THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

PART I

ATMOSPHERIC POLLUTION PREDICTION BY MODEL STUDIES OF INDUSTRIAL STACKS

F. K. Boutwell

PART II

TOPOGRAPHIC INFLUENCES ON THE BEHAVIOR OF STACK EFFLUENTS

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PART I

ATMOSPHERIC POLLUTION PREDICTION BY MODEL STUDIES OF INDUSTRIAL STACKS

F. K. Boutwell

Introduction

The study of the movement of the atmosphere in fairly close proximity of the earth and the methodical recording and accumulation of data enables one to quite accurately predict a great many natural occurrences with a high degree of accuracy. Statistical methods will for instance, indicate with reliability the expected total rain fall at a given location for a season as well as such weather data as mean temperature, hours of sunlight, and the like. Applied to the study of winds, these methods enable accurate prediction of the hours per year or season that the wind may be expected to blow in a particular direction; they can also predict the frequency with which a wind might exceed any particular speed in any direction on a yearly or a seasonal basis. The meteorologist can even predict for many locations the expected frequencies of inversion conditions which in effect sandwich the air in immediate contact with the earth. Studies of this nature are necessary in the problem of the pollution of air by industrial processes and the combustion of fuels but in many cases are not sufficient within themselves to lead to abatement of the problem by setting up economical design standards for a given installation. A problem of this nature requires that the aerodynamic influences of the movement of the air over and around obstructions be taken into consideration.

Basic Problem

When the wind flows over and around buildings and structures, at least two distinct regions may be observed. One is a highly turbulent region in which the local movement of the air can be nonsteady and in many cases having components of flow contrary to the general flow direction of the main body of air. This is particularly true in the lee of large structures which cause a large displacement of the passing air. The discharge of contaminents into such regions will result in high concentrations of pollutants in the area for some distance downwind since the turbulent region is continuously being disipated by the shedding of vortices which roll along the ground downwind. Vegetation and life in general will be affected to a degree dependent upon the rate of discharge and the net concentration of the pollutants. Turbulent regions are formed in the lee of structures of any description as well as by changes in the contour of the ground due to rapid elevation changes or forested areas. Adjacent to the highly turbulent regions the general air movement may be quite orderly and proceding in what is termed a stream line pattern very much as if a sheath were between the two regions of such a shape as to present a "streamlined" body consisting of structures and turbulent region to the air movement as a whole. Such an imaginary enclosure is hereafter referred to as the vortex sheath.

Gasses due to combustion processes are probably as great a concern in the area of air pollution as any other source of contaminent today. Formerly these gasses were emitted through a stack which provided the draft necessary for supplying the combustion air and were necessarily quite high. As a result they were high enough to disperse the products of combustion at a distance above the ground. As long as the total discharge from the stacks were low and the number of stacks in a given area was not very large, these heights were adequate in dispersing the gasses so that the diffusion processes could cut obnoxious concentrations to a tolerable level. The advent of forced and induced draft fans and higher and higher combustion rates, however, has resulted in a very large possible source of contamination from a single stack. Multiple stack installations add further complications to the overall situation so that a more detailed study of stacks is warrented.

Stack Considerations

When the wind flows around a stack, the same trend of the formation of a turbulent region in the lee of a stack as behind other obstructions is apparent. The fact that they consist of a regular cylinder as a rule (even though triangular stacks have been constructed) has lead to systematic studies of their aerodynamic behavior: (1) A region of low pressure exists immediately behind the stack and vortices are shed from this region in regular fashion (Karmin trails). At the tip of the stack, tip vortices are formed on each side of the stack. Since the low pressure region behind the stack is open at the top, a flow of air into this region takes place in a downward direction. The net result of the stack aerodynamics is the tendency to break up any jet which issues from the stack and to entrap it in the low pressure region behind the stack. If the plume from a stack is emitted in close enough proximity to or within the vortex sheath formed by adjacent structures or terrain very high concentration of pollutants is possible downwind of the stack. A proper stack design must therefore provide a sufficient discharge velocity to insure that the plume be able to escape the adverse aerodynamic stack turbulence as well as those of the natural and structural obstructions to the wind.

Simulation in a Wind Tunnel

The basic problem of forecasting the behavior of a certain stack design and operating condition then becomes one of the simulation of the movement of the atmosphere in a wind tunnel over a model of the terrain and pertinent structures to observe the influence of aerodynamic forces upon a source of pollution. In order that the studies performed be representative of the field conditions many factors must be considered. Among these are: the natural wind gradient, the atmospheric temperature gradient, the natural turbulence of the atmosphere, flotational effects of the plume, etc.

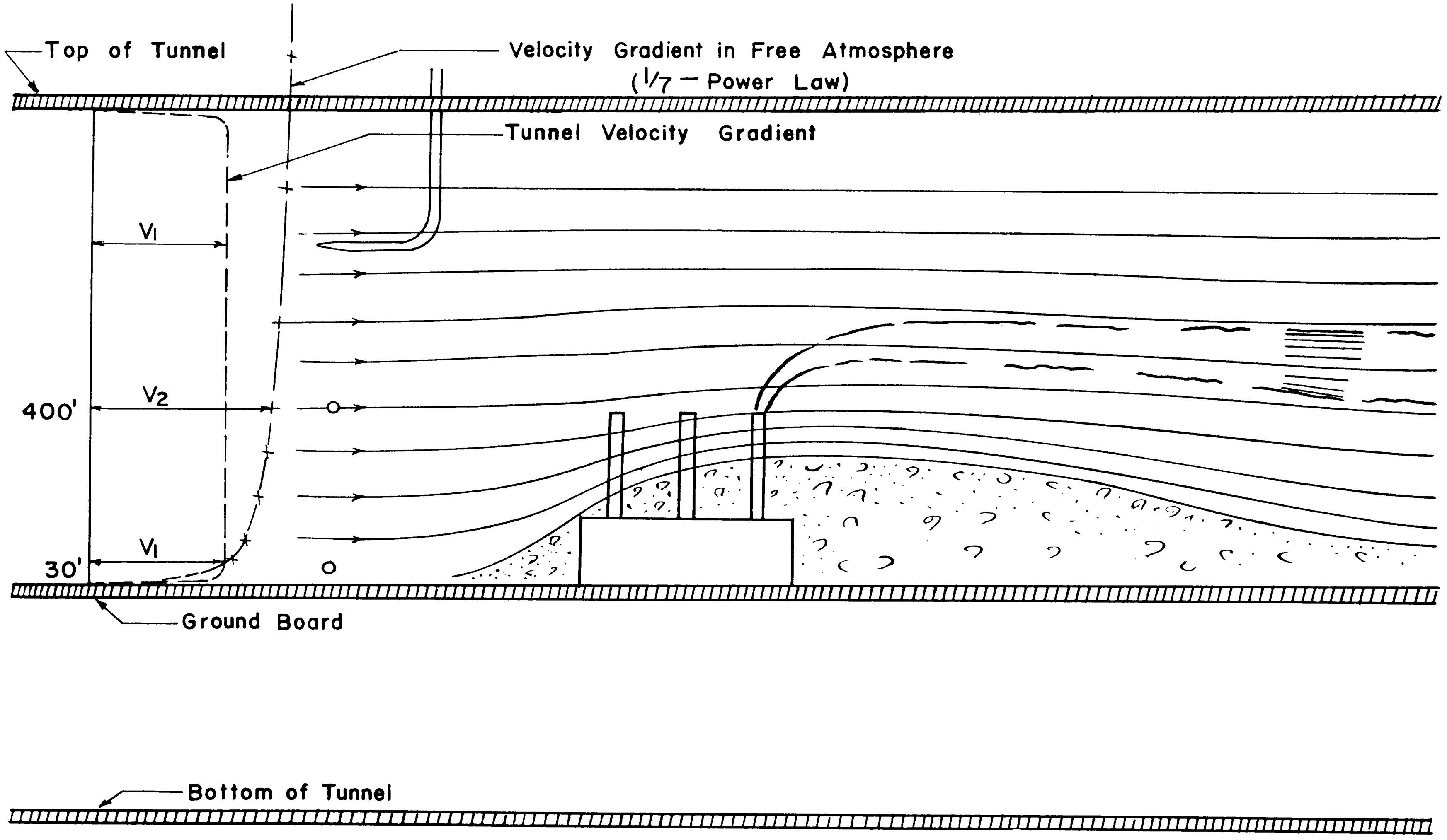
The natural wind variation with height in the atmosphere within limits can be approximated by a 1/7 power law where wind velocities increase with height above the earth's surface

$$(\mu = \mu_{30} (\frac{h}{h_{30}})^{1/7})$$

Such a gradient has been detailed in Figure 1 and may be approximated in a wind tunnel by the introduction of a resistance grid in front of the model so constructed as to introduce a greater resistance to flow near the model surface by a closer spacing of the grid members. Without such a grid wind speeds in a tunnel would be quite uniform with no gradient other than that of the small gradient at the tunnel boundaries. Some approximation to the natural gradient is also obtained by the simulation of the terrain for some distance upwind from the stack location. The natural turbulence in the velocity of the modeled terrain then creates a mean velocity profile closely approaching the natural gradient as well as simulating the natural aerodynamic turbulence present in the field.

Temperature gradients have also been simulated in the wind tunnel by a heating element grid so spaced as to heat the air to the desired gradient. The maintenance of this gradient with air movement throughout a test period is, however, a very difficult one and is not generally of most concern when the wind velocities are small and the aerodynamic forces are consequently of lesser importance.

Geometric and dynamic similarity must be maintained if similarity is to exist between the model and the prototype. Geometric



STREAMLINES AND VELOCITY PROFILES IN WIND TUNNEL AND IN FIELD

Figure 1. Streamlines and Velocity Gradients.

similarity is maintained by constructing the model to scale and in order to simulate a large enough area to assure proper wind gradient and structure across the model, scales of 1:400 are common. For dynamic similarity, the inertial to viscous force ratio should be the same for prototype and model. Since this ratio is indicated by Reynolds number $\left(\frac{VL\rho}{\mu}\right)$, it is obvious that for dynamic similarity the wind tunnel air velocities would have to be some 400 times wind speed since air is the working fluid in each case. Such speeds in a wind tunnel are not possible and therefore, true dynamic similarity cannot be achieved. Fortunately for Reynolds' numbers well within the turbulent region, similar flow conditions can be simulated with sufficient accuracy so long as points of separation between model and prototype are maintained in the same relative position.

Flow separation will occur along the edges of buildings and due to shrubs and small obstacles on the ground. Similar flow patterns are observed for the modeled structures since the sharp edges are geometrically similar to those of the prototype. The flow over terrain may be simulated with a stepped contour construction or with suitable small spoilers to cause separation usually present as the wind flows over shrubs and surface roughnesses.

To simulate the flotational rise of the plume due to temperature gravity forces must be considered and the ratio of inertial to gravity forces must be held constant for model and prototype (Froude number). In this case the wind speeds in the tunnel become so small for typical models (one to two feet per second) that accurate simulation is extremely tedious and of questionable accuracy. Since flotational forces are small in comparison to the aerodynamic forces, flotational effect is generally neglected until such time as it can be shown that the plume escapes turbulent regions and is free to respond to flotation. At such time, computations can be made with good accuracy to predict plume rise providing other effects are not present.

In order to simulate the discharge of gas from a stack into a passing stream of air it is necessary that the relative momentum between the two streams be maintained. If the two streams have a common density, this criteria will reduce to the ratio of the velocities of the two streams. Similarity of discharge behavior is then attained by operating the model and prototype at similar velocity ratios of stack-gas to wind velocity. It is necessary to apply a temperature correction factor in the stack velocity computation to account for the difference in density between the two mediums and thus correct the true momentum ratio values.

The influence of stack height and stack-gas velocity can thus be evaluated by wind tunnel studies and industrial stacks can thus be designed to minimize the entrapment of the plume by turbulent action. Testing in the tunnel is normally carried out with a non-bouyant plume of oil vapor which has been generated by vaporizing a low carbon oil in a stainless steel coil. The plume is emitted under controlled stack-gas velocities to simulate any desired velocity ratio of stack-gas speed to wind speed. Plume behavior is observed visually and photographically to study the influence of stack height and stack-gas velocity. Typical data pictures from the tunnel are shown in Figure 2. The pictures show an undesirable plume behavior in which a portion of the plume has been trapped in the stack vortex and a plume which has escaped adverse aerodynamic forces.

Wind Tunnel Results

If a minimum plume height can be established for a given location, correlation of a proposed stack-gas velocity and stack height with the statistical wind data enables one to compute the hours per year in which the plume will be below that criterian. This can be shown by the sequence shown in Figure 3. Wind tunnel data is given in the upper left chart as plume height at an arbitrary reference plotted against the ratio of stack-gas to wind velocity for a particular stack height and wind direction. If a plume height of 200 feet is deemed desirable in this instance, the figure indicated that a velocity ratio of 2.5 is necessary. For a given stack-gas velocity the 2.5 velocity ratio corresponds to a wind velocity of 18 mph (indicated by the upper right graph) after temperature corrections have been made. Statistical wind data as presented in the lower left graph shows that the 18 mph wind can be expected to be exceeded slightly over 3 per cent of the hours per year ($.03^+$ of 8760 or 275 hours). This information can be plotted as a point on the lower right graph as indicated. Other plume height criteria results in the curve shown. Results can also be given in a form similar to that of Figure 4 indicating effect of wind directions, stack-heights, and stack-gas velocity.

Remedial Devices

Very often devices are proposed which when placed on stacks would theoretically enable the plume to escape the adverse influences acting upon it. These devices generally take the form of either a variable discharge area to provide an increase in stack-gas velocity as the wind speed increases or a configuration mounted upon the top

Figure 2. Illustrations of Plume Behavior.

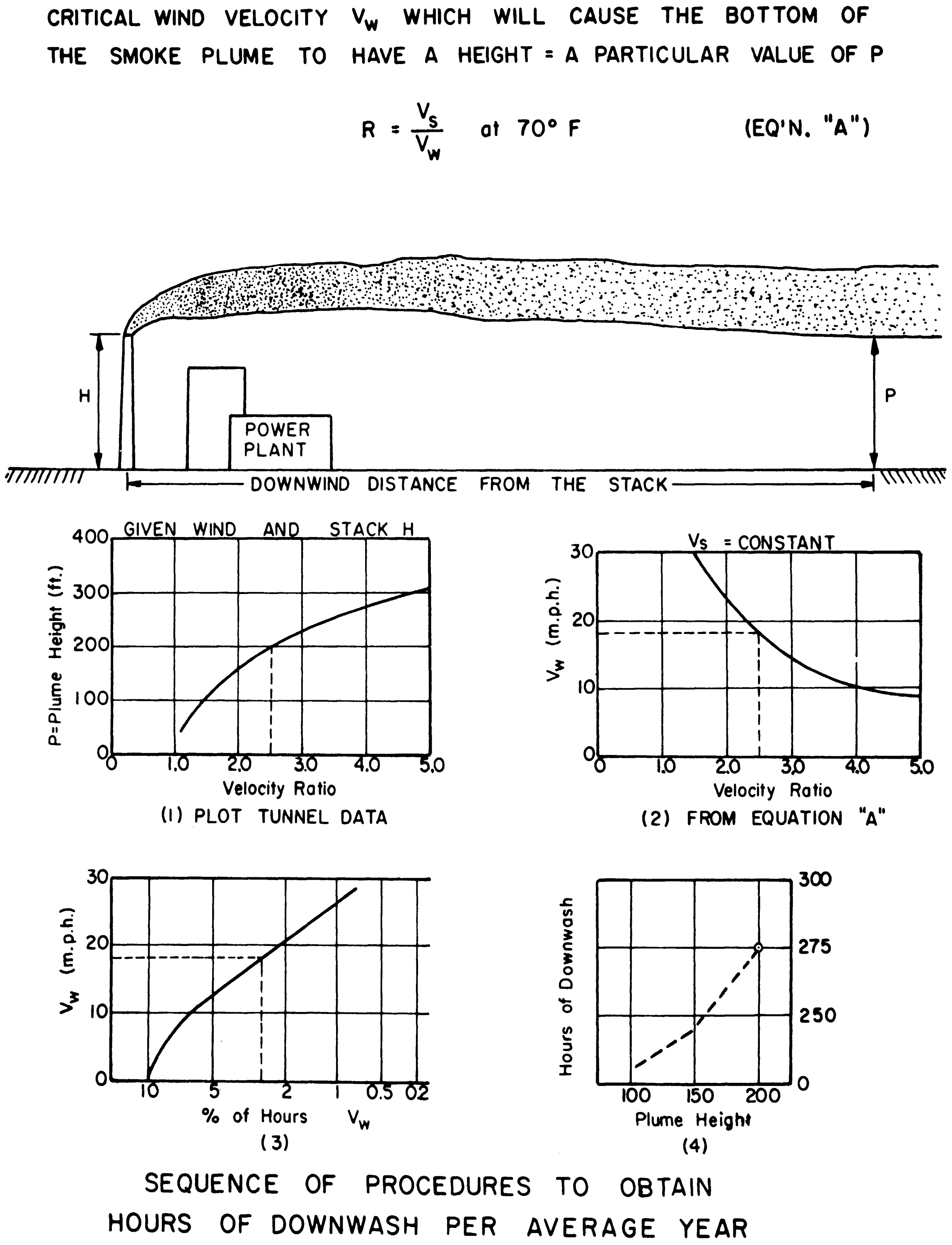


Figure 3. Computation Procedures.

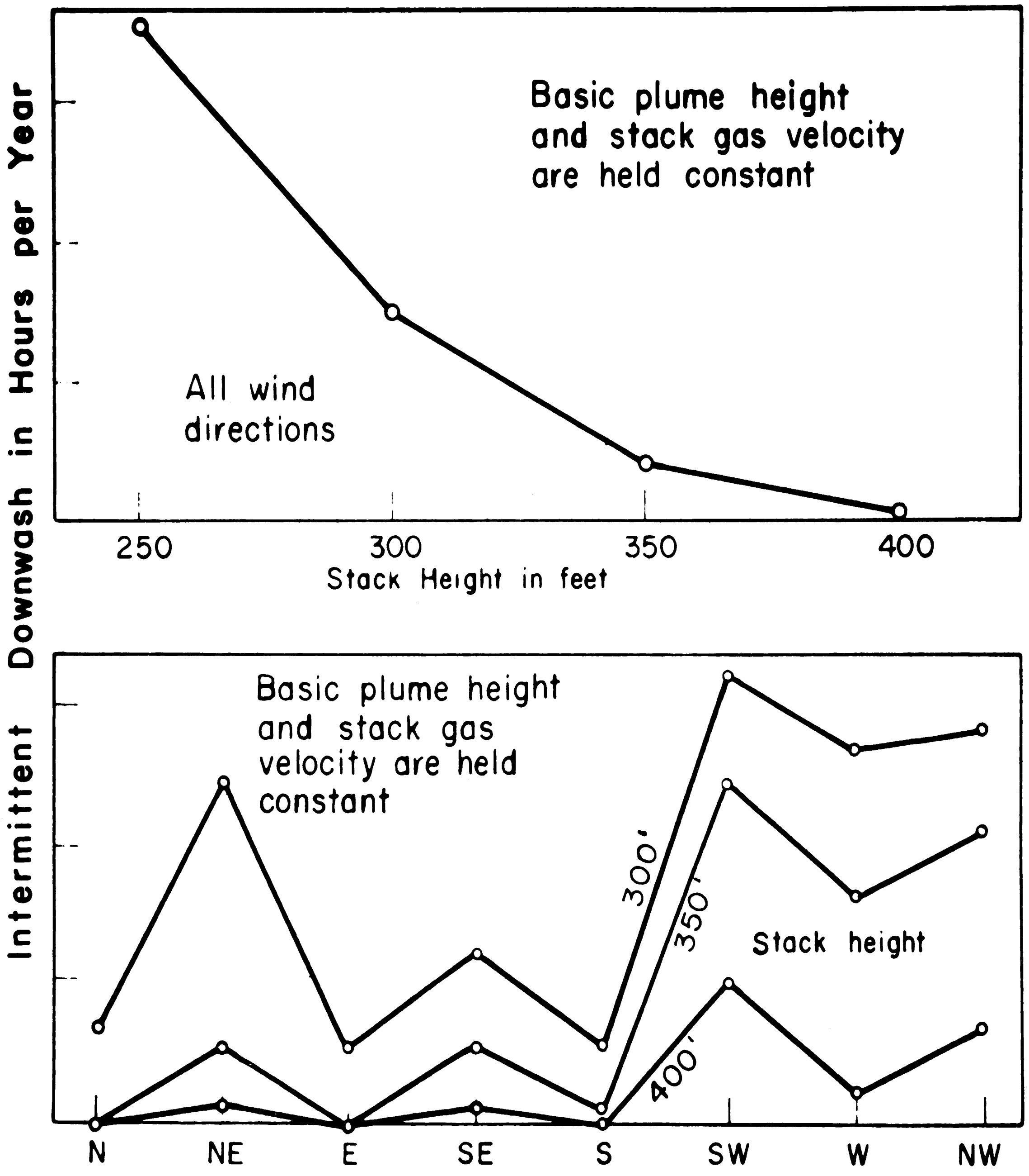


Figure 4. Resultant Graphs.

of the stack which is so designed as to provide additional lift to the plume. Many such devices have been tested in wind tunnel studies but limitations have always been apparent.

The variable-area stack discharge nozzle will provide additional plume momentum due to the increase of stack-gas velocity. However, the effectiveness of added penetration is in part reduced since the structure is proportionally larger than the jet. The aerodynamic forces upon the jet are thereby increased with consequent cancellation of a portion of the beneficial increase in momentum. This fact coupled with the maintenance problem has not encouraged their use to date.

Various guide vanes on the stack to provide additional lift to or to prevent the plume from entering the low pressure region in the lee of a stack have also been proposed. Many devices can be designed to provide beneficial effects so long as the wind impinges upon them from one direction. For winds from other directions these devices have the opposite effect. In order to benefit the overall situation it would be necessary to be able to position these devices according to wind direction which again presents a formidible design problem.

Typical Models

A typical model is shown in Figure 5. The scale of the model is evident as is the constructional details. Another model is shown in Figure 6 and is in position for testing in the wind tunnel. In this instance predicting the effect of the large cooling towers upon the stack plumes would have been impossible without tunnel tests. The scale of the model is indicated by the 'six foot man' located at the top of the white triangle in the foreground.

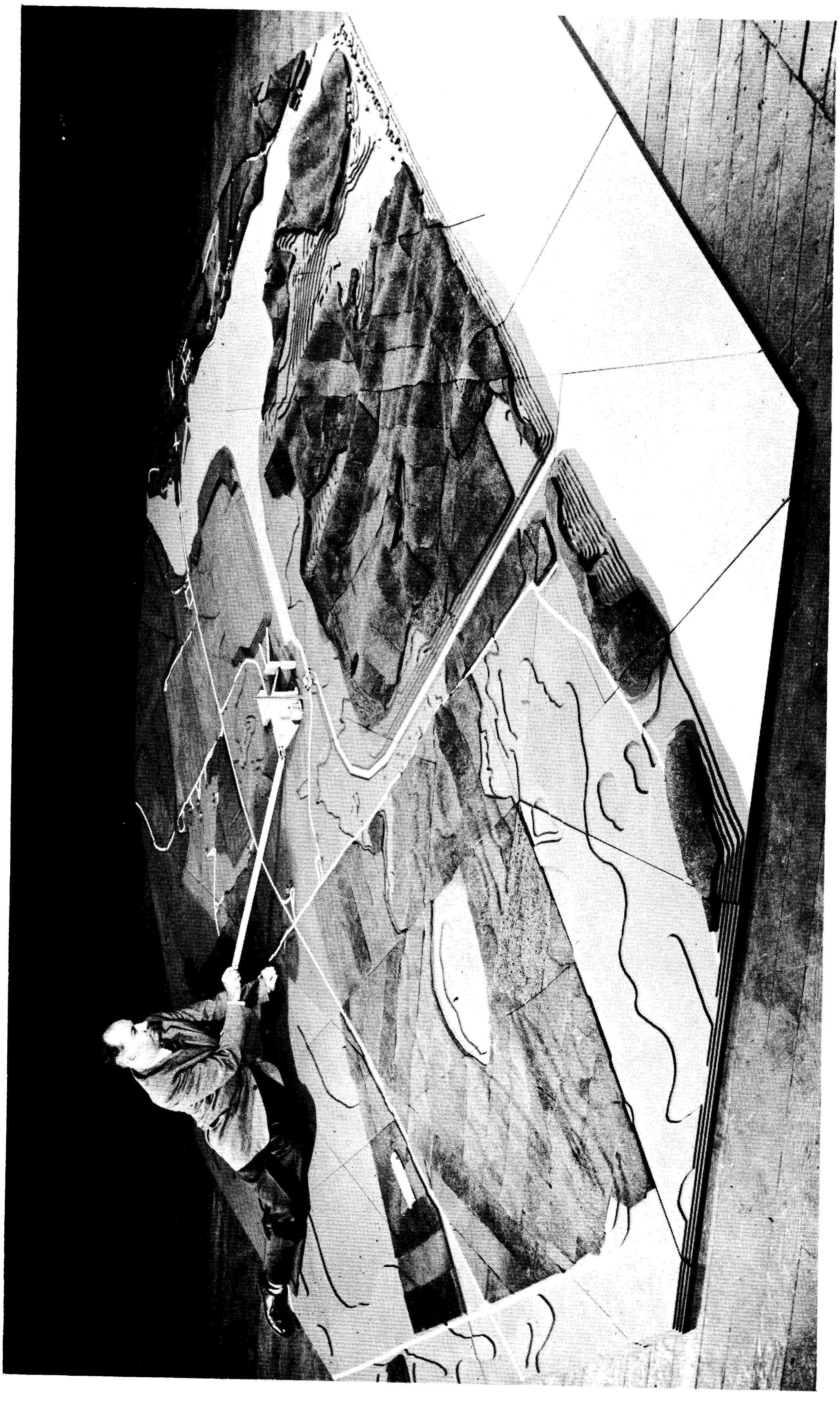


Figure 5. Terrain Model

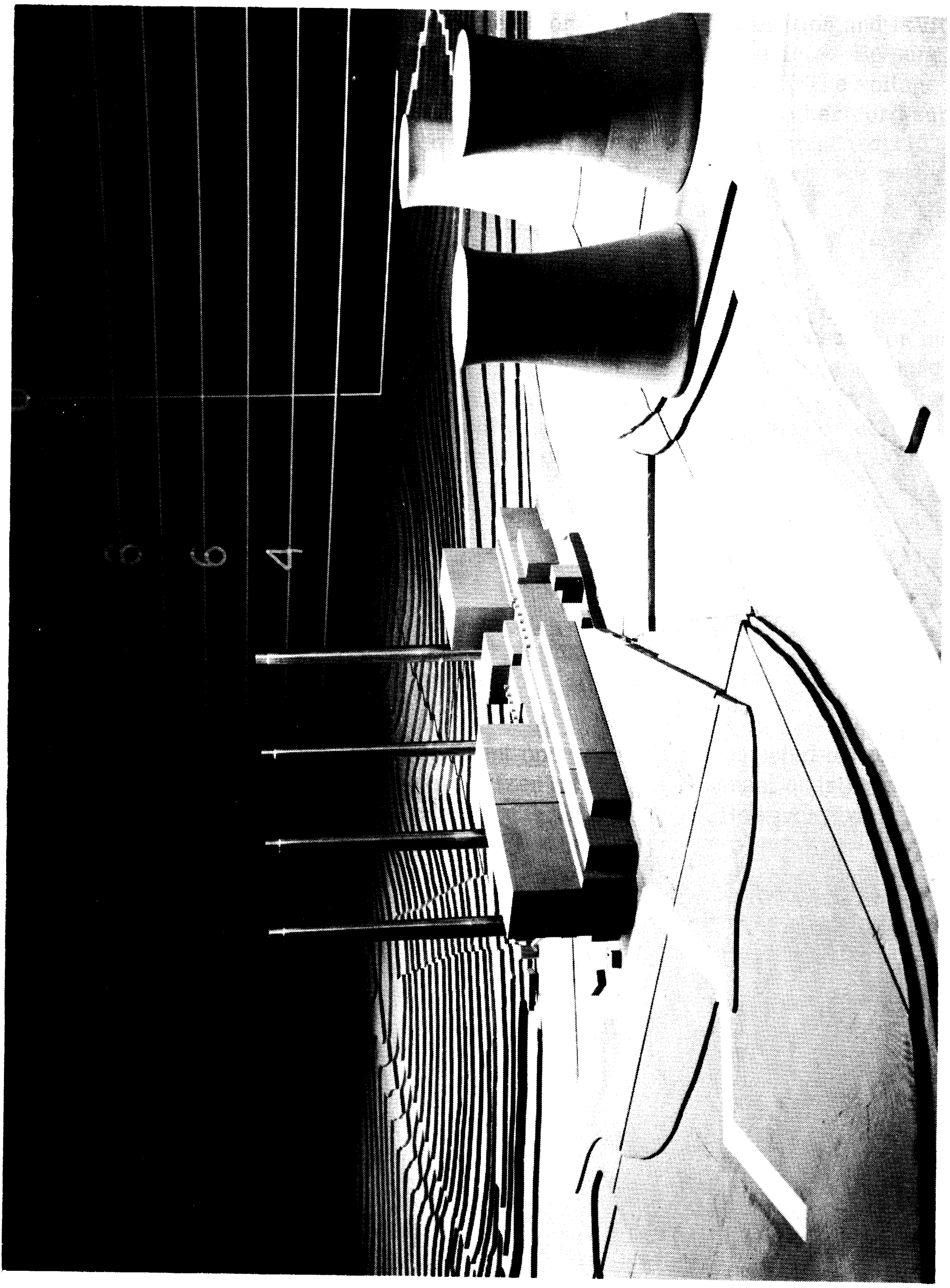


Figure 6. Model in Test Tunnel.

PART II

TOPOGRAPHIC INFLUENCES ON THE BEHAVIOR OF STACK EFFLUENTS

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Introduction

Even over uniform and level terrain there is a very wide range in the dilution which a given effluent will undergo depending on atmospheric conditions. At a given point downwind the concentration may be one thousand times greater, or even ten thousand times greater than it was a few hours or a few days earlier. Effluent temperature, exit speed, and pollution content may be the same; the only difference is in the prevailing meteorological conditions.

Most power plants are not located, however, on a flat plain with uniform surface characteristics. The need for large amounts of cooling water makes preferred locations of river valley bottoms and shore line areas. These topographic features sometimes result in better atmospheric diffusion than over relatively flat terrain. On the other hand, the topography may lead to substantially poorer diffusion. When the influence of topography is combined with the natural variability of the atmospheric diffusion processes, the analysis of meteorological aspects of practical diffusion problems becomes exceedingly complex.(1) Thus, we find that the commonly used diffusion equations, such as those of Sutton(2), are of limited usefulness where topographical features are prominent.

The present analysis will be limited to several examples where topography and the atmosphere combine to create special problems which have so far received relatively little attention. The first is that in which the power plant is located near a steep bluff.

Effluent Movement Near a Steep Bluff

Nearly all effluent transport and dispersion in the atmosphere are influenced by the prevailing atmospheric stability, and this is true near a steep bluff. The stability is governed by the rate of temperature decrease with height, i.e., by the vertical lapse rate. When the temperature drops off (lapses) very rapidly with height, at a rate greater than 6 F per 1000 ft., vertical and horizontal churning and overturning occur continuously and the air is unstable. This turbulent churning in an unstable layer of air, known as thermal turbulence, causes rapid mixing and therefore diffusion, both horizontally and vertically, of an effluent introducted into the layer. When the lapse rate is small but still positive, i.e., temperature decreases with height at a rate intermediate between 0 and 5 F per 1000 ft. and the air in the layer is stable. In such stable layers, mechanical turbulence occurs; its amount is related to the wind speed but is markedly dependent on the roughness of the underlying surface. With strong winds blowing over a rough land or vegetative surface, such as hillocks with large boulders and clumps of bushes and trees on them, mechanical turbulence and mixing, both horizontal and vertical, are pronounced although less than in unstable layers with their thermal turbulence. Mechanical turbulence and the associated mixing are less with lighter winds and smoother land surfaces. An *inversion* exists in a layer when the inverse or opposite of a temperature lapse occurs, i.e., when the temperature increases with height. The air in an inversion layer is *very stable* and very little vertical turbulence and mixing are found in it. Considerable horizontal turbulence and mixing occur in inversion layers, however, so that effluent from a stack flows as a ribbon of increasing width but of very limited vertical extent, with the ribbon having a considerable horizontal meander from side to side. The vertical diffusion in an inversion layer is so small, in fact, that a plume issuing from a high stack rarely if ever reaches the ground as long as the inversion persists. Usually the inversion breaks up before the plume has time to diffuse to the surface. The plume behavior will be discussed under two categories: when the effluent moves toward the bluff; and when the effluent moves away from the bluff.

Effluent Movement toward Bluff.

The behavior of a plume approaching a bluff depends primarily on the stability of the air at the time. Let us consider two limiting cases. On a clear summer afternoon, solar radiation heats the ground to a high temperature, which leads in turn to a large temperature lapse rate in the lower layers. In general, this lapse rate tends to be greater than the critical lapse rate of 5 F per 1000 ft. which marks the division between unstable and stable air. A large lapse rate, greater than the critical value, is illustrated in the upper portion of Figure 1(a). The air is unstable and pronounced churning of the air occurs, leading to looping(3) of the plume as shown in the upper parts of (b), (c), and (d) of Figure 1. The same freedom of vertical motion which permits the churning revealed by the looping plume allows the air mass containing the plume to rise over the steep bluff as the illustration shows. In this very turbulent air, mixing is pronounced and dilution of the effluent is very rapid. Thus even at the upper portion of the bluff the concentrations will be small, and even less with increasing distance downwind from it.

The other limiting case occurs on a clear night with light winds. Loss of heat to outer space from the ground leads to pronounced surface cooling which in turn cools the air layers above. An inversion develops,

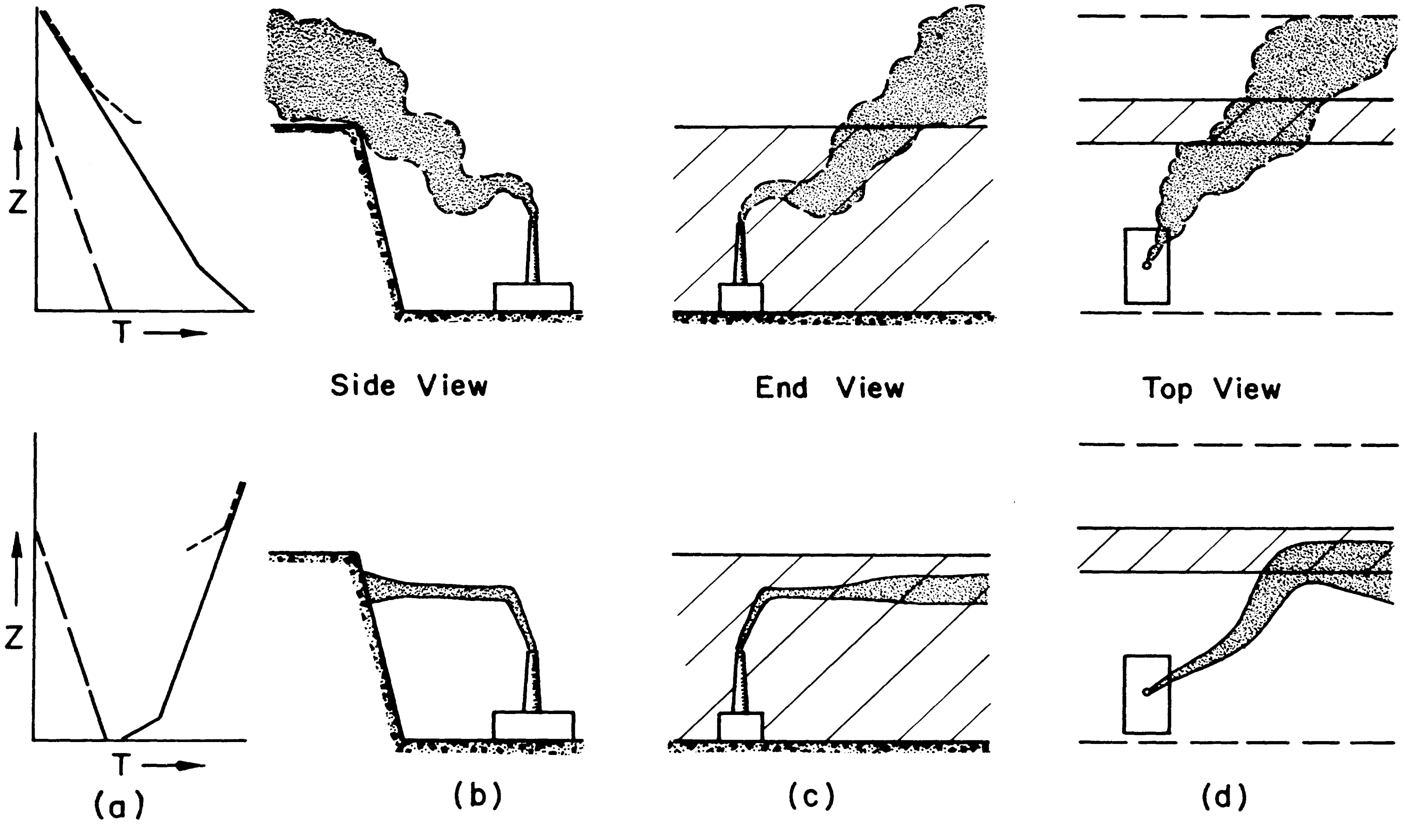

Figure 1. Plume behavior near a steep bluff when the air is unstable (above), and when it is very stable (below). (a) Vertical temperature lapse rates in relation to the critical lapse rate of 5 F per 1000 ft., shown by broken line sloping upward to left: full line - lapse rate measured from grade at plant; dotted line - lapse rate measured from top of bluff; both show effect of ground surface. Corresponding plume features as observed (a) looking horizontally parallel to steep bluff, (b) looking horizontally toward steep bluff, and (c) looking vertically downward from above. Note that when air is unstable, effluent moves up and over bluff but when the air is very stable, as with the inversion as shown, the bluff acts as a barrier to deflect the plume.

as shown in the lower part of Figure 1(a), and the air is very stable and vertical motion is strongly suppressed. This suppression leads to a fanning(3) plume in which vertical mixing is very limited but horizontal mixing is still appreciable, resulting in lateral growth only of the plume. Vertical motion of the whole air mass as well as of vertical turbulence is inhibited, so that the air approaching the bluff is deflected by it into horizontal flow parallel to the surface of the bluff. The plume moves correspondingly, as shown in the lower portion of (b), (c), and (d) of Figure 1.

No problem is presented by the plume in the position shown, or below, or well above. If the height of stack and bluff and the rise of the effluent due to jet action and buoyancy are such that the plume fans out horizontally downwind at the upper ground level at the top of the bluff, a serious situation arises if this plateau is inhabited by humans or livestock, or if it supports valuable crops or timber stands: concentrations in such a fanning plume are among the highest found in the atmosphere, and the design of stack and associated equipment must be such as to avoid the possibility of this occurring. If the plume is above the plateau, but not very far above, substantial concentrations will occur after sunrise for limited periods of half an hour or so when the inversion breaks up and leads to a fumigation(4) at the upper ground surface. A similar fumigation will occur at the base of the bluff if the plume flows along it as illustrated in the lower part of Figure 1. If high concentrations must be avoided both at the base of the bluff and on the plateau, the stack design must be such as to carry the plume well above the plateau and so to minimize(5) these fumigation concentrations on the plateau.

Effluent Movement Away from Bluff

When the wind blows from the plateau toward the plant, aerodynamic influences are also important , as pointed out by Scorer(6). Figure 2 shows smoke from a stack carried down to the ground if the stack orifice is located at the point where the flow rejoins the ground at the lee side of an eddy after separating at the top of the bluff.

There are several methods for evaluating the possibility that stack gases will be carried down in this way. The first employs wind tunnel studies of the type developed by Sherlock and his associates(7),(8), with a suitably scaled bluff included in the model. The other two involve field studies near the plant or plant side, which should be made under a variety of meteorological conditions. The air flow downwind from the bluff would be followed by zero-lift balloons(9) released at intervals from the top of the bluff. The three-dimensional motion of each balloon is tracked

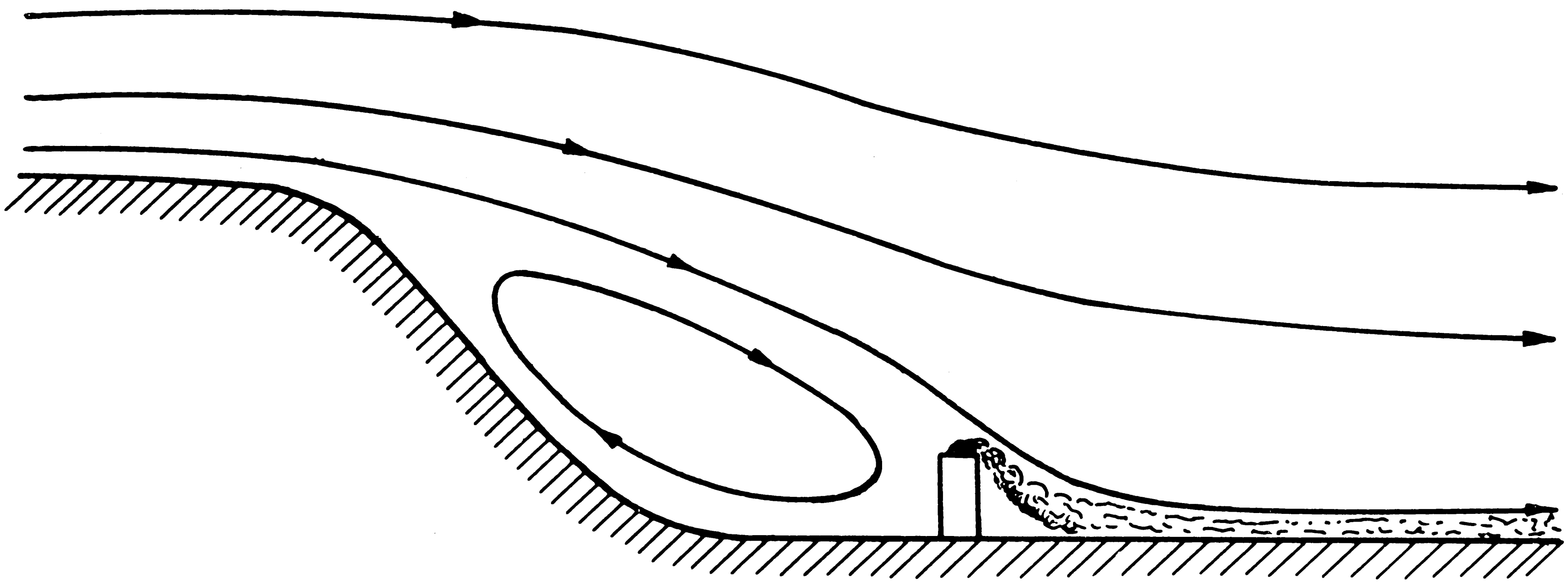

Figure 2. A smoke plume carried to the ground by aerodynamic downwash when the mouth of the stack is located at the point where the flow comes to the surface again at the downwind side of the large eddy after separation near the top of the bluff (after Scorer).

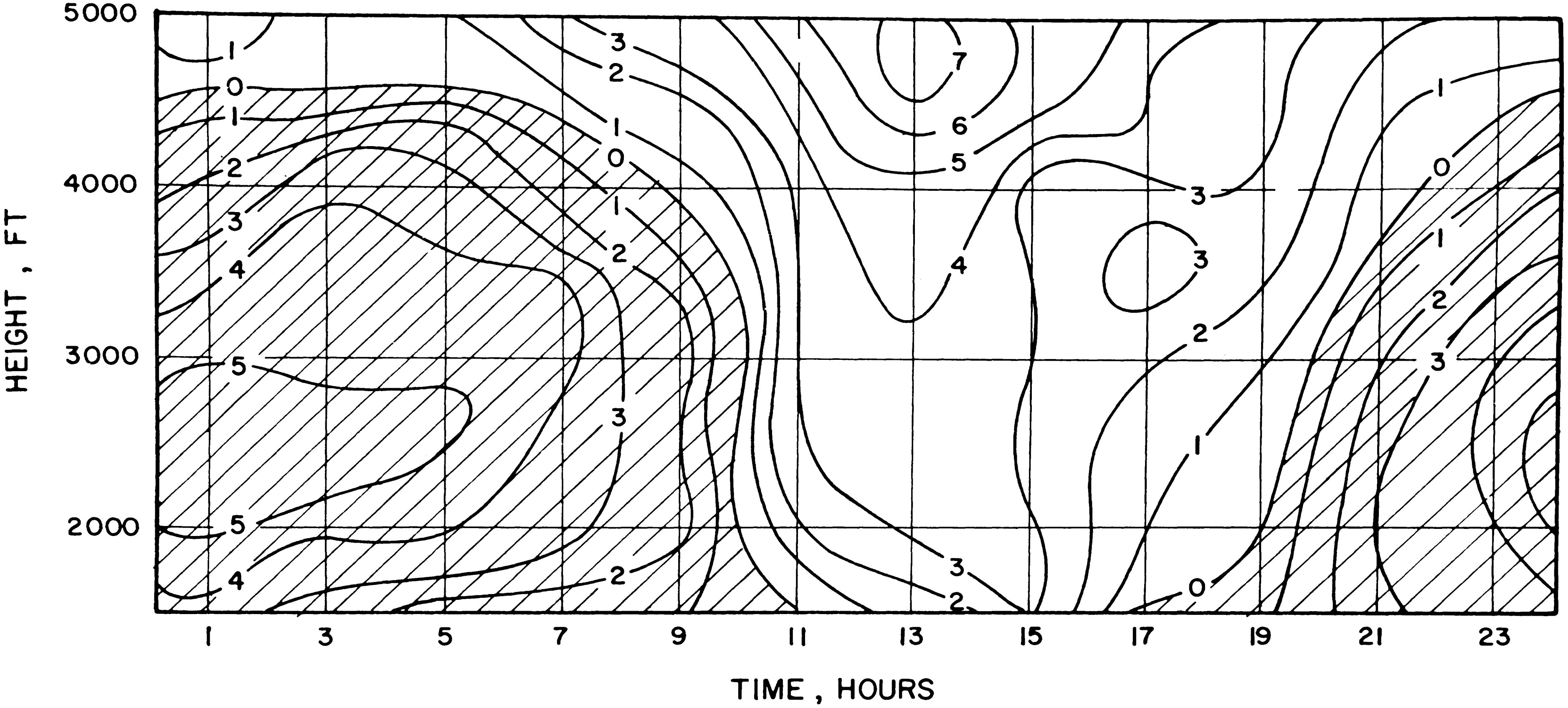

Figure 3. The diurnal variation of valley winds during the summer in the Columbia River Valley near Trail, B. C. Isopleths give average wind speed components in mph. Hatched areas: downvalley (north) wind components. Unhatched areas: upvalley (south) wind components (after Hewson and Longley).

by triangulation using two theodolites a known distance apart. The third method is to photograph a plume of smoke from a specially devised source either at the top of the bluff or supported aloft from the cable of a kite balloon.

The downwash tends to be more prolonged and continuous, with higher ground concentrations, when the air flowing over the plateau is stable than when it is unstable. On the other hand, if the air is very stable both at the base of the bluff and above, as in an inversion, the upper layer may flow out over the lower layer and travel many miles without descending at all. In this case there is practically no coupling between the two strata, each behaving independently of the other. This inherent complexity in the physical processes makes field studies using zerolift balloons or smoke as a tracer preferable to wind tunnel studies alone.

Effluent Movement Above or in a Valley

There are two cases of particular interest in the behavior of air pollution in a valley. In the first case a ground based radiational inversion grows upward from the valley floor during the night and early morning hours but after sunrise this inversion is destroyed by solar heating and is replaced by an unstable layer with a strong lapse rate. The second case is that in which there is an inversion aloft.

Ground-Based Inversion in Valley

Several investigations of air flow in valleys have been conducted. 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(10). 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 ft. above msl, and the sides of the valley extend up to heights of 4000 to 4500 ft. above msl. Figure 3 presents a slightly smoothed analysis of the average daily downvalley and upvalley wind pattern(11).

It will be noted that the prevailing wind above the valley, from 4000-4500 up to 5000 ft. 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 greater heights the downvalley flow ceases earlier than this. From 10 h to 17 h the wind is upvalley. By 17 h the sun is no longer heating the valley floor and radiational cooling with inversion development has commenced, as indicated by the beginning of a downvalley flow at that time. As the cool slope winds descent 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. This daily pattern of upvalley winds by day and downvalley winds at night has been confirmed by later studies, notably in the Carbon River Valley lying in the northwest corner of Mount Ranier National Park(12).

The pros and cons of building a power plant upvalley or downvalley from a city have been discussed in some detail in the light of ground-based inversion formation and breakup, and it is concluded that the meteorological regime points to the desirability of having a power plant located downvalley from the city(13).

Inversion Aloft in Valley

There are two main types of inversion aloft which are of importance in air pollution meteorology: frontal inversions and subsidence inversions(14). Of these, the warm frontal inversion and the subsidence inversion tend to be slowly moving and persistent, and thus present a more serious problem than the rapidly moving cold frontal inversion. The condition with a persistent low-level inversion aloft has been called trapping(14).

With an inversion aloft, the type of analysis required depends on the depth of the valley. In Figure 4(b) the valley is a shallow one in comparison with the height of the stack, and lateral diffusion is unimpeded as the sketch shows. The situation portrayed is likely to be a deceptive one however. Usually meteorological sensors do not extend as high as the stack, and in the case shown with unstable air and strong turbulence between the valley floor and the inversion base aloft as indicated in Figure 4(a), these sensors will indicate excellent diffusion. The diffusion is indeed excellent below the inversion, but these low-level sensors cannot detect the inversion aloft. In the absence of information on the presence of the inversion aloft, one would probably use the basic Sutton equation(1) for concentrations downwind from the stack, which is as follows:

$$\chi = \frac{Q \exp^{*}\left(-y^2/C_y^2 x^{2-n}\right)}{\pi C_y C_z u x^{2-n}} \left\{ \exp\left[-(z-h_e)^2/C_z^2 x^{2-n}\right] + \exp\left[-(z+h_e)^2/C_z^2 x^{2-n}\right] \right\} \qquad (1)$$

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* exp -ak is equivalent to e^{-ak}

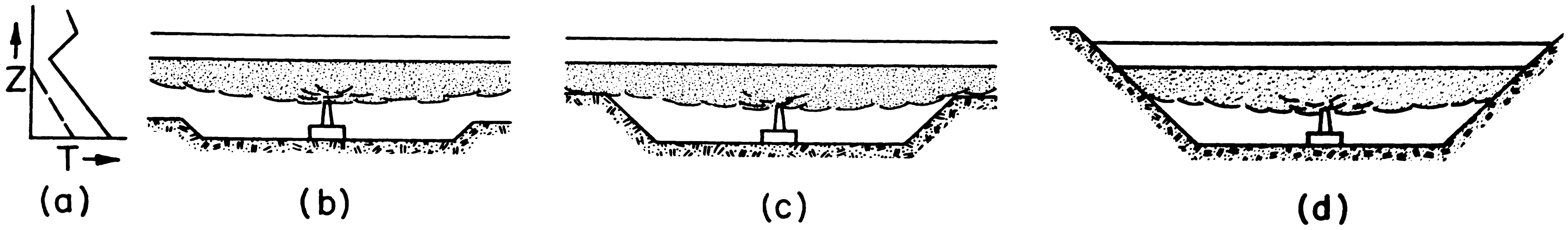

Figure 4. Trapping of an effluent below an inversion aloft, shown by the two horizontal lines. (a) Temperature lapse rate, full line, in and above the valley in relation to the critical lapse rate of 5 F per 1000 ft., shown by broken line sloping upward to left. Diffusion is excellent between the valley floor and the inversion base. No upward diffusion takes place through the inversion aloft, but in (b) and (c) the valley sides are low enough to permit rapid lateral diffusion whereas in (d) the effluent is confined in the valley by its walls and the inversion aloft. Condition (d) may lead to high concentrations throughout the valley.

where

χ = mass of contaminant per unit volume of air

Q = rate of contaminant emission from stack in mass per unit time

h_e = height above ground of center of horizontal portion of plume, i.e., effective stack height

u = mean wind speed

x, y, z = coordinates along wind, horizontally across wind, and vertically upward, respectively, of point for which concentration is being determined, origin being at ground level at base of stack

n = a dimensionless parameter related to atmospheric turbulence

C_y, C_z = virtual diffusion coefficients for diffusion in y and z directions, respectively.

The second exponential term on the right allows for complete reflection of the effluent from the ground surface. With $z = 0$. Equation (1) gives the surface concentration as

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

However, the base of an inversion aloft acts effectively as an impermeable barrier, so that the effluent is in fact reflected upward from the ground and downward from the inversion base. We have therefore modified the basic equations above to allow for multiple reflections both above and below using the method of virtual image sources. If the height of the inversion base is h_{ib}, then over level terrain for $0 < z < h_{ib}$, the trapping concentrations are given by

$$\chi = \frac{Q \exp\left(-y^2/C_y^2 x^{2-n}\right)}{\pi C_y C_z u x^{2-n}} \left\{\sum_N \exp\left[-(z-h_e+2Nh_{ib})^2/C_z^2 x^{2-n}\right] + \sum_N \exp\left[-(z+h_e-2Nh_{ib})^2/C_z^2 x^{2-n}\right]\right\} \qquad (3)$$

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

$$\chi_o = \frac{2Q \exp(-y^2/C_y^2 x^{2-n})}{\pi C_y C_z u x^{2-n}} \left\{ \sum_N \exp\left[-(2Nh_{ib}-h_e)^2/C_z^2 x^{2-n}\right] \right\} \qquad (4)$$

The use of the first several values of N gives sufficient accuracy for most purposes.

Returning now to Figure 4, in the case of a very shallow valley as in (b), the influence of the valley on the trapping process is negligible and it will be permissible to use Equations (3) and (4) in order to estimate trapping concentrations to be expected in the valley. The mean wind direction is parallel to the center line of the valley in (b), (c), and (d). With the deeper valley as in (c) but with the inversion base still well above the valley sides, these equations could still be used but the computed concentrations would have to be increased somewhat to allow for the influence of the valley. The amount of this upward adjustment would depend on the dimensions of the valley and on the height of the inversion base. It must be emphasized that values of n, C_y, and C_z appropriate for conditions of thermal turbulence(14), not for inversion conditions, are to be used. The sole but nevertheless critical role of the inversion aloft is to prevent upward turbulent diffision above its base.

The dominant influence of an inversion aloft where the inversion lies within the valley itself, as in Figure 4(d), was discovered in the Columbia River Valley(10). It is this meteorological condition which was later found to be the cause of Los Angeles smog: in the late summer and fall months the subsidence inversion aloft associated with the great Pacific subtropical anticyclone descends at intervals and sometimes stays for long periods below the mountains which ring Los Angeles County on three sides and thus prevents effective natural ventilation of the area. Although smaller stagnant anticyclones occasionally occur in higher latitudes and cause similar problems elsewhere(14), fortunately the period of stagnation in these latitudes is rarely prolonged enough to present an acute problem arising from a subsidence inversion aloft.

The smoke pattern shown in Figure 4 is that relatively near the stack, before the excellent diffusion in the lower portion of the valley has had an opportunity to spread the smoke uniformly throughout the cross section of the valley below the inversion. The average concentration $\bar{\chi}$ throughout a valley of average cross sectional area $\bar{A}$ below the inversion base is readily seen to be

$$\bar{\chi} = Q/\bar{u}\bar{A} \qquad (5)$$

when the rate of contaminant emission from the stack is Q and the wind speed along the valley averaged over cross sectional area $\bar{A}$ is $\bar{u}$. The actual value of the concentration at the valley floor will become equal to $\bar{\chi}$ at a relatively short distance downwind from the stack and will not decrease downwind thereafter unless the valley widens. Near the plant the values given by Equations (3) and (4) will be only slightly less than that given by Equation (5); the difference becomes progressively greater with increasing distance downwind from the plant. Equation (5) therefore gives the maximum ground level concentration to be expected anywhere in the valley for the extreme topographic trapping condition illustrated in Figure 4(d).

Effluent Movement Near a Shoreline

The following sections will discuss the general features of atmospheric movement and structure near a shoreline and will then describe the results of an investigation of air flow and effluent dispersion at the western end of Lake Erie, near the site of the Enrico Fermi Atomic Power Plant.

Atmospheric Flow and Structure Near a Shoreline. There is a well known tendency for local winds, known variously as land and sea breezes or land and lake breezes to develop near shorelines(15,16). On shore winds are characterized by higher speeds than winds from the same direction at inland locations. This feature is shown by a comparison of speeds of winds from NE through SSE which have an over water trajectory before reaching the Enrico Fermi Site near Monroe, Michigan with wind speeds from corresponding directions at the Detroit City Airport and the Toledo Express Airport, both some miles from large lakes as given in Figure 5. Such higher wind speeds imply better diffusion since all diffusion equations, including (1) through (5), show that other things being equal downwind concentrations vary inversely with the wind speed.

Another characteristic feature of lake shoreline winds is, at certain seasons of the year, a marked tendency for an on shore wind, the lake breeze, to occur during the warmer hours of the day and for an off shore wind, the land breeze, to occur at night during the early morning hours. Such breezes are only identified readily on days when the regional wind regime is light. Twenty-three such days were selected during June and July 1957 and the diurnal wind patterns at the Fermi Plant were analyzed in detail. The results of the analysis are presented in Figure 6. Between 60 and 70 per cent of all winds between noon and 6 p.m. were from the lake, whereas between 30 and 40 per cent between 3 and 9 a.m. were from the land. The figure also shows that these breezes minimize the average diurnal temperature variation at the Plant Site (Monroe) in comparison with that at the Toledo Express Airport.

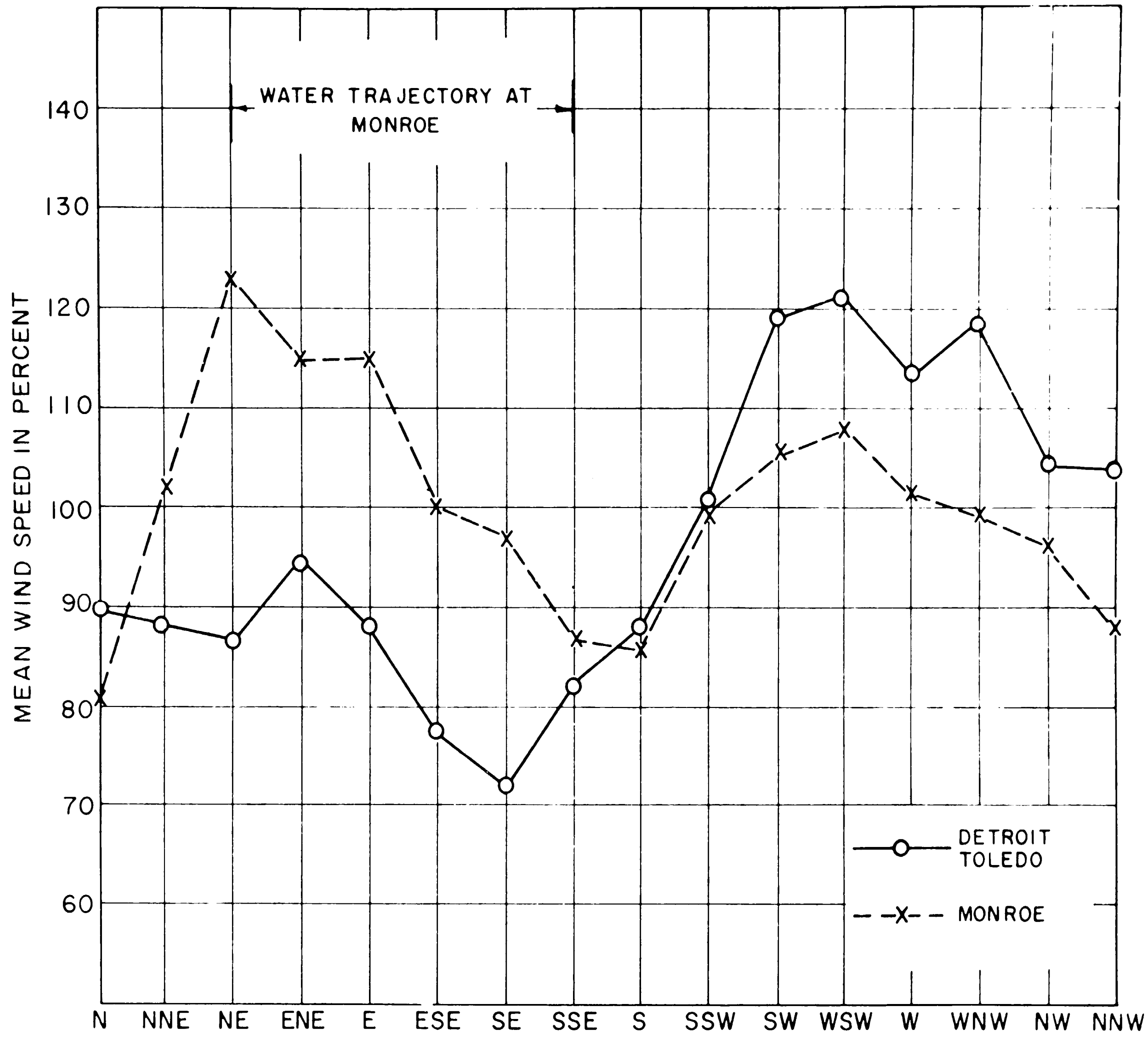

Figure 5. Mean wind speed for the Enrico Fermi Site on the Western shore of Lake Erie near Monroe, Michigan and for Detroit-Toledo Airports combined, for 16 directions, expressed as a percentage of the mean three-year wind speed for all directions, 1 December 1956 to 30 November 1959. Anemometers were located at heights from 72 to 102 ft. above ground.

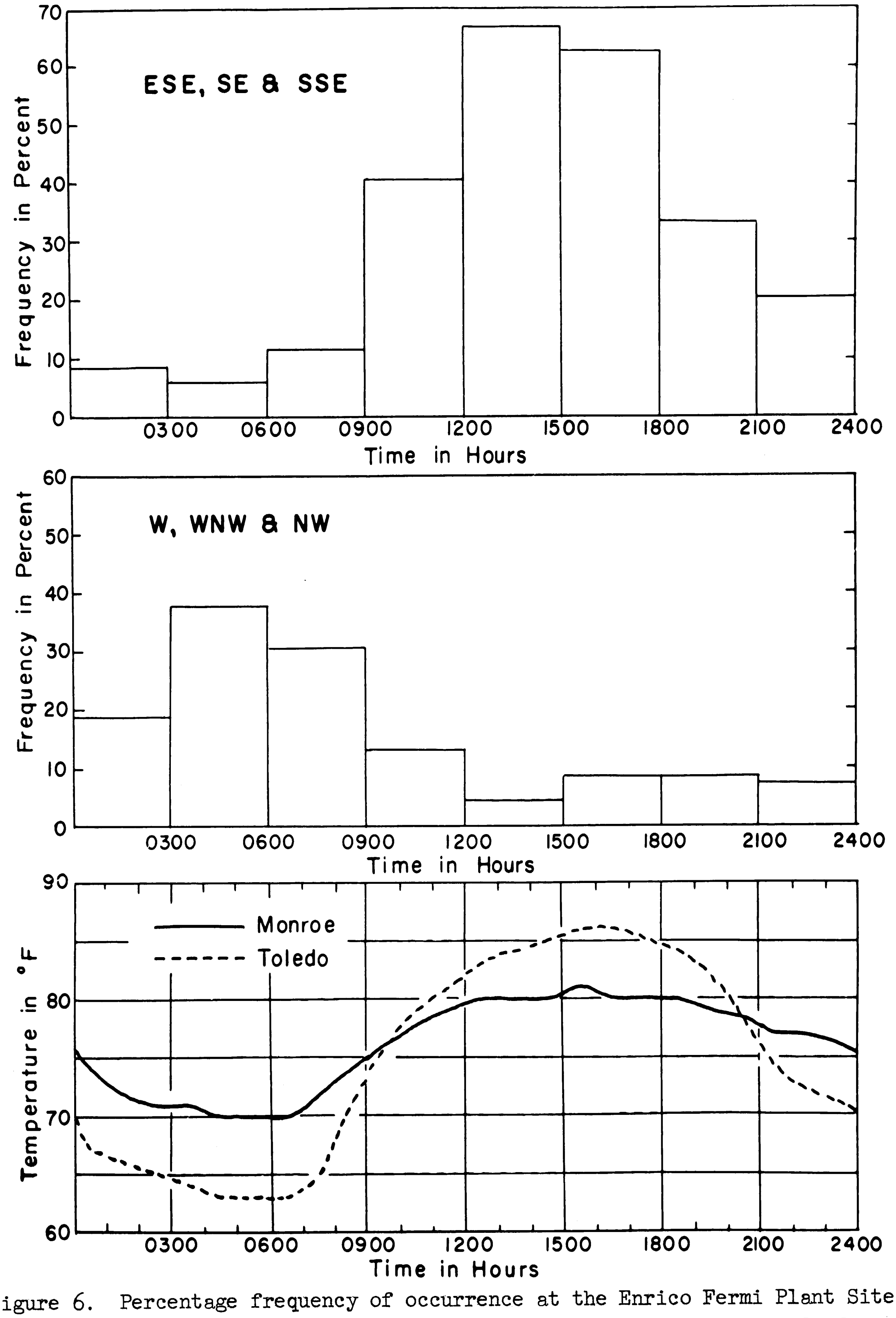

Figure 6. Percentage frequency of occurrence at the Enrico Fermi Plant Site of diurnal on shore lake breezes from ESE, SE, and SSE and of diurnal off shore land breezes from W, WNW, and NW for 23 selected days during June and July 1957. The lowest graph shows the average diurnal temperature variation for these same 23 days at the Plant Site (Monroe) and at the Toledo Express Airport.

During late spring and early summer expecially these on shore lake breezes tend to have a surface inversion present as they advance from the relatively cool water surface. Farther inland strong lapse rates, not inversions, are prevalent during the afternoon hours. As a result, the diurnal variation throughout the year of frequency of occurrence of inversions at the Plant Site is much less pronounced than at the WJBK-TV tower at an inland location in northwest Detroit, as shown in Figure 7. In addition, the minimum frequency occurs before noon at the Plant Site whereas it occurs in the late afternoon in northwest Detroit. The total number of hours of inversion for the 3-year period is approximately the same at both locations. The occurrence of continuous inversions of various durations at the Fermi Plant Site is also of interest and is presented in Figure 8. It will be noted that there were thirteen inversions each continuing for more than 30 hours. Most of these long lasting inversions were the result of the flow of relatively warm air over the cool lake waters; such inversions are rapidly broken up by mechanical or thermal turbulence or both as the air leaves the cool lake and advances over relatively rough and warm land surfaces. There is a corresponding rapid improvement of atmospheric diffusion as the inversion breaks up over land.

Atmospheric Diffusion Near a Shoreline. The diffusion patterns near a shoreline are more complicated than those over open level terrain, especially when there are pronounced temperature differences between land and water surfaces. Consider first the case in which warm unstable air flows over a cool underlying surface, i.e., as from land to water in spring and early summer or from water to land in autumn and early winter. Effluent leaving the stack is rapidly diffused by the prevailing thermal turbulence, but a surface inversion known as an advection inversion starts to develop as soon as the warm air advances over the cool surface. By this time, however, the contaminant in the developing surface inversion layer has been well diluted by the preceding thermal turbulence, and concentrations remain low in this layer even though vertical diffusion in it is inhibited(14).

When the flow is oppositely directed in these seasons the diffusion pattern is entirely different. Let us consider a warm air mass moving from the southeast over cool Lake Erie during the spring or early summer. The air reaching the Fermi Plant Site will have very little turbulence in it because of the smooth water surface over which it has been flowing and because of the inversion present. Under these circumstances a fanning plume characteristic of an inversion will leave the stack. Mechanical and thermal turbulence will grow from the ground upward as the air advances inland, the top of the turbulent layer reaching a height z given approximately by the relation

$$z^2 = 4\ Kt \qquad (6)$$

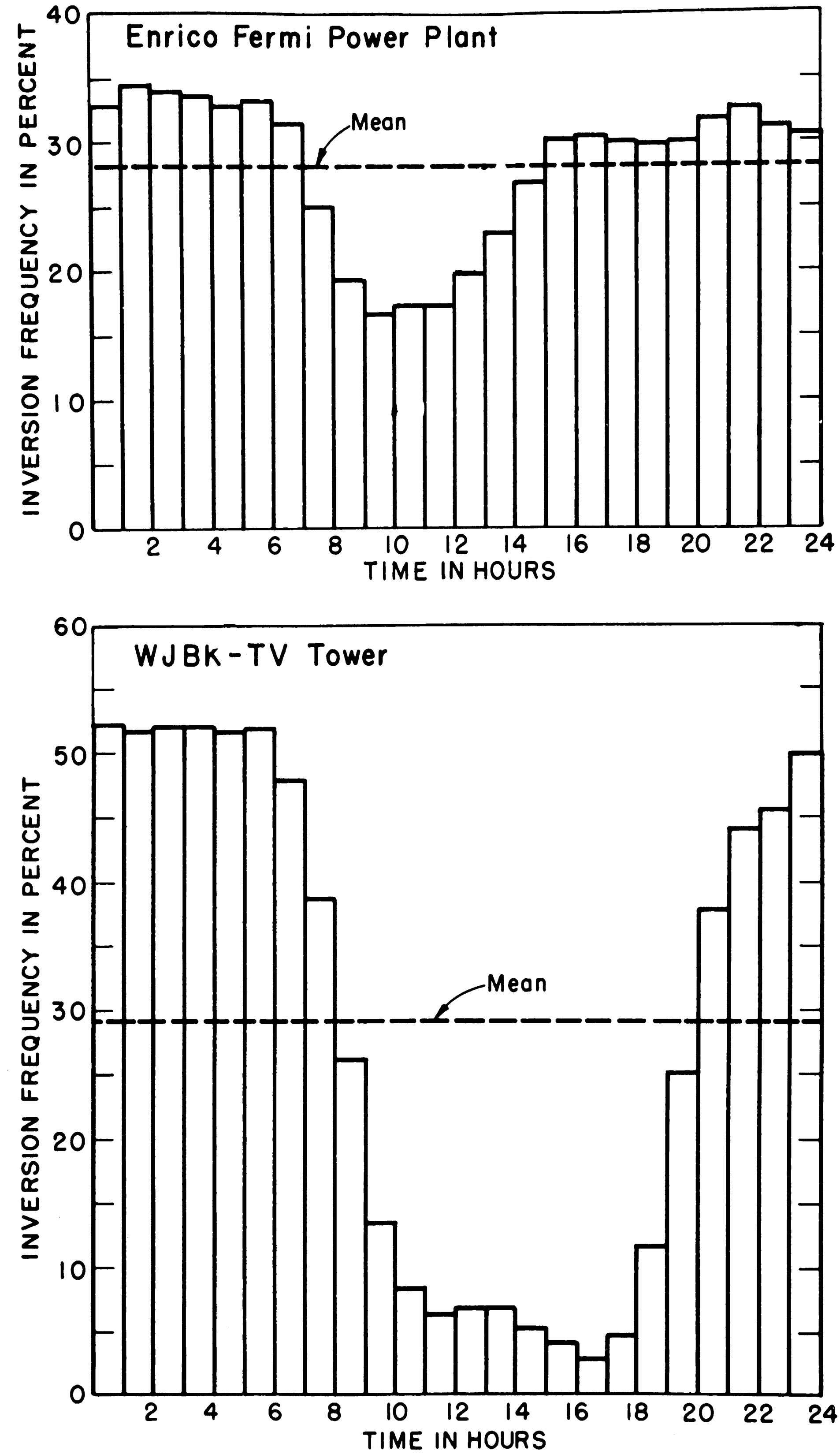

Figure 7. Diurnal variation of percentage frequency of occurrence of inversions at the Enrico Fermi Site (between 25 and 100 ft.) and at the WJBK-TV tower in northwestern Detroit (between 20 and 300 ft.) for the 3-year period from 1 December 1956 to 30 November 1959.

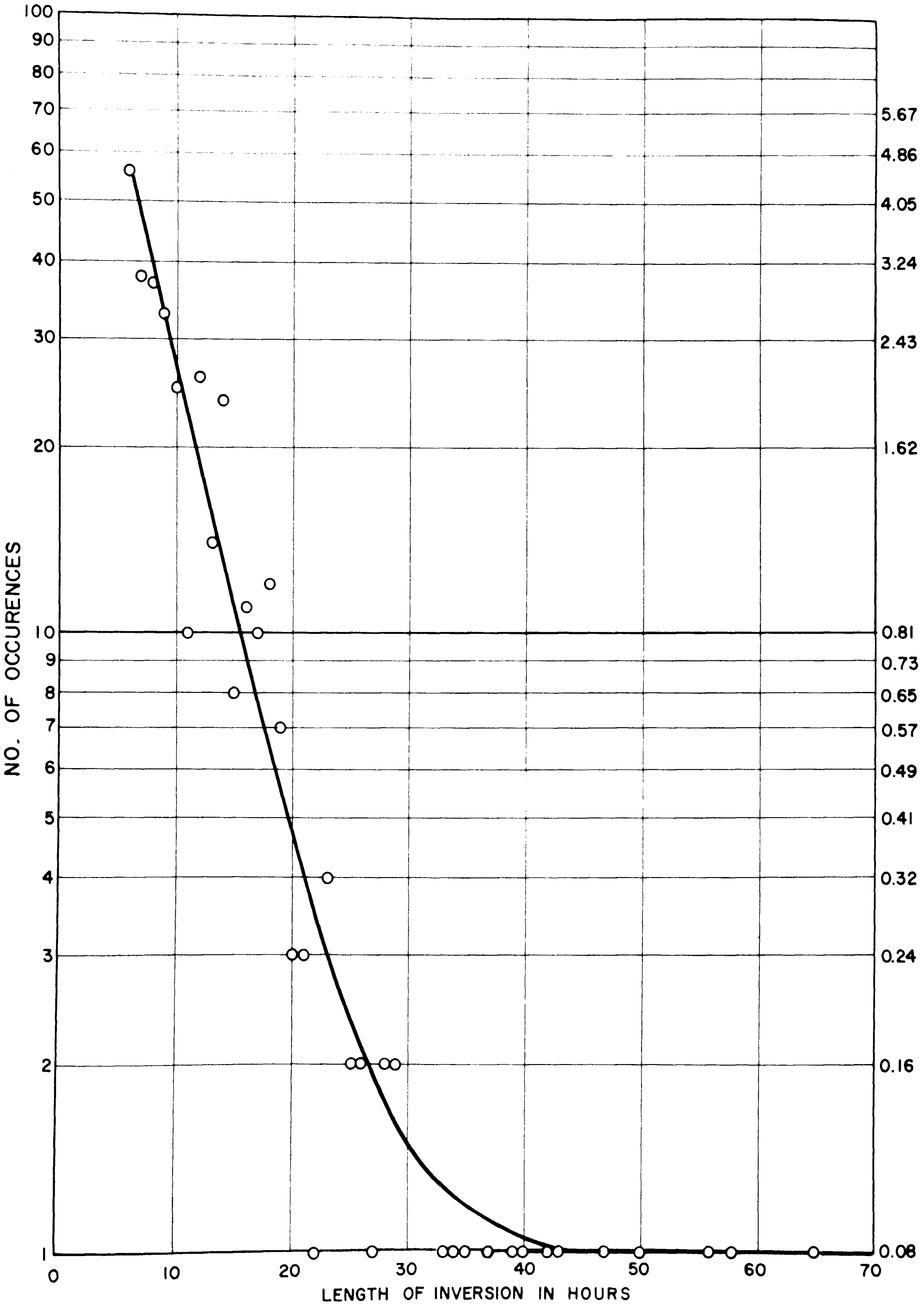

Figure 8. Occurrence at the Fermi Plant Site of continuous inversions (25 to 100 ft.) of various durations for the 3-year period 1 December 1956 - 30 November 1959.

where t is time elapsed since the air in question crossed the shoreline and K is a coefficient of vertical turbulent heat transfer(17). Representative values of K are: for turbulence which is primarily mechanical, $K = 1\ m^2 sec^{-1}$; for active thermal turbulence, $K = 10^2\ m^2 sec^{-1}$. At a certain distance downwind from the stack the upward growing thermal turbulence will reach the fanning plume; the fanning plume acts as a limited line source aloft for a second stage in the diffusion process in which the thermal turbulence brings the contaminant to the ground in moderately high concentrations. This process has been called a Type III fumigation(14).

Sutton's equations(18) may be used to estimate the surface concentrations to be expected with a Type III fumigation. Thus

$$\chi_o = \frac{Q_1 \exp(-h_e{}^2/C_z{}^2 x^{2-n})}{\pi^{\frac{1}{2}}\, C_z u x^{1-\frac{1}{2}n}} \left\{ \text{erf}^* \left[\frac{y_o - y}{C_y x^{1-\frac{1}{2}n}}\right] + \text{erf}\left[\frac{y_o + y}{C_y x^{1-\frac{1}{2}n}}\right] \right\} \qquad (7)$$

where $2y_o$ is the width of the fanning plume at the point at which the turbulent layer growing upward reached 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 use of Equation (7) assumes a uniformly distributed cross wind elevated continuous line source, which will not be a correct assumption for the above usage; the equation will nevertheless provide concentration values adequate for a first approximation(14).

A field investigation of shoreline diffusion has been conducted near the Enrico Fermi Atomic Power Plant at the western end of Lake Erie. The tracer substance employed was zinc cadmium sulfide fluorescent paint pigment. The particles had a mean diameter of approximately 2.7μ, with a normal size range of 1 to 8μ with 90 per cent of the particles being under 4μ in diameter. Such particles have a negligible settling speed. The particles were emitted at a known rate at a height of 56 ft. on the meteorological tower.

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

The techniques employed have been described in detail in an unpublished report(19). The tracer was sampled by a small airplane which flew in a carefully designed program of heights above the surface, both land and lake, and of distances from the source. Since the zinc cadmium sulfide particles were invisible a short distance from the dispenser in the amounts used, oil fog was emitted at intervals from a generator mounted on the tower to permit a visual estimate of the location of the invisible fluorescent tracer particles. Special measures were required to permit accurate guidance of the pilot and reliable fixes on the position of the plane, especially over the lake where the pilot had no reference points. Since sampling had to be done at considerable distances from the source and in poor as well as good visibility, a ship's navigational radar was mounted on the tower to permit constant monitoring of the airplane and a two-way radio communication system between tower and plane maintained. A section of the meteorological tower with some of the equipment is shown in Figure 9.

The samples obtained during flights with on shore easterly winds during the afternoon of 4 February 1960 are shown in Figure 10. Vertical temperature soundings made by the plane both over the land and over the lake are given in Figure 11 for the same afternoon; there was a weak lapse rate from the surface up to 600-800 ft. and an inversion above. As would be as anticipated for these conditions and as verified by Figure 10, both vertical and horizontal diffusion were limited.

The details of the experimental and analytical procedures will be published elsewhere. The values of the various coefficients as determined by these methods are summarized in Table I.

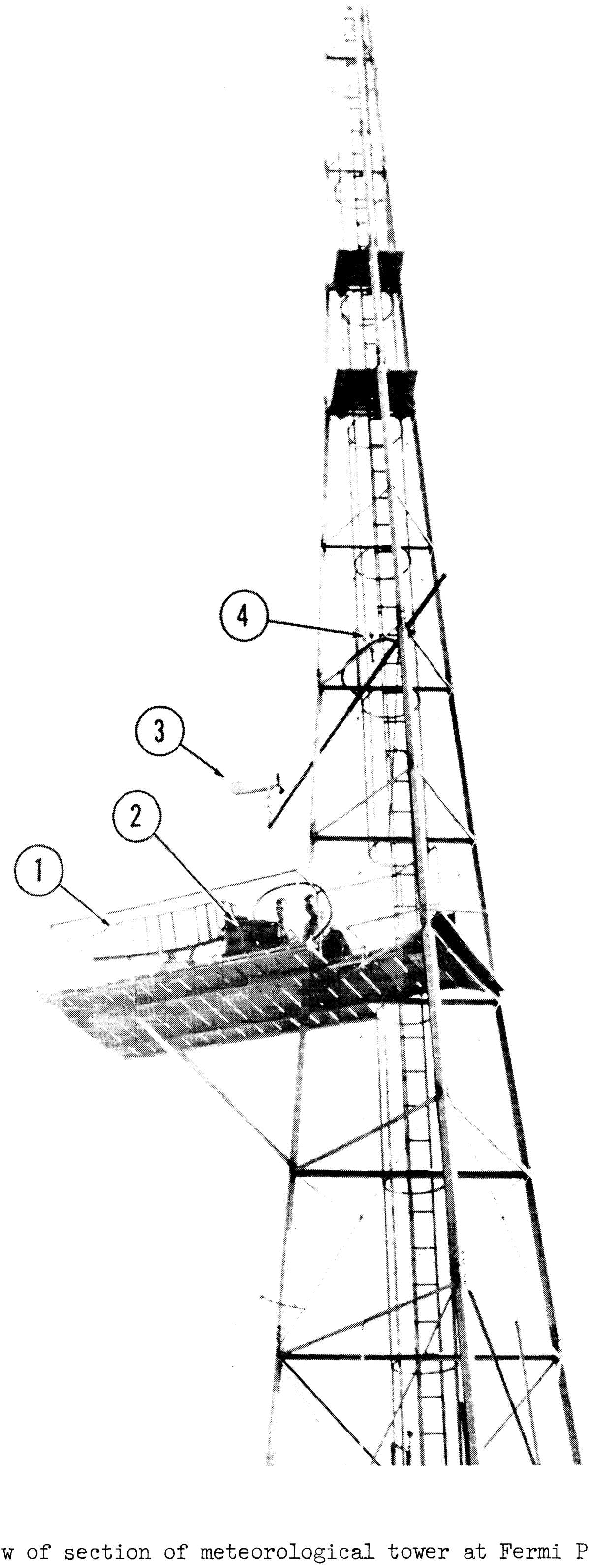

Figure 9. View of section of meteorological tower at Fermi Plant Site showing: (1) radar antenna at 40 ft. (2) oil-fog generator also at 40 ft. (3) Aerovane for wind measurements at 56 ft. and (4) aspirated thermocouple unit at 56 ft. for lapse rate measurements. During operations the fluorescent particle dispenser and a theodolite used as an auxiliary aid in locating both the plane and the oil-fog smoke were also located at the 56-ft. level.

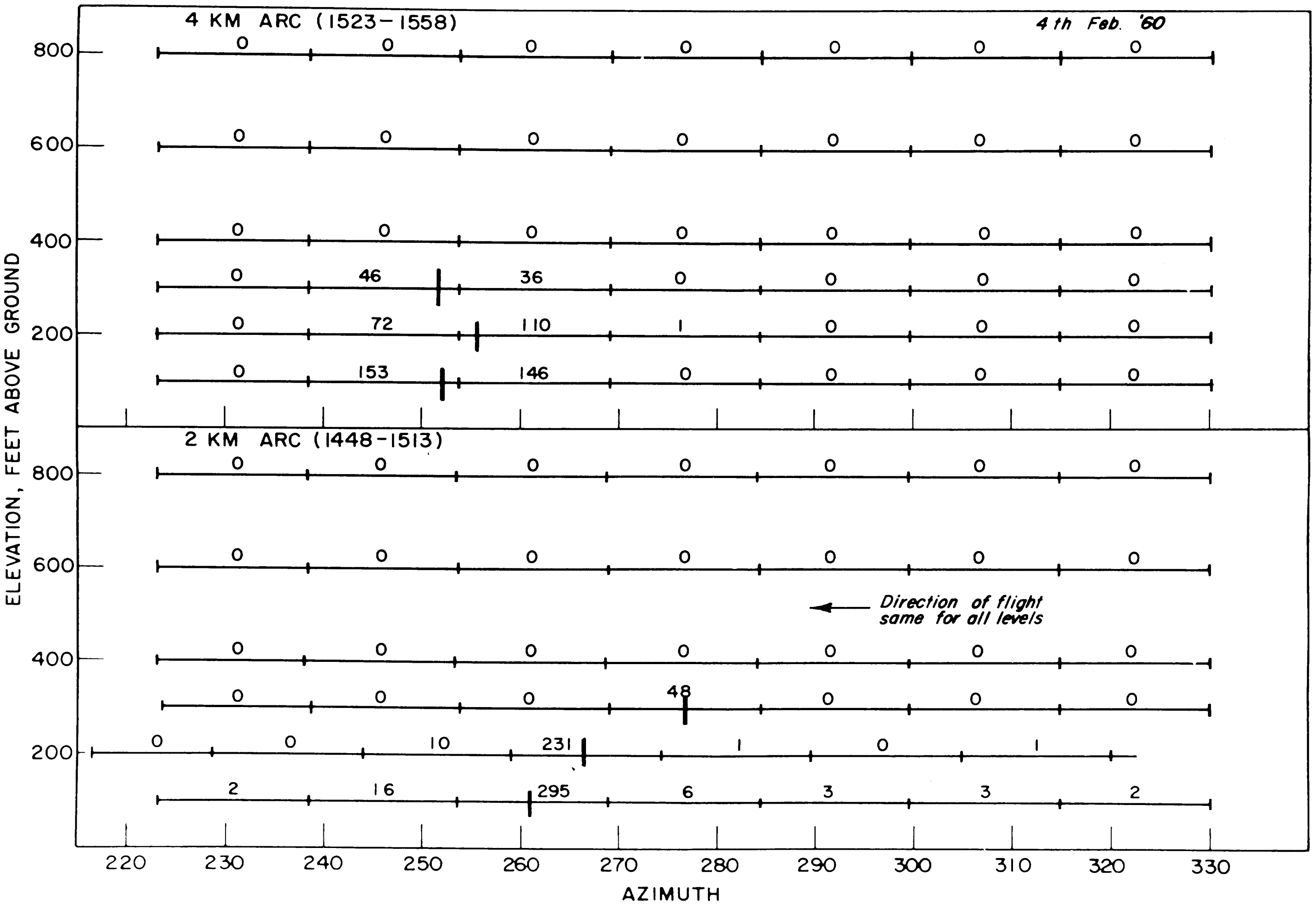

Figure 10. Counts of numbers of fluorescent tracer particles obtained by airplane sampling from 1448 to 1558 h on 4 February 1960. The wind was easterly, i.e., from the lake.

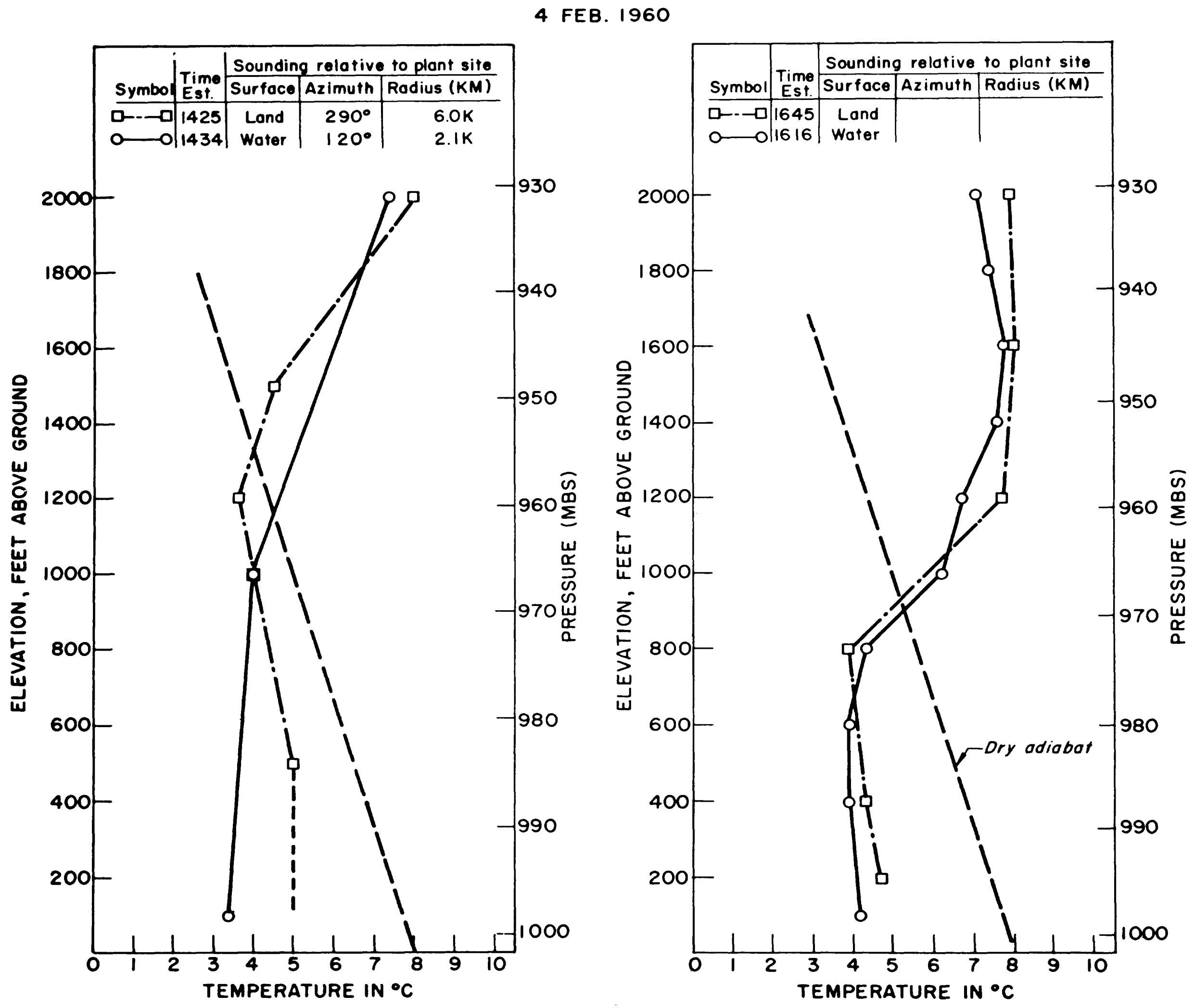

Figure 11. Plots of the vertical temperature distribution as recorded on the aerometeorograph during the afternoon of 4 February 1960.

TABLE I

MEAN COMPUTED VALUES OF C_z AND C_y AT THE ENRICO FERMI PLANT SITE

Day	n	$\bar{C}_z$	$\bar{C}_y$
6 August 1959 (run No. 1)	0.25	0.15	0.38
27 November 1959	0.20	0.14	0.64
4 February 1960	0.30	0.08	0.54
3 April 1960	0.30	0.09	0.61
8 May 1960	0.20	0.13	0.44
25 June 1960	0.23	0.14	0.37

Distinctive features of the coefficients are the relatively small values on n and $\bar{C}_z$ in comparison with the values of $\bar{C}_y$. Horizontal diffusion was in all cases pronounced; this fact, taken in conjunction with the relatively high winds and nearly complete absence of calms, suggests that a shoreline site has considerable merit from the point of view of atmospheric dispersal of contaminants.

Conclusions

Following this brief discussion of three plant locations, it may be concluded that topography is important in the behavior of stack effluents. Topography controls the effluent behavior in two distinct ways: directly, in that it channels the effluent as in a valley; and indirectly, in that the dispersion characteristics of the atmosphere are directly related to the local topography as is exhibited in the lake breeze land breeze regime.

The direct influence is dominant to the extent that no control can be exerted upon it. Therefore, the valley site is the poorest of the three because of the impermeable valley walls. With the adverse meteorological conditions of an upper level inversion, contaminant concentrations in a valley are high.

The bluff location, on the other hand, has not the physical restriction of the valley walls and hence diffusion will be better. In fact, if the stack is properly located, the down slope winds from the bluff can be used to create good mechanical mixing and thus cause lower concentrations of effluent material.

The site with the least direct restrictions, the lake shore location, experiences the best diffusion conditions. The proxomity of a land and water surface of differing temperatures leads to an average wind speed higher than that occurring inland. Although inversion conditions do occur often, they usually break up over land within a short distance of the shoreline leading to lower concentrations than would be expected from the lapse rates at the shoreline itself.

The effect of topography upon the behavior of stack effluents is highly significant and should be considered, in conjunction with the meteorology, in selecting a plant site, if an air pollution problem is to be avoided.

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