NUREG/CR-0936
BNL-NUREG-51045

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Prepared for
U. S. Nuclear Regulatory Commission

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BNL-NUREG-51045

RECOMMENDATIONS FOR METEOROLOGICAL MEASUREMENT PROGRAMS AND ATMOSPHERIC DIFFUSION PREDICTION METHODS FOR USE AT COASTAL NUCLEAR REACTOR SITES

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Manuscript Completed - February 1979
Date Published - October 1979

PREPARED FOR THE U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
UNDER CONTRACT NO. EY 76-C-02-0016
FIN NO. A3113-8

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

FOREWARD

The study contained herein was requested by the NRC staff to assess the state-of-the-art with respect to the adequacy of data and prediction methods for diffusion in coastal environments. The bases for the request eminated from staff experience on individual case reviews where it was found that significantly different diffusion conditions were observed at coastal sites. The recommendations by the contractor will be assessed by the NRC staff in terms of the need for additional research, the necessity for changes in regulatory practice, the benefits to be derived, and a value impact evaluation therefrom. The assessment, which is scheduled for completion in FY80, will become the basis for changes to Regulatory Guides, Standard Review Plans and incident response procedures.

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ABSTRACT

A study, based on a literature review, was performed to examine currently recommended meteorological measurement programs and diffusion prediction methods for nuclear power plants to determine their adequacy for plants located in coastal zones. Although procedures for handling the "near worst" case (stable, light wind situation) were judged adequately conservative, deficiencies in guidelines and procedures were found with respect to the following: failure to consider the role of coastal internal boundary layers, specifications for tower locations and instrument heights, methods of classifying atmospheric stability, methods of allowing credit for plume meander and models specified for diffusion calculations. Recommendations were made for changes in the guidelines applicable to these topics. Areas in which additional research is needed were identified.

A. INTRODUCTION

The Atmospheric Sciences Division at Brookhaven National Laboratory was requested by the U. S. Nuclear Regulatory Commission (NRC) to examine currently recommended meteorological measurement programs and atmospheric transport and diffusion prediction models for nuclear power plants to determine their adequacy for plants located in coastal zones where meteorological conditions are normally more complex than at inland sites and to make recommendations for changes to improve current procedures. Funds were provided for a limited evaluation based on a literature review to determine available knowledge on coastal meteorological processes and their influence on dispersion. The NRC specified that the study would be restricted to simple coastlines without complex terrain, that only effects within five miles of the plant should be considered and that models recommended should give conservative predictions for plant design purposes.

The term "plant design purposes" includes all non-realtime purposes for which diffusion estimates are desired for any time period or condition or any combination of time period and condition. These purposes include but are not restricted to site selection, characterization of a site in terms of diffusive capacity prior to construction or operation of a plant, safety analyses, study of environmental impacts, estimations of future daily, seasonal or annual averages and assessment of the consequences of potential future accidents. Calculations of concentration may be performed for selected meteorological conditions, to determine the "worst case", for instance, or for a representative range of meteorological conditions to give long-term averages. For all these purposes, a conservative estimate is needed to give an appropriate margin of safety. Thus, the model should over-predict rather than under-predict.

The use of models for realtime prediction using actual current input data as during an accidental release, for instance, is specifically excluded from "plant design purposes". Here, the nature of the input data, the methods of applying the model and the output desired may be quite different from those in a routine calculation and realistic, rather than conservative, predictions are needed to guide response to the situation.

Although this report was designed to respond to the NRC specifications for the study, more general considerations of meteorology and diffusion in coastal areas could not be excluded and are implicit in the discussions and recommendations below.

B. BACKGROUND

Currently recommended onsite meteorological programs are described in NRC Regulatory Guide 1.23 (NRC, 1972), which specifies measurement of wind direction, wind speed and ambient air temperature at a minimum of two elevations, the lower at 10 m above the ground and the upper at 30 m or more above the lower level. For stack releases, another set of sensors is specified at a height representative of the stack. Atmospheric diffusion parameters are based on stability classes determined from measured temperature lapse rates.

Currently recommended atmospheric diffusion models and instructions for their use are contained in NRC Regulatory Guide 1.145 (NRC, 1979) and 1.111 (NRC, 1977). The Gaussian plume model is specified to calculate relative concentrations at specified distances and for specific time periods, release heights, locations and stability conditions.

The Atmospheric Sciences Division (formerly Meteorology Group) at Brookhaven National Laboratory has been engaged in a study of coastal meteorology and diffusion since 1972. This program has been funded successively by the U. S. Atomic Energy Commission, the Energy Research and Development Administration, and the Department of Energy. The experience and data gained in that program plus information available in the published literature form the basis for the recommendations below.

C. PROBLEM AREAS

Preliminary consideration of the available data in the context of NRC's regulatory responsibilities and current regulatory procedures identified several problem areas in which present regulations or guidelines seemed inadequate or unsatisfactory for coastal sites. Therefore, the study was focused on the following areas:

1. Coastal internal boundary layers
2. Tower location
3. Instrument heights
4. Atmospheric stability classification
5. Plume meander
6. Diffusion calculations

Current guidelines with respect to 1, 2, 3, 5 and 6 are unsatisfactory scientifically in that they do not take into consideration the unique meteorological conditions near coastlines and are unsatisfactory from a regulatory standpoint with respect to "realistic" predictions (the 50% case) in that they are likely to lead to under-predictions of surface concentrations. Guidelines for 4 are unsatisfactory scientifically since the method specified often gives erroneous stability classifications which could cause either under- or over-prediction of concentrations. However, other guidelines make over-predictions and therefore conservative estimates most likely under current procedures for the "near worst" (5%) case. Each of the areas is discussed below with appropriate recommendations which are underlined in the text and summarized in Section E. These recommendations are made with respect to either the scientific or the regulation aspects of current procedures or both. Other potential problem areas are also pointed out. An earlier draft of this report was revised and expanded as the result of a review by NRC personnel.

D. JUSTIFICATION FOR RECOMMENDATIONS

1. Coastal Internal Boundary Layers

Coastal sites differ from those inland in several ways which affect atmospheric dispersion. These include the occurrence of sea or lake breezes, a more moderate climate with fewer or less intense radiation inversions at night and less convection during the day and the continuous presence of an internal boundary layer whenever the air flow crosses the coastline. This internal boundary layer is the key to understanding meteorological processes in coastal zones and must be considered in site selection, tower and instrument location and the formulation and use of diffusion models.

An internal boundary layer forms whenever air flows across the surface discontinuity between land and water. Since the two surfaces rarely have the same temperature and almost always differ in aerodynamic roughness, an interface is created between air whose properties were determined by passage over the upwind surface and air which is modified by passage over the downwind surface. This interface typically starts at the surface discontinuity and slopes upward in the direction of the flow at a rate dependent on the wind speed, the original characteristics of the air and the properties of the downwind surface.

Although the air flowing over the downwind surface starts to become modified immediately, some distance is required before complete adjustment to the new surface takes place. Thus, within the internal boundary layer there may be a lower layer of fully adjusted flow increasing in height with downwind distance and an upper layer of partially adjusted flow.

Although boundary layers occur on all scales from the microscopic to the planetary, those which are appreciably larger than the major surface features but smaller than the planetary boundary layer are most important in affecting diffusion and local climatology, particularly if they have a great enough horizontal extent so that they persist as more or less permanent or recurrent features of the local environment. Boundary layers formed by coastlines are usually in this category.

Coastal boundary layers may be caused by differences in surface temperature (thermal boundary layers) or by differences in surface roughness (roughness boundary layers) but are typically caused by differences in both properties. Two situations are of primary interest during onshore flows; land rougher and warmer than the water and land rougher and colder than the water. Cases with the two surfaces at the same temperature are rare and of brief duration while cases with land smoother than water seldom exist. Analogous situations occur for offshore flows.

Although the rate at which the properties of sea air are changed after it crosses a coastline affects the meteorology and climatology of the coastal zone, a more important effect from the regulatory standpoint is its effect on diffusion of airborne effluents. In coastal areas, the potential for adverse effects is higher than at inland sites as discussed below while the problems of predicting diffusion and in meeting safety requirements are more difficult. In fact, current ability to accurately predict diffusion and resulting concentrations or dosages from sources near coastlines is severely limited by inadequacies of the models available and by lack of experimental data on coastal boundary layer formation and characteristics.

Coastal boundary layers were discussed, and the data available at the time summarized in reviews by Prophet (1961) and Van der Hoven (1967). Echols and Wagner (1972) studied the lower levels of a boundary layer on the Texas coast. DiVecchio et al., (1976) evaluated the performance of a formula presented earlier by Raynor et al., (1975) for predicting boundary layer height. Venkatram (1977a) derived essentially the same formula from theoretical considerations. Hewson and Olsson (1967), Lyons and Olsson (1972), Lyons and Cole (1973), Collins (1974) and Dooley (1976) studied air pollution problems, including fumigation and plume trapping, associated with coastal boundary layers. Effects on atmospheric diffusion of meteorological processes in coastal zones were described by Raynor (1977). A recent paper by Raynor et al. (1978b) reported experimental studies of coastal boundary layer development and described the characteristics of the air within and outside of the boundary layer. This study was part of a comprehensive investigation of meteorology and diffusion in a coastal environment (Raynor et al., 1975, 1978a).

Among the topics reviewed by Prophet (1961), the only ones pertinent to this study are basic concepts of coastal meteorology, offshore trajectories and onshore trajectories. Basic concepts include the role of heat sources and sinks (land and water) and sea breeze circulations. Discussions of offshore and onshore flows were classified by travel time or distance (small-scale, intermediate-scale and large-scale). Prophet discussed the modification of air moving from one surface to another.

Based on a small amount of data obtained by aircraft flights over Massachusetts Bay, he found that the height of the boundary layer in the case of warm, unstable air moving over colder water was proportional to $\sqrt{D}$ where D is the travel distance. The height was also expressed in terms of travel time as proportional to $\sqrt{t/\Delta T}$ where t is travel time and ΔT is the initial air-water temperature differential. Neither expression is dimensionally correct or tested with independent data.

A similar formula was applied to overland travel of onshore flows during stable conditions over the water and unstable conditions at a distance inland. Here, height is proportional to $\sqrt{t/\Delta\theta}$ where $\Delta\theta$ is the initial overwater vertical stability. The equation was fitted to field data from the Enrico Fermi Nuclear Reactor on the shore of Lake Erie and to temperature data taken over Nantucket Island. Data from the Fermi site showed the height of the modified layer to vary from 61 - 183 m at an inland distance of 2 km.

No data were available for the case with land colder than water. Even for the cases discussed, the data are too few and not necessarily representative. Thus, the formulas are not recommended for operational use.

Van der Hoven (1967) also gave a general discussion of the transition from overwater to overland transport using data from earlier sources and described the classic fumigation situation. He gave no new formula for the height of the modified layer but presented a graph adapted from Prophet's (1961) equation for onshore flow.

Echols and Wagner (1972) studied the growth of the internal boundary layer to an inland distance of 90 m on a Texas beach. They found average heights of 7.2 m in the daytime and 5.9 m at night giving a mean slope of 1:13. However, data were taken on only four days in June and measurements did not extend far enough inland or to great enough heights for application to reactor releases except for extrapolations of dubious validity.

Raynor et al. (1975) presented an equation for predicting the height of the internal boundary layer based on aircraft and tower measurements obtained at the south shore of Long Island. Most of the data were taken during southwesterly flow to Long Island from the new Jersey coast or areas farther south but cases of flow over the beach to the Tiana tower were also fitted to the equation which is

$$H = \frac{u_*}{\bar{u}} \left[\frac{F(|\theta_1 - \theta_2|)}{|\Delta T/\Delta Z|} \right]^{1/2}, \qquad (1)$$

where

H height of inverted layer or internal boundary layer (m),

u_* friction velocity over the downwind surface ($m\ s^{-1}$),

$\bar{u}$ mean wind speed ($m\ s^{-1}$),

F fetch over downwind surface (m),

θ_1 low-level potential air temperature over the source region (^oK)

θ_2 temperature of downwind surface (^oK)

$|\Delta T/\Delta Z|$ absolute value of the lapse rate over the source region or above the inversion ($^oK\ m^{-1}$).

Equation (1) is not applicable under isothermal conditions but these are rare and usually temporary.

Use of the equation requires measurements or estimates of the values of the parameters specified. For the case of onshore flow, the friction velocity over the land can be determined from wind profile measurements or from values in the literature as a function of the surface roughness. The mean wind speed can be measured at a standard level (10 m) and the fetch from the shore to the point for which H is desired is either known or can be determined from a map. The low-level air temperature (θ_1) over the water can be measured at the shore for onshore flow. The land temperature (θ_2) is more difficult to obtain except with a remote sensing infrared thermometer but may be estimated from low-level air temperature over the land or by extrapolating a temperature profile to the surface. The lapse rate over the ocean can be measured at the shore for onshore flows.

Good agreement was found between the equation and the limited amount of data available (Raynor et al., 1975).

DiVecchio et al. (1976) tested the same equation against data taken at the proposed Jamesport nuclear power plant site about 1 km inland on the north shore of Long Island on six days from May to July. They found a correlation coefficient of 0.90 between measured and computed heights. Since this site has a steep bluff inland from the water and quite different roughness from Tiana Beach, the agreement is indicative of some generality in the equation.

In a later study, Raynor et al. (1978b) tested the equation with data from a set of 28 experiments in which the growth of the internal boundary layer was measured by aircraft flights across Long Island during southerly onshore flows. Somewhat poorer agreement was found, possibly because some of the parameters in the equation were not measured and had to be estimated. However, nearly all computed values were within a factor of two of the measured values. In this study, it was found that the slope of the internal boundary layer was steepest near the shore and decreased inland. The initial slope was steepest with unstable or neutral lapse rates over the ocean but the final height was greatest with low wind speeds and good surface heating inland.

Venkatram (1977a) used a slab model of the boundary layer to study the dynamics of the internal boundary layer associated with changes in surface temperature. The usual numerical procedure involving finite differences was avoided by solving the governing equations in a Lagrangian framework. The results of the modeling study showed that mixed-layer growth was enhanced by: (a) an increase in surface roughness; (b) an increase in the surface temperature change; and (c) a decrease in the horizontal velocity. It was found that the vertical velocity induced by variations in the horizontal velocity could play an important role in controlling the expansion of the mixed layer. These findings agree with the results of Raynor et al. (1978b).

The second part of the study involved the formulation of a model by simplifying the governing equations. The analytical solution obtained from the model compared favorably with the results of the numerical model. Furthermore, the analytical expression for the mixed-layer height was virtually identical to that presented by Raynor et al. (1975) to fit their observational data.

In view of the derivation of the same model from theoretical principles and from physical and dimensional reasoning and the generally good agreement between the model and field data, this model is recommended for operational use in preference to others in the literature.

Hewson and Olsson (1967) gave a descriptive account of lake effects on air pollution dispersion and discussed lake breezes, fumigation and the differences in diffusive capacity between modified and unmodified air. Lyons and Olsson (1972) reported on mesoscale pollution transport in lake breezes during a two-day field program in Chicago. Pollutants released within the inflow layer recirculated in the lake breeze circulation and fumigated as the air again moved inland causing a region of higher than expected concentrations. They also found a size sorting of small and large particles.

Lyons and Cole (1973) studied days with stable onshore flows on the western shore of Lake Michigan and found that fumigation and plume trapping caused a serious degradation of air quality. They described a Gaussian plume model modified to predict concentrations under plume trapping and continuous fumigation conditions. Limited air monitoring data appeared to confirm the diffusion model estimates and observations of plume behavior. This model is suggested to serve as a basis for an operational model for use in coastal zones.

Collins (1974) used data from smoke releases at a height of 67 m and meteorological measurements from a tower on the shore of Massachusetts Bay and from an aircraft to test the graph given by Van der Hoven (1967) for determining the height of the mixing layer as a function of initial overwater stability and overland travel distance. Seven tests were conducted in July and August. Predictions showed good agreement with the measurements. Distances at which the mixed layer were intercepted by the plume varied from 0.32 to 1.0 km.

Dooley (1976) studied plumes from two power plants on the west shore of Lake Michigan during fumigation episodes using a comprehensive array of ground-based and airborne instrumentation. He found that the model of Lyons and Cole (1973) predicted concentrations in good agreement with those measured.

The above five papers provide adequate documentation of the importance of plume trapping and fumigation in coastal areas and demonstrate the necessity of predictive methods for use in such situations. Lyons and Cole (1973) and Dooley (1976) have demonstrated the feasibility of modeling these phenomena. An explanation of their model is quoted directly from Lyons and Cole (1973). A similar explanation was given by Lyons (1975).

"3. Calculations of pollutant concentrations

Unfortunately, very little ambient air monitoring has been done near the power plant in question. It is, however, possible to estimate pollutant concentrations by using the relatively simple diffusion equations summarized by Turner (1969).* While having their imperfections, they have been widely used for ball-park estimates. The following is meant to be more illustrative than conclusive (in terms of absolute values of pollutants), but it clearly points the finger at areas needing immediate attention.

a. Dispersion in a homogeneous, infinite atmosphere

In an atmosphere where the stability (turbulence) classes are more or less uniform in the space occupied by a plume, it is commonly assumed that plume matter spreads horizontally and vertically from the center line in a Gaussian profile. The basic equation can be written

$$\chi(x,y,z:H) = \frac{Q\exp(-ax/\xi u)}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}, \quad (1) \quad *$$

where χ is pollutant concentration, Q is the source strength (mass per unit time), σ_y and σ_z the lateral and vertical standard deviations of concentrations within a Gaussian plume (implicit functions of x), u the mean wind speed, x, y, z the axial, transverse and vertical directions, H the effective stack height (plume centerline), a = 0.693, and ξ the half-life of the pollutant (assumed 3 hr for SO_x). For particulates, no fallout or reaction is assumed and the half-life exponential term drops from the equation.

The values of σ_y and σ_z, empirically derived by Pasquill (1961) and Gifford (1961) from actual observations, are grouped into six subjectively determined stability classes ranging from Class A (extremely unstable) to Class F (moderately stable). The application of (1) here assumes the ground is flat. While the western shore of Lake Michigan around Milwaukee does have steep bluffs about 30 m high, the ground has virtually no relief and a negligible slope for many miles inland.

b. Modeling plume trapping

If the mixing layer into which a plume was being emitted were not of infinite (or at least very great) depth, then vertical plume dispersion would be restricted by the overlying lid (usually the base of stable inversion layer aloft) at some distance downstream. Turner (1969) presents a scheme for calculating $\chi(x,y,z:H)$ for a plume trapped within a layer bounded by the surface and a discrete upper lid limiting

*References and equation numbers in this quotation are those given by the authors and do not correspond to those used elsewhere in this report.

the diffusion. After a given distance downwind from the source, the vertical concentration profile begins a transition from Gaussian to uniform. Horizontal dispersion is assumed to behave in a Gaussian manner throughout this process for all values of x. With Eq. (1) as is, and modified for a lid, it is possible to simulate the dispersion regime found on the western shore of the lake on 27 May 1970.

c. Modeling continuous plume fumigation

Turner describes a mathematical technique for predicting surface concentrations for the case of nocturnal inversion breakup fumigation, which causes unusually high pollutant concentrations for a short period of time. The shoreline fumigation is by contrast almost a steady-state process, and the procedure outlined below was used to modify Turner's technique for this specific application.

The dispersion regime downwind of an elevated source at the shoreline was divided into three zones. Separate equations (see Fig. 13) are used to compute $\chi_1(x,y,z:H)$; $\chi_2(x,y,z:H)$; $\chi_3(x,y,z:H)$. The first zone [in which $\chi_1(x,y,z:H)$ applies] is essentially the same as described in Section 3a, where an elevated plume is emitted into a homogeneous, relatively stable layer. For any part of the plume above the TIBL, (1) is rewritten, using $\sigma_z(s,x)$ and $\sigma_y(s,x)$ for the standard deviations for plume spreading in stable air (s), here explicitly written as function of downwind travel (x) from the source (x=0).

The second zone [where $\chi_2(x,y,z:H)$ applies] is that portion of the area where $x_b \leq x \leq x_e$ and $z \leq L(x)$, L(x) being defined as the (variable) height of the TIBL upper boundary. Point x_b occurs where $L(x)=H-2.15\,\sigma_z(s,x)$, that is, where the turbulence is just beginning to disturb the lower portion of the plume. At point x_e, $L(x)=H+2.15\,\sigma_z(s,x)$, and the bulk of the plume has been mixed into the deepening TIBL. In the area $x_b \leq x \leq x_e$, the profile of concentrations below L(x), that is, within the turbulent mixed layer, is considered to be uniform in the vertical (though still Gaussian in the horizontal). Thus, for $z \leq L(x)$, concentrations are found by

$$\chi_2(x,y,z:H) = \frac{Q\exp(-ax/\xi u)}{(2\pi)^{\frac{1}{2}}\sigma_{yf}(s,x)uL(x)}\left[\int_{-\infty}^{p}(2\pi)^{-\frac{1}{2}}\exp\left(-\frac{p^2}{2}\right)dp\right] \times\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{yf}(x,s)}\right)^2\right], \quad (2)$$

where

$$p=(L(z)-H)/[\sigma_z(s,x)], \quad (3)$$

$$\sigma_{yf}(s,x)=\sigma_y(s,x)+(H/8), \quad (4)$$

and $\sigma_{yf}(s,x)$ is the standard deviation in the y direction that applies in the fumigation zone $x_b \leq x \leq x_e$. It is used in place of $\sigma_y(s,x)$ in order to correct for the additional horizontal spreading that results from the intense mixing that is occurring at this time (Bierly and Hewson, 1962). Maximum ground level concentrations are predicted at distance x_e from the source. At this distance, the entire plume is assumed to have been mixed into the unstable boundary layer.

Zone three is essentially the same as plume trapping except that the lid height is variable. Concentrations are assumed to be uniform in the vertical below the lid. However, complications arise in the choice of appropriate σ_y values in this zone. Since the entire plume is now within the unstable layer, $\sigma_y(u,x)$ values based on x, the distance from the plume source, are unreasonably large since the unstable condition only begins affecting the plume between x_b and x_e. The use of $\sigma_y(u,x)$ based on actual distance from the source would grossly overestimate the lateral dispersion. More realistic plume widths and concentrations are estimated from $\sigma_y(u,x')$, a standard deviation based on x', the distance downwind from a virtual point source that lies between x_b and x_e. A schematic of the geometry used to define the virtual plume source is shown in Fig. 13b, wherein the x,y plane, two plume boundary lines for the unstable case are shown. These lines represent $\sigma_y(u,x)$ and $\sigma_y(u,x')$, the former originating at the actual source, the latter at the virtual point source, x_0'.

As drawn here, both lines are assumed to be straight and parallel (for $x \leq x_e$), an assumption which can be accepted, and which allows a simple trigonometric determination of x_0'. The distance downwind of the virtual source is found by noting that

$$x' = x - \left[x_e - (x_e - x_0')\right] ; \tag{5}$$

x_0' can be derived from the trigonometric identity

$$\tan\theta' = \sigma_y(u,x_e)/x_e = \sigma_{y\,f}(s,x_e)/(x_e - x_0'), \tag{6}$$

where θ' is the angle made by the intersection of the $\sigma_y(u,x')$ line and the plume centerline.

Thus, for zone three, concentrations are estimated by

$$\chi_3(x',y,z:H) = \frac{Q\exp(-ax/\xi u)}{(2\pi)^{\frac{1}{2}}\sigma_y(u,x')L(x)u} \times \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y(u,x')}\right)^2\right]. \tag{7}$$

In this equation, $\sigma_y(u,x')$ is based on x', the distance downwind of the virtual point source x_0'."

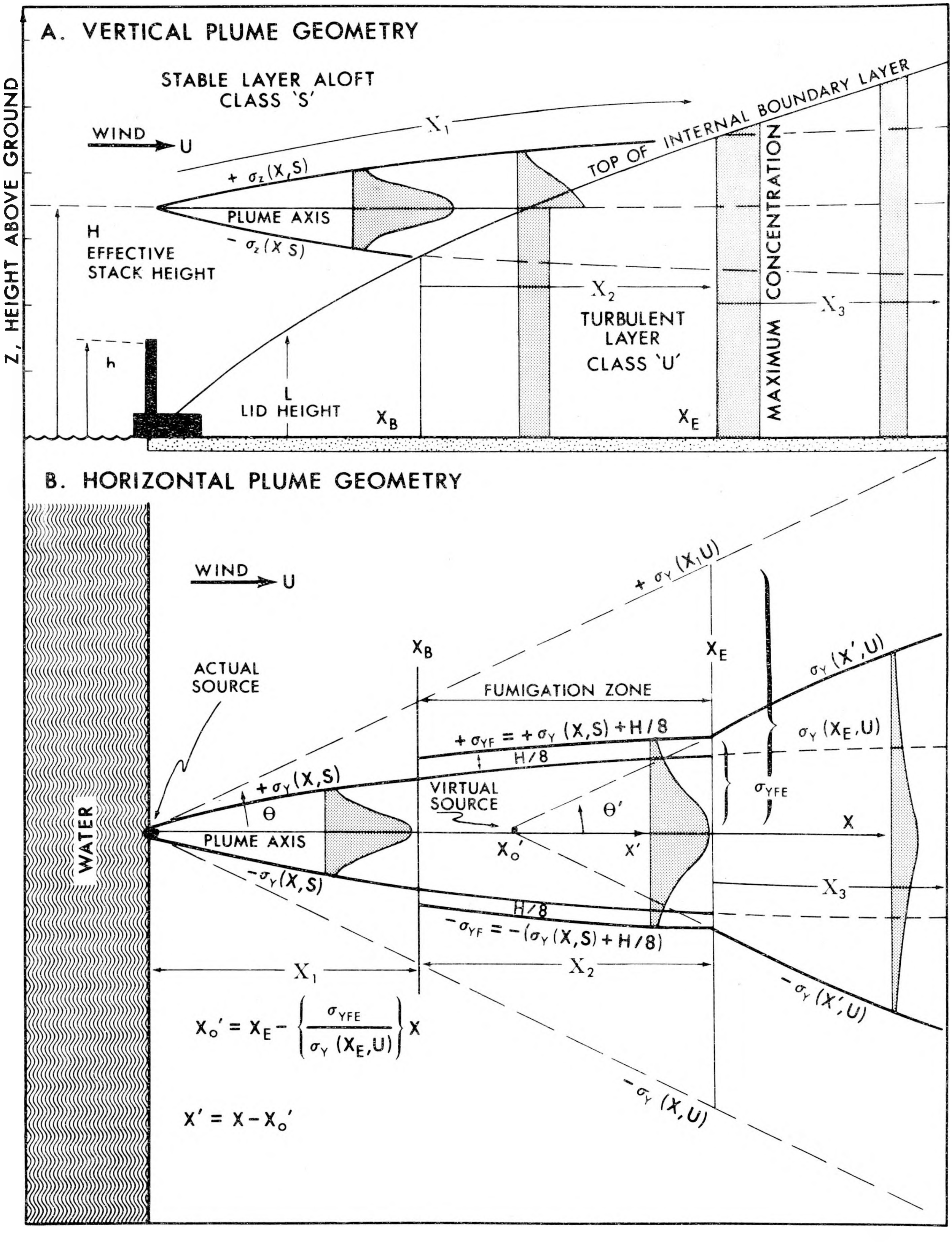

Figure 1. Figure 13 from Lyons and Cole (1973).
Geometry used in the calculation of pollutant concentrations during periods of continuous fumigation. See text for explanation.

Boundary layer development has also been treated theoretically. Modifications in the wind field due to changes in surface roughness have been studied by Elliott (1958) and Panofsky and Townsend (1964).

Elliott (1958) derived a complicated equation for the height (h) of the internal boundary layer but showed that it could be well approximated by the expression

$$(h/z_o)(\ell n\ h/z_o)^{1/5} \propto x^{0.8} \qquad (2)$$

where z_o is the roughness length and x is the downwind distance from the change of surface roughness. The same exponent (0.8) was also shown to be valid for a change of surface temperature. The relationship gave good agreement with a limited number of field observations. Panofsky and Townsend (1964) extended Elliott's theory but arrived at similar results, that the slope of the interface is of the order of 1:10.

Several numerical models exist that treat the airflow above changes in surface heat flux, temperature and roughness in varying degrees of sophistication and detail (Peterson, 1969; Taylor, 1969a, 1969b, 1969c, 1970, 1971). Peterson (1969) assumed that the horizontal shear stress is proportional to the turbulent energy and neglected the influence of pressure changes. Using the horizontal momentum, continuity and energy equations, with some boundary conditions, internal boundary layer development due to a change in roughness was computed for neutral conditions using numerical methods. Taylor (1969c) also used horizontal momentum and continuity equations but with the "mixing-length" hypothesis to predict the modification in airflow due to a change in surface roughness for neutral conditions. Taylor in a later analysis (1970) included a change in surface temperature and developed a numerical model based on horizontal momentum, heat and continuity equations with a mixing-length hypothesis. The Businger-Dyer hypothesis for the non-dimensional wind shear and heat flux was used. Neutral upwind and unstable downwind conditions were studied with both increase and decrease in surface roughness. The above numerical model was extended by Taylor (1971) to include downwind stable atmospheric conditions. These models essentially treat the growth of the internal boundary layer to a height of 100 m within the surface layer of the atmosphere. This restricts these models to short distances from the surface discontinuity. No theoretical or numerical model is found in the literature that treats the growth of an internal boundary layer with stable conditions upwind and unstable conditions downwind, a situation which prevails during much of the year.

Peterson's (1969) model predicts the growth of the internal boundary layer (h) as $h \sim F^{0.8}$ where F is the fetch. Peterson also gives a nomogram in which the non-dimensional height of the interface, h/z_o is given as a function of the non-dimensional downwind distance, F/z_o, for different $m = \ln(z_o'/z_o)$ where z_o' and z_o are the roughness lengths upwind and downwind, respectively. Typically $z_o' \simeq 0.001$ m and $z_o \simeq 1$ m for these experiments; hence for $m < 0$, a value for h of about 1000 m was obtained for a fetch of 10 km. Brookhaven observations indicate a height of 300 to 500 m at the same distance, depending upon the range of wind speeds (Raynor et al., 1978b). The greater height was found with wind speeds from 3.6 - 5.0 mps and the lesser height at speeds from 7.1 - 9.1 mps. The over-prediction by the model is probably due to two reasons: (1) stable upwind atmospheric conditions in the Brookhaven experiments and, (2) the lack of validity of the model at large downwind distances. Internal boundary layers are known to be steeper near the origin of the change in roughness. Peterson's $F^{0.8}$ relationship agrees with previous results of boundary layer height variation near the interface (Elliott, 1958; Panofsky and Townsend, 1964). Results of the Brookhaven experiments indicate that this slope is not the same for larger downwind distances and it is affected strongly by upwind and downwind stability conditions. It has been observed at least qualitatively in wind tunnels that internal boundary layers grow at a slower rate initially for surface-based inversions upwind as compared with neutral conditions (Sethu-Raman and Cermak, 1975).

At a distance of 60 cm from the edge of a heat island and 120 cm from the source, plumes reached a height of about 4 cm with a surface-based inversion upwind and about 10 cm with neutral lapse rates downwind. At a distance of about 150 cm, the plumes were about equal in height and at greater distances, the plumes with neutral conditions upwind were shallower than those with inversions upwind. This agrees with field data (Raynor et al., 1978b) that initial rate of rise of the internal boundary layer is dependent on the upwind lapse rate but that the eventual height is dependent on conditions at a distance downwind. No attempt was made to fit equations to the wind tunnel data.

In the Brookhaven study, the airflow was from a smooth to a rougher surface and the downwind stability conditions were unstable. A direct comparison of the Brookhaven data with Taylor's results is not feasible since his numerical models were not designed for large downwind distances.

In summary, the theoretical models may be useful for approximating the average height of the internal boundary layer in cases where the meteorological data needed for the model given by Raynor et al. (1975) and by Venkatram (1977a) are not available and cannot easily be estimated. However, these models have not been tested at heights above about 100 m and distances greater than 1 or 2 kilometers and their use should be restricted to these heights and distances.

The Brookhaven study (Raynor _et al._, 1978b) reached the following conclusions: Internal boundary layers typically develop at coastlines because of differences in temperature and roughness between the upwind and downwind surfaces. The modified and unmodified air differ in turbulence and wind speed and sometimes in wind direction. Average slope of the internal boundary layer is steep ($\sim$1:4) within the first few hundred meters from the interface and shallow ($\sim$1:100) at greater distances (beyond 20-30 km). Slopes gradually decrease in the intervening distance. In the absence of free convection or a sea breeze return flow, an equilibrium height is usually reached. The height of the boundary layer is inversely related to wind speed but correlated with temperature difference between the two surfaces. Near the interface, the lapse rate over the upwind surface influences the slope which is shallower with stable air and steeper with neutral and unstable lapse rates upwind. Models developed for predicting height at small downwind distances such as that of Peterson (1969) are not applicable to the distances and height intervals studied here but reasonably good predictions are given by the model developed by Raynor _et al._ (1975) and by Venkatram (1977a) which was discussed above.

Some consequences of these internal boundary layer characteristics are evident. Emission of effluents from a coastal source at a height above the internal boundary layer during onshore flows may result in prolonged periods of fumigation with resultant high surface concentrations. Similar releases with offshore flows may remain above the more shallow stable boundary layer over the water but fumigation would be expected if the plume passed over a body of water to another land mass. Emission into the unstable boundary layer with onshore flows would also result in higher than expected concentrations since vertical diffusion would be limited by the stable layer aloft which is often considerably lower than the height of the mixed layer at inland locations. Diurnal changes in mixing layer height and in diffusion rate may be much smaller at the coast than in typical inland locations, giving more prolonged periods of unchanging diffusion conditions. Application of these considerations to tower location, instrument height and diffusion prediction are given below but, in summary, it is recommended that the presence and characteristics of coastal internal boundary layers be considered in all measurement programs and modeling procedures at coastal sites and that the model developed by Raynor et al. (1975) and by Venkatram (1977a) be used to calculate the height of the coastal internal boundary layer.

2. Tower Location

Current guidelines for tower location as given in NRC Regulatory Guide 1.23 specify only that the tower should be at approximately the same elevation as finished plant grade and in an area where plant structure will have little or no influence on the meteorological measurements. Although these guidelines are probably adequate for most inland sites with no significant terrain features, they are inadequate for coastal sites.

As shown above, an internal boundary layer is a frequent feature of the coastal environment but its slope and height vary with the difference in temperature and roughness of the land and water surface, with wind speed, season, cloudiness and probably time of day (Raynor *et al*., 1978b). The same studies which include both tower and aircraft (SethuRaman *et al*.,1978) measurements, showed that diffusion conditions may be quite different within the internal boundary layer and upwind or above it. If flow is from a relatively smooth, cool body of water, for instance, to warmer and rougher ground, wind speed and therefore plume transport speed will typically decrease to about two-thirds of that at the same height over the upwind surface. Turbulence levels will typically increase several fold. In the mean of eighteen cases reported by Raynor et al. (1978b), $\sigma_u/\bar{u}$ increased from 0.12 at the coast to 0.33 at an inland site, σ_θ increased from 6.6 to 48.1 degrees and σ_ϕ fro, 1.6 to 15.1 degrees. The inland site (BNL) was about 15 km from the coast and fetches from the ocean ranged from about 17 to 22 km depending on the angle of the wind to the coast. However, the data are believed representative of any location in the fully adjusted region within the internal boundary layer. In addition, lapse rates may change from very stable (inversion) to very unstable (superadiabatic) as air is modified by flowing inland. If the upper limit of the internal boundary layer intersects the tower between measuring levels, lapse rates and wind profiles will be representative of neither regime and possibly misleading.

Jensen (1979) reported a small set of simultaneous measurements of turbulence over land and water taken on and near a suspension bridge in Norway. Average wind speed over water was 35% greater than over land and σ_w was about 40% greater. σ is the standard deviation of the vertical wind fluctuations.

The effect upon lapse rate and on stability class as estimated from lapse rate is complex since it is a function of the magnitude and direction of the land-water temperature difference and of the magnitude and sign of the lapse rates over the water and over the land. As shown in Table 1, eight cases were considered, four with the water (T_W) colder than the land (T_L) and four with the land colder than the water. In each set of four, positive and negative lapse rates were assigned as shown. Also tabulated are the stability class predicted when the internal boundary layer intersects the tower between measuring levels and the actual lapse rate below the internal boundary layer. Cases 1 and 2 give the most serious errors since they would lead to predictions of better diffusion conditions than actually exist, slightly stable or perhaps neutral depending on the magnitude of the lapse rate rather than stable or very stable. Cases 3-6 would probably not shift the prediction more than one or perhaps two stability classes, again depending on the slope of the lapse rates. Cases 7 and 8 would tend to lead to predictions of poorer diffusion than actually exist and thus give conservative predictions.

The percentage of time the eight cases would exist at any given coastal location is unknown and probably varies systematically with latitude. However, it is clear that the most non-conservative predictions would be made with inversions over the land, usually at night, when wind speeds are lighest and diffusion poorest.

At most coastal sites, the inland sector is of primary concern since few potential receptors exist at sea. Therefore, conditions inland or within the internal boundary layer will have the greatest effect on the dispersion of an effluent. This is the case whether the release is into the unstable air below the boundary or into the stable air above but later intersects the boundary causing fumigation. Therefore, it is recommended that the primary tower be in such a location that the upper measuring level is always within the internal boundary layer.

Few actual measurements of coastal internal boundary layers have been made but estimates of height as a function of distance can be obtained from the equation given by Raynor *et al*., (1975) or Venkatram (1977a). The equation given by Peterson (1969) will also give guidance, at least to an altitude of about 100 m. Until many more observational data are obtained on coastal internal boundary layers, it is recommended that computed heights be confirmed experimentally before the tower site is chosen. An acoustic sounder, balloon-borne instruments or other means could be used.

Measurements should be made during onshore flows at the location of the plant or at a similar distance from the coast in a nearby and comparable location. Measurement periods of one-half to one hour duration should be selected to give data representative of all times of day and night, a normal range of wind speeds and the range of air-land temperature differential prevailing at the site. At most locations, a one-year period would be desirable.

If the measurement program were planned to obtain each combination of the variables with perhaps 4-6 replications of each combination, from one hundred to two hundred short sampling periods would be necessary. If the measurements taken under a wide range of conditions agreed well with predictions of the model, further measurements could be omitted. If the model failed to give reasonable predictions at a chosen site, enough measurements to devise a site-specific prediction scheme would be necessary.

If the plant site is closer to the coast than the tower and releases are possible through a stack or upper building level which might be above the boundary, measurements in the unmodified air are also necessary to calculate diffusion and possible fumigation when the plume enters the internal boundary layer. The problems of fumigation and plume trapping have been studied by a number of investigators including Hewson et al. (1963), Hewson and Olsson (1967), Collins (1974), Lyons and Cole (1973), Heines and Peters (1973), Peters (1975), Lyons (1975), Dooley (1976), Venkatram (1977b), and van Dop et al. (1979). Hewson et al. (1963) conducted a photographic study of oil-fog smoke plumes released from a 256-foot (78-m) tower on the site of the Big Rock Point Nuclear Plant on the eastern shore of northern Lake Michigan. Associated meteorological measurements were made. They showed that stable air flowing in from over the water becomes neutral or unstable up to tower height within a few miles of the shore leading to rapid mixing or fumigation after the plume intersects the internal boundary layer. In plumes moving from unstable air over the land to stable air over colder water, the diffusion rate decreased markedly when the stable air was encountered.

Hewson and Olsson (1967) discussed lake effects on air pollution dispersion referring to previous studies. They emphasized the complexity of many shoreline locations and showed how the meteorology and topography of such sites caused diffusion conditions different from those inland. No numerical data were included.

Collins (1974) studied diffusion of smoke from a 220-foot (67-m) tower on the shore of Cape Cod Bay in a series of seven tests. Fumigation was observed on five of the seven days in July and August at distances from 0.32 to 0.90 km from the source which was 550 m from the shore on a 28-m terrace. Thus, the source was 95 m above the water and fumigation distances were from 0.87 to 1.45 km from the shore. Height to fetch ratios ranged from 1:9 to 1:15.

Lyons and Cole (1973) studied fumigation and plume trapping on the western shore of Lake Michigan and presented detailed case studies of two days. They showed that onshore gradient and sea breeze flows occurred on 65% of all warm season days and that continuous fumigation occurs on days with strong insolation. They also found that plume trapping occurred when a plume was emitted into a shallow layer of unstable air capped by a deep lid of stable air. This condition was frequent on overcast spring days. Both fumigation and plume trapping caused serious degradation of air quality. Their model, discussed above, was developed to predict diffusion under these conditions.

Heines and Peters (1973) conducted a theoretical study of the effects of a temperature inversion above the effective stack height on low level concentrations. They found that ground level concentrations with an inversion lid are always greater than those without an inversion but that differences become negligible when the inversion is higher than 0.6 effective stack height. Under the most restricted conditions, concentrations with an inversion are double those without. The model used the usual assumptions and boundary conditions for diffusion models. The results were not compared with experimental data but are probably indicative of actual conditions.

Peters (1975) presented two models, a boundary layer model and a flux model to predict fumigation when stably stratified air over a large body of water flows across a warmer land surface. The models depend on assumptions concerning the eddy thermal diffusivity or the energy flux respectively. Neither is suitable for operational use since the needed parameters are not normally measured or easily estimated. In addition, the two models give rather divergent results. However, they do give additional insight into the fumigation problem and the conditions under which it occurs.

Lyons (1975) presented a lengthy discussion of turbulent diffusion and pollutant transfer in shoreline environments based largely on research conducted by him and his colleagues around the shores of the Great Lakes but using data from other sources as well. The lecture includes comprehensive discussions of diffusion during onshore flows including plume trapping and continuous fumigation. The point source continuous fumigation model described above under Lyons and Cole (1973) is again presented and illustrated. All of the assumptions used in the model were considered highly conservative. Little field data were then available for validation but additional verification was provided by Dooley (1976). It was pointed out that meander may shift the location of fumigation frequently enough that time averaged concentrations at any position may be significantly less than short-period concentrations. This model accounts for the meteorological processes which are important in shoreline environments and is recommended for operational use until a better model is developed and tested.

Dooley (1976) applied the model of Lyons and Cole (1973) to SO_2 diffusion data from power plants at Waukegan, Illinois and Milwaukee, Wisconsin, both on the shores of Lake Michigan. Measurements were made from the ground and aloft. He studied a number of fumigation cases and showed that the location and size of the fumigation area is a function of the shape of the internal boundary layer. The field observations verified the plume geometry predicted by the model of Lyons and Cole (1973).

van Dop _et al_. (1979) presented a model very similar to that of Lyons and Cole (1973) but they assume that plume trapping occurs everywhere at the interface between the mixed layer and the overlying stable layer instead of in a well-defined finite region as assumed by Lyons and Cole (1973). No field data were used to validate this model and it is not likely that available data are adequate to determine which model is preferable.

Venkatram (1977b) used a mixed layer model in a Lagrangian framework to predict the development of the internal boundary layer associated with the flow of cold stable air from water onto warmer land. For the case of small distances from land, the model reduces to a form virtually identical to that given by Raynor _et al_. (1975) and by Venkatram (1977a) as discussed above. The author states that the relevance of the model to the prediction of fumigation is self-evident and does not elaborate. However, it is evident that the model can be used to predict the distance of fumigation from a source although not to predict concentrations.

The above ten studies suggest that fumigation may be a problem at any coastal site and may cause high concentrations for prolonged periods of time in contrast to inland sites where fumigation is usually a short period phenomenon occurring for only a brief period on some days.

The references discussed above suggest that continuous fumigation may occur as long as the causative conditions persist, namely onshore flow from colder water to heated land with a plume from an elevated source intersecting the internal boundary layer at some distance downwind. Due to the usual nocturnal cooling of the land, it is expected that these conditions will seldom persist longer than the duration of daylight although the presence of an urban heat island or enough cloud cover to prevent radiative heat losses from the surface could conceivably prolong fumigation into the night. In most cases, the location of fumigation will shift due to variation in the slope and height of the internal boundary layer with variations in surface heating, cloudiness, and wind speed during the day and with wind direction changes or wind meander. Under the most steady conditions, however, fumigation of one location could persist throughout the day. Due to the normal change in synoptic conditions, flows from a given direction seldom persist for more than a few days but during the sea breeze or lake breeze season, onshore flows occur on a large percentage of all days. Thus, repetitive fumigation episodes must be expected.

Plume trapping within the boundary layer may also increase concentrations for extended periods even if actual fumigation does not occur. In order to obtain measurements to adequately predict concentrations under such conditions, it is recommended that a secondary tower be placed at a location where measurements representative of conditions in the unmodified air can be obtained. If the plant site is on the shore of a shallow body of water, this tower could be in the water; otherwise the tower should be located at the immediate shore where onshore flow is not affected by the land. In either location, a relatively short tower should be adequate. A recent study at Brookhaven (SethuRaman and Raynor, 1978) showed that measurements at a shoreline are similar to those over the water during onshore flows.

If the plant site is located near a partially, or completely, enclosed body of water such as a bay, sound or estuary so that offshore winds pass over another land area within the distance of concern, measurements of conditions over the water are again necessary. In this case, however, the tower must be placed in such a location that measurements representative of overwater flow can be obtained entirely within the internal boundary layer over the water during flow which is offshore from the land on which the plant site is located. A tower in the water would be suitable for both this and the preceding purpose if far enough from land to give two measuring levels within the boundary layer over the water. Otherwise, the tower should be located at the shore on the opposite side of the water. Measurements from this tower plus the primary tower will be necessary in order to predict concentrations, including possible fumigation, at the second land area. For a site with land across a body of water, it is recommended that the primary tower be supplemented with a secondary tower in the water or two secondary towers on opposite shores.

3. Instrument Heights

Instruments for which heights are discussed here are those specified in Regulatory Guide 1.23 for measuring wind and temperature. The need for additional instruments will be discussed in Section 4 below but height requirements would be similar.

Instrument heights on the primary tower must be selected to avoid having one level within the internal boundary layer and the other above. If recommendations given above for tower location are followed, no changes in the heights specified in Regulatory Guide 1.23 are necessary.

If, for some reason, the tower cannot be located so that the uppermost level is always within the internal boundary layer, two levels should be located below the minimum height reached by the boundary layer at that location under any conditions. If these levels are so close together that temperature or wind speed differences between them are close to the possible errors in the measurements, a higher level should be instrumented also. In this case, profiles or differences should be computed from the two lower levels only when the upper level is above the internal boundary layer and between the lowest and highest levels at other times. Under no circumstances should profiles or differences be computed from one level within and another level above the internal boundary layer since results will be non-representative of either layer.

Determining whether the internal boundary occurs between measurement levels on a tower may be difficult if only two levels are instrumented with only wind and temperature instruments but is best accomplished by comparing wind and temperature profiles during onshore flows with those when flows come from other directions. Departures from a normal profile will usually identify this situation. Inspection of wind direction tracks should also be useful since direction fluctuations are typically much smaller in the more stable air above the internal boundary layer than in unstable air at the same level. If turbulence measurements are made, the much smaller turbulence levels in the unmodified air will be evident. If the tower is instrumented at three or more heights, the presence of the boundary layer can be identified by a kink or change in slope of the wind speed and temperature profiles. Routine use of an acoustic sounder or comparable instrument would eliminate these difficulties.

Instrument heights on secondary towers will depend on local conditions such as upwind fetch over the water from the direction of interest but should be chosen to give measurements representative of air within the internal boundary layer over the water. The lower level should be high enough so that spray during high wind conditions will not normally affect temperature sensors. Ten meters are probably necessary over or at the edge of a large body of water and five meters at the shore of smaller bays, estuaries or lakes. The separation between the upper and lower levels should be great enough so that likely differences in the quantities being measured are greater than the uncertainty in the measurements. Twenty meters is probably adequate for most locations since the internal boundary layer over water is typically more shallow than that over land with steeper gradients.

A regular schedule of sensor cleaning and calibration should be followed since some salt deposition on the sensors is to be expected even if they are not exposed to direct spray. A monthly schedule with additional visits following high wind episodes is recommended unless local experience shows that a longer time interval is adequate.

In summary, it is recommended that instrument heights be selected on the primary tower so that measurements representative of conditions within the internal boundary layer are obtained while maintaining adequate separation between levels. On secondary towers, instrument heights should meet the same criteria for the internal boundary layer over the water.

4. Atmospheric Stability Classification

Regulatory Guide 1.23 specified that atmospheric stability should be classified by reference to measured temperature lapse rates as defined in Table 2 of that Guide. Values of σ_y and σ_z are then determined from the curves shown in Figures 1 and 2 in Regulatory Guide 1.145. Numerous recent studies including Luna and Church (1972), Pendergast and Crawford (1974), Fulle (1976), Portelli (1976), Gifford (1976), Letizia *et al.* (1978) and Briggs and McDonald (1978) have shown generally poor agreement between lapse rate and stability class thus casting serious doubt on the validity and continued use of this method.

Luna and Church (1972) compared Pasquill stability classes computed from synoptic observations to turbulence intensity and stability ratio data from measurements on a tower 13 km away over a 13-month period. They found that the Pasquill classes and the stability ratios (bulk Richardson numbers) were on the average in the same order but that both stable and unstable stability ratios were found for every Pasquill class. They found a similar broad distribution of σ_A and σ_E, the standard deviations of the lateral and vertical direction fluctuations, within the Pasquill classes. Although no comparisons were made with actual diffusion measurements, the poor agreement between wind fluctuation measurements and the Pasquill stability classes suggests that use of the latter method would often lead to erroneous results whether the stability classes were determined from surface observations or from lapse rate classes.

Pendergast and Crawford (1974) used measurements from a 367-m tower in South Carolina to compare actual standard deviations of vertical and horizontal wind direction with estimates from other measurements. They found that measurements of lapse rate were inadequate to represent σ_θ, especially for values of σ_θ<4 degrees. They also found that large variations occur as a result of the choice of layers over which vertical temperature measurements are obtained. Dilution factors ($u\sigma_y\sigma_z$) for a release height of 91 m and a downwind distance of 5 km were computed from direct measurements and from various other methods of estimating σ_y and σ_z. They concluded that the errors caused by the use of lapse rate are greater than those involved in calculating σ_θ and σ_ϕ directly from measurements of

θ and ϕ or even from those obtained from the use of peak-to-peak values of θ and ϕ to estimate σ_θ and σ_ϕ. Although no comparisons were made with diffusion data, it is generally accepted that wind fluctuation measurements give the best available prediction of diffusion.

Fulle (1976) using data from several western locations for a year compared three methods of estimating the stability class, the Pasquill method, lapse rate and the Richardson number. Data for the Pasquill method were obtained from surface observations and for the other two methods from radiosonde ascents. Poor agreement was found between the Pasquill and both the lapse rate and Richardson methods but relatively good agreement was found between the lapse rate and Richardson methods. However, no comparison was made with either turbulence or diffusion data so application of these findings is uncertain.

Portelli (1976) conducted a similar study using radiosonde and minisonde data from seven Canadian locations. Of the total number of stability measurements made from temperature lapse rates, the Pasquill method predicted the correct stability class only 22% of the time and predicted within one stability class only 45% of the time. Again, no comparisons were made with turbulence or diffusion data but it is presumed that use of incorrect stability class would result in erroneous diffusion estimates.

Gifford (1976) reviewed turbulent diffusion-typing schemes and pointed out that attempts to relate the Pasquill classes to various objective stability criteria such as lapse rate and bulk Richardson number have been characterized by considerable scatter.

Letizia _et al_. (1978) conducted a comprehensive comparison of σ_θ and lapse rate as measures of atmospheric stability using two years of data from a tower in western Washington. They found poor agreement between the two methods, poorest during low and best during high wind speeds. They found that σ_θ indicated a much greater frequency of unstable conditions than did lapse rate. No comparisons were made with actual diffusion data.

In contrast to the studies reviewed above, Briggs and McDonald (1978) compared vertical diffusion data from the Prairie Grass field experiment to a number of non-dimensional prediction parameters. They found that the most versatile relationship in terms of applicability to sites of any roughness is given by

$$h/L = X/(1 + x^{\frac{1}{2}}) \qquad (3)$$

where

h = vertical spread of the plume

L = Monin-Obukhov scaling length

X = downwind distance.

They found that temperature difference is a good categorizer in stable conditions if it is measured through the layer occupied by the plume but appears to be worthless in unstable conditions. However, this analysis was confined to one data set from one site and cannot be generalized without further testing. In addition, horizontal dispersion was not considered. It provides one more piece of evidence, however, on the inadequacy of using Δt measurements to predict diffusion.

The above seven studies may be summarized as follows: Various methods of predicting diffusion conditions agree poorly with each other. The Pasquill method and the ΔT method agree poorly with wind fluctuation data. Although little comparison has been made to actual diffusion data, it is believed that methods which do not agree with measures of turbulence will not predict diffusion adequately since turbulent motions are responsible for diffusion in the atmosphere.

The problem of selecting values for σ_y and σ_z may be less satisfactory at coastal than at inland sites since the relationship between ΔT and stability class used by NRC was presumably derived from data taken at inland locations. A consideration of the changes which take place with the development of a coastal internal boundary layer points out the probable differences. If the site is far enough from the coast so that the meteorological tower and all possible release points are always in fully adjusted flow within the internal boundary layer, the relationship between ΔT and stability class should be similar to that at inland sites in comparable terrain and climate. In this case, the site could be treated as an inland one except for flow in the direction of the water. However, flow does not adjust immediately and completely to the new surface as it passes a surface discontinuity even though the internal boundary layer forms immediately. Some finite time and distance are necessary and these depend on the same factors which govern the slope and height of the internal boundary layer including wind speed, land-water temperature difference and lapse rates over the two surfaces. In this transition region, lapse rates and turbulence are intermediate between those upwind and those in fully adjusted flow downwind but it is not known if turbulence and lapse rate adjust at the same rate. If not, the relationship between ΔT and stability class would be different in the transition zone than in fully modified air.

Measurements at a single tower can only give diffusion estimates for the region in which the tower is located. At most coastal sites, the coastline is irregular enough that air moving more or less parallel to the coast, for instance, may pass from a fully adjusted region to a transition region or even to unmodified air over a coastal bay or indentation in the coastline. In such situations, measurements at both inland and coastal or offshore towers are needed for realistic diffusion estimates.

The problem of how best to determine stability classification and diffusion rates has been the subject of several recent papers (Gifford, 1976; Weber, 1976; Pasquill, 1976a; Weber et al., 1977). The problem was further explored at an American Meteorological Society Workshop in 1977 and a summary of recommendations in which essentially all participants concurred was published (Hanna et al., 1977). It was generally agreed that for short distances, the horizontal and vertical spread of a plume, σ_y and σ_z, are proportional to the horizontal and vertical fluctuations of the wind direction, σ_θ and σ_ϕ and that measurements of these parameters are preferable to indirect methods of estimating diffusion.

Instruments with all-weather capability are now available at moderate cost for measuring the vertical as well as the horizontal wind components. Modern data acquisition and processing systems are also available at reasonable cost for computing σ_θ and σ_ϕ on either a discrete time period or running mean basis.

The only condition under which the σ_θ,σ_ϕ method is not preferable is the stable, light wind case when wind speeds are too low to cause adequate response of the wind or turbulence instruments (usually 0.5-1.0 mps depending on the instrument in use). Under such conditions, alternate methods are necessary for selection of diffusion parameters.

Several recent field studies of diffusion under light-wind, stable conditions have been reported and may be used for guidance.

Nickola et al. (1974) conducted two 30-minute diffusion tests from a release height of 0.3 m and sampled at 127 locations at a height of 1.5 m to distances of 300 m. These tests were conducted over flat desertlike terrain in Washington.

Sagendorf (1975) reported eleven tests over flat terrain in Idaho in which SF_6 was released at a height of 1.5 m and sampled to distances of 400 m at heights of 2-9 m on a circular grid around the release point.

Wilson et al. (1976) reported eleven tests in which SF_6, C Br_2 F_2 and oil-fog smoke were released at a height of 1 m in a forested valley in Tennessee. Sampling was conducted near ground level on circular arcs to a distance of 200 m and to greater distances on partial arcs. Helicopter samples were also taken. Most tests were made in early morning with cloudy skies. Fog with drizzle or rain occurred during almost half of the tests.

Several other similar experiments are referenced in Regulatory Guide 1.145 and by Van der Hoven (1976) who reviewed and summarized all data available at that time. In all experiments, concentrations were appreciably lower than calculated using the NRC ΔT method. The differences are primarily due to greater horizontal rather than vertical spread. The differences from calculated concentrations were greater over rough terrain (50-500) than over smooth surfaces (20-40). Although none of these tests were conducted in coastal regions, it is not expected that diffusion would differ significantly there when light-wind, stable conditions occur. However, such conditions are likely to occur less frequently at most coastal sites than in most inland areas.

Under these conditions, the best estimate of σ_z can be obtained by the ΔT method as currently recommended. Such estimates should have adequate conservatism. Selection of a value for σ_y is more difficult. The most conservative approach would be to use an unmodified ΔT determined value here also. However, all available data show that considerable meander or random wind direction fluctuations almost always occur during near-calm stable conditions so the above method may be considered unduly restrictive. If winds are too light to be measured to give a valid measure of σ_y, continued use of Σ_y as given by the correction factor to σ_y shown in Figure 3 of Regulatory Guide 1.145 should give at least sufficiently conservative values of σ_y and is recommended for continued use. In order to obtain the best possible estimates of diffusion rate, it is recommended that σ_θ and σ_ϕ instrumentation be required at all coastal nuclear reactor sites but that the use of temperature instruments for estimation of diffusion category from ΔT measurements be continued for light wind stable conditions and as a back-up system. It is further recommended that such measurements be made in both the modified and unmodified air on either side of the coastal internal boundary layer. σ_θ and σ_ϕ instrumentation should be mounted at the upper levels of the tower.

5. Plume Meander

Instructions given in Regulatory Guide 1.145 for calculation of relative atmospheric concentrations, χ/Q for short time release periods permit reduction of calculated concentrations by use of Σ_y instead of σ_y where Σ_y represents plume standard deviation under conditions of wind meander. This method is permitted under neutral and stable conditions with wind speeds less than 6 mps if values calculated by that method (Eq. 1) are less than the higher value calculated from the expression which gives a reduction for building wake effects or from the related expression which reduces concentrations by a factor of three. Σ_y is defined as a multiple of σ_y where the meander factors, Σ_y/σ_y, are given in Figure 3 of Guide 1.145

These values were estimated from tests at an inland reactor site and there is no evidence that they are applicable to coastal sites. Hallanger et al. (1962) observed waves in aerosol diffusion trials on the California coast but these were probably induced by terrain effects. Otherwise little or no information is available on wind meander over the water or at the shore except that obtained during smoke diffusion experiments by Brookhaven National Laboratory (Raynor et al., 1976, 1978a). In these studies, σ_y was defined as the mean of a series of standard deviation measurements taken during successive passes across a plume by vehicle or boat. Thus, σ_y is representative of plume width over a 4-8 minute sampling time. For comparison, the Pasquill curves were based on 3-minute sampling times (Pasquill, 1976a). Σ_y was defined as the standard deviation of the summation of the successive passes and includes both simple diffusion and plume meander. It is representative of plume widths over 30-60 minute periods. A summary of results is given here since an analysis of the data has not been published.

The ratio Σ_y/σ_y similar to M of Guide 1.145 was calculated for all runs at the south shore of Long Island (Raynor et al., 1975, 1976)(Table 2) and all tests conducted at Great Gull Island (Raynor et al., 1978a)(Table 3). At least a small amount of meander was measured in all sets of passes which usually lasted from 30 to 60 minutes. In the series of 39 sets of traverses on the south shore, the mean ratio was 2.11 and the range from 1.20 to 6.75. The value of 6.75 was from a case with a 20° wind direction shift during the series of traverses and is not representative of meander only. The next largest ratio was 3.59 which is more representative of large meander. Thus, meander on the average only doubled σ_y and in 7 of the 39 cases increased it by less than 50%, i.e., the ratio was less than 1.5.

In the Great Gull Island series of 17 tests with emission from the boat undisturbed by the island, the mean ratio was 2.25 and the range from

1.31 to 4.25. In three of the seventeen tests, σ_y was increased by less than 50%. In the 17 releases from the island, the mean ratio was 2.27 and the range from 1.25 to 7.75. In three of these tests, σ_y was increased by less than 50%. The larger values in both boat and island releases also included wind direction changes so ratios for pure meander only would be somewhat less.

The tests at the two locations were taken at all seasons, at distances from the source of 0.1 to 6.7 km, with a range of wind speeds and with stable, neutral and unstable conditions over the water. No trend in the ratio from the south shore data was found with distance from the source, season, stability, wind speed or the magnitude of σ_y. However, no tests were conducted with wind speeds of less than 3.2 mps at 16 m above the beach. In the Gull Island data, a slight but probably not significant trend towards larger ratios with lower wind speeds was evident but no tests were made with wind speeds less than 3.0 mps at 10 m above the surface. No trends were apparent with any of the other variables.

These data suggest that wind meander at the coast may only increase σ_y by a factor of two on the average and sometimes less. In addition, periods were observed visually when a stable plume did not meander at all and extended periods of constant wind direction have been observed on a wind direction recorder at the beach. These observations indicate that meander does not always occur with stable conditions over the water. On the other hand, no smoke diffusion tests were made during very low wind speeds and no data are available from other locations. However, low wind speeds occur less frequently at the coast than at typical inland locations. Although this difference is generally known, it is well documented in mostly yet unpublished studies of transport and diffusion climatology of the U. S. east coast being conducted at Brookhaven National Laboratory, (Raynor and Hayes, 1976).

No data are available to determine if meander increases, decreases or remains the same when air flows inland from the coast. Observations at BNL show that some meander or small-scale periodic change in mean wind direction is observable much of the time but is largely obscured by the much greater turbulent fluctuations during neutral and unstable conditions. Since the turbulent fluctuations govern diffusion, meander becomes unimportant during these periods. Since meander is a long wave length phenomenon compared with turbulence, it is expected that it would require a much greater distance to change its character as air flows inland in contrast to the high frequency turbulent fluctuations which are affected more quickly by the new surface. Thus, its presence or absence would still be significant during periods of stability over the land. During coastal diffusion tests (Raynor, et al., 1975) stable plumes were observed and photographed from the air during several tests at distances of several kilometers inland over a wooded surface. No evidence of increased meander was noted.

Based on these observations, our best assumption is that plume meander or lack of it in the transition region is similar to that in the flow approaching the shore. Thus, in some cases, meander will be absent or negligible.

In view of the limited data available from the Brookhaven studies, the lack of low wind speed data and the complete lack of available data from other sites, no firm recommendations can be made concerning credit for meander in diffusion calculations at higher wind speeds. Meander is included in the recommendations above for low wind speed stable conditions. Further research is clearly needed to document the percent of time meander occurs at a representative number of coastal sites, to determine the magnitude and temporal frequency of the oscillatory movements and to investigate the meteorological conditions under which meander occurs. In the meantime, it is recommended that current procedures for using meander to reduce computed concentrations at wind speeds above 1 mps should be considered tentative and subject to revision if additional data show them to be insufficiently conservative.

6. Diffusion Calculations

Regulatory Guide 1.145 and other NRC procedures specify methods for calculation of relative atmospheric concentration values (χ/Q) for specified time periods, release heights, distances and stabilities and includes instructions for calculating concentrations during fumigation conditions. Various forms of the Gaussian plume diffusion model are specified for diffusion calculations except when site specific diffusion data are available or when unusual siting, meteorological or terrain conditions dictate the use of other models or considerations. To some extent, coastal sites should always be considered unusual and thus require special methods. Several situations where modifications to current models or procedures are needed for coastal sites are discussed below.

For non-routine releases at or near ground level, the "near worst" conditions or those for which χ/Q is exceeded 5% of the time are generally low-wind speed, stable cases. For these conditions, the simple Gaussian plume model with appropriate values of the diffusion parameters is quite adequate for the calculation of χ/Q as long as the effluent is transported over uniform terrain.

At some coastal sites, there are wind directions that can transport effluents alternately over land and water. This can happen with a bay or other body of water between the plant and the mainland. It can also happen at an irregular coastline for directions nearly parallel to the shore. For such trajectories, the Gaussian plume model, if used with σ's appropriate for over-land diffusion, could underpredict χ/Q.

An extremely conservative position would be to require that the smaller of the over-water or over-land σ be used if a trajectory crosses water. This would also be a simple approach computationally.

A more reasonable, though still conservative approach, would be to use a model in which the plume growth is decreased for segments over the colder surface. The usual method for this situation is the assumption of a virtual source after the plume enters a different diffusion regime. For example, consider a plume entering region "b" from region "a". Assume that diffusion in region "a" is characterized by $\sigma = \sigma_a$ (for either σ_y or σ_z). If in region "b", the plume growth function is $\sigma = f(x-x_o)$ (e.g., $\sigma = C(x-x_o)^p$) where x is the downwind location and x_o is the source location, one solves for the source location that would result in σ_a if the diffusion had taken place in region "b" only. That is, one solves $\sigma_b = f(x_1-x_v)$ for x_v where $x_v = x_b-(\sigma/C)^{1/p}$ and x_1 is the location of the boundary between regions "a" and "b". One then determines σ from $\sigma = f(x-x_o)$. This procedure would be repeated at each interface. The model of Lyons and Cole (1973) discussed earlier also makes use of a virtual source.

The difficulty with this procedure is that it assumes an abrupt transition at the boundary between regions. For a rough to smooth (land to water) or an unstable to stable transition, this is a conservative assumption. For a transition in the reverse direction, the effective boundary should be shifted downwind approximately $3s\sigma_z$ from the true interface where σ_z is the plume height over the stable region and s is the boundary layer slope (an average value of 1/4 is reasonable within a few kilometers of the surface discontinuity) and a plume "height" equal to 3 σ_z is assumed. Use of these procedures should result in more realistic but still conservative predictions of concentrations when the plume traverses two or more different diffusion regimes.

If one considers the "realistic" accident conditions (those for which χ/Q is exceeded 50% of the time), the simple Gaussian plume model can under-predict χ/Q if the limitation to vertical diffusion caused by an inversion lid or a stable layer aloft, as in the case of emission into the unstable layer within a coastal internal boundary layer, is neglected. Whether or not this "50% case" will occur depends on the climatology of the particular site but it is recommended that any model used for calculating diffusion at a coastal site take this situation into account.

For the case of emission into a layer beneath an inversion lid of constant height, the well known procedure is to consider a series of image sources to simulate reflection at the upper boundary (Calder, 1971). In this procedure, the $1/\sigma_z$ term is replaced by

$$\frac{2}{\sigma_z} \sum_{n=o}^{\infty} \exp\left[-\frac{1}{2}\left(\frac{2nL}{\sigma_z}\right)^2\right] \quad \text{where} \qquad (4)$$

L is the height of the lid or layer aloft.

Pasquill (1976b) has recommended a simplification in the calculation procedure that takes into account the fact that the lid has little effect for small σ_z and that for large σ_z the material uniformly fills the mixed layer. For σ_z <0.5L, one uses the $1/\sigma_z$ term unmodified. For $\sigma_z \geq 0.85L$, one replaces $1/\sigma_z$ by 1/L, assuming the material to be uniformly mixed. For intermediate values of σ_z, one linearly interpolates $\ln(\frac{\chi}{Q})$ between the two previous expressions.

It should be noted that to use these procedures, the form of the wake correction (Eq. 2, NRC, 1977a) would require modification. Instead of using a form such as

$$\frac{1}{(\pi \sigma_y \sigma_z + A/2)} \quad \text{where} \qquad (5)$$

A is the building cross sectional area, one would have to use something like

$$\frac{1}{\pi (\sigma_y + C_y B_y)(\sigma_z + C_z B_z)} \quad \text{where} \qquad (6)$$

B_y and B_z are characteristic horizontal and vertical building dimensions and C_y and C_z are constants. It would then be $\sigma_z' = \sigma_z + C_z B_z$ that would appear in equation (4).

A difficulty with the above procedure is that it assumes a lid height unchanging with distance. An extremely conservative assumption would be to use the height of the internal boundary layer at the source position as the constant L. A more realistic method would be to use a changing lid height in the model if the slope is known or can be estimated. However, routine methods to accomplish this are not available. Development of a procedure for this purpose would require a theoretical effort beyond the scope of this project. Such a study could be done using either a numerical solution to the diffusion equation with varying boundary conditions or by an analysis using a more complete image source method.

For an elevated source, the NRC recommended procedure (NRC, 1977a) for the "conservative" accident condition calls for the assumption of fumigation conditions for four hours. The model is extremely conservative in that it is equivalent to having a lid at source height and does not give credit for horizontal diffusion that would be expected to accompany the vertical mixing to the ground.

The model of Lyons and Cole (1973) may be slightly less conservative because it only allows that portion of the plume below the boundary to fumigate rather than the whole plume and includes horizontal spreading while the plume is mixing downward.

An assumption that is in the non-conservative direction for coastal plants is the use of a σ_y equivalent to moderately stable conditions (F) instead of a σ_y appropriate to stable flow over the water which can be considerably less as discussed above. This is particularly important during stable onshore flows because experiments (Raynor et al. 1975, 1976; Slade, 1962) have shown that σ_y over water can easily be a factor of two less than the value given for the Pasquill Class F and σ_z can be a factor of 1.6 less than the F value. If the recommendations given above are followed for using measured values of σ_θ and σ_ϕ in both layers for calculating σ_y and σ_z, appropriate values will be available without use of Pasquill class, ΔT or other indirect methods. The relationships suggested by Hanna et al. (1977) are recommended for calculation of σ_y and σ_z from σ_θ and σ_ϕ.

The limit of four hours for fumigation conditions is also non-conservative for steady-state conditions at coastal sites as discussed earlier. However, conditions seldom remain steady for extended periods and it is possible that these somewhat non-conservative assumptions for fumigation conditions are outweighed for most potential situations by the conservative assumptions.

In summary, it is recommended that values of σ_y and σ_z be determined from values of σ_θ and σ_ϕ measured in the layer or layers for which diffusion calculations are to be made, that the model used for diffusion calculations entirely within the internal boundary layer be modified to provide for a lid of fixed or changing height formed by the stable air aloft and that a model be used with provision for changing diffusion parameters when the plume crosses a boundary into different diffusion conditions.

7. Other Problem Areas

Two other potential problem areas exist, one within and one beyond the scope of this study. Credit in diffusion calculations for wake effects at the plant structure is based solely on experiments conducted at inland sites. It is expected that wake effects around a coastal plant with stable onshore air flow may be appreciably less although firm data are lacking. In the diffusion tests conducted at Great Gull Island (Raynor et al., 1978a) under stable conditions, smoke plumes were observed to flow across the island, following the contours of the hills with no discernable spreading or disturbance of the plume. Similar behavior might be expected at coastal plants when conditions are stable both over the water and over the land. Therefore, the wake correction for coastal plants should also be considered tentative and subject to revision if additional data show it to be insufficiently conservative.

Although beyond the scope of this study, long-range transport of effluents over water to another land area during stable conditions over the water could occur with very little diffusion as observed in the Brookhaven experiments (Raynor et al., 1975) and result in high concentrations on the downwind shore. Such transport could take place with southwest winds from a plant on the New Jersey coast to Long Island or across Long Island Sound with almost any wind direction.

E. SUMMARY OF RECOMMENDATIONS

The recommendations below are made with respect to either or both scientific and regulatory aspects of current procedures.

1. The presence and characteristics of coastal internal boundary layers should be considered in all measurement programs and modeling procedures at coastal sites and the model developed by Raynor et al. (1975) and by Venkatram (1977a) should be used to calculate the height of the coastal internal boundary layer.

2. The primary meteorological tower should be in such a location that the upper measuring level is always within the internal boundary layer. Computed heights of the internal boundary layer should be confirmed experimentally before the tower site is chosen. For a site with a simple coastline, a secondary tower should be placed at a location where measurements representative of conditions in the unmodified air can be determined. For a site with another area of land across a body of water, one secondary tower should be located in the water or two secondary towers should be located on opposite shores.

3. Instrument heights should be selected on the primary tower so that measurements representative of conditions within the internal boundary layer are obtained while maintaining adequate separation between levels. On secondary towers, instrument heights should meet the same criteria for the internal boundary layer over the water.

4. Instrumentation for measuring σ_θ and σ_ϕ should be required at all coastal nuclear reactor sites but the use of temperature instruments for estimation of diffusion category from ΔT measurements should be continued for light wind stable conditions and as a back-up system. The above measurements should be made in both the modified and unmodified air on either side of the coastal internal boundary layer. Instrumentation for measuring σ_θ and σ_ϕ should be mounted at the upper level of the tower.

5. Current procedures for using meander to reduce computed concentrations at wind speeds above 1 mps should be considered tentative and subject to revision if additional data show them to be insufficiently conservative.

6. Values of σ_y and σ_z for use in diffusion models should be determined from values of σ_θ and σ_ϕ measured in the layer or layers for which diffusion

calculations are to be made except for light wind stable conditions when current procedures should be continued. Any model used for diffusion calculations entirely within the internal boundary layer should be modified to provide for a lid of fixed or changing height formed by the stable air aloft. Any model used for predicting concentrations when a plume crosses a boundary into different diffusion conditions should have provision for changing diffusion parameters at the discontinuity.

7. The value of the wake correction to the diffusion equation should be considered tentative and subject to revision for coastal sites if additional data show it to be insufficiently conservative.

F. SUGGESTIONS FOR FUTURE RESEARCH

Preliminary recommendations for further research were made earlier. Additional search of the literature and continued consideration of those problem areas involved reinforce the opinion that such research is required before the problem of diffusion in coastal areas can be treated with confidence on the basis of adequate knowledge. Therefore, the research suggestions made earlier are repeated here with only minor changes and others are added.

1. The following aspects of horizontal wind direction meander should be investigated:

    1. The diurnal and seasonal frequency of meander, particularly during onshore flows.
    2. The mean frequency and amplitude of the oscillating waves and the variability in these parameters.
    3. The geographic variability of the above factors.
    4. The relationship between meander and other meteorological variables.
    5. The relationship of wind direction meander to plume diffusion.

This study would be conducted using existing wind and meteorological data from BNL and other sites.

2. A study of coastal internal boundary layers should also be conducted. This would be primarily an observational study but would also use available data from meteorological towers at coastal sites. Some of the unknowns that need study are as follows:

1. The slope of the coastal internal boundary layer as a function of season, time of day, flow direction, wind speed, land and water surface temperature, terrain and other pertinent physical variables.
2. The equilibrium height and the distance at which it occurs or the distance and height at which the coastal internal boundary layer merges into the planetary boundary layer or well-mixed layer.
3. The wind speed and turbulence characteristics of the modified and unmodified air as a function of height and the variables listed in 1 above.
4. The most feasible method of measuring the height of the coastal internal boundary layer. This would include a comparison of available instrument systems such as acoustic sounder, slow speed radiosonde, tethered balloon, etc.
5. The effects of the boundary layer on fumigation and both local and long distance diffusion.
6. The best means of including the horizontal and vertical step changes at boundary layers in diffusion models.

3. The magnitude of wake effects at coastal plants during stable onshore flows should be investigated. Measurements could be obtained at existing structures by tracer experiments under selected conditions.

4. The possibility of long-range transport over water between land areas of plumes undergoing little or no diffusion during periods of extreme stability over the water should be investigated. This could be done by SF_6 tracer experiments in which the tracer is released on the southern New Jersey coast, for instance, and sampled from aircraft and vehicles along the south shore of Long Island.

ACKNOWLEDGEMENTS

This study was assisted by helpful suggestions from and discussions with Earl Markee and John Goll, Meteorology Section, Hydrology-Meteorology Branch, Division of Site Safety and Environmental Analysis, U. S. Nuclear Regulatory Commission. Data and suggestions were contributed by Robert M. Brown, Atmospheric Sciences Division, Brookhaven National Laboratory. Walter A. Lyons, Mesomet, Inc. and the American Meteorological Society kindly gave permission to quote directly from an article previously published in the Journal of Applied Meteorology.

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TABLE 1

Probable Prediction Errors as a Function of Land and Water Temperatures and Lapse Rates over the Two Surfaces

Case	T_W	T_L	ΔT_W	ΔT_L	Predicted Stability	Actual Stability	Type of Prediction
1	cold	warm	+	+	slightly stable	stable	non-conservative
2	cold	warm	-	+	unstable	stable	non-conservative
3	cold	warm	+	-	unstable	unstable	correct
4	cold	warm	-	-	unstable	unstable	correct
5	warm	cold	+	+	stable	stable	correct
6	warm	cold	-	+	stable	stable	correct
7	warm	cold	+	-	slightly stable	unstable	conservative
8	warm	cold	-	-	slightly stable	unstable	conservative

Table 2

Standard Deviations and Their Ratio from Coastal Diffusion Tests

Test	Date	Distance (km)	Σ_y (m)	σ_y (m)	$\frac{\Sigma_y}{\sigma_y}$
2	8-17-72	1.9	131.5	91.0	1.45
		5.5	79.8	63.3	1.26
3	8-31-72	2.7	161.1	44.9	3.59
		6.7	68.3	41.7	1.64
4	10-3-72	2.3	121.8	84.1	1.45
		2.3	151.9	72.8	2.09
6	5-23-73	2.6	86.9	54.8	1.59
		2.6	89.9	38.2	2.35
		0.5	35.5	22.8	1.56
		0.9	62.9	32.3	1.95
		1.8	75.1	37.1	2.02
7	6-1-73	4.3	56.9	31.3	1.20
8	6-15-73	1.4	227.2	121.9	1.86
		0.5	120.0	42.5	2.82
9	7-13-73	4.9	79.1	45.1	1.75
10	9-20-73	3.4	140.3	97.4	1.44
11	4-11-74	0.9	82.6	43.3	1.91
		1.9	82.5	45.2	1.83
12	5-14-74	5.6	456.2	67.6	6.75*
		2.7	37.3	29.9	1.25
13	6-14-74	4.8	351.5	133.9	2.63
14	7-18-74	0.9	70.4	42.5	1.66
		1.8	93.4	48.4	1.93
		3.5	148.2	43.9	3.38
		3.5	140.9	51.7	2.73
15	3-6-75	2.1	73.7	42.2	1.75
		0.5	131.6	50.4	2.61
17	6-24-75	0.8	83.1	24.9	2.34
		1.6	57.8	25.0	2.31
		3.8	120.2	73.5	1.64
18	9-11-75	2.0	79.5	39.5	2.01
19	9-18-75	0.3	89.7	71.1	1.26
		1.7	98.7	46.6	2.12
21	2-26-76	3.3	59.3	23.6	2.51
22	5-11-76	3.0	95.6	45.1	2.12
		2.2	89.3	42.6	2.10
		3.9	92.1	54.9	1.68
23	6-4-76	1.8	71.4	33.8	2.11
24	6-8-76	0.9	51.9	32.8	1.58

* Case with wind direction shift.

Table 3

Standard Deviations and Their Ratio from Tests at Great Gull Island

Test	Date	Source	Distance (km)	Σ_y (m)	σ_y (m)	$\frac{\Sigma_y}{\sigma_y}$
1	9-23-74	Boat	0.70	341.0	193.4	1.76
		Island	0.40	168.3	97.9	1.72
2	9-24-74	Boat	0.90	129.3	30.4	4.25
		Island	1.10	363.5	120.3	3.02
4	9-25-74	Boat	0.30	106.5	52.6	2.02
		Island	0.20	108.8	57.5	1.89
5	9-25-74	Boat	1.00	146.9	86.2	1.70
		Island	0.90	142.8	89.6	1.59
6	9-26-74	Boat	1.10	154.6	74.1	2.09
		Island	1.40	212.9	91.1	2.34
7	9-26-74	Boat	2.00	314.6	117.4	2.68
		Island	2.30	303.6	147.3	2.06
8	9-27-74	Boat	1.60	250.7	104.6	2.40
		Island	1.80	230.0	121.6	1.89
9	4-21-75	Boat	0.90	147.2	73.8	1.99
		Island	0.60	252.7	100.3	2.52
10	4-22-75	Boat	1.50	79.8	59.9	1.33
		Island	1.80	181.5	71.0	2.56
11	4-22-75	Boat	0.90	241.8	70.3	3.44
		Island	0.70	568.9	73.4	7.75
12	4-23-75	Boat	0.90	131.5	56.3	2.34
		Island	0.50	96.8	74.0	1.31
13	4-23-75	Boat	2.10	194.2	58.2	3.34
		Island	1.60	93.6	62.3	1.50
14	4-28-75	Boat	1.10	74.0	56.6	1.31
		Island	1.10	110.7	56.5	1.96
15	4-28-75	Boat	2.40	81.2	56.8	1.43
		Island	2.10	78.0	62.6	1.25
16	4-28-75	Boat	1.10	114.6	68.4	1.68
		Island	1.40	138.3	70.6	1.96
17	5-1-75	Boat	1.80	109.7	54.3	2.02
		Island	1.60	74.3	51.5	1.44
19	5-3-75	Boat	1.20	274.5	109.2	2.51
		Island	0.80	195.9	111.1	1.76
20	5-3-75	Boat	0.10	63.3	39.2	1.61
21	5-3-75	Boat	1.40	195.0	86.0	2.27

NRC FORM 335 (7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-0936
BNL/NUREG-51045

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Recommendations for Meteorological Measurement Programs and Atmospheric Prediction Methods for Use at Coastal Nuclear Reactor Sites

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
Gilbert S. Raynor, Paul Michael and S. SethuRaman

5. DATE REPORT COMPLETED

MONTH	YEAR
February	1979

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Atmospheric Sciences Division
Department of Energy and Environment
Brookhaven National Laboratory
Upton, New York 11973

DATE REPORT ISSUED

MONTH	YEAR
October	1979

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
U. S. Nuclear Regulatory Commission
Hydrology-Meteorology Branch
Washington, D. C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
EY-76-C-02-0016

13. TYPE OF REPORT
Formal NUREG-BNL

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14 *(Leave blank)*

16. ABSTRACT *(200 words or less)*

A study, based on a literature review, was performed to examine currently recommended meteorological measurement programs and diffusion prediction methods for nuclear power plants to determine their adequacy for plants located in coastal zones. Although procedures for handling the "near worst" case (stable, light wind situation) were judged adequately conservative, deficiencies in guidelines and procedures were found with respect to the following: failure to consider the role of coastal internal boundary layers, specifications for tower locations and instrument heights, methods of classifying atmospheric stability, method of allowing credit for plume meander and models specified for diffusion calculations. Recommendations were made for changes in the guidelines applicable to these topics. Areas in which additional research is needed were identified.

17. KEY WORDS AND DOCUMENT ANALYSIS

Coastal sites
Diffusion models
Meteorological measurements
Nuclear power plants
Internal boundary layer

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

Unlimited

18. AVAILABILITY STATEMENT

19. SECURITY CLASS *(This report)*

21. NO. OF PAGES

20. SECURITY CLASS *(This page)*

22. PRICE
$