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INDUSTRIAL AIR POLLUTION METEOROLOGY

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INTRODUCTION

Increased concern with air pollution problems has led to a growing awareness of the complexity of the problem. So much research has been conducted in recent years on various phases that even the meteorological aspects of the problem must be limited to a specific area if a compact presentation of the important facts is to be achieved. The present treatment is confined to meteorology in relation to industrial air pollution, defined as the pollution from a single plant or a group of plants in a limited area under the control of a single company or corporation.

In a large industrial city the pollution from such a plant or group of plants is only a small part of the total problem of urban air pollution caused by other sources such as incinerators, automobiles, and household furnaces. In a company town the industrial and urban problems are effectively one and the same, whereas there is no urban pollution problem with an isolated industry. The important influences of weather and climate on industrial air pollution defined in this way are set forth below.

ATMOSPHERIC INFLUENCES ON DISPERSION AND THEIR MEASUREMENT

Wind direction, speed, and turbulence are the fundamental meteorological elements by which air pollution is dispersed and diffused.

Wind Direction

The Influence of Wind Direction

The primary function of wind direction is, of course, to determine the direction in which atmospheric contaminants released from a plant will be carried by the wind. Thus a north wind, for example, will transport pollution to the south. Although this is a simple concept, it is more complicated than appears at first sight, as the following considerations show.

Change of Wind Direction With Height--In the first place, the wind direction\changes with increasing height in the lower layers of the atmosphere, the rate of change being especially rapid near the surface. In an extreme case, for example, the surface wind may be from the west, that at the top of a tall stack may be from the west, northwest, whereas at several times that height the wind may be from the northwest. A wind which changes in direction in this clockwise manner is said to veer with height. This veering with height occurs only at latitudes greater than 15 or 20° N. In the southern hemisphere at latitudes greater than 15 or 20° S the wind vector rotates in a counterclockwise manner with increasing height, i.e., the wind backs with height. Taking the corresponding extreme case for middle and higher latitudes in the southern hemisphere, with a west wind at the surface there would be a south southwest wind at the top of the tall stack and a southwest wind higher still. In equatorial latitudes no simple relationships of this type exist. Friction between the moving air and the underlying surface retards the air motion near the latter. The layer of air near the surface subject to this frictional influence is known as the friction layer; the top of this layer extends to heights ranging from several hundred meters to one kilometer or more depending on meteorological and topographical conditions. Above the top of the friction layer is the free atmosphere, free in the sense of not being directly affected by frictional forces originating at the earth's surface.

Change of Wind Direction with Height Over Various Terrains--Secondly, this variation of wind with height depends to a marked degree on the nature of the underlying surface. The nature of this dependence in the northern hemisphere is shown in Figure 1. The surface wind is denoted by u_s and the wind in the free atmosphere, just above the top of the friction layer, is denoted by u_f. The curve in each case gives the locus of the end points of the wind vectors. It will be noted that the maximum difference in wind direction occurs over rough terrain and the minimum over smooth land surfaces and over water surfaces such as those of oceans, seas, and large lakes. The angular differences of 40°, 20°, and 10° shown are representative values only. The actual values found will differ somewhat from these depending on meteorological conditions. For convenience the corresponding changes in wind speed with height are also shown in Figure 1; these will be discussed in a later section.

Diurnal Variation of Wind Direction in the Friction Layer--Finally, there is a tendency for a diurnal variation of the wind direction in the friction layer over land surfaces, the greatest variation being near the ground, a tendency which is especially pronounced when the free

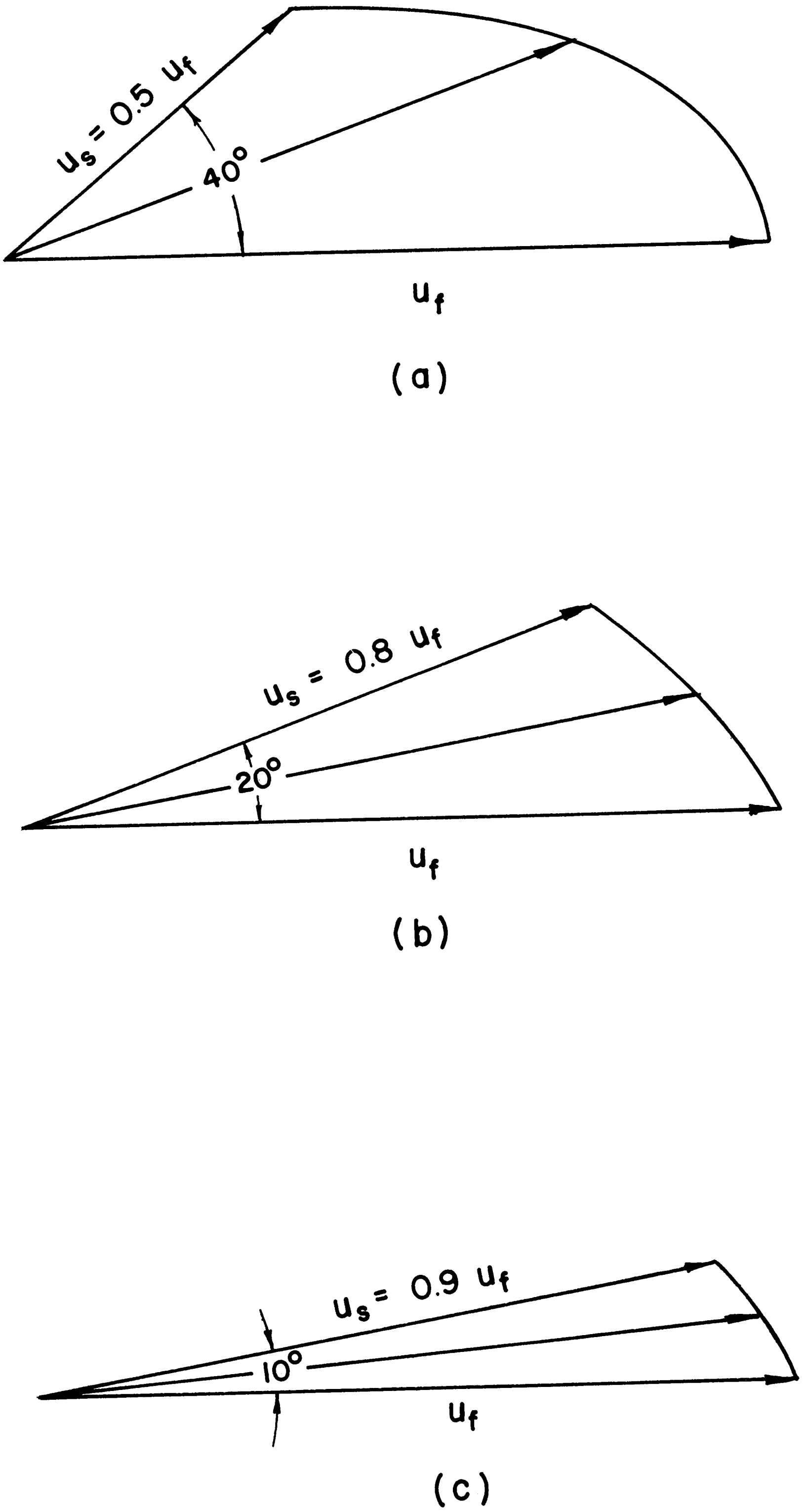

Figure 1. The variation of wind direction and speed with height in the friction layer (northern hemisphere), from the surface wind u_s to the wind u_f in the free atmosphere for: (a) rough terrain; (b) average terrain; and (c) smooth terrain or a water surface. The middle vector in each diagram represents the wind at an intermediate height such as that of the top of a tall stack.

atmosphere winds aloft are light and the sky is clear. As Figure 2 indicates, the variation of wind direction with height tends to be greater at night than during the day. There is a corresponding diurnal variation in the thickness of the friction layer, its top being relatively low at night and high during the day.

Significances of Wind Direction Changes with Height-- The significance of the foregoing facts becomes readily apparent when one considers that industrial air pollution may occur in high concentrations at nearly any height in the friction layer, and that most of it is found in the lower half of the layer where the rate of change of wind direction with height is the greatest. Since the peak concentrations of pollution from the same source are found over a wide range of heights depending on meteorological conditions, it is impossible to measure continuously the wind direction at the height of maximum concentration except at prohibitive cost. The problem then becomes one of choosing the optimum height for measurements in the particular situation encountered keeping all pertinent factors in mind. These various factors are discussed in the next section.

The Measurement of Wind Direction

There are two main techniques of measuring wind direction: by means of a wind vane mounted on a suitable structure, and by tracking a freely rising small balloon by one or more theodolites.

Wind Vane Measurements--There are four main types of wind vanes to be considered.

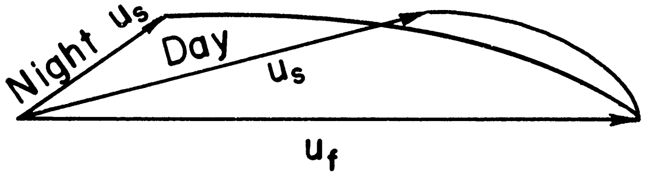

Figure 2. The surface wind u_s in relation to the free air wind u_f by day and by night.

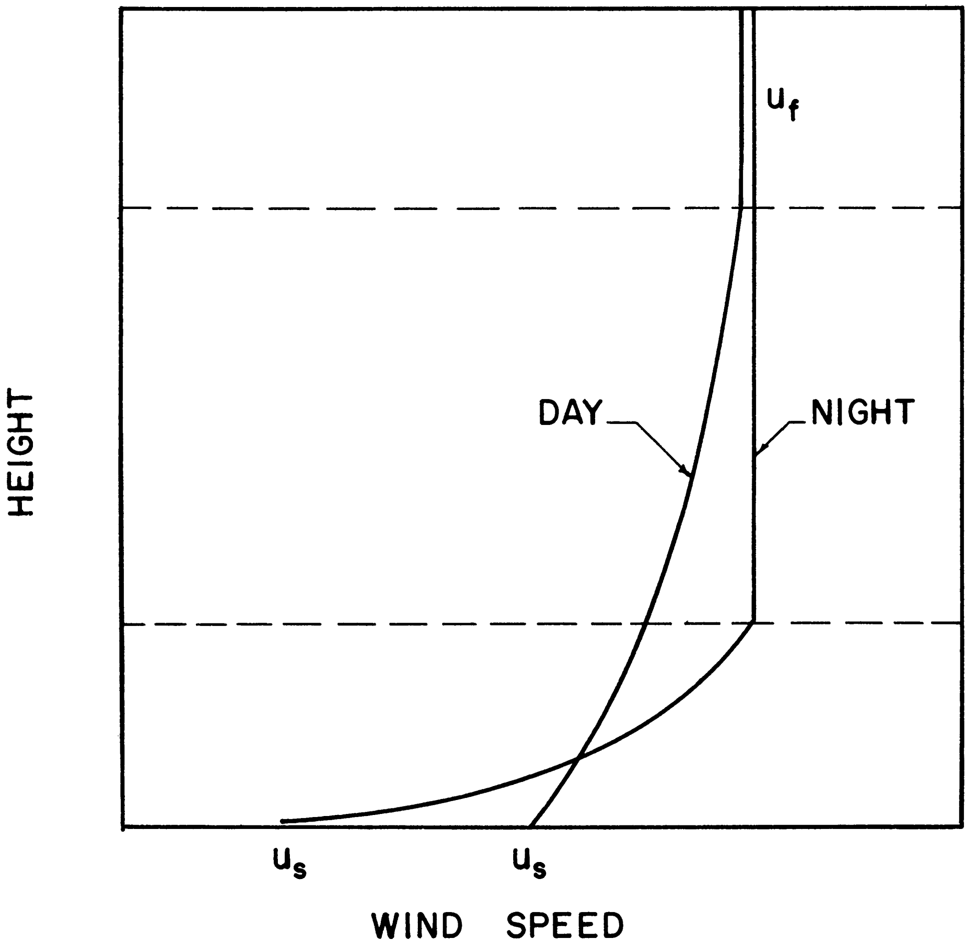

Figure 3. Typical variation of wind speed with height in the friction layer for average daytime conditions and for a night with clear skies.

(a) The flat plate vane. In this a flat plate attached to the end of a horizontal rod is mounted on a freely rotating vertical shaft. A small counterweight at the opposite end of the horizontal rod is kept heading into the wind by the wind pressures acting on the flat plate at the opposite end.

(b) The splayed vane. This vane is similar, but instead of a single plate has two identical flat plates joined at a small angle and attached at the joint to one end of a horizontal rod. Viewed from above this vane has the appearance of a Y.

(c) The airfoil vane. This type is similar to the flat plate vane above but the wind sensitive element has an airfoil section instead of being flat.

(d) The multiple element vane. This instrument consists of two or more plates or airfoil sections combined in one of several arrangements.

Any of the first three vanes listed is satisfactory for most measurements of wind direction; the multiple element vane has not been widely used.

Electrical circuits provide the most convenient method of transmitting information on the azimuth angle of the freely rotating vertical shaft of the system and hence the wind direction.(67)

Pilot Balloon Measurements--This technique is used only when winds up to considerable heights in the friction layer or higher are required for comprehensive air pollution surveys. A freely rising balloon is tracked using one(9) or more(107) theodolites. It is difficult to follow the balloon very far in the conditions of restricted visibility which characterize many air pollution conditions unless radar tracking of a target attached to the balloon can be used.

Exposure of Wind Vanes--Unless the horizontal plane in which a wind vane lies is free in all directions from large obstructions, erroneous values of wind direction are likely to be measured. An obstacle may cause a wind direction at the instrument which is not representative of the general air flow in the area. For the same reason a wind vane mounted near a cliff or on the side of a hill will not give representative values.

A useful rule-of-thumb is that the instrument should be located a distance from any obstruction which is equal to at least ten times the height of the obstruction.(54) Thus a wind vane should be at least 150 meters from a grove of trees 15 meters high. The standard height for measuring wind direction is 10 meters. If the instrument is to be mounted on a building, it should be at least 10 meters above the highest part of the building. If the building is very large, however, even this height may not be sufficient to ensure representative measurements.

Mounting of Wind Vanes--If the instrument can be mounted at the top of a 10-meter mast or metal tower there is no particular problem involved. When a vane is to be attached below the top of a steel tower, however, it should be mounted at the end of a horizontal boom at a distance which is at least equal to the width of the tower at that height, and preferably twice that distance.

For an elevated source such as the top of a stack, it is desirable to mount the vane if possible at a height near that of the top of the stack. A vane should not be mounted near and above the mouth of the stack; the effluent gases will influence the local wind direction there a probably corrode the instrument as well. One or two vanes at the end of horizontal booms attached to the stack near its top may be satisfactory. A single instrument will be sufficient if winds over a limited angle only are to be measured. Thus if the critical area in which air pollution must be minimized lies to the north of a plant, the vane should be mounted at the end of a horizontal boom extending sourthward. South winds will be measured accurately whereas the air flow will be disturbed by the stack with winds coming from the north and adjacent directions. A vane in this situation has even been observed to rotate more or less continuously as a result of the action of Karman vortices shed by the stack. If the boom is twice as long as the diameter of the stack at that height, accurate values will be obtained for winds from the northeast through south to northwest. If wind directions from all directions must be measured, the solution is to attach two booms extending in opposite directions from the stack with a vane at the end of each boom. With this arrangement one of the two vanes will always give accurate values depending on wind direction.

Special Precautions--It may be necessary to take steps to prevent the accumulation of ice on the vane. Severe icing may destroy the balance of the vane or even stop its rotation completely. In some areas artificial heating to melt the ice may be required. Ice shields to protect the vane have also been used.

Vertical Extrapolation of Surface Wind Directions--If it is not practical to mount a vane near the top of a stack, vertical extrapolation of measured winds at a lower level to the height of the smoke plume may be attempted. The information supplied in earlier sections on the variation of wind direction with height under various conditions will be sufficient for a plant located on smooth terrain. In a shallow valley, however, such extrapolation is more difficult if the lower winds tend to be channeled in the valley but the stacks are tall and their tops extend above the valley sides. Similar difficulties may be encountered near a shoreline. In such circumstances it may be necessary to take a series of pilot balloon observations for various wind directions and speeds under a number of meteorological conditions. From these the essential relations between surface (10-meter) winds and those at the height of the smoke plume may be determined.

Wind Speed

The Influence of Wind Speed

The wind speed influences air pollution in a number of ways. Before describing these, however, it will be well to discuss the variation of wind speed with height in relation to terrain types and time of day.

In general the wind speed increases with height in the friction layer. A power law of the type

$$u = u_{10} \left(\frac{z}{z_{10}}\right)^{1/7} \qquad (1)$$

has been found to hold under average meteorological conditions. In this equation u_{10} is the mean wind speed at the standard height z_{10} of 10 meters and u is the mean wind speed at some greater height z.

Referring back to Figure 1, this vertical variation corresponds approximately to Figure 1(b), which shows the change of wind direction and speed with height over average terrain. Over rough terrain the surface wind speed is much less and over smooth terrain or water it is somewhat greater than the free air wind speed aloft as indicated in (a) and (c) of Figure 1. The approximate relations between surface wind speed u_s and free air speed u_f are as follows:

Rough terrain: $u_s = 0.5\ u_f$

Average terrain: $u_s = 0.8\ u_f$

Smooth terrain or water: $u_s = 0.9\ u_f$

During the day the surface wind speed tends to be greater than that at night as indicated by Figure 2, which may be considered as typical for rougher terrain. Characteristic variations with height within the friction layer for an average day and for a night with clear skies are shown in Figure 3. This diagram brings out an important point for industrial air pollution. During a clear night the top of the friction layer is relatively low and the surface wind light, but at and above the top of a tall stack the wind speed may be substantially greater even than that at the same level during the day. This relationship should be kept in mind if the wind aloft in the layer of maximum pollution concentration is to be estimated from the wind as measured at some lower level.

Dilution of Effluent in Relation to Wind Speed--The dilution of an effluent is defined as the ratio of its concentration at the source to that at a specified point downwind. Thus if the concentration at the source is 2.7×10^3 gm m^{-3}* and is 3 gm m^{-3} at a point 2 km downwind, the dilution is 900 at that point. Neglecting for the moment factors other than wind speed which cause dilution, the dilution is directly proportional to wind speed as the following considerations readily show.

Let us assume that, in the absence of other diluting influences, the plume from a stack occupies a cylindrical volume with its axis horizontal and lying in the direction of the mean wind at the top of the stack. The volume of such a cylinder from the stack to a distance x

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* The notation gm m^{-3} is equivalent to grams per cubic meter.

downwind and with a radius r is given by

$$\text{Volume} = \pi r^2 x$$

If the wind speed is u and the time required for the air and its contaminants to travel a distance x is t, the above expression may be written

$$\text{Volume} = \pi r^2 ut$$

Thus the volume of the cylinder containing the contaminants emitted in time t is directly proportional to the wind speed u, and if the rate of emission is constant it follows directly that the dilution of the contaminants is also directly proportional to the wind speed u.

Aerodynamic Downwash of Stack Gases in Relation to Wind Speed--As the wind speed increases there is a marked tendency for stack gases to be carried near the ground, especially if the stacks are located on or near large buildings, as a result of aerodynamic disturbances of the air flow by the stacks or buildings or by both.(130,131) In general, aerodynamic downwash becomes serious at wind speeds of about 9 m $\sec^{-1}$ (20 mph), although for short stacks near large buildings it may become significant at considerably lower wind speeds. The influence of aerodynamic at downwash will be discussed in greater detail later.

Mechanical Turbulence in Relation to Wind Speed--Mechanical turbulence is a type of turbulence produced in the lower portions of the friction layer by obstructions such as trees, bushes, small hills, buildings, etc. The turbulence induced by such objects as the air flows over and around them has a marked tendency to increase with the wind speed. Since turbulence is the primary diffusing agency in the atmosphere it will be discussed further in a later section.

The Measurement of Wind Speed

An instrument for measuring wind speed is known as an anemometer. There are a number of types(67) of anemometers, of which the rotation anemometers are the most useful for industrial air pollution studies. Pilot balloon observations may be employed to obtain weed speeds higher in the friction layer.

Rotation Anemometer Measurements--There are two main types of rotation anemometer: the propeller or windmill type; and the cup type.

The propeller or windmill anemometer consists of a propeller-type assembly or windmill at one end of a horizontal shaft and a wind vane at the other. This shaft is mounted at the top of a vertical shaft in such a way that it is free to swing in a horizontal plane. The wind causes the propeller or windmill to rotate on the horizontal shaft at a rate proportional to the wind speed; the wind vane at the opposite end serves to keep the rotating sensor headed into the wind. This instrument may therefore be conveniently used as both an anemometer and a wind vane. The rotating sensor may drive a small dc generator to produce a voltage directly proportional to wind speed which may be read directly on a calibrated voltmeter or from the trace on a strip chart recorder. Instruments of this type have been found to perform well in conditions of snow and freezing rain.

Cup anemometers of modern design consist of three cups of a modified conical shape mounted at the end of three horizontal shafts which come together at an angle of 120°. This assembly is attached to a vertical shaft which is mounted on bearings so as to be free to rotate at a rate proportional to the wind speed. If instantaneous wind speed values are required, a small dc generator may be used as in the propeller or windmill anemometer. Alternatively, mean wind speed over a specified time interval may be obtained by counting the number of rotations of the cups. For example, if a make and break in an electrical circuit is counted each time a mile of wind passes the anemometer, the number of such counts in an hour gives the mean wind speed during the hour directly in miles per hour. Severe snow and icing conditions may cause errors in the measured wind speeds.

Pilot Balloon Measurements--Since pilot balloon measure give wind speeds as well as wind directions aloft, the earlier section on the latter should be consulted for details and references.

Exposure, Mounting, and Special Precautions for Anemometers--Essentially the same criteria as given for wind vanes also apply to anemometers.

Wind Turbulence

Turbulence in the wind is by far the most important agency by which air-borne contaminants are diffused through the atmosphere; molecular diffusion taken by itself as completely negligible in comparison with it. Even under the worst atmospheric conditions turbulent diffusion is of the order of a thousand times more effective in dispersing contaminants than molecular diffusion. With the best atmospheric conditions turbulent diffusion may be a million times more effective.

The Physical Process of Turbulent Diffusion

The mechanism by which wind turbulence acts to diffuse a plume of smoke may be seen by considering Figure 4. In (a), the broad details of a portion of the top of the plume are shown; the distance A-A might be several hundred meters. Part (b) shows the central section, B-B, on an enlarged scale, and reveals parcels of the smoky air penetrating into clear air and vice versa. This interpenetration is caused by turbulence in the wind. Further details are brought out in (c), where the section C-C has been further enlarged. It is seen that smaller masses of smoky air and clear air have broken off from their parent bodies. Further enlargements would reveal still finer breaking up of the plume in the same manner. There is a whole spectrum of eddy sizes in the turbulent wind, ranging from very large to very small, and each plays a part in the diffusion process. These eddies serve the very important function of breaking the plume into smaller and smaller volumes on which in the final stage molecular diffusion acts. Without the action of the eddies in bringing clear air into

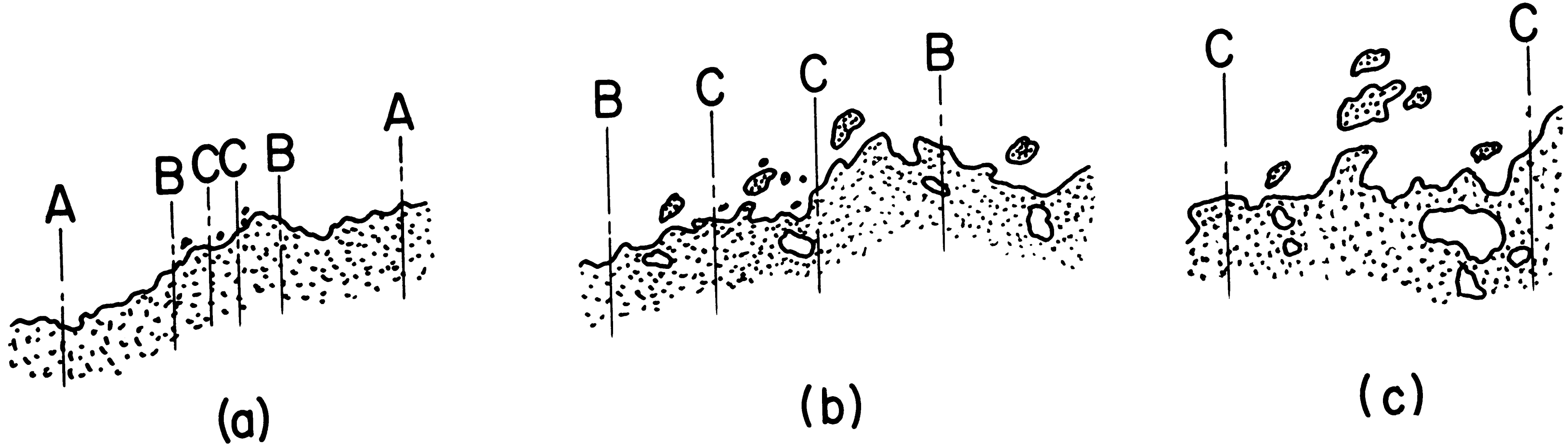


Figure 4. The action of wind turbulence in diffusing a portion of a smoke plume: (a) large scale features; (b) medium scale features; and (c) small scale features.

the plume and carrying smoky air into the surrounding clear air, molecular action would be highly ineffective in diffusing the smoke.

Atmospheric Stability in Relation to Turbulent Diffusion

The degree of turbulence present depends greatly on the stability of the atmosphere, which in turn is determined by the rate at which temperature decreases with height, a quantity known as the lapse rate of temperature. When the temperature decreases at a rate less than 10 C km^{-1} (5.4 F per 1000 ft), a quantity known as the dry adiabatic lapse rate or the dry adiabatic rate of cooling, the air is stable for vertical motions and the ascent and descent of air parcels does not readily occur. In an inversion, a layer in which the temperature increases with height, the air is very stable and because incipient vertical motions are damped out, vertical turbulent action and hence vertical diffusion are very slight. On the other hand, when the lapse rate of temperature is greater than 10 C km^{-1}, a condition known as a superadiabatic lapse rate, the air is unstable, vertical motion is promoted, not suppressed, turbulence is pronounced and diffusion rapid. This active eddying motion with marked vertical as well as horizontal components is called thermal turbulence. When the observed temperature decrease is equal to 10 C km^{-1} the air is said to be neutral. In this condition vertical motions are neither promoted nor inhibited, and turbulence and diffusion are less marked than when the air is unstable.

Thermal Turbulence--Thermal turbulence tends to be most pronounced in middle latitudes during the summer on clear days with light winds. The solar radiation heats the ground surface which in turn warms the air above to progressively greater heights and leads to the superadiabatic lapse rates in the lower layers which are a necessary condition for thermal turbulence. The pronounced variations of wind speed and direction which characterize thermal turbulence in unstable air are illustrated in the lower portion of Figure 5. The intense mixing associated with thermal turbulence leads to rapid diffusion of stack effluents. If there are large scale vertical eddies, however, as is often the case, one of these may bring smoke to the ground near the stack in high concentrations. Farther from the stack the concentrations will be very low except under special meteorological conditions in a valley to be described later. A significant characteristic of unstable atmospheric conditions is the tendency of the air to flow over as well as around obstacles such as buildings, groves of trees, small hills, etc. With a stable atmosphere there is more of a tendency for the air to resist vertical displacement and therefore to flow around obstacles.

Mechanical Turbulence--As mentioned earlier, mechanical turbulence is irregular air flow induced by surface roughness. The upper part of Figure 5 illustrates wind speed and direction fluctuations characteristic of mechanical turbulence. The degree of mechanical turbulence depends on three factors: surface roughness, wind speed, and atmospheric stability.

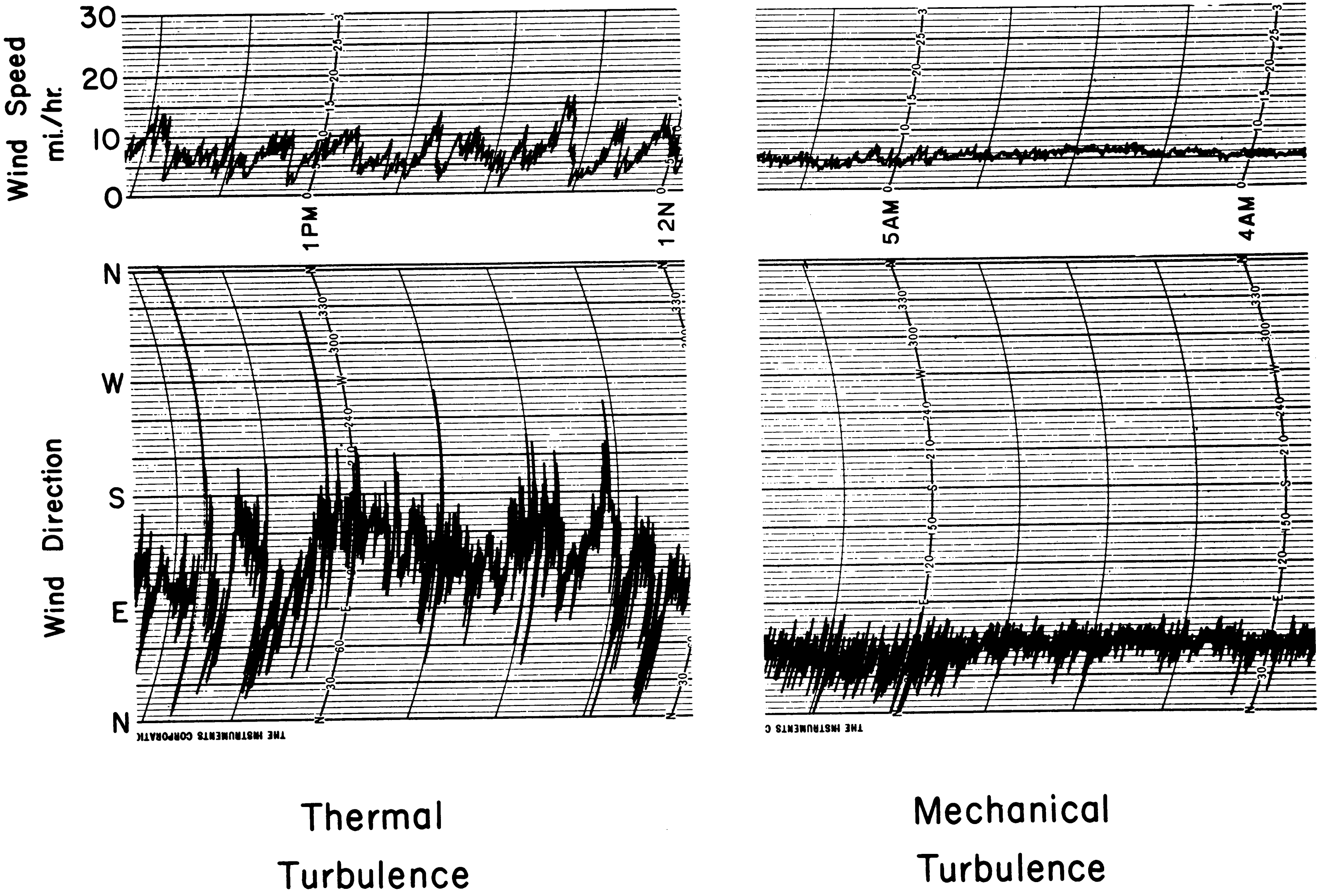


Figure 5. Wind speed and direction chart traces characteristic of mechanical and thermal turbulance.

Variation with Surface Roughness--Other things being equal, the intensity of the mechanical turbulence and the height to which it extends varies directly with the height of the surface roughness elements. For example, such turbulence is slight over a smooth desert, moderate over rolling, tree-dotted terrain, and very pronounced over rocky and mountainous areas.

Variation with Surface Wind Speed and Stability--Mechanical turbulence also tends to vary directly with surface wind speed and inversely with atmospheric stability. These two quantities are intimately related, however: with appreciable surface roughness and a strong wind the pronounced mechanical turbulence maintains the air in a neutral condition with a lapse rate of approximately 10 C km^{-1}; on the other hand, if the underlying surface is substantially cooler than the air flowing over it the stability increases and the low level winds decrease, leading to a variation of wind speed with height similar to that shown by the night time curve of Figure 3.

An Example of Complex Interdependence--Because of the interrelationships among turbulence, wind speed, and atmospheric stability and the additional complication introduced by surface roughness, the estimation of turbulent diffusion requires an intimate knowledge of the meteorological factors and the ability to achieve a physically logical synthesis of their several effects. Let us take, for example, an industrial plant located at the shore of a large lake and first consider the behavior of a smoke plume during the fall of the year when the water is warmer than the surrounding land. With an offshore wind at the plant and neutral stability there will be considerable turbulence arising from the surface roughness over land upwind from the plant. As the air flows over the warm lake surface it becomes unstable leading to increased turbulence and excellent diffusion. An onshore wind will also be unstable, with excellent turbulence which will decrease somewhat, however, with increasing distance inland.

In the spring the behavior of a smoke plume will be quite different. With an offshore wind and neutral stability the turbulent mixing at the plant will be good but as soon as the air moves over the cooler lake an inversion commences to develop upward from the surface with a consequent reduction of turbulent diffusion. The smoothness of the lake surface also contributes to the reduction. As a result the smoke plume may reach the opposite side of the lake in significant concentrations. An onshore wind will also have an inversion with poor diffusion at the plant. The warmer land with its greater surface roughness will convert the inversion to a neutral layer with improved diffusion as the air moves inland.

The analysis of practical problems in air pollution may involve evaluation of other complex factors of this nature. Some of these will be discussed in later sections.

Variation with Height--Much less is known about the variation of wind turbulence with height than is known about the variations of speed and direction. In general the friction layer is shallowest and turbulence decreases most rapidly with height over smooth terrain when an inversion and light winds occur together. Conversely, the friction layer and turbulence extend highest over rough terrain with strong winds, or when light winds and superadiabatic lapse rates occur together, a condition of thermal turbulence.

The Measurement of Wind Turbulence--Direct Method

There are, in general, two methods of measuring wind turbulence. Since the primary manifestation of turbulence is the fluctuation of wind speed and direction, measurements of such fluctuations may be referred to as the direct method. On the other hand, since the stability of the air as revealed by temperature lapse rate or other measurements exerts a controlling influence on turbulence, such measurements may be used and referred to as the indirect method. The direct method of determining wind turbulence may utilize measurements of the fluctuations of either wind speed or wind direction.

Direct Method--Wind Speed Fluctuation Measurements--The first direct measurements of wind turbulence on an industrial operational basis were made at the smelters of the Consolidated Mining and Smelting Company of Canada, Limited, at Trail, British Columbia.(70) Comprehensive studies were made of the relative merits of wind speed and wind direction variability as indicators of the rate of diffusion of stack effluents. These investigations showed relatively little difference between the two indicators, and the wind speed fluctuations were chosen as the turbulence indicator for operational requirements. The instrument developed for the purpose and known as a gust accelerometer consists essentially of a bridled cup anemometer, i.e., a cup anemometer bridled so as to restrict rotation to no more than 360°, in contrast to the ordinary cup anemometer which is free to rotate without limit. The sensor is a horizontal aluminum wheel mounted on a vertical shaft; around the outside of the wheel are 22 equally spaced vertical curved surfaces, each of which acts as a cup. The rotation of the wheel in the wind is constrained by two chains which wind or unwind on the vertical shaft and is linearized with wind speed by the systems of coiled springs under tension to which the chains are attached. Viewed from above, the bladed wheel rotates slowly counterclockwise when the wind speed is increasing, is motionless when the wind is steady, and rotates slowly clockwise when the wind speed diminishes. Each change of wind speed of 2 mph makes or breaks an electrical circuit. These makes and breaks are recorded and summed to give the average gust acceleration in miles per hour per hour for any desired time interval. A number of these gust accelerometers have been in use for direct turbulence measurements for periods of years and have given excellent service with a minimum of maintenance.

Ordinary cup anemometers of the type which record instantaneous wind speeds on a moving chart may also be used for direct turbulence measurements. One measure of turbulence known as the gustiness G has been defined as follows:

$$G = \left(\frac{\overline{V'^2}}{V^2}\right)^{1/2} \qquad (2)$$

where V' is the difference between the wind speed at any instant and the mean value V of the wind speed for the period and the bar signifies the mean value for the period, in this case the mean value of all the squared differences. Since in statistical usage the quantity $\left(\overline{V'^2}\right)^{1/2}$ is the standard deviation σ_V, Equation (2) may be written

$$G = \sigma_V/V \qquad (3)$$

A simpler but less representative measure of the gustiness has the form

$$G = (V_{max} - V_{min})/V \qquad (4)$$

where V_{max} and V_{min} are the maximum and minimum wind speeds recorded during the period.

Because of the inertia of the cups, cup anemometers of either the bridled or ordinary types tend to overestimate the mean wind speed and to underestimate the standard deviation of the fluctuations and both errors therefore combine to underestimate the true gustiness. The gustiness which is not measured is of the small scale type which is of limited significance in the process of large scale diffusion of a smoke plume so that the error introduced is not serious. The behavior of ordinary cup anemometers in gusty winds has been analyzed in detail.(58)

The propeller or windmill anemometer may be used in exactly the same manner as the ordinary cup anemometer for the direct measurement of wind turbulence. It is also subject to the same type of errors. The gust accelerometer has an advantage over these two instruments in that it records the average turbulence for a period as a number, the gust acceleration, whereas the gustiness must be calculated from values obtained from the chart record of a cup or windmill anemometer. The gust accelerometer is also readily adapted to record instantaneous wind speeds as well as gust accelerations. There are many other types of anemometers which could be used for direct turbulence measurements, but the instruments described have proven to be the most satisfactory for general use.

The requirements for exposure, mounting, and special precautions for direct turbulence indicators involving the measurement of fluctuating wind speeds are the same as those for wind vanes as described in an earlier section. Although no standard height for direct measurements of turbulence has been established, the standard

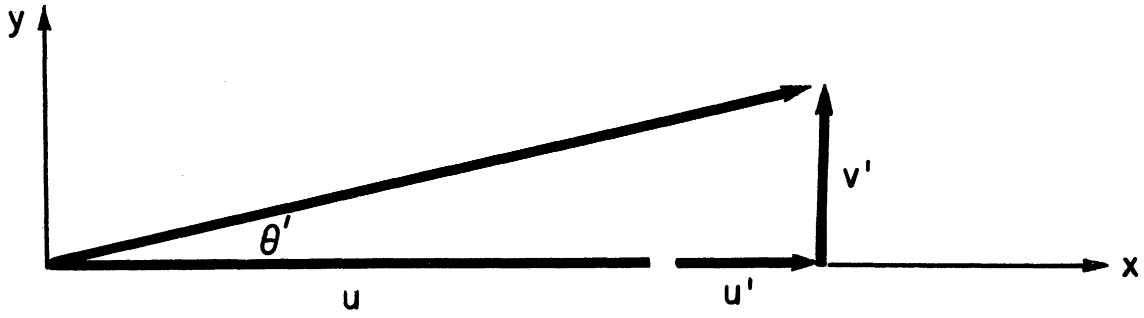


Figure 6. An instantaneous horizontal wind velocity vector as the sum of three components. The x axis is taken in the direction of the mean wind with speed u; the y axis is at right angles. Instantaneous deviations from the mean wind have speeds of u' and v' along the mean wind and across the mean wind, respectively.

height of 10 meters for wind speed and direction is convenient to use for turbulence also. In general, however, direct turbulence measurements should be made at a height as near as possible to that of the plume of effluent which is of concern. Lacking measurements at that level, extrapolation from measurements at a lower standard level may be attempted, using the general criteria for the variation of turbulence with height as set forth in the final paragraph of the preceding section and additional information in following sections. A mean value of the turbulence from the center line of the plume to the surface, the layer of maximum significance for ground concentrations, is sufficient for most purposes.

Direct Method--Wind Direction Fluctuation Measurements--

As indicated at the beginning of the previous section, wind direction fluctuation measurements have also been shown to be satisfactory indicators of wind turbulence. The fluctuations may be readily obtained from the chart trace made by a recording wind vane. For example, if θ' is the angular deviation of the wind direction at a given instant from the mean wind direction during a specified time interval, then the standard deviation σ_θ of the direction fluctions is given by $(\overline{\theta'^2})^{1/2}$, using the same conventions as in the preceding section. For an interpretation(11) of σ_θ, let us refer to Figure 6 in which the instantaneous horizontal component of the wind in the direction of the mean wind is made up of two parts, u, the mean wind speed and u' the instantaneous speed deviation from the mean wind in that direction, the instantaneous horizontal component of the wind at right angles to the mean wind is v', and the angle between the instantaneous wind velocity vector and the mean wind direction is θ'. We will define a horizontal across wind component of the gustiness as follows:

$$G_y = \left(\frac{\overline{v'^2}}{u^2}\right)^{1/2}$$

Now we see that, if θ' is small and $u' \ll u$,

$$\tan \theta' = \frac{v'}{u + u'} \approx \theta' \approx \frac{v'}{u}$$

so that

$$\sigma_\theta \approx \left(\frac{\overline{v'^2}}{u^2}\right)^{1/2} \approx G_y \qquad (5)$$

Thus the y - component of the gustiness is given directly to a first approximation as the standard deviation of the fluctuating wind direction about its mean.

The wind vane, using the same principle as the gust accelerometer, is readily adapted to give a direct measure of wind turbulence.(70) Each angular rotation of the vertical shaft holding the vane, of a specified amount, say 10°, is recorded and summed for a time interval to give directly a number proportional to the average turbulence for that period.

It is often advantageous to be able to measure directly the vertical component of wind turbulence. This is conveniently done by means of a bivane, a special type of wind vane which is free to swing vertically as well as horizontally.(100) A precision instrument of this type has been developed for use when very rapid response to wind direction fluctuations is required.(47) The vertical component of the gustiness G_z may be obtained from the standard deviation σ_φ of the elevation angle φ of the bivane about its mean position. Thus, by analogy with Equation (5) we have

$$G_z = \left(\frac{\overline{w'^2}}{u^2}\right)^{1/2} \approx \sigma_\varphi \qquad (6)$$

where w' is now the vertical component of the wind speed deviation from the mean wind. The values of G_y and G_z are generally quite similar except in inversions where $G_z < G_y$. The use of a bivane is recommended in air pollution investigations and analyses where the meteorological factors are expected to be of critical importance and therefore require special attention.

A counting bivane has been developed whose simplicity of operation makes it desirable for industrial air pollution investigations.(146,147) Ratchet mechanisms are attached to both the vertical and horizontal rotating shafts of the bivane. A light gear train is driven in one direction by the movements of the bivane through the action of a gentle friction clutch but prevented from moving in the other direction by the ratchet mechanism. Contacts are made for each 1000° of rotation of the shafts in one direction. A counter may be read at intervals or deflections in a chart trace may be read off directly, thus giving both the vertical and horizontal across wind components of wind turbulence. This bivane has given satisfactory service for years at the plants of the American Smelting and Refining Company near Salt Lake City, Utah.

The Measurement of Wind Turbulence--Indirect Method

The indirect method of measuring wind turbulence involves the determination, to a greater or lesser degree of accuracy, of the vertical stability of the lower layers of the atmosphere. Since turbulence, both mechanical and thermal, is largely controlled by vertical stability, a measurement of the prevailing lapse rate will permit an estimate of the turbulence. Although stability determinations are an indirect indicator of turbulence, the concept of atmospheric stability involves an assessment of temperature lapse rate and hence of turbulence within a layer; since diffusion occurs within layers this represents an advantage over the direct methods which determine turbulence only at the height of the sensor. There are considerable advantages in using the direct and indirect methods in conjunction, the direct method at one height and the indirect method to assist with vertical extrapolation.

Temperature Lapse Rate Measurements--If the variation of temperature with height is to be measured accurately enough to permit adequate estimates of stability, it is essential that the temperature sensing elements be located considerable vertical distances apart. There are two disadvantages to locating them close together:

(a) highly precise and expensive sensing and recording equipment are required to obtain temperature differences between nearby levels with the required accuracy; and

(b) a shallow layer only is being probed, and lapse rate conditions in this layer may not be representive of those in the greater layer in which diffusion takes place.

Since temperature differences rather than absolute values of temperatures are required, a method which measures temperature differences directly is to be preferred. One or more systems of differential thermocouples have proven to be highly satisfactory. It is convenient to have a reference junction which is at a practically constant temperature by burying it perhaps 6 meters in the ground where diurnal temperature variations are absent and annual ones very small. If temperature differences between several levels are to be measured, a stepping switch may be used to take the output from each pair of thermocouples in succession to a sensitive recording potentiometer. The lapse rate installation at the site of the Enrico Fermi Nuclear Power Plant at the west end of Lake Erie near Monroe, Michigan is of this type; using iron-constantan thermojunctions with an output of 50 microvolts per deg C and with a time constant of about 1 min, and a Bristol High-Speed Dynamaster Recorder with zero input at the center of the chart and a range of ± 500 microvolts, the system records temperature differences of ± 10 C with an accuracy of ± 0.1 C for three atmospheric layers in succession at 1-min intervals.(71)

To insure obtaining air-temperature differences to the required degree of accuracy it is essential that the temperature sensors measure the air temperature only. To prevent during light winds heating of the sensor by solar radiation during the day or cooling by terrestrial radiation at night it is necessary to protect each sensor by a radiation shield and to draw air past it at a steady rate. In the above installation a Spencer Turbo Exhauster housed at the base of the tower draws air over each thermojunction at a rate of about 4 m sec^{-1} (9 mph) through hose lines of 1 1/4-in. inside diameter connected to each radiation shield.

The temperature sensor with its radiation shield should be mounted at the end of a boom extending horizontally from the tower. Since the tower members may be heated by solar radiation or cooled by terrestrial radiation and thus may heat or cool the air flowing around them, the sensor and shield should be a horizontal distance from the nearest point of the tower which is at least as great as the largest horizontal dimension of the tower at that height in order to avoid nonrepresentative air temperature values.

NATURAL CLEANSING PROCESSES IN THE ATMOSPHERE

The manner and rate at which contaminants are removed from the atmosphere by natural processes is of obvious importance in the general problem of air pollution. Some of the natural cleansing processes are of more significance than others for the local problem of industrial air pollution. The four basic processes are as follows: rain-out; wash-out; gravitational settling; and turbulent impaction on surfaces.

Rain-Out

The term rain-out is defined as the air contaminant brought to the earth's surface by rain in which the contaminant has been collected by the cloud particles prior to their growth and descent as rain drops. This process has been analyzed by Greenfield(53) who finds that very small particles of diameter $d < 0.01\ \mu$ are collected by cloud drops by the combined action of Brownian motion and turbulent motion on the very small particles. If the effluent from a stack flows into air in which cloud is subsequently formed, the small particles may also act as nuclei on which condensation occurs. If the cloud produces rain at a later time these particles will be carried to the ground in the rain. However, only in unusual circumstances will significant amounts of contaminant be removed near the source and the process is therefore of limited significance for the industrial types of pollution under discussion here and will not be discussed further.

Wash-Out

The term wash-out refers to contaminants swept out and carried to the earth's surface by precipitation. This process has also been discussed in the paper by Greenfield mentioned above(53) and elsewhere.(105) The main results of the analyses are as follows. Effectively no particles with diameter $d < 1\mu$ are swept out by precipitation. According to Greenfield, approximately 8 per cent of the particles of diameter 2μ are scavenged by 2.5 mm of rain falling in 1 hour. The percentage removed increases rapidly with drop size thereafter; for the same rate of rainfall the percentage is 94 for particles 10μ in diameter. The rate of wash-out of SO_2 has also been calculated.(105) The corresponding removal of SO_2 for 2.5 mm of rain in 1 hour is approximately 45 per cent. These values have not been verified by experiments under natural atmospheric conditions, but should give the range of values to be expected. Wash-out will be referred to again in a later section.

Gravitational Settling

Gravitational settling is an important natural cleansing process mainly for larger particles. Spherical particles of diameter 20μ and specific gravity 2.5 have in still air, according to Stokes' Law, a settling speed of 3 cm sec^{-1}. For larger particles the settling speed increases rapidly with diameter, becoming 75 cm sec^{-1} for 100μ particles. For smaller particles the settling speed is so small as to be negligible in comparison with the speed of vertical currents in the atmosphere. For this reason, 20μ has often been taken as the lower limit of particle size for which gravitational settling is significant. A detailed discussion of the various factors involved in gravitational settling is available.(105)

A rough calculation of the distance at which large particles settle out is often sufficient for most purposes. For example, if the fall speed of 150μ particles is taken as 1 m sec^{-1} and if the wind speed is 10 m sec^{-1}, then the 150μ particles will reach the ground at a horizontal distance which is ten times the height of the source, e.g., at 1 km from a 100-m stack. Larger particles will land nearer the stack and smaller ones farther from it. A useful rule-of-thumb is that the maximum deposit of larger particles whose vertical motion is controlled primarily by gravitational settling will occur at a distance which is ten times the height of the stack. Modern precipitators, however, collect virtually all such larger particles before they leave the stack and the small particles present a more acute problem.

Turbulent Impaction on Surfaces

The particles smaller than 20μ have little motion relative to that of the plume of smoke in which they originate. Their history after leaving the stack is as follows. As they move with the wind they are distributed throughout the plume, both vertically and horizontally, by atmospheric turbulence. Some will be higher than the stack and others lower. If and when the plume reaches the ground some of the lowest particles will be deposited on surfaces by turbulent impaction. This may be visualized as a sort of centrifugal action of small swirling eddies by means of which the larger particles are deposited on branches and leaves of trees, blades of grass, etc. and the smaller particles on fine structures such as cobwebs and the delicate fibers of natural vegetation. Over surfaces there is a thin laminar sublayer of air, probably less than 1 mm in thickness, into which particles may be injected by the centrifugal action of turbulence. Brownian motion may then force the very fine particles into contact with a vertical surface, where they remain until washed off by rain. Over a horizontal surface both gravitational settling and Brownian motion may carry the fine particles down through the laminar sublayer and onto the underlying surface.

The final stages of removal of very small particles are obviously complex and have as yet received very little serious study and analysis.

METEOROLOGICAL INFLUENCES ON CHEMICAL REACTIONS IN THE ATMOSPHERE

Evidence is accumulating that meteorological elements may have a pronounced effect on the chemical composition of atmospheric contaminants.

Two processes have received attention: gas reactions with aerosols; and photochemical reactions in contaminants irradiated by sunlight.

Gas Reactions with Aerosols

Fundamental research in this area has been done on the mechanism of SO_2 oxidation in dilute catalytic solutions.(83) The fact that sulfate is a very common constituent of fog droplets has suggested that reactions of SO_2 with fog droplets in polluted atmospheres is a common occurrence. In the laboratory investigation SO_2 in very low concentration in dry air was bubbled through reagent solution: it was observed that the oxidation stops after a certain pH value is reached. For the same catalytic solutions the maximum SO_4^{--} formation is a linear function of the SO_2 partial pressure in the air.

This mechanism of SO_4^{--} formation can account for observed SO_4^{--} concentrations in fog and smog only if neutralizing cations in the aerosols or traces of NH_3 in the air are present. It is estimated that, in the presence of NH_3, the oxidation of the SO_2 is completed in 1 hour for fog droplets of 20μ diameter. Quantitative information has been provided for two representative atmospheric conditions: (1) for clean country air, $SO_2 = 20\ \gamma\ m^{-3}$ and $NH_3 = 3\ \gamma\ m^{-3}$; and (2) for highly polluted city air $SO_2 = 500\ \gamma\ m^{-3}$ and $NH_3 = 10\ \gamma\ m^{-3}$ ($\gamma = 10^{-6}$ gm). Using these values gives the variation of SO_4^{--} produced as a function of the liquid water content of the fog illustrated in Figure 7. The maximum amount of (SO_4^{--}) is produced as the liquid water content approaches infinity and is controlled by the $(NH_3)_0$ value. Using 0.1 gm m^{-3} as the average

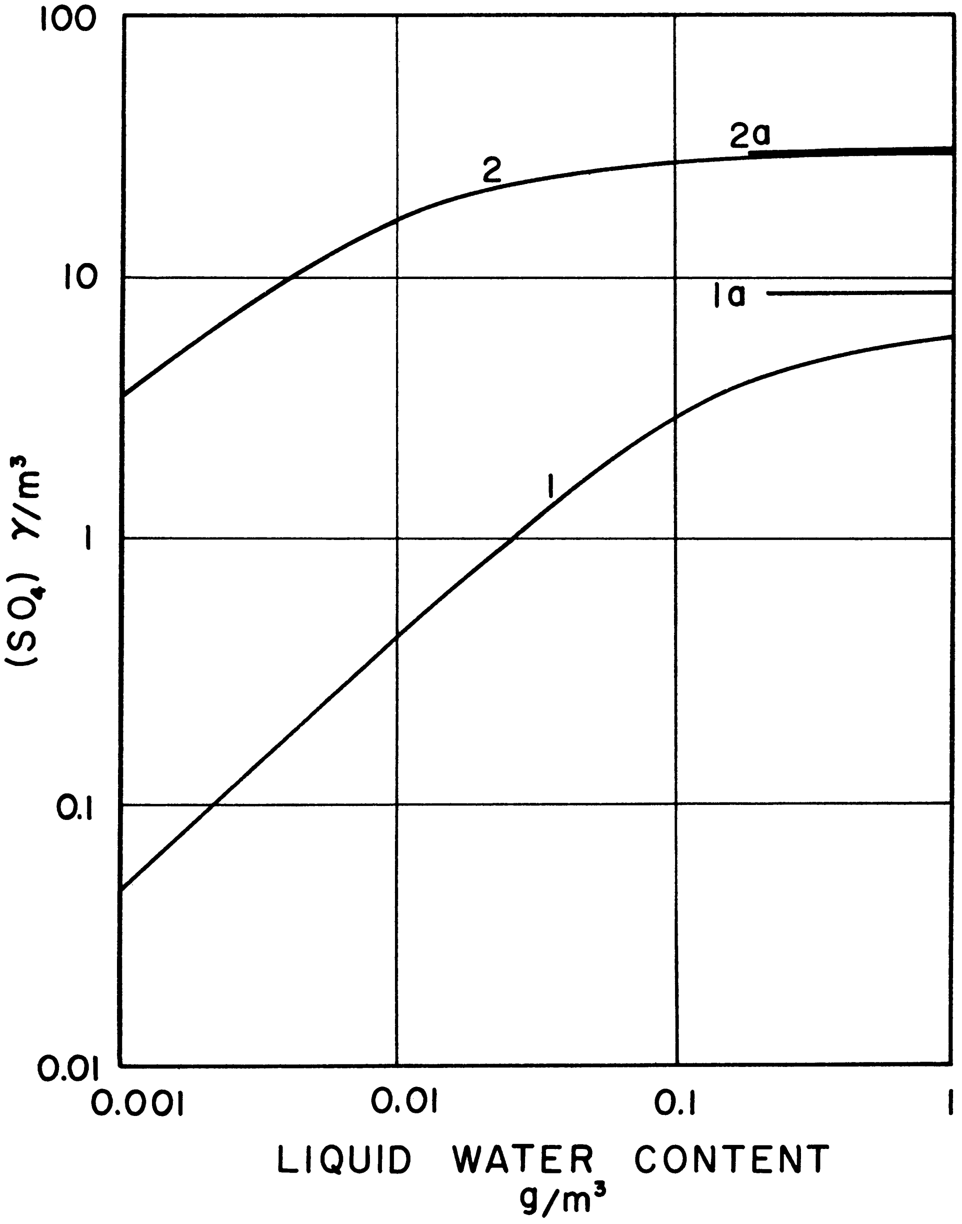


Figure 7. (SO_4^{--}) values shown as functions of the liquid water content of fog: in clean country air, 1; and in polluted city air, 2. The curves marked 1a and 2a give the maximum values for large liquid-water contents (after Junge and Ryan).

liquid water content of fogs, additional data for such fogs are presented in Table 1.

TABLE 1

$(NH_4)_2$ SO_4 FORMATION IN FOG WITH A LIQUID WATER CONTENT OF 0.1 gm m^{-3} (AFTER JUNGE AND RYAN)

	$(SO_2)_o$ (γm^{-3})	% SO_2 oxidized	(SO_4^{--}) (γm^{-3})	$(NH_3)_o$ (γm^{-3})	% NH_3 converted to $(NH_4)_2SO_4$	(NH_4^+) (γm^{-3})	pH
Country air	20	9.7	2.9	3	34	1.1	5.1
Polluted city air	500	3.5	26.2	10	98	10.4	4.5

Similar conclusions have been reached independently using droplets 300μ in diameter suspended on a glass fiber 15μ in diameter in an exposure chamber in which the equilibrium concentration of SO_2 corresponded to 20 to 200 p.p.m. at atmospheric pressure.(81) Assuming that a fog with a liquid water content of 0.2 gm m^{-3} consisting of droplets 20μ in diameter each formed on a 1μ crystal of Mn SO_4 exists in an atmosphere of 1 p.p.m of SO_2, then the estimated rate of oxidation of SO_2 is 1 per cent per minute, a rate which is nearly 500 times the rate of photochemical oxidation mentioned in the next section. The residual acid droplets formed by the catalytic reaction in fog are probably substantially larger than those formed by photochemical oxidation, which were only 0.2 to 0.4μ in diameter.

These studies raise the interesting possibility that dense aerosol formations in SO_2 polluted atmospheres may be substantially decreased, not only by reducing the emission of SO_2 but also by decreasing the amount of NH_3 and of good catalytic aerosols in the atmosphere. Since fogs over land mostly occur with light winds and stagnant atmospheric conditions when atmospheric diffusion of contaminants is very slow, gas reactions with aerosols of this type are likely to occur near the source. Because fog particles with a diameter of 20μ have a gravitational settling speed of about 1 m min^{-1}, this process could be effective in removing SO_2 from the atmosphere under very nonturbulent conditions. The further implications of these basic findings for industrial air pollution should be explored thoroughly.

Photochemical Reactions in Sunlight

Photochemical action by solar radiation on atmospheric contaminants is proving to be an important means by which the chemical composition of these contaminants may be changed. Two examples will be given: photochemical action on sulfur dioxide and on hydrocarbons.

Photochemical Oxidation of Sulfur Dioxide in Air

The reaction rate of photochemical oxidation of SO_2 in air mentioned above is slow, about 0.1 to 0.2 per cent conversion per hour in intense natural sunlight in SO_2 concentrations of 5 to 30 p.p.m.(43) The reaction rate was not influenced by the presence of NaCl nuclei or of NO_2 or by changes in the relative humidity in the range from 30 to 90 per cent. The sulfuric acid aerosol produced was very small, varying from 0.2 to 0.4μ in diameter.

It is estimated that air containing 1.0 p.p.m. of SO_2 would have to be exposed to bright sunlight for 100 hours in order to reduce the visibility to one mile. Thus the process is unlikely to be of primary importance in fog or smog formation.

Photochemical Oxidation of Hydrocarbons in Air

Photochemical oxidation of hydrocarbons has been studied mainly in connection with the Los Angeles smog problem,(55,91) but may be important also near individual industries such as chemical processing plants. Most organic compounds are not readily oxidized when completely pure but in the presence of other substances may be oxidized by sunlight. Most hydrocarbons do not have absorption bands in the wave length spectrum of sunlight for a direct photochemical reaction. Similar reactions may occur in an indirect way when a substance is present which absorbs the light energy and subsequently transfers it to the hydrocarbon and oxidizes it. In polluted atmospheres nitrogen dioxide functions as an oxidation catalyst in this way. Nitrogen dioxide absorbs solar radiation strongly from the near ultraviolet through the blue part of the spectrum and is dissociated into atomic oxygen and nitric oxide. The atomic oxygen may react with molecular oxygen to form ozone; atomic oxygen may also remove hydrogen from a hydrocarbon, with the formation of an alkyl radical. Reactions between nitric oxide and alkyl and alkylperoxy radicals may occur. Direct combination of photochemically produced nitric oxide and peroxy radical leads to the formation of a peracylnitrite.(56)

It has been found that eye irritation produced by photochemical changes in polluted atmospheres does not require the full intensity of solar radiation characteristic of the latitude of Los Angeles.(123) Careful laboratory studies in controlled polluted atmospheres have shown that the degree of eye irritation (slight, moderate, or heavy) is dependent upon the intensity of light only up to a certain point--namely, two-thirds the intensity of direct sunshine. In other words, it takes only two-thirds the intensity of natural direct sunlight to produce heavy eye irritation. This significant finding carries the implication that industrial communities at higher latitudes where solar radiation may be less intense than at Los Angeles have a potential eye irritation problem and that this problem may become severe in the vicinity of chemical process industries especially unless preventive action is taken.

The Measurement of Solar Radiation

It will be clear from the foregoing that the intensity of solar radiation may be an important factor in determining the composition of air contaminants, and that it may be desirable to measure this intensity on a regular basis. A very complete discussion of the various instruments for measuring the intensity of solar radiation is available, including details of installation, calculation of corrections, maintenance, calibration, accuracy, and sources of error.(59) These instruments are known by various names, of which the most common are actinometers, solarimeters, and pyrheliometers. The operating principles and characteristics of several types are described briefly below.

Bimetallic Thermometer Principle--In this instrument two bimetal strips are mounted side by side under a glass hemispherical dome. One strip is coated with a dull black material which absorbs solar radiation. The other strip has a reflective coating and is further protected from the sun's rays by shielding. Thus the sun heats the black strip but not the other. The differential motion of the strips is transmitted to a pen which draws a trace on a drum driven by clockwork.(35) The instrument is relatively inexpensive and requires no power supply and under optimum conditions will give an accuracy of ± 5 per cent.

Thermopile Principle--A well established instrument employing this principle is the Eppley pyrheliometer. In this the sunshine passes through a 3-in. sealed glass bulb and falls on two concentric silver rings, the inner being coated with lamp black and the outer cold ring being coated with reflective magnesium oxide. Either 10 or 50 thermocouple junctions form the thermopile, the output of which may be taken to a millivolt recorder.

Null Thermopile Instrument--The Angstrom pyrheliometer employs the null principle. The rate of absorption of heat by a blackened metal strip which is exposed to the sun's rays is determined by measuring the electric current necessary to heat a similar shielded strip to the same temperature. Thermocouples attached to the backs of the strips form the thermopile which enables their temperatures to be equalized as shown by no current passing through a galvanometer. Both the thermopile and null thermopile types are relatively accurate but also expensive.

Precautions--In all types the covering glass dome must be kept clean for satisfactory results. In heavily polluted atmospheres frequent cleaning is therefore necessary. With the bimetallic type the blackened strip must be dusted at intervals and occasionally recoated with fresh blackening material; the inside of the glass dome must also be kept clean. Snow must also, of course, be removed.

TOPOGRAPHY IN RELATION TO AIR FLOW AND ATMOSPHERIC DIFFUSION

The meteorology of a region is so greatly influenced by the local topography that the two must be considered together. Most industrial plants require a substantial water supply and tend to be located in a river valley or near the shoreline of a large body of water. The behavior of slope winds, valley winds, canyon winds, and shoreline winds will therefore be briefly discussed.

Slope Winds

As the name implies, slope winds are those which form over slopes. For simplicity it will be assumed that the slope lies between an extensive plateau above and an extensive plain below.

Wind Speed and Direction Over a Slope

Slope winds tend to vary primarily with the time of day, amount of cloud cover, steepness and roughness of the slope, and season of the year.

Slope Winds at Night--Slope winds are most pronounced when the general wind over a region is light. With clear skies at night the surface of the earth, including the slope, loses heat by long-wave terrestrial radiation to the higher atmosphere and outer space and consequently cools. There is therefore a flow of heat from the air just above to the surface resulting in a cooling of this air. The amount of this air cooling decreases with height, becoming effectively zero at higher levels. Thus the air just above the slope becomes cooler and denser than the air at the same height near the center of the valley which, being some distance above the valley floor, is cooled very little. These local density differences lead to local pressure differences which cause the dense surface air to flow down the slope in a shallow layer known as the downslope wind.

Slope Winds During the Day--As the morning advances the heat gained by the surface from solar radiation exceeds that lost by terrestrial radiation and the soil temperature rises, warming the air just above. The density of the air over the slope decreases relative to that of the air at the same level near the center of the valley. The resulting pressure differences may cause the air to flow up the slope as an upslope wind. If the solar heating of the ground is strong enough to cause a large unstable lapse rate there may be vertical motion of unstable parcels of air which leads to a deeper layer of upslope flow but with a much smaller surface upslope speed than the corresponding downslope speed. The upslope wind is observed much less frequently than the downslope wind.(30)

Other Influences on Slope Winds--Cloud reduces both the loss of heat by terrestrial radiation from the surface and the gain of heat by solar radiation by it, so that both downslope and upslope winds are lighter with cloudy skies. The speed attained by slope winds is related to the degree of slope of the surface over which they occur and its roughness: over average slopes they are a few meters per second but may be much stronger over unobstructed steep slopes. Over a tree covered slope they will be light or absent. There is a seasonal difference as well: in winter the downslope winds are stronger and upslope winds are light or absent, especially on snow covered or north facing slopes.

The above discussion is based on the assumption that a large scale prevailing wind is light or absent. If there is a prevailing wind over the region, the air flow over the slope will be approximated by the vector sum of the prevailing and slope winds.

Wind Turbulence Over a Slope

The presence or absence of slopes has relatively little direct effect on turbulence, which is governed mainly by degree of surface roughness and atmospheric stability and instability.

Valley Winds

Valley winds are defined as those which move up or down the main axis of a valley. Slope winds may occur over isolated slopes and without any connection with valley winds. Slope winds are always, however, an essential part of valley winds. The initial stages of development of valley winds are shown diagramatically in Figure 8 for the simple case of a uniform valley and no regional prevailing wind.

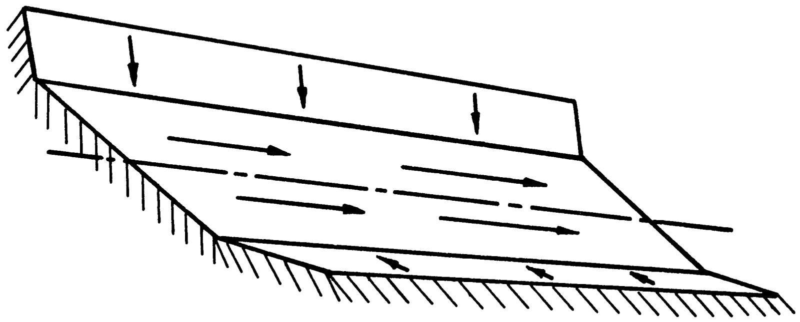
Wind Speed and Direction in a Valley

As with slope winds, the behavior of valley winds depends on the time of day, amount of cloud present, slope and roughness of the valley floor, season of the year, and strength of the prevailing wind.

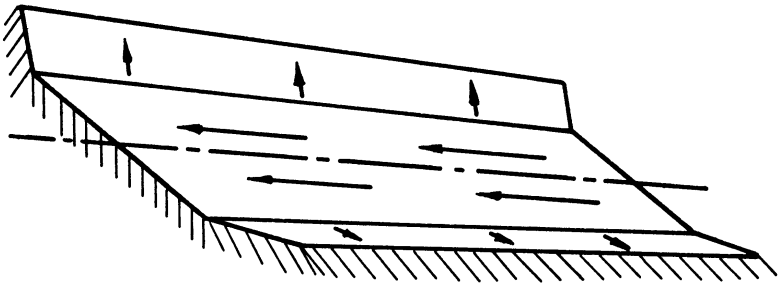
Valley Winds at Night--On a night with clear skies the surface air in the valley is cooled by the ground, and since the valley floor has a slope as well as the valley sides the dense surface air commences to flow downvalley after sunset. At the same time slope winds flow down the two valley sides and converge on the valley floor, augmenting and reinforcing the downvalley wind. Figure 8 illustrates the initial phase only: later in the night the downslope winds on the valley sides develope a downvalley component as the river of cold air flowing down the valley rises higher and higher and finally reaches the tops of the valley sides.

Valley Winds During the Day--On a clear day solar heating of the valley sides and floor may cause, by the reverse of the physical process described above, an upvalley wind as shown in Figure 8. In general, the upvalley wind is weaker and less likely to occur than the downvalley wind.

Other Influences on Valley Winds--As in the case of slope winds, cloudy skies will reduce the gain of heat by the ground during the day and the loss of heat at night, so that valley winds are light if they are present at all. The strength of valley winds tends to vary directly with the slope of the valley floor and inversely with the vegetative



NIGHT



DAY

Figure 8. Initial stages of development of downvalley winds at night and upvalley winds during the day.

coverage of the valley floor and sides. A heavily treed valley will be less subject to radiational heating and cooling, which will minimize valley winds; the trees will also serve to obstruct the air flow. Downvalley winds are stronger and more persistent in winter than in summer, especially in a snow covered valley. In such conditions true upvalley winds in winter are rare or entirely absent.

Again it has been assumed for simplicity that no regional wind exists over the valley. Such a regional wind will enhance or reduce the valley wind, depending on the direction of the former. It should be emphasized, however, that unless a valley is very broad and shallow, a regional crossvalley wind will not cause a crossvalley wind in the lower portions of the valley: in general, the low level valley wind is either downvalley or upvalley.

Observed Valley Winds--It is instructive to see how the above general description corresponds with the results of a comprehensive field investigation of valley winds. In one such investigation approximately one thousand sets of pilot balloon observations of valley winds were made at successive 2-hour intervals in the Columbia River Valley near Trail, British Columbia, Canada, during portions of the summers of 1938, 1939, and 1940 in the course of an extensive survey of air pollution in the valley.(70) At the point of observation the valley runs in a north-south direction, descending to the south; the valley floor there is about a mile wide, about 1500 feet above msl, and the sides of the valley extend up to heights of 4000 to 4500 feet above msl. Figure 9 presents a slightly smoothed analysis of the average

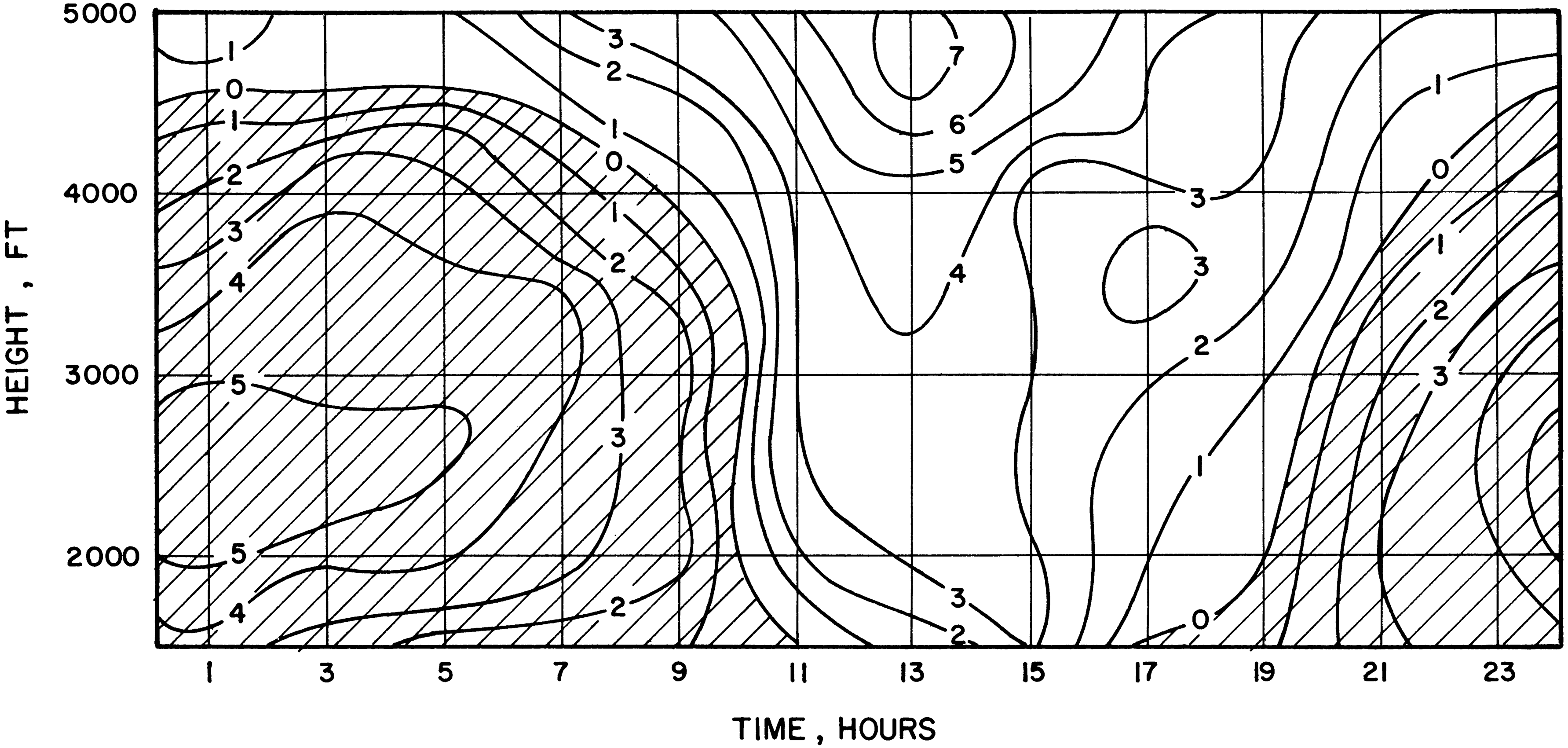


Figure 9. The diurnal variation of valley winds during the summer in the Columbia River valley near Trail, B. C. Isopleths give average wind speed components in mph. Hatched areas: downvalley (north) wind components. Unhatched areas: upvalley (south) wind components (after Hewson and Longley).

daily downvalley and upvalley wind pattern.(73) It will be noted that the prevailing wind above the valley, from 4000-4500 up to 5000 feet above msl, had an upvalley (south) component throughout the day with maximum wind components of 7 mph in the early afternoon, at 13 h. In the valley itself the average wind is downvalley until 10 h, although at higher levels the downvalley flow ceases earlier than this. From 10 h to 17 h the wind is up the valley. By 17 h the sun is no longer heating the valley floor and radiational cooling has commenced, as indicated by the beginning of a downvalley flow at that time. As the cool slope winds descend from the valley sides causing an increase in density at greater and greater heights, the wind gradually shifts with height from up to down the valley until by midnight all the air in the valley is moving downvalley. Similar analyses were made for the cross-valley(east-west) wind components.(70, 73)

Wind Turbulence in a Valley

Minimum turbulence tends to occur in a valley at the same time as downvalley winds since both conditions are related to the pronounced stability associated with radiational cooling of the ground on clear nights. During the day the sun heats the valley floor and sides and thus the valley air may become unstable and highly turbulent as it slowly ascends the valley as an upvalley wind. Thus diffusion tends to be slow in downvalley winds and rapid in upvalley winds.

Local Winds in Complex Valleys

For a simple and uniform valley it is relatively straightforward to predict the occurrence of downvalley and upvalley winds in the absence of a pronounced prevailing wind over the area. It is more difficult to assess the influence of a regional prevailing wind on the air flow in a valley. In a complex valley system which meanders and has slopes and tributary canyons at odd angles a field program of wind measurements both at the surface and aloft is necessary to gain information on the detailed structure of the complicated winds.(70)

Canyon Winds

The diurnal wind systems in canyons with a large slope and steep sides are much more regular than those in broad valleys with a valley floor having a small slope. The downcanyon and upcanyon winds measured during October, 1938 at the surface of a small canyon extending upward to the east from the Columbia River Valley near Trail, B. C. are shown in Figure 10.(70,73) Downcanyon winds (NE-E-SE) occur nearly every night all night; upcanyon winds (SW-W-NW) occur during the day with somewhat less regularity. Such canyon winds may complicate the air flow in the main valley into which the canyon leads.

Shoreline Winds

Shoreline winds are formed in much the same manner as valley winds, as a result of differential heating and cooling of a land surface with respect to an adjacent body of water.

Wind Speed and Direction Near a Shoreline

The characteristics of shoreline winds vary with the time of day, amount of cloud, roughness of terrain bordering the water, season of the year, and strength of the prevailing wind.

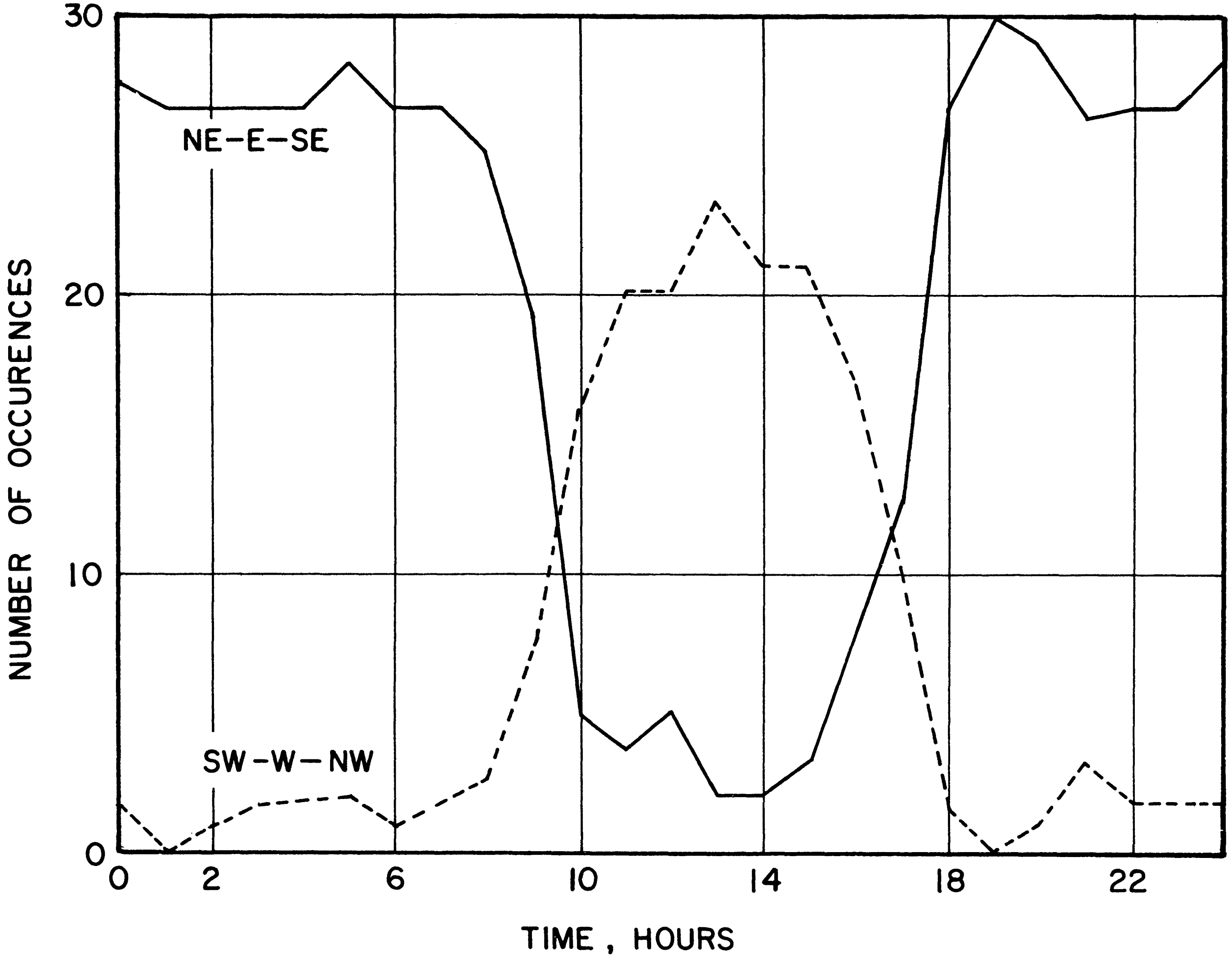


Figure 10. Number of occurrences during October 1938 of downcanyon winds (NE-E-SE) and of upcanyon winds (SW-W-NW) in a canyon descending westward to the Columbia River Valley near Trail, B. C. (after Hewson and Longley).

Shoreline Winds During the Day--On a clear summer day a ground surface and the air just above is much more strongly heated by the sun than is an adjacent body of water and the air above it. The air over the land becomes less dense than that over the water and the local pressure over the land decreases, leading to the development of an onshore wind known as a sea breeze or lake breeze. This breeze will be pronounced only if the regional prevailing wind is light or absent. By 11 h, just before noon, the onshore breeze is blowing perpendicular to the shoreline in the idealized case shown in Figure 11. As the breeze freshens and brings in air from farther out over the water, the deflecting force of the earth's rotation, often referred to as the Coriolis force, becomes significant and causes the wind to veer, perhaps from south at 11 h to southwest at 14 h. The wind speed and the Coriolis force continue to increase, with the result that by late afternoon, perhaps 17 h, the wind is west, i.e., parallel to the shoreline. Thereafter as the radiational heat loss becomes greater than the radiational gain from the setting sun, the sea or lake breeze dies away.

Shoreline Winds at Night--An offshore wind known as the land breeze will develop during a clear night with a negligible prevailing regional wind, but in general its speed and persistence are much less than those of the sea or lake breeze. As a result the land breeze is less influenced by the Coriolis force and it tends to blow perpendicular to the shoreline as illustrated in Figure 11, although it may veer slightly during the night.

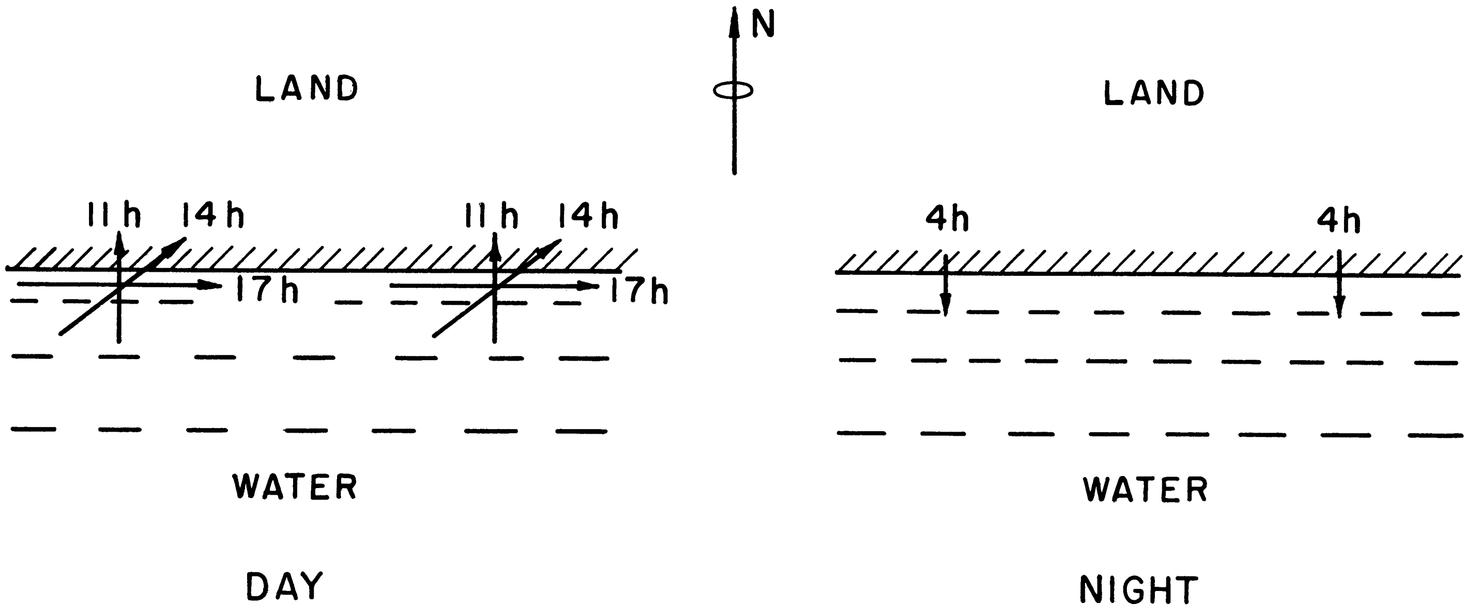


Figure 11. Idealized sketch of typical shoreline winds: onshore sea or lake breeze during the day and offshore land breeze at night. Wind speed is proportional to length of arrows.

Other Influences on Shoreline Winds--The wind behavior described above is most nearly characteristic of long straight flat coastlines in clear summer weather. On cloudy summer days or during the winter solar heating of the land is less and these breezes are lighter or absent entirely. A pronounced regional wind field along the shoreline acts mainly to modify the wind speed and direction slightly. For example, if in Figure 11 there is a regional south wind of 14 mph at 11 h, the wind by 17 h may be 19 mph from the south southwest. Over a lake, unless it is very large and has long stretches of straight shoreline, the local wind pattern is much more complex and requires detailed study.

It must be emphasized that pronounced lake and land breeze regimes are found only near large bodies of water. Shoreline effects near lakes having dimensions of a few miles only are small and relatively unimportant in the analysis of industrial air pollution problems.

Observed Shoreline Winds--Measurements of lake and land breezes have been made at the site of the Encrico Fermi Nuclear Power Plant which is located, as was mentioned earlier, close to the shoreline at the west end of Lake Erie near Monroe, Michigan.(72) Tower measurements of the lapse rate between 25 and 100 feet showed that there were 23 days in June and July, 1957 with afternoon inversions arising from the flow of warm air over the relatively cold water whose presence was attributed to a lake breeze. Since the shoreline of Lake Erie runs nearly southwest-northeast in the vicinity of the plant site, winds from ESE, SE, and SSE were taken to be lake breezes and winds from W, WNW, and NW were considered as land breezes. Figure 12 shows the precentage frequency of occurrence

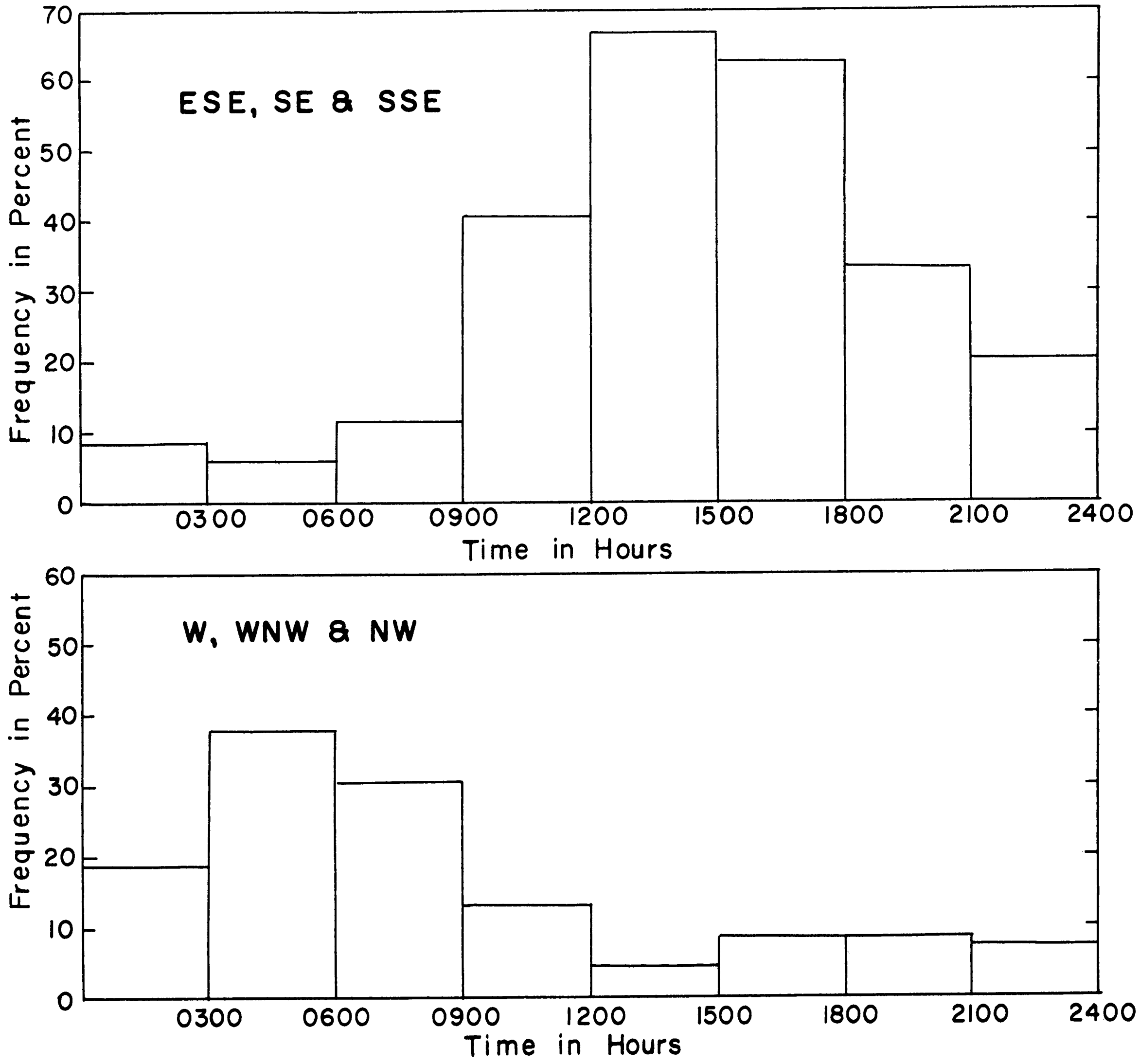


Figure 12. Diurnal variation of shoreline winds on 23 selected days in June and July 1957 as measured at 102 ft at the site of the Enrico Fermi Nuclear Power Plant at the west end of Lake Erie near Monroe, Michigan. Above: percentage frequency of occurrence of lake breezes, from ESE, SE, and SSE. Below: percentage frequency of occurrence of land breezes, from W, WNW, and NW (after Hawson, Gill, and Baynton).

of winds from these two sectors. The maximum occurrence of lake breezes, from 12 to 18 h, was between 60 and 70 per cent, whereas the maximum occurrence of land breezes, from 3 to 9 h, was between 30 and 40 per cent. On the average, the prevailing regional wind was light and its direction was such as to reinforce the lake breeze effect; under these circumstances the combination of the two influences led to an onshore breeze during the afternoon which averaged about 10 mph.

Wind Turbulence Near a Shoreline

There are marked variations, both in time and space of wind turbulence near a shoreline. Only the most general cases will be discussed here. During the spring and summer lake or sea breeze air approaching a shoreline may have, owing to the relatively low temperature of the underlying water, a surface inversion layer in which turbulence and diffusion are a minimum. As this air crosses the shoreline and advances over the warm land, however, the inversion is rapidly destroyed and replaced by a layer of air with a superadiabatic lapse rate and associated active thermal turbulence and diffusion, as illustrated in the upper portion of Figure 13. If in addition the terrain beyond the shore is rough the diffusion will be further increased by mechanical turbulence superimposed on the thermal turbulence. The sequence for the land breeze is the same in those seasons, as shown in the lower part of Figure 13, even though the wind is in the opposite direction. The air leaving the land has a surface inversion with very limited turbulence and diffusion but these develop rapidly over the water as a large lapse rate develops upward from the surface.

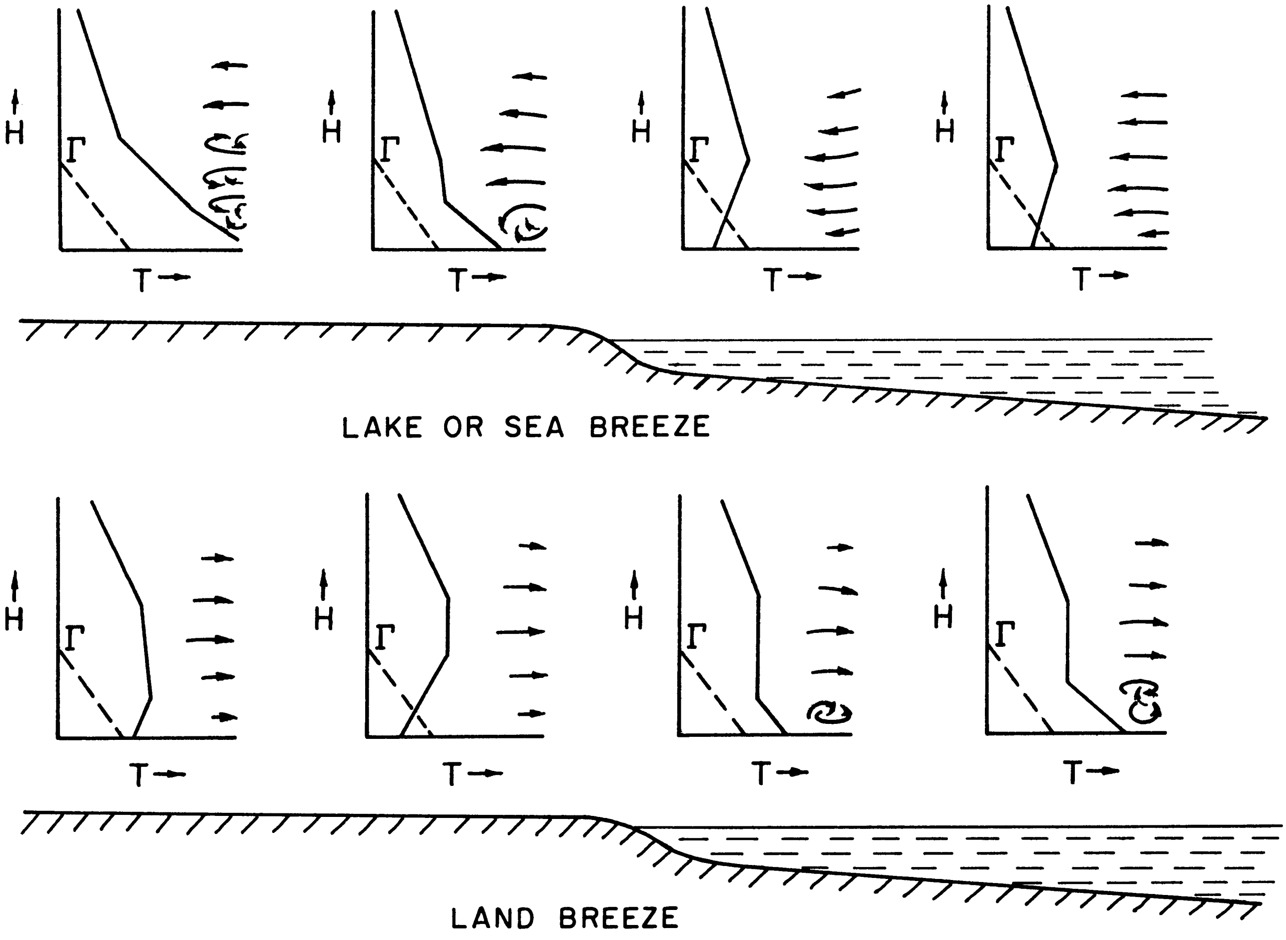


Figure 13. Variations of lapse rate and stability — and associated atmospheric turbulence and diffusion with time, distance from shoreline, and height as a lake or sea breeze (above) or a land breeze (below) advances across a shoreline. Wind speeds are proportional to lengths of arrows. The dry adiabatic rate of cooling Γ (10 C km^{-1}) is represented by the broken line in each temperature-height diagram.

At a shoreline plant site the preponderance of inversions in spring and summer may occur with lake or sea breeze types of winds. The frequency of occurrance of noninversions and inversions and the variation of wind speed with wind direction at the Enrico Fermi plant site in the spring (March, April, May) of 1957 are displayed in Figure 14.(72) It will be noted that inversions occur most frequently with onshore winds which were initially warm before crossing the cold lake from the SSW, S, SSE, and SE. Onshore winds from the ESE, E, and ENE are not of the lake breeze type but are regional winds and have few inversions but many noninversions because the air coming over the lake from these directions tends to be cooler than the lake. These latter winds are therefore relatively unstable with marked turbulence and good diffusion.

It must be emphasized that the seasonal turbulent characteristics of winds from various directions depend on the location of a shoreline plant relative to a large lake or the sea. With the principles described above it will be possible to estimate the local lake and land breeze regime for each location and the diffusing characteristics of the winds, both local and regional.

Local Winds Near Complex Shorelines

The above type of analysis is readily applied to long, straight, flat shorelines. If, however, the shoreline is highly irregular with substantial bays and points the analysis is more difficult and the desirability of a local program of meteorological measurements should be considered. When the terrain along an irregular shoreline is rough

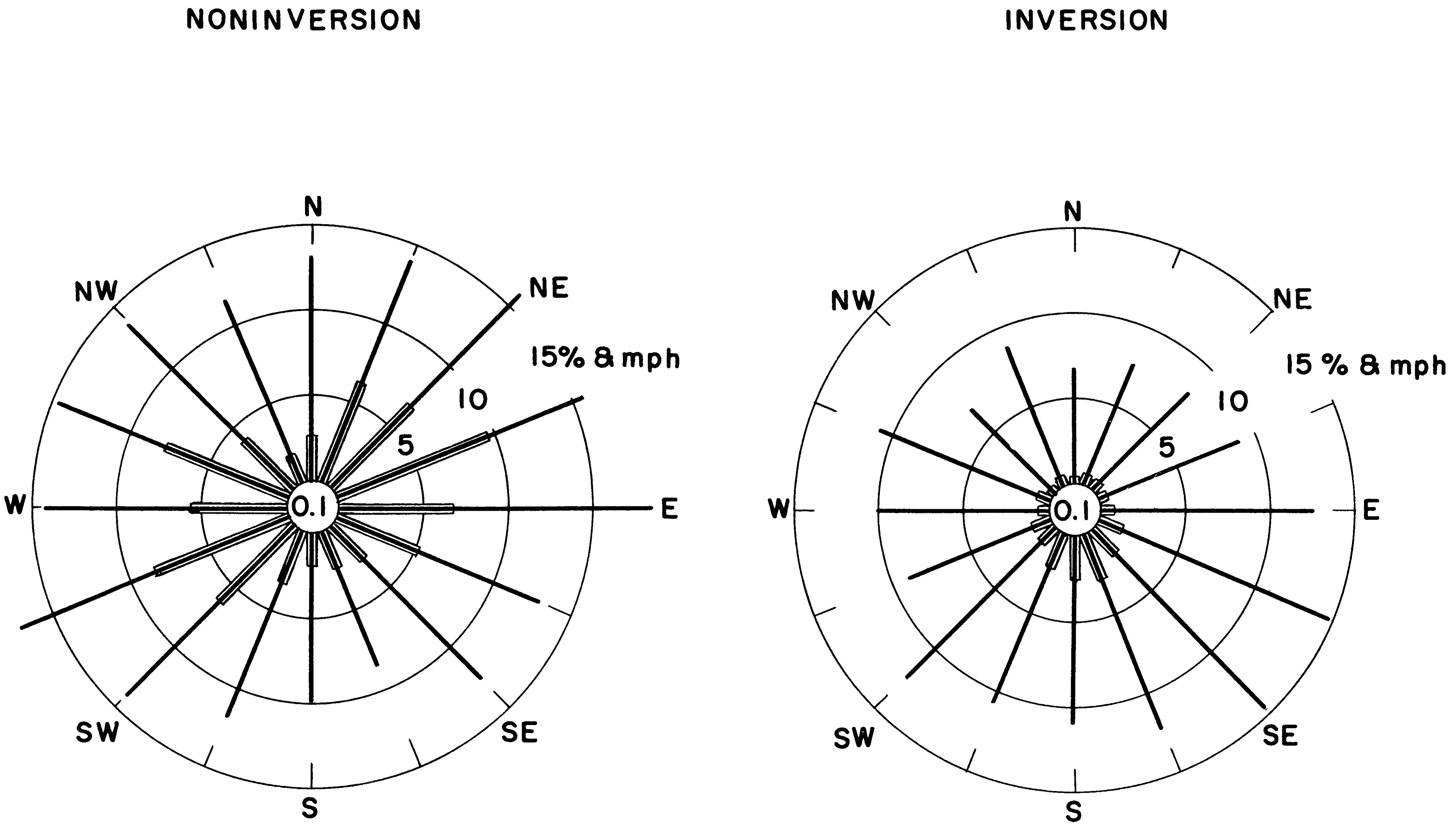


Figure 14. Percentage frequency of occurrence between 25 and 100 ft of inversions and noninversions (double lines) associated with winds at 102 ft from sixteen directions and corresponding wind speeds in miles per hour (single lines) during the spring (March, April, May) of 1957 at the site of the Enrico Fermi Nuclear Power Plant at the west end of Lake Erie near Monroe, Michigan; center figures give percentage of calm conditions (after Hewson, Gill, and Baynton).

so that the air flow is further complicated by local slope and valley effects an adequate analysis cannot be made without local meteorological measurements.

THE EFFECTIVE STACK HEIGHT

Since much industrial air pollution is caused by stack effluents, a detailed discussion of the behavior of these effluents is in order. Only in special circumstances will the height of the axis of the smoke plume some distance away from a stack be the same as the height of the stack itself. The height of the horizontal axis of a smoke plume emitted from a stack is known as the effective stack height.

Both stack gases released with a high exit velocity and those with a positive buoyancy resulting from high initial temperature will have an effective stack height which is greater than the actual stack height. On the other hand, aerodynamic downwash induced by nearby buildings or by the stack itself may occur and result in an effective stack height which is lower than that produced by buoyancy and jet action alone; evaporative cooling of a stack effluent containing small water droplets may also lead to a lowered effective stack height.

The Influence of Exit Gas Velocity and Temperature

These two influences may be discussed separately but for convenience they will be examined together. A great deal of theoretical analysis of the effects of exit velocity and temperature on plume rise has been published.(below*) However, there are not yet enough experimental data available to permit an adequate assessment of these various theories and only the more promising and immediately applicable approaches will be discussed here.

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* Ref. 28, 109-112, 116-117, 120-121, 124-125, 143.

Plume Stages and Virtual Sources

For purposes of analysis the motion and behavior of a typical plume have been divided into four stages,(116,124) three of which with their virtual point sources are illustrated in Figure 15.

Stage 1: An initial vertical stage occurs as the smoke leaves the stack as a jet; the virtual point source for this stage lies on the vertical axis of the stack and below its orifice.

Stage 2: In the next phase the plume is bent over by the wind, with the assumption that the horizontal component of the effluent velocity in the bent-over plume is equal to the existing wind velocity; the mixing with the surrounding air in this phase is due to turbulence created by the bent-over jet in the shear zone around it and is independent of the existing natural atmospheric turbulence.(116)

Stage 3: At the beginning of the third phase there are still some buoyancy and upward motion but the velocity of the plume has become effectively that of the surrounding air so that the shear zone disappears and the residual buoyancy and vertical motion are reduced to negligible values at the end of the stage by mixing at a rate which is controlled by the intensity of the natural environmental turbulence;(116) the virtual origin for the second and third stages is at the height of the stack orifice but upwind from it.

Stage 4: In the final stage the plume moves passively with the wind and is subject only to diffusion by atmospheric turbulence, the plume axis being horizontal; the virtual origin for this stage, the highest of the three shown in Figure 15, lies on this horizontal passive-plume

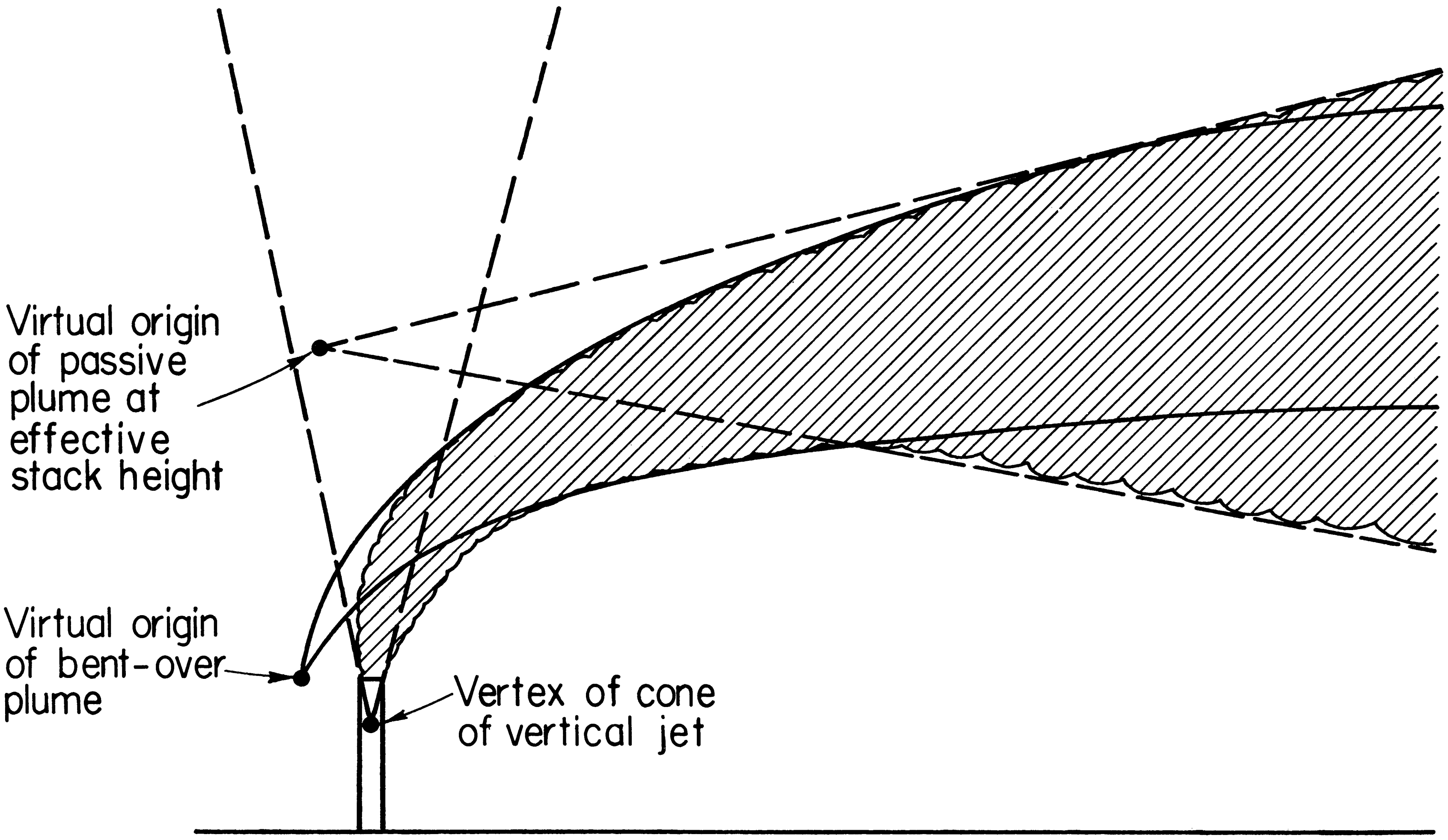

Figure 15. Stages in the development of a smoke plume from a stack, from the initial buoyant vertical jet through the bent-over plume phases, to the final stage of a passive plume with horizontal axis which is influenced only by the characteristics of the natural wind; the corresponding virtual origins are also shown (after Scorer).

axis but upwind from the plume and is at the effective stack height.(124)

Calculation of the Effective Stack Height for a Buoyant Jet Plume

The method of determining effective stack height developed by Bosanquet(15,13) is relatively simple to use and appears to give sufficient accuracy for most purposes, although the limited observations available for testing theory suggest that Bosanquet's equation underestimates heights by 15-20 per cent. The effective stack height h_e is given by the equation

$$h_e = h + B\,u\left[\,f_I(a) + f_{II}(a_o) - 0.615 a_o^{\frac{1}{2}}\left(\frac{W^2}{u^2} + 0.57\right)^{-\frac{1}{2}}\,\right] \tag{7}$$

where h is actual stack height;

u is average wind speed;

W is stack gas exit velocity;

$B = 9.42\ gQ\theta/Tu^4$;

g is acceleration of gravity;

Q is volume of effluent per unit time if effluent density is adjusted to be equal to atmospheric density at absolute temperature T;

T is as defined by Q above;

$T + \theta$ is actual exit temperature of effluent;

$a = (t + t_o)/B$;

$a_o = t_o/B$;

t is time elapsed since the effluent left the stack;

$t_o = 4WT/3g\theta$;

$t + t_o$ has a maximum value of 200 sec;

$Buf_I(a)$ is height of rise of hot stack gas above virtual origin within stack;

$Buf_{II}(a_o)$ is additional rise due to exit velocity and dilution of stack effluent with surrounding atmosphere;

$0.615\, Bua_o^{\frac{1}{2}}\left(\frac{W^2}{u^2} + 0.57\right)^{-\frac{1}{2}}$ is vertical distance from virtual origin to top of stack;

$f_I(a)$ is a function related to buoyant rise whose value is given in Table II; and

$f_{II}(a_o)$ is a function related to jet action rise whose value is given by Table III.

In these tables A is a number introduced so that the tables cover all values of a and a_o from 10^{-3} to 10^4; the value of a or a_o is the product of A and the number at the head of the column.

In nearly calm conditions the values of a and a_o are small and may be below the range of the tables. For such very small values:

$$f_I(a) = 1.054\, a^{3/4}; \text{ and}$$

$$f_{II}(a_o) = -0.527\, a_o^{3/4} .$$

For very large values of a and a_o:

$$f_I(a) = \ln a - 0.12; \text{ and}$$

$$f_{II}(a_o) = 1.311\, a_o^{\frac{1}{2}} - \tfrac{1}{2}\ln a_o - 1.$$

The method gives the combined effects of buoyancy and exit velocity. The two effects cannot be separated since a large exit velocity causes an initially rapid rate of mixing and dilution which reduces the thermal effects. At very low wind speeds an increase of emission velocity may actually decrease the total rise.

TABLE II

VALUES OF FUNCTION $f_I(a)$ FOR BUOYANT PLUME RISE
(AFTER BOSANQUET)

A	$\frac{a}{A} = 10^{-3}$	10^{-2}	10^{-1}	1	10	100	1000
1.0	0.0059	0.0323	0.170	0.767	2.33	4.50	6.79
1.2	0.0067	0.0370	0.193	0.852	2.49	4.68	6.97
1.4	0.0075	0.0414	0.215	0.930	2.64	4.83	7.13
1.6	0.0083	0.0456	0.235	1.00	2.75	4.97	7.26
1.8	0.0091	0.0497	0.255	1.07	2.86	5.08	7.38
2.0	0.0098	0.0537	0.274	1.13	2.95	5.19	7.48
2.5	0.0116	0.0632	0.319	1.27	3.16	5.41	7.71
3.0	0.0133	0.0721	0.360	1.39	3.33	5.59	7.89
3.5	0.0149	0.0806	0.398	1.50	3.48	5.74	8.04
4.0	0.0164	0.0887	0.434	1.59	3.61	5.88	8.18
4.5	0.0179	0.0965	0.469	1.68	3.72	5.99	8.29
5	0.0194	0.104	0.501	1.76	3.82	6.10	8.40
6	0.0222	0.119	0.562	1.90	4.00	6.28	8.58
7	0.0249	0.132	0.619	2.03	4.15	6.43	8.74
8	0.0274	0.145	0.671	2.14	4.28	6.57	8.87
9	0.0299	0.158	0.720	2.24	4.40	6.69	8.99
10	0.0323	0.170	0.767	2.33	4.50	6.79	9.09

TABLE III

VALUES OF FUNCTION $f_{II}(a_o)$ FOR JET ACTION PLUME RISE

(AFTER BOSANQUET)

A	$\frac{a_o}{A} = 10^{-3}$	10^{-2}	10^{-1}	1	10	100	1000
1.0	-0.0028	-0.0138	-0.044	0.155	1.99	9.9	37.0
1.2	-0.0032	-0.0156	-0.045	0.212	2.28	11.1	40.9
1.4	-0.0036	-0.0172	-0.046	0.269	2.58	12.2	44.5
1.6	-0.0039	-0.0186	-0.046	0.325	2.88	13.2	47.8
1.8	-0.0043	-0.0200	-0.045	0.380	3.15	14.1	50.9
2.0	-0.0046	-0.0213	-0.043	0.43	3.41	15.0	53.8
2.5	-0.0054	-0.0242	-0.037	0.56	4.01	17.1	60.6
3.0	-0.0061	-0.0268	-0.030	0.69	4.56	19.0	66.8
3.5	-0.0068	-0.0291	-0.020	0.80	5.07	20.7	72.4
4.0	-0.0075	-0.0312	-0.010	0.91	5.54	22.3	77.7
4.5	-0.0081	-0.0331	0.002	1.02	6.00	23.9	82.6
5	-0.0087	-0.0347	0.014	1.12	6.43	25.3	87.4
6	-0.0099	-0.0375	0.041	1.32	7.24	28.0	96.1
7	-0.0110	-0.040	0.068	1.50	7.98	30.5	104.1
8	-0.0120	-0.042	0.096	1.67	8.68	32.8	111.6
9	-0.0129	-0.043	0.125	1.84	9.33	35.0	118.6
10	-0.0138	-0.044	0.155	1.99	9.95	37.0	125.3

Illustrative Example of Calculation of Effective Stack Height

Problem--The effluent rate from a 100-meter stack is 100 $m^3 sec^{-1}$ leaving the stack with a velocity of 10 m sec^{-1}. If the wind speed is 5 m sec^{-1}, the temperature of the waste gas if adjusted to have atmospheric density is 300K, and the actual exit temperature is 420K, calculate the effective stack height.

Solution--$B = 9.42\ gQ\theta/Tu^4$

$= 9.42 \times 9.81 \times 100 \times 120/300 \times 5^4$

$= 5.91$ sec

$t_o = 4WT/3g\theta$

$= 4 \times 10 \times 300/3 \times 9.81 \times 120$

$= 3.40$ sec

Let $t + t_o = 200$ sec, the maximum value.

(i) $a = (t + t_o)/B = 200/5.91 = 33.8$

$a = 33.8 = 3.38 \times 10 = A \times 10$,

so that $a/A = 10$ (Col. 6 in Table II)

From Col. 1 and Col. 6 of Table II:

For $A = 3.0$ and $a/A = 10$, $f_I(a) = 3.33$; and

For $A = 3.5$ and $a/A = 10$, $f_I(a) = 3.48$

Thus by linear interpolation, for $A = 3.38$, $f_I(a) = 3.44$

(ii) $a_o = t_o/B = 3.40/5.91 = 0.575$

$a_o = 0.575 = 5.75 \times 10^{-1} = A \times 10^{-1}$,

so that $a_o/A = 10^{-1}$ (Col. 4 in Table III)

From Col. 1 and Col. 4 of Table III;

For $A = 5$ and $a_o/A = 10^{-1}$, $f_{II}(a_o) = +0.014$; and

For $A = 6$ and $a_o/A = 10^{-1}$, $f_{II}(a_o) = +0.041$

Thus by linear interpolation, for $A = 5.75$, $f_{II}(a_o) = 0.034$

(iii) $0.615\ a_o^{\frac{1}{2}}\left(\frac{W^2}{u^2} + 0.57\right)^{-\frac{1}{2}} = 0.615 \times (0.575)^{\frac{1}{2}}\left(\frac{10^2}{5^2} + 0.57\right)^{-\frac{1}{2}} = 0.218$

Hence

$$h_e = 100 + 5.91 \times 5\ (3.44 + 0.034 - 0.218) = 196 \text{ meters}$$

Observed Values of Effective Stack Height

A limited number of observations of effective stack height have been made and comparisons with various theories undertaken.(below*)

A Comparison of Observations with Theory--A number of observations of the effective stack height near the 61-m stack of the BEPO nuclear reactor at Harwell, England have been made.(139) This stack discharges warm air containing a small amount of radioactive argon A^{41}. The effective stack height of the plume is found to depend on the wind speed and on the vertical temperature gradient, having an average value of 125 m for a wind speed of 7 m sec^{-1} and a temperature lapse rate of 10 C km^{-1}, the dry adiabatic value. A comparison of the observed effective stack heights for three wind speed ranges with calculated values based on Bosanquet's theory is shown in Figure 16. It will be noted that the theory underestimates the plume rise, especially in the wind speed range from 5.5 to 8.5 m sec^{-1}.

A Balloon Method for Estimating Effective Stack Height--Zero-lift balloons made of laminated terylene and polythene and filled with hydrogen or helium have been inserted at the base of a stack and carried up and into the atmosphere by the stack gases. By tracking the subsequent flight of the balloons it has been possible to estimate effective stack heights at distances where plumes are generally no longer visible.(98)

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* Ref. 2, 16, 78, 104, 116, 139.

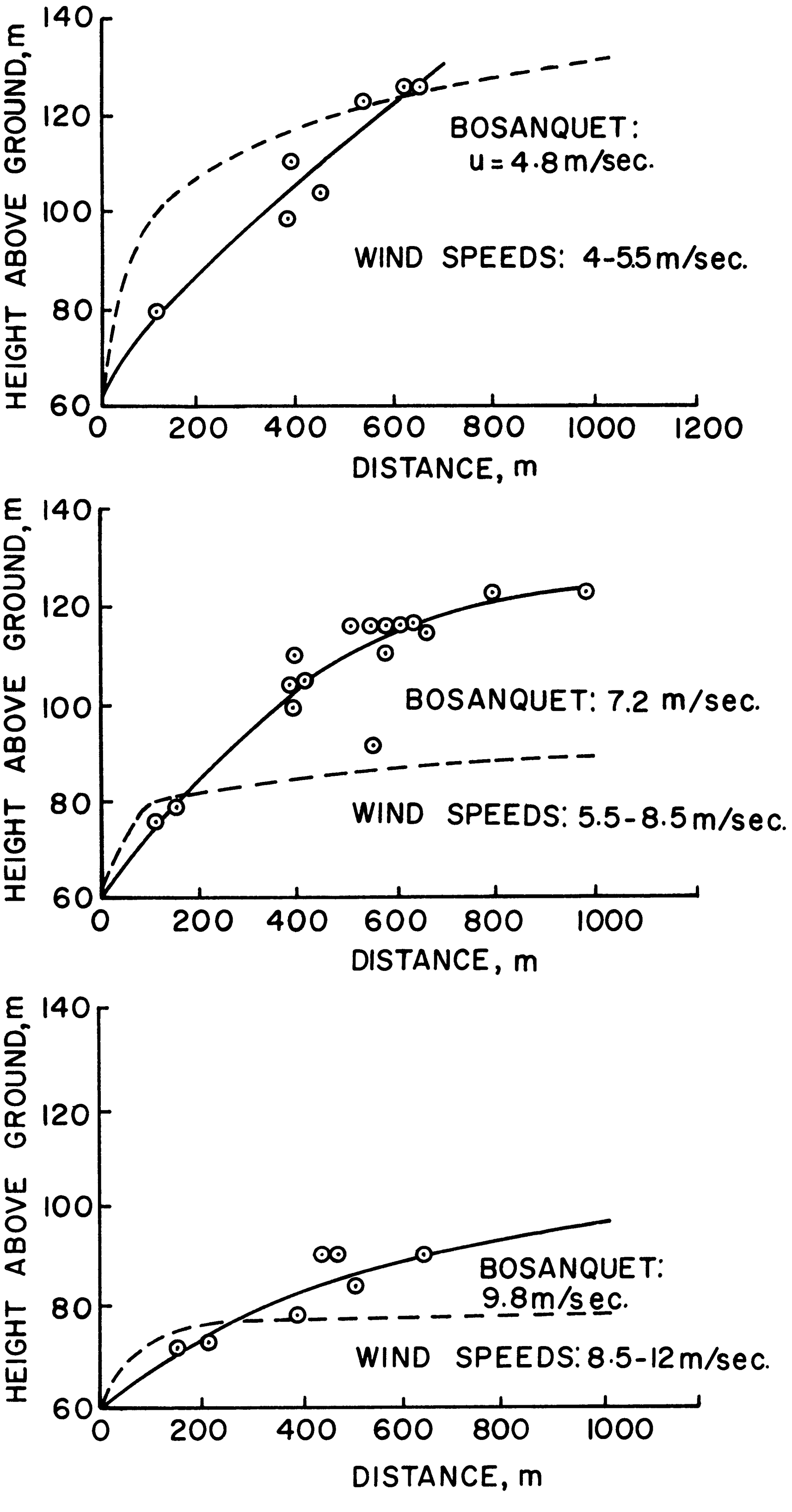


Figure 16. Comparison of observed effective stack heights near the 61-m stack of the BEPO nuclear reactor at Harwell, England with calculated values based on Bosanquet's theory (after Stewart, Gale, and Crooks).

The method requires a high degree of refinement in the experimental techniques used if seriously erroneous estimates are to be avoided. Before employing the results obtained, the adequacy of the experimental procedures should be checked thoroughly by ascertaining that the balloon stays within the plume when meteorological conditions are such that the smoke plume remains visible for considerable distances downwind from the stack. Observations at night may be made by attaching a small flashlight bulb and battery to the balloon.

The Influence of Aerodynamic Downwash on Effective Stack Height

The effect of aerodynamic downwash is to lower the effective stack height, as has been shown by wind-tunnel model studies.(130,131) Downwash may occur as the result of one or both of two processes. In the first, vortices known as Karman vortices may form just in the lee of the stack near its top; unless the exit velocity of the smoke is high, it may be drawn downward by the low pressure in these vortices. An effluent-colored stain around the upper portion of a stack suggests that downwash of this kind may be of relatively frequent occurrence. The second type occurs when the stack is situated on or near a large building; the plume may descend in large eddies formed in the lee of the building as the air flows over and around it.

Effective Stack Height Near a Large Plant Building

Aerodynamic downwash near a plant building occurs when the wind speed exceeds certain critical values. This critical speed varies with the aerodynamic properties of the building, with the location of the stack relative to the building, with the direction of the wind, and with the stack gas effluent velocity, and is conveniently evaluated by means of wind-tunnel model studies of the type illustrated in Figure 17.(128,129) The downwash is more pronounced when the wind approaches the building diagonally, as shown in Figure 17, than for any other direction. A typical variation of downwash with wind direction is shown in Figure 18. For a building height of 40 m and a stack height of 80 m, the curves give critical ratios of stack gas exit speed to wind speed required to maintain the base of the plume at heights of 30 m, 45 m, 60 m, and 75 m. To maintain the height of the base of the plume at 60 m, the wind tunnel studies summarized in Figure 18 show that for a southwest wind (direction 11), which is one approaching the plant building diagonally, the critical velocity ratio is 3.4, whereas for a wind parallel to the line of stacks, i.e., from the west (direction 13), the critical velocity ratio is only 1.9. These ratios are converted to critical wind speeds in the following manner. In comparisons involving the momentum of stack and model effluents the difference in density should be allowed for. For example, if the temperature of the stack effluent is 394 K and its exit velocity is 25 m $\sec^{-1}$, the equivalent stack velocity for the temperature 294 K of the model plume is given by

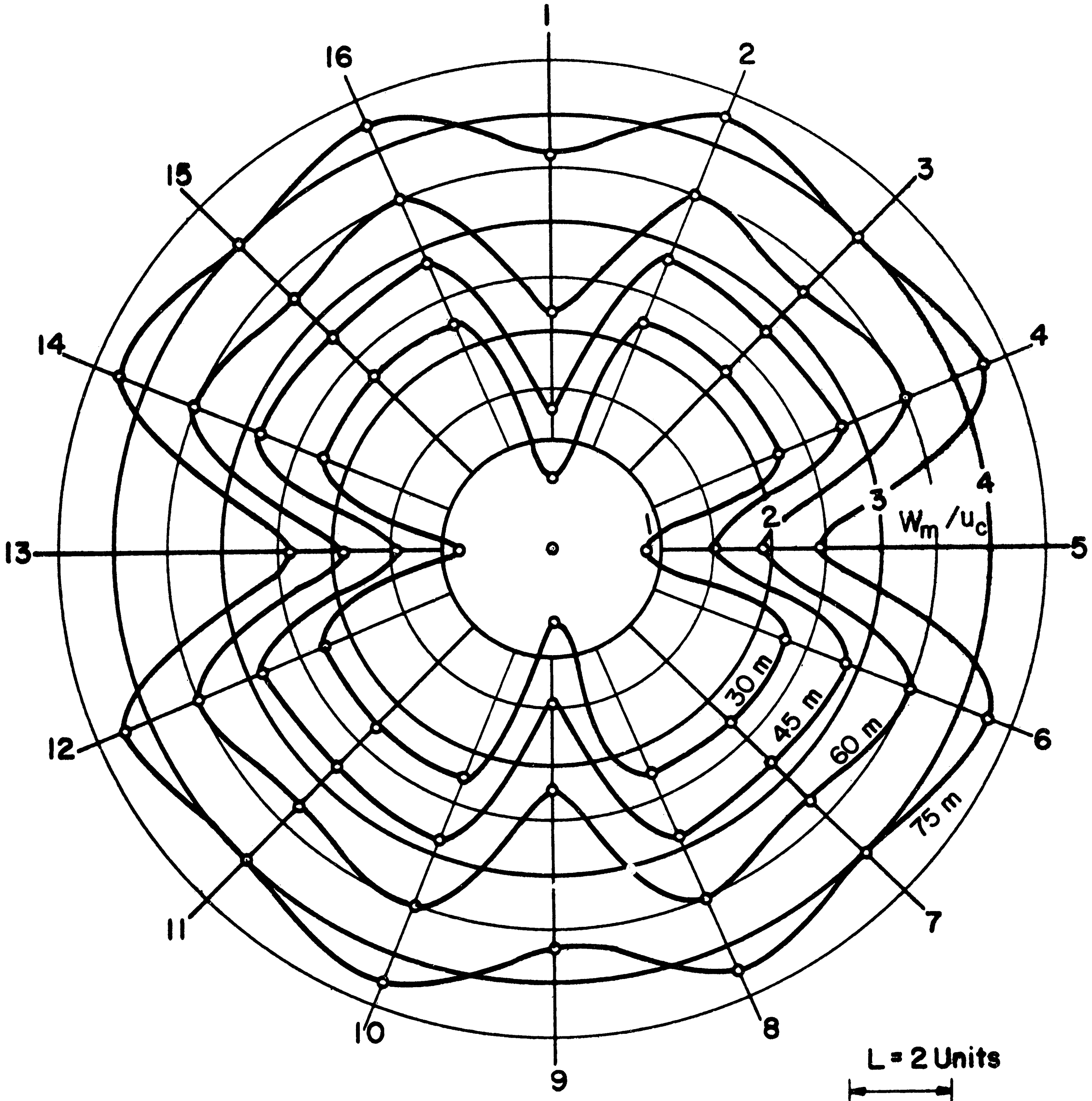
$$W_m = 25 \times 294/394 = 18.7 \text{ m sec}^{-1}$$

Thus the critical wind speeds u_c which must be exceeded if aerodynamic downwash is to bring the base of the plume lower than 60 m are:

For southwest wind (direction 11) $u_c = 18.7/3.4 = 5.5$ m $\sec^{-1}$

For west wind (direction 13) $u_c = 18.7/1.9 = 9.8$ m $\sec^{-1}$

Figure 17. Wind-tunnel model studies illustrating the aerodynamic downwash which occurs when the wind approaches the plant building and line of stacks diagonally (after Sherlock and Lesher).



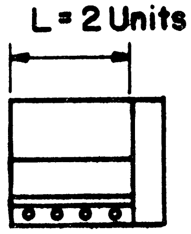


Figure 18. Data obtained from wind-tunnel studies of aerodynamic downwash in the vicinity of a hypothetical model plant. The polar diagram gives critical ratios of model stack gas exit velocity W_m to critical wind velocity u_c required to maintain the base of the model plume at heights, corrected for scale, of 30, 45, 60, and 75 m as a function of wind direction. The stack height h is 80 m and the building height H is 40 m (after Sherlock and Lesher).

It should be noted that these are the critical wind speeds at which the base of the plume descends to 60 m; the effective stack height is then obtained by adding one-half of the vertical diameter of the plume. It has been found from an inspection of a large number of photographs of the plume in the wind tunnel of the type shown in Figure 17 that, at a distance of several stack heights downwind from the source, the vertical diameter of the plume, adjusted for scale, was 76 m. Thus the effective stack height for these critical wind speeds is 98 m.

It should be emphasized that Figure 18 may be used to obtain the critical velocity ratios only when the plant building and stacks stand on level terrain and have the approximate shape and location indicated in Figure 18. For unusual terrain or a markedly different plant and stack configuration, a wind-tunnel study is required.

Frequency of Occurrence of Aeordynamic Downwash

The annual frequency of occurrence of downwash in any direction from a plant, planned or already existing, may readily be calculated from wind speed and direction records for a number of years.(127) A 5-year record from a nearby United States Weather Bureau Station, where the differences in terrain and topography between weather station and plant site are so small that the wind regimes are essentially the same at both locations, has been found satisfactory. A shorter record, although less reliable, will nevertheless yield valuable information.

The method used in brief form is as follows: The local Climatic Summary published by the United States Weather Bureau gives the frequency of occurrence of winds from each direction according to wind speed intervals.* The data for each required wind direction are plotted on a graph having as ordinate hourly average wind speed and as abscissa the per cent of annual hours with a wind speed equal to or greater than a given value indicated by the ordinate, and a Pearson Type III curve fitted to the plotted points. Taking the example in the previous section, the graph (not shown) for southwest winds (direction 11) indicates that southwest winds equal to or greater than 5.5 m sec^{-1} occurred on 4.2 per cent of the 8760 hours of the year, i.e., on 368 hours. Similarly, the graph (not shown) for west winds (direction 13) indicates that west winds equal to or greater than 9.8 m sec^{-1} occurred on 0.57 per cent of the 8760 hours of the year, i.e., on 50 hours.

Thus with southwest winds the effective stack height will be equal to or less than 98 m for 368 hours during the year, whereas for west winds it will be equal to or less than 98 m for only 50 hours.

Again, it should be noted that, if plant and stack arrangement differ much from that shown in Figure 18 or if the terrain is not level, wind tunnel studies using models of the plant and nearby terrain are required to obtain reliable values for the critical velocity ratios. If the frequency of occurrence of downwash must be determined but there is some question about the applicability of existing nearby wind data, it may be necessary to take wind observations at the plant site for comparison with the long-term record. A comparison of simultaneous

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* More detailed analyses of the wind records, as by season of the year or by time of day, may be obtained for a nominal charge by writing to: Director, Office of Climatology, United States Weather Bureau, Washington, D.C.

winds at each station for a year is desirable, but continuous measurements for one month in each of the four seasons may prove to be adequate.

The Influence of Evaporative Cooling of the Plume on Effective Stack Height

When stack effluents are wet washed before emission in order to remove gases, such as SO_2, the air becomes saturated and in the process its temperature is lowered to the wet-bulb temperature of the air before the washing took place. If after leaving the wet washing stage but before release to the atmosphere the stack gases are cooled by contact with and conduction of heat to relatively cold surfaces, either liquid or solid, condensation of some of the saturated water vapor occurs to form small water droplets which become part of the effluent leaving the stack. As this effluent leaves the stack and mixes with surrounding drier air the water droplets will evaporate and the plume will cool as the required latent heat of vaporization is removed from the air.(124)

The mass of liquid water per unit mass of dry air in the effluent as it leaves the stack orifice is readily obtained from the upper scale of Figure 19, which gives the number of grams of saturated water vapor mixed with one kilogram of dry air at the temperature shown on the horizontal scale just below. Thus if the initial wet-bulb temperature of the stack gases approaching the wet washing stage is 60 C, the air leaving this stage is saturated at 60 C and contains 155 gm of water vapor per kgm of dry air. If subsequent cooling reduces the temperature of the gases to 30 C, they will contain 27.6 gm of water vapor per kgm of dry air, the difference between 155 and 27.6 gm kgm^{-1}, or 127.4 gm kgm^{-1} having

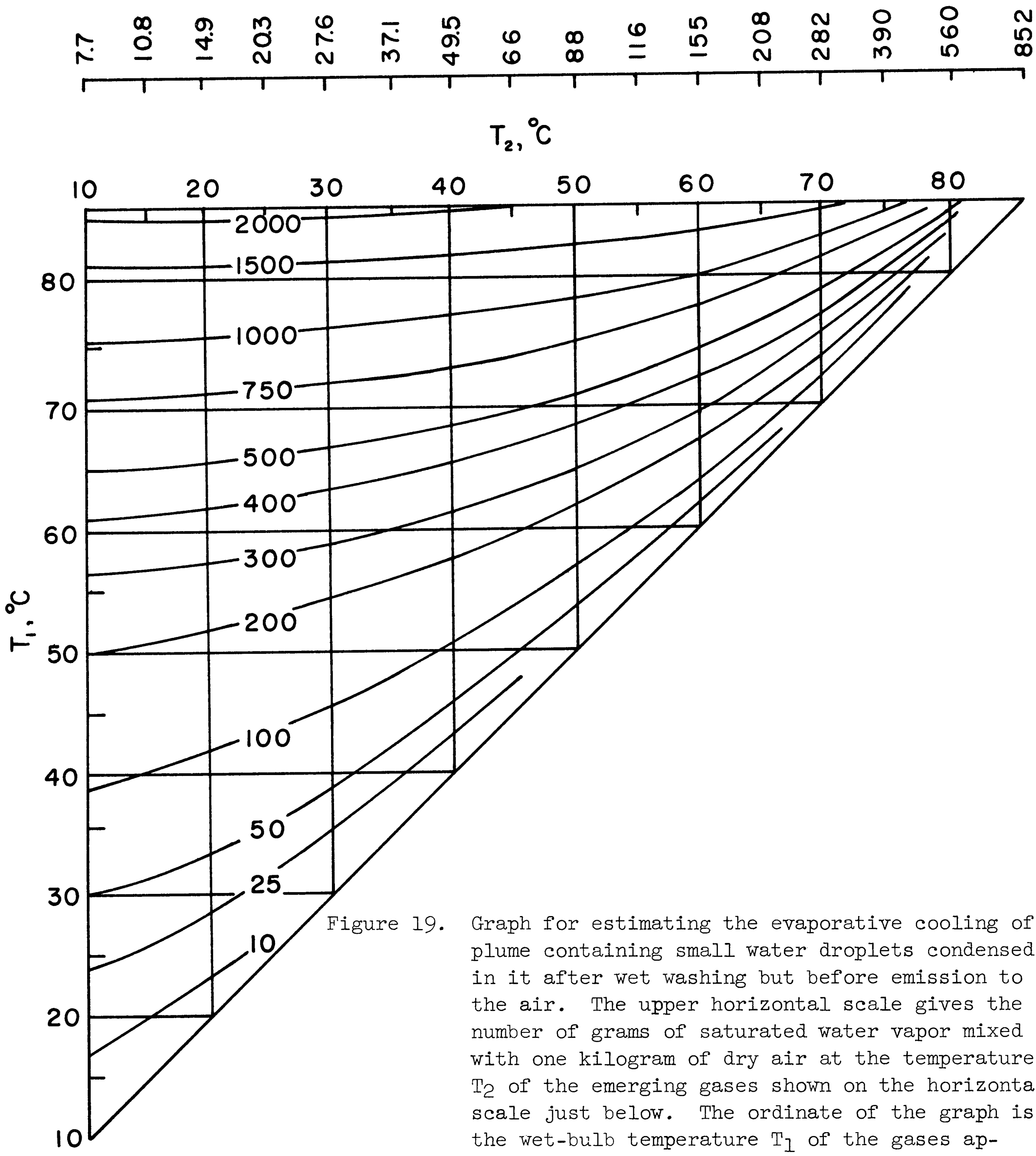


Figure 19. Graph for estimating the evaporative cooling of a plume containing small water droplets condensed in it after wet washing but before emission to the air. The upper horizontal scale gives the number of grams of saturated water vapor mixed with one kilogram of dry air at the temperature T_2 of the emerging gases shown on the horizontal scale just below. The ordinate of the graph is the wet-bulb temperature T_1 of the gases approaching the wet washing stage which is also the actual temperature of the saturated air leaving the wet washing stage. The curved isopleths give the evaporative cooling in C assuming immediate and complete cooling upon emergence from the stack. Complete evaporative cooling occurs only after considerable dilution of the plume with surrounding drier air, however, so that the isopleth numbers could be taken more realistically to indicate the factor by which the effluents must be diluted for them to cool by 1 C owing to evaporation of the small water droplete initially in the plume (after Scorer).

condensed into very small water droplets, most of which emerge from the stack.

The lower portion of Figure 19 gives approximately the evaporational cooling of the plume if all the water droplets evaporated immediately upon emerging from the stack. The ordinate scale is for the wet-bulb temperature in C of the stack gases approaching wet washing, which is the actual temperature of the gases just after wet washing; the abscissa is for the temperature in C of the effluent just as it leaves the stack. The curved isopleths give the evaporative cooling in C assuming immediate and complete cooling upon emergence from the stack. Using the temperatures given above, 60 C and 30 C, the instantaneous evaporative cooling is seen to be about 320 C from the graph. However, the cooling does not occur instantaneously, but slowly as the initially saturated plume mixes with surrounding drier air. If the evaporation is complete after each unit volume of the emerging plume has mixed with 100 unit volumes of surrounding air, then the evaporative cooling of each portion of the enlarged plume consisting of 101 unit volumes will average 3.2 C. Alternatively, we may say that after evaporative cooling has been completed the plume will behave in the same way as a plume emerging from the stack with a temperature about 320 C less than that of the actual plume.

Thus the plume will have negative buoyancy and the effective stack height is thereby reduced. The behavior of the plume may be studied by the method of mirror images, as illustrated in Figure 20. The cooled plume may be thought as emerging from the orifice of an inverted stack situated above the actual stack. The theoretical analysis of the problem

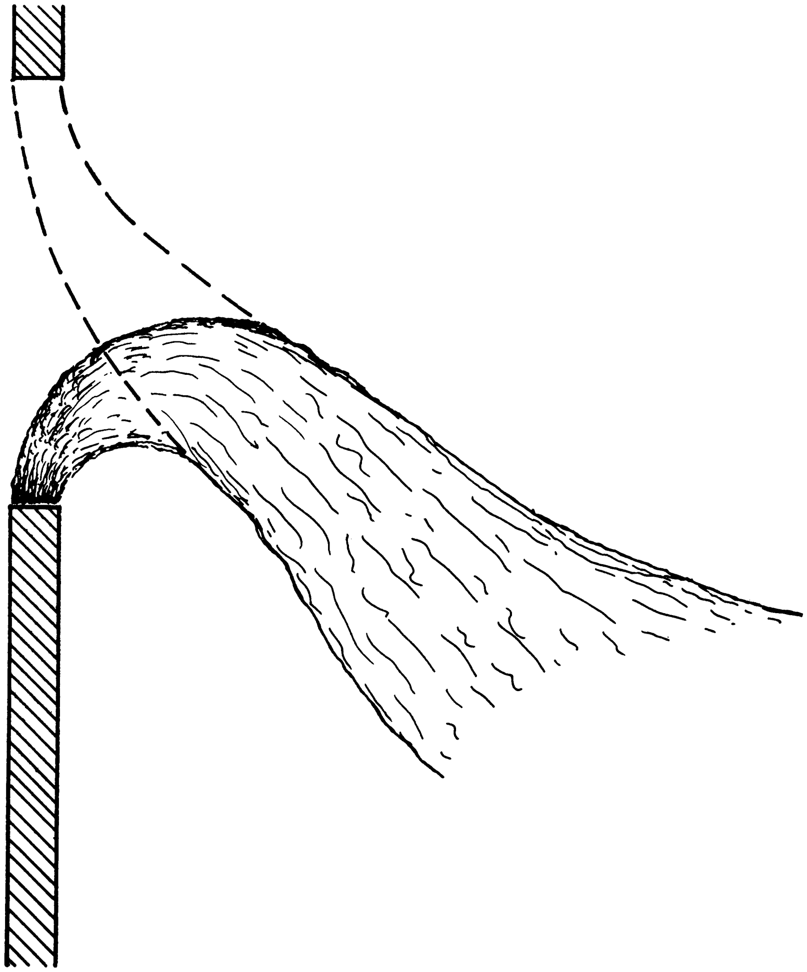


Figure 20. Representation of the lowered effective stack height resulting from evaporative cooling and consequent negative buoyancy of the plume by an inverted mirror image of a plume with a correspondingly increased effective stack height (after Scorer).

has not yet advanced far enough to permit a reliable estimate of the lowering of the effective stack height as a result of evaporative cooling, nor are there observations available against which theory may be tested. It is obvious, however, that wet washing of stack gases may raise serious problems; in many instances a more effective and economical solution can be found.

THE BEHAVIOR OF SMOKE PLUMES

Of the various influences on a smoke plume the most important is undoubtedly diffusion by atmospheric turbulence, as described in the first section of this chapter, but those of wind speed, wind shear, gravitational setting of larger particles, and wash-out of gases and particles by rain may also be significant in industrial air pollution. All of these influences will be described in later sections, but the discussion will be introduced by a description of inversion types which have such a dominant influence on plume behavior. The second section will then discuss the various plume types.

Inversion Types

As described in the first main section of this chapter, an inversion is a meteorological condition in which the temperature increases upward in a layer of air. The air is very stable for vertical motion of individual parcels of air, but not for horizontal motions. As a result, vertical mixing is strongly suppressed in an inversion but appreciable horizontal mixing still occurs.

Radiation Inversions

Radiation inversions occur frequently in middle latitudes on clear nights and may persist throughout the day over snow covered surfaces.

Late in the afternoon a time comes when the heat lost by the ground as a result of long-wave radiation of energy to the atmosphere at high levels and to outer space exceeds the energy received by the ground by long-wave radiation from H_2O vapor and CO_2 in the atmosphere and that received by short-wave radiation from the sun. At this point the ground temperature starts to drop. After sunset, solar heating ceases and the rate of ground cooling increases. Heat flows by turbulent transfer from the air above to the cooling ground, with the result that an inversion layer grows upward from the ground in the manner illustrated in Figure 21(a).

Cloudy skies or high winds prevent the formation of such inversions. Radiation inversions are most intense over dry, sandy soils, are less pronounced over wet ground with a vegetation cover, and are absent within forests and over large water bodies. Over cities, however, there is evidence that local sources of heat may prevent the development of surface inversions.(34) It has been estimated that built-up areas frequently produce instability up to about three times roof height in otherwise stable air.

Advection Inversions

When a warm air mass flows over a substantially cooler surface a surface inversion, known as an advection inversion, will result. The term advection is used to identify horizontal motion of air, in contrast to convection which implies vertical motion. Pronounced advection inversions occur in spring and early summer when warm air flows from a land area over a cool lake or ocean surface. The development of such an advection inversion is illustrated in Figure 21(b).

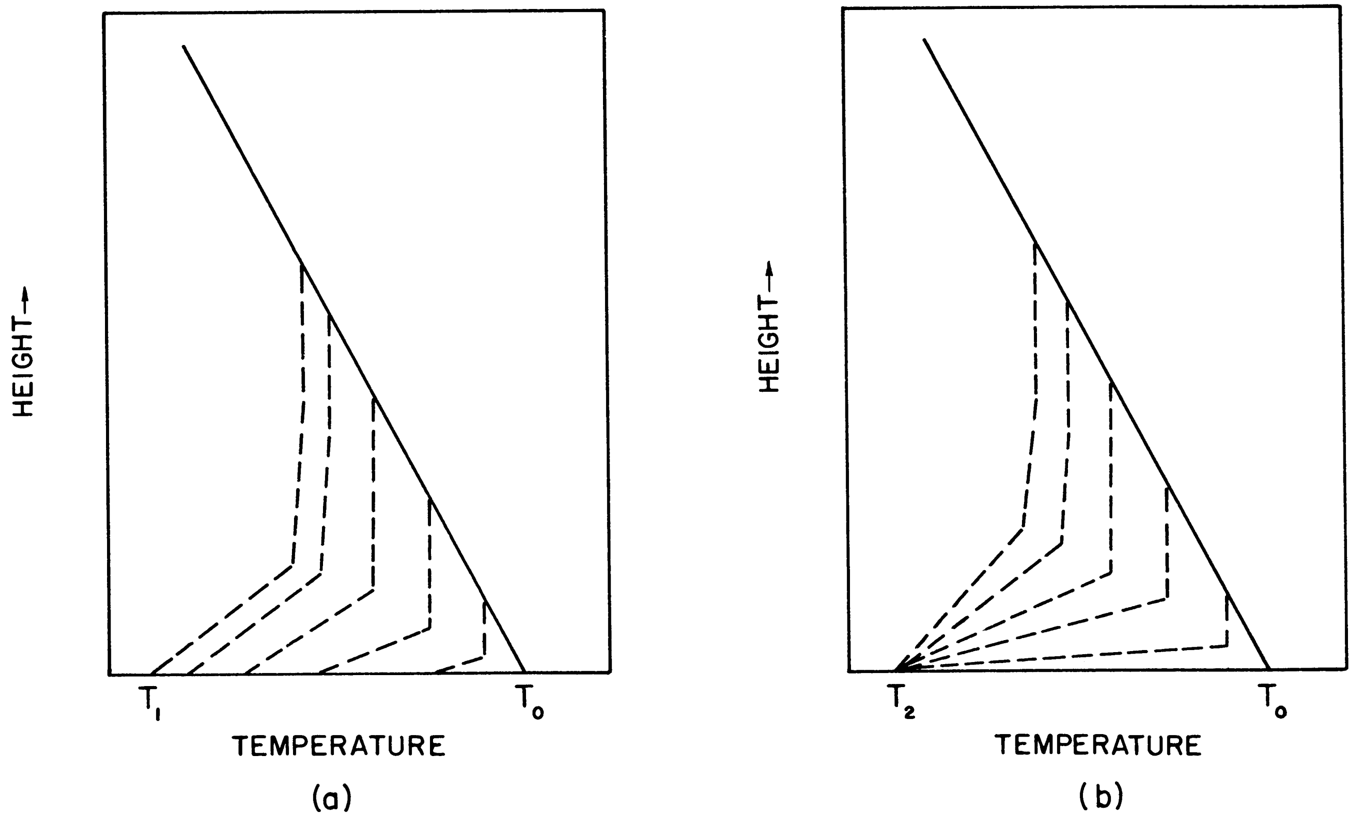


Figure 21. The upward growth of surface inversions: (a) radiation inversion on a clear night — full line, late afternoon lapse rate with surface temperature T_o just as radiational cooling commences, — broken lines, successive lapse rates during the night until surface temperature falls to T_1 after sunrise, after which it starts to rise; (b) advective inversion as warm air flows over a cool water surface — full line, lapse rate of warm air with surface temperature T_o just as it leaves land area, -- broken lines, successive lapses rates as air flows out over cool water surface with temperature T_2.

Industrial Significance of Surface Inversions

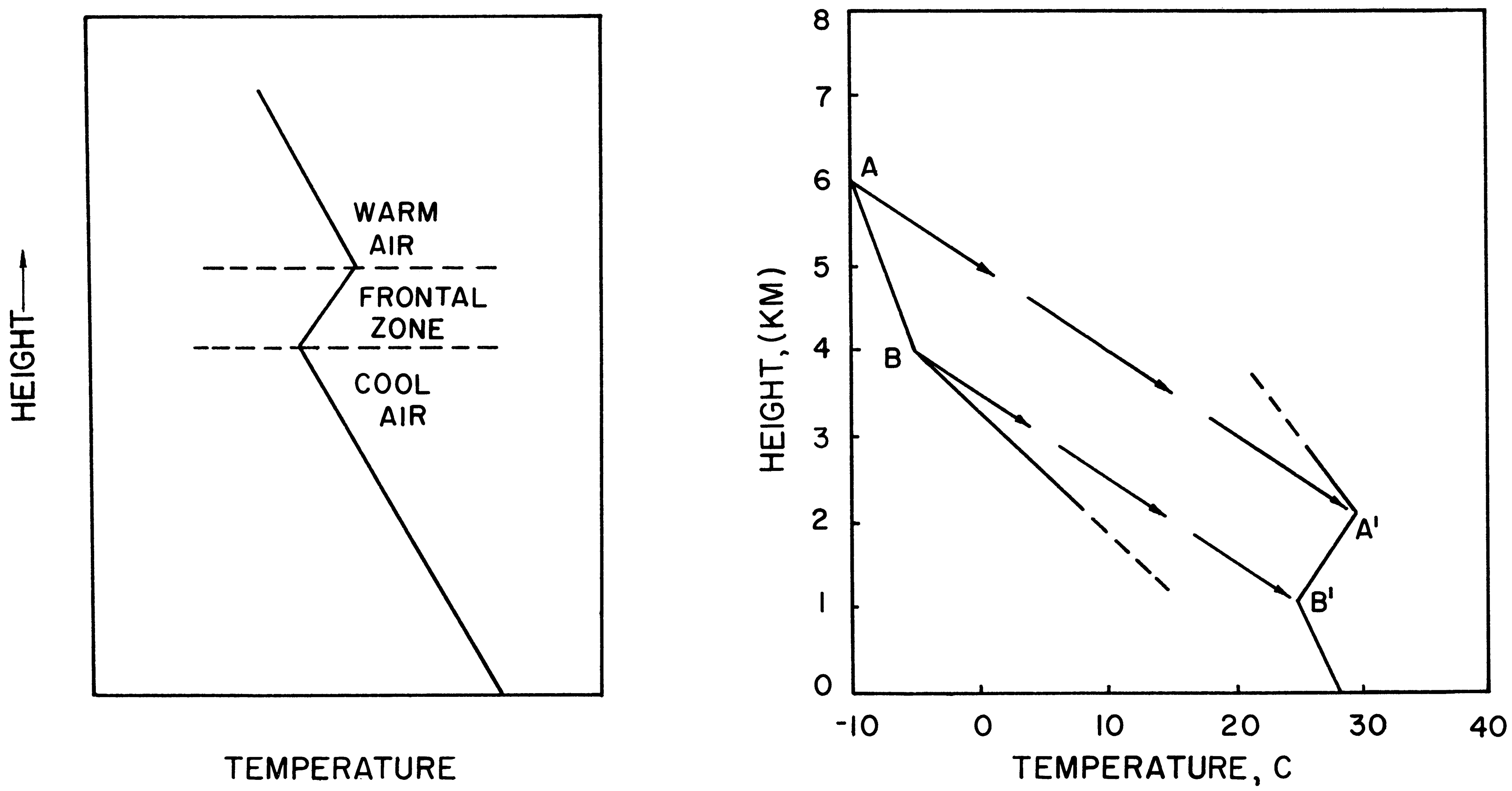
Radiation inversions are of particular importance for industrial plants with an inland location. Such inversions present an especially serious problem for a plant located in a deep and narrow valley where they tend to be especially frequent and intense; in addition, the valley sides present a physical barrier to horizontal diffusion which over level terrain aids materially in diluting the plume.

Advection inversions are significant primarily for industrial plants located near the shoreline of a large lake, an attractive site because of the nearby water supply. With offshore winds in spring and summer contaminants from a plant may be carried far over the lake with limited diffusion in the advection inversion which has formed and cause a problem to a community on the opposite side of the lake. This possibility is greater for a plant on the south side of such a lake than for one on the north side since the south winds will be warmer and hence more intense advection inversions will develop over the lake in them than in the cooler north winds. Onshore advection inversions may occur throughout the day in spring and summer or may develop only with the lake breeze, as described earlier in the section on shoreline winds. The adverse effect of an onshore advection inversion containing contaminants will be limited to a relatively narrow coastal strip; mechanical turbulence over the land combined with possible thermal turbulence as the cool lake air is heated in flowing over the warm land again will increase mixing and lead to rapid diffusion of the contaminants.

Frontal Inversions

As the name implies, frontal inversions are those accompanying frontal systems. A frontal zone is a layer of transition between two air masses, each having relatively uniform properties in the horizontal. When a frontal zone passes a fixed point in the atmosphere, it is known as a warm frontal zone if warm air replaces cold air as the frontal zone passes or as a cold frontal zone if cold air similarly replaces warm air. At the earth's surface the corresponding terms are warm front and cold front. With both frontal zones the cold air lies as a very shallow wedge, with a slope of about 1/100, under the relatively warm air. The warm frontal zone slopes upward in the direction of motion of the zone whereas the cold frontal zone slopes downward in the direction of motion.

The frontal zone exists as a consequence of the presence of relatively warm air lying above a mass of cool air, as illustrated in Figure 22(a). When the contrast between warm and cold air is pronounced there is a very definite inversion; with a less pronounced temperature contrast the frontal zone may consist of an isothermal layer or even a layer with a weak lapse rate. Cold frontal zones are generally more pronounced and more likely to have an inversion than warm frontal zones are. Low frontal inversions only are significant in air pollution problems. Thus, although diffusion may be good below the frontal inversion, if the base of the inversion is not far above the top of the stack its presence limits upward diffusion and thereby increases surface concentrations, as was first discovered during the Trail Smelter meteorological investigations.(70)



(a)

(b)

Figure 22. The characteristics and development of inversions aloft: (a), a frontal inversion; and (b), a subsidence inversion.

Subsidence Inversions

In the pressure systems known as anticyclones characterized by high central pressure around which the winds blow clockwise in the northern hemisphere and counterclockwise in the southern hemisphere there is frequently marked descent of the air with vertical convergence and horizontal divergence occurring as the descending air approaches the earth's surface. If the air at upper levels is initially stable, as it usually is, this sinking and converging motion frequently leads to the formation of inversions known as subsidence inversions.

The process by which subsidence inversions develop is readily seen by reference to Figure 22(b). Consider the layer of air AB initially lying between 4 and 6 km, with temperatures of -10°C at the top A and -5°C at the base B. The initial lapse rate in the layer is thus $2\frac{1}{2}$° C km^{-1}. As the layer descends and contracts vertically it heats at the dry adiabatic rate of 10°C km^{-1}. If the top of the layer subsides from 6 to 2 km, its temperature increases by 40°C, from -10°C at A to 30°C at A'. Similarly, if the base of the layer descends from 4 to 1 km, its temperature increases by 30°C, from -5°C at B to 25°C at B'. Corresponding temperature increases occur between top and bottom of the layer, so that the lapse rate after subsidence is -5°C km^{-1}, a substantial inversion. Additional subsidence and vertical contraction will further intensify the inversion.

Subsidence within the great North Pacific tropical anticyclone produces a very extensive subsidence inversion. The eastern portion of this inversion extends over Los Angeles during the late summer and autumn and is the primary cause of the acute smog problem there.

Industrial Significance of Inversions Aloft

Both frontal and subsidence inversions are found aloft, although subsidence inversions do occasionally reach the earth's surface and thereby intensify the air pollution problem. In general, however, with these inversions the diffusion is satisfactory in the surface layers but accumulations of contaminants nevertheless develop because upward diffusion is limited by the inversions when their base is low. Low inversions accentuate even the problem of a single industrial plant by increasing local concentrations as well as more distant one

The problem is particularly acute for a plant located in a valley, especially if the valley is deep and narrow. The valley sides limit horizontal diffusion and the inversion aloft prevents upward diffusion so that the pollution accumulates as in a giant pipe.

Plume Types

For convenience in analysis, plumes have been divided into six categories based on their behavior and appearance under various conditions of atmospheric turbulence.(23,104) These types of behavior are called looping, coning, fanning, lofting, fumigation, and trapping and are illustrated in Figure 23.

Plume Looping

Looping occurs when the lapse rate is superadiabatic, i.e., greater than 10°C km^{-1}, the air is unstable, and thermal turbulence is highly developed. The looping occurs because large thermal eddies carry

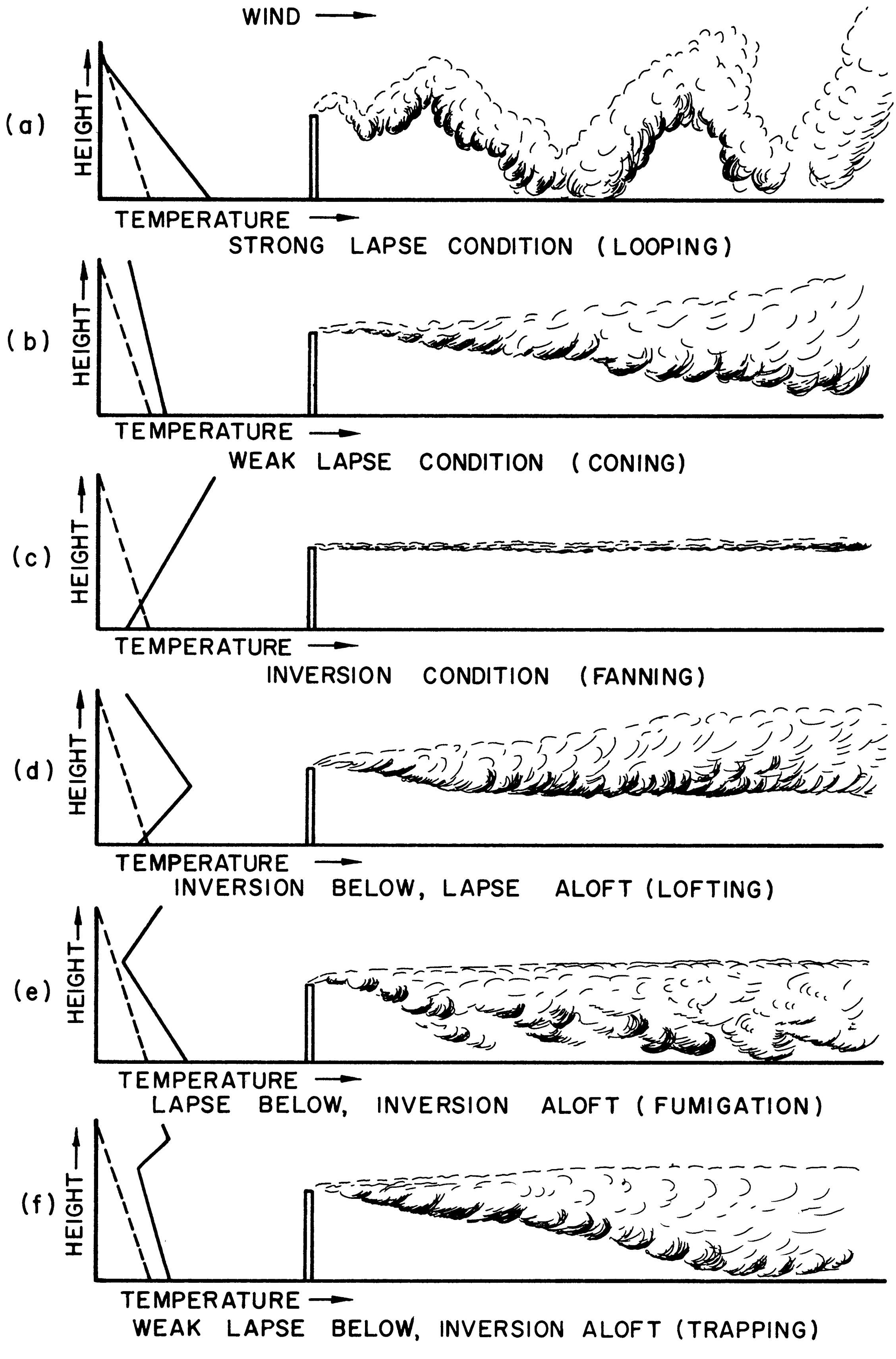


Figure 23. Six types of plume behavior, under various conditions of stability and instability. At left: broken lines, dry adiabatic lapse rate; full lines, existing lapse rates.

portions of the plume rapidly upward and downward as shown in Figure 23(a). Effluents diffuse rapidly, but sporadic puffs with high concentrations are at intervals brought to the ground near the base of the stack for a few seconds during light winds. Looping occurs usually during clear daytime conditions in seasons when solar heating of the ground is strong, and not with cloudiness, strong winds, or a snow cover.

Plume Coning

When the existing lapse rate of temperature lies between the dry adiabatic lapse rate, 10°C km^{-1}, and the isothermal value, 0 C km^{-1}, the stability of the air is moderate and turbulent mixing in both the horizontal and vertical is present but not intense. The plume therefore tends to take the form of a cone with its vertex at the effective stack height and its axis horizontal, behavior known as coning. The distance from the stack at which the stack gas first reaches the surface is greater than with looping since thermal eddies are absent. Coning is prevalent in cloudly and windy climates and may occur day or night, but is less frequent in dry climates. Most of the diffusion equations given in the next section are of limited usefulness in describing the other plume types but have been moderately successful in predicting concentrations when coning occurs.

Plume Fanning

If the temperature increases from the surface upward, as in a radiation or advection inversion, the air is very stable and vertical turbulence and mixing in the vertical are strongly suppressed but horizontal turbulence and mixing are still active, although somewhat less than those which produce coning. This free horizontal mixing associated with highly suppressed vertical mixing lead to a horizontal spreading and meandering of the plume known as fanning. At inland locations fanning occurs primarily during nights with clear skies and light winds. Fanning may also occur in plumes from shoreline plants, but this will be described in more detail later.

Although plume concentrations are relatively high with fanning and it may therefore be considered as an unfavorable condition, this is not necessarily so. As long as the fanning effluent remains aloft it presents few problems; if the gases come to the surface when the inversion breaks up, or if they reach a populated area on high ground in the area, then problems are encountered.

Plume Lofting

At sunset on a clear evening there is a period of time when there is a shallow radiation inversion with a temperature lapse above, as illustrated in Figures 21(a) and 23(d). During this time there is rapid upward diffusion but downward diffusion extends only to the top of the surface inversion. This plume behavior is referred to as lofting.

Because gases do not reach the surface under these conditions and there is rapid vertical diffusion, when the plume is lofting may be a good time to perform maintenance operations such as boiler cleaning which release additional effluents. Large particles with appreciable falling speeds should not be released, however, since these will settle through the radiation inversion.

Plume Fumigation

When a surface inversion is replaced by a superadiabatic lapse rate, thermal turbulence may suddenly bring the high concentrations in a fanning plume to the surface simultaneously along the length of the fanning plume. This process is known as fumigation, and was first analyzed during the Trail investigation.(65) Three types of fumigation may be specified.

Type I Fumigation--This type occurs over inland areas in summer when solar heating in the morning destroys a nocturnal radiation inversion in which fanning of a plume has been occurring. As a superadiabatic lapse rate is established in a layer which grows upward, thermal turbulence brings high concentrations to the ground when the top of the unstable layer reaches the fanning plume. Fortunately, the high surface concentrations persist for a limited time only, about half an hour, around 8 a.m.

Type II Fumigation--Another variety of fumigation which occurs in cities in the early evening during the autumn and winter has been described.(86) Heat sources in the city maintain an unstable lapse rate up to two or three roof heights, as described earlier, whereas the air above which has come from surrounding rural areas is stable as a result of radiational cooling. This leads to a mild fumigation for several hours over the city in the early evening until the radiational heat losses cause stability in the city as well as in adjacent rural areas.

Type III Fumigation--Warm onshore winds at a shoreline plant during the spring and summer may have a surface advection inversion extending up to and perhaps above the effective stack height. Thus fanning will occur as the plume leaves the stack. But during the day the surface lake air is rapidly heated as it moves over the warm land surface and thermal turbulence grows upward to the fanning plume and brings high concentrations to the surface during the warmer parts of the day. No fumigation occurs at night because the land surface is also cool.

Conversely, offshore winds on clear nights will be characterized by a surface radiation inversion extending up to and above the effective stack height where a fanning plume will develop. During autumn and winter the surface temperature of a lake large enough to remain unfrozen will be relatively high, so that an unstable layer with thermal turbulence will grow upward over the lake. When this layer reaches the fanning plume, the gases will be brought to the lake surface and lead to a fumigation. If the land is snow covered a similar fumigation will occur during the day. Unless there are areas of concern in the lake in the near vicinity, such as inhabited islands, additional effluents may be safely released under such conditions. A lake with a frozen surface acts effectively as a snow covered land surface, so that no Type III fumigations are to be expected near such a lake.

With Type III fumigations there will be no descent of gases near the stack such as occur with Type I fumigations, except under special circumstances. The Type III fumigations over land during the summer present a problem if the areas where the gas may descend are populated or have valuable crops.

Plume Trapping

A sixth plume type is herewith added to the five types initially proposed by Church in order to draw attention to the importance of low frontal and subsidence inversions aloft which has apparently not been generally recognized hitherto. Coning occurs with a weak lapse rate; when, in addition, there is the base of a low inversion not far above the effective stack height, upward diffusion is greatly reduced and surface concentrations increased. Thus, although the diffusion is good at the effective stack height and below, the plume is trapped between the ground and the low inversion base aloft and the process, illustrated in Figure 23(f), is referred to as plume trapping. Such trapping was first observed and analyzed in a deep and narrow valley, where it may present a particularly difficult problem because the physical barrier presented by the valley sides causes horizontal trapping in addition to vertical trapping.(70)

The occurrence of plume trapping illustrates the need of having turbulence information above the effective stack height, either direct measurements or lapse rate data from which to estimate turbulence and mixing aloft. Trapping may cause pollution accumulation over a whole city, as in the case of Los Angeles, as well as locally near an industrial plant.

Dilution of a Plume by Wind Speed

Some dilution of a plume occurs immediately as the gases leave the stack orifice. This dilution is directly proportional to the wind speed. For example, doubling the wind speed while other influences are constant doubles the volume of air in which the stack effluent released per unit time mixes, in the manner described in the first section of this chapter.

Dilution of a Plume by Turbulent Diffusion

The theory of turbulent diffusion in the atmosphere is a highly complex subject.(7,108,141) Only the results of most direct application which have been tested by field experiments will be described here.

An important point which cannot be emphasized too strongly is that the results of applying theory depend greatly on the time interval over which observed quantities are averaged. For example, the results obtained from using an averaging time of several minutes will, in general, be substantially different from those using an averaging time of an hour. Thus, the maximum horizontal crosswind concentration downwind from a continuous point source will be less for a long sampling period than it will be for a short sampling period, as illustrated in Figure 24: for the 10-minute sampling time the plume was less concentrated and broader at 50 m from the source than it was for the 1/2-min sampling time. This intimate relationship between averaging time of meteorological variables and associated contaminant concentrations, measured or calculated, must continually be kept in mind in the following analyses and in their application.

Elevated Continuous Point Source - Bosanquet and Pearson

Using dimensional analysis and statistical concepts, Bosanquet and Pearson developed a number of useful equations for the concentration of pollution from a point source.(14,17) One such equation gives the

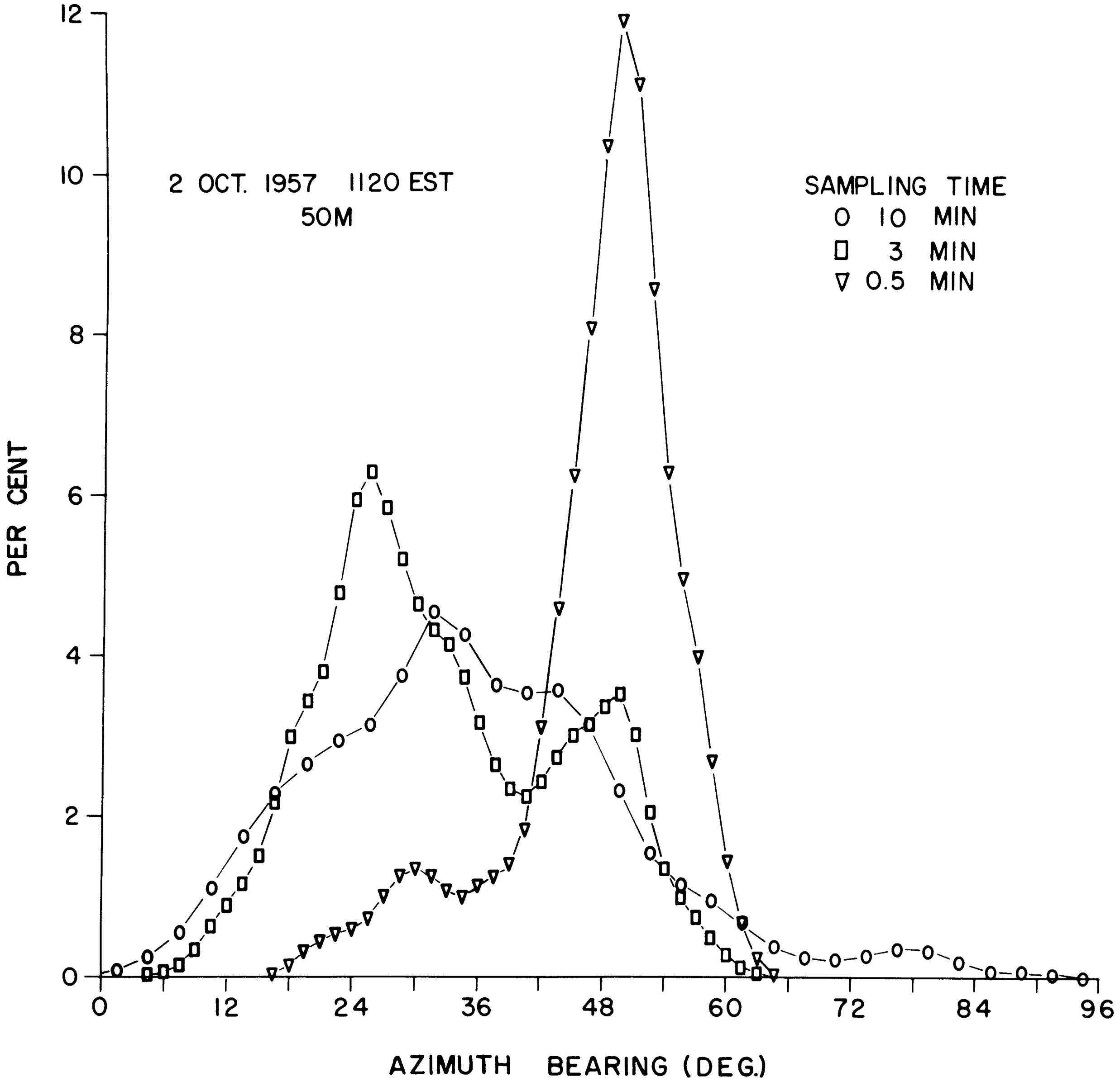


Figure 24. The variation with sampling time of plume width and distribution of concentrations of SO_2 across the plume at 50 m from the source. Both the source and sampling equipment were located near the ground; the measurements were made under conditions of strong midday heating at 11:20 a.m. on 2 October 1957. The points plotted are slightly smoothed values of concentrations at individual sampling stations along an arc 50 m from the source expressed as percentages of the sum of all concentrations for the arc, the position of each sampler being indicated by its azimuth bearing angle measured at the source (after Cramer and Record).

concentration which is effective in cumulative processes, such as the blackening of a neighborhood by soot and the attack of structures by acid constituents of the stack effluents. Thus, if the fraction of the year during which the wind direction falls within an arc θ is $a\theta$, then the average value of the concentration for the whole year is given by

$$\overline{X} = \frac{Qa}{pux^2} \exp^* (-h_e/px), \qquad (8)$$

where Q is the mass of contaminant emitted per unit time, u is the average wind speed, x is the distance downwind from the source, h is the effective stack height, and p is a numerical coefficient whose value depends on the vertical component of the atmospheric turbulence.

Bosanquet and Pearson also give an equation for the ground-level concentration X_o during a brief time interval, in the form

$$X_o = \frac{Q}{(2\pi)^{\frac{1}{2}}\, pqux^2} \exp (-h_e/px - y^2/2q^2x^2), \qquad (9)$$

where y is the distance crosswind from the axis of the plume, and q is a second numerical coefficient whose value depends on the horizontal crosswind component of turbulence. The maximum ground concentration downwind is

$$X_{om} = \frac{4Q}{(2\pi)^{\frac{1}{2}}\, e^2 u\, h_e^2} \left(\frac{p}{q}\right), \qquad (10)$$

which occurs at a distance from the source of

$$x_{om} = h_e/2p. \qquad (11)$$

---

* exp (-bx) represents e^{-bx}

Representative values of the turbulent diffusion coefficients for average terrain are given in Table IV.(51)

TABLE IV

BOSANQUET AND PEARSON TURBULENT DIFFUSION COEFFICIENTS

Degree of turbulence	p	q
Low turbulence	0.02	0.04
Average turbulence	0.05	0.08
Moderate turbulence	0.10	0.16

Techniques for obtaining numerical values by graphical methods are available.(51)

Elevated Continuous Point Source - Sutton

Somewhat similar equations, which have been used more widely than those of Bosanquet and Pearson, have been developed by Sutton.(142) The general expression applicable for concentrations anywhere above the ground is

$$X = \frac{Q \exp\left(-y^2/C_y x^{2-n}\right)}{\pi C_y C_z u x^{2-n}} \left\{ \exp\left[-(z - h_e)^2/C_z{}^2 x^{2-n}\right] + \exp\left[-(z + h_e)^2/C_z x^{2-n}\right] \right\} \qquad (12)$$

where z is distance upward from the ground, C_y and C_z are virtual diffusion coefficients for the crosswind and vertical directions, respectively, and n is a numerical coefficient whose value is related to the diffusion characteristics of the turbulence. The meaning of the other symbols is as given earlier. The second exponential term on the right allows for reflection of the effluent from the ground surface. With $z = 0$, Equation (12) gives the concentration at the surface as

$$X_o = \frac{2Q}{\pi C_y C_z u x^{2-n}} \exp\left[-x^{n-2}\left(y^2/C_y{}^2 + h_e{}^2/C_z{}^2\right)\right] \qquad (13)$$

and its maximum as

$$X_{om} = \frac{2Q}{\pi e u h_e{}^2}\left(\frac{C_z}{C_y}\right), \qquad (14)$$

which occurs at a distance x_{om} from the source, given by

$$x_{om} = (h_e{}^2/C_z{}^2)^{1/(2-n)} \qquad (15)$$

The coefficient n may be obtained by fitting the observed variation of wind speed with height to the theoretical profile

$$u = u_{10}\left(\frac{z}{z_{10}}\right)^{n/(2-n)} \qquad (16)$$

where u_{10} is the average wind speed at the standard height z_{10} of 10 m and u is the average wind speed at some greater height z. Equation (1) is this expression where n has the value of 0.25 which is characteristic of average meteorological conditions.

The equations given above apply only to effluents consisting of gases or very fine particles with negligible falling speeds. With larger particles modified methods must be used, as described later.

Typical values of Sutton's virtual diffusion coefficients for representative values of n are given in Table V.(142) Corresponding values in English units, $ft^{n/2}$, have also been published.(51) It must

TABLE V

SUTTON TURBULENT DIFFUSION COEFFICIENTS*

(3-MIN SAMPLING PERIOD)

Height of source, m	Large lapse, n = 0.20		Neutral, n = 0.25		Inversion			
					Moderate, n = 0.33		Large, n = 0.5	
	C_z	C_y	C_z	C_y	C_z	C_y	C_z	C_y
0	.36	.64	.12	.21	.048	.084	.030	.053
10	.36	.64	.12	.21	.048	.084	.030	.053
25	.36	.36	.12	.12	.048	.048	.030	.030
50	.30	.30	.10	.10	.040	.040	.025	.025
75	.27	.27	.09	.09	.036	.036	.022	.022
100	.21	.21	.07	.07	.028	.028	.018	.018

* Units of C_y and C_z are $m^{n/2}$

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be emphasized that the values presented in Table V are to be used only if average concentrations for a period of about 3 min are desired and for distances downwind from the source of 1 km or less. These values are derived mainly from surface diffusion measurements for relatively short distances over "undulating downland" to use Sutton's phrase, and must therefore be used with caution when applying them to diffusion over other types of terrain. Unfortunately, too few investigations over various terrain types have been made to permit estimating the influence of surface roughness. One investigation over very rough country during unstable conditions suggests such erratic behavior of the effluent that values such as those in Table V have little if any significance.(85)

If hourly average values of concentrations are required, the values given in Table VI should be employed.(135)

TABLE VI

SUTTON TURBULENT DIFFUSION COEFFICIENTS
(AFTER SMITH AND SINGER)
(1-HR SAMPLING PERIOD)

Meteorological Conditions	n	C_y ($m^{n/2}$)	C_z ($m^{n/2}$)
Typical lapse	0.25	0.40	0.40
Typical inversion	0.55	0.40	0.05

It is assumed that no significant variation of the coefficients with height exists. Comparison of Tables V and VI reveals one notable difference: for inversion conditions the value of C_y is much greater for a 1-hour sampling period than for a 3-minute one. This results from the slow horizontal meandering and swinging of a fanning plume which leads to a low hourly average concentration at a fixed point made up of perhaps only two or three highly peaked concentrations each lasting several minutes as the plume swings by; the values of the individual highly peaked concentrations would be given by the C_y values in Table V. Again, these values should not be used for rough terrain or for distances much greater than 1 km downwind from the source.

Methods of Estimating Coefficients and Concentrations

In the present state of knowledge of atmospheric diffusion, the best method of obtaining accurate diffusion coefficients for given terrain and meteorological conditions is to conduct a carefully planned and executed program of sampling a tracer substance emitted from a source at a known rate and of simultaneously measuring the significant meteorological variables. In most cases, however, this is a counsel of perfection because such a program is very expensive and time consuming. A much more limited program may be possible and may yield important information.

Several past investigations have obtained coefficients and concentrations and have compared results with those to be expected from using various equations.(50,102,139) These publications should be consulted for the helpful information they may provide in analyzing the significant factors at another plant location. In addition, visual methods of estimating the values of diffusion coefficients, nomograms to facilitate determining diffusion coefficients and concentrations, and high-speed electronic computer techniques for calculating concentrations have been developed.

Visual Methods--The visual techniques depend on observations of plume dimensions. One procedure uses photographic techniques for estimating coefficient values.(24) A simpler method makes use of the following equation

$$C_z = 2.33 \, x_t^{n/2} \, (Z_m/x_t)$$

where x_t is the length of the visible plume and Z_m is its maximum half-width in the vertical direction.(45) The ratio Z_m/x_t may be measured using any convenient scale, such as the number of fingers subtended at arm's length. Since the value of n ranges from about $\frac{1}{2}$ to $\frac{1}{4}$, x_t appears essentially as a fourth to eighth root and its precise determination is therefore unnecessary. This method is simple, rapid, and adequate for many purposes.

Nomographic Methods--A nomogram is available for determining rapidly ground-level concentrations from Bosanquet and Pearson's equation for the concentration from an elevated continuous point source such as a stack.(140) The procedure takes into account the effective stack height. Similar types of nomograms may be used in conjunction with Sutton's equations.(104)

Electronic Computer Methods--The National Bureau of Standards has developed an analog computer for predicting, given the necessary weather data, the geographical fallout pattern of radioactivity resulting from a nuclear explosion.(132) Although a nuclear explosion represents a vertical instantaneous line source, a similar analog computer could no doubt be developed for an elevated continuous point source.

Elevated Continuous Point Source - Other Equations

A comprehensive review of the various diffusion equations that have been proposed is available.(104) One approach emphasizes the vertical wind profile in the surface layers of the atmosphere(19); another makes use of large-scale characteristics of the atmosphere to evaluate small-scale atmospheric diffusion(144); a third uses standard deviations of the azimuth and elevation angles of the wind direction as measured by a bivane as the horizontal and vertical diffusion coefficients(27); a fourth analyzes the problem in relation to the spectrum and scale of turbulence(60); and a fifth makes allowance, for the first time, for the meandering which occurs in varying degrees with all plumes.(46) An interesting evaluation of Sutton's approach to the continuous point source problem has been made using a close sampling network over very level and uniform terrain in Nebraska.(4) It is found that Sutton's hypothesis predicts the observed concentration distributions only if there are two values of n, n to characterize horizontal crosswind diffusion and n to characterize vertical diffusion, and that neither is equal to the n as defined by Sutton and given by Equation (16). A better fit to the data is obtained if Equation (12) is modified to the form

$$\chi = \frac{Q \exp\left(-y^2/C_y^2 x^{2-n_y}\right)}{\pi C_y C_z u x^{2-(n_y + n_z)/2}} \left\{ \exp\left[-(z-h)^2/C_z^2 x^{2-n_z}\right] + \exp\left[-(z+h)^2/C_z^2 x^{2-n_z}\right] \right. \quad (17)$$

Since this form is found applicable to observations taken with the source near the ground and samplers extending to a height of 17.5 m, it is not clear as yet whether the same equation is equally valid for higher sources. Suggested values for n_y and n_z appropriate for a 10-minute sampling period are given in Table VII.(3)

TABLE VII

VALUES OF COEFFICIENTS n_y AND n_z
(AFTER BARAD)
(10-MIN SAMPLING PERIOD)

Meteorological Conditions	n_y	n_z
Moderate instability	0.30	-0.30
Neutral stability	0.45	0.00
Moderate stability	0.80	0.35

Elevated Continuous Point Source - Looping

A bivane installed at the height of the top of a stack and exposed so as to be free from stack interference with the wind flow will give the minimum distance $x_{o\ min}$ from the stack base at which a looping plume will reach the ground. If φ_{max} is the maximum azimuth angle of the bivane which occurs with downward moving gusts, then

$$x_{o\ min} = h \cot \varphi_{max} \tag{18}$$

Similarly, the average distance $x_{o\ av}$ at which a looping plume will reach the ground is given by

$$x_{o\ av} = h \cot \varphi_{av} \tag{19}$$

where φ_{av} is the average azimuth angle of the bivane for downward moving gusts. Experimental work has shown that $x_{o\ av}$ is three stack heights, which corresponds to a value of φ_{av} of about 20°.(95)

A method for estimating the maximum ground concentrations resulting from looping has been suggested.(78)

Elevated Continuous Point Source - Coning

Various aspects of the behavior of a coning plume are well expressed by Equations (9) to (15) inclusive.

Elevated Continuous Point Source - Fanning

An approximate evaluation of the concentrations aloft in a fanning plume may be obtained by using in Equation (12) the inversion values of the coefficients n, C_y, and C_z as given in Table V or VI.

Sampling within the fanning plume aloft has produced additional information. There are indications that Sutton's equations are adequate to specify the horizontal rate of diffusion but fail to specify the vertical rate, with the result that the equations underestimate the concentration at moderate and large distances.(74,77) Another investigation suggests that turbulence induced by the stack or by jet action of the effluent causes larger initial diffusion, during the first several hundred meters downwind from the stack, than occurs farther downwind where induced turbulence has largely decayed.(136) If accurate concentration values in a fanning plume are required, the use of two sets of coefficients and suitable equations may be needed.

Elevated Continuous Point Source - Lofting

Reference to Figure 23(d) shows that lofting of a plume occurs when the top of a surface inversion is located below the effective stack height, with a large lapse rate above the inversion top. If the inversion top is a distance h_{it} above the ground, lofting concentrations for $z > h_{it}$

are given by the following slightly modified form of Equation (12).

$$X = \frac{Q \exp \left(-y^2/C_y{}^2x^{2-n}\right.}{\pi C_yC_z ux^{2-n}} \left\{ \exp\left[-(z-h_e)^2/C_z{}^2x^{2-n}\right] + \exp\left[-(z+h_e-2h_{it})^2/C_z{}^2x^{2-n}\right] \right\} \qquad (20)$$

The concentrations at the top of the inversion, where $z = h_{it}$, are obtained from Equation (20) which reduces to the following form,

$$X_{it} = \frac{2Q}{\pi C_yC_z ux^{2-n}} \exp \left\{ -x^{n-2} \left[y^2/C_y{}^2+(h_e-h_{it})^2/C_z{}^2 \right] \right\} \qquad (21)$$

which corresponds to Equation (13). For a plume made up of small to medium sized particles, the pattern of gravitational settling through the inversio and onto the ground is given approximately by Equation (21). It should be noted that both Equations (20) and (21) assume complete "reflection" of the plume from the inversion top, an assumption not entirely justified since some of the plume will penetrate into the inversion.

Elevated Continuous Point Source - Fumigation

Maximum values of Type I fumigation concentrations at the ground may be estimated by means of the following expression.(106)

$$X_o = Q/\pi^{\frac{1}{2}}C_y uh_e x^{(2-n)/2} \qquad (22)$$

The following approximate equation may also be used.(68)

$$X_{o\ av} = 36\ Q/\pi\ uh_e(x_2+ x_1) \qquad (23)$$

where $X_{o\ av}$ is the average value of the ground concentration occurring over the distance interval from x_1 to x_2 downwind from the source for the quarter hour to half hour period of highest concentrations. The quantity h_e is the effective stack height for the initially fanning plume. Equation (23) assumes that the plume fans over a 5° angle from the source.

Ground concentrations for Type II and Type III fumigations may be estimated using Equation (33) in the section on elevated continuous line sources.

Elevated Continuous Point Source - Trapping

Plume trapping occurs when there is an inversion base above the effective stack height, with a weak lapse rate from the surface up to the inversion base as illustrated in Figure 23(f). Coning of the plume occurs initially but subsequently there are multiple reflections of the effluent, upward from the earth's surface and downward from the inversion base. If the height of the inversion base is h_{ib}, then for $0 < z < h_{ib}$ the trapping concentrations are given by

$$X = \frac{Q \exp(-y^2/C_y{}^2 x^{2-n}}{\pi C_y C_z u x^{2-n}} \left\{ \sum_N \exp\left[-(z-h_e+2Nh_{ib})^2/C_z{}^2 x^{2-n}\right] + \sum_N \exp\left[-(z+h_e-2Nh_{ib})^2/C_z{}^2 x^{2-n}\right] \right\} \quad (24)$$

where N = 0, ± 1, ± 2, ± 3, etc. Ground-level trapping concentrations are given by Equation (24) with $z = 0$, which reduces to

$$X_o = \frac{2Q \exp(-y^2/C_y{}^2 x^{2-n})}{C_y C_z u x^{2-n}} \left\{ \sum_N \exp\left[-(2Nh_{ib}-h_e)^2/C_z{}^2 x^{2-n}\right] \right\} \quad (25)$$

Use of the first several values of N is sufficient for most purposes.

Elevated Continuous Line Source - Bosanquet and Pearson

Emission from a line of stacks at right angles to the wind is often conveniently represented by the equation for an elevated continuous infinite line source.(17) The form for surface concentrations corresponding to Equation (9) is

$$X_o = \frac{Q_1}{pux} \exp(-h_e/px) \qquad (26)$$

where Q_1 is the time rate of emission of the contaminant per unit length of the line source. Corresponding to Equations (10) and (11), the maximum ground concentration is

$$X_{om} = Q_1/euh_e \qquad (27)$$

which occurs at a distance from the source of

$$x_{om} = h_e/p \qquad (28)$$

Elevated Continuous Line Source - Sutton

Sutton's relationships may be expressed for either an infinite line source or a limited line source.

Infinite Line Source--The expression corresponding to Equation (13) is

$$X_o = \frac{2Q_1}{\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \exp\left(-h_e{}^2/C_z{}^2 x^{2-n}\right) \qquad (29)$$

Forms corresponding to Equations (14) and (15) are

$$X_{om} = 2Q_1/\,(2\pi e)^{\frac{1}{2}}\, uh_e \qquad (30)$$

and

$$x_{om} = (2h_e^2/C_z^2)^{1/(2-n)} \qquad (31)$$

Limited Line Source--If the line of stacks is short, it is preferable to use another equation. If the wind is at right angles to a line of stacks of length $2y_o$, the general equation has the form

$$X = \frac{Q_1}{2\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \left\{ \exp\left[- \frac{(z-h_e)^2}{C_z^2 x^{2-n}} \right] + \exp\left[- \frac{(z+h_e)^2}{C_z^2 x^{2-n}} \right] \right\}$$

$$\cdot \left[\text{erf*} \left(\frac{y_o - y}{C_y x^{1-\frac{1}{2}n}} \right) + \text{erf} \left(\frac{y_o + y}{C_y x^{1-\frac{1}{2}n}} \right) \right] \qquad (32)$$

Ground-level concentrations are given by Equation (32) with $z = 0$, which reduces to

$$X_o = \frac{Q_1 \exp(-h_e^2/C_z^2 x^{2-n})}{\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \left[\text{erf}\left(\frac{y_o - y}{C_y x^{1-\frac{1}{2}n}} \right) + \text{erf}\left(\frac{y_o + y}{C_y x^{1-\frac{1}{2}n}} \right) \right] \qquad (33)$$

Equation (33) may be used to calculate surface concentrations for Type II and Type III fumigations, in which case $2y_o$ is the width of the fanning plume at the point at which the turbulent layer growing upward reaches it, the distance x is measured downwind from this point not from the stack, and $Q_1 = Q/2y_o$ where Q is the mass of contaminant emitted per unit time from the stack. The height z to which turbulence grows upward in time t is given by(18)

$$z^2 = 4Kt$$

where K is the eddy diffusivity. Consider a Type III fumigation by an effluent from a stack located at a shoreline: if x_e is the distance from the shoreline at which the upward growing surface layer of turbulence reaches the fanning plume aloft at height $z = h_e$, then $t = x_e/u$ and

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*The error function erf $z = (2/\pi^{\frac{1}{2}}) \int_0^z e^{-v^2} dv$. Its values are given in statistical tables.

$$x_e = uh_e^2/4K \qquad (35)$$

Thus to evaluate Type III fumigation concentrations at the surface, $x - x_e$ should be substituted for x in Equation (33) for all values of $x > x_e$. There will be no effluent at the surface for $x < x_e$. If the upward growing turbulence is primarily mechanical, $K = 1\ m^2sec^{-1}$ approximately; according to Table V, 3-min average concentrations for $h_e = 100$ m would be obtained using $n = 0.25$ and $C_y = C_z = 0.07\ m^{1/8}$. For active thermal turbulence, $K = 10\ m^2sec^{-1}$ approximately and the corresponding values are $n = 0.20$ and $C_y = C_z = 0.21\ m^{1/10}$. To summarize,

For mechanical turbulence: $x_e = uh_e^2/4$; $n = 0.25$; $C_y = C_z = 0.07$

For thermal turbulence: $x_e = uh_e^2/40$; $n = 0.20$; $C_y = C_z = 0.21$

Surface Continuous Source - Sutton

Expressions for surface continuous point, infinite line, and limited line sources are given below.

Continuous Point Source--This expression may be obtained from Equation (12) with $h_e = 0$, as follows.

$$X = \frac{2Q}{\pi\ C_yC_zux^{2-n}} \exp\left[-x^{n-2}\left(\frac{y^2}{C_y^{\ 2}} + \frac{z^2}{C_z^{\ 2}}\right)\right] \qquad (36)$$

The ground concentration is found with $z = 0$,

$$X_o = \frac{2Q\ \exp(-y^2/C_y^{\ 2}x^{2-n})}{\pi\ C_yC_zux^{2-n}} \qquad (37)$$

The center-line ground concentration becomes, for $y = 0$,

$$X_{oc} = 2Q/\pi\ C_yC_zux^{2-n} \qquad (38)$$

Continuous Infinite Line Source--The general expression for a continuous crosswind infinite line source is

$$X = \frac{2Q_1 \exp(-z^2/C_z{}^2x^{2-n})}{\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \tag{39}$$

where Q_1 is defined as for Equation (26). The ground concentration for Equation (39) with z = 0, is

$$X_o = 2Q_1/\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n} \tag{40}$$

Continuous Limited Line Source--For a continuous crosswind limited line source of length $2y_o$ the general equation is

$$X = \frac{Q_1 \exp(-z^2/C_z{}^2x^{2-n})}{\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \left[\text{erf} \left(\frac{y_o - y}{C_y x^{1-\frac{1}{2}n}} \right) + \text{erf} \left(\frac{y_o + y}{C_y x^{1-\frac{1}{2}n}} \right) \right] \tag{41}$$

where the terms used are as defined for Equation (32). For the ground concentration with z = 0,

$$X_o = \frac{Q_1}{\pi^{\frac{1}{2}} C_z u x^{1-\frac{1}{2}n}} \left[\text{erf} \left(\frac{y_o - y}{C_y x^{1-\frac{1}{2}n}} \right) + \text{erf} \left(\frac{y_o + y}{C_y x^{1-\frac{1}{2}n}} \right) \right] \tag{42}$$

Deformation and Dilution of a Plume by Wind Shear

For convenience the influence of wind shear on plume deformation and dilution may be considered under two headings: first, the influence of an increasing wind speed with height, neglecting wind direction changes with height; and then, the influence of a changing wind direction with height, neglecting wind speed changes with height.

The Influence of Wind Speed Shear on Plume Deformation and Dilution

Since wind speed shear acts to deform a plume in a direction parallel to its axis the effect is difficult to observe. The higher wind speeds aloft carry the upper part of the plume along rapidly; the smaller wind speeds at lower levels carry the lower portion of the plume along less rapidly.

Near the beginning of the chapter it was shown that plume dilution is directly proportional to wind speed and that this effect is independent of turbulent diffusion. Up to this point any possible influence of a variation of wind speed with height on plume concentrations has been neglected. It has been pointed out, however, that the observed wind speed increase with height will have such an influence.(133) The effect is illustrated, in exaggerated form for emphasis, in Figure 25. The result of the wind speed shear is to decrease the concentrations at heights above the source where the wind speed is greater and to increase them below the source where the wind speed is smaller, as indicated in Figure 25 by the distribution curve of concentrations with its peak skewed toward heights lower than the source.

A theoretical analysis of eddy diffusion in shear zones has been undertaken, but it is not clear whether the analysis does, in fact, deal solely or even primarily with turbulent diffusion.(93) Wind speed shear has not been shown to be significant in the analysis of industrial air pollution, although close to a stack the effect illustrated in Figure 25 might become significant in special circumstances.

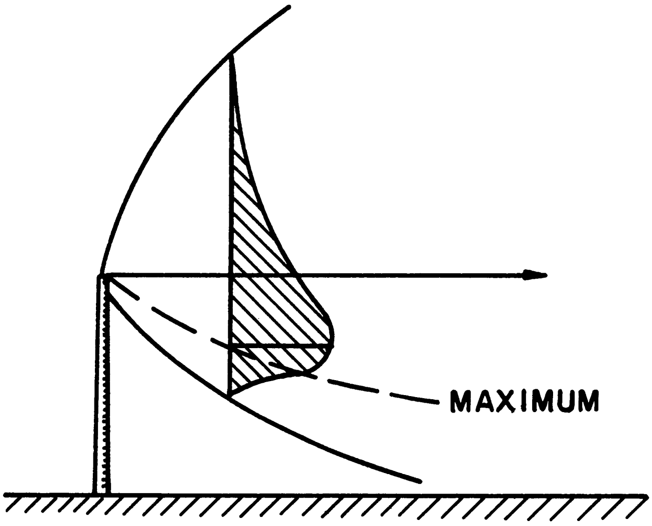

Figure 25. Sketch showing, in exaggerated form for emphasis, the influence of wind speed shear with increasing height in producing a skewed distribution of concentrations along the vertical near the source (after Smith).

Wind speed shear is especially marked in inversions, as shown by Figure 3; when the low-level jet(12) is highly developed as in nocturnal inversions, the wind speed shear may be especially pronounced. However, the vertical extent of a fanning plume such as occurs under inversion conditions is so limited that the influence of wind speed shear is likely to be small. A greater effect is to be expected with a thicker plume even although the actual wind shear may be smaller.

The Influence of Wind Direction Shear on Plume Deformation and Dilution

The manner in which wind direction shear acts to deform a plume is first described. The influence of this deformation on plume dilution by turbulent diffusion is then considered.

Plume Deformation--The action of wind direction shear in deforming a plume is most readily seen by a simplified example, such as that illustrated in Figure 26. Consider first a wind with no direction shear present blowing perpendicularly into the paper; at some distance downwind from the stack a cross section of the plume is shown, represented for convenience of discussion by the small square whose sides each of length a are drawn by broken lines. Next consider the same layer in which the average wind direction is the same, i.e. blowing perpendicularly into the paper, but now with a wind direction shear greatly exaggerated for purposes of illustration. The cross section of the plume at the same distance downwind from the stack is now the small parallelogram shown by full lines. Since the length of the horizontal top and base is each a and the length of each sloping side

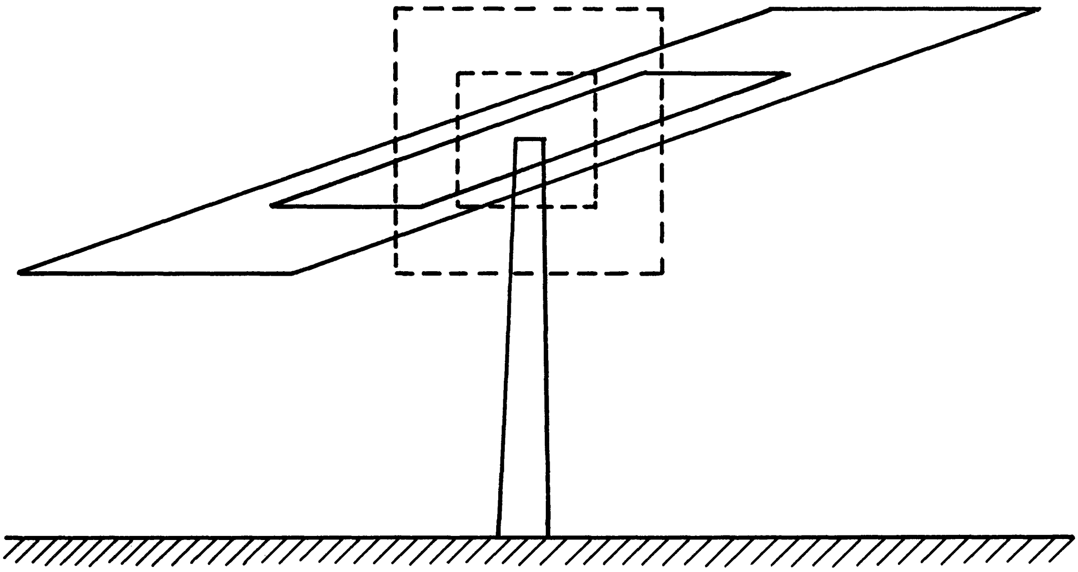

Figure 26. Simplified representation of deformation of a plume by wind direction shear. Squares show cross section of plume without direction shear at two distances from stack; parallelograms show corresponding cross sections of plume with wind direction shear, chosen extreme for purposes of illustration.

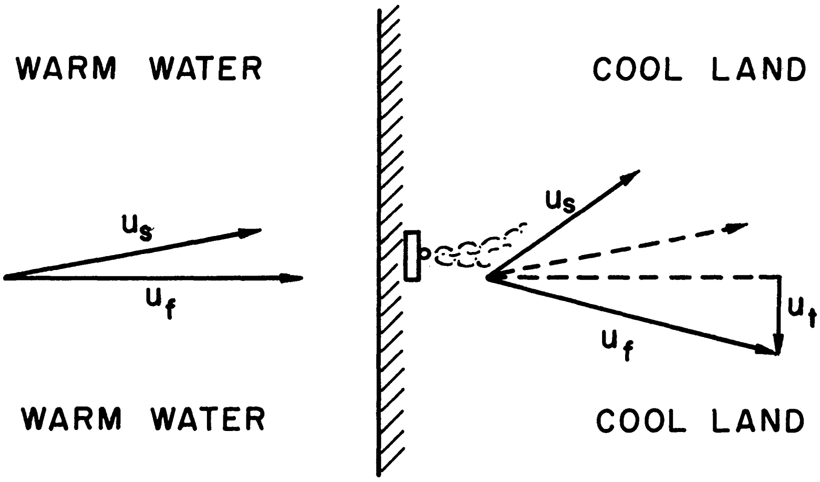

Figure 27. Diffusion in transitional states during the autumn and early winter at a shoreline plant location P. Wind direction shear is much greater over the cool land than over the warm water owing to greater surface friction over the land plus the effect of the thermal wind over the land; the result is increased deformation and dilution of a plume under such conditions.

is drawn to be 3a, the perimeter of the small parallelogram is 8a, just twice the perimeter of the small square which is 4a. The cross sectional area of each is the same, however, and equal to a^2. The large square and parallelogram represent corresponding cross sections of the plumes at twice the distance downwind from the stack. The cross sections would, of course, be more appropriately shown as circles and ellipses, and essentially the same conclusions hold for them, i.e., wind direction shearing of the indicated amount results in doubling the perimeter of the plume without increasing its cross sectional area.

Plume Dilution--Deformation of a plume by wind direction shear of the type illustrated in Figure 26 may have a substantial effect on dilution of a plume by turbulent diffusion. Since mixing of the plume with the surrounding clean air occurs around the perimeter of the plume, if a large direction shear doubles the perimeter it will also, perhaps only approximately, double the rate of dilution of the plume by turbulent mixing. The direction shear shown in Figure 26 is excessive. A smaller shear will have a smaller but still significant effect.

Dilution of a plume by wind direction shear will be pronounced when the plume is spread vertically by turbulence soon after leaving the stack and an inversion with strong wind direction shear simultaneously grows upward, as at a shoreline plant location. Consider Figure 27, which shows air advancing from a warm lake surface over a cool land surface, a frequent occurrence in autumn and early winter. As shown in Figure 1(c), there is limited wind direction shear over the water, perhaps 10° from the water up to the level of free atmospheric flow u_f. The large lapse rate in the air reaching plant P ensures active turbulence and rapid vertical diffusion of a plume. At the same time, however, an inversion develops as the air crosses the shoreline and moves from the warm water on to the cool land. Mechanical turbulence over the land causes rapid upward growth of the inversion top, at a rate which may be calculated from Equations (34) or (35).

When there is a strong horizontal temperature gradient such as shown in Figure 27 the wind changes direction with height, the change being specified by the thermal wind component u_t.(102) The magnitude of the thermal wind component is given by

$$u_t = \tfrac{1}{2}g \, \Delta z(T_2 - T_1)/Td \, \omega \sin \varphi \qquad (43)$$

where g is the acceleration of gravity, 9.8 m $\sec^{-1}$; Δz is the thickness of the layer; T_2 and T_1 are the average temperatures in degrees Kelvin of the warm and cold air respectively a horizontal distance d apart; T is the average of T_2 and T_1; ω is the angular velocity of the earth, 7.29×10^{-5} radians $\sec^{-1}$; and φ is the latitude. The direction of u_t is specified by the rule that if a person faces the cool air with his line of sight at right angles to the cool air isotherms (lines of constant temperature), the thermal wind component is directed to his right in the northern hemisphere, to his left in the southern hemisphere. Thus in Figure 27 the thermal wind component u_t causes the free air flow u_f over the cool land to veer 15° from its direction over the warm water.

In addition, surface friction over the land in the inversion causes the surface wind u_s to back perhaps 25° from its direction over the water in a manner similar to that of the night wind u_s in Figure 2; the daytime strong lapse corresponds to the strong lapse over the warm water and the night radiation inversion corresponds to the advection inversion over the cool land. Thus the wind direction shear over the water of 10° increases to $25° + 10° + 15° = 50°$ over the land, a value 5 times as great. If, in addition, the free wind level where u_f is first attained drops over the cool land to one-half its value over the warm water, the actual gradient of wind direction change will be 10 times greater over the land than over the water.

With the plume initially well spread out vertically near the stack, this wind shear in the inversion would lead to a large deformation in the plume, although not as large as suggested in Figure 26, with dilution by turbulent mixing being substantially greater than with a ordinary fanning plume. Diffusion of this type may be referred to as "diffusion in transitional states."

A similar type of diffusion occurs in the spring and early summer at a shoreline location. The land is warm and the water cool. Figure 28 presents a detailed description of the behavior of the plume. Because of the relatively smooth lake surface the vertical growth of the inversion is much slower, in the case illustrated reaching the effective stack height h_e only after the air has moved 50 km out over the lake surface. The figure illustrates clearly the deformation of

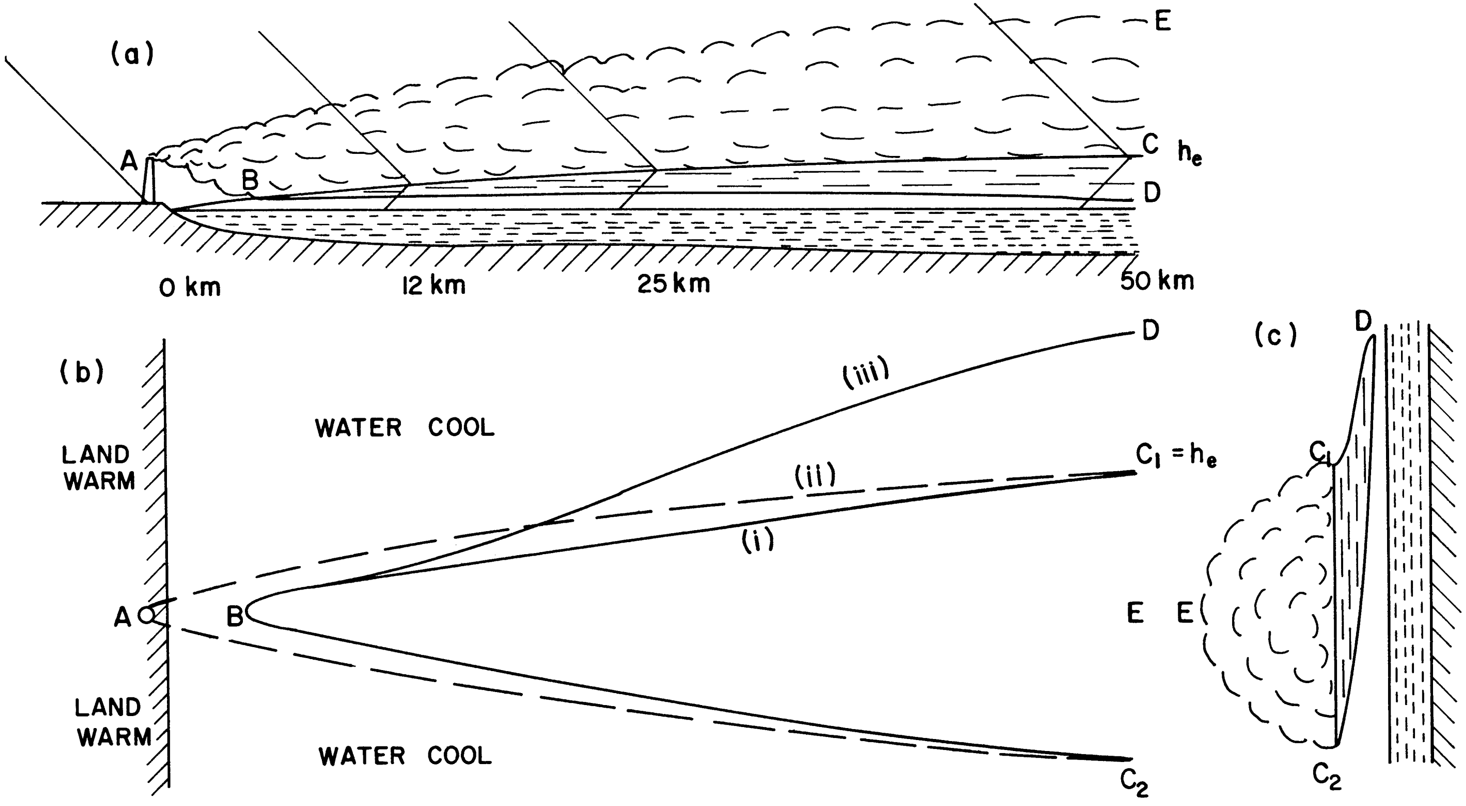

Figure 28. A sketch of a shoreline pattern of diffusion from stack A found in spring and early summer: (a) a vertical section showing inversion heights, the first at B, at successively greater distances from the shore, reaching a height C equal to the effective stack height h_e at a distance of 50 km from the shore; below the inversion top vertical diffusion is extremely slight, whereas above it the plume is coning; (b) a view from above showing (i) the outline C_2AC_1 of the coning upper portion of the plume, (ii) the outline C_2BC_1 of the upper portion of the inversion plume which lies below the coning part of the plume, and (iii) the outline C_2BD of the lower portion of the inversion plume showing how pronounced wind direction shear has deformed it; and (c) a vertical cross section at 50 km looking toward the stack which also illustrates the deformation of the inversion plume by wind direction shear.

the inversion plume below the coning plume by wind direction shear of the type shown schematically in Figure 26.

Deposition of Particulates From a Plume

As was pointed out in connection with Equations (8) to (15) inclusive, and indeed applied to the subsequent equations as well, the foregoing analysis applies strictly to gaseous contaminants which are not absorbed at nearby surfaces or to plumes consisting of very fine particles in which there is negligible gravitational settling or deposition on surfaces. For example, a lake surface may absorb appreciable amounts of SO_2 flowing over it.

When deposition of particulates from a plume must be taken into account, an inherently complex problem becomes even more complex.(52) For example, the effect of the atmospheric electric field on deposition of particulates may be greater than that of gravity, but the variability and complexity of the distribution of the atmospheric field and of the electric charge on particles make evaluation of the effect impossible at the present time.(118)

Dry Deposition From An Elevated Continuous Point Source

There have been a number of analyses of this problem.(below)* Only results of most direct and immediate applicability will be mentioned briefly here.

Bosanquet, Carey, and Halton's Relationships--The average rate of deposition D_b in mass of dust deposited per unit area per unit time over a 45° sector downwind from a stack of effective height h_e may

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* Ref. 6, 16, 20, 21, 29, 48, 88, 148.

be expressed as(16)

$$D_b = 1.27 \frac{Qbp^2}{h_e^2} \left[\frac{(f/pu)(h_e/px)^{2+f/pu} \exp(-h_e/px)}{\Gamma\ (1+f/pu)} \right] \quad (44)$$

where Q is the mass of dust emitted per unit time, b is the fraction of time that the wind blows toward the 45° sector, f is the free falling speed of the particles, Γ is the gamma function, and p, u, and x are as specified for Equation (8). The gamma (Γ) functions of the values of (1+f/pu) and values of the free falling speed f of the particles are available.(51) Calculated values of deposition rates based on Equation (44) for the vicinity of the Little Barford Power Station near Cambridge, England(36) are shown in Figure 29. The observed values as given by deposit gages showed poor correlation with the calculated values because analysis of the gage contents proved that a great deal of deposited matter had other origins. One significant conclusion of the investigation was that most of the very fine dust which made up a substantial fraction of the effluent was not deposited within two miles of the plant but was carried away and dispersed at higher levels.

The theoretical axial deposition rate D_a is given by the expression

$$D_a = 0.282 \frac{Qp}{h_e^2} \left[\frac{(f/pu)(h_e/px)^{2+f/pu} \exp(-h_e/px)}{\Gamma\ (1+f/pu)} \right] \quad (45)$$

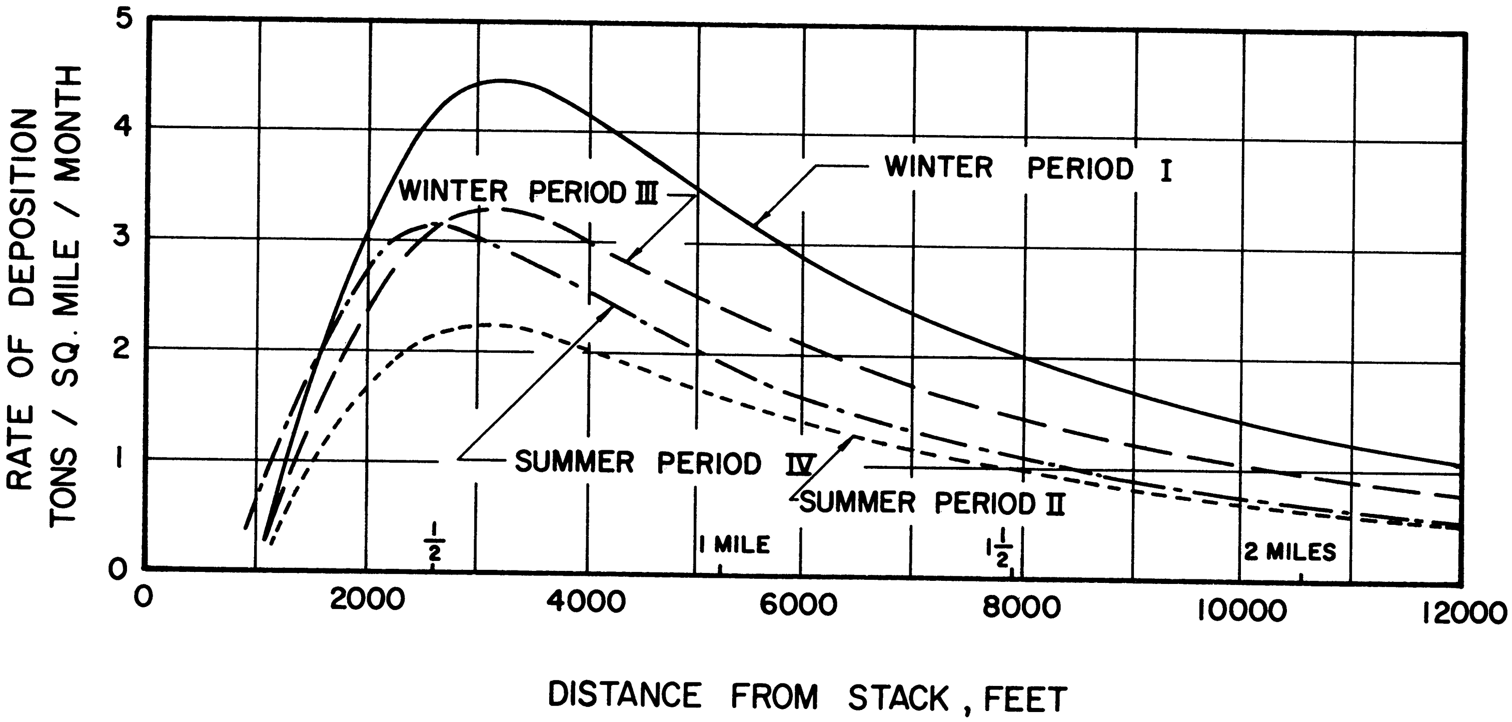

Figure 29. Dust deposition rates, calculated using Eq. 44, near the Little Barford Power Station in the vicinity of Cambridge, England (after England, Crawshaw, and Fortune).

Csanady's Analysis Using Sutton's Basic Equation--Csanady has adapted Sutton's basic equation, Equation (12), so as to allow for the free falling speed f of the particles and also for partial reflection of the particles at the earth's surface.(29) The equation for the mass concentration of the particles is given by

$$X = \frac{Q\,\exp(-y^2/C_y^2x^{2-n})}{\pi\,C_yC_zux^{2-n}}\left[\exp\left\{-\frac{[z+(f/u)x-h_e]^2}{C_z^2x^{2-n}}\right\} + \alpha\,\exp\left\{-\frac{[z-(f/u)x+h_e]^2}{C_z^2x^{2-n}}\right\}\right] \qquad (46)$$

where α is the reflection coefficient which represents that fraction of the downward flux of dust at ground level that is returned to the atmosphere above all turbulence.(82) The rate of dust deposition D in mass of dust deposited per unit area per unit time is given by

$$D = \frac{Qf}{\pi\,C_yC_zux^{2-n}}\exp\left\{-\frac{y^2}{C_y^2x^{2-n}} - \frac{[(f/u)x-h_e]^2}{C_z^2x^{2-n}}\right\}\left[2-\frac{2}{(1-\frac{1}{2}n)(uh_e/xf-1)+2}\right] \qquad (47)$$

Field experiments using a source 15 m high over gently rolling prairie(112) suggest a linear relationship between wind speed and reflection, from $\alpha = 0$ at $u = 0$ to $\alpha = 1$ at $u = 7$ m sec^{-1}. Total reflection is suggested for all wind speeds greater than 7 m sec^{-1}. Soil sampling for uranium compounds around three Atomic Energy Commission plants(88) revealed a decrease of soil concentration which was inversly proportional to the square of the distance from the stack for two plants emitting largely insoluble material, whereas the rate of decrease with radial distance was much less around the third plant which released soluble salts, mainly UO_2F_2.

Dry Deposition from Continuous Ground Sources

Deposition from point and line sources will be described briefly, as well as deposition on living and inert surfaces, and refloatation.

Point Source--Sutton's equation, Equation (36), has been modified by Chamberlain(20) to make allowance for particle deposition. The concentration of particles in mass of particulates per unit volume of air is given by

$$X = \frac{2Q \exp(-y^2/C_y{}^2x^{2-n})}{\pi C_yC_zux^{2-n}} \exp\left(-\frac{4 w_dx^{n/2}}{\pi^{\frac{1}{2}} nuC_z}\right) \exp\left(-\frac{z^2}{C_z{}^2x^{2-n}}\right) \qquad (48)$$

and the rate of deposition as

$$D = \frac{2Q w_d \exp(-y^2/C_y{}^2x^{2-n})}{\pi C_yC_zux^{2-n}} \exp\left(\frac{4 w_dx^{n/2}}{\pi^{\frac{1}{2}} nuC_z}\right) \qquad (49)$$

where w_d is the speed of deposition which specifies the speed at which particles are deposited as a result of the confined effects of turbulence and gravitational settling. For large particles or for light winds and limited turbulence, as in an inversion $w_d \approx f$. For typical weather conditions the values of w_d are found to range from 0.01 to 0.1 m sec^{-1}. Typical peak concentrations and deposition rates on the axis of the plume as calculated from Equations (48) and (49) are given in Table VIII.

At any distance x downwind, the deposition will become a maximum for one particular speed of deposition whose value is given by

$$w_{dm} = \frac{1}{4} \pi^{\frac{1}{2}} nuC_zx^{-n/2} \qquad (50)$$

TABLE VIII

CALCULATED PEAK CONCENTRATIONS AND DEPOSITION RATES ON THE AXIS OF A PLUME FROM A CONTINUOUS POINT SOURCE AT GROUND LEVEL ($Q = 1$ gm sec^{-1}, $u = 5$ m sec^{-1}, $C_y = 0.21$, $C_z = 0.12$, AND $n = 0.25$) (QUOTED FROM GREEN AND LANE, 1957).(58) FOR AVERAGES GREATER THAN SEVERAL MINUTES THE VALUES OF COEFFICIENTS GIVEN IN TABLE VI SHOULD BE USED.

Distance from Source m	Peak Cloud Concentration at Ground Level mg/m^3			Deposition Rate mg/m^{2}sec	
	$w_d = 0$	$w_d = 0.02$ m/sec	$w_d = 0.04$ m/sec	$w_d = 0.02$ m/sec	$w_d = 0.04$ m/s
100	1.6	0.94	0.55	1.9×10^{-2}	2.2×10^{-2}
1,000	2.8×10^{-2}	1.4×10^{-2}	0.68×10^{-2}	2.8×10^{-4}	2.7×10^{-2}
10,000	5.0×10^{-4}	2.0×10^{-4}	0.76×10^{-4}	3.9×10^{-6}	3.0×10^{-6}

The maximum rate of deposition that will occur at a given distance x is given by

$$D_m = nQ/2\pi^{\frac{1}{2}} e C_y x^{2-(n/2)} \qquad (51)$$

A nomogram to facilitate use of this equation is available.(106).

Line Source--A similar type of analysis has been developed for a line source at the ground.(82)

Deposition on Living and Inert Surfaces--In one study, paper "leaves" made of appropriately shaped pieces of Whatman No. 4 filter paper attached to growing plants were exposed to radioiodine vapor, I^{131}, in the open air and in a wind tunnel and comparisons made of the deposition on the leaves of the plant and on the filter paper.(21) The results were as follows:

1. With clover, dandelion, and bean plants, the ratio of the deposition on the leaves of living plants to that on similarly shaped pieces of paper was less than one.

2. The ratio was nearer to unity in good light than in poor light or darkness.

These findings suggest that the uptake of I^{131} by the plant may be limited not only by the rate at which the radioiodine is brought into contact with the leaf by diffusion processes but also by the metabolic condition of the leaf, and in particular on whether the stomata are open or closed.

Refloatation of Dust--The extent to which deposited dust is carried into the atmosphere again depends on a number of factors. Taking the case of dry dusts, a simple equation has been given

$$X = X_0 \, (z/z_0)^{-20f/u} \qquad (52)$$

where X_0 is the concentration of dust maintained at a height z_0 just above the surface of the ground.(97)

Coagulation in Relation to Deposition

A comprehensive review of knowledge of coagulation of particles has been published.(52) Appreciable coagulation in a plume will increase the particle size and thus increase the rate of deposition. For further information the research of Tunitskii(52) and Teverovsky(52) should be referred to. The coalescence of droplets has also been studied.(10)

Wet Deposition From a Continuous Point Source--Wash-Out

The general principles of wash-out of particulates by rain have been discussed earlier in the section on natural cleansing processes in the atmosphere. The industrial problem of immediate concern is the wash-out of particulates from a plume. For a continuous point source at the ground, Sutton's basic equation, Equation (36), has been modified to the form(52,20)

$$X = \frac{2Q \exp(-\Lambda x/u)}{\pi C_y C_z u x^{2-n}} \exp\left[-x^{n-2}\left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \qquad (53)$$

where the scavenging coefficient Λ is the proportion of the cloud above a unit area removed per unit time. The rate of wet deposition by wash-out by rain is given by

$$D_r = \frac{\Lambda Q \exp(-\Lambda x/u)}{\pi^{\frac{1}{2}} C_y u x^{(2-n)}/u} \exp\left(-y^2/C_y^2 x^{2-n}\right) \qquad (54)$$

The scavenging rate which will produce the maximum deposition at a given distance x from the source is

$$\Lambda = u/x \qquad (55)$$

The maximum rate of wet deposition by rainfall that will occur at a given distance x is

$$D_{rm} = Q/\pi^{\frac{1}{2}} e C_y x^{2-(n/2)} \qquad (56)$$

A nomogram for this equation has been published.(106) Characteristic values of the removal of particulates by wash-out are shown in Figure 30.

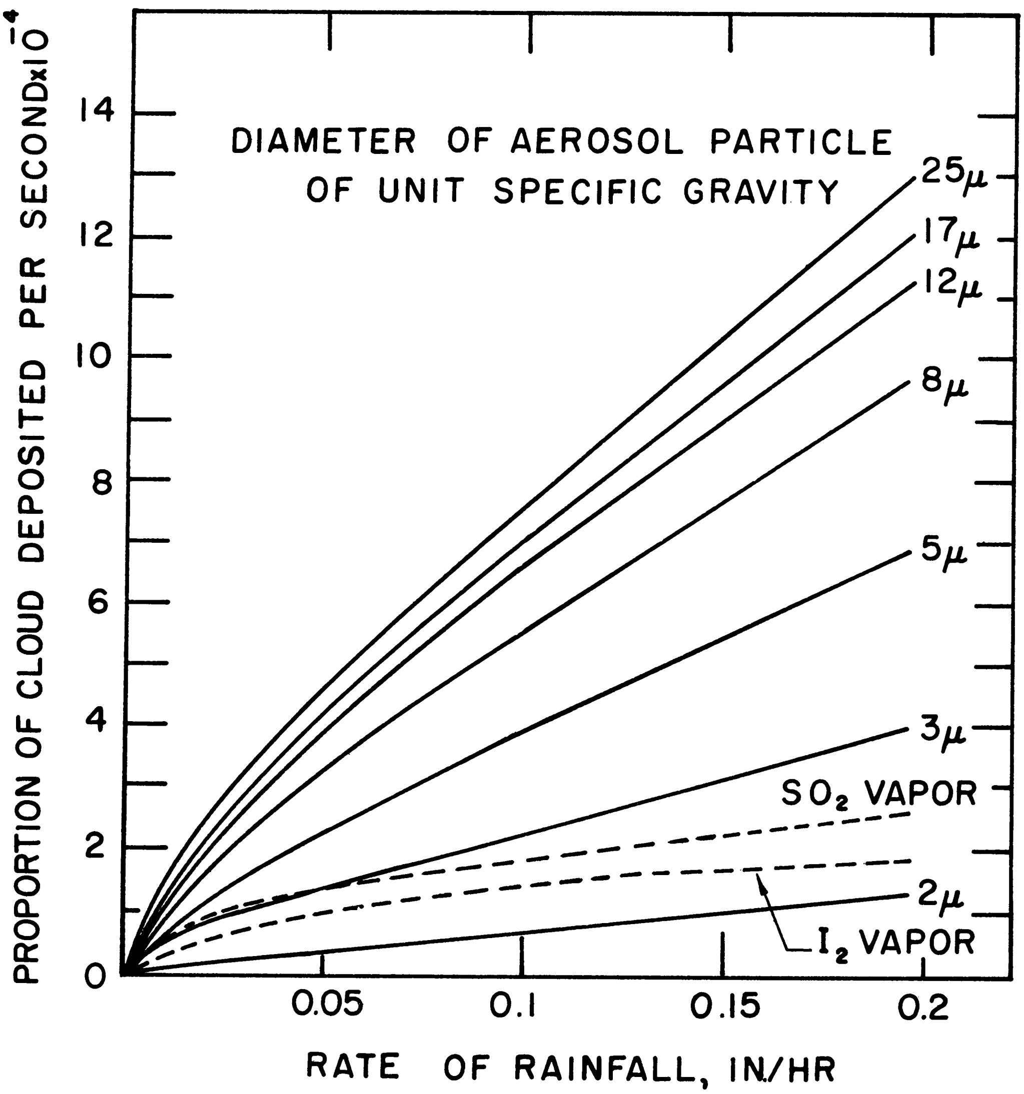

Figure 30. Removal of particles from a plume according to particle size and rate of rainfall, with corresponding curves for SO_2 and I_2 (after Chamberlain).

PLANT LOCATION

The choice of a suitable industrial plant location requires consideration of a number of factors, among which the capability of the atmosphere for dispersing contaminants is becoming increasingly important. There are a number of factors involved, such as regional weather patterns, local weather patterns and the influence of terrain features with which they are often associated, town planning criteria, and possible results of an accidental release of a contaminant.

Regional Weather Patterns

Patterns of regional weather should be among the first factors to be considered. For example, a plant located within the area of influence of one of the great subtropical anticyclones with their extensive and persistent subsidence inversions may produce a substantial air pollution problem. The problem may be especially severe over the region dominated by the eastern portion of the subtropical anticyclone where subsidence is more pronounced than in the western portion.

The prime example of the influence of pronounced subsidence over the eastern portion of a subtropical anticyclone is the Los Angeles smog problem.(99) A comprehensive analysis of the meteorological aspects of air pollution for the whole of California has been made.(8) This study reveals a considerable air pollution potential in other areas of the state, as illustrated by Figure 31. This diagram shows the distribution along the coast of three subsidence inversion parameters: inversion base height, z; inversion thickness, Δz; and inversion stability, $\Delta\theta/\Delta z$. The potential

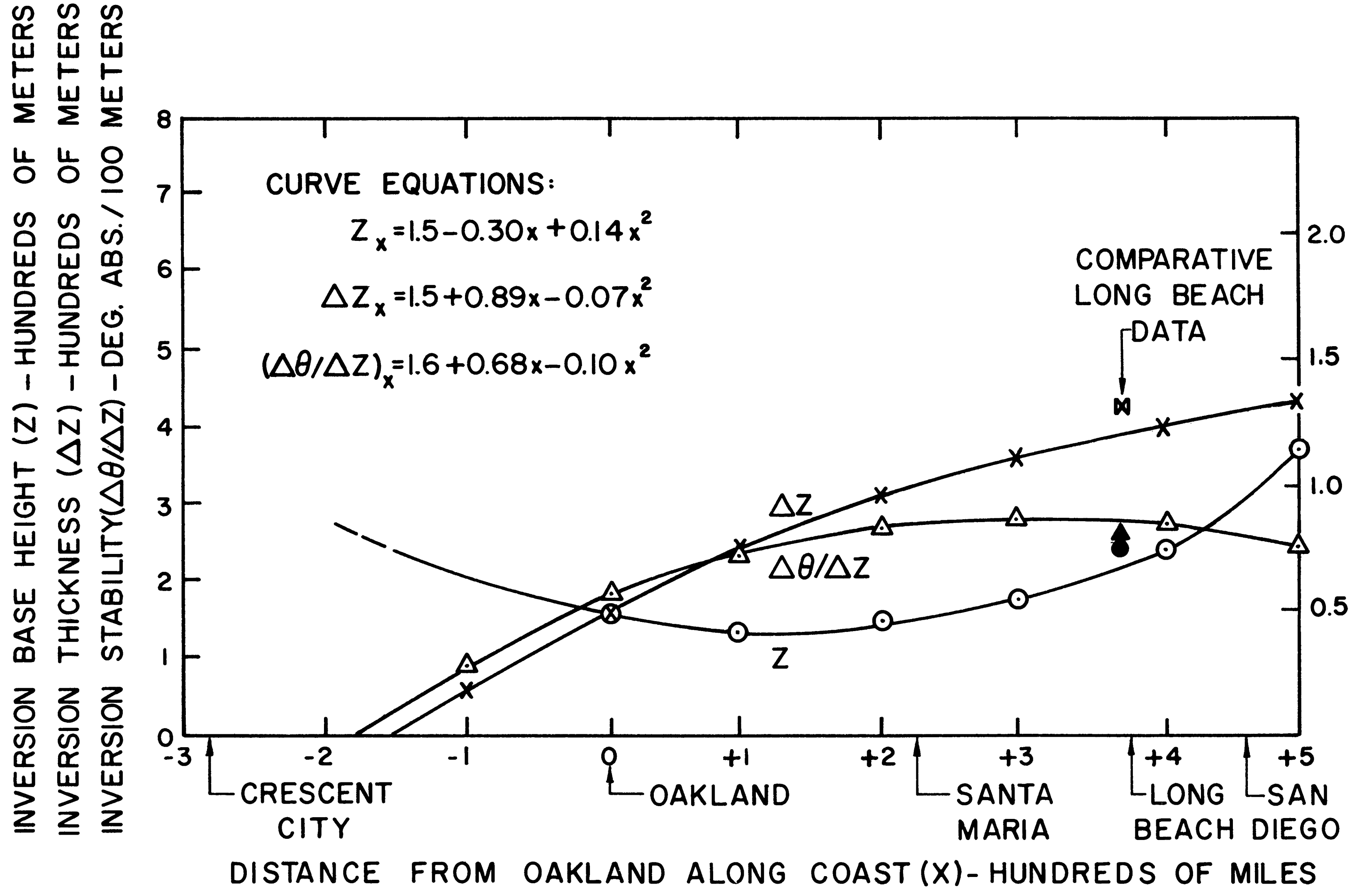

Figure 31. Calculated distribution of subsidence inversion parameters along the coast of California October 1950-51 (after Bell).

temperature θ is a property of air which remains constant during dry adiabatic ascent or descent of the air. For unstable air, $\Delta\theta/\Delta z < 0$; for neutral air, the limiting condition between instability and instability, $\Delta\theta/\Delta z = 0$; and for stable air $\Delta\theta/\Delta z > 0$, the degree of stability increasing as $\Delta\theta/\Delta z$ increases. Thus in inversions $\Delta\theta/\Delta z$ has relatively large positive values. Of the three parameters shown, small values of z lead to the most severe air pollution problems because these limit the vertical thickness of the volume in which active vertical mixing occurs. Figure 31 shows the minimum value of z at a distance 100 miles south of Oakland, indicating that the San Francisco Bay area faces a potential air pollution problem in the autumn which may become, unless preventive action is taken, as serious as that of Los Angeles. The absence of many pollution sources over the Bay itself, limited to pollution produced by shipping, has no doubt prevented the emergence of a serious problem as yet. As more industrial plants locate around the edges of the Bay, however, air quality will deteriorate unless strict control measures are instituted. The topographic features accentuate the problem, of course, at both Los Angeles and San Francisco by reducing wind speeds and limiting horizontal diffusion.

In middle latitudes anticyclones tend to be especially persistent in autumn and early winter and may cause serious air pollution problems for whole cities and regions.(126) This fact is illustrated by Table IX, which gives for the period from January 1899 to June 1939 the number occurrences of anticyclones which persisted three days or longer and which covered the Tennessee Valley within the first or second closed central isobar.(87) Another analysis of stagnant anticyclones,

TABLE IX

TOTAL NUMBER OF THREE-DAY ANTICYCLONES OVER THE TENNESSEE VALLEY, JANUARY 1899 TO JUNE 1939 (AFTER KLEINSASSER AND WANTA)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec.	Total
4	0	1	2	2	3	4	4	9	20	9	7	65

defined as those whose innermost isobar remained in each 10° square of latitude for at least 3 days, has been made for the continental United States for the months August to December, inclusive, for the period 1899 to 1930.(115) The results may be summarized as follows.

August. One pronounced center of stagnation only, in the eastern Great Lakes area.

September. A broader region of stagnation, extending from the Great Lakes to northeastern Texas.

October. One pronounced area of maximum stagnation extending southward from the Great Lakes to Kentucky, with a secondary maximum over North Dakota and eastern Montana.

November. Two pronounced maxima, one over Tennessee and the other over western Montana.

December. One very pronounced maximum over eastern Idaho, with a weaker maximum over Tennessee.

Five-Month Total. Two maxima, one over Kentucky and the other over Idaho.

A more detailed study has been made for the United States east of the Rockies, for each month of the year during the period 1936-1956 inclusive.(89) Using four or more days of stagnation as the criterion, the results for the first seven months of the year are as follows.

January. A weak center of stagnation off the northern coast of Florida: maximum, 4 cases.

February. Similar to January: maximum, 3 cases.

March. A weak maximum over central Florida: maximum, 5 cases.

April. A broak weak maximum centered over the southeastern Atlantic Coast, extending from the east coast of Florida northward nearly to southern Ohio: maximum, 5 cases.

May. A more pronounced center of stagnation over South Carolina: maximum, 10 cases.

June. Two weaker maxima, one off the coast of Georgia and the other centered over eastern Tennessee: maxima, 6 cases in each.

July. One center over Georgia: maximum 4 cases; a second center south of Lakes Erie and Ontario: maximum, 3 cases.

The results for the remaining five months are essentially the same as given in the study described earlier,(115) although there are differences in detail.

The dangers of prolonged stagnation are real. Although medical opinion is divided on the possible long-range health hazards of smog as it ordinarily occurs, it may become lethal to susceptible persons under prolonged exposure in stagnant anticyclonic conditions as the following examples show. During the period 1-5 December 1930, severe air pollution occurred near Liége in the Meuse Valley in Belgium, with 63 deaths occurring on December 4 and 5.(37) A similar disaster occurred in Donora, Pennsylvania during the last few days of October 1948 when 20 persons died. Lethal smogs have occurred in the Greater London area, England at intervals over a period of many years, as follows; December 1873; January 1880; February 1882; December 1891; December 1892; November 1948; December 1952, 4000 deaths; January 1956, 1000 deaths; and December 1957, 300 deaths.(94,126)

Local Weather Patterns

Many of the general features of local weather patterns are related to terrain features, proximity to bodies of water, etc., as described in earlier sections. The problems that arise are many and diverse, and only a few representative examples can be given.

Plant Location in Relation to Topography

Four specific cases in which local weather and diffusion patterns are influenced by topography will be discussed briefly: plant location in a valley, near a shoreline, downwind from hills, and upwind from hills.

Plant Location in a Valley--If a plant is to be built near a city in a valley, the question arises as to the relative merits of sites upvalley and downvalley from the city. Unless unusual complicating factors are present, the downvalley site is to be preferred for reasons set forth elsewhere.(69)

Plant Location near a Shoreline--A shoreline location involves a number of special influences, some of which have been discussed earlier in the sections on Shoreline Winds and on Type III fumigations. The various factors are brought together into a unified concept subsequently in the discussion of site selection for nuclear power plants and reactors.

Plant Location Downwind From Hills--When the prevailing wind passes over hills before reaching an industrial plant, the hills may serve either to accentuate or to alleviate the air pollution problem. If the plant is situated near the base of the hills, the plume may be carried downward by aerodynamic downwash in the lee of the hills as illustrated in Figure 32.(124) Lee eddies and such extreme downwash are more likely to occur when the air is relatively stable than when it is unstable. If the hills are rough and irregular in shape and spacing there may be highly localized downwash but the general result is to increase the turbulence and hence the diffusion. If field studies can be arranged, these could advantageously be made under various meteorological conditions by releasing zero-lift balloons(98) from the top of the hill and tracking their motion by triangulation using two theodolites a known distance apart. An alternative method is to photograph a plume of smoke from a specially devised source either at the hilltop or supported aloft from the cable of a kite balloon. If personnel and time are limited, wind tunnel studies of the type illustrated in Figure 17 may be conducted, with suitably scaled terrain included in the model.

Plant Location Upwind From Hills--If the plume is carried toward the hills by the prevailing wind, problems arise only if residential areas or valuable crops or timber stands are situated on the hills. Again zero-lift balloon studies may be made or tracer substances released at the plant site under consideration and sampled on and above the hills under various meteorological conditions.

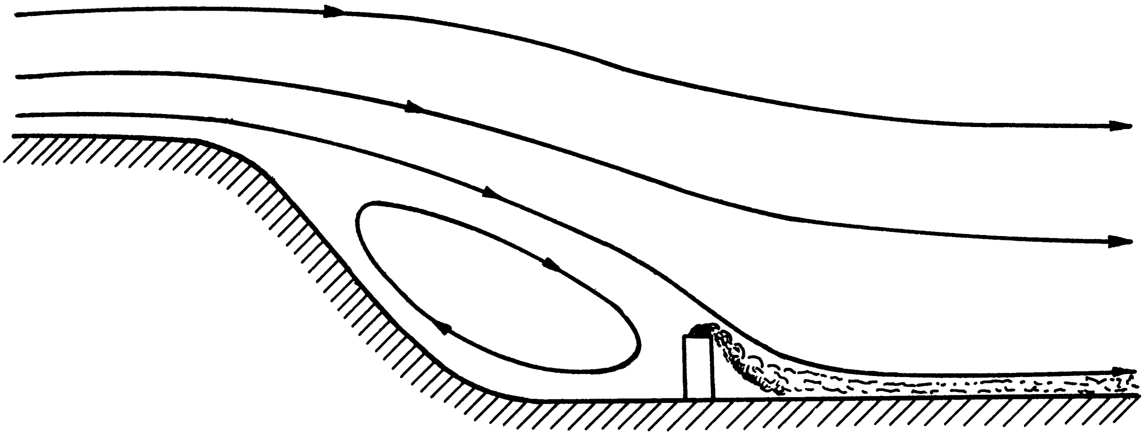

Figure 32. A plume carried to the ground by aerodynamic downwash if the stack is located at the point where the flow rejoins the ground at the lee side of the large eddy after separating at the hill top (after Scorer).

Alternatively, wind-tunnel model studies will give results of general validity although details of plume behavior may not be revealed.(128) Calculations of concentrations on the hills may be made using Equation (12) suitably modified for the presence of the hills. A few general principles for guidance may be stated, such as: if the air is very stable, as in an inversion, it tends to flow around rather than over an individual hill; if the air is unstable, with thermal turbulence present, the air tends to flow over the hill rather than around it. Other than these concepts, very little is known about air flow in the vicinity of a complex of hills.

Baseline Pollution Concentrations in Relation to Meteorological Factors

If it has been decided to locate a plant in an area in which pollution from other sources is likely to occur, it will be advantageous to sample the air in order to determine accurately the existing levels of pollution before the new plant goes into operation. These concentrations may then be used as baseline values on which the contribution of the new plant is superimposed. However, such baseline concentrations will have little value for this purpose unless concurrent observations of wind direction, wind speed, wind turbulence and lapse rate, and precipitation are made. The reason is readily seen: the background concentrations which provide the baseline will vary widely with meteorological conditions, and these will have to be known in determining under actual operating conditions which part of the measured concentration is background and which part is due to the new plant.

Since a new plant is likely to be suspected as the main cause if an increase in pollution levels does in fact occur, this precaution of obtaining baseline concentrations with the appropriate meteorological observations will permit management to determine whether the increase is due to an increase in the background because of a temporary change in the meteorological regime, such as often occurs, or whether the increase is due primarily to the new plant.

Plant Location, Urban Meteorology, and City Planning Criteria

In locating a new plant in or near a city, it is desirable to be acquainted with the types of urban air pollution which may be encountered and the relationship between meteorological and climatological variables on the one hand and city planning criteria which must be observed on the other hand. Table X gives a brief comparison of the two principal types of smog which have been identified.(119)

There are many aspects of weather and climate of cities: these have been comprehensively reviewed and described.(90) The patterns of city pollution in relation to meteorological and climatic conditions have been studied and general descriptions published.(63,1,96,84,80) A start has been made in the analysis of city planning criteria in relation to air pollution meteorology but much remains to be done in this field.(39,113) For example, one important matter is the optimum location of a city airport in order to minimize reduction in visibility resulting from air pollution.(79)

TABLE X

COMPARISON OF TWO TYPES OF SMOG
(AFTER L. H. ROGERS)

Characteristic	Los Angeles	London
Temperature at time of occurrence	75-90°F.	30-40°F.
Relative humidity	< 70%	85% (+ fog)
Type of temperature inversion	Subsidence	Radiation
Wind speed	< 5 mph	Calm
Visibility at time of maximum occurrence	< $\frac{1}{2}$ to 1 mile	< 100 yards
Months of most probable occurrence	August-September	December-January
Major fuel used	Petroleum products	Coal & petroleum products
Principal components	Ozone, organic matter, nitrogen oxides, carbon monoxide	Sulfur compounds, particulate matter, carbon monoxide
Types of reactions	Photochemical plus thermal	Thermal
Effect on chemical reagents	Oxidation	Reduction
Time of maximum occurrence	Midday	Early morning
Principal effects on humans	Temporary eye irritation	Bronchial irritation; coughing; sometimes increased deaths among those with respiratory diseases

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Plant Location and Air Pollution Climatology

The recent development of nuclear reactors and power plants has focused attention on the problem of site selection. The details of an air pollution climatology to aid in site selection for an ordinary industrial plant will first be described briefly.

Air Pollution Climatology for General Industrial Plant Site Selection

Some of the factors to be considered are as follows: meteorological information required; duration of observation period; utilization of existing long-period climatological records in the area; wind turbulence data; sources of data; and methods of analysis.

Meteorological Information Required--The required data are wind direction, wind speed, and wind turbulence. If the site under consideration is in comparatively level terrain and there is a weather observing station nearby, the wind direction and speed records available there may be sufficient. If the nearest weather station is located in an area having different topographic surroundings, it will be desirable to take some wind observations at the proposed plant site for comparison with those at the regular weather station. The observations should include direct measurements of wind turbulence or, alternatively, lapse rate measurements from a tower at least 100 ft high.

Duration of Observation Period--For most purposes a wind speed and direction record for the preceding five years will form an excellent basis for an air pollution climatology. If no topographical complications are present, the five-year record from the regular weather station may be taken to apply directly to the plant site. If topographical complexities make a program of measurement at the plant site necessary, observations for a full year at the site would be ideal but are rarely if ever possible; the minimum is continuous recording of wind direction, speed, and turbulence for a full month.

Utilization of Existing Long-Period Records--If a short record of observations at or near the plant site is to be used to aid in the interpretation of a longer record taken some distance away, certain precautions should be observed. For example, the values should be homogeneous, i.e., the variations should be due only to climatic influences. A series may not be homogeneous owing to instrumental errors, observation errors, changes in exposure of the instruments, etc. The relative homogeneity of the two series of observations should be established. A climatological series is relatively homogeneous with respect to a synchronous series at another place if the differences (or ratios) of pairs of homologous averages constitute a series of random numbers that satisfies the law of errors. The relative homogeneity may be tested using Helmert's Criterion or Abbe's Criterion.(25) Wind speeds have been shown to obey a Pearson Type III distribution law, and methods of analyzing winds for frequency and duration in ways appropriate for air pollution studies have been developed.(127)

Wind Turbulence Data--Wind turbulence in air pollution climatology presents a special problem because, unlike wind direction and speed, it is not a standard weather element which is regularly measured. Thus if only routine measurements are available, as for a five-year period, the best that can be done is to infer diffusion conditions from the frequency of light winds and clear skies at night which suggest radiational inversions and plume fanning, of light winds and clear skies during the day which indicate superadiabatic unstable lapse rates and looping plume conditions, and of moderate wind speeds which suggest plume coning either day or night. Such inferences should be made on a seasonal basis. If recorder charts of speed or direction have been kept or arrangements can be made to have current charts kept for analysis, the fluctuations shown may be used to evaluate the turbulence by means of Equations (2, 3, 4, or 5).

If it is found necessary to take observations for a month or longer, these should include measurements of speed or direction fluctuations, or measurements of lapse rate, or of both fluctuations and lapse rate. By careful correlation of these with the simultaneous wind records at the regular weather station, it will be possible to make a reasonably satisfactory extrapolation to earlier conditions and hence obtain a long-period turbulence climatology for the site.

Sources of Observational Data--The best single source for long-period wind records is the United States Weather Bureau* or corresponding national meteorological services in other countries. The military services maintain weather stations from which data may be obtained, and a few other agencies as well.

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* For the nearby sources of wind data and analysis, services available at nominal cost, contact: Director, Office of Climatology, U.S. Weather Bureau, Washington 25, D. C.

Methods of Climatological Analysis--The general methodology of climatological analysis has been described.(25) and the specific types of analysis suitable for air pollution surveys have been presented.(38) Additional references to publications containing descriptions of methods of climatological analysis are given in the next section.

Air Pollution Climatology for Nuclear Reactor and Nuclear Power Plant Site Selection

There have been a variety of analyses of the numerous factors, including climatology, which enter into site selection for nuclear installations.(below*) The characteristic analysis is similar in many ways to that described above, but there are several important differences.

Special Features of Climatological Analyses for Nuclear Installations--The most striking difference is that a radioactive contaminant need not come into physical contact with humans and animals to exert a harmful effect. A radioactive cloud overhead may subject an individual to a substantial dosage of radiation, the sum of which is known as the "total integrated dosage." A second factor is that the potency of the radioactive contaminant decreases with time: its "half life" may be expressed in minutes, days, months, or years. A third factor, of particular meteorological interest, is that wash-out by precipitation assumes enhanced importance.

Such wash-out may be beneficial or otherwise, depending on circumstances. If rain brings the contaminant to the ground over an uninhabited area, the result is a desirable one. On the other hand, if rain brings the radioactive material to the surface over a city and leaves buildings, vegetation, streets, etc. highly contaminated, the result is disastrous.

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* Ref. 106,149,145,26,103,49,61,92,72.

Principles and Application of Climatological Analysis--Some of the principles of analysis will be illustrated by a brief analysis of a simplified problem in plant location.

Problem: A deep lake at latitude 40°N is 20 miles long and 5 miles wide, with its long axis lying in an eastwest direction. The surrounding terrain is low and relatively flat. The only highly populated area in the vicinity is a city at the midpoint of the north shore. A nuclear power plant is to be built on the lake shore. What are the relative merits from an air pollution point of view of the plant location being chosen at the midpoint of

(a) the west shore;
(b) the south shore;
(c) the east shore

considering,

(i) the routine operational release of small amounts of radioactive contaminants as required for plant maintenance?

(ii) the accidental release of large amounts of radioactive contaminants?

Analysis: The role of each significant weather element at each site will be discussed briefly.

Wind Direction--The prevailing westerlies make the west site the least attractive. A wind-rose analysis will permit a more precise assessment of the relative merits of the three sites. The terrain is low and flat so that there will be no slope, valley, or canyon winds. There will be land and lake breezes but these, by themselves, are unlikely to carry radioactive materials from any of the three sites to the city.

Wind Speed--The differences in wind speed among the three sites will be small, on the average, and unlikely to be significant in this analysis.

Wind Turbulence--In autumn and winter the lake, being deep, will remain unfrozen and relatively warm. Cool winds, whether from the east or west, will tend to become unstable and lead to excellent diffusion as they flow over the warm lake. There will be less diffusion over the lake with warm east or west winds. South winds will be warmer and hence less unstable over the lake, so that diffusion will be less than with cool east or west winds. On clear nights radiation inversions will develop over land and lead to a fanning plume; if the fanning plume extends over the lake a Type III fumigation might occur, possibly near the city. If the ground is snow covered, a Type III fumigation might occur during the day as well and persist for a considerable period.

Low cold frontal inversions as shown in Figure 22(a) occurring with surface west winds may cause trapping of a plume of the type illustrated in Figure 23(f), but strong horizontal diffusion in the mixing layer below the inversion combined with the relatively short duration of trapping because of the characteristic rapid movement of cold frontal systems will tend to minimize the problem. Low warm frontal inversions which are often accompanied by surface winds from the sector south through east may also lead to plume trapping; because warm frontal systems are in general slower moving than cold ones, a trapped plume flowing from the south or east shore toward the city would tend to last longer than one from the west shore moving toward the city. Persistent subsidence inversions in stagnant anticyclonic conditions are most likely to occur in autumn and winter, but these may be expected to influence plume characteristics at all three sites equally. Trapping concentrations may be calculated with the aid of Equation (24).

In spring and summer the lake will tend to be cooler than the adjacent land area, especially during the day. Pronounced advection inversions will develop over the lake with warm west, south, and east winds and lead to plumes of the type illustrated in Figure 28. If such a plume extends across the lake and to the city, mechanical and thermal turbulence induced as the air moves over the warm land will bring the materials previously confined within the advection inversion down on the city. With cooler west and east winds the effect will be less pronounced.

Precipitation--During the summer in a primarily continental area the precipitation will occur mainly as showers, as in thunderstorms, with the shower clouds moving from the southwest and at times from west southwest.(73) Thus contaminants from the west-shore site might be carried to the city and washed out on it by showery rainfall. However, thermal turbulence and diffusion are pronounced in such showery conditions, although some of the contaminants might be retained in the surface advection inversion over the lake and washed out on the city. However, the probability of the necessary conjunction of circumstances is very small, and if wash-out did occur it would tend to be small in amount. Furthermore, the development of the advection inversion over the lake will cut off the supply of energy of the shower clouds, so that active precipitation may continue until the city is reached only with the largest clouds, such as thunder clouds.

In autumn, winter, and spring the precipitation will be mainly of the frontal type.(73) Cold front precipitation is of the showery type and is of short duration. It will occur with northwest, west, southwest or intermediate winds, so it is relevant to the west site. The analysis is similar to that for summer showers, the main difference being that the lake will be warm relative to the air, especially in autumn and winter, and shower activity will be enhanced rather than suppressed over the lake. There will be a strong lapse rate rather than an inversion over the lake, with associated strong turbulence and diffusion. As a result the amount of contaminant that might be washed out is very, very small. Warm front precipitation is more widespread in extent and longer in duration and occurs with surface winds from the south, southeast or east and so must be considered in relation to the south and east sites. If, in addition, the warm frontal inversion has a low base, trapping of the contaminants below may occur to further complicate the situation. Warm front precipitation with a low frontal inversion base presents the most serious precipitation problem in this analysis. The wash-out for such a situation may be computed using a combined form of Equations (24), (53), and (54).

Refloatation--The problem of refloatation of radioactive particulates has been discussed in the literature,(61) and should be mentioned in this analysis. Although refloatation of particulates deposited on the lake surface is not expected, deposition on a nearby land surface and subsequent refloatation should be considered. A detailed evaluation would require a substantial study of dry and wet deposition in relation to wind direction, precipitation occurrence, etc. for each of the three possible sites.

Details of Analysis--Space does not permit describing all the details of such an analysis. For example, one portion of an analysis of a lake shore site includes 67 tables and 32 figures, two of which are Figures 12 and 14, in which the analysis of the data is set forth.(72)

Synthesis: Assuming that the power generated by the nuclear plant is to be used by the city, one nonmeteorological factor appears immediately: the transmission line length for the west or east sites would be half that for the south site. Coming to climatological factors, the south site suffers from the fact that it is less than half as far from the city as the west and east sites, and hence affords less distance for dilution of a contaminant to take place. Practically all the other climatological considerations are against the south site, making it the least desirable. The principal drawback of the west site is its location with respect to the prevailing westerly winds; on the other hand, these favor the east site. The main disadvantage of the east site is the possibility of trapping of a contaminant under a low warm frontal inversion, either with or without wash-out of particulates by precipitation.

Since routine operational releases of small amounts of contaminants required for maintenance presumably may be scheduled in accordance with meteorological conditions, so that releases during warm frontal inversion trapping can be avoided, the east site is clearly the best from the point of view of routine operations. The advantages of the east site considering the possibility of an accidental release are less clear cut. A fully reliable evaluation of the accidental release problem would require a detailed study of the frequency of occurrence of warm frontal inversion trapping, both with and without precipitation, at the east site in comparison with the other factors at the east site and those at the west site.

In the absence of such a detailed study, however, and considering both routine operations and a possible accidental release, the east site may be taken as the most desirable, the west site as less desirable, and the south site as the least desirable.

PLANT DESIGN AND LAYOUT

With a knowledge of the various meteorological and climatological factors involved, it is possible to arrange individual buildings, structures, dumping areas, etc. in an industrial plant complex in such a way as to minimize air pollution problems within the complex and in the near vicinity.

Plant Design and Layout to Minimize Aerodynamic Downwash

The primary guiding principle to be followed in order to minimize the undesirable effects of aerodynamic downwash is to see that sensitive buildings and areas are not located where they will be subject to frequent and intense downwash from nearby plumes.

Influence of Building Orientation

The influence of building orientation is brought out in Figure 18, which shows that for a given wind speed, maximum downwash occurs when the wind approaches a plant building at an angle of about 45°. Accumulated experience gained with many wind tunnel studies of the kind illustrated in Figure 17 indicates that relative downwash varies with building orientation with respect to prevailing strong winds in the manner shown in Figure 33.

Influence of Position of Stack Relative to Building

Both wind-tunnel studies and field experience indicate that a stack position upwind from the building is preferable to one downwind from the building, as suggested by Figure 34. The reason is readily apparent: in the downwind location the stack orifice is in the region of maximum downsweep of the streamlines of air flow, whereas upwind the plume gains height in going over the building.

Influence of Orientation of a Line of Stacks

Valuable data have been obtained from one of the larger TVA (Tennessee Valley Authority) steam power plants.(41) The plant consists of 10 units each served by a 250-ft stack. Sulfur dioxide records were made as each successive unit was built and put into operation. Table XI shows the maximum average relative SO_2 concentration averaged over 30-min

TABLE XI

MAXIMUM AVERAGE RELATIVE SO_2 CONCENTRATION, ONE TO TEN UNITS (AFTER GARTRELL, THOMAS, AND CARPENTER).

Units on Line	1	2	3	4	5	6	7	8	9	10
Relative Concentration	1.0	1.9	2.7	3.3	3.9	4.4	4.7	5.0	5.1	5.2

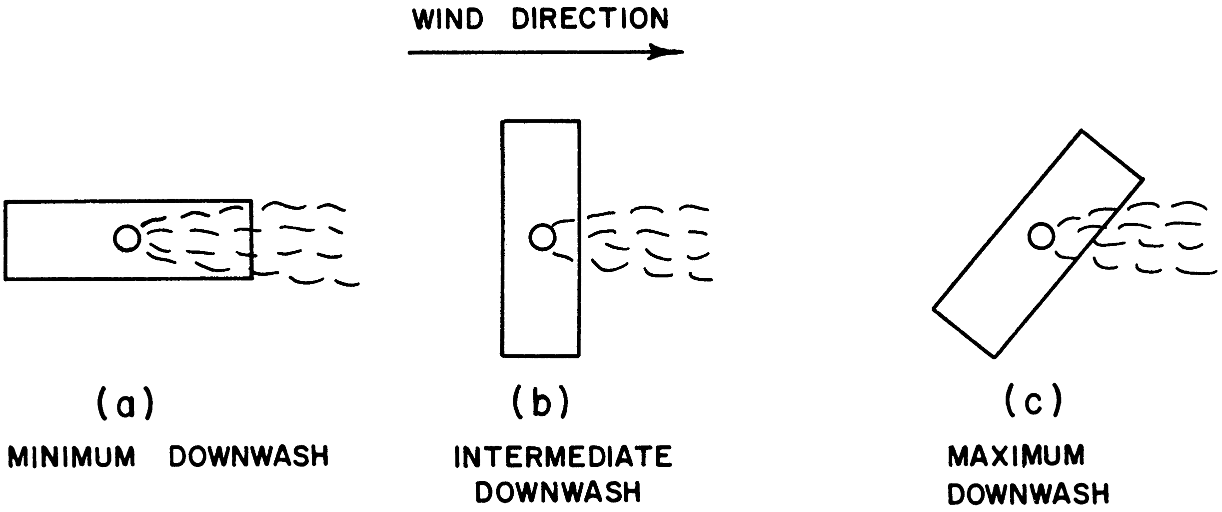


Figure 33. Variation of aerodynamic downwash with building orientation in relation to direction of prevailing strong winds.

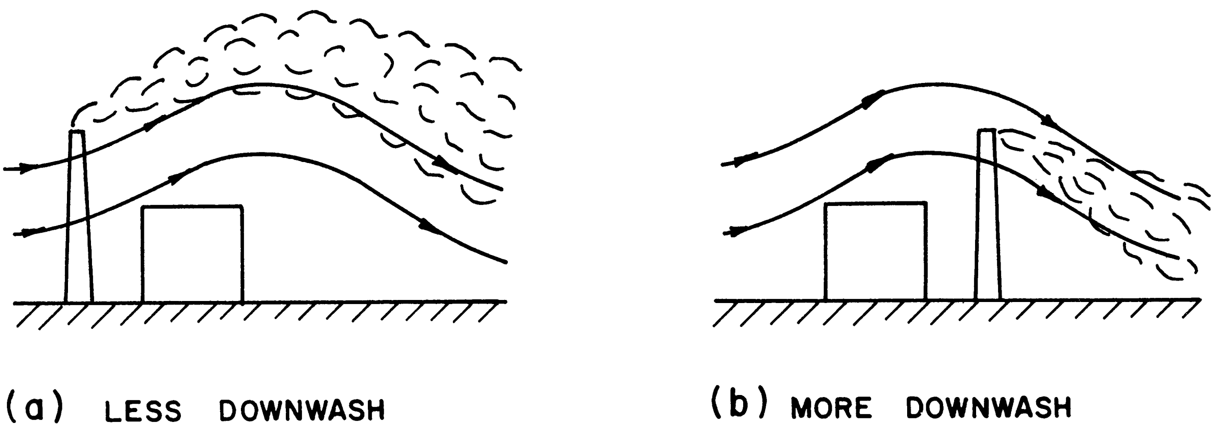


Figure 34. Variation of aerodynamic downwash with position of stack relative to building.

periods as recorded by an instrument located approximately 1.5 mi from the plant in a direction normal to the long axis of the plant and the line of stacks and in the direction of the most frequent wind travel. A recording SO_2 sampler located in line with the stacks showed a similar increase as the number of units in operation increased; this somewhat unexpected result was attributed to increased buoyancy of the effluent as the wind blew along the length of the plant and received additional heating in the process. Another factor not mentioned by the authors is that less aerodynamic downwash would be anticipated for the "in-line" flow as suggested by Figure 33(a) and (b). It thus appears that the orientation of a line of stacks is not of major significance.

Relative Merits of a Single Stack vs. a Line of Stacks

Table XI above suggests that the maximum concentration normal to a line of 8 or 10 stacks may be approximately one-half of that with the same total output from a single larger stack of the same height. However, this conclusion neglects the higher effective stack height of the plume from such a single larger stack. Many cost factors are also involved, and the relative merits are probably best evaluated for each particular plant by calculations based on Equations (13) and (33) used in conjunction with wind-tunnel studies.(68)

Influence of Stack Height

A rule-of-thumb that has been used frequently is that a stack must be at least 2½ times as high as the tallest nearby building if aerodynamic downwash is to be avoided. However, this rule is unsatisfactory for all but the most uncomplicated situations. A more reliable procedure based on calculations used in conjunction with wind-tunnel model studies is available.(68) Figure 35 shows the number of hours per year when, with southwest winds, the concentration of SO_2 in ppm by volume from one stack or four stacks lies within the limits shown over the $22\frac{1}{2}$-deg segmental area to the northeast of the plant. The concentrations for four possible stack heights are shown: 360, 432, 504, and 576 ft. The 3 hours of highest concentrations shown are due to Type I fumigations.

Influence of Stack Shape

The shape of a stack has a pronounced effect on aerodynamic downwash, and especially on downwash occurring as a result of reduced pressure in Kármán or tip vortices shed near the top of a stack as described earlier. Discoloration of the upper portion of a stack by an effluent suggests that aerodynamic downwash of this type is of frequent occurrence. Several stack shapes are illustrated in Figure 36 and their design characteristics with regard to aerodynamic downwash indicated. Designs (a), (b), (c), and (d) are assessed with respect to stack downwash resulting from Kármán vortices; the annulus extending horizontally outward from the stack orifice as shown in Figure 36(d) is effective provided its outer radius is at least three times that of the top of a stack. Such an annulus is installed on a stack located at St. Auban sur Durance, France.(124) The purpose of the nozzle shown in Figure 36(e) is to reduce building downwash by increasing the effective stack height by increasing jet action by means of the nozzle.

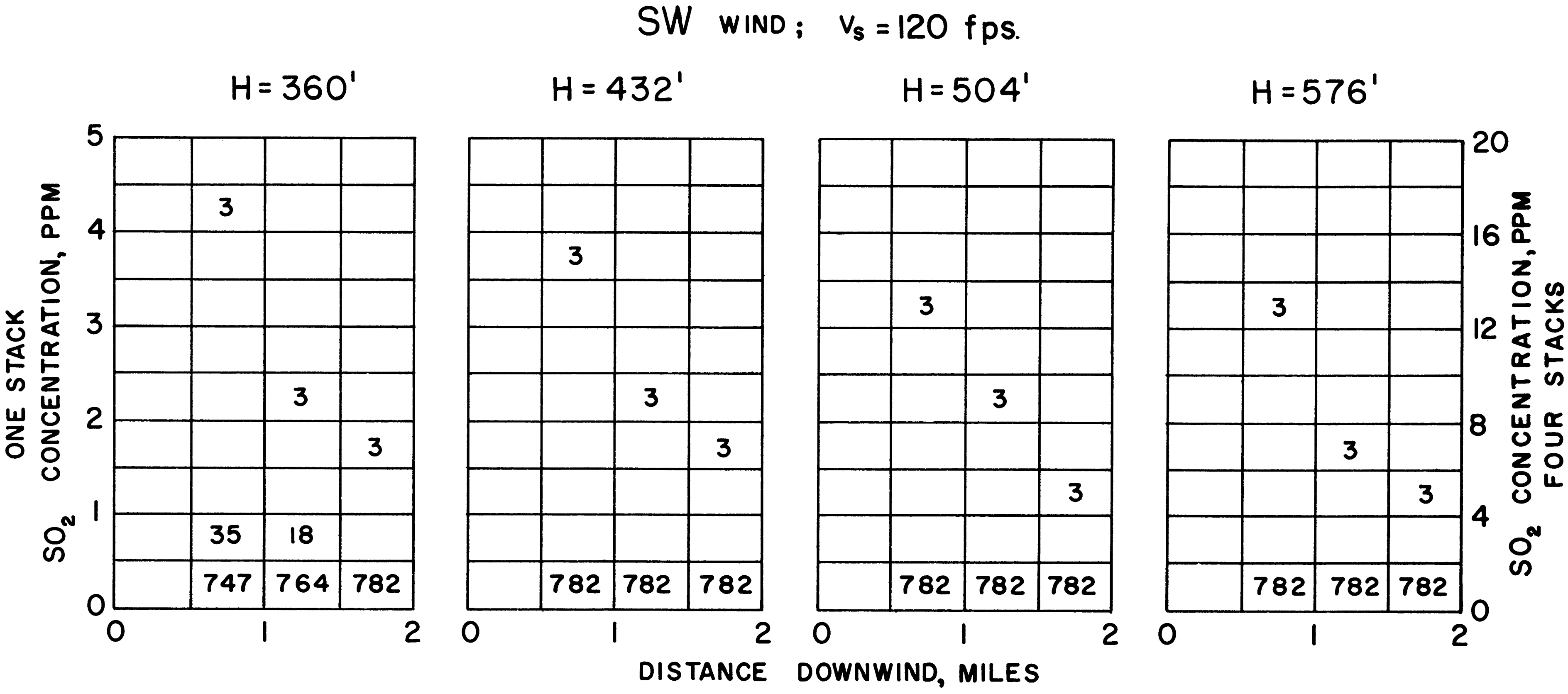


Figure 35. Concentrations of SO_2 in ppm by volume to be expected for four stack heights: 360, 432, 504, and 576 ft. The numbers give the hours per year when the SO_2 concentration lies within the limits indicated over the $22\frac{1}{2}$-deg segmental area to the northeast of the plant. Southwest wind; stack gas exit velocity = 120 fps. (after Hewson).

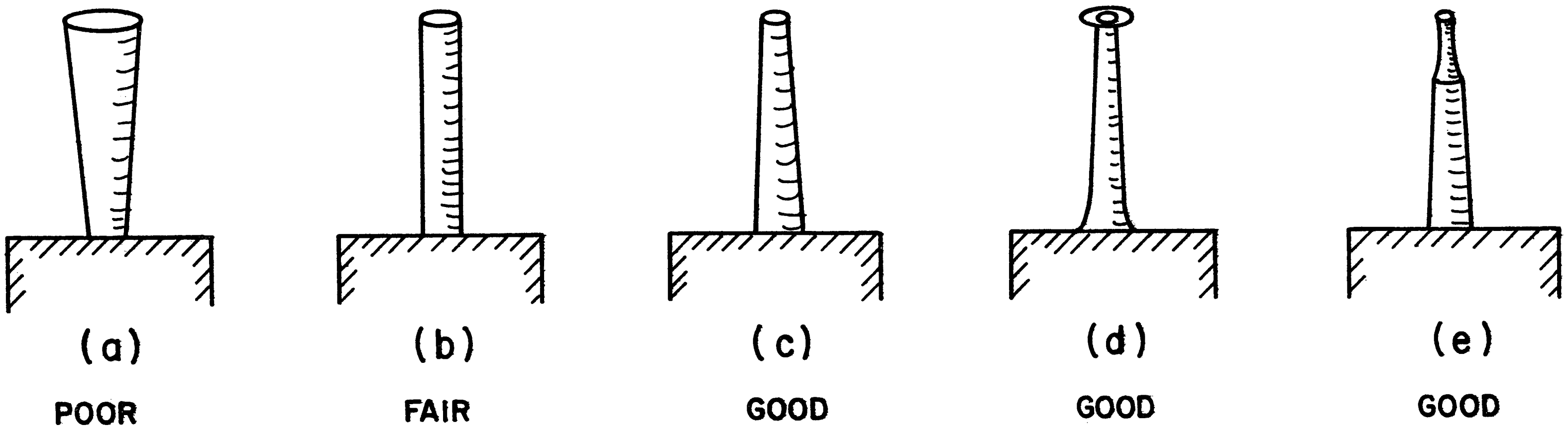


Figure 36. Various stack shapes and their properties with regard to aerodynamic downwash: (a) flared stack, poor design, pronounced stack downwash induced; (b) straight stack, fair design, some stack downwash; (c) tapered stack, good design, little stack downwash; (d) tapered stack with horizontal annulus at top, good design, little stack downwash; (e) nozzle at upper part of stack, good design, little stack downwash and reduced building downwash.

Influence of Terrain Upwind

If a plant is located near a marked terrain feature such as a cliff or bluff, pronounced aerodynamic downwash of a plume may occur as illustrated in Figure 32. The stack height and location required to avoid such downwash may be determined by methods outlined in the text in which Figure 32 is discussed.

Plant Design and Layout to Minimize Effects of Plume Trapping

Plume trapping caused by a low level inversion as illustrated in Figure 23(f) may lead to prolonged and relatively high concentrations near the source. Studies made in the vicinity of TVA power plants show that the highest concentrations near the plants occur with a weak lapse rate of temperature, high winds, and local frontal systems.(41) This conjunction of factors suggests that the high concentrations near the plant are due to plume trapping under low cold or warm frontal inversions, augmented perhaps by aerodynamic downwash. The relative 30-min average ground SO_2 concentrations with maximum values about 2 mi from the plant are shown in Figure 37. Although the plume is described as coning-streamline, it is probably a coning plume trapped by a low level frontal inversion which produces a pronounced streamline motion to the upper portion of the plume, as shown in Figure 23(f), with some aerodynamic downwash superimposed.

Since in the northern hemisphere surface winds from the sector from south through southeast to east generally occur under warm frontal inversions, with such conditions high concentrations are to be expected in the 90-deg quadrant lying to the northwest of the stack, as shown

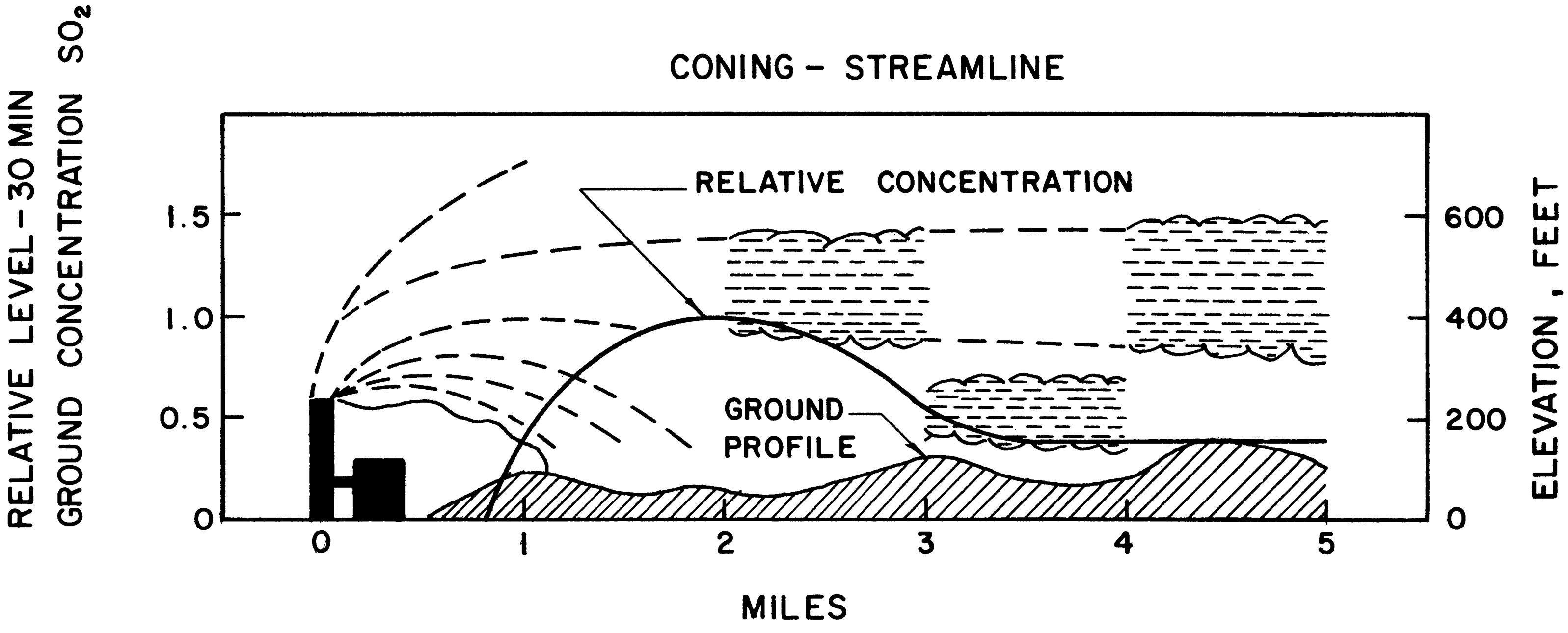


Figure 37. High relative SO_2 concentrations (30-min average) measured near a TVA power plant with high winds and frontal systems nearby (after Gartrell, Thomas, and Carpenter). The high concentrations are probably due to trapping of coning plumes under low frontal inversions acting in association with aerodynamic downwash, the streamline effect being due to the influence of the low frontal inversions on the upper portion of the plumes as illustrated in Figure 23 (f).

schematically by the horizontally hatched area of Figure 38. Similarly, surface winds from the sector from west through northwest to north occur under cold frontal inversions, so that plume trapping is to be expected in the 90-deg quadrant lying to the southeast of the stack, as shown schematically by the vertically hatched area of Figure 38. Clearly the unhatched areas are preferred zones for buildings in which air pollution is to be minimized. The limits of the zones will vary somewhat from one locality to another and will be influenced by local topographic conditions, and may be determined more accurately by an analysis of the actual meteorological observations taken in the area.

Plant Design and Layout to Minimize Effects of Plume Looping

A looping plume sometimes carries pollution to the ground quite near to the base of the stack and thus may present a problem on plant property or in adjacent areas. A simple method of using a bivane to evaluate looping was described in an earlier discussion of looping. Several detailed analyses of looping plumes reaching the ground near an elevated source have been published,(5,31) and these should be referred to for details. The results of one set of experiments are given in Figure 39. Since the source was 185 ft above the ground, the figure shows that on this occasion the plume reached the ground with maximum frequency at a horizontal distance from the source of five times the source height. As would be expected, it was found that for plumes moving downward as they left the source, the horizontal distance at which they reached the ground was directly proportional to wind speed

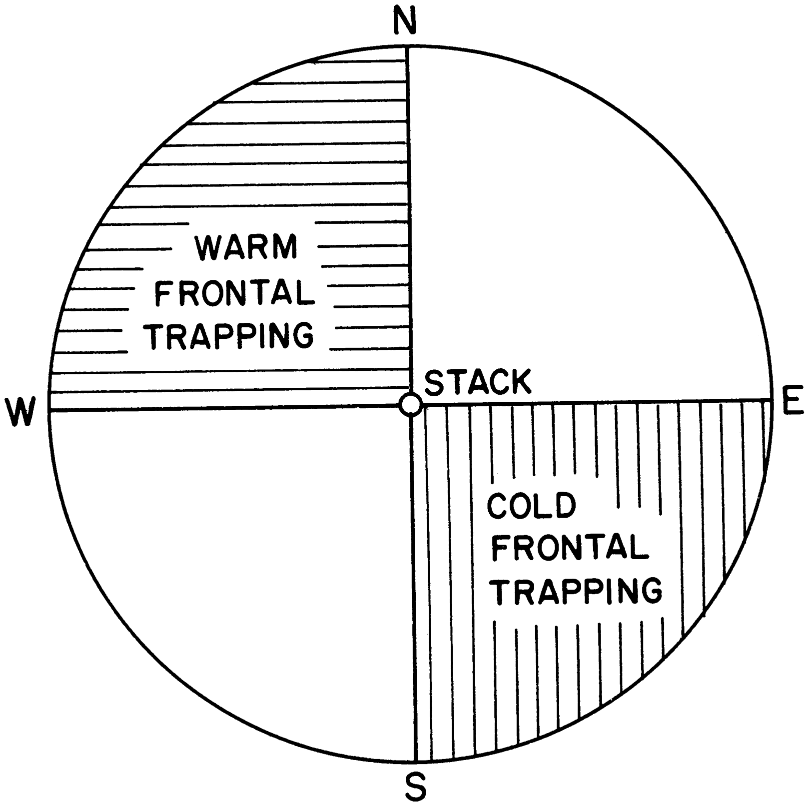


Figure 38. Schematic diagram of quadrants in which, for the northern hemisphere, plume trapping by low level frontal inversions is to be expected. Unhatched areas are preferred zones for buildings in which air pollution is to be minimized.

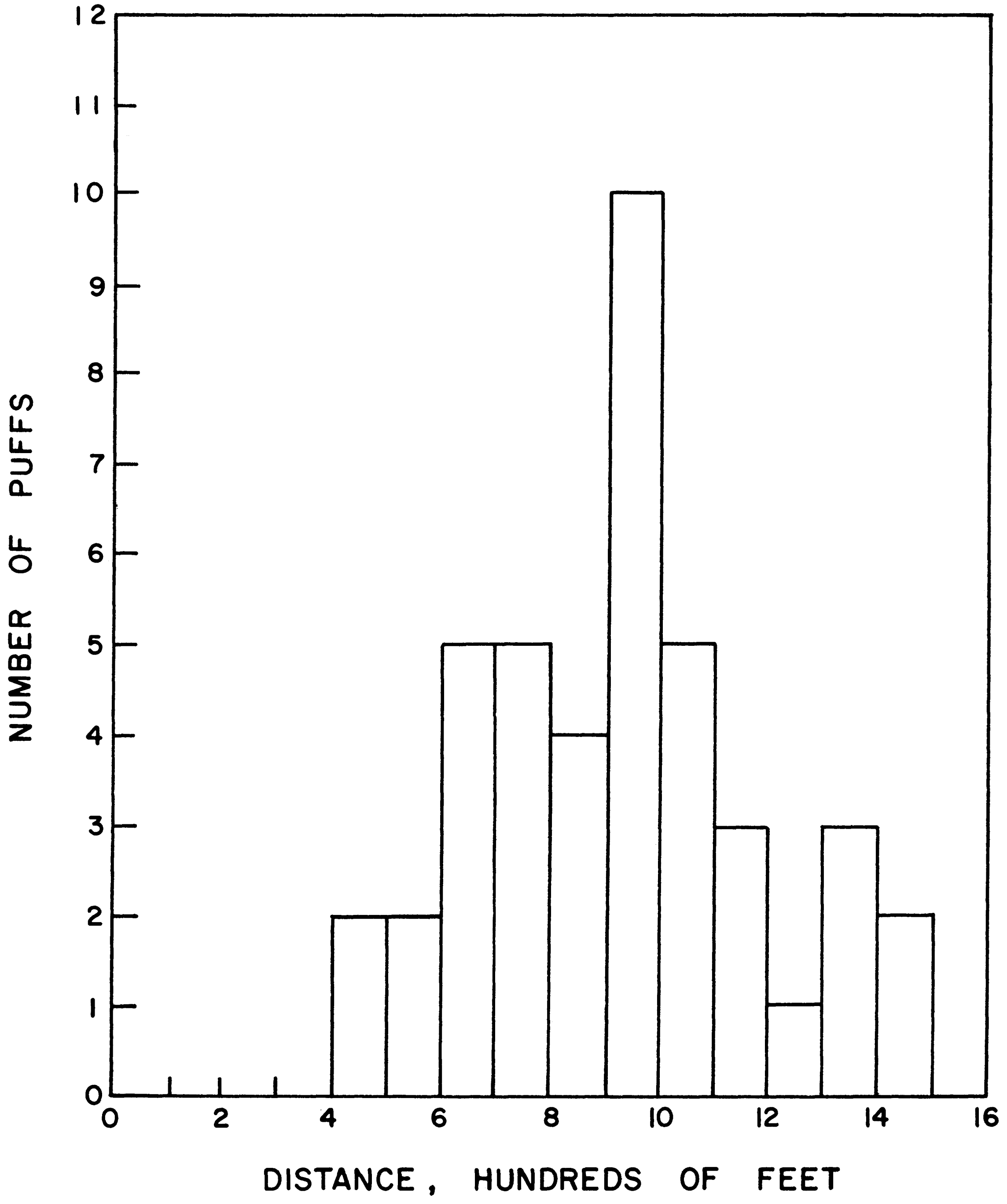


Figure 39. Distribution with distance of looping plumes reaching the ground during a period of 51 min. within 1500 ft of a source located at a height of 185 ft - 22 August 1951 (after Barad and Shorr).

Thus a climatological analysis of wind speeds and directions for the superadiabatic lapse rates in which looping occurs, taken in conjunction with bivane measurements under the same conditions at the height of the top of the stack, will permit a determination of nearby areas which are relatively free from looping plumes. Differences with wind direction, time of day, season of the year, etc. will be particularly pronounced for a plant located at a shoreline or in a valley, so that for these such a study will be especially helpful in locating areas for buildings which will be infrequently visited by looping plumes.

Plant Design and Layout to Minimize Entrance of Stack Effluents into Buildings

Contaminants may enter a building through and around open or closed windows and doors, through small cracks, and through the intake of a ventilating system. An analysis of the penetration of particulates into a small building with natural ventilation only in relation to meteorological conditions, with a bibliography of earlier related investigations, is available.(33)

It is useful to have some method of estimating the probable frequency of occurrence of concentrations at several distances from a stack at which buildings might be located. Valuable data for such a purpose are given in Figure 40. The diagram presents a semi-logarithmic plot of the frequency of 30-min average SO_2 concentrations over a period of one year of stable plant operation recorded by three samplers located 0.6, 1.0, and 1.3 mi from a steam plant belonging to the TVA system.(41) The straight line distributions also provide a convenient means for

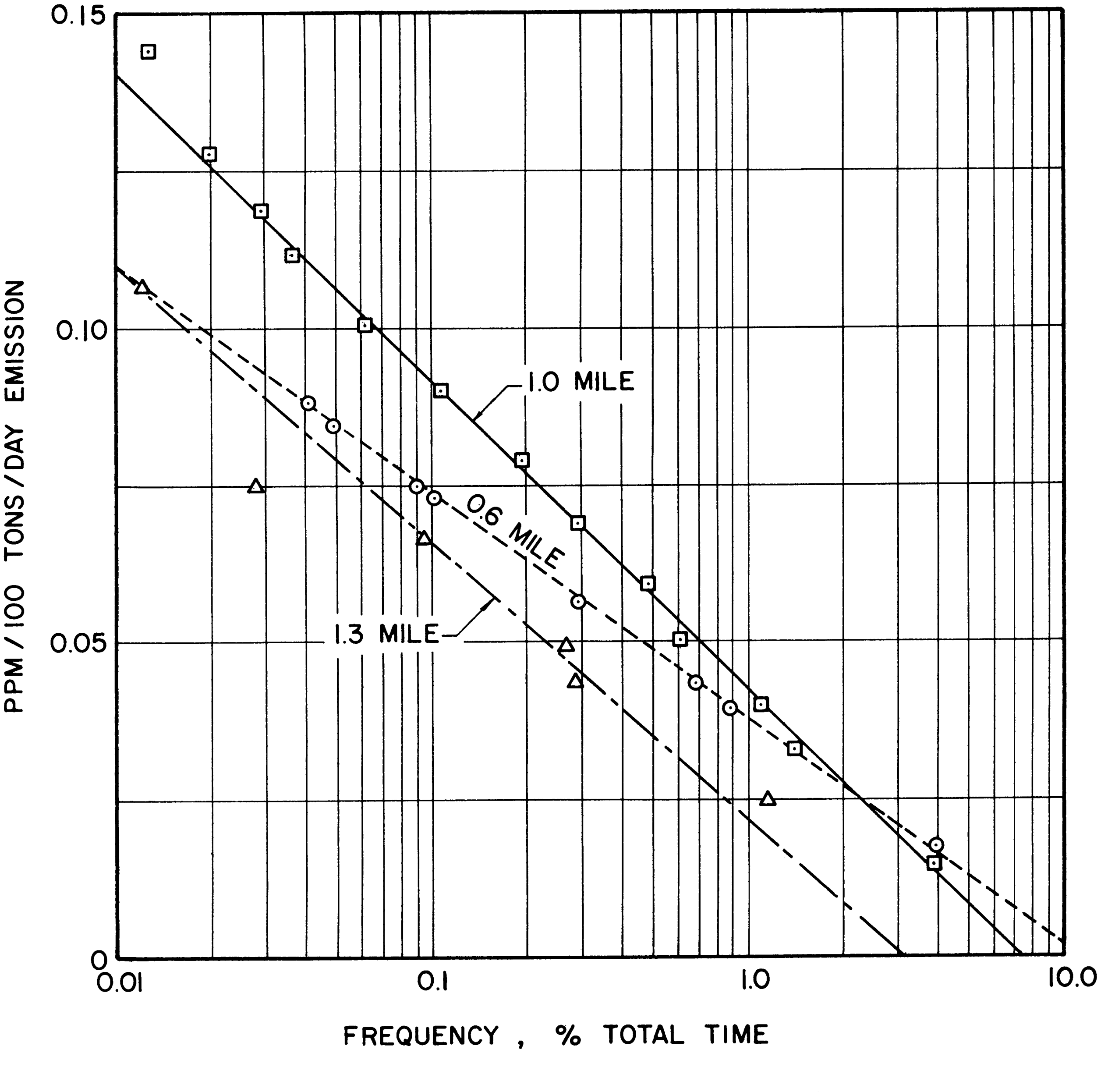


Figure 40. Frequency distribution of specific 30-min average SO_2 concentrations during a 1-yr period near a large steam power plant of the TVA system (after Gartrell, Thomas, and Carpenter).

estimating concentrations beyond the range of actual experience. Values at the 0.01 per cent frequency (two 30-min periods per year) have approximated the maximum SO_2 ground concentrations that have been measured. Similar data for greater distances as well which were obtained near Richland, Washington are available.(40,76) Figure 41 shows maximum average concentrations for periods of 1 to 2½ hours of an effluent from a source 185 ft high as a function of distance from the source for various conditions of atmospheric stability. Corresponding concentrations calculated from Sutton's equation are presented for comparison.(76) Some of the difference between theory and observation may be attributed to differences in sampling period.

It has been found that areas subject to smoke visitations from a single steam plant tend to be highly localized. This fact emphasizes that a careful choice of a building site in relation to major sources of effluents based on adequate meteorological data will minimize the problem of entrance of contaminants into the sensitive building as a result of looping, trapping, and aerodynamic downwash of plumes.

The preceding paragraphs have been concerned with the entrance of contaminants from nearby sources into various buildings which make up an industrial complex and into other adjacent buildings. The behavior of an effluent near the building from which it is released will now be mentioned briefly.(106,57) A major problem is to prevent a contaminant released from short stacks or otherwise from re-entering the building through the intake of the ventilating system. This problem has been approached by means of wind-tunnel model studies,(57) some results of

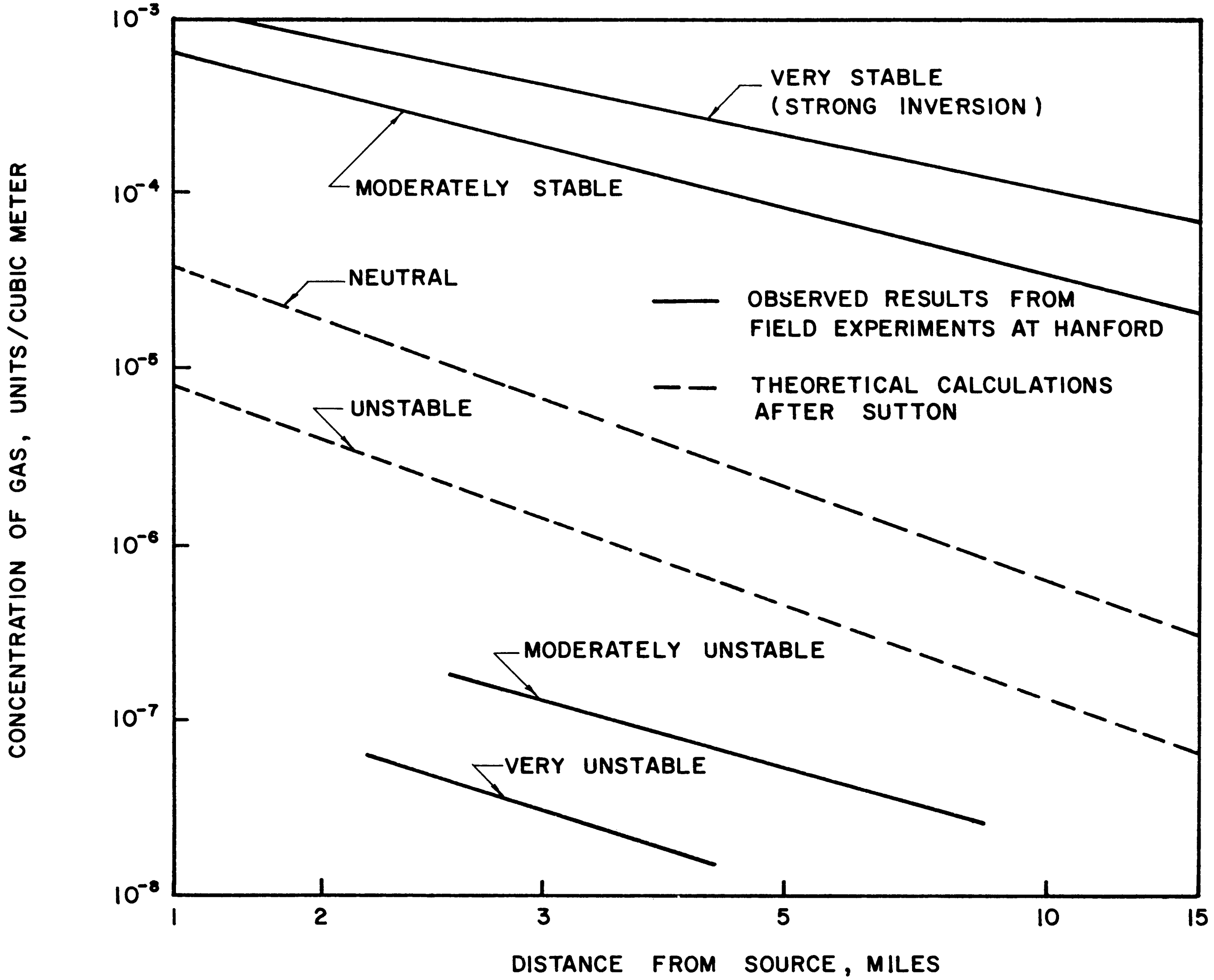
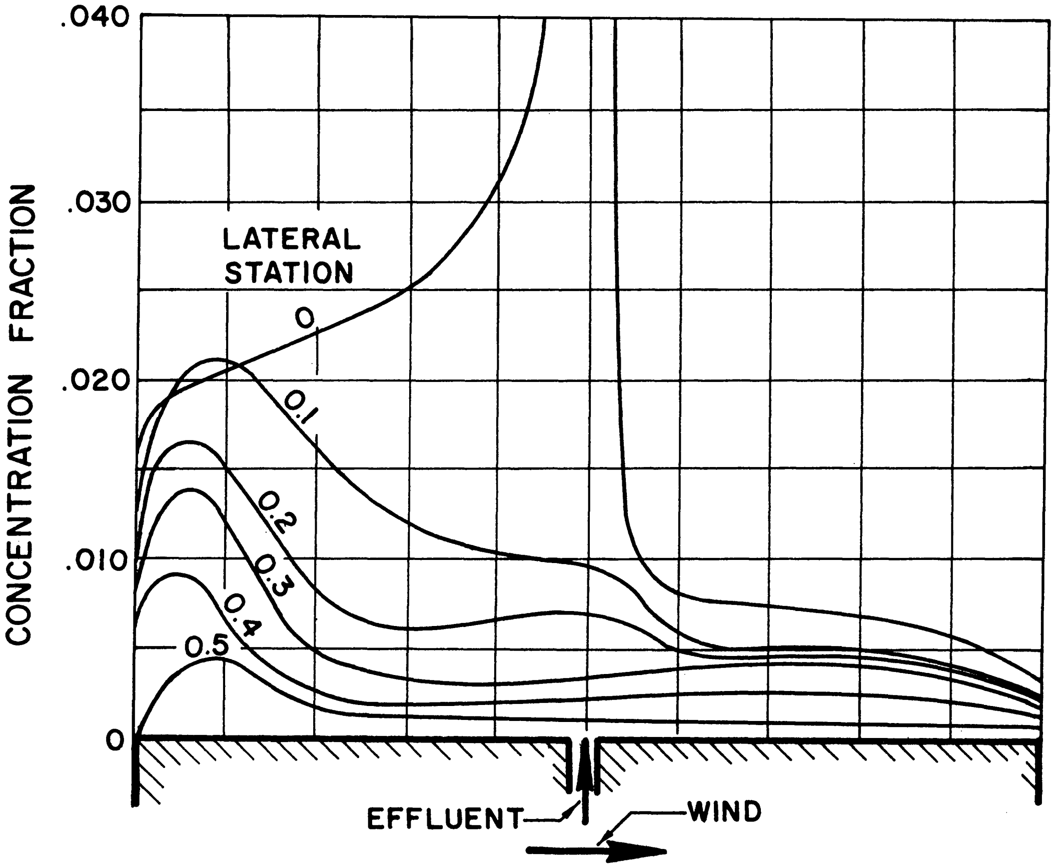


Figure 41. Maximum average concentrations in relation to distance from a stack 185 ft high as measured under various stability conditions near Richland, Washington. Sampling period: 1 to $2\frac{1}{2}$ hours. Broken lines give corresponding values calculated from Sutton's equations (after Hilst).

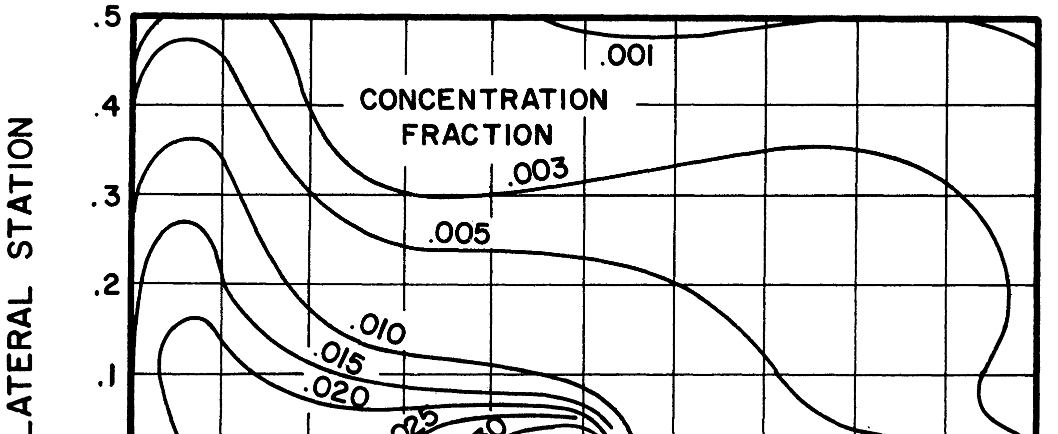
which are shown in Figure 42. A cubical box was mounted in the wind tunnel and SO_2 was released from a flush hole in the center of the roof. The high concentrations form a ridge in the shape of a T extending upwind from the source and across the roof just behind the leading edge. The apparent anomaly of a gas diffusing into the wind rather than with the wind is explained by the separation of air flow from the sharp corner of the roof and the establishment of a transverse vortex which induces a flow along the roof from right to left, 180 deg from the free stream wind direction. Wind-tunnel studies of this type may permit locating an effluent orifice and ventilation intake in such a manner that the effluent is kept away from the intake for the great majority of meteorological conditions. Additional prototype studies in the natural outdoors atmosphere are needed, however, for comparison with the results of model studies in the wind tunnel to permit verification of individual findings and the enunciation of principles of general applicability.

Plant Design and Layout to Permit, Where Possible, Some Variation of Effluent Output with Meteorological Conditions

Methods of control of air pollution based on varying the output of a contaminant in accordance with meteorological conditions, high output when atmospheric dispersion is good and low output when atmospheric dispersion is poor, are described in the final section of this paper. This method of control is based on the concept that the atmosphere is an important natural resource to be conserved by wise management policies. Thus the dispersive powers of the atmosphere, which are frequently very great, should be used to their full capacity while at the same time acceptable air quality is maintained.



ROOF ELEVATION



ROOF PLAN

Figure 42. Concentration distribution of SO_2 on the roof of a cubical box simulating a building and mounted in a wind tunnel. Concentration at source = 1.000; ratio of SO_2 exit velocity to wind velocity = 0.5 (after Halitsky).

An alternative philosophy is that all contaminants should be removed before release of an effluent. Such a procedure has attractive features: one is that it is positive and clear cut--no air pollution occurs except perhaps as a result of an unavoidable accidental release of a contaminant. And in those cases where the removed materials can be used in by-product manufacture at a profit or at cost, such a solution is clearly the best one. But where removed materials cannot be so used, their collection, storage, and ultimate disposal may be a major problem. A number of industries are already faced with this disposal problem, and with the rapid rate of increase of industrialization throughout the world, the problem will in the not-too-distant future become more widespread and locally acute.

It is clearly impractical to modify any but a few existing industries to permit the degree of flexibility in plant operation required for an adequate degree of meteorological control. If, however, the processes planned for a new plant were designed to permit the needed flexibility of operation, it might well turn out that atmospheric disposal of waste products is less expensive than removing the wastes at the source and then disposing of them by any available means.

Flexibility in the time and amount of release of contaminants may be achieved in one or more of a number of ways. It may be best to halt completely for poor diffusion periods those plant processes which contribute significantly to the contaminants leaving the stack. During slack market conditions reduced production might well be accomplished in this way. Another method would be to schedule production and hence contaminant release to the air according to a diurnal cycle which coincided with the diurnal variation of diffusion conditions, thus maintaining regularity of production but minimizing contaminant concentrations in sensitive localities. Another possibility which merits serious attention is the use of dust precipitators and collectors only during periods of low turbulence and poor diffusion.(66) With high turbulence and excellent diffusion fine dust is spread over such wide areas in such low concentrations that it presents no problem. A further development of this approach would be to collect dusts when diffusion is poor and then to reintroduce them into the flue gases during the next period of high diffusion. Research may reveal methods of adsorption of gases such as SO_2 on suitable materials and of releasing them again for emission to the atmosphere during periods of high diffusion. A serious exploration of such avenues when drawing up improved plant designs and processes might well yield handsome returns in reducing the costs of air pollution control.

In areas where ordinances are set up for air pollution control, some change might be required in existing ordinances to permit such variations in the output of contaminants with meteorological conditions. A demonstration that the public interest is adequately protected by ordinances permitting such variations in output in accordance with scientifically established meteorological criteria should be sufficient to effect the necessary legal changes.

Climatological studies may make a major contribution to efficient plant and process design. Perhaps part of a contaminant is to be used in the manufacture of by-products and the remainder released to the atmosphere in accordance with meteorological criteria. An analysis of climatological records will reveal the annual variation of diffusion conditions to be expected, including the best and the worst, and will tell management how large a by-product plant is required to avoid a pollution problem. It will also help to indicate the optimum seasonal distribution of and balance between main-product and by-product output. If the market also fluctuates seasonally, this information can also be used to plan the best over-all production program.

The purpose of this section is to draw attention to the desirability of considering new methods of air pollution control before increasing industrialization and a growing public demand for clean air force hasty and unsatisfactory action which could have been avoided by taking appropriate steps before the situation became acute.

PLANT OPERATION

There are a number of ways in which meteorological information, current or forecast, may be used in plant operations to minimize air pollution problems. Some of these ways will be mentioned briefly.

Control of Ventilation Problems

As discussed in the preceding section, it sometimes happens that, despite efforts to arrange plant layout so as to minimize or eliminate the entrance of stack effluents into the intakes of ventilating systems, aerodynamic downwash of plumes, or plume fumigation, looping, or trapping carries a contaminant to such an intake. If the plant buildings were not initially designed and laid out so as to minimize intake of contaminants, the problem will be correspondingly worse.

If it has been established which meteorological conditions cause trouble, weather forecasts may be used to alert operating personnel that ventilating systems may have to be turned off to avoid drawing contaminated air into the systems. Another alternative, when the air within the building must be cooled, is to close the intake for the period when there is a likelihood of a contaminant entering, and thus to allow air circulation through the cooling unit and through the building but without bringing an outside contaminant in.

Dumping Operations

It may be necessary at intervals to dump fuming materials in the open. If, for example, these fuming substances are dumped in a line, as in a trench, they should be dumped only when diffusion is good and the wind direction is such that the fumes will not be carried to sensitive areas. Weather forecasts will provide information on these points, and equally important, on the duration of the favorable meteorological conditions.

For such a line source, Equation (42) may be used to calculate the distance at which concentrations will have decreased to acceptable values. If the fuming dump is effectively a point source, Equation (37) or (38) may be used; if appreciable deposition on the ground is occurring, Equation (48) should be used instead.

Operations in the Vicinity of a Plume

It is sometimes necessary for workers to conduct operations, such as maintenance and repair, near plumes. Since safety standards must be met in the exposure of workers, some convenient method of determining the probable concentrations at various distances downwind from the source is required. The following example shows how this problem was effectively met in one instance.(44)

A roof vent was emitting NO_2 which produced a visible plume 5 to 10 ft long of the characteristic bright orange color. Workmen occupied on the roof might be exposed to a certain amount of the gas. How far should they keep away from the plume? As an alternative to a complicated and costly NO_2 sampling program the following was suggested. The concentration at which NO_2 is just visible is known, say P ppm. If the visible length of the plume is x_t ft, at which distance the axial concentration is equal to P, then the axial concentration X ppm at any greater distance x ft is, from Equation (38),

$$X = P(x_t/x)^{2-n}$$

where the value of n varies with atmospheric conditions as given in Table V.

By applying this result the industrial hygienists were able to specify safe distances for workmen from the visible NO_2 plume. The method, of course, is not restricted to NO_2 but will work for any gas which has some established visible or olfactory threshold concentration, e.g., H_2S.

Operation of Collectors

Substantial economies may be effected, as mentioned earlier, by operating collectors when diffusion is poor but not when it is good, in order to save power, the cost of the scrubbing agent, and the cost of disposing of the material collected. It is also advantageous to schedule shutdowns of collecting apparatus for maintenance and repair for periods of good diffusion in order that production may be continued during the shutdown.(51)

Emergency Precautions

Accidental releases of contaminants to the atmosphere have occurred in the past. On 24 November 1950 at Poza Rica, Mexico an accidental release of H_2S led to the hospitalization of 320 persons and the death of 22.(101) On 10 October 1957 an accident occurred in pile No. 1 at the nuclear installation at Windscale, England during a routine Wigner energy release, i.e., release of energy stored in irradiated graphite.(138,151) The passage of a cold front about 10 hr after the accident led to a complex pattern of distribution of the radioactive contaminants. After traversing England the cloud reached Mol, Belgium about 7 p.m on October 11, Frankfurt, Germany at 10 p.m. on October 12, and Sola, Norway on October 15. Figure 43 shows the variation of radioactivity with time as the cloud passed Harrow, Middlesex, England. The leading edge of the cloud reached Harrow at 4 p.m. on October 11, about 3 hr after the passage there of the cold front, with maximum values at 2 a.m. the next morning. It is clear from the figure that very considerable dispersion had already occurred by the time the cloud reached Harrow.

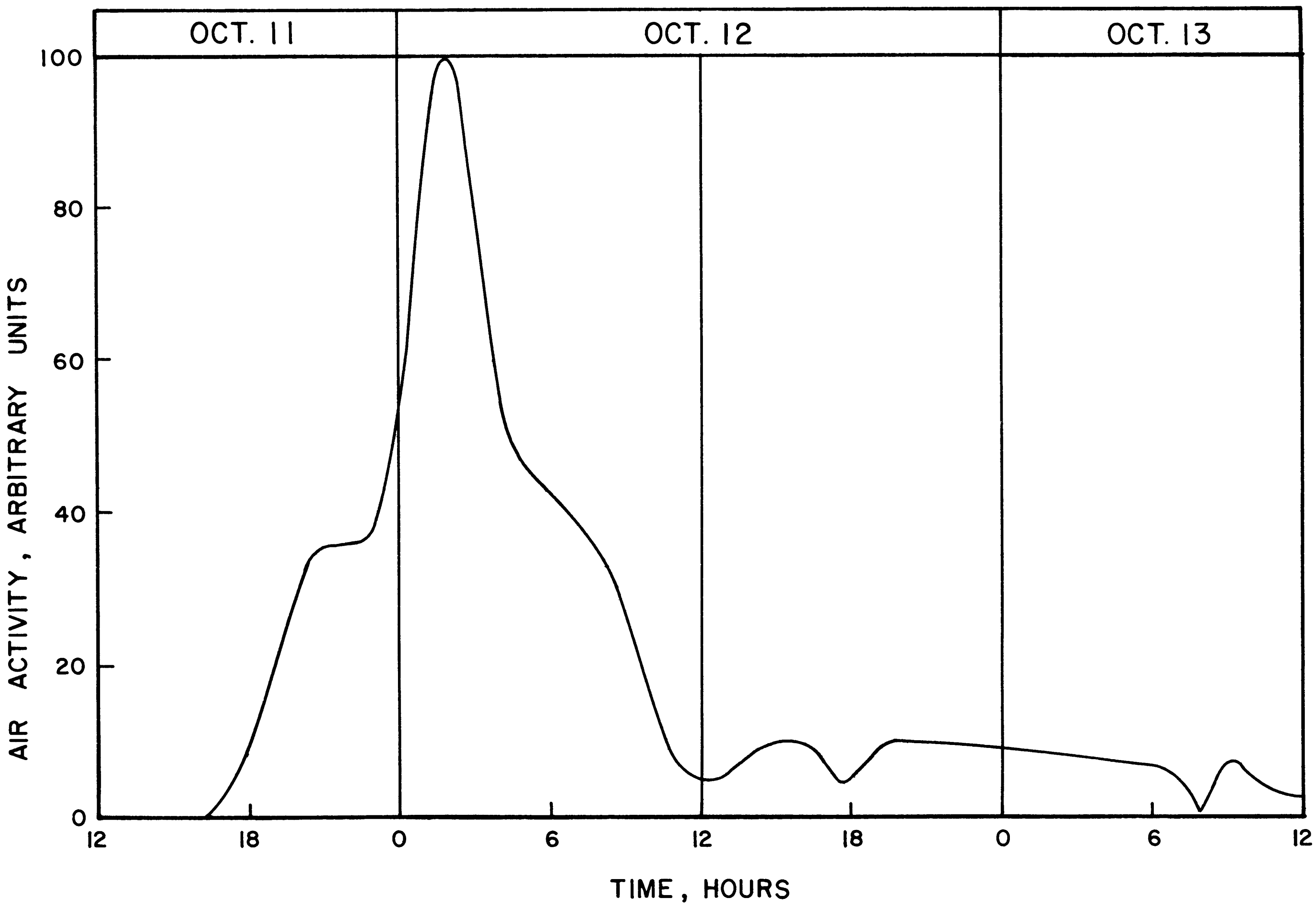


Figure 43. The passage at Harrow, Middlesex of the radioactive cloud released to the atmosphere by the accident in nuclear pile No. 1 at Windscale, England which occurred about noon on 10 October 1957. The leading edge of the cloud reached Harrow at 4 p.m. on October 11, about three hours after the passage of a cold front (after Stewart and Crooks).

There has been considerable analysis of two types of emergency which require precautionary steps involving meteorology: emergencies caused by accidental releases of contaminants(below**); and emergencies arising from contaminant accumulations in a stagnant anticyclone.(87,22)

Emergency Precautions for Accidental Releases

An example of an accidental release of the type for which emergency precautions are required is that which occurred with pile No. 1 at Windscale, England.(138,151) An elaborate analysis of the danger distance around a reactor, i.e., the distance from the reactor within which rapid evacuation must be planned in case of an accidental release if deaths are to be avoided, has been made.(103) Some of the results are given in Table XII. A boiling accident is one in which there is a gradual release of some fraction of the fission products contained in the reactor by a series of events that cause uncontrolled boiling of the liquid moderator. The basic diffusion expression used in the development is that of Sutton for a continuous point source at the ground, Equation (36). A puff accident is visualized as a sudden release to the atmosphere of fission products in the form of noble gases and particulate matter. Because of the great release of heat and consequent buoyancy of the cloud, it has been estimated that such a puff would rise 6000 ft before leveling off for a reactor operating at 600 MW. On this basis the breathing and direct radiation hazard are considered negligible in comparison with the rainout hazard, so that breathing and radiation are not included in Table XII. Sutton's equation for the concentration of particles,

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** Ref. 42,49,62,75,92,103,106,135,145,150.

TABLE XII

EXPRESSIONS FOR AND REPRESENTATIVE VALUES OF THE DANGER DISTANCE (MILES) AROUND A NUCLEAR REACTOR (AFTER MENEGUS AND RING)

Type of Accident	Type of Exposure	Danger Distance (miles) Average Conditions	 Inversion Conditions
Boiling accident	Breathing of the cloud	$\left(\frac{2.89\ pfat_e}{uT}\right)^{0.571}$ 1.07	$\left(\frac{413\ pfat_e}{uT}\right)^{0.667}$ 33.5
	Radiation from the cloud	$\left(\frac{15.1\ pfat_e}{uT}\right)^{0.571}$ 3.01	$\left(\frac{2160\ pfat_e}{uT}\right)^{0.667}$ 100
	Rainout from the cloud	$\left(\frac{4.9\ pfacgt_e}{uT}\right)^{1.14}$ 2.49	$\left(\frac{58.5\ pfacgt_e}{uT}\right)^{1.33}$ 76
Puff accident	Rainout from the cloud	$(36.4\ pfacgt_e)^{0.571}$ 46	$(5200\ pfacgt_e)^{0.667}$ 2400

neglecting gravitational settling, from an instantaneous point source with effective height far above the surface is

$$X = \frac{Q}{\pi^{3/2} C_x C_y C_z (ut)^{3(2-n)/2}} \exp\left[-(ut)^{n-2}\left(\frac{x^2}{C_x^2} + \frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \qquad (57)$$

where Q is total number of particles emitted, t is time since emission, and x, y, and z are distances from the center of the cloud or puff. This equation is used in evaluating the puff accident in Table XII.

The symbols used in Table XII have the following meanings, and assumed values for calculations:

p is reactor power level; 600 MW;

f is fraction of the reactor fission products rendered airborne, assumed to be $\frac{1}{2}$;

a is afterheat fraction of full power due to fission products decay, for which a representative value is 1/80;

t_e is the exposure time, the period during which a person is exposed to the radioactivity, taken for illustration to be 6 hours;

u is the wind speed, assumed 8.23 mi hr^{-1};

T is the time during which airborne radioactive materials are released from the reactor, assumed to be 6 hours;

c is the fraction of fission products contained in a vertical column of unit cross section which is washed out by precipitation and deposited on unit area of the ground; and

g is the fraction of this deposited radioactive material which does not percolate into the soil but remains on or near the surface, the product of c and g being conservatively estimated, in the absence of detailed reliable information, as being unity.

Inserting these values in the expressions given in Table XII leads to the distances shown under each, which range from 1.07 to 2400 mi. The latter figure is highly unrealistic: widespread, deep, and persistent inversions occur at heights of 6000 ft only in subtropical or stagnant midlatitude anticyclones, and precipitation does not occur under such conditions. The greatest realistic distance is thus 100 mi, due to radiation from the plume or cloud from a boiling accident which occurs during inversion conditions. The danger distances for both average and inversion conditions are probably too large; the values for average conditions used, $C_y = C_z = 0.19m^{1/8}$, are Sutton's and are appropriate for 3-min periods. Values of $C_y = C_z = 0.40m^{1/8}$ appropriate for 1-hr periods, as given in Table VI, would be preferable. Similarly $C_y = C_z = 0.04m^{1/4}$ was taken for inversions, but the 1-hr values in Table VI of $C_y = 0.40m^{1/8}$ and $C_z = 0.05m^{1/4}$ are preferable.

To convert these danger distances to controlled distances around any specific nuclear reactor site, it is necessary to introduce population density in various directions around the reactor, to calculate from climatological records the probability of winds from various directions with various speeds, and the probability that heavy rain will occur with each wind direction and wind speed interval. For details the original paper should be consulted.(103)

One may associate the exposure hazard not to death, as has been done above, but to a figure that specifies the allowable emergency concentration in the air if no long term physiological damage is to result. If this is done the danger and controlled distances obtained are in general much greater.

If continuous measurements of wind direction, speed, and turbulence and of precipitation are made, an analysis of the above type may be used to establish emergency evacuation procedures, perhaps involving an electronic computer, which will go into action automatically several minutes after an accident has occurred.

Emergency Precautions During Stagnant Anticyclonic Conditions

Although the hazard associated with an accidental release may be increased in inversions occurring in stagnant anticyclonic conditions, as suggested in Table XII, such meteorological conditions may also lead to a dangerous situation by permitting lethal concentrations of ordinary and routinely released contaminants to accumulate. The air pollution disasters which occurred, as described earlier, in the Meuse River valley near Liege, Belgium, at Donora, Pennsylvania, and in London, England were of this type. The details of preventive precautions are available.(87,22) In general, a close check on current and forecast meteorological conditions is required if an anticyclone gives evidence of stagnating in an area. If the situation becomes acute, severe curtailment of contaminant emission will be required: by industry, by plant shutdowns if no other effective means are available; by automobile users, by using other means of transportation; by incinerator operators, by postponing burning until the crisis is past; and by other major contributors to air pollution in the affected area.

Meteorological Control of Emissions

A number of methods of limiting air pollution by modifying the atmosphere, especially by the elimination of inversions, have been suggested, but none has proven to have a sound engineering basis.(114) The energy expenditures would be enormous and the accomplishments of doubtful value.

On the other hand, the possibility of reducing pollution by varying the output of contaminants in accordance with existing or forecast meteorological conditions is receiving increased attention. For example, coal burning electrical generating stations are using low-sulfur coal during periods of adverse diffusion in order to reduce the output of SO_2 to the atmosphere. The economies of meteorological control have been discussed in some detail.(75) This analysis leads to the conclusion that meteorological control by varying the collection and recovery of wastes at the source will be profitable if

$$\frac{\text{Net cost of partial recovery + Cost of meteorological services}}{\text{Net cost of total recovery}} < 1$$

The cost of waste recovery must include the cost of acquisition, operation, maintenance, and depreciation of the recovery equipment, the cost of storage or reprocessing of recovered wastes, and the market value, if any, of these wastes. If waste recovery is not profitable, partial recovery based on full utilization of the atmosphere for waste disposal in a way which protects the public interest, can produce substantial savings in plant operation. When diffusion is good, the atmosphere can safely accept at least 100 times the amount of wastes it can safely accept when diffusion is poor. Since good diffusion conditions prevail for a substantial part of the time in most localities, the potential economies in plant operation are apparent.

Meteorological control has been in effect or proposed at a number of plants.(below**) Meteorological control has been established for a number of years at the Trail Smelter of the Consolidated Mining and

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** Ref. 32,64,65,75,134.

Smelting Company of Canada, Ltd., which is located in British Columbia, Canada, in the Columbia River valley.(64,65) There, in order to prevent damage to vegetation to the south in the state of Washington, an upper limit to emission of SO_2 for various meteorological conditions has been set. The various criteria are: atmospheric turbulence; wind direction; wind speed; time of day; and season of the year. The turbulence is specified by the gust accelerometer described earlier in this paper. Winds at Trail from the north, east, south, southwest, and intermediate directions, and with a speed of 5 mi hr^{-1} or more, generally do not carry the smoke downvalley and into the state of Washington, and so are considered favorable. Winds from directions other than these and a wind from any direction with a speed less than 5 mi hr^{-1} are unfavorable. Because the degree of susceptibility of vegetation to damage by SO_2 varies with the time of day and the season of the year, the permissible maxima have corresponding variations--high maxima for low susceptibility and vice versa. The upper limits are specified by the Trail Smelter Arbitral Tribunal are given in Table XIII. Overriding safeguards are provided in other clauses in the control regime. Because of the great difficulty of forecasting winds and turbulence in such a valley, the control is based on current, not forecast, conditions. Over more uniform terrain, forecast diffusion conditions are used.(75,134) Various other features of the control methods used at the Trail Smelter have been described.(137)

There is little doubt that meteorological control methods will become more widespread as increasing industrialization makes the problem of total removal of contaminants at the source and their disposal more and more acute.

TABLE XIII

MAXIMUM PERMISSIBLE SULFUR EMISSION BY THE TRAIL SMELTER (TONS OF CONTAINED SULFUR PER HOUR)

Time	Season	Turbulence*						
		0-74		75-149		150-349		350
Midnight to 3 a.m.	Growing	2	6	6	9	9	11	11
	Nongrowing	2	8	6	11	9	11	11
3 a.m. to 3 hr after sunrise	Growing	0	2	4	4	4	6	6
	Nongrowing	0	4	4	6	4	6	6
3 hr after sunrise to 3 hr before sunset	Growing	2	6	6	9	9	11	11
	Nongrowing	2	8	6	11	9	11	11
3 hr before sunset to sunset	Growing	2	5	5	7	7	9	9
	Nongrowing	2	7	5	9	7	9	9
Sunset to midnight	Growing	3	7	6	9	9	11	11
	Nongrowing	3	9	6	11	9	11	11

* Deflections recorded by gust accelerometer per half hour. Sulfur emission for unfavorable winds (left columns) and for favorable winds (right columns).

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