other sulfur contents.

HIGH WIND, NEUTRAL FUMIGATION (Figure 1)

Plume rise was calculated from Holland's formula,

$$\Delta h = \frac{1.5 V_s d_s + 0.409 \times 10^{-4} Q_H}{u} \qquad (1)$$

and the maximum ground-level concentration from Sutton's equation,

$$X m = \frac{2Q}{\pi e u h^2 \rho_{SO_2}} \qquad (2)$$

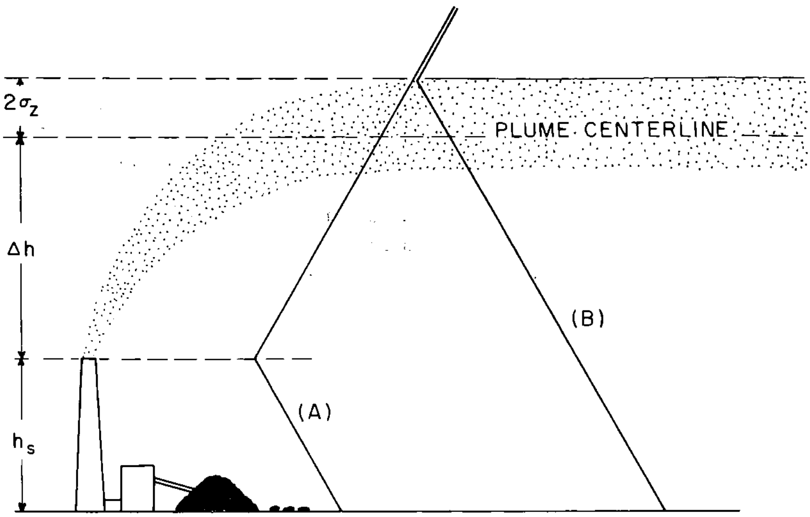
Calculations were made for four wind speeds 5, 10, 15, and 20 meters per second; and for three stack heights 200, 400, and 600 feet. Concentrations at intermediate values were obtained by graphical interpolation.

INVERSION BREAKUP FUMIGATION (Figure 2)

A formula for plume rise was developed from dimensional considerations:

$$\Delta h = \left[\frac{\pi \Delta \rho g d_s^2 \, v_s T a}{4 \rho_a \frac{\delta \theta}{\delta z} u (u + v_s)^2} \right]^{1/2} \qquad (3)$$

It was assumed that the effluent plume rises some distance through the inversion layer and becomes stabilized with the plume centerline a distance Δh above the top of the stack. Thereafter, as the plume moves downwind, it widens with downwind travel but the depth is constant. It was assumed that the maximum ground-level concentration occurs when the plume elements emitted at the time that a surface-based mixing layer has developed just to stack-top level are later mixed to ground level as the mixing layer builds up to plume level, resulting in the minimum time after emission for plume travel within the inversion layer. It was assumed that the mixing layer would have to develop to the top of the plume, defined here as $2\sigma_z$ above the plume centerline (see Figure A1). The



(A) Temperature profile at time of emission. ($t = o$)

(B) Temperature profile at time of fumigation. ($t = t_m$)

Figure A1.

net amount of heating of the mixing layer required (proportional to the area enclosed between curves A and B) is given by

$$q = \rho_a c_p \frac{\delta\Theta}{\delta z} (\Delta h + 2\sigma_z)(h_s + 1/2\Delta h + \sigma_z). \quad (4)$$

This heating is given by the product of net heating rate of the air by solar radiation multiplied by the time required to develop the mixing layer, or

$$q = Rt_m. \quad (5)$$

Solving (4) and (5) for t_m, the distance x at which the maximum ground-level concentration will occur can be obtained from $x = ut_m$. The maximum concentration was computed by assuming that the plume would then become uniformly mixed through the depth of the mixing layer, with a Gaussian horizontal distribution appropriate to that distance, or

$$X_m = \frac{Q}{\sqrt{2\pi}\, u\, H\sigma_y \rho_{SO_2}}, \quad (6)$$

where $H = h_s + \Delta h + 2\sigma_z$, with σ_z assumed to be 30 meters for the 1000-Mw plant and 45 meters for the 5000-Mw plant; and $\sigma_y = C_y (x + x_v)^{\frac{2-n}{2}}$, where $x_v = \left(\frac{\sigma_y}{C_y}\right)^{\frac{2}{2-n}}$ at $t = 0$. Values of $C_y = 0.05657\ m^{1/8}$ and $n = 0.25$ were assumed. Initial plume widths were represented by assuming $\sigma_y = 60$ meters and $\sigma_y = 120$ meters for the 1000-Mw and 5000-Mw plants, respectively, at $t = 0$. For each plant size, calculations were made for wind speeds of 2.5, 5.0, 7.5, and 10.0 meters per second, for stack heights of 200, 400, 600, and 800 feet. Concentrations at intermediate values were obtained by graphical interpolation.

LIGHT-WIND, LIMITED MIXING LAYER FUMIGATION (Figure 3)

It was assumed that the plume rises and tilts so that when it reaches the inversion base at height H the plume element emitted per unit time is a binormal cylinder of length u, and the standard deviations, both across the wind and vertically, are σ_H. It was assumed that the plume would stabilize partly within the inversion layer capping the surface-based mixing layer, with the greatest penetration by the warmest and hence most polluted part of the plume. If it is assumed that $\sigma_H = \frac{\pi}{18} H$ (equivalent to a total plume spread of about 40°), the maximum excess temperature ΔT_m in the plume when it reaches the top of the mixing layer will be given by

$$\Delta T_m = \frac{Q_H}{2\pi\rho_a c_p u \sigma_H^2} = \frac{162\, Q_H}{\pi^3 \rho_a c_p u H^2}. \quad (7)$$

The mixing layer must be heated by this same amount to release the total amount of effluent from the stable layer (see Figure A2). The height of

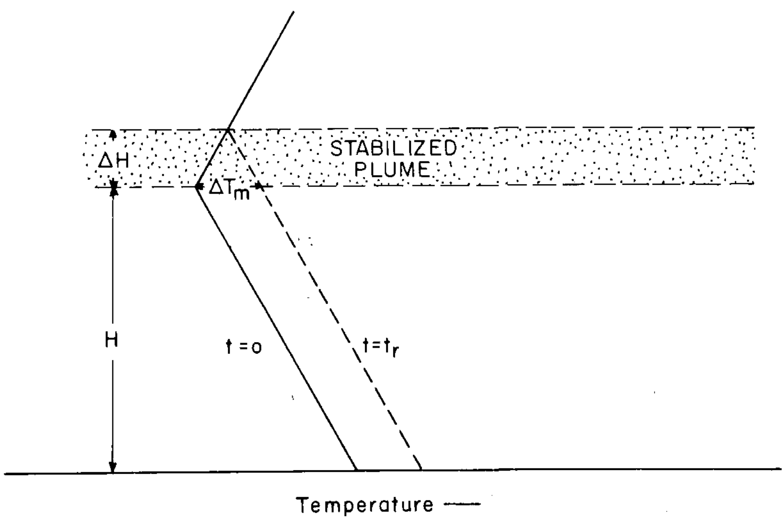


Figure A2.

stabilization above the inversion base of any plume element will be proportional to the excess temperature of the element, and inversely proportional to the stability of the layer. The maximum penetration ΔH will thus be given by

$$\Delta H = \frac{\Delta T_m}{\frac{\delta \theta}{\delta z}} \tag{8}$$

The effluent will be uniformly distributed in the layer from H to $(H + \Delta H)$.

For the plume elements at $(H + \Delta H)$ to become re-incorporated into the mixing layer, the mixing layer must increase in depth by an amount ΔH, or the temperature of the mixing layer must be increased by T_m. If ΔH is small compared to H, the required heating per unit area of surface is given by

$$q = H \rho_a c_p \Delta T_m \tag{9}$$

Also $q = Rt_r$. Hence,

$$t_r \quad \frac{\rho_a c_p H \Delta T_m}{R} \quad \frac{162 Q_H}{\pi^3 u H R} \tag{10}$$

It was further assumed that, once released, the plume elements subside and mix back to ground level according to a vertical velocity distribution $\frac{dz}{dt}$ $0.5 + 0.001z$. Integrating, the subsidence time t_s is given by

$$t_s \quad 1000 \ln(1 + 0.002H) \tag{11}$$

The maximum ground-level concentration when the total plume is stirred back to ground level is given by

$$X_m = \frac{Q}{\sqrt{2\pi}\, u H \sigma_y \rho_{SO_2}} \tag{12}$$

where $\sigma_y = C_y \left[u(t_r + t_s) + x_v\right]^{\frac{2-n}{2}}$; values of C_y ~ $1.00\, m^{1/4}$, $n = 0.50$ were assumed, whence x_v $(\sigma_H)^{1.33}$

Calculations of X_m were made for wind speeds of 1, 2, 3, and 4 meters per second, and mixing layer depths of 500, 1000, 1500, and 2000 meters. Concentrations at intermediate values were obtained by graphical interpolation.

The maximum (centerline) ground-level concentration X_t for a time of travel t other than $(t_r + t_s)$ as a fraction of the maximum concentration is given by

$$\frac{X_t}{X_m} = \frac{(t - t_s)}{t_r} \left[\frac{u(t_r + t_s) + x_v}{ut + x_v}\right]^{0.75} \quad \text{for } t_s \leq t \leq (t_r + t_s) \tag{13a}$$

$$\frac{X_t}{X_m} \quad \left[\frac{u(t_r + t_s) + x_v}{ut + x_v}\right]^{0.75} \quad \text{for } t \geq (t_r + t_s) \tag{13b}$$

$$X_t \quad 0 \quad \text{for } t \leq t_s \tag{13c}$$

These equations could also be expressed in terms of distance through the equality $x \quad ut$. Together with Equation (12), these equations show that for a given set of meteorological conditions (u, H, and R), the ground-level concentration initially increases with travel time t at the same rate for all plant sizes; however, the larger the plant, the longer the travel time over which ground-level concentration increases, and hence the higher the maximum concentration.

Table A1. DEFINITIONS AND DIMENSIONAL UNITS OF SYMBOLS AND NUMERICAL VALUES

c_p	specific heat of air at constant pressure, 0.240 cal g^{-1} $^{o}K^{-1}$.
C_y	horizontal diffusion coefficient, $(\text{meters})^{n/2}$.
d_s	stack diameter, meters.
e	base of natural logarithms, 2.71828....
g	acceleration of gravity, 9.806 m sec^{-2}.
h	$(=h_s + \Delta h)$ plume height above ground, meters.
h_s	stack height, meters.
Δh	plume rise, meters.
H	depth of mixing layer, meters.
ΔH	increase in depth of mixing layer, meters.
n	dimensionless exponent related to distance-dependence of diffusion rate.
p	percentage sulfur in coal.
q	net heating of an air column, cal m^{-2}.
Q	emission rate of SO_2, g sec^{-1}.
Q_H	emission rate of heat, cal sec^{-1}.
R	net rate of sensible heating of an air column by solar radiation, assumed constant equal to 0.4 Langleys min^{-1} 66.67 cal m^{-2} sec^{-1}.
t	travel time, seconds.
t_m	time required for mixing layer to develop to top of plume, seconds (for inversion breakup).
t_r	time required for mixing layer to develop to top of plume, seconds (for light wind).
t_s	time required for plume elements to descend from top of mixing layer to the surface, seconds (for light wind).
T_a	ambient air temperature, assumed constant at $15^{o}C = 288.16^{o}K$.
ΔT_m	maximum temperature difference between plume elements and surroundings, ^{o}C (for light wind).
u	wind speed, m sec^{-1}.
v_s	stack exit speed, m sec^{-1}.

x travel distance, meters.

x_v virtual travel distance to represent initial plume spread, meters.

$\frac{\delta \Theta}{\delta z}$ vertical potential temperature gradient, $^{\circ}C\ m^{-1}$; assumed constant at $1.96 \times 10^{-2}\ ^{\circ}C\ m^{-1}$ for inversion breakup.

π constant, 3.14159....

ρ_a ambient air density, assumed constant at $1.209 \times 10^3\ g\ m^{-3}$.

$\Delta \rho$ density difference between stack effluent and ambient air, assumed constant at $0.3658 \times 10^3\ g\ m^{-3}$.

ρ_{SO_2} density of SO_2 at ambient conditions, assumed constant at $2.671 \times 10^{-3}\ g\ cm^{-3}$.

σ_H vertical and crosswind standard deviations of plume distribution at height H, meters (for light wind).

σ_y crosswind standard deviation of plume distribution, meters.

σ_z vertical standard deviation of plume distribution, meters.

X_m maximum ground level concentration, ppm (vol).

X_t centerline ground level concentration at travel time t, ppm (vol).

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