Some Restrictive Meteorological Conditions to be Considered in the Design of Stacks[1,2,3]

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ABSTRACT

There are several restrictive meteorological conditions that are of great importance in the design of stacks. The conditions considered are fumigation, aerodynamic downwash, looping and trapping. Each condition is explained and formulae are given for the computation of ground level concentrations. Methods for determining the percentage of occurrence of these restrictive conditions from observed data are also discussed very briefly.

1. Introduction

Industrial designers are relying more and more upon the engineering meteorologist for aid in the design of stacks. When confronted with such a problem, there are definite steps that can be taken by the meteorological consultant. Stack design work contains a whole spectrum of variables, only a few of which are truly meteorological in nature. For the sake of discussion let it be assumed that the location of the stack has been determined using sound meteorological judgment, that the effluent will be at ambient air temperature when it reaches the top of the stack, and that within the stack there is a known amount of pollutant to be diluted with a known volume of air. The problem then is to determine the optimum stack height and stack diameter from an analysis of meteorological conditions.

The major meteorological problem is to compute maximum concentrations either on the ground or at some significant point in space such as a nearby air conditioning intake. There are several patterns of effluent behavior that are likely to provide high concentrations. These flow patterns are "fumigation" as defined by Hewson (1945), "aerodynamic downwash" as defined by Sherlock,[4] "looping of the plume" as defined by Church (1949), and "trapping" as defined by Hewson (in press). Several of these behavior patterns are shown in Fig. 1. Each situation will be discussed separately, and the formula for computing the concentration will be given. Methods of estimating the percentage frequency of occurrence of these conditions as they are obtained from meteorological observations will also be discussed briefly.

2. Stack height

Assistance in the determination of the height of the stack is a useful service which the meteorologist can render. Most of the standard diffusion formulae utilize the term effective stack height as one of the basic parameters in the equations. Effective stack height according to Beers (1949) is defined as the height above the surface of the horizontal axis of the emitted plume. Variation of this parameter under several restrictive meteorological situations should provide sufficient data for the consumer to enable him to decide how high a stack will have to be built.

In most calculations it is best to assume that the effective stack height is no greater than the actual stack height. Such an assumption is conservative in that it usually increases the computed ground level concentrations. If the computed values of concentration are acceptable whether for local public health codes or federal agency codes, then the observed ground level concentrations will in general be less owing to positive buoyancy and the momentum of the effluent which create the effect of an increased stack height.

There are cases when the conservative procedure is to take the effective stack height to be less than the actual stack height. Such a procedure may be used with aerodynamic downwash around buildings or with the condition of negative buoyancy when a wet plume is cooled by evaporation. The determination of effective stack height has been dealt with by Hewson (1955), Bosanquet (1957) and Scorer (1959).

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[2] Contribution No. 16 from the Great Lakes Research Division, Institute of Science and Technology, The University of Michigan.

[3] Research conducted under Grant No. G-11404 from the National Science Foundation.

[4] Sherlock, R. H., and E. A. Stalker, 1941: A study of flow phenomena in the wake of smokestacks. Eng. Res. Bull. No. 29, The Univ. of Michigan, Ann Arbor, Mich.

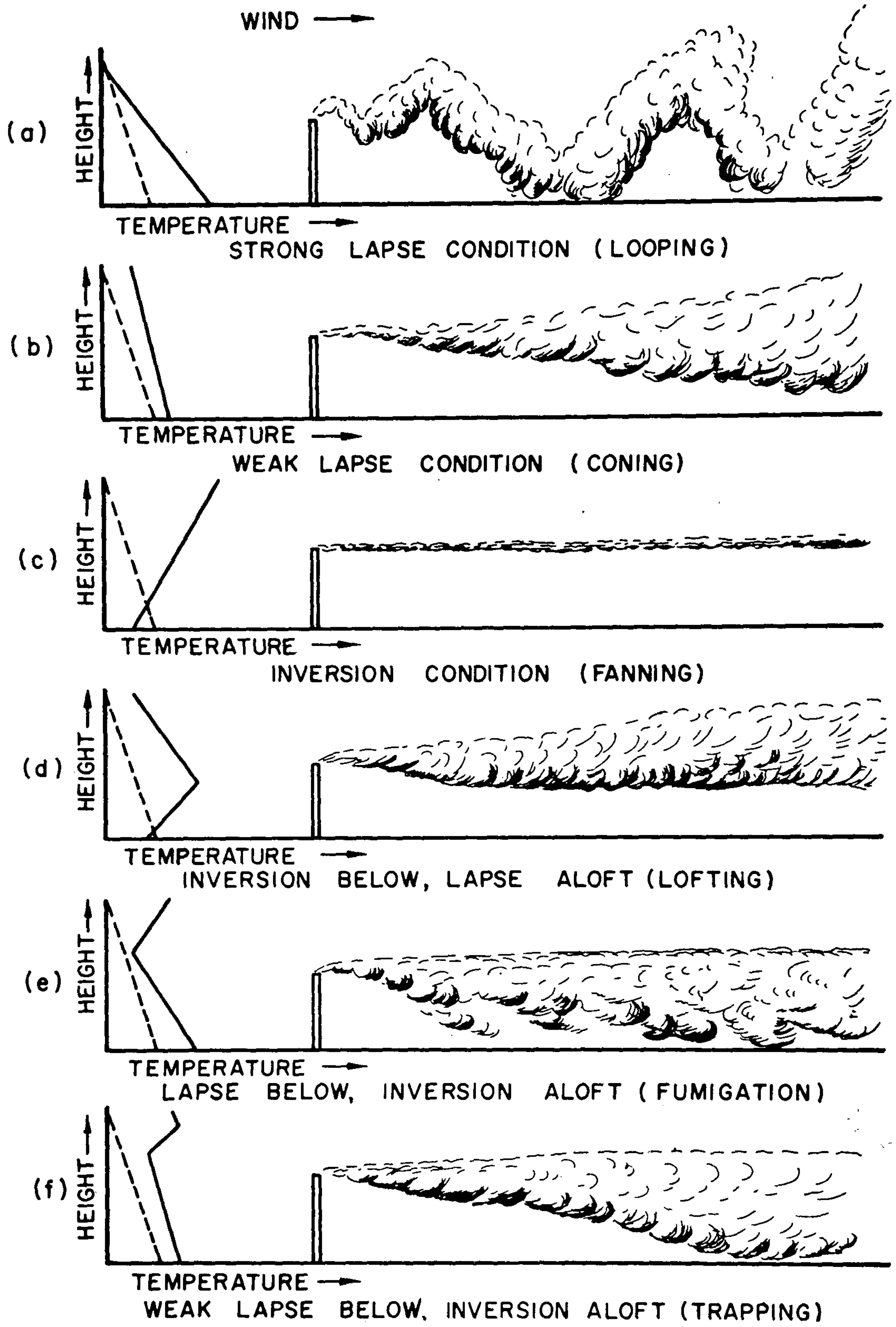

FIG. 1. Six types of plume behavior under various conditions of stability and instability. At left: broken lines, dry adiabatic lapse rate; full lines, existing lapse rates.

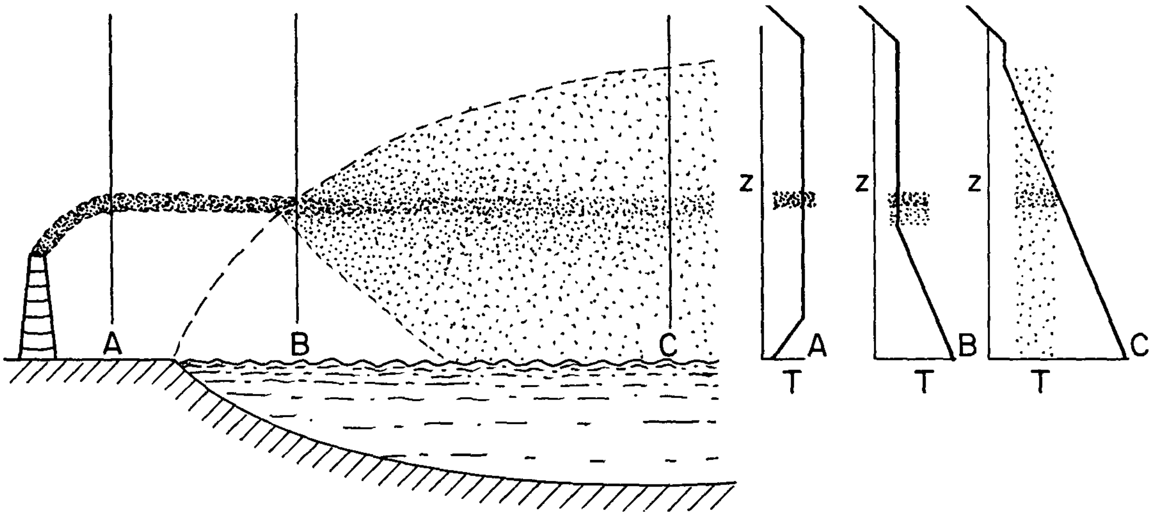

FIG. 2. Type III fumigation. The vertical distribution of material downwind from the stack and accompanying lapse rates at A, B and C as the plume passes from an over land to an over water trajectory are indicated on the right.

3. Fumigation

The first of the restrictive meteorological conditions to be discussed will be fumigation as defined by Hewson (1945), which is illustrated in Fig. 1(e). Under nocturnal conditions with clear skies and light winds, radiation inversions develop allowing the effluent plume to fan from the stack in a thin horizontal layer. With solar heating after sunrise a layer of unstable turbulent air grows upward from the heated ground. When this turbulent layer reaches the fanning plume aloft, the effluent is brought to the ground suddenly in high concentrations. Fortunately the high surface concentrations persist for only short periods of time usually of the order of half an hour. This process is known as fumigation and was first explained by Hewson at Trail, British Columbia, where high surface concentrations of SO_2 were observed simultaneously at stations on the valley floor up to distances of 10 km from the source.

The fumigation mentioned above results from a temporal change in the turbulence regime and is here referred to as a Type I fumigation. There are also spatial discontinuities in the turbulence field which cause fumigations. These additional types, II and III, have been described by Munn (1959) and Hewson (in press). Type II fumigation results from the low level heating of air as it passes over a city or other artificial heat source. The heat sources in the city maintain an unstable lapse rate up to two or three times the roof level. Air coming over the city from rural areas in the early evening is already stable as a result of radiational cooling. The resulting convection reaches up to the level of the effluent in the stable air aloft bringing it to the ground in high concentrations. As radiation cooling continues, the fumigation concentrations decrease or cease due to the subsequent stability over the urban area as well as over the surrounding rural areas. The degree of stabilization during the night and early morning hours is greater for small than for large cities (Duckworth and Sandberg, 1954).[5]

Type III fumigation is a similar phenomenon except that the heat source is a natural one as contrasted with the artificial source of Type II. Examples of Type III fumigation might be near a shore line with onshore winds during the day in spring and summer or with offshore winds on clear nights during autumn and winter. A sketch illustrating Type III fumigation is shown in Fig. 2. The vertical distributions of contaminants through three successive downwind cross sections are sketched to indicate changes in the concentration due to passage of the plume over areas having different turbulence regimes. With the Type III fumigation there usually is no descent of gases near the stack as in Type I fumigation because the effluent is transported with limited vertical diffusion for some distance from the stack before the fumigation process begins. In such fumigations the concentrations will not be as high as in Type I fumigations.

Equations for the computation of fumigation concentration have been published by both Holland (1953) and Hewson (1955). Both these equations were developed for use at a distance from the stack and for a Type I fumigation. At distances of a mile or greater from the source, the results of using Eq (1) and (2) are similar. Holland's equation is:

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[5] Perkins, W. A., 1962: Proceedings of a Symposium on the Air Over Cities, Cincinnati, Ohio, 6–7 November 1961.

$$\chi(x,0,0)=\frac{Q}{\pi^{\frac{1}{2}}C_y\bar{u}h_e x^{(2-n)/2}},\qquad(1)$$

where the point source equation for isotropic diffusion is integrated from 0 to ∞ with respect to z and the resulting amount of material is distributed through a layer of depth h_e. Values of C_y for a large inversion and a small sampling time are recommended. Such values might range from 0.05 for a 10-m stack to 0.02 for a 100-m stack. The corresponding equation given by Hewson is:

$$\chi(x,0,0)=\frac{36Q}{\pi\bar{u}h_e(x_2+x_1)},\qquad(2)$$

where it is assumed that the plume fans over a 5-deg angle at the effective source height and over a 15-deg angle on the ground. In the derivation of Eq (2) an average angle of 10 deg is therefore assumed. The contaminant is distributed uniformly between distances x_1 and x_2 from the source. For both Eq (1) and (2)

Q = source strength, mass per unit time
$\bar{u}$ = mean wind speed
h_e = effective stack height
x, x_1, x_2 = horizontal distances from the source
n = a dimensionless number between 0 and 1 indicating the stability of the layer
C_y = diffusion coefficient in crosswind direction.

Eq (1) and (2) give unreasonably high values close to the stack, that is within the first 100 m, because the stack is considered as a point source in both Eq (1) and (2). To find the ground level concentration near the stack the following variant of Eq (2) may be used:

$$\chi(x,0,0)=\frac{Q}{\bar{u}h_e[(\pi x/36)+d+h_e\tan 15°]},\qquad(3)$$

where d = stack diameter.

Eq (3) assumes that the fanning plume extends horizontally over a 5-deg angle from a virtual point source which is located a distance $36d/\pi$ upwind from the mouth of the stack. It allows for horizontal crosswind diffusion of the contaminant as it descends with the inversion breakup by assuming that the effluent is diffused uniformly over a vertical area in the form of a truncated isosceles triangle whose apex has a half angle of 15 deg and whose height is h_e.

Eq (1), (2) and (3) are useful for Type I fumigations but may not be acceptable for the other types. For Types II and III it is recommended that ground level concentrations be computed from the following equation which is a modification of the limited line source equation of Sutton (1953).

$$\chi(x,y,0)=\frac{Q_1\exp^{\dagger}(-h_e^2/C_z^2x^{2-n})}{\pi^{\frac{1}{2}}C_z\bar{u}x^{(2-n)/2}}\times\left[\mathrm{erf}^{*}\frac{y_0-y}{C_yx^{(2-n)/2}}+\mathrm{erf}\frac{y_0-y}{C_yx^{(2-n)/2}}\right],\qquad(4)$$

where

$2y_0$ = the width of the fanning plume at the point where the growing turbulent layer reaches the plume
x = the horizontal distance downwind from the intersection of the turbulent layer and the plume
y = the horizontal distance crosswind at a distance x downwind
$Q_1 = Q/2y_0$, mass per unit time per unit length of the line source
C_z = vertical diffusion coefficient.

Recommended values of the diffusion parameters for various conditions are given in Table 1.

TABLE 1. Recommended values of diffusion coefficients for Eq (4) with a 100-m stack.

Type of turbulence	Sampling time	n	C_y	C_z
Thermal	3 min	0.20	$0.21\mathrm{m}^{1/10}$	$0.21\mathrm{m}^{1/10}$
	1 hr	0.20	$0.40\mathrm{m}^{1/10}$	$0.40\mathrm{m}^{1/10}$
Mechanical	3 min	0.25	$0.07\mathrm{m}^{1/8}$	$0.07\mathrm{m}^{1/8}$
	1 hr	0.25	$0.40\mathrm{m}^{1/8}$	$0.40\mathrm{m}^{1/8}$

Values of $2y_0$ can be estimated with the aid of information on the width of the source. For instance, in Type II fumigation if the polluted air passing over a city originated from a group of factories upwind, then an estimate of the width of the plume as it passes over the city would be necessary. During the evening, when such a fumigation occurs, the plume width over the city would not exceed by much the width of the stack complex. In a Type III fumigation the width of the plume as it comes from a single stack may be estimated at any distance downwind by assuming a horizontal fanning of the plume over a 5-deg angle.

The frequency of fumigation conditions is closely correlated with the frequency of the various types of inversions. The optimum installation provides for a measure of the lapse rate to the height of the stack right at or near the stack, but rarely are such installations available. The problem then resolves itself to an accurate estimate of the lapse rate. Wind profiles or even

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[*] Erf = error function, erf $z=(2/\pi^{\frac{1}{2}})\int_0^z e^{-v^2}dv$. Values are found in statistical tables.

[†] $\mathrm{Exp}(-2x)=e^{-2x}$ where e is the base of the Naperian logarithms.

the record of wind velocity from a single point can be helpful in this estimation. Radiosonde data from the nearest station making upper air soundings can be useful if topographic influences and any local meteorological influences are known to be insignificant. Probably the best estimate is obtained by a climatological evaluation coupled with a micrometeorological analysis of radiation effects in the lower levels. There are certain areas of the world at certain times of the year that are known to have the conditions necessary to produce fumigation regularly. All of these factors must be weighed by the meteorologist in order to make an estimate of the probability of fumigation occurrence at the location under consideration.

Fumigation often is thought to be the worst of these restrictive meteorological conditions; but whether it is the worst or not, it certainly is significant in many localities and therefore should be considered in stack design.

4. Aerodynamic downwash

The condition of aerodynamic downwash as defined by Sherlock[6] is caused by one or both of two separate processes associated with moderate to high winds. Karman vortex trails may be formed in the lee of the stack itself, in which case the effluent may be carried down in the vortices and may approach the ground. Aerodynamic downwash may also be induced in the lee of buildings: the effluent is swept downward toward the ground. The net result of either process is to lower the effective stack height and thereby to increase the surface concentrations.

Aerodynamic downwash occurs when the wind speed reaches some critical value which is a function of wind direction since the aerodynamic characteristics of a building change with wind direction, as illustrated in Fig. 3. The critical value is also a function of the exit

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[6] Sherlock, R. H., and E. A. Stalker, *op. cit.*

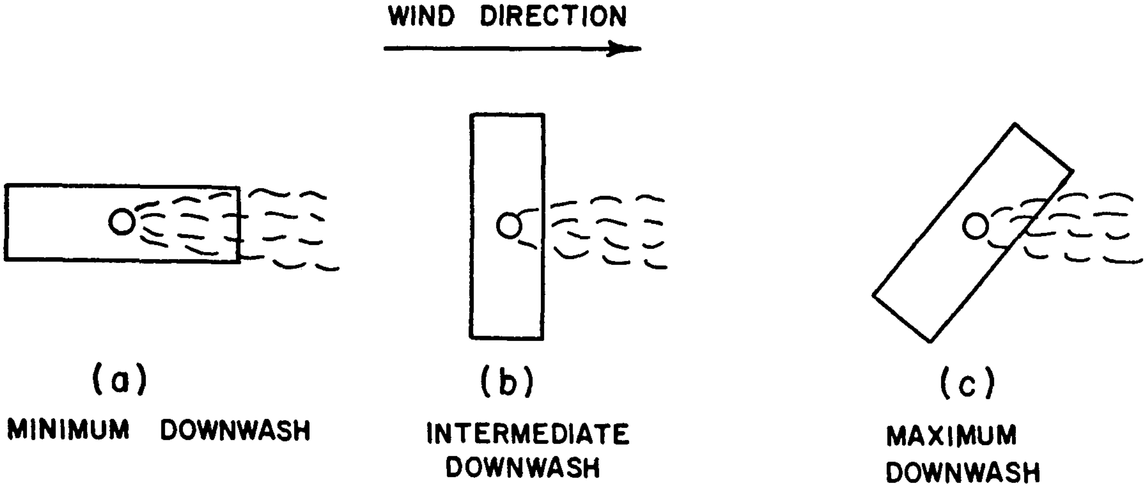

FIG. 3. Variation of aerodynamic downwash with building orientation in relation to direction of prevailing strong winds.

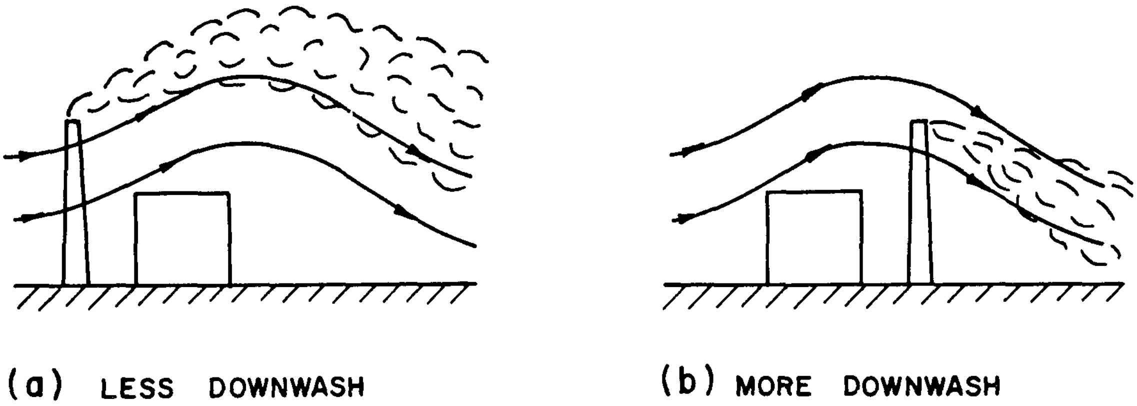

FIG. 4. Variation of aerodynamic downwash with position of stack relative to building.

velocity of the plume and of the position of the stack relative to the building, as shown in Fig. 4. The critical wind speed values can be obtained from wind tunnel studies where the ratio of exit speed of the gases to wind tunnel speed necessary to maintain the plume at a given height above the surface can be evaluated. Sherlock (1951, 1955) has developed this technique and his works should be referred to if aerodynamic downwash is a major problem.

Eq (5) is the formula to be used in computing centerline ground level concentrations due to aerodynamic downwash.

$$\chi(x,0,0)=\frac{2Q}{\pi C_y C_z \bar{u} x_1^{2-n}}, \tag{5}$$

where

x_1 = the distance from the top of the stack to a point on the ground a horizontal distance x from the stack, or $x_1=(x^2+h^2)^{\frac{1}{2}}$, where h is the actual stack height.

The other quantities are as defined previously.

Typical values to be used in Eq (5) for a 100-m stack are as follows: $\bar{u}=10$ m sec^{-1} and $n=0.20$; for 3-min average values use $C_y=C_z=0.21$ m$^{1/10}$; for 1-hr average values use $C_y=C_z=0.40^{1/10}$. Under particularly unfavorable circumstances, substantial downwash may occur with wind speeds as low as $\bar{u}=5$ or 6 m sec^{-1}. A more complex method has been described by Hewson (1955).

The frequency of occurrence of downwash may readily be calculated using the methods of Sherlock and Lesher (1955). The meteorological variables needed for the estimate are the wind speed and wind direction records for at least 5 yr; however, a shorter record is usable but less reliable. If off-site wind data are used extreme caution must be exercised to insure that such off-site data are truly representative of winds at the site itself.

It is generally accepted among air pollution engineers that aerodynamic downwash may be a major restrictive meteorological condition and as such should be designed for wherever possible. Management must decide whether adequate design and construction are worth the effort and cost, for although high concentrations may last only short periods of time, their occurrence may cause damage to surrounding vegetation and inconvenience to nearby residents.

5. Plume looping

The effect of plume looping as defined by Church (1949) is similar to that of aerodynamic downwash. The process is illustrated in Fig. 1(a). Looping plumes occur when thermal eddies carry portions of the plume to the ground. Diffusion is generally regarded as good but sporadic during such conditions thus allowing high concentrations of effluent to be brought to the surface. Looping occurs only during daylight hours, usually on a warm, clear day when a superadiabatic lapse rate develops in the lower levels coupled with light winds. Looping will not occur with such conditions as cloudiness, strong winds, snow cover, etc.

Eq (5) may be used to compute the concentrations using a maximum value of $\bar{u}$ of 4 m sec^{-1}. Because thermal eddies are responsible for the looping, the value of n should indicate great instability so that $n=0.20$. With a 100-m stack, 3-min average peak concentrations are given with $C_y=C_z=0.21$ m$^{1/10}$ and 1-hr average peak concentrations are obtained with $C_y=C_z=0.40$ m$^{1/10}$.

The frequency of occurrence of looping is given by the frequency of occurrence of clear, warm days in which there are light winds. An analysis of observations from the site or from the nearest first order Weather Bureau station will give the desired information. Because the regional pressure gradient is usually negligible on such a day, it must be ascertained that there are no local wind or thermal effects at the site that are not also present at the observing station, especially if off-site data are used.

6. Plume trapping

As the name suggests, plume trapping as defined by Hewson (in press) refers to the situation where the effluent from a stack is physically trapped between the surface of the earth and an upper inversion. Trapping is illustrated in Fig. 1(f). Diffusion may be good between the earth's surface and the inversion, but the net effect is an increase in surface concentrations due to the multiple reflection of the trapped material.

The upper inversion may be a subsidence inversion as in the Los Angeles area where trapping conditions persist for weeks and months or it may be a frontal inversion where the trapping occurs for a day or less. Whatever the cause or however long it persists, concentrations under such conditions are usually significant. Should the significant concentrations persist, then the effect may even become a health hazard.

The following equation is used to compute centerline concentrations at some height z in space under trapping conditions.

$$\chi(x,0,z)=\frac{Q}{\pi C_y C_z \bar{u} x^{2-n}} \times\Big[\sum_N \exp\{-(z-h_e+2Nh_{ib})^2/C_z^2x^{2-n}\} +\sum_N \exp\{-(z+h_e-2Nh_{ib})^2/C_z^2x^{2-n}\}\Big], \tag{6}$$

where

z = vertical distance above the surface
h_{ib} = height of the inversion base above the surface
$N = 0, \pm 1, \pm 2, \pm 3$, etc.
h_e = effective stack height

and the other quantities are as specified earlier.

Eq (6) considers the multiple reflections of the effluent from the base of the inversion and from the surface of the ground as long as the effective height of the stack is below the inversion base and the point in space $(x, 0, z)$ is somewhere between the surface and the base of the inversion. Only the first several values of N need be used for practical purposes. For distances downwind greater than 1 or 2 km, the pollutant is probably mixed uniformly through a height interval of h_{ib}.

Since the layers beneath the inversion layer are usually characterized by a weak lapse rate the following values of the diffusion parameters are recommended

$$n = 0.25, \quad C_z = C_y = 0.07 \text{ m}^{1/8}.$$

The frequency of occurrence of trapping situations can be determined from radiosonde data in which the soundings are analyzed to detect such a condition. Climatology and a knowledge of local effects such as the proximity to a large body of water or a large city will also aid in the detection of trapping situations. Areas around a stack in which trapping occurs due to frontal inversions aloft are shown ideally in Fig. 5. It may indicate to users areas relative to a stack which should be considered when dealing with trapping conditions. An analysis of trapping situations from actual weather maps would permit developing segmental areas appropriate for any particular climatic region.

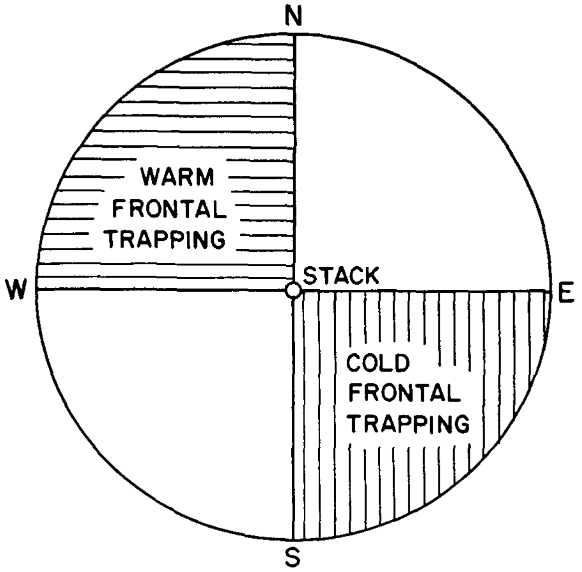

FIG. 5. Schematic diagram of quadrants in which, for the northern hemisphere, plume trapping by low level frontal inversions is to be expected. Unhatched areas are preferred zones for buildings where air pollution is minimized.

7. Stack diameter

The diameter of the stack is subject to less restrictive meteorological design criteria than is the height of the stack. The exit velocity from the stack is determined by the stack diameter, given a constant volume of effluent. A change in exit velocity or in the amount of internal dilution within the stack does not change the source strength, that is the mass of contaminant per unit time, but it may have an effect on the rise of the exhaust gases. The basic meteorological criterion to be used as an aid in the determinaton of stack diameter then is the maximum wind speed. To insure that aerodynamic downwash is minimized, the stack exit velocity should be equal to or greater than the maximum wind speed anticipated or observed at the site of the stack.

The value of maximum wind speed anticipated can be determined in several ways all of which are well enough known that no further discussion is warranted. It is important that if off-site data are used, then the topography of both places should be very similar, otherwise small topographic differences may cause large effects in the wind distributions.

8. Summary

There are several restrictive meteorological conditions that should be considered when designing stacks for waste disposal. These conditions are "fumigation," "aerodynamic downwash," "plume looping" and "trapping." A consideration of the ground level concentrations or concentration at other points, such as at the air intakes of ventilating systems of nearby buildings, should lead to an adequate design of the stack. The computation of typical concentrations before the stack is built may be of great benefit to the company not only financially but also from a public relations standpoint. In certain cases such computations are a necessary procedure before operating licenses are granted by government regulatory agencies.

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