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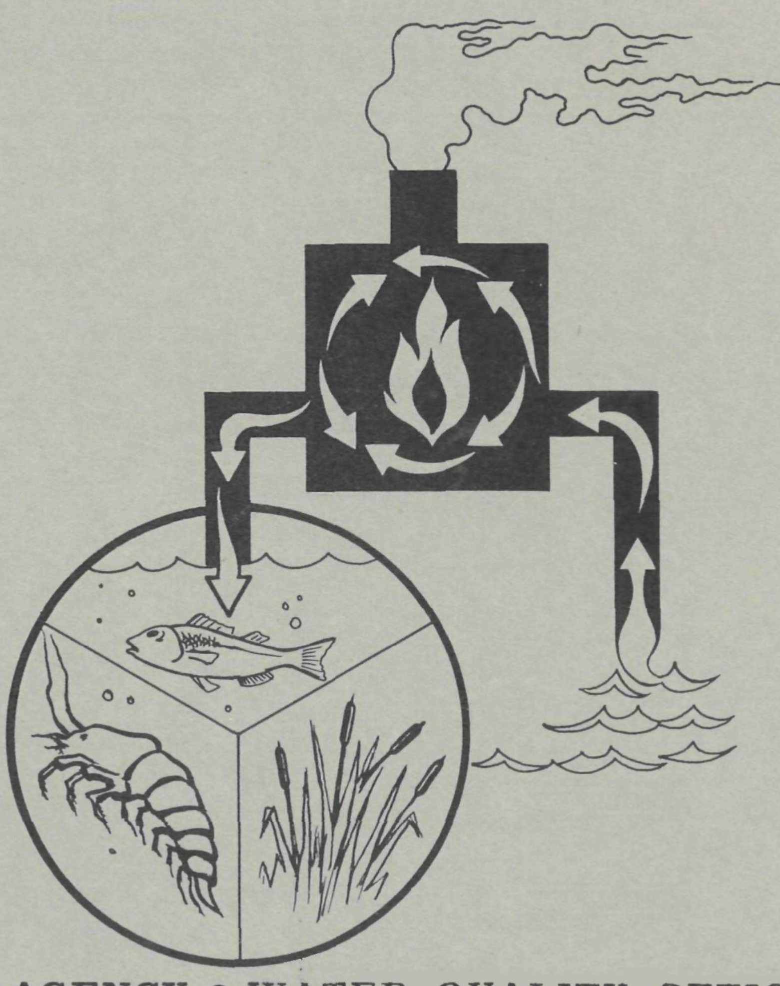
POTENTIAL ENVIRONMENTAL MODIFICATIONS PRODUCED BY LARGE EVAPORATIVE COOLING TOWERS



ENVIRONMENTAL PROTECTION AGENCY ● WATER QUALITY OFFICE

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POTENTIAL ENVIRONMENTAL MODIFICATIONS
PRODUCED BY LARGE EVAPORATIVE COOLING TOWERS

by

E G & G, Inc.

Environmental Services Operation

Boulder, Colorado

for the

WATER QUALITY OFFICE

ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

The objective of the study was to develop techniques for evaluating the extent of plumes from large evaporative cooling towers. Analytical techniques were used to describe the dynamics of the wet cooling tower plume and its interaction with the environment. Primary emphasis was placed on predicting the height of the plume. Classical atmosphere diffusion theory was used to determine the downwind spread.

The study showed that the saturation deficit of the atmosphere clearly controls the downwind spread of the ejected liquid water. Except for cases where the relative humidity approaches 100%, downwind propagation is limited to periods when the air temperature falls below the freezing point. For a given set of atmospheric conditions, increases in the tower radius, the saturation temperature, and the initial vertical velocity of the plume contribute to increasing the final plume height.

The potential for adverse atmospheric effects due to cooling towers was analyzed on a national basis and is presented in the form of a map of the United States.

A computer program was developed to perform the necessary calculations. The Appendix contains a description of the program, including input specifications.

This report was submitted in fulfillment of contract number 14-12-542 under the sponsorship of the Water Quality Office of the Environmental Protection Agency.

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SECTION 1.0

INTRODUCTION

Recent studies indicate that the electrical power needs in the United States are doubling every 6 or 7 years. To meet this need an increasing number of steam electric generating facilities are required. One of the salient features of these plants is that they require large quantities of cooling water. This increased demand for cooling water has brought forth an environmental problem called "thermal pollution", which is caused by the discharges of large quantities of waste heat from the electrical power plants into various natural waterways. Due to the likely adverse consequences of increased temperatures from the discharged effluent on aquatic life, there has been an increasing demand for alternative methods of cooling which would dissipate the waste heat in a more preferable manner.

One of the more favored means of solving the thermal pollution problem is the use of large evaporative cooling towers, which dissipate the waste heat directly into the atmosphere. With the recent application of large cooling towers in the United States, some concern has been expressed about the possible adverse environmental consequences of the effluent discharges to the atmosphere from the towers. In certain climates, the evaporation of water at rates of several thousands of gallons per minute may create modifications to the local environment through formation of fog, icing on nearby structures, and "flashing" of transmission lines downwind of the tower. Other possible adverse conditions such as haze formation, icing of bridges, and destruction of crops have also been suggested.

The probability of a cooling tower causing adverse environmental modifications is a function of the characteristics of the tower (height, exhaust velocities, temperature, etc.) as well as the characteristics of the local climate near the tower site. Certain areas have wind, stability, and humidity conditions necessary for occurrence of adverse effects whereas many areas have conditions where the tower effluent is dispersed effectively with insignificant environmental modification resulting.

It is important to the orderly development of our national economy that a rational delineation of the potential of inadvertent environmental modification by cooling towers be obtained as soon as possible. Thus, this study was initiated to analyze the physical consequences of the ejections of cooling tower effluents and their subsequent dispersal into the environment. The prime objective of the study has been to develop a predictive model from which the general behavior of the cooling tower plume can be assessed in terms of various meteorological conditions and local terrain features. In addition, geographical regions throughout the United States have been classified as to the potential for adverse effects occurring from the application of cooling towers.

1.1 Tower Characteristics

Cooling towers may be classified as wet type where water and air come in direct contact or dry type where cooling is through indirect contact of heat exchangers. The movement of air for both types may be created either by mechanical draft with fans or by natural draft through a chimney.

In the dry type cooling tower, indirect heat transfer is by conduction and convection through finned tube cooler sections, instead of evaporation. There is no evaporative loss with subsequent water makeup requirements, but greater air movement is necessary to reject the heat. Cooled water from the tower is introduced into a direct contact jet condenser where it picks up heat and then is returned to the tower for cooling. The dry type has poorer efficiency than the wet type, and hence is less economical. Since no water is lost in the dry type, it does not represent as clear a potential for inadvertent environment modification as does the wet type, and it will not be considered in this study.

In the wet type cooling tower, water is sprayed onto a lattice network (packing) through which air is moved resulting in evaporative heat transfer. One type of tower currently favored, the hyperbolic natural draft unit, is shown in Figure 1.

The evaporation process in a tower such as shown in Figure 1 results in cooling of the water by about 20°F. The cooled water is collected in a basin under the fill. Solids in the water accumulate in the basin, and the wastes are periodically removed by blow-down. Make-up water in the order of 3% of the flow circulated is necessary to replenish evaporation and blow-down losses. The make-up water may be chemically treated to protect the fill from deterioration and the spray nozzles from plugging.

Typical large evaporative towers discharge 10,000 gpm and several towers may be utilized at a given site. The subsequent interaction with the atmosphere of these large fluxes of water is the primary concern in terms of possible adverse effects.

1.2 Scope of the Study

The main objective of this study has been the development of techniques to model and predict the behavior of cooling-tower effluents when discharged into the atmosphere under various meteorological conditions. The study is limited to numerical calculations of the general characteristics of plume behavior. Parameters used in the numerical model are those for typical wet-type natural

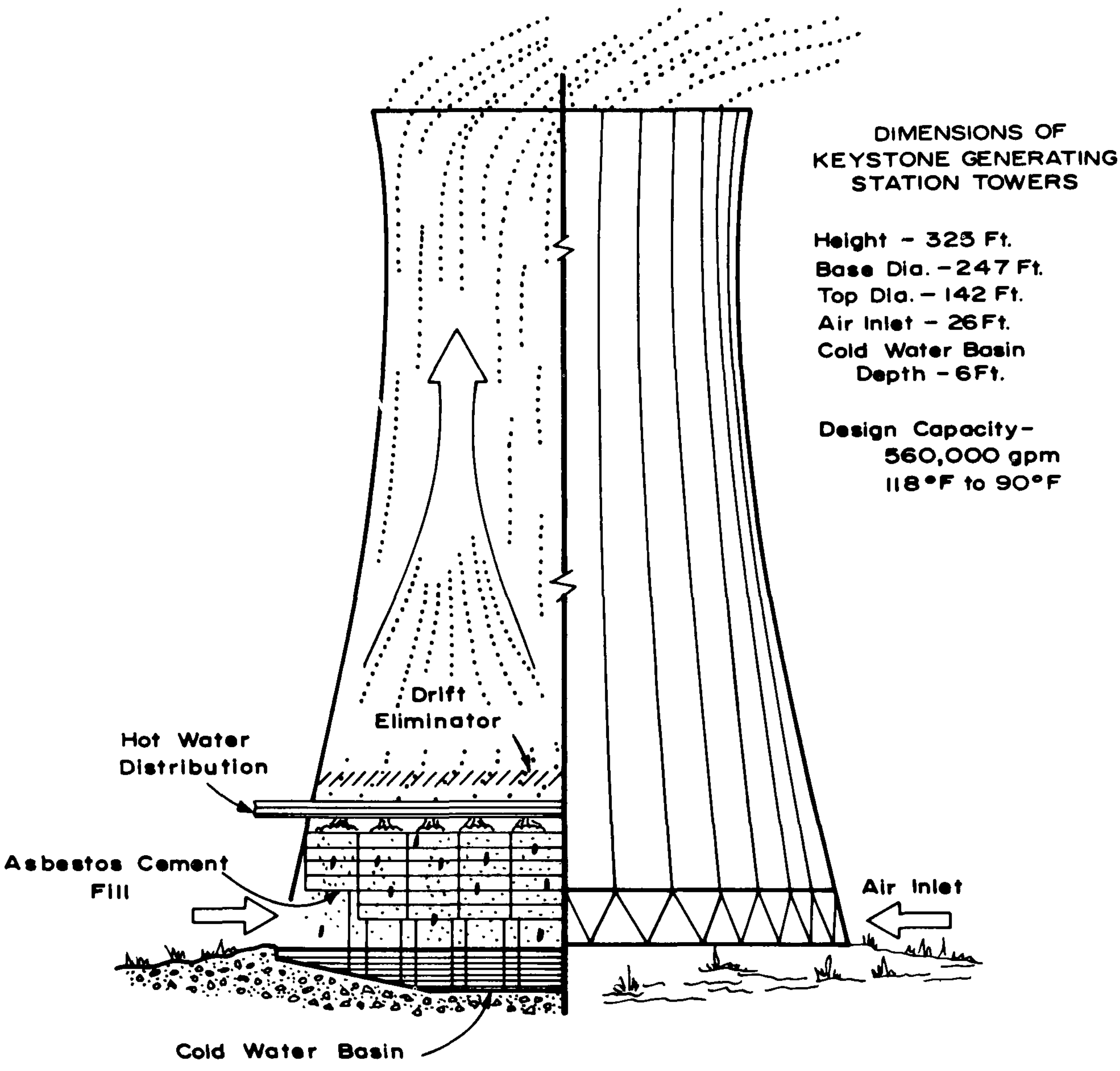

FIGURE 1. NATURAL DRAFT WET (Evaporative) COUNTERFLOW TOWER FROM FWPCA (1968)

draft (hyperbolic) towers such as those at the Keystone Site in Pennsylvania. Some consideration is also given to the behavior of plumes from mechanical draft towers.

Due to the complexity of the problem, a considerable number of empirical and parameterized concepts have been employed to develop a practical model. The overall aim has been to develop a model that is readily useable rather than one of rigor and complexity. Definition of important parameters and their sensitivity to local variations has been a part of the study.

Various climatic regions throughout the United States have been classified in terms of the frequency of meteorological conditions favorable to adverse effects from cooling tower plumes.

Clearly, a firm understanding of environmental modification by cooling towers will have to be established by proper measurements in the vicinity of operational towers, in order to validate and refine the theoretical concepts. However, field measurements are beyond the scope of the present study. Besides proper meteorological measurements, ecological monitoring will also be necessary to evaluate the total influence of the tower effluent on the environment.

In summary, this study is regarded as one step in what necessarily must be a broad program to properly evaluate the general application of large evaporative cooling towers throughout the United States.

SECTION 2.0

TOWER PLUME AND DIFFUSION MODEL

Study of the ejection of cooling tower effluents into the atmosphere and subsequent dispersal into the environment involves knowledge of several complex processes. In this study we have considered the problem in the following phases:

(a) Dynamics of the wet effluent plume and its immediate interaction with environment through entrainment. Primary emphasis has been placed on predicting the height to which the plume penetrates.

(b) Horizontal diffusion of the ejected water vapor and its contribution to the local saturation deficit.

A subdivision of the problem into conditions in the immediate vicinity of the tower (vertical plume) and those downwind (diffused plume) is of obvious use in clarifying the important meteorological parameters.

2.1 Plume Dynamics

The phenomena controlling the vertical growth of the wet plumes from cooling towers are different from those controlling the movement of dry particulate smoke, due to the energies involved in evaporation and condensation in the wet plume and the buoyancy accelerations produced. In this situation, the buoyancy forces are produced locally rather than being a function of the initial temperature of the effluent alone. Thus, the dynamics of the cooling tower is more closely related to that of an isolated cumulus cloud, where condensation warms the core of the plume while evaporation and chilling occur near the edges.

Clearly the buoyancy of the wet plume will significantly influence the vertical penetration. In fact, it is known that the observed plume rise of cooling tower effluents is considerably greater than the values calculated on the basis of initial effluent temperature alone. This additional penetration is obviously important in assessing the close-in characteristics.

Most previous studies of the behavior of effluent from stacks have been based on the concept that the horizontal diffusion is equivalent to that from a source at an "effective" stack height in place of the actual source, where the effective stack height is defined as the height at which the plume becomes nearly horizontal. Methods for determining effective stack height have produced varying results. A summary of the present status has been prepared recently by Briggs (1968). In this study we will assume that the plume grows in a vertical column (tilted due to wind shear) and that the maximum height of penetration of the column is of importance for prediction of local modification (subsequently horizontal diffusion will be used to spread the column downwind).

Over the past several years considerable progress has been achieved in the application of numerical models to cumulus clouds (alikened to moist buoyant plumes). One of the more widely used cumulus models is the one-dimensional dynamic model with parameterized entrainment and microphysical relationships. In this study, we proceeded by modifying the cumulus model (Davis, 1967, Weinstein and Davis, 1968) such as to make it more applicable to wet effluent plumes.

The approach used in the model is to apply the vertical equation of motion and the first law of thermodynamics with parameterized relations for plume mixing, water particle growth, fallout, and evaporation. Numerical calculations are carried out by lifting incremental portions of the plume adiabatically through successive vertical steps, and at each interval allowing mixing or entrainment to occur with the environment.

The mathematical form of the model will be outlined here with emphasis on those features unique to the cooling tower plume. For a detailed derivation of the basic cumulus model equations, see Weinstein and Davis (1968).

The vertical equation of motion can be written as (see list of symbols):

$$\frac{1}{2}\frac{dw^2}{dz} = \frac{dw}{dz} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g - \text{Drag}$$

where the drag forces will be provided by the weight of liquid water in the air and by mixing with entrained air. Thus,

$$\frac{1}{2}\frac{dw^2}{dz} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g\,(1+Q) - \mu\, w^2$$

Assuming that the plume environment is in hydrostatic equilibrium, and that there is no horizontal pressure gradient between the plume and outside air,

$$\frac{\partial P}{\partial z} = \rho_e g,$$

and so

$$\frac{1}{2}\frac{dw^2}{dz} = g\left[\frac{T_v - T_{ve}}{T_{ve}}\right] - gQ - \mu w^2 \qquad (1)$$

Equation (1) is the energy equation for our plume model. The first term on the right is the buoyancy term, the second the drag due to the liquid water, and the third the loss due to mixing with the slow-moving or stationary environmental air.

The temperature distribution with height in the ascending plume can be derived using the first law of thermodynamics and the Clapeyron equation for variation of saturation vapor pressure with temperature. The result is:

$$\frac{dT}{dz} = \frac{\frac{-g}{c_p}\left(1 + \frac{qL_e}{RT}\right) - \mu(T-T_e) - \frac{\mu L_e}{c_p}(q-q_e) + \frac{L_f Q}{c_p dz} + \frac{\Delta\rho w L_s}{c_p dz}}{1 + \frac{\epsilon L_e^2 q}{c_p RT^2}} \qquad (2)$$

The terms on the right represent (from left to right) the moist adiabatic temperature decrease, (the change in temperature resulting from adiabatic expansion, with latent heat of condensation released by the condensation of all vapor over saturation) the loss of heat to warm the entrained air, the loss of heat to resaturate the entrained air, the heat released by freezing liquid water, and the heat realized by the sublimation of the excess vapor after freezing. The last two terms are applicable only to the height increment, dz, during which the phase change is occurring. After the glaciation procedure has been completed, the moist adiabatic process is assumed to be ice saturated and L_s replaces L_e in the first part of equation (2).

In this model, it is hypothesized that mixing or entrainment occurs through a continuous incorporation of environmental air around the edges of the upward moving plume. Several theoretical and observational studies have suggested that the entrainment rate is inversely related to the plume radius,

$$\frac{1}{M}\frac{dM}{dz} = \mu = \frac{A}{R} \qquad (3)$$

where the entrainment μ has dimensions $(\text{length})^{-1}$, R is the plume radius and the dimensionless constant A depends upon the specific character of the plume and thus must be determined experimentally.

Laboratory studies suggest that the value of A should be .15 to .22. In this study we have used A = .20. The variation of R with height along the plume has been taken to be:

$$R = R_s + z \sin \alpha \tag{4}$$

where R_s is the stack radius, z is height, and α is the half-angle of the plume spread.

The correction to the computed vertical velocity due to the shear of the horizontal wind follows the concepts outlined by Malkus (1952). The slope of the plume as a result of a vertical shear of the horizontal wind is given by:

$$\tan \theta = \frac{w}{U_p}$$

where the vertical velocity is w and the horizontal speed of the air in the updraft is U_p. If the vertical velocity (w_p) calculated from equation (1) is taken as the hypotenuse of the triangle given by the above relationship, the true vertical velocity can be calculated.

$$w^2 = w_p^2 - (U_p)^2$$

U_p is obtained by considering the horizontal momentum in the cloud mass before and after entrainment of environmental air.

$$(\text{Momentum})_2 = (\text{Momentum})_1 + (dM)U_e \quad \text{or}$$

$$U_2 (M + dM) = MU_1 + (dM)U_e$$

with the definition of μ, $\mu = \frac{1}{M}\frac{dM}{dz}$, the above relationship can be stated as:

$$U_2 = \frac{U_1 + \mu dz U_e}{1 + \mu dz}$$

Substituting the above into the solution for w given earlier yields the final form of the relationship:

$$w^2 = w_p^2 - \left(\frac{U_1 + \mu dz U_e}{1 + \mu dz}\right)^2 \tag{5}$$

Utilizing the above set of equations, along with specifications of the initial conditions (tower radius, initial plume velocity, effluent temperature) and the environmental conditions (vertical distributions of temperature, humidity, and wind) calculations of plume updraft velocities, change in plume radius, liquid-water content, and maximum plume height can be obtained. These vertical profiles of plume parameters are used in the next sections as inputs for the second phase of the model which covers the diffusion and downwind spread of the plume.

2.2 Downwind Diffusion

The common practice for the analysis of diffusion of stack effluents is to use an "effective" stack height in conjunction with relationships derived for horizontal and vertical diffusion. The most widely used formulas are slight modifications of those first proposed by Sutton (1953). The relationships selected for use in the cooling tower problem are of the form

$$X = \frac{Q^*}{2\pi \sigma_y \sigma_z u} \exp\left[-\frac{z^2}{2\sigma_z^2} - \frac{y^2}{2\sigma_y^2} \right] \qquad (6)$$

where X is the concentration of the effluent, Q^* is the rate of release of the effluent, u is the wind velocity, and σ_y and σ_z are the standard deviations of the horizontal and vertical concentration distributions. The standard deviations, σ_y and σ_z, are functions of the distance downwind from the source and must be specified in equation (6).

Clearly the most important part of using equation (6) for the downwind spread of the effluent relies in obtaining z_e, σ_z, and σ_y. We assume that the dynamics of the plume can be adequately handled as previously described in order to obtain z_e (defined as the altitude where $w \rightarrow 0$). The dependence of σ_y and σ_z on the downwind distance and on local meteorological and terrain factors is much more difficult. In fact, it is unlikely that a single functional relationship can be found to describe the dependence of σ_y and σ_z on the downwind distance for all values of the downwind distance. During the early phase of the plume propagation the primary mechanism of dispersal is the self-generated turbulence of the plume, or is due to turbulence generated by local structures such as buildings and other towers. On the other hand, at sufficiently large times the dispersal is primarily controlled by the ambient turbulence of the atmosphere. The dispersion at intermediate times would presumably depend on both the self-induced and ambient turbulence.

Csanady (1968) proposes that during the initial phase (within about 2 km from the source) the standard deviations can be assumed to grow linearly with distance from the source. That is, one can let

$$\sigma_y = p_y x \text{ and } \sigma_z = p_z x \qquad (7)$$

where p_y and p_z are constant. Equation (7) implies that the concentration profiles are self-preserving with increasing distances from the source. It can also be easily demonstrated that equation (7) is equivalent to assuming that the entrainment parameter, A, is a constant, since equation (7) essentially implies a linear rate of growth of the plume. In practice, we have chosen p_y and p_z empirically to give observed rates of plume spread consistent with the angle α introduced in equation (4).

At sufficiently large distances from the source the influence of the ambient turbulence on the dispersion is of primary importance. Sutton (1953) gives the following expressions:

$$\sigma_y = \frac{c_y}{\sqrt{2}} x^{\left(\frac{1}{1+p}\right)}$$

$$\sigma_z = \frac{c_z}{\sqrt{2}} x^{\left(\frac{1}{1+p}\right)} \qquad (8)$$

where c_y and c_z are appropriate constants (depending on the atmospheric conditions) and the quantity p is the index corresponding to a power-law fit for the atmospheric wind profile. That is, the wind profile is approximated as

$$\left(\frac{u}{u_1}\right) = \left(\frac{z}{z_1}\right)^p \qquad (9)$$

where u_1 and z_1, are convenient reference values.

Pasquill (1961) and Turner (1967) have conveniently reduced these relationships and observations of plume spread to a simple set of graphs which express σ_y and σ_z as functions of distance and stability class. Turner's curves are given in Figures 2 and 3.

In the present study, equation (7) has been used for distances less than 2 km from the source, and for distances greater than 2 km values of σ_y and σ_z were obtained from Figures 2 and 3 with proper selection of stability class.

2.3 Summary of Numerical Model

The model developed to simulate the behavior of the cooling tower effluent can be divided into two phases; (a) the immediate stack region (less than 2 km from the source), and (b) the downwind region where ambient dispersal

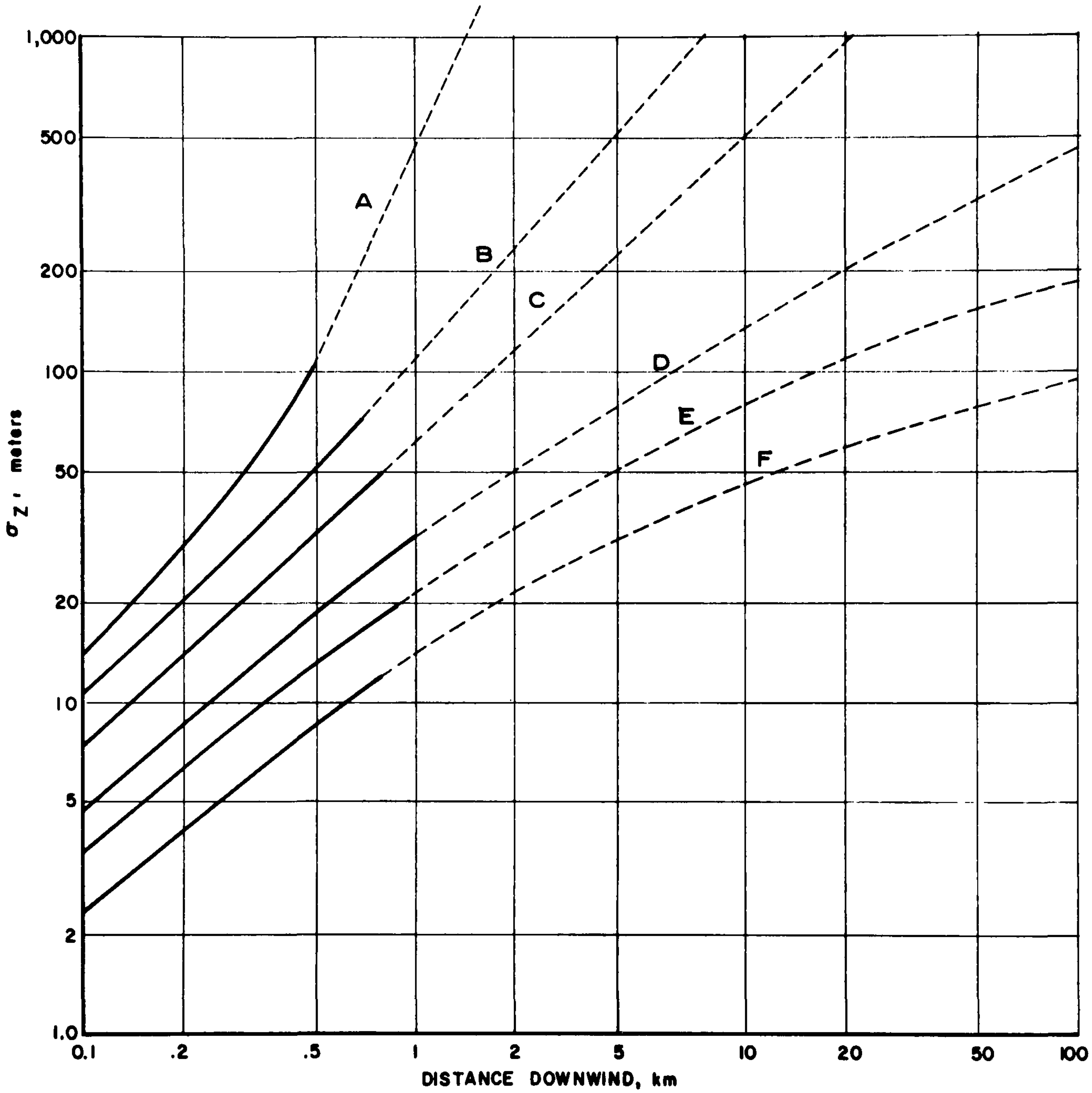

FIGURE 2. VERTICAL DISPERSION COEFFICIENT AS A FUNCTION OF DOWNWIND DISTANCE FROM THE SOURCE. FROM TURNER (1969)

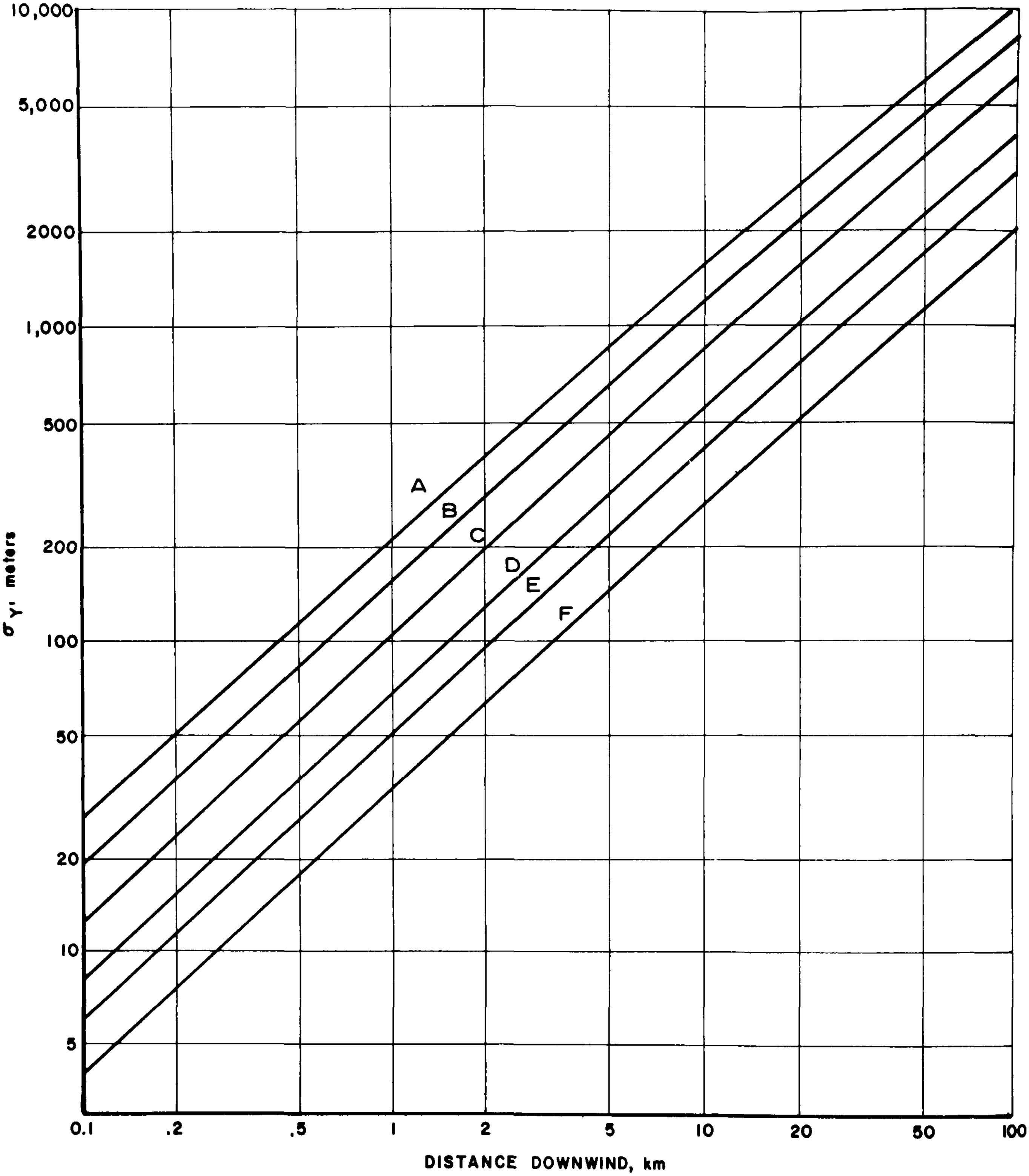

FIGURE 3. HORIZONTAL DISPERSION COEFFICIENT AS A FUNCTION OF DOWNWIND DISTANCE FROM THE SOURCE. FROM TURNER (1969)

is predominent. In the immediate stack region the internal dynamics and the vertical penetration of the plume is of prime importance.

Here we assume the cooling tower effluent to behave as a moist jet similar to isolated cumulus clouds. We compute the temperature and buoyancy changes in the plume using equation (2) which accounts for moist adiabatic ascent, the losses due to mixing and evaporation, and the possible additional heat derived from freezing of the effluent water. The computations are accomplished using vertical steps of 50 m intervals. Next, vertical velocities of the plume are obtained from equation (1). The local buoyancy is used to accelerate the plume while the weight of the water material and the entrainment of environmental air drag the plume and cause it to decelerate.

The most critical relation in this phase of the plume growth is the parameterization used to simulate the self-induced turbulence and hence entrainment. Our best information at this time is that the relations in equation (3) and (4) appear to be adequate. However, further field measurements will be necessary to confirm these relations.

Utilization of initial conditions (tower parameters), the atmospheric soundings, and equations (1-4) allow the computation of the vertical profile of the plume core and yield distributions of plume temperature, vertical velocity, liquid water content, and spread of plume radius. The horizontal tilt of the vertical plume due to wind drag is obtained using equation (5).

In the immediate vicinity of the tower (<2km) the diffusion of material from the edges of the plume is obtained using relations for σ_z and σ_y given in equation (7), where p_z and p_y are related to the half-angle spread, α, which has been determined empirically. Due to the high internal vertical velocities of the plume, local erosion near the height of the stack is small except for atmospheric conditions in which the winds are gusty and the environment is unstable. The emphasis on this portion of the model is the adequate determination of plume penetration heights as a function of the tower parameters, and the local meteorological conditions.

In the second phase of the model the distributions of effluent are dispersed downwind utilizing diffusion parameters which are related to the ambient turbulence. The main result is to diffuse the effluent near the maximum height of the plume (where the plume vertical velocity approaches zero and the horizontal tilt is large) in the downwind direction. This is equivalent to the standard stack-diffusion procedures which utilize equation (6) and Figure 2 and 3.

Thus, the model simulates in numerical form the buoyant rise of the plume, which is dragged by the weight of the material and depleted by the local entrainment of environmental air. The height at which the plume's accelerations are depleted and it is bent over by the horizontal wind is critical to the subsequent downwind spread of the material by ambient diffusion. The immediate or local diffusion is obtained by linear expansion of the local entrainment.

Throughout this portion of the model we have not discussed the effluent water particle distribution or microphysical processes influencing the plume. These relations will be discussed subsequently. Thus far, we view the effluent as small water droplets moving through the plume area and evaporating at the edges. The evaporated water mass is then diffused outward and contributes to raising the ambient water vapor content.

SECTION 3.0

SATURATION REQUIREMENTS

The major emphasis of this study is the concern over the modifications to the local and downwind environment as the result of the ejection and diffusion of the cooling tower vapor effluent. Specifically, the concern is to determine what conditions are necessary for the additional water from the tower to be of sufficient quantity to raise the local humidity to saturation, and hence lead to formation of fog and haze. In addition, the relative distances and volumes of the modification are of concern.

In order to properly define this aspect of the problem it is important to point out how the water vapor content necessary to saturate the atmosphere varies with temperature in the following manner:

Temperature - °C	Saturation Vapor Content - $g\ m^{-3}$
-20°	0.894
-10°	2.158
0°	4.847
+10°	9.401
+20°	17.300

Next, we will define the saturation deficit, q_d as the difference between the saturation mixing ratio at a given temperature, q_s, and the local ambient mixing ratio, q_e. Since the cooling tower effluent merely adds an incremental amount of water vapor, Δq, to the local atmosphere, the relation of importance for non-fogging is:

$$q_s - q_e = q_d > \Delta q$$

The importance of ambient temperature can now be seen since Δq, several kilometers downwind for typical cooling towers is the order of 0.1 to 0.5 g m^{-3}. If the ambient temperature is 10°C and the local humidity is 50% (q_e = 4.7 g m^{-3}) then q_d = 4.7 g m^{-3}. The addition of Δq = 0.2 g m^{-3} from a cooling tower would only change the humidity 3%. On the other hand, at -10°C and 90% humidity the addition of Δq = 0.2 g m^{-3} would lead to saturation. Thus, clearly the ambient temperature is of prime importance in determining the saturation deficit and thus the conditions for the tower effluent to contribute enough water vapor to cause fog development.

3.1 Properties of Natural Fogs

The formation of natural fog occurs through local cooling of the atmosphere by radiation losses, or through advective changes in temperature or moisture, with subsequent mixing leading to saturation. Table 1 summarizes the properties of "typical" fogs classified as radiation (inland) and advection (coastal). It can be seen that the typical water contents are .1 to .2 g m^{-3}, the droplet diameters average 10μ to 20μ, and particle concentrations vary from 40 cm^{-3} to 200 cm^{-3}. Around industrial areas where sources of pollution are prevalent droplet concentrations will tend to be higher.

The visual range or horizontal visibility in a fog is related to the average size of the fog droplets and the liquid water content by the following equation which was derived by Trabert in 1901.

$$V = \frac{C}{Q_c} \frac{\sum n_r r^3}{\sum n_r r^2} \cong K \frac{\overline{r}}{Q_c}$$

where Q_c = liquid water content, n_r = number of droplets of radius r, C = constant, and K = constant. Clearly the visibility decreases with increasing liquid water content and with smaller average droplet diameters.

Visibility reduction can begin at humidity values well below 100% due to water

TABLE 1

PHYSICAL FOG MODELS

Fog Parameters at the Surface	Radiation (Inland) Fog	Advection (Coastal) Fog
1. Average Drop Diameter	10 μ	20 μ
2. Typical Drop Size Range	5-35 μ	7-65 μ
3. Liquid Water Content	110 mg/m^3	170 mg/m^3
4. Droplet Concentration	200 cm^{-3}	40 cm^{-3}
5. Vertical Depth of Fog		
a. Typical	100 m	200 m
b. Severe	300 m	600 m
6. Horizontal Visibility	100 m	300 m

absorption by hygroscopic nuclei. Thus, the characteristics of the plume chemicals and other nearby industrial pollutants become important as intermixture with the water vapor plume may occasionally enhance the reduction in visibility.

3.2 Dropsize Characteristics of Cooling Towers

Very little observational data are available as to the dropsize characteristics of the cooling tower effluent. Ledbetter, (1969) has recently completed a laboratory study in which he attempted to simulate the cooling tower and subsequently measure the dropsize distributions generated.

Figure 4 is an example of the results obtained by Ledbetter. The distribution was found to be bi-modal with the first peak $<5\mu$ diameter (probably 2-3μ) and the second in the range 20-40μ. These experiments suggest that the water droplet size distribution of cooling tower effluents is similar to that of natural fogs. The reason for the distinct bi-modal distribution is not clear, however.

3.3 Parameterized Cloud Physics

To simulate the microphysical processes which occur in the moist ascent of the plume we have used the parameterized representation given by Kessler (1962, 1963, 1964). It is assumed that the development of water droplets can be divided into three phases: condensation (vapor to liquid), auto conversion (bulk process for changing the small condensed droplets to larger drops), and coalescence (the collection of droplets by the larger drizzle-size drops).

It is further assumed that the liquid water content of the plume can be represented by two groupings called cloud water (droplets with no appreciable fall velocity) and hydrometeor water (larger drops with fall speeds).

The change in cloud water is expressed as:

$$\frac{dQ_c}{dz} = -\frac{dq_s}{dz} - \frac{K_1\,(Q_c - a)}{w - V_t} - \frac{K_2\,Q_c\,Q_h^{0.875}}{(w - V_t)} - \mu(q - q_e + Q_c) \qquad (11)$$

In addition, the change in hydrometeor water is:

$$\frac{dQ_h}{dz} = \frac{K_1\,(Q_c - a)}{(w - V_t)} + \frac{K_2\,Q_c\,Q_h^{0.875}}{(w - V_t)} \qquad (12)$$

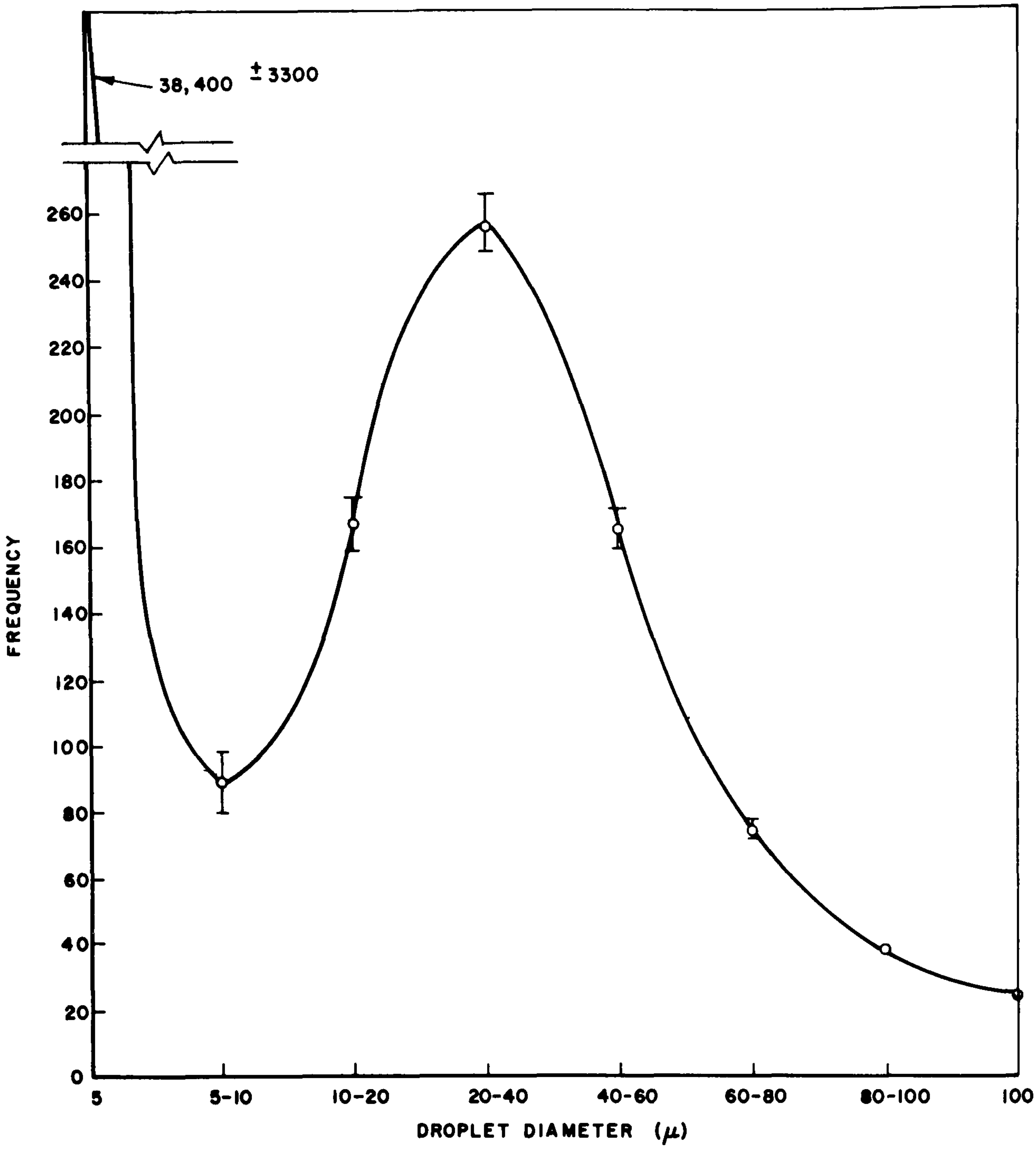

FIGURE 4. DROPLET SIZE DISTRIBUTION FROM LABORATORY EXPERIMENTS (LEDBETTER, et al, 1969)

where K_1, K_2, and (a) are coefficients relating to the microphysical conversion rates. The terminal fall velocity is expressed as:

$$V_t = 4.5Q_h^{0.125} \tag{13}$$

assuming the drop size distribution given by Marshall and Palmer (1948).

The model computes the total rainfall from the plume assuming that the fallout is developed (conversion to hydrometeor water) during the vertical ascent in the plume, and all converted hydrometeor water subsequently falls out of the plume somewhere downwind. The computed rainfall is the maximum possible, since evaporation below the plume is not included here. Thus, total rainfall is given by:

$$R_o = \int_o^z \rho Q_h \, dz \tag{14a}$$

which is approximated by:

$$R_o = \sum \rho R_{oi}$$

where

$$R_{oi} = \frac{(Q_{h2} + Q_{h1})\, dz}{2} \tag{14b}$$

This computation of "total rainfall" is useful in the original cumulus cloud model, as it gives an estimate of total precipitation during the lifetime of an isolated convective cloud. However, total rainfall is not really relevant to a continuing convective plume, as from cooling towers, except as a relative measure of precipitation potential. But it is also possible to convert the computed water content into rainfall rate and radar reflectivity. With the assumption that the hydrometeors are formed into a Marshall-Palmer drop size distribution, the following well-known relations are obtained:

$$Q_h = 72 \times 10^{-3} R_1^{0.88} \tag{15}$$

where Q_h is in g/kg and R_1, the rainfall rate, is in mm/hr; thus,

$$R_1 = 14\ Q_h^{1.136} \qquad (16)$$

and radar reflectivity Z, in units of mm^6/m^3 is

$$Z = 200\ R_1^{1.6}$$

At temperatures below 0°C, freezing is allowed to occur and release additional latent heat. The microphysical conditions are handled in a similar manner as above, but with different values for K_1, K_2, a, and V_t. Experience has shown that natural freezing of moist plumes in the atmosphere is unlikely until the ambient temperatures approach -20°C.

SECTION 4.0

CALCULATIONS

The computerized version of the model that has been presented was used to analyze the behavior and subsequent downwind spread of cooling tower plumes. The input data used were the tower parameters and the vertical distributions of ambient temperature, wind and relative humidity. A number of model runs were obtained to analyze the effects of various parameters on the general plume behavior.

4.1 Tower Parameters

Most computer runs were conducted using the following tower characteristics: Height = 50m, Velocity = 5.0 m/sec, Radius = 30m, and Saturated Temperature of 90°F. However, variations of these parameters were also studied. Figure 5 shows a typical profile of vertical velocity, and plume temperature along with the variation of plume radius as derived by the model. The effect of tower radius is shown in Figure 6. It can be readily seen that the penetration height is significantly greater for increasing tower radii. This is due to the fact that local entrainment and erosion is inversely proportional to the radius of the local updraft.

The height of the tower above ground was found to have a negligible effect on the penetration of the plume. This is due to the large buoyancy of the initial updraft, which overshadows any reasonable changes in tower height. The height of the tower must be considered when other structures are placed in the vicinity, however, because local turbulence generated by additional structures can change the above results.

Increases in tower temperature (saturation) and in the initial vertical velocity clearly increase the penetration height of the tower plume. Thus, in the design of towers, factors which promote greater penetration are first the tower radius, and secondly the effluent temperature and draft velocity.

The preceding results are directly relevant to natural draft cooling towers. The model is equally applicable to mechanical draft towers, since the only tower parameters that need to be specified are height, radius, velocity, and temperature. Since individual mechanical draft towers are limited in radius to approximately 10 meters or less, it can be seen from Figure 6 that mechanical draft towers generally have limited penetration height compared to the larger natural draft towers.

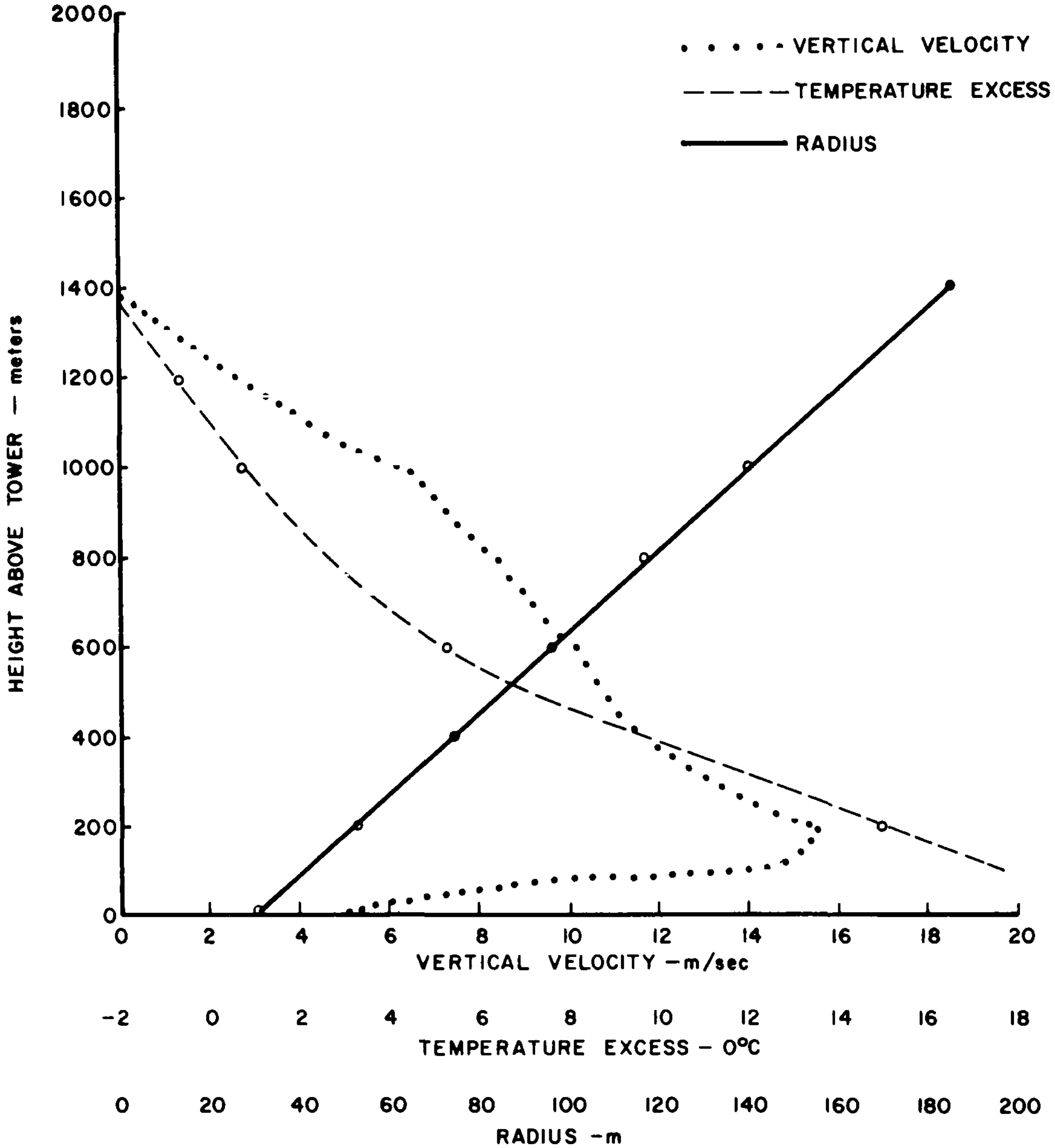

FIGURE 5. EXAMPLE OF NUMERICAL MODEL RESULT FOR A COOLING TOWER PLUME.

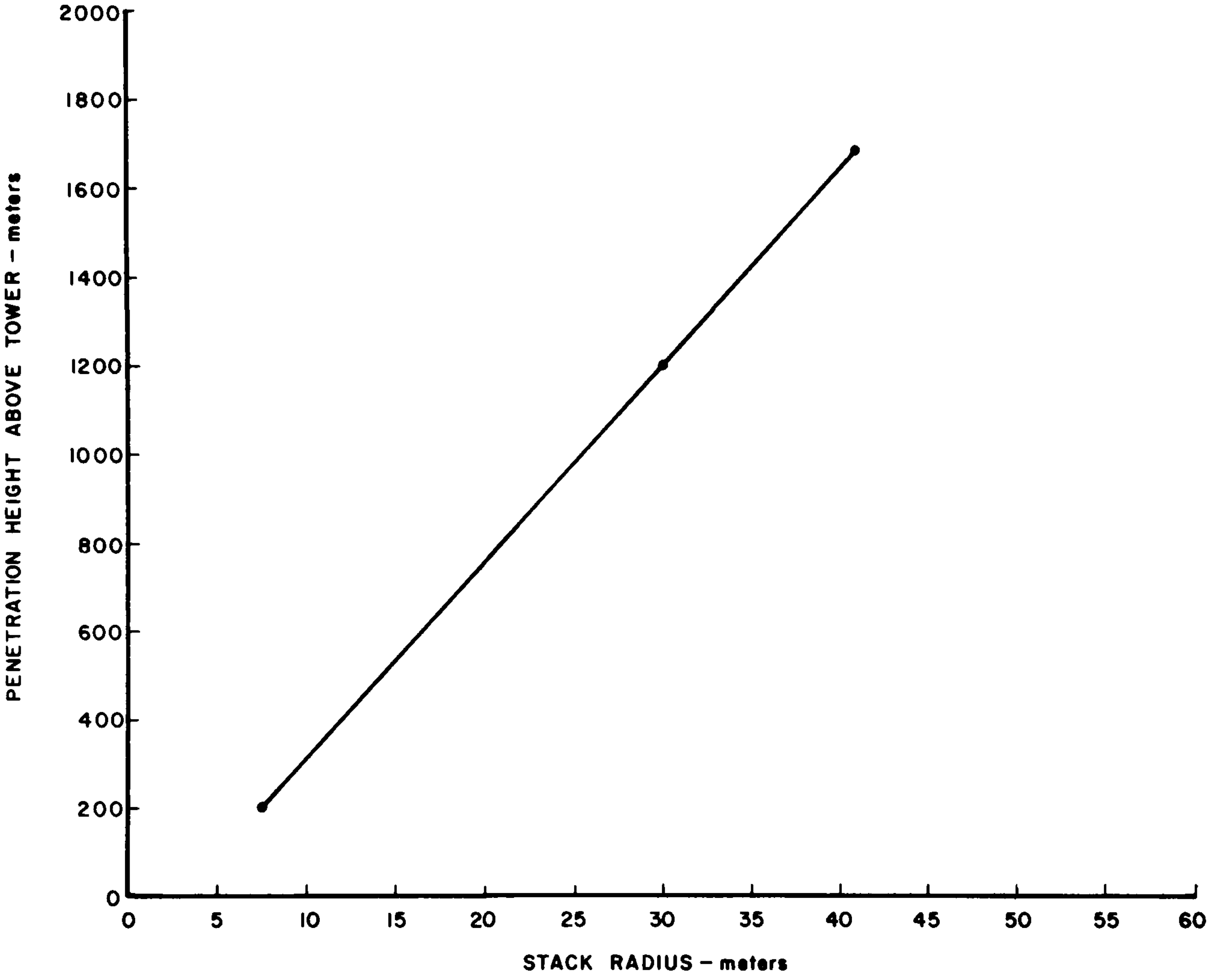

FIGURE 6. EFFECT OF STACK RADIUS ON PENETRATION HEIGHT

Several mechanical draft towers are usually used to provide a capacity equal to a single large natural draft tower. In general, the combined plume from the mechanical towers will have less vertical penetration than would a plume from a single hyperbolic tower having equal volume. The discrete small plumes may merge, but they do so with a large initial increase in entrainment, because of the dry environmental air from between individual towers. The modeling results indicate that mechanical draft towers as currently used will always result in less penetration and greater potential for adverse environmental effects than typical large natural draft towers.

4.2 Penetration Height of the Plume

Figure 7 shows the effects of atmospheric stability on the penetration height. Distributions are given for isothermal conditions, for a 5°C inversion and a 10°C inversion (up to 300m, then isothermal above, all for surface T=0°C). These curves clearly show that the initial buoyancy of the cooling tower plume is sufficient to penetrate many low-level inversions if the wind is not strong.

Wind and wind shear tend to accentuate the effects of stability and bend the plume over, reducing the total penetration height. This is due to the increased momentum exchange and the overall drag, causing the plume to yield to the horizontal momentum of the atmosphere. Calculations show that the plume core has vertical velocities in excess of 10 m/sec for the first few ten's of meters and then decelerates very rapidly to the plume top (see Figure 7). The large decelerations when coupled with horizontal wind drag result in decreasing the effective plume height and lead to increases of water vapor downwind, which under proper saturation deficit can yield fog formation.

4.3 Moisture Effects

As pointed out in Section 3.0, the moisture deficit in the atmospheric layer penetrated by the plume is of most significance in evaluating the adverse conditions caused by fogging downwind from cooling towers. Figure 8 shows a set of computations for a situation with a 10°C inversion and relative humidity in the plume layer varying from 50% to 100%. It is clear that the atmosphere's capacity to receive water fluxes typically generated by cooling towers is generally good for these temperatures and normal humidities. Thus, it can be clearly established that conditions suitable for fogging and downwind visibility effects from cooling towers are related to moisture deficits, which are controlled by the local relative humidity and temperature.

4.4 Case Studies

Several computer runs using actual atmospheric data have been made. These will be used here to further indicate the behavior of the cooling tower plume

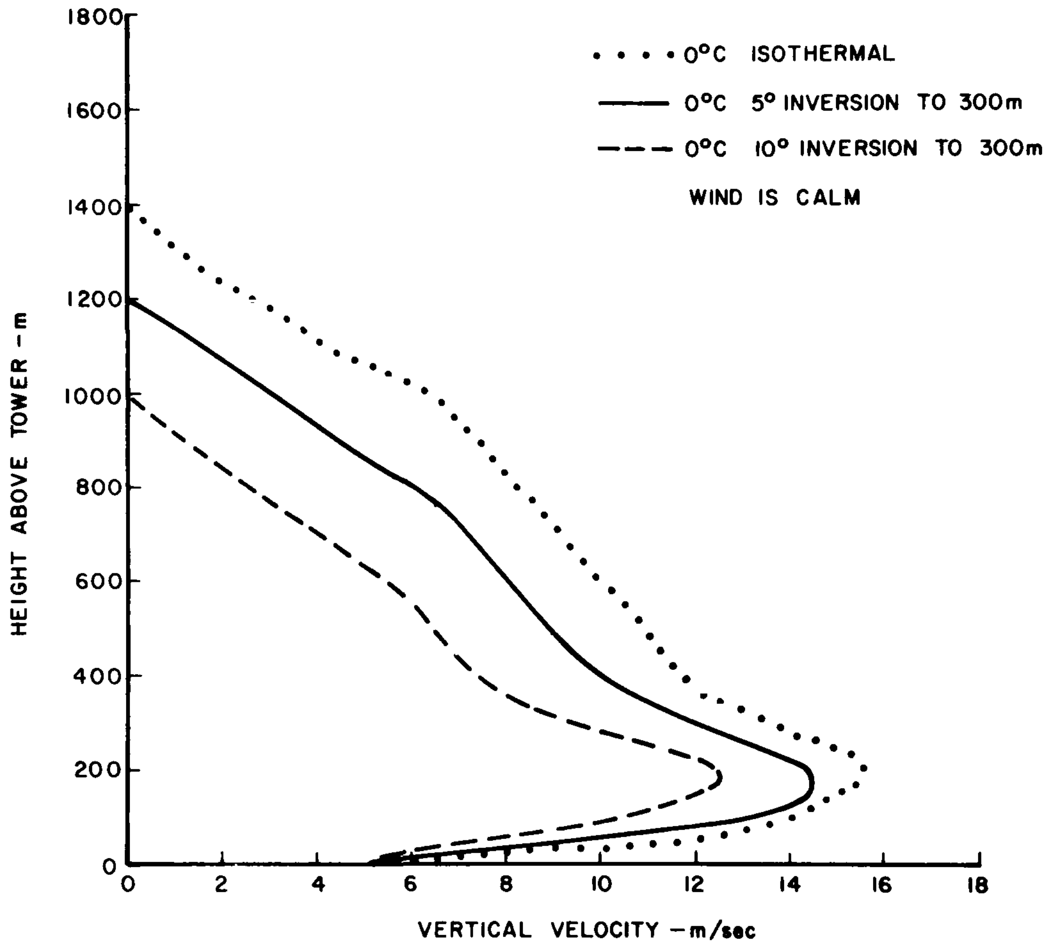

FIGURE 7. EFFECT OF STABILITY ON PENETRATION HEIGHT

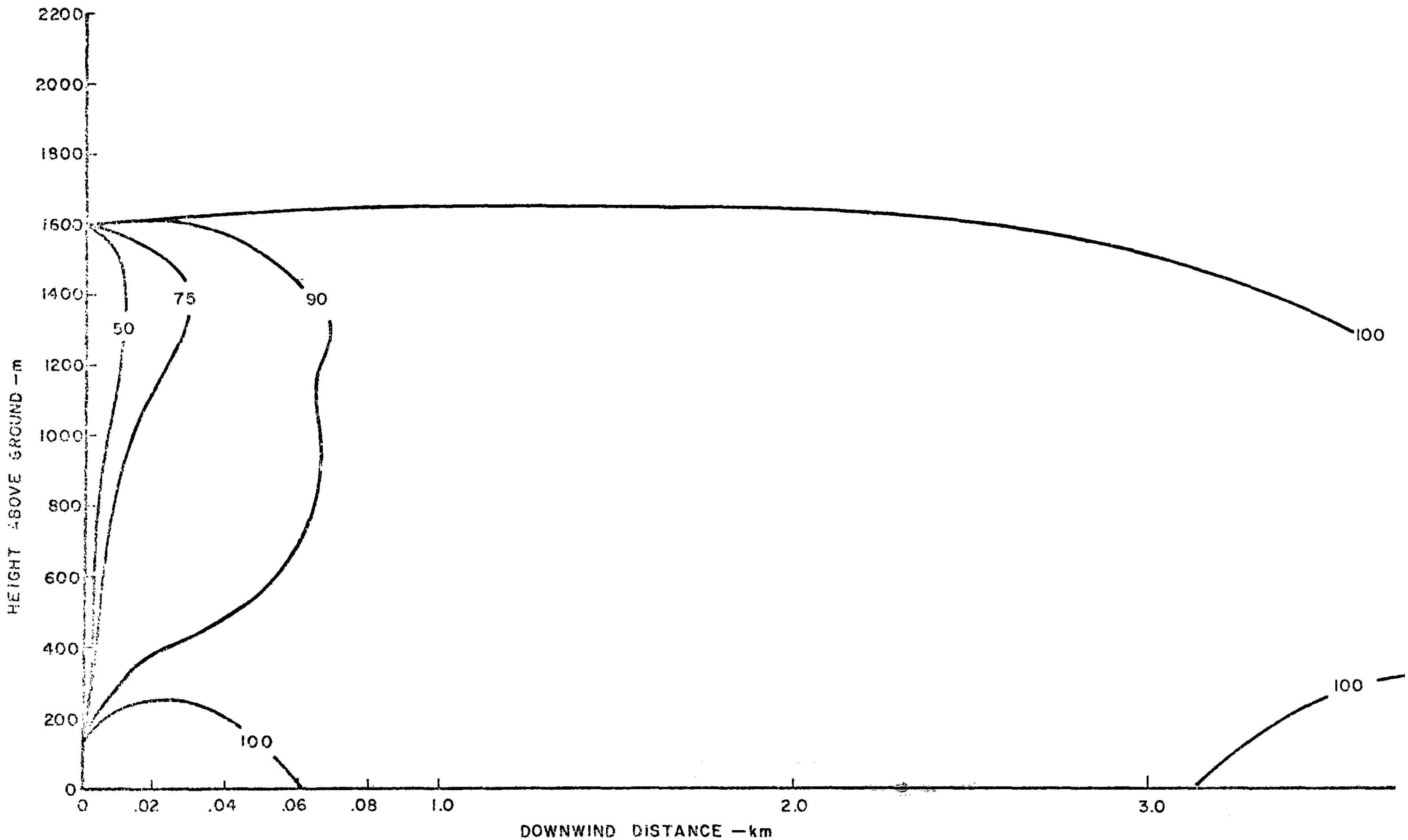

FIGURE 8. DOWNWIND SPREAD OF LIQUID-WATER CONTENT, 0.05 g/m^3 CONTOURS FOR VARIOUS VALUES OF RELATIVE HUMIDITY EXPRESSED IN %

The first case is for the Pittsburgh, Pennsylvania, sounding of 1200Z on February 28, 1968 (Figure 9). Conditions for the Keystone Site were utilized; Figure 10 shows the vertical profile of the plume parameters while Figure 11 shows the results of the downwind dispersion of the plume. Verification for this case was obtained through personal communications with Dr. Charles Hosler*, who observed that the height of the plume was at about 7000 ft. MSL and that the plume spread downwind for a considerable distance with very light snow flurries falling from the plume. Photographic measurements of the width of the individual tower plumes indicated a radius of about 300 meters near the top, which is in close agreement with the computed radius in Figure 10.

Another example is the Salem, Oregon, sounding for 1200Z on November 11, 1969 (Figure 12). This case is used to demonstrate the effects of a deep layer of atmospheric moisture which is capped by an inversion and dry air aloft. Figure 13 shows the distribution of liquid water downwind from a typical hyperbolic tower.

Many additional runs have been completed which contribute to the general understanding of the movement of moisture downwind from typical towers. They will not be presented here but the overall results are given in Section 4.7.

4.5 Topographical Effects

Since it is desirable to extrapolate the results of dispersion of cooling-tower effluents at one location to other locations, one of the necessary assessments that has to be made is the influence of topographical variations on plume dispersal. The influence of topography on the plume dispersal may occur in three ways; firstly, through an effect on the local wind speed and direction, secondly, through an effect on the characteristics of the atmospheric turbulence, and thirdly, through the distribution of local moisture sources.

Most of the analyses mentioned above apply to an idealized "infinite-plane" ground for which the roughness characteristics are assumed to be statistically uniform. Moreover, all ambient conditions are assumed to be uniform and parallel to the ground. Such conditions are seldom realized in the atmosphere and even over "gently rolling" terrain influences can occasionally be significant. A wind blowing more or less parallel to a valley may be "channeled" in a direction parallel to the sides of the valley.

*Dean, College of Earth and Mineral Sciences, Pennsylvania State University, University Park, Pennsylvania.

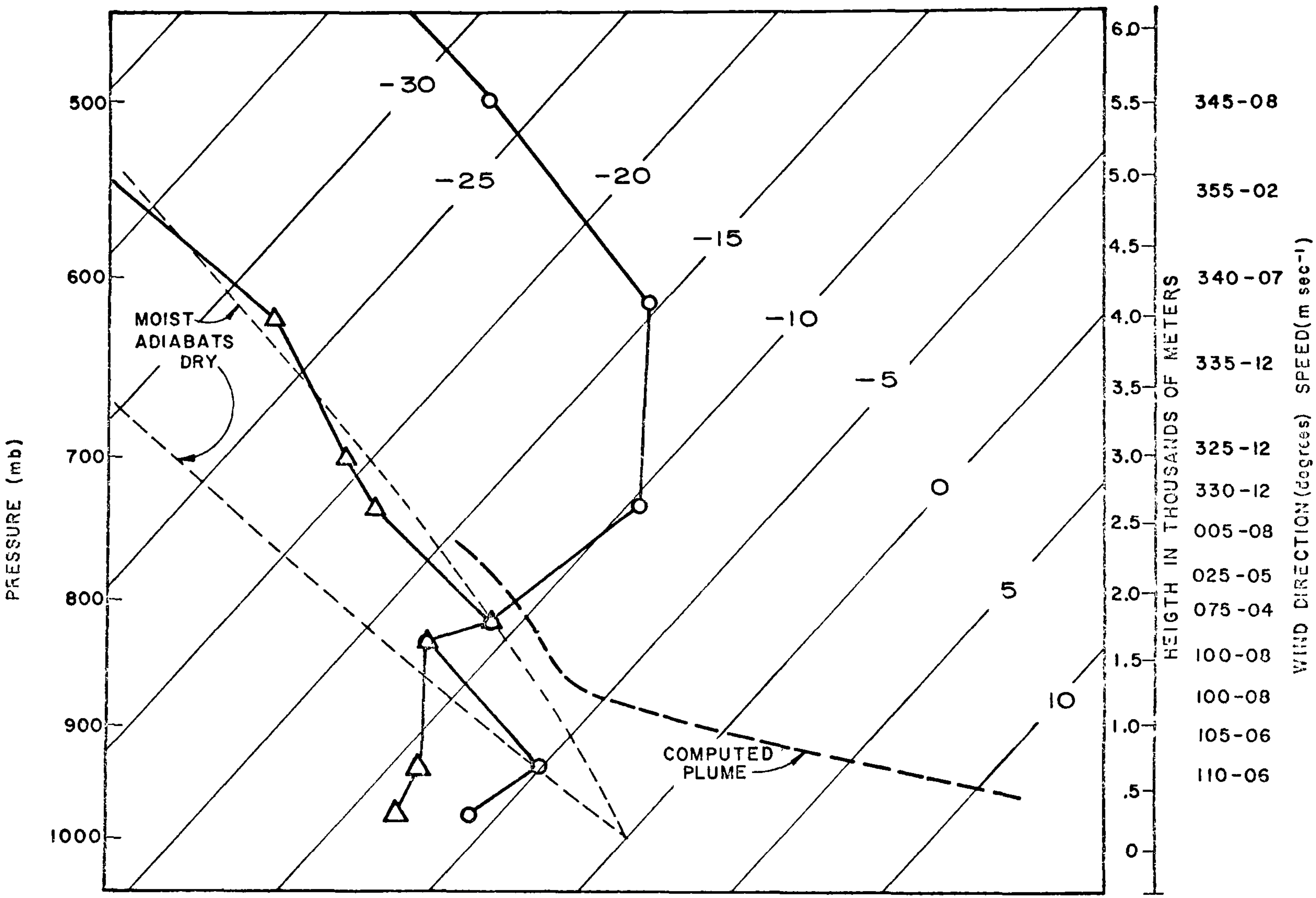

FIGURE 9. PITTSBURGH SOUNDING, FEBRUARY 28, 1968 1200 Z
O TEMPERATURE △ DEWPOINT

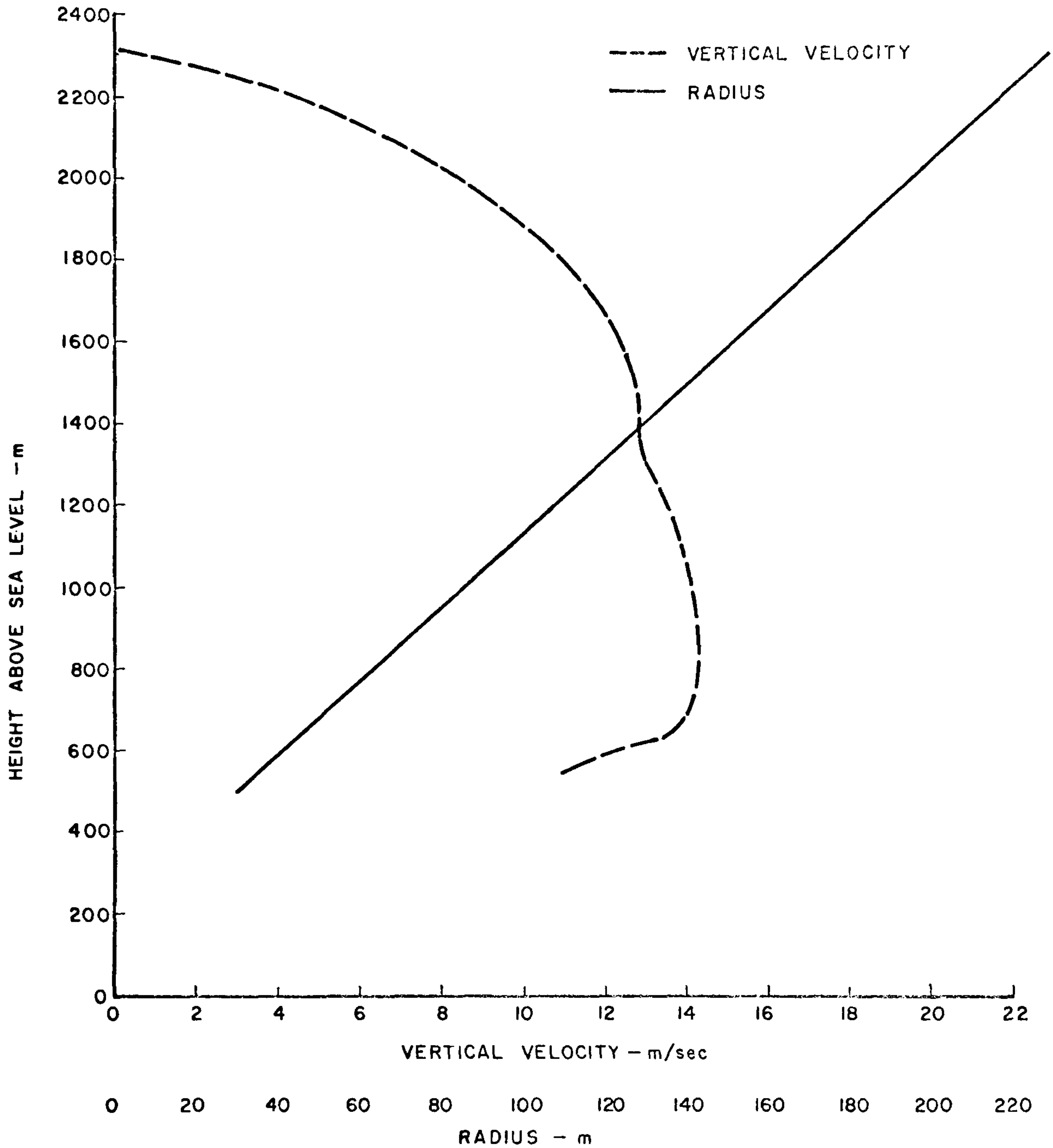

FIGURE 10. VERTICAL PROFILES FOR PITTSBURGH CASE

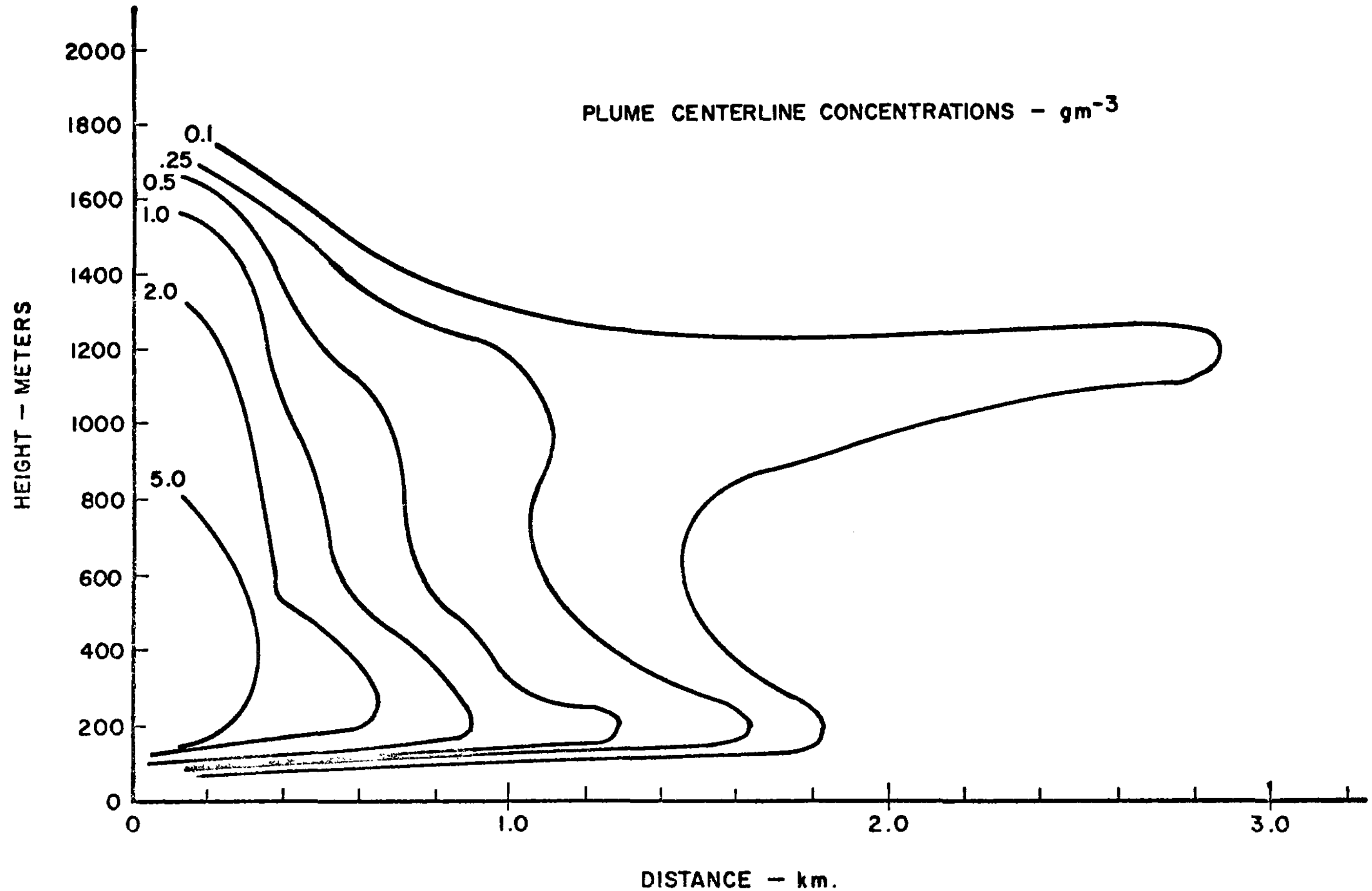

FIGURE 11. Predicted Downwind Liquid Water Content for Pittsburgh Sounding

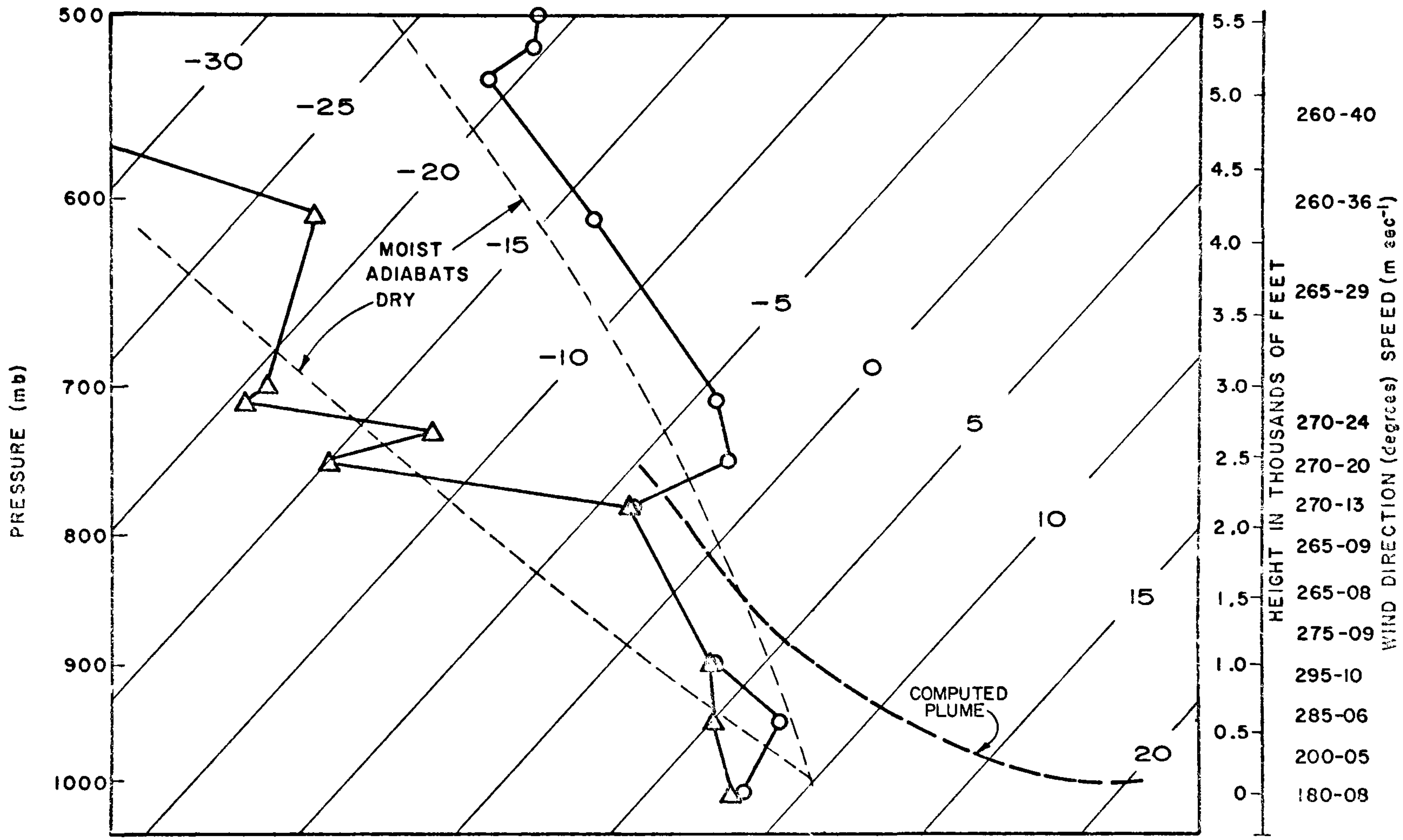

FIGURE 12. SALEM SOUNDING, NOVEMBER 11, 1969, 1200Z
O TEMPERATURE, △ DEWPOINT

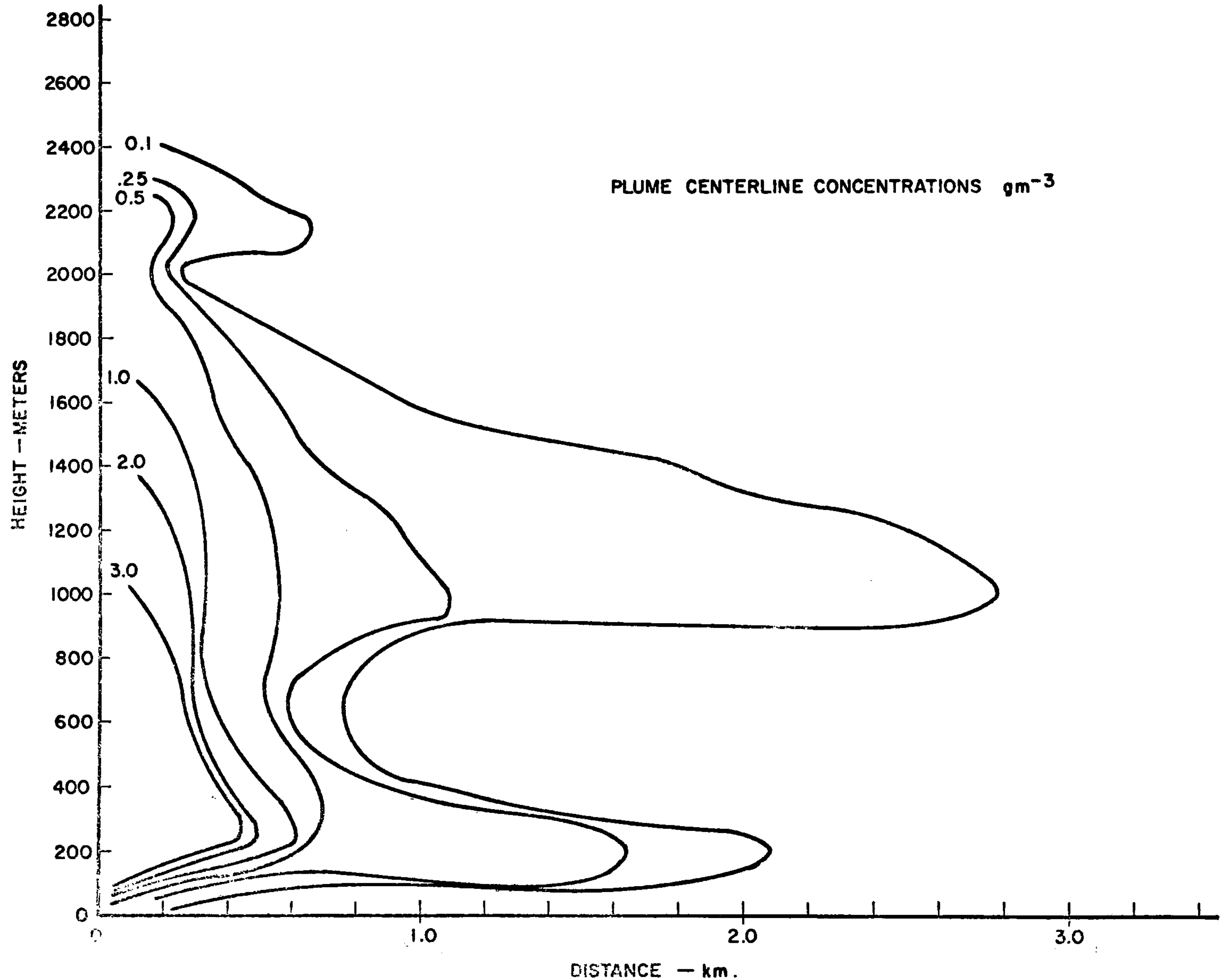

FIGURE 13. Predicted Downwind Liquid Water Content for SLE Fog Sounding - 11 Nov. 1969

Moreover, when a strong geostrophic wind is blowing parallel to the valley there may be a funnel effect, and this may influence the cooling-tower plume. When the geostrophic wind is blowing nearly normal to the axis of the valley, complex downwash and upwash effects may occur along the slopes of the valley. The effects of aerodynamic downwash on chimney plumes have been studied in laboratory wind tunnels. The cooling-tower plumes from sources located in valleys may also be influenced significantly by the katabatic and anabatic winds due to differential cooling or heating.

Topographical features may also influence the dispersion of cooling-tower effluents through their effect on the characteristics of the ambient atmospheric turbulence. Topograhical features may cause different rates of heating at different places, and thus create convective turbulence.

Local sources of water vapor such as rivers, lakes, ponds, etc. will influence the local saturation deficit and hence be of importance in determining the cooling tower effects.

4.6 Summary of Calculations

From the series of model runs the following results were obtained:

(a) For a given set of atmospheric conditions, increases in the radius of the tower, the saturation temperature, and the stack velocity contribute to increasing the penetration height of the tower plume. The height of the tower above ground has a negligble influence on penetration height.

(b) For a given set of tower parameters, stability influences the penetration height as does the bending-over effect of wind and wind shear. The most significant parameter in determining the vertical plume dynamics is the entrainment relation, which is determined by the stack radius and the angular spread of the plume. Environmental relative humidity is important in controlling the evaporative cooling at the plume edges and hence the rate of depletion of thermal buoyancy.

For most cases of light winds (< 3 msec^{-1}), penetration heights of 300-1000 meters are obtained but for stable air with strong wind, the penetration heights are reduced to a few hundred meters.

(c) The saturation deficit of the atmosphere clearly controls the downwind spread of the ejected liquid water. Except for cases where the relative humidity approaches 100%, downwind propagation is limited to the colder temperature periods typical of fall and winter (< 0°C).

Under calmer winds, penetration is sufficient and little problem is to be expected near the tower. However, stability can limit penetration such that strong winds can cause looping. On the other hand, typical moisture deficits occurring with windy conditions may be sufficient to completely eliminate the appearance of the plume in a very short distance.

In summary, moderate winds with stable lapse rates and low moisture deficits (high humidity and generally temperatures colder than about 0°C) provide proper conditions for possible fogging and adverse modifications downwind of typical cooling towers.

4.7 Prevention of Adverse Conditions by Seeding

It is well known that seeding of stable liquid-water clouds with properly sized particles of sodium chloride or other hygroscopic materials can modify the drop-size distribution in the clouds and, under certain conditions, lead to an improvement in visibility. The physical process is one of producing an initial small population of relatively large droplets. The hygroscopic particles grow faster and have a larger equilibrium size than natural droplets which have formed on less hygroscopic condensation nuclei. Given the artificially broadened drop-size distribtuion, the large droplets continue to grow to precipitation-particle size.

In terms of our cooling-tower model, the affect of seeding would be to change the conversion constants, K_1 and K_2 in eqns. (11) and (12). The end result would be a more rapid conversion from cloud water to hydrometeor water. (Conversely, seeding with very large numbers of uniformly small hygroscopic particles will produce a cloud of large numbers of small droplets with no large droplets. Such a cloud, similar to many natural fogs, is extremely stable with very slow conversion to precipitation.)

The beneficial affects on visibility to be obtained by broadening the drop-size distribution can readily be seen from Trabert's equation for visibility given previously. An increase in the mean droplet radius, for constant liquid water content, leads directly to an increase in horizontal visibility. Any subsequent decrease in water content due to precipitation further improves the visual range.

Results of the model calculations and limited observations from cooling towers suggest that where tower plumes have large vertical penetration, natural conversion will take place, leading to formation of precipitation particles. With more limited vertical rise, less liquid water is condensed, and a narrower drop-size distribution such as shown in Figure 4 would be expected.

When persistent stable plumes form downwind of cooling towers, there is little question that the visibility in the plume could be improved by seeding with properly sized hygroscopic particles. It is less clear that routine seeding in a wide range of meteorological conditions would be advantageous. Certainly the production of fallout (precipitation) downwind of the tower would not ordinarily be regarded as a beneficial effect. Further, an increase in the number of large droplets will usually lead to longer travel times and distances before the plume completely dissipates.

In the case of serious fogging episodes from towers, seeding offers a technique for reducing the adverse effects. For optimum results the seeding should probably be done downwind of the tower where the effects are most serious, rather than at the tower itself. The most efficient practical methods for performing the seeding would have to be determined by experiment. Such experiments at a tower location where adverse effects are relatively frequent are recommended.

The above discussion has been directed toward warm (above 0°C) plumes. Supercooled tower fogs could be effectively dissipated by seeding with freezing nuclei such as silver iodide, or with dry ice. In tower locations where fogs are occasionally formed at temperatures lower than about -5°C, silver iodide seeding of the plume at the tower could be utilized in problem situations to change the fog into ice crystals which would fall out in a relatively short travel distance.

SECTION 5.0

REGIONAL CHARACTERISTICS

Based on the results obtained from the model computations, it is now possible to investigate various geographical regions of the United States in order to rate these areas in terms of the potential for adverse effects downwind of cooling towers. The model results show that typical summer conditions with warm temperatures (high moisture deficit) and unstable lapse rates generally will not lead to downwind propagation of a cooling tower plume. The prime season of interest is the late fall and winter where stable air and colder temperatures are prevalent.

Statistical data necessary for proper definition of low-level moisture deficit, stability, and general dispersion is typically difficult to obtain on a regional basis. For the purposes of this study we have used the following three sources as a means of evaluating the geographical potential for cooling tower production of fog:

(a) "Fog Frequency in the United States", A. Court, and R. Gerston, The Geographical Review, p. 545.

(b) "Low-Level Inversion Frequency in the Contiguous United States", C. R. Hosler, Monthly Weather Review, Vol. 89, No. 9, September 1961, p. 319-339.

(c) "Estimates of Mean Maximum Mixing Depths in the Contiguous United States", G. C. Holzworth, Monthly Weather Review, Vol. 92, No. 5, May 1964, p. 235-242.

A qualitative classification for the potential for adverse cooling tower affects has been made based on the following criteria:

(a) High Potential: Regions where heavy fog is observed over 45 days per year, where during October through March the maximum mixing depths are low (400-600m), and the frequency of low-level inversions is at least 20-30%.

(b) Moderate Potential: Regions where heavy fog is observed over 20 days per year, where during October through March the maximum mixing depths are less than 600m, and the frequency of low-level inversions is at least 20-30%.

(c) Low Potential: Regions where heavy fog is observed less than 20 days per year, and where October through March the maximum mixing depths are moderate to high (generally >600m).

Figure 14 is a depiction of the results of this evaluation for the United States. The main areas of high potential are the West Coast, Pacific Northwest, the Appalachian Valleys, and the far Northeast Coast. The areas of moderate potential are the Gulf and Atlantic Coasts, the Great Lakes region, and leeward of the Continental Divide.

From the data obtained with the model calculations, these areas have the most suitable climatic conditions for producing adverse effects downwind from cooling towers. However, since the local microclimate of a given region can vary considerably from the larger-scale features, each site will have to be evaluated on the basis of the local parameters. As pointed out in Section 4. 6, local topographic influences can be significant and will have to be included in any site evaluation. Valleys with local moisture sources (ponds, rivers, lakes) will obviously increase the fogging potential. On the other hand, tops of hills or raised areas with greater roughness will disperse the effluent more efficiently.

5. 1 Site Evaluation

To facilitate further evaluation of the cooling tower modifications it will be necessary to derive certain data as statistics for given sites. From the modeling concepts, the following meteorological parameters are needed for site evaluation:

(1) Temperature measurements from the surface to heights several hundred meters in excess of the expected plume penetration.

(2) Relative humidity as a function of height.

(3) Wind speed and direction as a function of height.

These data, which provide input conditions for use of the numerical model, are generally only available from standard radiosonde stations, and are only taken every 12 hours. Thus, the standard U. S. Weather Bureau data are not totally adequate for proper evaluation. In addition, observations on local terrain effects such as valley winds, sea breeze, lake effects, etc., will have to be obtained.

5. 2 Specific Criteria

It would clearly be advantageous to have a quantitative set of criteria that could be utilized in evaluating potential cooling tower sites. Unfortunately, such criteria could not be derived within the scope of the present study. Because the behavior of a tower plume depends on the interaction of several tower characteristics (radius, updraft, velocity, and temperature) and the ambient meteorological conditions through a depth of atmosphere, no simple

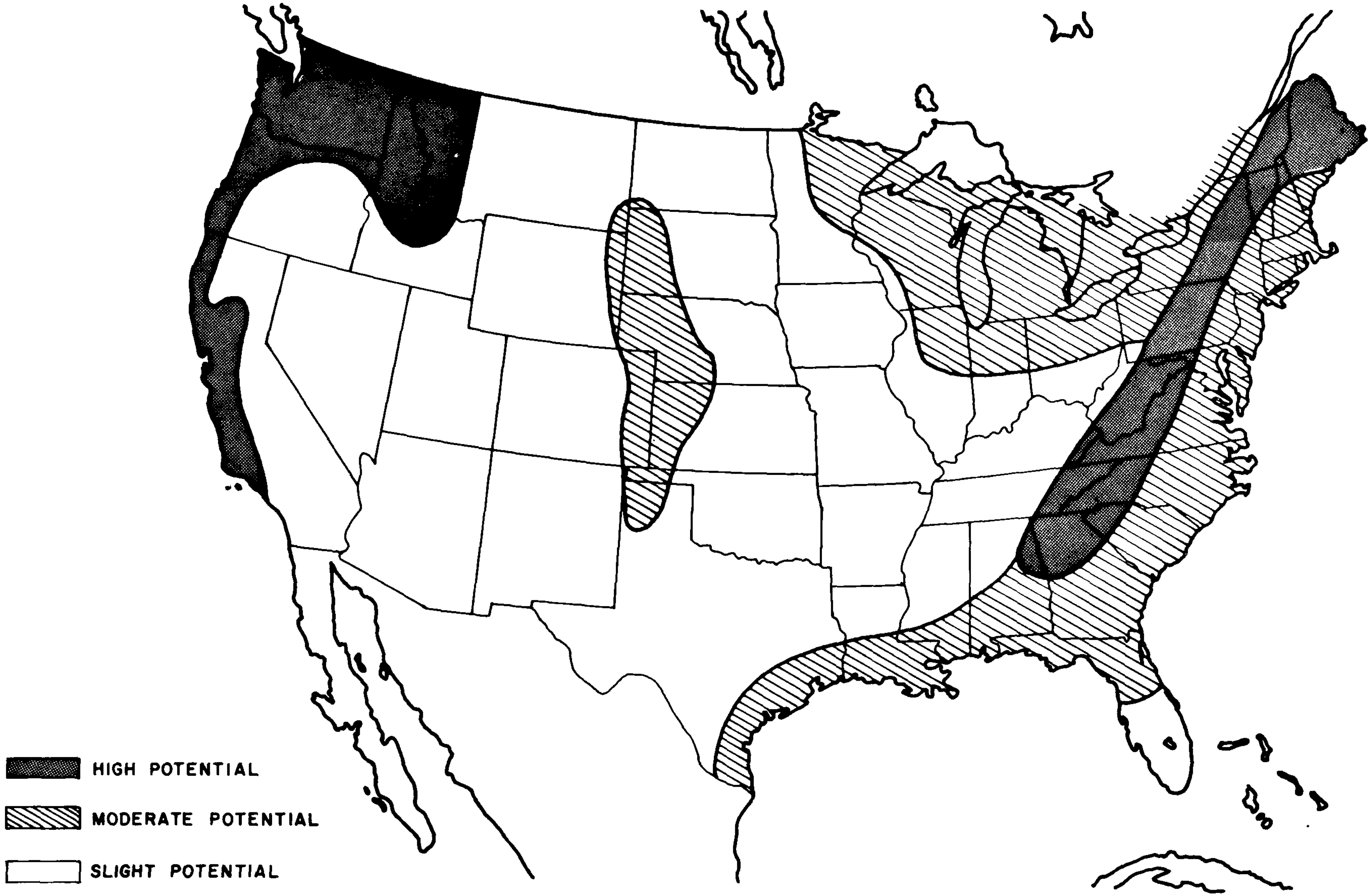

FIGURE 14. GEOGRAPHICAL DISTRIBUTION OF POTENTIAL ADVERSE EFFECTS FROM COOLING TOWERS, BASED ON FOG, LOW-LEVEL INVERSION AND LOW MIXING DEPTH FREQUENCY.

direct parameter could be determined which effectively measured these complex interactions. Such a parameter could be derived empirically by making a large number of model runs. However, far more runs would be needed than could be done in this preliminary study.

General geographic criteria more quantitative than those represented by Figure 14 could be derived by processing historical weather data from existing radiosonde stations. Such an evaluation should determine, from actual atmospheric soundings:

(a) mean moisture deficit, surface to 2000 feet

(b) mean wind speed, surface to 2000 feet

(c) potential temperature gradient, surface to 2000 feet

The 2000 feet height is somewhat arbitrary, but is selected on the basis that if the plume penetrates to at least that height, and small moisture deficits do not exist below that height, there can be reasonable assurance that no serious adverse plume effects will occur at the ground.

Given a sizeable statistical sample of soundings from a given radiosonde station, the frequency of occurrence of unfavorable values of these three quantities could be determined.

The recommended evaluation procedure for a specific planned tower site is as follows:

(a) From local surface data and upper-air soundings, determine the frequency of occurrence of low-level inversions and lower atmosphere stability (potential temperature gradients).

(b) Determine the frequency distribution of wind speed and direction.

(c) Utilize the numerical plume model to calculate penetration heights for the most common (and for potentially troublesome) wind and stability conditions. Actual tower characteristics, or a range of planned characteristics should be used as input.

(d) Evaluate the climatological frequency of moisture deficits through the computed plume rise intervals.

(e) The magnitude and relative frequency of moisture deficits in the plume layer will be direct measures of the potential for persistent plume fogs.

(f) The model should be further utilized to predict fog extent and density in the most unfavorable situations.

(g) Finally, consideration should be given to any purely local small-scale factors due to topography, moisture sources, etc., which would modify the fog potential indicated by the model.

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LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

c_p	specific heat of air at constant pressure (cal g^{-1} deg^{-1})
c_y, c_z	Sutton dispersion parameters in the horizontal and vertical directions ($m^{n/2}$, where n is a dimensionless constant) ($n = 2p/1+p$)
dz	(equation 2) height increment where freezing occurs (m)
g	acceleration of gravity (m sec^{-2})
K_1, K_2	Conversion coefficients in parameterized cloud physics equations (sec^{-1})
L	Latent heat (cal g^{-1}), L_e evaporation, L_f freezing, L_s sublimation
M	Mass of cloud (plume) air (g)
N_r	Number of cloud droplets of radius r per unit volume
P	Atmospheric pressure (dynes cm^{-2})
p	Power-law wind profile exponent (dimensionless)
p_y, p_z	Proportionality constants in horizontal and vertical directions for linear (short-range) growth of plume standard deviations (dimensionless)
Q*	Source strength (release rate) of effluent from tower (g sec^{-1})
Q	Liquid water content of cloud (plume) (g of water per g of air), Q_c cloud liquid water, Q_h hydrometeor water. (See equations 11 and 12.)
q	Mixing ratio (total water, vapor and liquid, per unit mass of air) (g water per g air). In the text, q is sometimes used interchangeably with the absolute humidity, $q\rho$, the mass of water per unit volume of air.
q_e	mixing ratio in environment
q_s	saturation mixing ratio (a function of temperature)

q_d	$q_s - q_e$
Δq	additional mixing ratio at a given point due to effect of cooling tower.
R	Gas constant for air (erg g^{-1} deg^{-1}) (eq. 2)
R	Radius of plume (m)
R_s	Radius of plume at top of cooling tower (m)
R_o	Total rainfall (g m^{-2})
R_1	Rainfall rate (mm hr^{-1})
r	Radius of cloud droplet (microns -μ)
T	Absolute temperature (deg K)
T_e	Air temperature in environment of plume
T_v	Virtual temperature $T_v = T(1 + g/\epsilon)/(1 + g)$, a ficticious temperature at which dry air would have the density of actual moist air
T_{ve}	Environmental virtual temperature
t	Time (sec)
U, u	Horizontal wind speed (m sec^{-1})
U_p	Horizontal wind speed in tower plume
U_e	Horizontal wind speed in environment
U_1	Horizontal wind speed in plume before mixing with environment
U_2	$= U_p$, Horizontal wind speed in plume after mixing
u_1	Horizontal wind speed at a reference height
V_t	Terminal fall speed of cloud droplets or precipitation particles (m sec^{-1})
w	Vertical velocity of air in plume (m sec^{-1})

w_p	Calculated vertical velocity before wind shear is taken into account (value obtained from eqn 1)
x, y, z	Cortesian space coordinates
X	Concentration of material in plume (from diffusion equation) (g m^{-3})
Z	Radar reflectivity (mm^6 m^{-3})
z_e	Maximum height of penetration of plume
α	Angle between plume axis and the outer edge of rising, spreading plume (half-angle of plume spread)
θ	Angle between the vertical and the center-line (axis) of rising plume. (Tilt of plume due to horizontal wind)
ϵ	Ratio of the molecular weights of water and dry air
ρ	Density of air (g m^{-3})
ρ_e	Density of air in plume environment
μ	Entrainment parameter (eqn 3) (m^{-1})
T_y, T_z	Standard deviations of the spatial distribution of material in the plume in horizontal (y) and vertical (z) directions. (m)

APPENDIX A

COMPUTER PROGRAM

MANUAL FOR EG &G COOLING TOWER MODEL

(Adapted From Penn State Cloud Dynamics Model MOD 2)

I. Introduction

The Steady State Cumulus Dynamics model was developed to provide an on-site evaluation of the seedability of cumulus clouds in the field. The model has steadily evolved to its present state where it is now being used by several organizations involved in cloud physics research. The modification for cooling tower plumes was developed by EG &G under the present contract.

The computer program is written in Fortran IV. A listing of the program and subroutines is given at the end.

II. Model Structure

The model can be subdivided into four sections: interpolation, calculation, diffusion, and output.

In the interpolation section, a standard radiosonde sounding is broken down into a sounding at constant height increments.

The calculation section of the program carries out the model calculations producing profiles of vertical velocity, cloud temperature, temperature excess, cloud mixing ratio, cloud and hydrometeor liquid water content, radar reflectivity factor, and updraft radius.

The diffusion subroutine takes the calculated plume properties and computes the spread of water in three dimensions due to atmospheric diffusion.

The last section outputs the profiles in tabular form and prints a summary table of total rainfall, duration, cloud top height, and cloud top temperature and updraft area for all boundary conditions put into the model.

III. Input Parameters

The model requires, as input data, the following:

1) A standard radiosonde sounding of pressure (mb), temperature (°C), relative humidity (%), and, if desired, wind speed (m/sec) starting at the top of the cooling tower.

2) The vertical grid interval desired. (Meters)

3) The cooling tower height (cloud base). (KM)

4) The entrainment rate parameter (A in the relationship μ = A/updraft radius)

5) The conversion and collection rates for temperatures above and below the ice nucleation temperature.

6) The initial updraft radius. (KM) (diameter of top of cooling tower)

7) The ice nucleation temperature. (°A)

Several other input parameters are also required as keys to the options of the program.

IV. Options

The model was originally constructed with maximum versatility in mind. For this reason there are some extra input parameters and several extra steps in the program that allow utilization of model options. Several of these are not relevant to the cooling tower application, but they will be briefly described so that the complete program can be understood.

In the interpolation section, either only the initial sounding, or both the initial and interpolated soundings may be printed out. The key for this option is a parameter, JN. If JN = 0, only the input sounding is printed.

In the model calculation section there are four options.

If desired, the model can be run with or without a correction of the vertical velocity due to shear of the horizontal wind. The parameter NS is the key for this option. If the calculations are desired without the wind shear correction (as would be the case when wind data are not available) the parameter NS is set to the word "No". If the wind shear correction is desired, the parameter NS is left blank.

The original model calculation could be run with the updraft radius varying with height as dictated by continuity considerations (as the vertical velocity increases with height, the updraft decreases) or with the updraft radius constant with height. The parameter for this option is NCR (positive for constant radius, zero for variable radius). For the cooling tower program, a linear increase of radius with height is specified in the program, and the variable radius option should always be used.

In the energy equation used to determine the vertical velocity, the source term is, of course, the cloud buoyancy. This buoyancy, however, must be reduced by the weight of the liquid water being carried aloft. It is still unclear how much liquid water should be carried aloft. An option is allowed here. If the parameter, LWC, is set to zero, the total liquid water (cloud water and hydrometeor water) is used to retard the buoyancy. If the parameter, LWC, is set to 1, the buoyancy is retarded by the weight of the cloud water only, whenever the terminal velocity of the median volume drop diameter of the hydrometeor water (assumed distributed in a Marshall-Palmer distribution) exceeds the vertical velocity in the cloud. If the terminal velocity does not exceed the vertical velocity, the total water is again used to retard the buoyancy.

The model was originally constructed to be run with a series of different updraft radii and ice nucleation temperatures, to simulate natural and artificially stimulated clouds of different sizes. Under these conditions it is unnecessary to carry out the calculations starting from cloud base each time. If the program is run with two successive initial conditions, differing only in the ice nucleation temperature (to see the difference between a seeded and non-seeded cloud of the same size), it is only necessary to start the calculations from cloud base for the seeded case (higher nucleation temperature). When the non-seeded case is run, the calculations need only start from the level of ice nucleation in the seeded case. The profiles below this level are the same for seeded and non-seeded cases. For the cooling tower application, where tower parameters or environment conditions may be changed, it is necessary to start the calculations from cloud base on every calculation

The model handles this choice of cloud base or ice nucleation level with the parameter NBS. If NBS is set to 1, the calculations will start at cloud base. If NBS is set to zero, the calculations start at the first level below the ice nucleation level of the previous run. The profiles below this level are taken from the previous run.

V. Input Formats

For every run, the following input cards are needed:

1) A Sounding Identifier card

2) A Ground Level Sounding Card

3) One card for each level of the input sounding

4) A blank card

5) A boundary conditions card for each different boundary condition

6) A run termination card

The formats for these cards are given below:

1) Sounding Identifier Card

Columns 1-78 Any identifying information (alphabetic or numeric.

Columns 79-80 Key JN (0 or blank - only input sounding printed. 1 or -1 - input and interpolated sounding printed)

2) Ground Level Sounding Card (conditions at tower exit level)

Columns 1-10 Pressure (mb)

Columns 11-20 Temperature (°C)

Columns 21-30 Effluent Temperature (°C), EFT

Columns 31-40 Relative Humidity (100%)

Columns 41-50 Height (meters)

Columns 51-60 Wind Speed at Cloud Base (m/sec)

Columns 71-80 Vertical grid increment (meters)

3) Input Sounding Cards (one for each level)

Columns 1-10 Pressure (mb)

Columns 11-20 Temperature (°C)

Columns 21-30 Blank

Columns 31-40 Relative Humidity (%)

Columns 41-50 Wind Speed (m/sec)

4) Blank card to separate input sounding from Boundary Condition Card.

5) Boundary Condition Cards (up to 30)

Column 1 — Updraft Radius option (NCR)
Blank - variable updraft radius
1 - Constant Updraft radius

Column 2 — Cloud Base Option (NBS)
Blank - Calculations start from ice nucleation level
1 - Calculations start from cloud base

Column 3 — Buoyancy Option (LWC)
Blank - Buoyancy decreased by weight of total water (cloud water and hydrometeor water) throughout cloud
1 - Buoyancy decreased by weight of cloud water only when terminal velocity ≥ vertical velocity

Columns 4-7 — Entrainment Rate parameter - (A1)
Entrainment Rate (μ) = A1/Radius

Columns 8-17 — Conversion Rate below Ice Nucleation Level (AK1)
Cloud water is converted to hydrometeor water at a rate AK1 below ice nucleation level

Columns 18-27 — Conversion Rate above Ice Nucleation level (AKF1)
Cloud water is converted to hydrometeor water at a rate AKF1 above ice nucleation level

Columns 28-37 — Collection Rate below Ice Nucleation level (AK2)
Hydrometeors collect cloud water at a rate AKF2 above ice nucleation level

Columns 38-47 — Collection Rate above Ice Nucleation level (AKF2)
Hydrometeors collect cloud water at a rate AKF2 above ice nucleation level

Columns 48-57 — Cooling tower (Initial Updraft) Radius (CRAD)
Radius in km

Columns 58-67 — Ice Nucleation Temperature (TF)
Temperature in °A

Columns 68-69 Vertical Wind Shear option (NS)
NO - No correction due to vertical shear of horizontal wind
Blank - Invoke correction due to vertical shear of horizontal wind

Columns 70-73 Vertical Plume Velocity (W)
Velocity in meters/sec.

6) Run Termination Card

Column 2-1

A Sample set of input cards is given below:

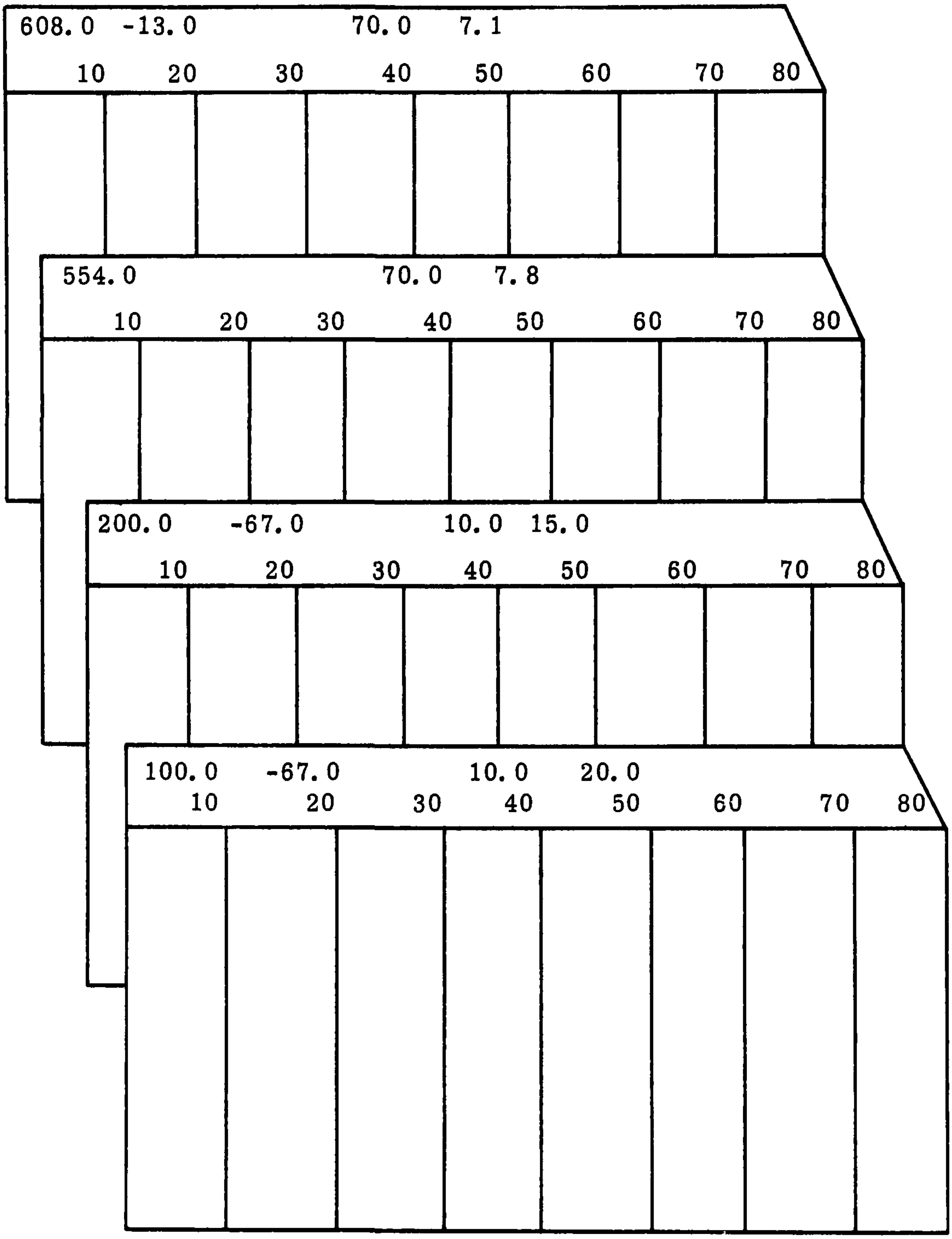
1) Sounding Identifier Card

Hypothetical Sounding	0 1
1	787980

2) Ground Level Sounding Card

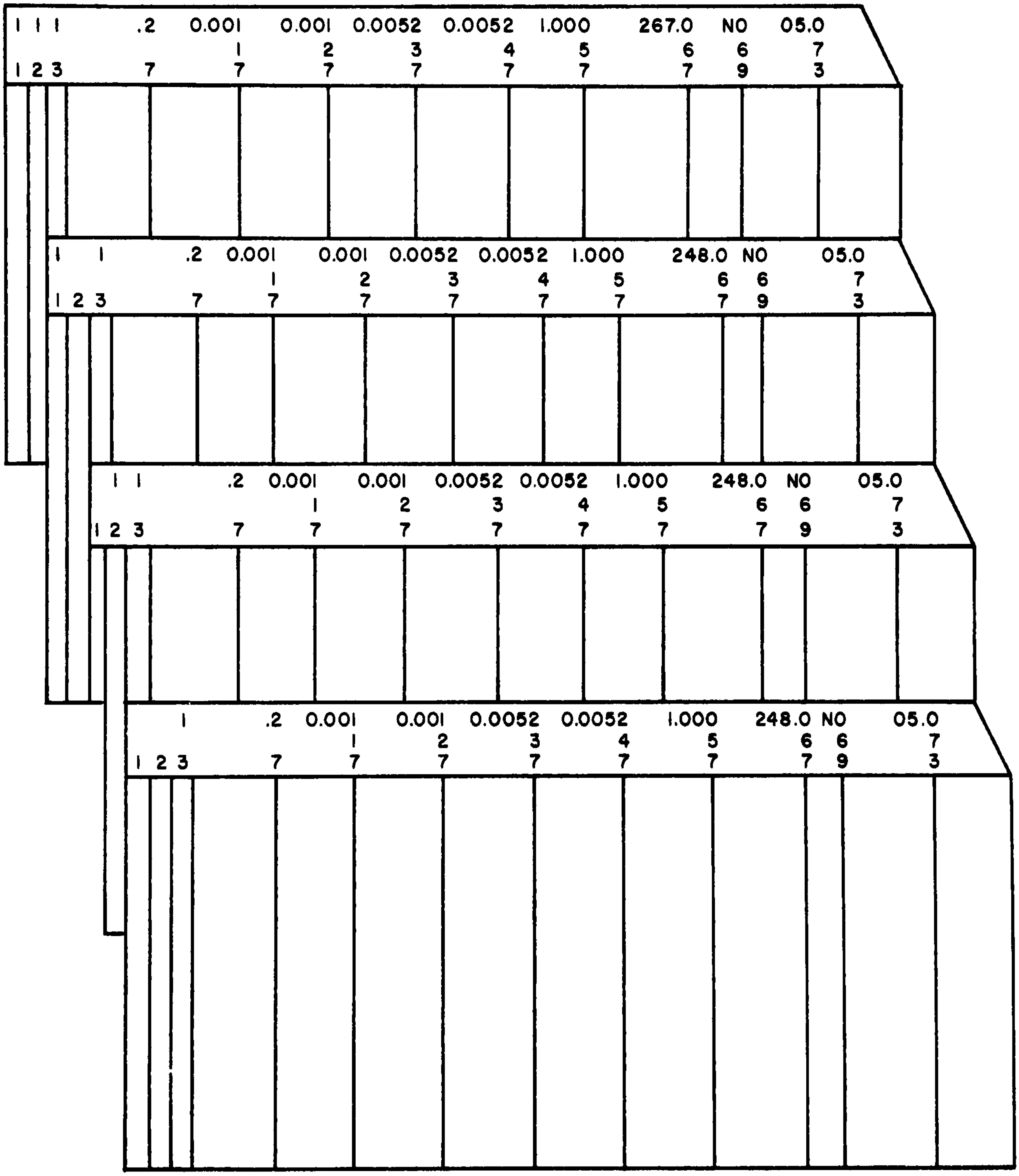
800. 0		5. 0		70. 0	100. 0	5. 0	50. 0
1	10	20	30	40	50	60	70

3) Input Sounding Cards



4) Blank Card

5) Boundary Conditions Cards



The four boundary conditions cards represent the common conditions of:

1) Cloud Buoyancy decreased by weight of cloud water only when terminal velocity of hydrometeor is ≥ vertical velocity.

2) $\mu = .2/R$

3) AK1 = AKF1 = 0.001

4) AK2 = AKF2 = 0.0052

5) CRAD = 1.0 km (example is for a cumulus cloud; for cooling tower CRAD is tower radius)

6) No correction due to vertical shear of the horizontal wind.

7) Initial vertical velocity (W) = 05.0 mps

In addition, the options exercised on each card are as follows:

Card 1 -
1) Constant updraft radius
2) Calculations start from cloud base
3) The ice nucleation temperature is -6°C (267°A)

Card 2 -
1) Constant Updraft Radius
2) Calculations start at first level below -6°C level. Profiles below this level are taken from previous runs.
3) Ice nucleation temperature is -25°C (248°A)

Card 3 -
1) Variable Updraft radius
2) Calculations start from cloud base
3) Ice nucleation temperature is -6°C (267°A)

Card 4 -
1) Variable Updraft radius
2) Calculations start at first level below -6°C level
3) Ice nucleation temperature is -25°C (248°A)

VI. Listing

A listing of the program follows Table A1.

Table A1 contains a complete description of the notation used in the listing.

Figures A1 and A2 show flow diagrams for the interpolation and calculation portions of the program.

TABLE A1

DESCRIPTION OF PROGRAM SYMBOLS

SYMBOL	DESCRIPTION
AK1	Conversion coefficient before freezing.
AKF1	Conversion coefficient after freezing.
AK2	Collection coefficient before freezing.
AKF2	Collection coefficient after freezing
AO, A1	Entrainment parameter (μ = A1/Radius).
AREA	Updraft area.
CONC	Concentration of liquid water ($g\ m^{-3}$) from diffusion equation
DA	Heat realized from freezing of liquid water.
DEFX	Difference between saturation and environmental moisture concentration
DEN	Density of cloud air.
DUR	Duration of precipitation.
DZ, NDZ	Vertical grid interval.
IDENT	Characters on Sounding Identifier Card.
ILEVL	Key indicating if new input sounding level has been read in.
INDOC	Grid interval desired in print out.
IT	Key to indicate ice nucleation level has been reached.
ITOP	Cloud top height (height at which vertical velocity goes to zero).
JN	Key to indicate if listing of interpolated sounding is desired.
LWC	Key indicating if buoyancy should be decreased by weight of total water or only cloud water.

TABLE A1 (Cont'd)

NBS	Key indicating if calculations should proceed from cloud base or from previous ice nucleation level.
NCR	Key for variable or constant updraft radius.
NFRZ	Key to indicate freezing level has been reached.
NTF, TF	Ice Nucleation temperature.
NS	Key for correction due to shear of horizontal wind.
NUM	Initial condition card number.
P	Pressure of initial input sounding.
PE	Pressure of interpolated sounding.
PRAD	Normalized updraft radius (UPRAD/CRAD).
Q	Total liquid water content.
QCL, AQC	Cloud liquid water content.
QH, AQH	Hydrometeor liquid water content.
RA, RO	Total rainfall.
RH	Relative humidity of initial sounding.
RHE	Relative humidity of interpolated sounding (environment R. H.).
RHO	Density of environment air
DES	Difference between saturated vapor pressure over water and ice
SIZE, CRAD	Initial updraft radius.
SIGY, SIGZ	Standard deviations of plume width in y and z directions.
T, TC	1) Temperature of initial input sounding in interpolation section.
	2) Cloud temperature in calculation and output sections.
TE	Temperature of interpolated sounding (environment temperature).
TEMPT	Cloud top temperature
TH	Wind direction in initial sounding.
THE, TTHE	Wind direction in interpolated sounding (environment wind direction)
TVE	Environment virtual temperature
U	Horizontal wind speed in initial sounding.
UE	Horizontal wind speed in interpolated sounding (environment wind speed).

UPRAD	Updraft radius.
W, AW	Cloud vertical velocity.
X, AX	1) Mixing ratio in initial input sounding in interpolated section. 2) Cloud mixing ratio in calculation and output sections.
XE	Mixing ratio in interpolated sounding (environment mixing ratio.
XK1, XK2, XK3, XK4	Constants in equation to determine XS.
XL	Latent Heat
XMU, XMU1	Entrainment parameter.
XS	Saturated mixing ratio.
Z	Height in initial sounding.
ZE	Height in interpolated sounding.
ZFZC	Radar Reflectivity factor.

```
      PROGRAM COOLTW3(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COOLING TOWER MODEL ADAPTED FROM PENN STATE CUMULUS MODEL
      ENTRAINMENT WIND SPEED SOURCE STRENGTH   4 OCT 70
      DIMENSION P(2),T(2),X(2),Z(2),Q(2),QCL(2),QH(2),TVE(2),W(2),U(2),
     1TH(2),RH(2),DEN(2),PE(100),TE(100),XE(100),ZE(100),UE(100),
     2THE(100),RHE(100),AW(100),AQH(100),AQC(100),TC(100),AX(100),
     3UPRAD(100),AD(30),RA(30),DUR(30),ITOP(30),NTF(30),SIZE(30),
     4AREA(30),TEMPT(30),DES(30),IDENT(78),NS(2),XS(100),CONC(50,7,50),S
     5IGY(50),SIGZ(50),DEFX(100),TTHE(100),CONC2(50),QECL(100)
      DATA(DES=0.55,1.02,1.41,1.73,2.00,2.21,2.39,2.51,2.60,2.66,2.68,
     12.69,2.68,2.64,2.60,2.54,2.48,2.40,2.31,2.22,2.13,2.04,1.94,1.84,
     21.75,1.65,1.56,1.47,1.38,1.29)
  100 READ (5,110) (IDENT(I),I=1,78),JN
  110 FORMAT (78A1,I2)
      NSR=1HN
      NUM=1
      WRITE (6,120) (IDENT(I),I=1,78)
  120 FORMAT (1H1,78A1)
      *****  PART 1  INTERPOLATION  *****
      WRITE (6,130)
  130 FORMAT (1H ,40X,16HINITIAL SOUNDING)
      N=2
      WRITE (6,140)
  140 FORMAT (* PRESSURE*,3X,*HEIGHT*,3X,*TEMPERATURE*,3X,*RELATIVE HUM*
     1,3X,*WIND SPEED*,3X,*WIND DIRECTION*//)
      READ (5,150) P(1),T(1),RH(1),Z(1),U(1),TH(1),DZ
  150 FORMAT (2F10.0,10X,4F10.0,F10.0)
      NDZ=DZ
      INDOC=50/NDZ
      TE(1)=T(1)+273.3
      PE(1)=P(1)/10.0
      IHT1=Z(1)
      RHE(1)=RH(1)/100.0
      ZE(1)=Z(1)
      UE(1)=U(1)
      THE(1)=TH(1)
      ILEVL=0
  160 READ (5,170) P(2),T(2),RH(2),U(2),TH(2)
  170 FORMAT (2F10.0,10X,3F10.0)
      WRITE (6,180) P(1),Z(1),T(1),RH(1),U(1),TH(1)
  180 FORMAT (1H ,F8.2,F9.2,F14.2,F15.1,F13.2,F17.0)
      IF (P(2)) 260,260,190
  190 Z(2)=Z(1)+ALOG(P(1)/P(2))*287.0*(T(1)+T(2)+546.6)/19.74
      XLNP=ALOG(P(2)/P(1))
      DTDP=(T(2)-T(1))/XLNP
      DRHDP=(RH(2)-RH(1))/(XLNP*100.0)
      DUDP=(U(2)-U(1))/XLNP
      DTHDP=(TH(2)-TH(1))/XLNP
      DO 240 J=N,250
      IF (ILEVL) 200,200,210
  200 PE(J)=PE(J-1)*EXP(-9.87*DZ/(287.04*TE(J-1)))
      DP=ALOG(PE(J)/PE(J-1))
      TE(J)=TE(J-1)+(DTDP*DP)
      RHE(J)=RHE(J-1)+(DRHDP*DP)
      UE(J)=UE(J-1)+(DUDP*DP)
      THE(J)=THE(J-1)+(DTHDP*DP)
      GO TO 220
  210 P(1)=P(1)/10.0
      PE(J)=P(1)*EXP(-9.87*(ZE(2)-Z(1))/(287.04*(T(1)+273.3)))
      DP=ALOG(PE(J)/P(1))
      TE(J)=T(1)+(DTDP*DP)+273.3
      RHE(J)=RH(1)/100.0+(DRHDP*DP)
      UE(J)=U(1)+(DUDP*DP)
      THE(J)=TH(1)+(DTHDP*DP)
```

```
      ILEVL=0
  220 ZE(2)=ZE(1)+DZ
      IF (ZE(2)-Z(2)) 230,230,250
  230 ZE(1)=ZE(2)
  240 CONTINUE
  250 Z(1)=Z(2)
      P(1)=P(2)
      T(1)=T(2)
      U(1)=U(2)
      TH(1)=TH(2)
      RH(1)=RH(2)
      N=J
      ILEVL=1
      GO TO 160
  260 IF (JN) 310,310,270
  270 WRITE (6,280)
  280 FORMAT (1H ,40X,*INTERPOLATED SOUNDING*)
      WRITE (6,140)
      ZE(1)=IHT1-NDZ
      DO 290 I=1,N
      ZE(1)=ZE(1)+DZ
  290 WRITE (6,300) PE(I),ZE(1),TE(I),RHE(I),UE(I),THE(I)
  300 FORMAT (1H ,1PF8.2,0PF9.2,F14.2,2PF15.3,0PF13.2,F17.0)
  310 DO 320 I=1,N
      ES=(10.0**((22.5518*TE(I)-2937.4)/TE(I)))/(TE(I)**4.93)
      XS(I)=(0.622*ES)/(PE(I)-ES)
      XE(I)=XS(I)*RHE(I)
      DEFX(I)=(XS(I)-XE(I))*3480.0*PE(I)/TE(I)
      TTHE(I)=THE(I)
  320 THE(I)=THE(I)*(3.14159/180.0)
      PRINT 999,(XS(I),XE(I),DEFX(I),I=1,N)
  999 FORMAT(3P2F15.5,0PF15.5)
C     *****  PART 2  MODEL COMPUTATIONS  *****
  330 READ (5,340)NCR,NBS,LWC,A1,AK1,AKF1,AK2,AKF2,CRAD,TF,(NS(I),I=1,2)
     1,W(1)
  340 FORMAT (3I1,F4.0,6F10.0,2A1,F4.1)
  350 SIZE(NUM)=CRAD
      DO 10 I=1,50
      DO 10 J=1,7
      DO 10 K=1,50
      CONC(I,J,K)=0.0
   10 CONTINUE
      AO(NUM)=A1
      NT=273.0-TF
      ZE(1)=IHT1
      WRITE (6,360) AO(NUM),CRAD,AK1,AKF1,AK2,AKF2,TF,W(1),(NS(I),I=1,2)
  360 FORMAT(*1MU=*,F5.3,*/RUP*,2X,*RUP=*,F6.3,* KM*,4X,*K1=*,F5.3,2X
     1,*K1F=*,F5.3,2X,*K2=*,F6.4,2X,*K2F=*,F6.4,4X,*TF=*,F6.1,2X,*W1=*,F
     14.1,2A1,* SHEAR CORRECTION*)
      RAD1=1000.0*CRAD
      XMU1=AO(NUM)/RAD1
      WRITE (6,370)
  370 FORMAT (*0*,2X,*HEIGHT*,4X,*HEIGHT*,3X,*PRESSURE*,2X,*VERTICAL*,
     13X,*CLOUD*,6X,*TEMP.*,4X,*MIXING*,4X,*CLOUD*,5X,*HYDRO*,7X,*Z*,
     28X,*UPDRAFT*)
      WRITE (6,380)
  380 FORMAT(* *,31X,*VELOCITY*,3X,*TEMP.*,5X,*EXCESS*,4X,*RATIO*,5X,
     1*WATER*,5X,*WATER*,5X,*FACTOR*,5X,*RADIUS*)
      WRITE (6,390)
  390 FORMAT (* *,1X,*(METERS)*,3X,*(FEET)*,5X,*(MB)*,5X,*(MPS)*,4X,
     1*(DEG A)*,4X,*(DEG C)*,2X,*(GM/KG)*,3X,*(GM/KG)*,3X,*(GM/KG)*,3X,
     2*(MM6/M3)*,4X,*(METERS)*)
      WRITE (6,400)
  400 FORMAT (1H0)
      *****  INITIALIZATION  *****
      IF (NBS) 420,420,410
```

```
410 J=1
    NFRZ=0
    TH(1)=THE(1)
    U(1)=UE(1)
    T(1)=305.0
    TC(1)=305.0
    X(1)=XE(1)/RHE(1)
    QH(1)=0.0
    AQH(1)=0.0
    QCL(1)=0.0
    AW(1)=W(1)
    IHT=IHT1
    RO=0.0
    RAD=RAD1
    UPRAD(1)=1.0
    DTMAX=0.0
    SDTMX=0.0
    JDTMX=0
    JSDTM=0
    GO TO 440
    *****  INITIALIZATION AT PREVIOUS FREEZING LEVEL  *****
420 J=ITOB
    DTMAX=SDTMX
    JDTMX=JSDTM
    T(1)=TC(ITOB)
    X(1)=AX(ITOB)
    QCL(1)=AQC(ITOB)
    QH(1)=AQH(ITOB)/1000.0
    W(1)=AW(ITOB)
    RAD=UPRAD(ITOB)*RAD1
    RO=ROD
    TH(1)=THTH
    U(1)=UU
    IHT=IHT1
    IST=INDOC+1
    DO 430 I=IST,ITOB,INDOC
    IHT=IHT+NDZ*INDOC
    IHTT=IHT*325/100
    A=TC(I)-TE(I)
    PRAD=UPRAD(I)*RAD1
    BQH=AQH(I)/1000.0
    C=(14000.0*BQH)**1.136
    ZFZC=200.0*(C**1.6)
430 WRITE (6,790)IHT,IHTT,PE(I),AW(I),TC(I),A,AX(I),AQC(I),BQH,ZFZC,
   1PRAD
440 TVE(1)=T(1)*(1.0+.61*X(1))
    Q(1)=QCL(1)+QH(1)
    DEN(1)=PE(J)/(287.04*TE(J))
    INDIC=0
    XL=2500000.0
    DA=0.0
    XK1=22.5518
    XK2=2937.4
    XK3=4.93
    XK4=15.39
    AKA=AK2
    AK=AK1
    UBASE=UE(1)
    THBSE=THE(1)
    IT=0
450 J=J+1
    IF (N-J) 330,460,460
460 IHT=IHT+NDZ
    RAD=RAD1+(0.12*(IHT-IHT1))
    XMU=AO(NUM)/RAD
    INDIC=INDIC+1
```

```
      ***** MOIST OR ICE ADIABATIC ASCENT *****
      A=-0.00983*DZ
      B=1.0+((X(1)*XL)/(287.04*T(1)))
      C=1.0+.622*XL*XL*X(1)/(1004.0*287.04*T(1)*T(1))
      T(2)=T(1)+(A*B+DA)/C
      ***** MIXING AT CONSTANT PRESSURE *****
      ES=(10.0**((XK1*T(2)-XK2)/T(2)))/(T(2)**XK3)
      X(2)=(.622*ES)/(PE(J)-ES)
      A=(XMU*DZ*XL/1004.0)*(X(2)-XE(J))
      B=(XMU*DZ)*(T(2)-TE(J))
      C=1.0+(.622*XL*XL*X(2))/(1004.0*287.04*T(2)*T(2))
      T(2)=T(2)-(A+B)/C
      ES=(10.0**((XK1*T(2)-XK2)/T(2)))/(T(2)**XK3)
      X(2)=(.622*ES)/(PE(J)-ES)
      ***** CLOUD PHYSICS TERMS *****
      IF (QCL(1)-.0005) 470,470,480
  470 A=0.0
      GO TO 490
      ***** CONVERSION *****
  480 A=(QCL(1)-.0005)*AK
      ***** COLLECTION *****
  490 B=423.0*AKA*QCL(1)*QH(1)**.875
      A=(A/W(1)+B/ABS(W(1)-XK4*QH(1)**0.125))*DZ
      QCL(2)=QCL(1)-(X(2)-X(1))-A
      IF (QCL(2)) 500,510,510
  500 QCL(2)=0.0
      QH(2)=QH(1)
      GO TO 550
  510 QECL(J)=(X(2)-XE(J)+QCL(1))*DZ*XMU
      QCL(2)=QCL(2)-XMU*DZ*(X(2)-XE(J)+QCL(1))
      IF (QCL(2)) 520,530,530
  520 QCL(2)=0.0
  530 QH(2)=QH(1)+A
      IF (QH(2)) 540,550,550
  540 QH(2)=0.0
  550 IF (LWC) 560,560,570
  560 Q(2)=QCL(2)+QH(2)
      WATER=Q(2)
      GO TO 590
  570 IF (W(1)-4.5*QH(1)**.125) 580,580,560
  580 Q(2)=QCL(2)+QH(2)
      WATER=QCL(2)
  590 ES=T(2)*(1.0+.61*X(2))
      TVE(2)=TE(J)*(1.0+.61*XE(J))
      ***** VERTICAL VELOCITY COMPUTATION *****
      A=ES-TVE(2)
      D=(TVE(2)+TVE(1))*.5
      B=9.87*DZ*((A/D)-WATER)
      A=(1.0-2.0*XMU*DZ)*W(1)*W(1)+2.0*B
      ***** CORRECTION DUE TO SHEAR OF THE HORIZONTAL WIND *****
      IF(NSR.EQ.NS(1)) GO TO 600
      ALPHA=U(1)/(1.0+XMU*DZ)
      BETA=((XMU*DZ)/(1.0+XMU*DZ))*UE(J)
      GAM=2.0*ALPHA*BETA*(COS(THE(J))*COS(TH(1))+SIN(THE(J))
     1*SIN(TH(1)))
      EPSLN=2.0*ALPHA*UBASE*(COS(TH(1))*COS(THBSE)+SIN(TH(1))*
     1SIN(THBSE))
      ZETA=2.0*BETA*UBASE*(COS(THE(J))*COS(THBSE)+SIN(THE(J))*
     1SIN(THBSE))
      DVEL=ALPHA*ALPHA+BETA*BETA+UBASE*UBASE+GAM-EPSLN-ZETA
      A=A-DVEL
      ALPHA=(1.0/(1.0+XMU*DZ))**2.
      BETA=XMU*DZ
      GAM=COS(TH(1))*COS(THE(J))+SIN(TH(1))*SIN(THE(J))
      U(1)=ALPHA*(BETA*BETA*UE(J)*UE(J)+U(1)*U(1)+2.0*BETA*UE(J)*U(1)*
     1GAM)
```

```
      U(1)=U(1)**.5
      TTH=(U(1)*SIN(TH(1))+BETA*UE(J)*SIN(THE(J)))/(U(1)*COS(TH(1))
     1+BETA*UE(J)*COS(THE(J)))
      TH(1)=ATAN(TTH)
  600 IF (A) 610,670,670
  610 IF (T(2)-TF) 630,630,620
  620 NFRZ=1
      GO TO 810
  630 IF (IT) 640,640,810
  640 DEN(2)=PE(J)/(287.04*TE(J))
      ROD=RD+(QH(2)+QH(1))*(DEN(2)+DEN(1))*.25*DZ
      ITOB=J-1
      IF (JDTMX-ITOB) 650,650,660
  650 SDTMX=DTMAX
      JSDTM=JDTMX
  660 UU=U(1)
      THTH=TH(1)
      GO TO 810
  670 W(2)=A**.5
C     *****  FREEZING  *****
      IF (IT) 680,680,720
  680 IF (T(2)-TF) 690,690,720
  690 IT=IT+1
      XL=2800000.0
      XK1=9.5553
      XK2=2667.0
      XK3=0.0
      XK4=11.58
      AK=AKF1
      AKA=AKF2
      DA=330.0*Q(2)+(DES(NT)*0.622*2.8E6/(PE(J)*1004.0E2))
      ITOB=J-1
      IF (JDTMX-ITOB) 700,700,710
  700 SDTMX=DTMAX
      JSDTM=JDTMX
  710 UU=U(1)
      THTH=TH(1)
      ROD=RD
      GO TO 460
  720 DA=0.0
C     *****  UPDRAFT RADIUS  *****
      DEN(2)=PE(J)/(287.04*TE(J))
      IF (NCR) 730,730,740
  730 RAD=RAD1+(0.11*(IHT-IHT1))
C     *****  TOTAL PRECIPITATION  *****
  740 RD=RD+(QH(2)+QH(1))*(DEN(2)+DEN(1))*.25*DZ
C     *****  RADAR REFLECTIVITY FACTOR  *****
      C=(14000.0*QH(2))**(1.136)
      ZFZC=200.0*(C**1.6)
C     *****  UPDRAFT AREA  *****
      IF (T(2)-TE(J)-T(1)+TE(J-1)) 750,770,770
  750 IF (DTMAX-T(1)+TE(J-1)) 760,770,770
  760 HT=IHT-IHT1-NDZ
      DTMAX=T(1)-TE(J-1)
      AREA(NUM)=DTMAX/(T(1)-TE(1)+.0098*HT)
      JDTMX=J
  770 IF (INDIC-INDOC) 800,780,780
  780 INDIC=0
C     *****  TABULAR OUTPUT OF PROFILES  *****
      D=T(2)-TE(J)
      IHTFT=IHT*325/100
      CALL DIFFZ(XS,XE,TE,W,PE,QCL,RAD,UE,J,IHT.CONC,TTHE,DIFX,QECL,IHT1
     1)
      WRITE (6,790)IHT,IHTFT,PE(J),W(2),T(2),D,X(2),QCL(2),QH(2),ZFZC,
     1RAD
  790 FORMAT (I8,I10,1PF11.4,0PF10.5,2F10.4,3P3F10.6,2X,0PE10.2,F10.2)
```

```
C       *****  STORE PROFILES FOR GRAPHICAL OUTPUT  *****
  800 ITAB=J
      AW(ITAB)=W(2)
      TC(ITAB)=T(2)
      AQH(ITAB)=QH(2)*1000.0
      AX(ITAB)=X(2)
      AQC(ITAB)=QCL(2)
      UPRAD(ITAB)=RAD/RAD1
C       *****  PREPARE FOR NEXT GRID STEP  *****
      Q(1)=Q(2)
      TVE(1)=TVE(2)
      T(1)=T(2)
      X(1)=X(2)
      QCL(1)=QCL(2)
      QH(1)=QH(2)
      DEN(1)=DEN(2)
      W(1)=W(2)
      GO TO 450
C       *****  TOTAL PRECIPITATION  *****
  810 RA(NUM)=RO*39.37
      *****  DURATION OF PRECIPITATION  *****
      A=IHT-IHT1
      WRITE(6,40)  QH(2),XK4
   40 FORMAT(* *,5X,*QH2=*,E15.5,5X,*XK4=*.E15.5)
       IF(QH(2)) 35,45,35
35       CONTINUE
      DUR(NUM)=2*(A/(XK4*QH(2)**.125))/60.0
       GO TO 55
45       DUR(NUM)=0.0
55       CONTINUE
      *****  CLOUD TOP HEIGHT  *****
      ITOP(NUM)=IHT
C       *****  FREEZING TEMPERATURE (DEG C)  *****
      NTF(NUM)=-NT
      WRITE(6,30) NTF(NUM)
   30 FORMAT(* *,5X,*NTF=*,E15.5)
      *****  CLOUD TOP TEMPERATURE (DEG C)  *****
      TEMPT(NUM)=T(2)-273.3
      WRITE (6,820) RA(NUM),DUR(NUM),ITOP(NUM),AREA(NUM)
  820 FORMAT(* TOTAL RAIN =*,F10.4,* INCHES PER CLOUD*,5X,* RAIN LASTS*
     1,F10.2,* MINUTES*,5X,*CLOUD TOP=*,I5,*METERS*,3X,*UPDRAFT AREA=*,
     2F6.4//)
      INDX5=1
  821 IF(INDX5.LT.0)GO TO 829
      DO 834 J=1,2
      DO 834 K=1,50
      DO 834 I=1,50
      CONC(I,J,K)=CONC(I,J,K)-DEFX(K)
      IF(CONC(I,J,K).LE.0.0)CONC(I,J,K)=0.0
  834 CONTINUE
  836 FORMAT(1H-)
  829 DO 832 J=1,2
      PRINT 836
      PRINT 831,J
  831 FORMAT(*-AZIMUTH ANGLE =*,I3)
      PRINT 836
      DO 822 I=1,50
      PRINT 833,(CONC(I,J,K),K=1,17)
  822 CONTINUE
      PRINT 836
      DO 823 I=1,50
      PRINT 833,(CONC(I,J,K),K=18,34)
  823 CONTINUE
      PRINT 836
      DO 824 I=1,50
      PRINT 835,(CONC(I,J,K),K=35,50)
```

```
824 CONTINUE
832 CONTINUE
833 FORMAT(1H ,17F7.4)
835 FORMAT(1H ,16F7.4)
    INDX5=INDX5+1
    IF(INDX5.LE.0)821,830
    *****  IF TOP DOES NOT REACH WARMEST FREEZING LEVEL,  *****
    *****  PROCEED TO NEXT BOUNDARY CONDITION CARD  *****
830 READ (5,340) NCR,NBS,LWC,A1,AK1,AKF1,AK2,AKF2,CRAD,TF,(NS(I),I=1,2
   1),W(1)
    IF(NBS)840,840,870
840 IF(NFRZ)870,870,850
850 WRITE (6,860) AO(NUM),CRAD,AK1,AKF1,AK2,AKF2,TF,W(1),(NS(I),I=1,2)
860 FORMAT (* MU=*,F3.1,*/RUP*,2X,*RUP=*,F5.3,* KM*,4X,*K1=*,F5.3,2X
   1,*K1F=*,F5.3,2X,*K2=*,F6.4,2X,*K2F=*,F6.4,4X,*TF=*,F5.1,2X,*W1=
   1*,F4.1,2A1,*SHEAR CORRECTION-TOP TEMP ABOVE TF*)
    GO TO 830
870 NUM=NUM+1
    IF(CRAD)880,880,350
    *****  SUMMARY TABLE  *****
880 WRITE (6,120) (IDENT(I),I=1,78)
    WRITE (6,890)
890 FORMAT (1H0,44X,*CLOUD*,6X,*CLOUD*)
    WRITE (6,900)
900 FORMAT (3X,*MU*,3X,*RADIUS*,3X,*TF*,3X,*DURATION*,3X,*RAINFALL*
   1,4X,*TOP HT.*,4X,*TOP TEMP.*,5X,*UPDRAFT AREA*)
    WRITE (6,910)
910 FORMAT (1H ,8X,*(KM)*,3X,*(C)*,4X,*(MIN)*,6X,*(INCH)*,5X,*(METER)*
   1,5X,*(DEG C)*//)
    NUM=NUM-1
    WRITE (6,920) (AO(I),SIZE(I),NTF(I),DUR(I),RA(I),ITOP(I),TEMPT(I),
   1AREA(I),I=1,NUM)
920 FORMAT (1H ,F3.1,*/R*,F8.3,2X,I4,F9.2,F11.4,I11,F13.2,F18.5)
    IF(NSR.EQ.NS(1)) GO TO 930
    NUM=1
    IF (CRAD) 330,940,330
930 IF (CRAD) 100,940,100
40  GO TO 100
    END
    SUBROUTINE DIFFZ(XS,XE,TE,W,PE,QCL,RAD,UE,J,IHT,CONC,TTHE,DEFX,QEC
   1L,IHT1)
    DIMENSION DEFX(100),TTHE(100),CONC(50,7,50),UE(100),QCL(2),PE(100)
   1,W(2),TE(100),XE(100),XS(100),SIGY(50),SIGZ(50),X(100),CONC2(50),Q
   2ECL(100)
    DT=50.0/W(2)
    RHO=3480.0*((PE(J-1)+PE(J-2))/2.0)/((TE(J-1)+TE(J-2))/2.0)
    VOL=50.0*UE(J)*DT*RAD*2.0
    WGT=RHO*VOL
    Q=WGT*QECL(J)/DT
    IF(Q.LE.0.0)GO TO 60
    X(1)=0.0
    DX=0.2
 12 DO 15 I=2,50
    X(I)=X(I-1)+DX
    SIGY(I)=0.910*(ALOG10(X(I)))+1.838
    SIGY(I)=10.0**SIGY(I)
    IF(X(I).LE.1.0)13,14
 13 SIGZ(I)=0.843*(ALOG10(X(I)))+1.518
    SIGZ(I)=10.0**SIGZ(I)
    GO TO 15
 14 IF(X(I).LE.10.0)16,17
 16 SIGZ(I)=0.637*(ALOG10(X(I)))+1.595
    SIGZ(I)=10.0**SIGZ(I)
    GO TO 15
 17 SIGZ(I)=0.520*(ALOG10(X(I)))+1.623
    SIGZ(I)=10.0**SIGZ(I)
```

```
 15 CONTINUE
    HT=IHT+50.0-IHT1
    UAVG=UE(J)
    DO 30 I=2,50
    A=Q/(6.28*SIGY(I)*SIGZ(I)*UAVG)
    Z=0.0
    DO 20 K=1,50
    B=-(0.5*(((Z-HT)/SIGZ(I))*((Z-HT)/SIGZ(I))))
    C=-(0.5*(((Z+HT)/SIGZ(I))*((Z+HT)/SIGZ(I))))
    CONC1=A*(EXP(B)+EXP(C))
    CONC(I,1,K)=CONC(I,1,K)+CONC1
    CONC2(K)=CONC1
    Z=Z+50.0
 20 CONTINUE
    DY=0.0
    DO 25 M=2,2
    DY=DY+1.0
    D=-(0.5*((DY*34.95*X(I))/SIGY(I))*((DY*34.95*X(I))/SIGY(I)))
    E=EXP(D)
    DO 25 K=1,50
    CONC(I,M,K)=CONC(I,M,K)+CONC2(K)*E
 25 CONTINUE
 30 CONTINUE
 60 RETURN
    END
7
```

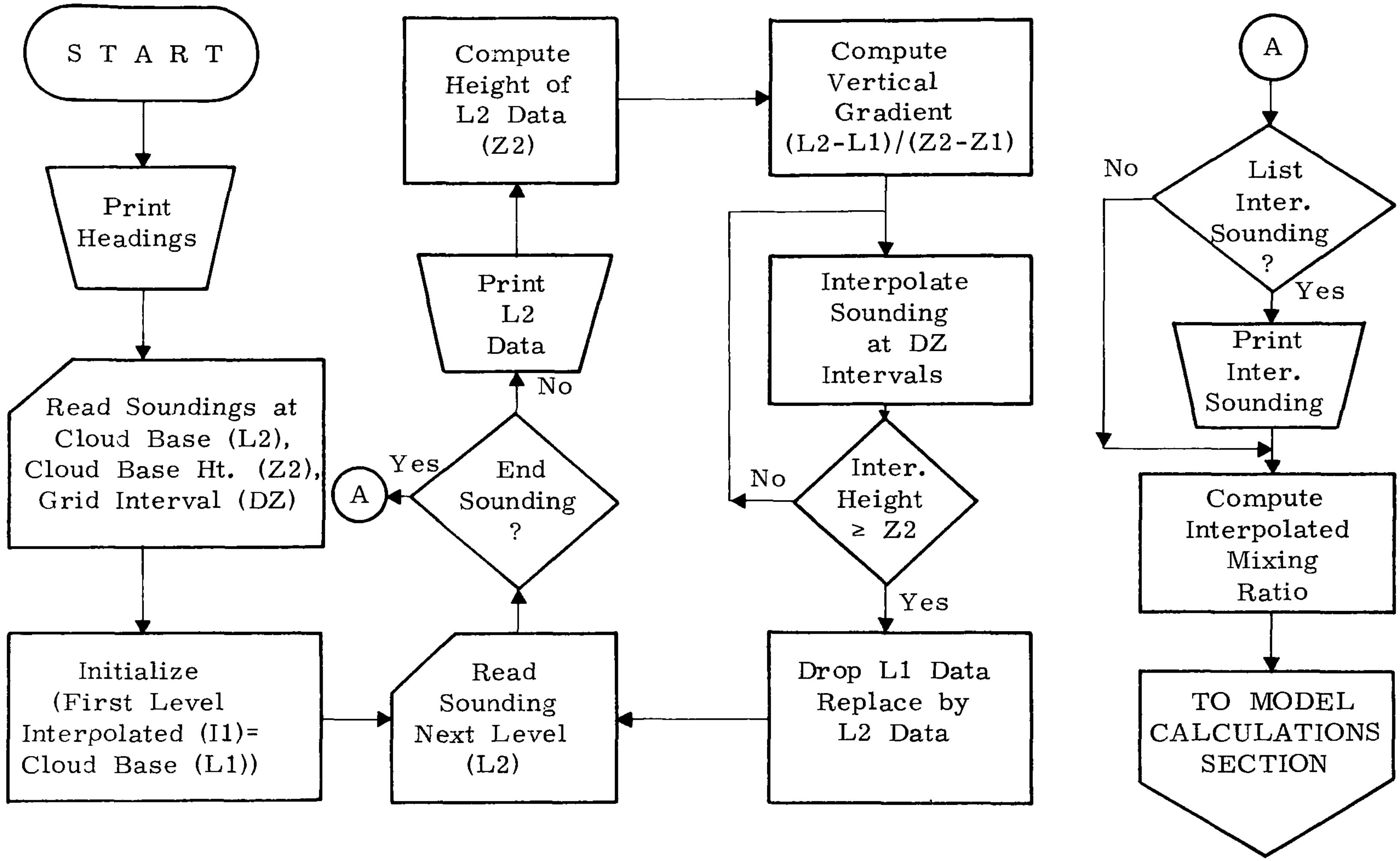


Figure A1. Flow diagram for interpolation section of steady-state cumulus model.

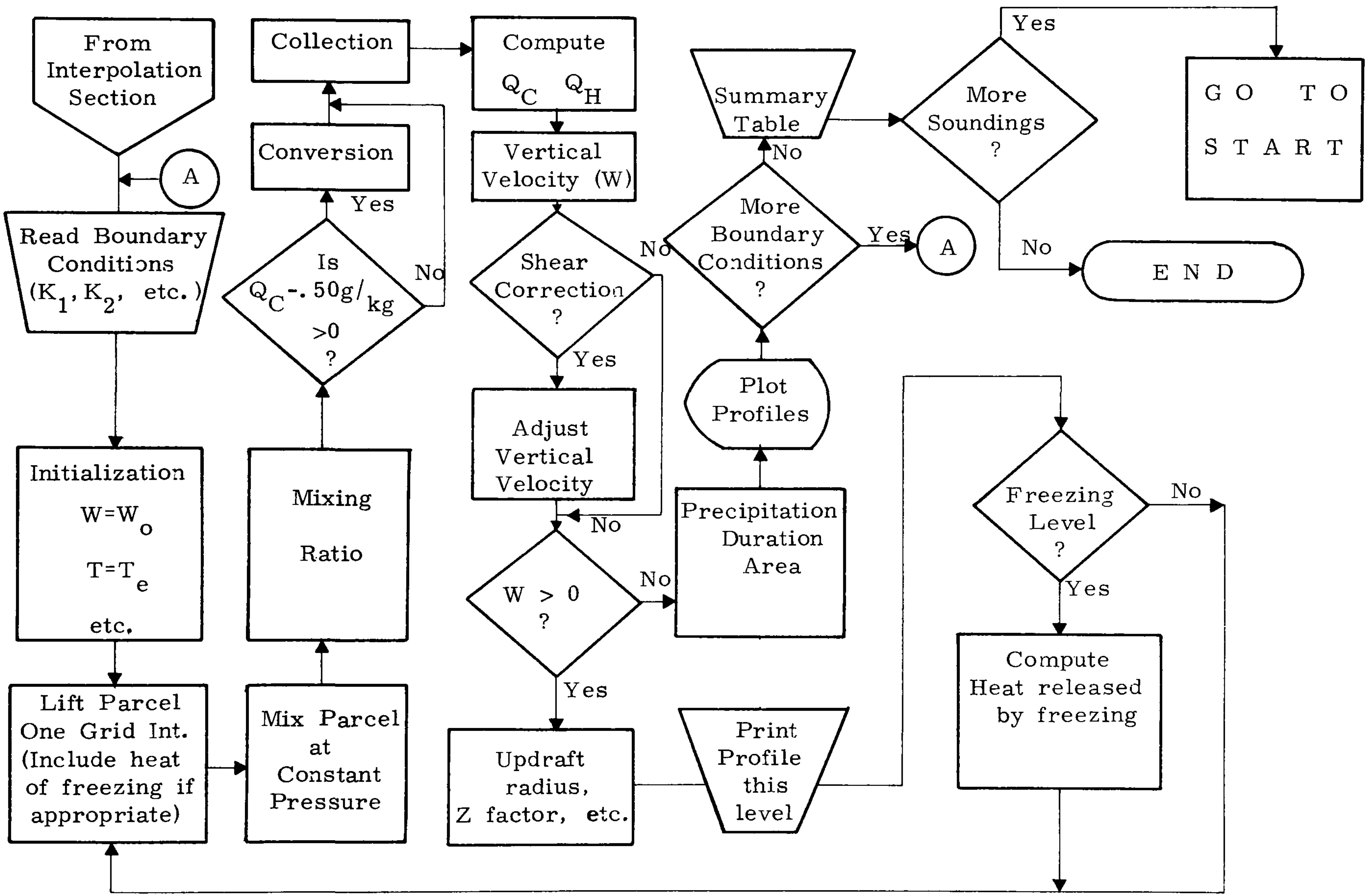


Figure A2. Flow diagram for calculation section of steady-state cumulus model.

VII. Output

Examples of the output from the program follow. The first portion of the output gives the input atmospheric sounding and the interpolated sounding. These are clearly labeled and self-explanatory. Units are pressure-mb, height-m, temperature-deg C, relative humidity-%, and wind speed-m sec^{-1}.

The second portion of the output lists parameters of the cooling tower plume itself as computed by the cloud physics and dynamics portion of the model. These parameters are also clearly labeled and show the cloud properties at 200m vertical intervals. Above the table are given the values of input parameters and constants used in the run. The conversion factors (A)K1, K1F, K2, and K2F, and the ice nucleation temperature (TF) are always given the values shown in the example. These have proven to be appropriate in our computer runs both for natural clouds and cooling tower plumes. The initial updraft radius (RUP) and updraft velocity (W1) should be taken to match the characteristics of the tower being modeled. The entrainment rate μ(MU) has been taken as 0.2/ updraft radius, and this relationship has proven to be appropriate for cooling tower plumes as well as can be judged from presently available data. As shown in the program, we have used $R = R_o + 0.12Z$ for the variation of updraft radius with height (R = Radius, R_o = initial radius, Z = height). Further experience may indicate a modification of the factor 0.12, or a variation of the proportionality parameter with meteorological conditions, but for the present the program is written for the value 0.12, and the relationship $\mu = 0.2/R$ is recommended.

The final portion of the output gives the concentration of cloud water (excess of available plume water over that required to saturate the atmosphere) in g m^{-3} as a function of height, downwind distance from the tower, and horizontal angle measured from the mean wind direction. Azimuth Angle 1 refers to the centerline of the plume, i.e., the mean wind direction. Angle 2 is a direction 2 deg on either side of the wind direction.

The example shown includes only a portion of the output cloud water field. The horizontal axis is height; columns are for heights at 50m intervals. The vertical axis is downwind distance; each row is for a separate distance and in this example the grid spacing is 100m in the horizontal. The complete output continues this table to include heights and distances beyond those shown in the sample. Then similar tables are given for Azimuth Angle 2.

Normally, the model computes water concentration directly from downwind transport of plume water only at 50m vertical increments (the same heights for which plume properties are computed). Concentrations at intermediate heights are obtained by assuming all material to be released at the 200m grid points.

and letting diffusion spread it vertically thereafter. Thus for example, the sample shown indicates a water concentration of 41.78 g m^{-3} at a height of 900m (above sea level) and a distance of 0.3km downwind (entry in 3rd row, 5th column from the right). At this height, the concentration decreases to a value of 0.08 g m^{-3} at a distance of 1.5km (15th row). The adjacent columns (for 850 and 950m height) show lower concentrations resulting from vertical diffusion. A more realistic vertical distribution of water is obtained if the tabular values are averaged or smoothed in the vertical.

Note also that the origin of the vertical scale is arbitrary, depending on the choice of sounding and tower heights. The first primary cloud water column in the output corresponds to the first height in the plume properties table for which a value of cloud water is obtained, in this case 900m.

PIT 29OCT69 1 Z KEYSTONE COOLING TOWER CASE

INITIAL SOUNDING

PRESSURE	HEIGHT	TEMPERATURE	RELATIVE HUM	WIND SPEED	WIND DIRECTION
989.00	500.00	-1.90	86.0	6.00	-0
962.00	719.77	1.40	73.0	11.00	-0
905.00	1205.44	-1.10	60.0	9.00	-0
850.00	1701.70	-1.10	22.0	11.00	-0
777.00	2414.92	.80	20.0	13.00	-0
700.00	3241.08	-2.90	21.0	20.00	-0
500.00	5603.01	-20.00	10.0	30.00	-0

INTERPOLATED SOUNDING

PRESSURE	HEIGHT	TEMPERATURE	RELATIVE HUM	WIND SPEED	WIND DIRECTION
989.00	500.00	271.40	86.000	6.00	-0
964.25	700.00	274.42	74.099	10.58	0
940.54	900.00	273.78	68.198	10.26	0
917.21	1100.00	272.75	62.852	9.44	0
894.25	1300.00	272.20	52.760	9.38	0
871.94	1500.00	272.20	37.448	10.19	0
850.19	1700.00	272.20	22.135	10.99	0
828.97	1900.00	272.73	21.442	11.56	0
808.33	2100.00	273.26	20.880	12.12	0
788.24	2300.00	273.80	20.320	12.68	0
768.75	2500.00	273.72	20.102	13.72	0
749.68	2700.00	272.83	20.343	15.40	0
731.02	2900.00	271.94	20.585	17.09	0
712.76	3100.00	271.04	20.827	18.79	0
694.78	3300.00	270.02	20.755	20.22	0
677.30	3500.00	268.72	19.922	20.98	0
660.19	3700.00	267.42	19.086	21.74	0
643.43	3900.00	266.12	18.245	22.50	0
627.01	4100.00	264.80	17.400	23.27	0
610.94	4300.00	263.48	16.551	24.04	0
595.20	4500.00	262.16	15.698	24.82	0
579.79	4700.00	260.82	14.840	25.60	0
564.70	4900.00	259.48	13.978	26.38	0
549.93	5100.00	258.14	13.112	27.17	0
535.48	5300.00	256.78	12.241	27.96	0
521.32	5500.00	255.42	11.365	28.76	0
507.48	5700.00	254.05	10.485	29.56	0
493.92	5900.00	252.68	9.600	30.36	0

MU= .200/RUP RUP= .030 KM K1= .001 K1F= .001 K2= .0052 K2F= .0052 TF= 248.0 W1= 5.0NO SHEAR CORRECTION

HEIGHT (METERS)	HEIGHT (FEET)	PRESSURE (MB)	VERTICAL VELOCITY (MPS)	CLOUD TEMP. (DEG A)	TEMP. EXCESS (DEG C)	MIXING RATIO (GM/KG)	CLOUD WATER (GM/KG)	HYDRO WATER (GM/KG)	Z FACTOR (MM6/M3)	UPDRAFT RADIUS (METERS)
700	2275	964.2543	15.12982	290.3840	15.9631	12.951597	0.000000	0.000000	0.	52.00
900	2925	940.5402	11.26220	282.7493	8.9727	8.010377	2.323961	0.000000	0.	74.00
1100	3575	917.2087	10.15187	278.0140	5.2655	5.920146	2.148326	.032391	4.75E+01	96.00
1300	4225	894.2537	8.59639	274.7310	2.5310	4.805571	1.673263	.083676	2.67E+02	118.00
1500	4875	871.9435	5.98962	272.2292	.0292	4.107339	1.160076	.162880	8.95E+02	140.00

CH2= 4.87680E-04 XK4= 1.53900E+01
NTF= -0.
TOTAL RAIN = .0018 INCHES PER CLOUD RAIN LASTS 6.74 MINUTES CLOUD TOP= 1700METERS UPDRAFT AREA=1.000

AZIMUTH ANGLE = 1

75

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	*5.0131	0.0000	0.0000	0.0000	*7.7042
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	41.7832	0.0000	0.0000	0.0000	57.1380
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	19.6296	0.0000	0.0000	.1515	26.9718
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.7968	11.1566	.6544	0.0000	1.5286	15.4342
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.1444	6.9741	1.0024	0.0000	2.0023	9.7390
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.9577	5.0271	.8168	0.0000	1.7489	7.0878
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.7935	3.5865	.6568	0.0000	1.5284	5.1262
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.6033	2.5882	.4749	0.0000	1.2755	3.7669
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.4146	1.8638	.2994	0.0000	1.0282	2.7806
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.2386	1.3192	.1407	0.0000	.8013	2.0394
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0792	.8984	.0013	0.0000	.5989	1.4669
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.5660	0.0000	0.0000	.4205	1.0151
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.2987	0.0000	0.0000	.2640	.6523
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0807	0.0000	0.0000	.1264	.3569
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	.0050	.1133
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

BIBLIOGRAPHIC: E G & G, Inc., Environmental Services Operation, "Potential Environmental Modifications Produced by Large Evaporative Cooling Towers," FWQA Publication No. 16130---01/71.

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ABSTRACT: The objective of the study was to develop techniques for evaluating the extent of plumes from large evaporative cooling towers. Analytical techniques were used to describe the dynamics of the wet cooling tower plume and its interaction with the environment. Primary emphasis was placed on predicting the height of the plume. Classical atmosphere diffusion theory was used to determine the downwind spread.

The study showed that the saturation deficit of the atmosphere clearly controls the downwind spread of the ejected liquid water. Except for cases where the relative humidity approaches 100%, downwind propagation is limited to periods when the air temperature falls below the freezing point. For a given set of atmospheric conditions, increases in the tower radius, the saturation temperature, and the intial vertical velocity of the plume contribute to increasing the final plume height.

The potential for adverse atmospheric effects due to cooling towers was analyzed on a national basis and is presented in the form of a map of the United States.

A computer program was developed to perform the necessary calculations. The Appendix contains a description of the program, including input specifications.

This report was submitted in fulfillment of contract number 14-12-542 under the sponsorship of the Water Quality Office of the Environmental Protection Agency. (Tichenor-EPA)

KEY WORDS

Cooling Tower Plumes
Atmospheric Diffusion
Cooling Towers
Meteorology
Weather Modification
Fog

1 Accession Number	2 Subject Field & Group	
	Ø5C	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 *Organization*

E G & G, Inc., Environmental Services Operation, Boulder, Colorado

6 *Title*

"Potential Environmental Modifications Produced by Large Evaporative Cooling Towers"

10 *Author(s)*

E G & G, Inc.
Environmental Services Operation

16 *Project Designation*

FWQA Contract No. 14-12-542

21 *Note*

22 *Citation*

Report No. 16130 DNI 01/71, Water Pollution Control Research Series, Water Quality Office, EPA, 1971, 75 p.

23 *Descriptors (Starred First)*

*Cooling towers, *Meteorology, *Weather modification, *Fog, Cloud physics, Thermal pollution, thermal power plants, air pollution, evaporation, mathematical models, computer programs, cloud seeding

25 *Identifiers (Starred First)*

*Cooling tower plumes, *Atmospheric diffusion

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