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MATHEMATICAL MODEL FOR MULTIPLE COOLING TOWER PLUMES

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report presents a procedure for estimating the nature and extent of dispersions of moist plumes that are emitted from cooling towers. The estimates are useful in assessing environmental impact of these systems.

A. F. Bartsch
Director, CERL

ABSTRACT

A mathematical model is developed resulting in a computer program for the prediction of the behavior of plumes from multiple cooling towers with multiple cells. A general integral method based on the conservation of mass, momentum, energy (heat), and moisture fluxes (before and after a plume merging), were employed in the prediction scheme. The effects of ambient stratifications of temperature, moisture, and wind are incorporated in the model.

An axisymmetric round plume is assumed to be emitted from each individual cell before interference with neighboring plumes. A finite length slot plume in the central part and two half round plumes at both ends of the merged plume were used to approximate the plume after merging. The entrainment and drag functions are calculated based on the modified merged plume shape.

The computer output provides the predicted plume properties such as excess plume temperature, humidity and liquid phase moisture (water droplet), plume trajectory, width, and dilution at the merging locations and the beginning and ending points of the visible part of the plumes. Detailed printout and contour plots of excess temperature and moisture distribution can also be obtained if desired.

Based on comparison with laboratory data this model gives good predictions for the case of dry plumes (no moisture involved). It should be noted that several empirical coefficients are as yet not accurately known. Verification of this model for the wet plume (such as for prototype cooling tower plumes) and the determination of the values for these empirical coefficients to be used in prototype applications must await detailed comparison with field data.

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TABLE OF CONTENTS

Chapter		Page
1.	INTRODUCTION	1
2.	THEORETIC MODEL	4
	2.1 Formulation	5
	2.2 Entrainment	13
	2.3 Merging Process	17
3.	COMPUTER PROGRAM	28
4.	RESULTS, COMPARISONS AND DISCUSSIONS	31
5.	CONCLUSIONS AND RECOMMENDATIONS	57
REFERENCES		59

APPENDIX A: COMPUTER PROGRAM

APPENDIX B: EXPLANATIONS OF THE IMPORTANT SYMBOLS IN THE PROGRAM MTP

APPENDIX C: LISTING OF PROGRAM

LIST OF FIGURES

Figure		Page
2.1	Top View of the Coordinate System Associated with the Cooling Tower Configuration	6
2.2	Side View of the Coordinate System Associated with the Cooling Tower Configuration	6
2.3	Merged Plume Shape	19
2.4	Definition Sketch	20 21
2.5	Modified Merged Plume Shape	24
2.6	Correction of Δy for the Merged Plume	26
3.1	Flow Chart of the Computer Program	30
4.1	Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction	32
4.2	Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction	33
4.3	Excess Liquid Phase Moisture Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction	34
4.4	Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction	35
4.5	Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction	36
4.6	Excess Liquid Phase Moisture Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction	37
4.7	Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction	38
4.8	Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction	39
4.9	Excess Liquid Phase Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction	40

LIST OF FIGURES (Continued)

Figure		Page
4.10	Excess Temperature Distribution for the Case of 5 Towers in Round Array	41
4.11	Excess Humidity Distribution for the Case of 5 Towers in Round Array	42
4.12	Excess Liquid Phase Moisture Distribution for the Case of 5 Towers in Round Array	43
4.13	Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for $F = 20$ and $K = 8$	45
4.14	Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for $F = 40$ and $K = 8$	46
4.15	Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for $F = 80$ and $K = 16$	47
4.16	Comparisons of Plume Excess Temperature Between the Present Theory and Chan et al.'s (1974) Experiments for $F = 4$ and $K = 1.02$	48
4.17	Comparisons of Plume Trajectories Between the Present Theory and TVA (1968, TVA-11, single tower) Field Data in a Stable Atmospheric Condition ($\partial\theta/\partial z = 0.59°K/100$ m)	50
4.18	Comparisons of Plume Trajectories Between the Present Theory and TVA (1968, TVA-14, two towers) Field Data in an Atmosphere with an Inversion ($\partial\theta/\partial z = 1.42°K/100$ m)	51

LIST OF TABLES

Table		Page
4.1	Input Data Cards for Example Cases (Different Wind Directions to a Line Array (3 cases) and Round Array (one case) of Towers)	52
4.2	Input Data Cards for Three Cases of Fan's (1967) Experiments with $F = 20$, $K = 8$; $F = 40$, $K = 8$; and $F = 80$, $K = 16$	53
4.3	Input Data Cards for Chan et al.'s (1974) Experiment with $F = 4$, $K = 1.02$	54
4.4	Input Data Cards for TVA (1968, TVA-11, single tower) Field Data in a Stable Atmospheric Condition ($\partial\theta/\partial z = 0.59°K/100$ m)	55
4.5	Input Data Cards for TVA (1968, TVA-14, two towers) Field Data in an Atmosphere with an Inversion ($\partial\theta/\partial z = 1.42°K/100$ m)	56

LIST OF SYMBOLS

a_1	Entrainment coefficient associated with jet type entrainment
a_2	Entrainment coefficient associated with the effect of buoyancy
a_3	Entrainment coefficient associated with thermal type entrainment
a_4	Entrainment coefficient associated with ambient turbulence
a	Finite length of the slot plume in the central part of the merged plume
A	Finite length of the slot plume in the central part of the modified merged plume
b	Plume radius
b_{r1}, b_{r2}	Plume radii at the ends of the merged plume
b_s	Plume width of the slot plume in the central part of the merged plume
B1,B2	Plume radii at the ends of the modified merged plume
BXZ	Plume half height of the cross-section normal to s-axis
BY	Plume half width
C	Tracer concentration
C_d	Drag coefficient
C_{pa}	Specific heat at constant pressure
e_s	Saturation vapor pressure
E	Volume rate of entrainment
E_{1r}	Volume rate of entrainment associated with the effects of momentum and buoyancy for a round plume
E_{1s}	Volume rate of entrainment associated with jet type entrainment for slot plume
E_2	Volume rate of entrainment associated with thermal type entrainment

LIST OF SYMBOLS (Continued)

E_3	Volume rate of entrainment associated with ambient turbulence
F	Sum of excess vapor and liquid phase moisture fluxes (H+W)
F^2	Densimetric Froude number $(m^{5/2}/\mu^2\beta)$
Fr_L	Local densimetric Froude number $(U_p^2/[(\rho_a-\rho_p)bg/\rho_o])$
Fr_{LC}	Critical local densimetric Froude number
g	Acceleration of gravity
G	$T - L_v W/C_{pa}$
H	Excess vapor phase (humidity) moisture flux
HT	Total height of the merged plume
L_v	Latent heat of evaporation or condensation
m	Kinematic momentum flux $(\int_A u_p^2 dA)$
M	Excess kinematic momentum flux
p_d	Dry air absolute pressure
p_t	Total absolute pressure $(p_d + e_s)$
P	Plume periphery
q	Specific vapor phase moisture (humidity)
Q	Plume volume flux
s	Plume trajectory
t	Temperature
t_s	Steam point temperature
T	Excess temperature flux
U	Velocity
U_a'	Measure of ambient turbulent fluctuation
U_{r1}, U_{r2}	Plume velocities at both ends of merged plumes

LIST OF SYMBOLS (Continued)

U_s	Plume velocity at central part of merged plume
W	Excess liquid phase moisture flux
W_d	Plume width
WD	Total width of the merged plume
x	x-coordinate (parallel to wind direction)
y	y-coordinate (normal to x-axis)
z	z-coordinate (vertical coordinate)
α_j	Entrainment coefficient for pure jet ($F_1 \rightarrow \infty$)
α_p	Entrainment coefficient for pure plume
β	Buoyancy flux ($\int_A gU_p(\rho_a-\rho_p)/\rho_a dA$)
Γ	Adiabatic lapse rate
θ	Angle between the tangent of s and x-axis
ρ	Density
σ	Liquid phase moisture
ϕ	Angle between the centerline of the (inclined) plume cross-section and the horizontal line parallel to y-axis
μ	Volume flux ($\int_A U_p dA$)
$(\ )_a$	in ambient
$(\ )_o$	at tower exit
$(\ )_p$	in plume

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CHAPTER 1

INTRODUCTION

The use of multiple cooling towers is a common means of disposal of waste heat from large power plants. A better understanding of the behavior and interaction of plumes from multiple towers would be useful not only to cooling tower design and operation, but also in the assessment of their environmental impact. Due to the relatively close proximity of neighboring tower exits, the individual plumes from multiple cooling towers rapidly interfere with one another, thus changing the overall plume shape and its mixing characteristics. In addition, the ambient stability (temperature profile), humidity, wind velocity and wind direction to the tower array also influence the plume behavior. In this report a mathematical model resulting in a computer program is developed which will provide the framework to allow reasonable predictions to be made of the characteristics of plumes from multiple cooling towers under various ambient conditions.

Throughout this report, no distinction will be made between a plume and a jet. Neither will the distinction be made between the multiple plumes from the several cells of a tower and the multiple plumes from several individual towers.

The plume from a cooling tower is a buoyant jet which has been studied in the past by numerous investigators, such as Morton, et al. (1956), Morton (1957), Slawson and Csanady (1967,1971), Koh and Brooks (1975). Several existing single tower plume models, including dry and wet plumes, were developed by Briggs (1969), Hoult et al. (1969), Abraham (1970), Fox (1970), Csanady (1971), Wigley and Slawson (1971, 1972),

Hirst (1971), Hanna (1972), Weil (1974), Wigley (1975a,b), and Schatzmann (1977).

A model for multiple plumes was first developed by Koh and Fan (1970) in analysing the analogous problem of disposal of waste heat into the ocean by multiple port diffusers. The integral method was used and the individual round buoyant jets were approximated by a two-dimensional slot jet after interference. A transition region during merging was considered. Although a discontinuous centerline temperature resulted at the point of merging, the overall predictions of the plume properties were quite satisfactory. Jirka and Harleman (1974) approached the multiple port diffuser problem by replacing it with an equivalent slot jet having the same mass and momentum fluxes as the multi-port discharge. As expected this method generally over-estimates dilution except for those instances when the plumes are very close to each other initially. Briggs (1974) added an enhancement factor to his single tower equation for plume rise by considering the effects of number of towers and tower spacing. Meyer et al. (1974) modified Briggs' equation and used a "peak factor" to develop a model which can give a fairly good prediction of visible plume length. However, the prediction of the plume trajectory is less accurate. Davis (1975) developed a mathematical model for calculating plume rise and dilution from multiple cell mechanical draft cooling towers with the wind normal to the tower array. The entrainment function used includes the effects of plume interference and the changing entrainment surfaces during merging. The model also provides calculation techniques for various modes of plume development. The plume properties remain continuous when the calculations proceed

smoothly from one zone to another. The values of the coefficients in his entrainment function still need to be determined from suitable laboratory and field experiments.

Data from multiple towers are very scarce. Chan et al. (1974) made laboratory simulations of plumes from multiple towers using water as the fluid medium. Two sets of normalized excess temperature distributions were presented. These are useful for model comparisons. The studies by Carpenter et al. (1968) and Slawson et al. (1975) at TVA gave field data on plume trajectory and some plume properties. More complete data including plume trajectory, width, dilution, and ambient conditions (i.e. temperature, humidity and wind velocity profiles, wind direction to tower array, tower configuration, etc.) however are required for proper verification.

The model developed in this report is based on a general integral method applied to the conservation equations for mass, momentum, energy, and moisture fluxes. An axisymmetric round plume is assumed initially for each tower exit. As the plumes merge, combinations of round and slot plumes are employed to simulate the shape of the resulting merged plumes. The merging criteria, merging processes, changes of plume shape and entrainment functions are a part of the model and are discussed in Chapter 2. Some results of model predictions and comparisons with laboratory and field data are presented and discussed in Chapter 4. A computer program has been written to perform the calculations and is included in Chapter 3 and Appendices A and C.

CHAPTER 2

THEORETICAL MODEL

The present mathemtical model is developed for the prediction of plume properties from multiple cooling towers. These include plume temperature, moisture (vapor and liquid phases), excess temperature, excess moisture, velocity, width, dilution, trajectory and visible plume length. For ease of application to practical situations, this model is capable of handling rather arbitrary vertical profiles of ambient temperature, humidity, and velocity; arbitrary but steady wind direction to the tower array; and randomly arranged tower configurations.

The assumptions made in developing this model are as follows:

1. The flow is fully turbulent. Molecular transport can be neglected in comparison with turbulent transport so that there is no Reynolds number dependence.

2. Longitudinal turbulent transport is small compared with longitudinal advective transport.

3. Pressure is hydrostatic throughout the flow field.

4. The cross-plume profiles are similar for plume velocity, temperature, density, humidity and liquid phase moisture.

5. The Boussinesq assumption is valid. This implies that the variations of fluid density throughout the flow field are small compared with the reference density chosen. The variations in density are only considered in the buoyancy term.

Using these assumptions, a general integral model for multiple cooling tower plumes based on the conservation of mass, momentum, energy and moisture fluxes along the plume trajectory is developed. By providing

the ambient conditions and the empirical equations for entrainment and drag, the conservation equations are integrated stepwise for the center line properties along the plume trajectory. Before interference the plumes are assumed to be individual, axisymmetric, round buoyant jets. During the merging process, a combination of a finite slot jet in the central part and two half round jets at both ends is assumed to be the cross-sectional shape of the merged plume as an approximation but only for the calculation of entrainment and drag. Finally, the completely merged plume gradually tends to become round in cross section again, whereupon the individual axisymmetric analysis is reapplied. The formulations of the basic plume conservation equations, entrainment function, merging criterion and merging process are presented in the following sections.

2.1 Formulation

The coordinate system chosen with a typical cooling tower configuration is shown in Figures 2.1 and 2.2. The x-axis is parallel to the steady ambient wind direction. s is the coordinate along the plume path and θ is the angle between the tangent to s and the x-axis. The individual plumes from the cooling tower cells are presumed to be discharged vertically into a stratified atmosphere, and bent over due to the effect of ambient wind. The plume properties are defined as velocity U, density ρ, temperature t, specific humidity q, and liquid phase moisture σ. Here, the specific humidity (vapor phase moisture) q and liquid phase moisture σ are defined as the ratio of mass of vapor (or liquid) phase moisture to the total mass of the mixture in a unit volume. The subscripts o, p, and a are used for the values at tower

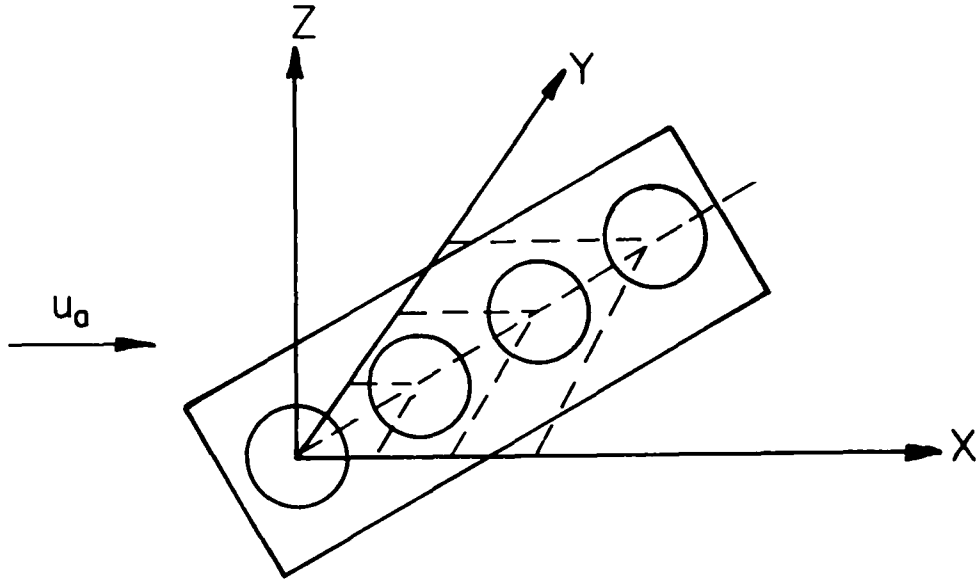


Figure 2.1 Top View of the Coordinate System Associated with the Cooling Tower Configuration

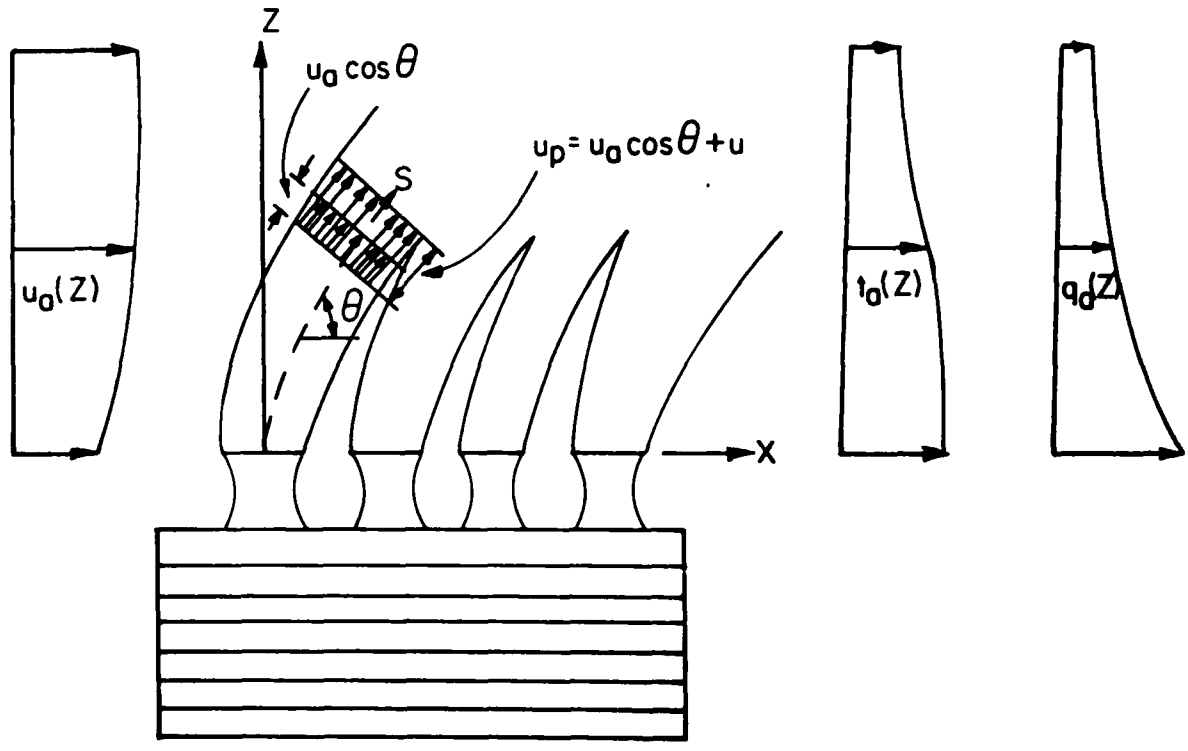


Figure 2.2 Side View of the Coordinate System Associated with the Cooling Tower Configuration

exit, in the plume, and in the ambient atmosphere, respectively. The plume volume flux Q, kinematic momentum flux M, temperature deficiency flux T, vapor phase moisture (or humidity) deficiency flux H, and liquid phase moisture deficiency flux W are defined as follows:

$$Q = \int_A U_p \, dA \tag{2.1}$$

$$M = \int_A U_p^2 \, dA \tag{2.2}$$

$$T = \int_A (t_p - t_a) \, U_p \, dA \tag{2.3}$$

$$H = \int_A (q_p - q_a) \, U_p \, dA \tag{2.4}$$

$$W = \int_A (\sigma_p - \sigma_a) . U_p \, dA \tag{2.5}$$

Any 'rainout' of liquid droplets in the ambient atmosphere will be neglected so that σ_a is equal to zero.

The conservation of mass equation is:

$$\frac{d}{ds} \left\{ \int_A \rho_p \, U_p \, dA \right\} = \rho_a E \tag{2.6}$$

where E is the volume rate of entrainment of ambient fluid. The function used for E is an empirical expression including the effects of plume geometry, local mean velocity, buoyancy and ambient turbulence. The detailed form of E is presented in Section 2.2.

The conservation equation for horizontal momentum flux is:

$$\frac{d}{ds} \left\{ \int_A \rho_p \, U_p^2 \, dA \cdot \cos\theta \right\} = \rho_a U_a E + \frac{1}{2} \rho_a U_a^2 \sin^2\theta \, C_d \, W_d |\sin\theta| \tag{2.7}$$

where the first term on the right hand side of equation (2.7) is due to the momentum of the entrained ambient fluid and the second term is due to the horizontal drag force (Fan, 1967) on the plume; C_d is a drag coefficient to be determined empirically and W_d is the width of the plume; the absolute value of $\sin\theta$ is used in order to account for both the ascending and descending parts of the plume.

The conservation equation for vertical momentum flux is:

$$\frac{d}{ds}\{\int_A \rho_p U_p^2 \, dA \cdot \sin\theta\} =$$

$$g\int_A (\rho_a-\rho_p)\, dA - g\int_A \rho_p\sigma_p dA \mp \frac{1}{2}\rho_a U_a^2 \cdot \sin^2\theta \, C_d W_d \cos\theta \tag{2.8}$$

where the first term on the right hand side of equation (2.8) is the buoyancy force due to the density difference between the plume and ambient fluid; the second term is the effect of the weight of liquid droplets suspended in the plume; the third term is the vertical drag force on the plume with the negative and positive signs corresponding to $0 \leq \theta \leq \pi/2$ and $-\pi/2 \leq \theta < 0$, respectively.

Koh and Fan (1970) have shown that the governing equation for the flux of a tracer quantity C is as follows:

$$\frac{d}{ds}\int_A (C_p - C_a)\, U_p \, dA = -\frac{dC_a}{ds}\int_A U_p \, dA \tag{2.9}$$

where C_p and C_a are the tracer concentrations in the plume and the ambient, respectively. Now considering the temperature flux and also taking into account the effects of atmospheric adiabatic lapse rate Γ

and the liberation of latent heat due to condensation of water vapor inside the plume (Csanady, 1971), the conservation equation for energy (or heat) flux is derived as follows:

$$\frac{d}{ds}\int_A (t_p - t_a)\, U_p\, dA = -\left(\frac{d\,T_a}{dz} + \Gamma\right) \sin\theta \int_A U_p\, dA + \frac{d}{ds}\int_A \frac{L_v}{C_{pa}}\, \sigma_p\, U_p\, dA \tag{2.10}$$

where L_v is the latent heat of evaporation (or condensation) i.e., $L_v(t) = [597.31 - 0.57x(t°C)] \times 4.1868\ Jg^{-1}$ for $t \geq 0°C$ and $L_v = [677 + 0.622 \times (t°C)] \times 4.1868$ for $t<0°C$, and C_{pa} is the specific heat of air at constant pressure.

The conservation equation for (vapor and liquid phase) moisture flux is:

$$\frac{d}{ds}\int_A (q_p - q_a)\, U_p\, dA + \frac{d}{ds}\int_A \sigma_p\, U_p\, dA = -\frac{dq_a}{dz} \sin\theta \int_A U_p\, dA \tag{2.11}$$

We assume a top-hat distribution of plume properties across the plume. Therefore, U_p, T_p, ρ_p, q_p, and σ_p are constants inside the plume. In particular, U_p is defined as follows:

$$U_p = U_a \cos\theta + U \tag{2.12}$$

where U is the 'net' plume velocity relative to the ambient wind.

Applying the relationship between temperature and density for a constant pressure process (pressure variations in the plume cross section is neglected) we can write:

$$\frac{\rho_a}{\rho_p} = \frac{t_p}{t_a} \; ; \text{ and } \frac{\rho_a - \rho_p}{\rho_p} = \frac{t_p - t_a}{t_a} \tag{2.13}$$

The conservation equations may now be rewritten as:

$$\frac{dQ}{dS} = \frac{t_p}{t_a} E \tag{2.14}$$

$$\frac{d}{ds} \{M \cos\theta\} = \frac{t_p}{t_a} \{U_a E + 0.5 U_a^2 \sin^2\theta \, C_d W_d |\sin\theta|\} \tag{2.15}$$

$$\frac{d}{ds} \{M \sin\theta\} = g \left\{\frac{t_p - t_a}{t_a} - \sigma_p\right\} \int_A dA \mp \frac{t_p}{t_a} 0.5 U_a^2 \sin^2\theta \, C_d W_d \cos\theta \tag{2.16}$$

$$\frac{d}{ds} \{T - \frac{L_v}{C_{pa}} W\} = - \left(\frac{d\, t_a}{dz} + \Gamma\right) \cdot \sin\theta \cdot Q \tag{2.17}$$

$$\frac{d}{ds} \{H + W\} = - \frac{dq_a}{dz} \cdot \sin\theta \cdot Q \tag{2.18}$$

In addition, the equations for the geometrical relations yield

$$\frac{dx}{ds} = \cos\theta \tag{2.19}$$

$$\frac{dz}{ds} = \sin\theta \tag{2.20}$$

Since U_p, t_p, σ_p and W_d can be written in terms of M, Q, T and W (Koh and Fan, 1970); for instance, $U_p = 2M/Q$ for round plume, the system of equations (2.14) to (2.20) constitute seven ordinary differential equations for the eight unknowns, Q, M, θ, T, H, W, x and z as functions of s. For closure, one more equation is needed. This extra condition is:

$$\sigma_p = 0 \qquad \text{for } q_p < q_{sp} \text{ (dry plume)}$$

$$q_p = q_{sp}(t_p) \qquad \text{for } q_p \geq q_{sp} \text{ (wet plume)} \tag{2.21}$$

where q_{sp} is the plume saturation specific humidity.

Equation (2.21) implies that when the plume is unsaturated, no liquid phase moisture due to condensation need be considered and when the plume is saturated, the plume humidity is equal to the plume saturation specific humidity. To calculate the saturated specific humidity, thermodynamic equilibrium between liquid and vapor is assumed. The Clausius-Clapeyron equation (or tabulated values) can then be used to calculate the saturated humidity. The equation used in the model to calculate the saturated specific humidity q_s is (Linsley et al., 1975):

$$q_s(t,p) = \frac{0.622 e_s(t)}{P_t - 0.378\, e_s(t)} = \frac{0.622\, e_s(t)}{P_d(z) + e_s(t) - 0.378\, e_s(t)} \tag{2.22}$$

where t and p are absolute temperature and pressure, respectively; P_t is the total pressure which is the sum of the dry air pressure $P_d(z)$ and the saturated vapor pressure $e_s(t)$.

Since the variation of pressure is small (for instance, ΔP = 1% of P corresponding to $\Delta z \approx 100M$), the absolute pressure at sea level (i.e., P_d = 1013.25 mb) is used in equation (2.22), which becomes:

$$q_s(t) = \frac{0.622\, e_s(t)}{1013.25 + 0.622\, e_s(t)} \tag{2.23}$$

An approximate expression of $e_s(t)$ was developed by Richards (1971) as

$$e_s(t)=1013.25 \times \exp(13.3185\ t_v - 1.9760\ t_v^2 - 0.6445\ t_v^3 - 0.1299\ t_v^4)$$

where

$$t_v = 1 - \frac{t_s}{t}$$

and t_s is the steam point temperature (°K). The result from this equation is very accurate (to within 0.1%) over the wide range of temperature -50°C to 140°C (Wigley, 1974). Within the range 0° to 100°C it is accurate to within the limits of accuracy of the accepted Goff-Gratch formula. In this study t_s is equal to 373.16°K. Because both q_s and t are unknown in the governing equations, the implicit form of equation (2.23) would require an iteration scheme in the calculation. In the model, the Newton method was adopted for this iteration.

With the additional equation (2.23) and the Newton iteration method, the system of equations (2.14) to (2.21) may now be solved given the initial values of the unknowns at tower exit (or s=o). The initial values are as follows;

$$Q_o = \int_A U_p\ dA = \frac{\pi}{4} D_o^2\ U_o$$

$$\theta_o = 90°$$

$$M_o \cos\theta_o = 0$$

$$M_o \sin\theta_o = \int_A U_p^2\ dA = \frac{\pi}{4} D_o^2\ U_o^2 = Q_o\ U_o$$

$$G_o = T_o - \frac{L_v}{C_{pa}} W_o = \frac{\pi}{4} D_o^2\ U_o\ (t_o - t_{ao} - \frac{L_v}{C_{pa}} \sigma_o) \qquad (2.24)$$

$$= Q_o(t_o - t_{ao} - \frac{L_v}{C_{pa}}\ \sigma_o)$$

$$F_o = H_o + W_o = \frac{\pi}{4} D_o^2\ U_o\ (q_o - q_{ao} + \sigma_o)$$

$$= Q_o\ (q_o - q_{ao} + \sigma_o)$$

$$x_o = 0$$

$$z_o = 0$$

where the subscripts o and ao are associated with the values at tower exit (or initial values) and the ambient at the same level, and $L_v(t) = [597.31 - 0.57 \times t_o(°C)] \times 4.1868\ Jg^{-1}$, and $C_{pa} = 1.005\ Jg^{-1}°K^{-1}$.

2.2 Entrainment

The entrainment of ambient fluid into the plume is a function of plume geometry, local mean velocity, buoyancy, and ambient turbulence. The entrainment function first proposed by Morton et al. (1956) is:

$$E_{1r} = \alpha\ 2\pi b\ U_p \tag{2.25}$$

where α is entrainment coefficient determined from experiments; b is the round jet radius; and U_p is the jet centerline velocity.

Based on the integral conservation equations of mass, momentum, energy, and mechanical energy, and assuming similar profiles, Fox (1970) and Hirst (1971) derived an entrainment function for round jets which includes the effect of buoyancy to the entrainment. It reads as follows:

$$E_{1r} = (a_1 + \frac{a_2}{Fr_L} \sin\theta)\ 2\pi b\ U_p \tag{2.26}$$

where a_1 and a_2 are entrainment coefficients, and Fr_L is the local densimetric Froude number defined as $Fr_L = U_p^2/[(\rho_a - \rho_p)\ b\ g/\rho_o] = U_p^2/[(t_p - t_a)\ t_o bg/t_p\ t_a]$, and g is gravitational acceleration. Based on experimental results, a_1 was determined to be 0.057 for pure round jet with Gaussian profile distribution (i.e., $Fr_L \to \infty$). Hirst (1971) suggested the value of $a_2 = 0.97$. This appears to be too large when his results are compared with experiments. A better estimate of the value of

a_2 can be made from the work of List and Imberger (1973), who, based on dimensional analysis and experimental data, derived a similar expression for E_{1r} for round jets (Koh and Brooks, 1975)

$$E_{1r} = (0.057 + \frac{0.083}{F^2})\ 2\pi b\ U_p \tag{2.27}$$

where $F^2 = m^{5/2}/\mu^2\beta$ with m being the kinematic momentum flux $= \int_A U_p^{\ 2}\ dA$, μ the volume flux $= \int_A U_p\ dA$, and β the buoyancy flux $= \int_A gU_p \frac{\rho_a - \rho_p}{\rho_a}\ dA$.

Comparing equations (2.26) and (2.27) in a quiescent ambient (i.e. $\sin\theta = 1$) and calculating F^2 by using the Gaussian similarity profiles for U_p and ρ_p, one finds $a_2 = 0.083\ Fr_L/F^2 \simeq 0.4775$. Hence equation (2.26) becomes

$$E_{1r} = (0.057 + \frac{0.4775}{Fr_L}\ \sin\theta)\ 2\pi b\ U_p \tag{2.28}$$

The entrainment coefficient α in equation (2.25) has the extreme values for pure jet (i.e., $Fr_L \to \infty$) $\alpha_j = 0.057$ and pure plume (i.e., $Fr_L \to 0$) $\alpha_p = 0.082$ in a quiescent ambient. A critical value of Fr_L may be determined from

$$0.082 = 0.057 + \frac{0.4775}{Fr_{LC}}$$

which gives

$$Fr_{LC} = 19.1$$

For Gaussian similarity profiles of plume properties it will be assumed that

$$\begin{aligned} E_{1r} &= (0.057 + \frac{0.4775}{Fr_L}\ \sin\theta)\ 2\pi b\ U_p \quad \text{for } Fr_L > 19.1 \\ &= 0.082 \cdot 2\pi b\ U_p \qquad\qquad\qquad \text{for } Fr_L \leq 19.1 \end{aligned} \tag{2.29}$$

which implies that $Fr_L = 19.1$ was considered a small number below which the entrainment of a buoyant jet is similar to that of a pure plume.

Experimental results for two-dimensional slot jet are not sufficiently comprehensive to obtain a similar entrainment expression [i.e., equation (2.29)] (Koh and Brooks, 1975). Therefore, based on the experimentally determined entrainment coefficient, the following form will be used for the slot jet with Gaussian profile distribution, viz.,

$$E_{1s} = 0.14 \cdot 2A \cdot U_p \tag{2.30}$$

where A is the length of the slot jet.

The entrainment functions embodied in equations (2.29) and (2.30) are based on Gaussian profiles of plume properties. In this study, top-hat similarity profiles are assumed. The difference in the resulting entrainment functions [equations (2.29) and (2.30)] due to this is a factor of $\sqrt{2}$. Therefore, equations (2.29) and (2.30) can be rewritten as follows:

$$\begin{aligned} E_{1r} &= \left(0.0806 + \frac{0.6753}{Fr_L} \sin\theta\right) 2\pi b\, U_p \quad \text{for } Fr_L > 19.1 \\ &= 0.1160 \quad 2\pi b\, U_p \quad \text{for } Fr_L \leq 19.1 \end{aligned} \tag{2.31}$$

$$E_{1s} = 0.198 \cdot 2AU_p \tag{2.32}$$

As the plume bends over towards the direction of the ambient wind, the plume velocity is about equal to the wind velocity. Then the entrainment should be nearly as if the plume were a two-dimensional thermal in a stagnant atmosphere. This entrainment is proportional to the jet periphery and the velocity of the thermal. Abraham (1970) proposed the

following form

$$E_2 = a_3 \; P \; U_a \; \sin\theta \; \cos\theta \qquad (2.33)$$

where P is the jet periphery, $\cos\theta$ is arbitrarily chosen to diminish the thermal type of entrainment closed to the initial stage of the vertical jet, and a_3 is the entrainment coefficient for a line thermal. For large Reynolds number, the experimentally determined value of a_3 is 0.5 (Richards, 1963). But a better value suggested by Koh and Chang (1973) from their plume measurements and numerical model is 0.3536, which will be used in this present model. Thus

$$E_2 = 0.3536 \; P \; U_a \; \sin\theta \; \cos\theta \qquad (2.34)$$

Another type of entrainment is associated with ambient turbulence, and expressed as

$$E_3 = a_4 \; P \; U_a' \qquad (2.35)$$

where a_4 and U_a' are the entrainment coefficient and a measure of turbulent velocity fluctuations. Based on dimensional analysis, Briggs (1969) found that U_a' is associated with eddy energy dissipation in the inertial subrange and gave an estimate of $a_4 = 1$. In practice, the root-mean-square value of the ambient wind velocity fluctuation may be used to approximate U_a', which is equal to a few percent of the mean wind velocity under normal atmospheric conditions.

Finally, we may combine equations (2.31), (2.32), (2.34) and (2.35) to construct a complete entrainment function as

$$E = P \; \{\alpha|U| + 0.3536 \; U_a |\sin\theta| \cos\theta + 1.0 \; U_a'\} \qquad (2.36)$$

where for a round jet,

$$P = 2\pi b$$

$$\alpha = 0.0806 + \frac{0.6753}{Fr_L}|\sin\theta| \quad \text{for } Fr_L > 19.1$$

$$= 0.1160 \qquad \text{for } Fr_L \leq 19.1$$

and for a slot jet,

$$P = 2A$$

$$\alpha = 0.198$$

Here U is the net velocity in the plume relative to the ambient velocity; the absolute value is used here to account for both the ascending and descending parts of the plume.

In the literature on buoyant jets, various investigators employing the integral approach have devised differing entrainment functions. A recent survey for the round jet can be found in Wright (1977). The entrainment function expressed in equation (2.36) and incorporated in the present model is but one possible expression. Should a different form be shown to be superior in the future, the model can readily be modified.

2.3 Merging Process

The individual plumes from the multiple cells of a cooling tower typically merge within a relatively short distance from the exits. Before the plumes merge, equations for individual round buoyant jets are applied in this model to calculate the plume behavior. When several individual plumes are merged, the resulting plume cross-section is no longer round, but rather tends to be elliptical in shape. In this model,

this merged plume is approximated by a slot jet in the central part and two half round jets at the two ends of the merged plume as shown by the solid lines in Figure 2.3. The nonuniform size of the plume is due to the effect of the wind direction with respect to the tower configuration. In general, it is necessary to consider all types of plume merging including all the possible combinations between individual round plumes and modified merged plumes as shown in Figure 2.4. The basic merging criterion considered here is that the plume cross-sections are in contact with each other. An additional criterion is incorporated for the merging between two individual round plumes: the area of the trapezoid should be equal to the sum of the areas of the two half round plumes as circled by the dashed lines in Figure 2.3. When the plumes satisfy these merging criteria, they are merged. The fluxes of the merged plumes are summed to maintain the conservation of fluxes. Moreover, the new shape and the new centroids of the merged plumes are determined, and the integration of the equations is continued. Upon merging, the entrainment and drag functions are altered due to the change in plume shape. The merged plume shape is characterized by the radii B1 and B2 of the two half round plumes, length of the slot jet A, and the angle ϕ (shown in Figure 2.3) between the centerline of the (inclined) plume cross-section and the horizontal line parallel to the y-axis. As the plumes merge a new set of B1, B2, A and ϕ should be determined in order to calculate the entrainment and drag and to check if any other new plume merging occurred. To determine B1, B2, A and ϕ the plumes are classified into two categories: one will be called horizontal for which the total width (WD) of the new merged plume is larger than the total

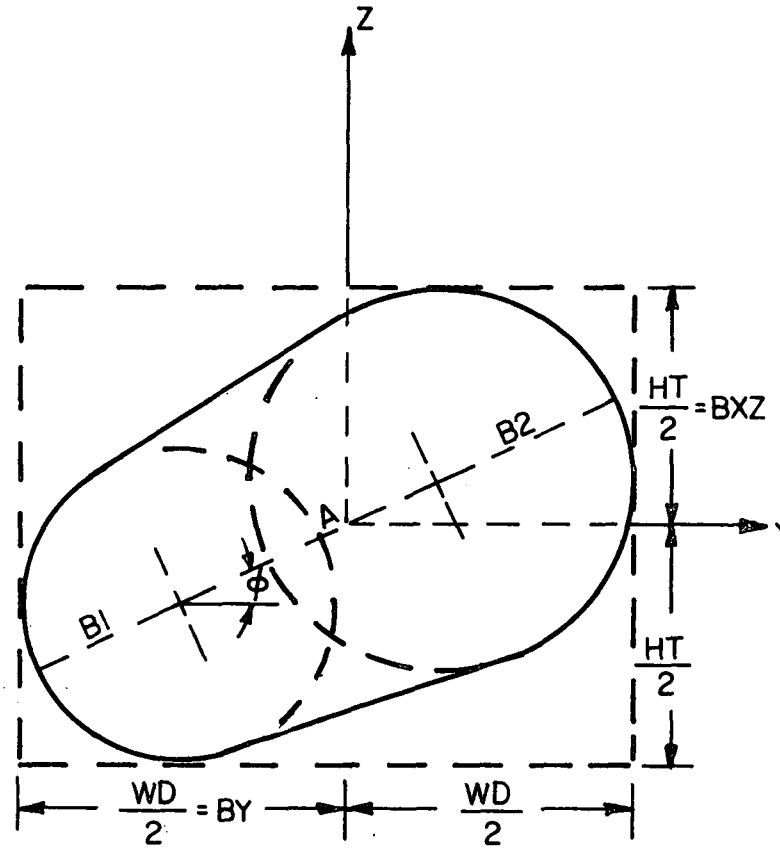


Figure 2.3 Merged Plume Shape

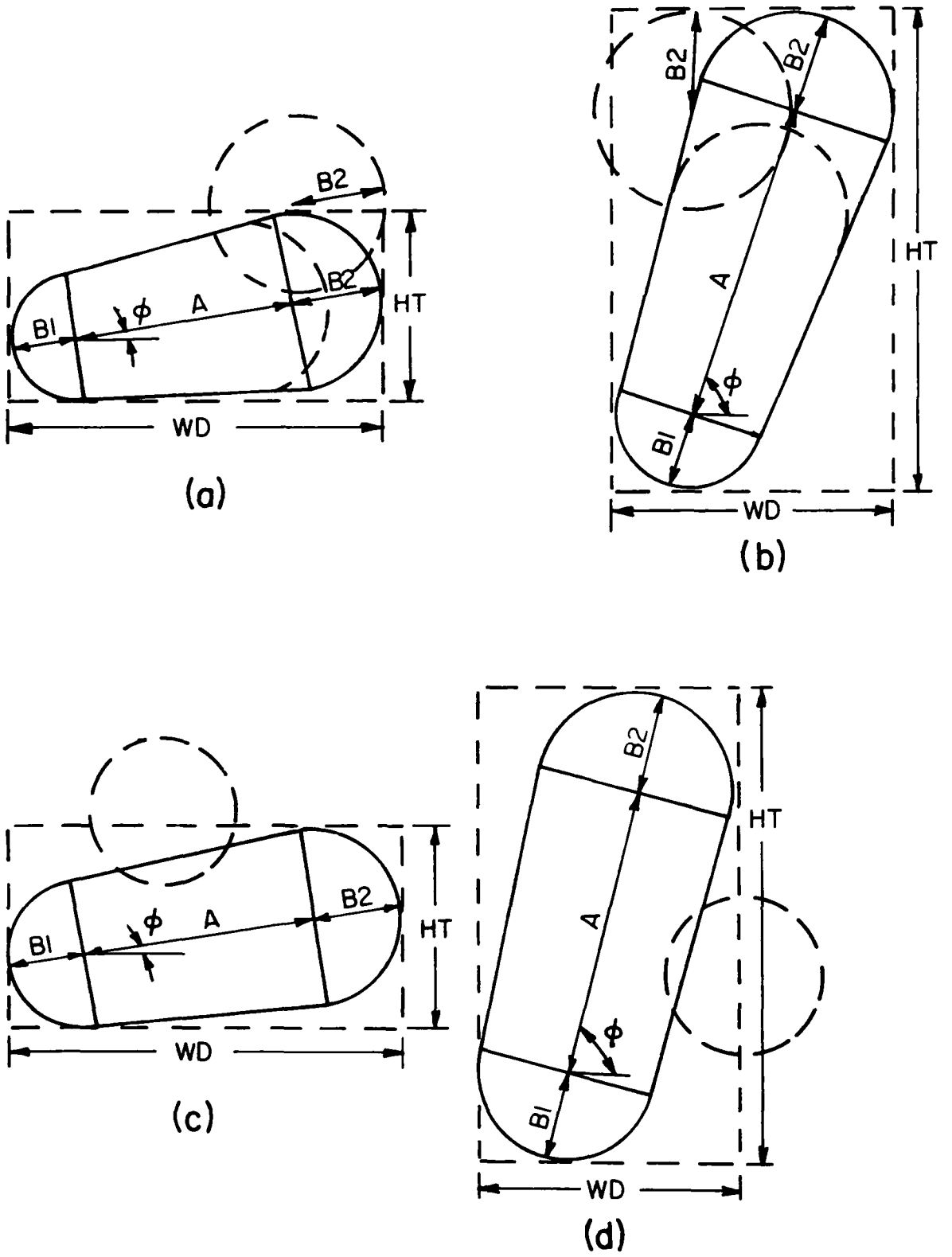


Figure 2.4 Definition Sketch

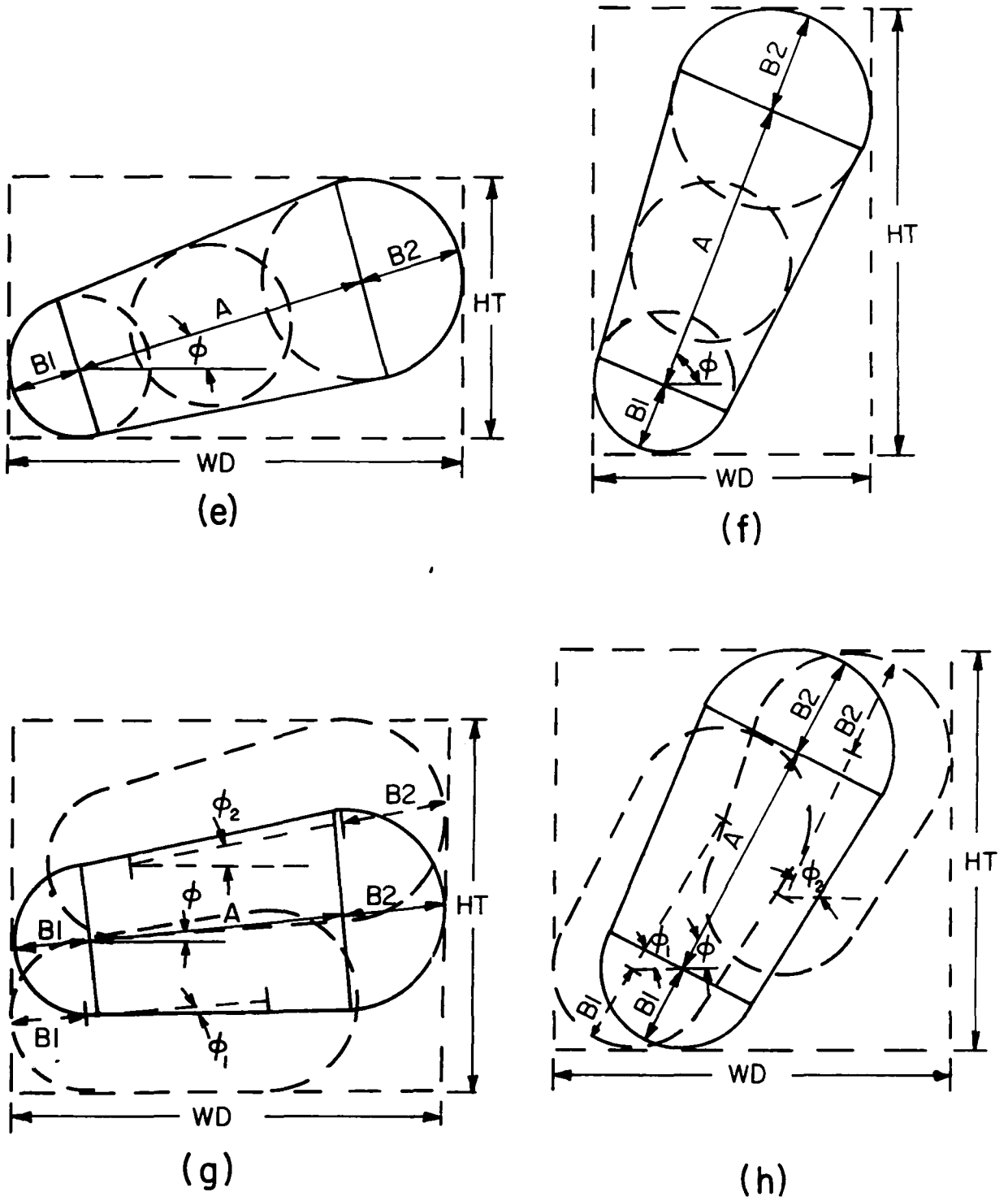


Figure 2.4 Definition Sketch

height (HT), otherwise, it will be called vertical. Both types are illustrated by Figures 2.4(a), (c) and (e); and (b), (d) and (f), respectively. These two categories are not different in substance and the distinction is made primarily for coding convenience in the computer program. B1 and B2 are chosen to be the radii of the left end (or lowest end) and the right end (or highest end) of the horizontal (or vertical) plumes, respectively. The left end of the plume is the end closer to the x-axis. For the cases of merging among individual round plumes as shown by Figure 2.4(a) and (b), ϕ is the angle between the horizontal line and the line connecting the two centers of the merged ending plumes. For the cases of merging between merged plumes, ϕ is the average of angles ϕ_1 and ϕ_2 of the merging plumes 1 and 2, respectively, as shown in Figures 2.4(c) and (d). For the cases of individual round plume 2 joining the merged plume 1 as shown in Figures 2.4(e), (f), (g) and (h), ϕ is assumed to maintain the original value of the merged plume 2 since the resulting merged plume is envisioned to be dominated by the merged plume 2. After B1, B2 and ϕ are determined, A can be calculated by the following equations.

For horizontal plumes:

$$A = (WD-B1-B2)/\cos\phi \qquad \text{for } \cos\phi \neq 0$$

$$A = HT-B1-B2 \qquad \text{for } \cos\phi = 0$$

For vertical plumes:

$$A = (HT-B1-B2)/\sin\phi \qquad \text{for } \sin\phi \neq 0$$

$$A = WD-B1-B2 \qquad \text{for } \sin\phi = 0 \qquad (2.37)$$

When the new shape of the merged plume is determined, then the calculation can be performed forward one integration step for the round jets at

the ends and the slot jet (with unit fluxes found by dividing the total fluxes of the slot jet by the finite length A) in the central part. This will result in new values for the radii of the round jets at the ends of the merged plumes, b_{r1} and b_{r2} and the half width and length of the central part slot jet b_s and a. Because of the different entrainment rates for round and slot jets, the calculated plume cross-section determined by b_{r1}, b_{r2}, b_s and a may not be smooth enough to represent a realistic shape. The discontinuities occurring at the junctions of the round and slot jets are demonstrated by the dashed line curve in Figure 2.5. In order to eliminate the discontinuity and to obtain a modified smooth plume cross-section described by B1, B2, and A, the following set of equations is proposed:

$$0.5\pi\ (b_{r1}^2\ U_{r1}\ + b_{r2}^2\ U_{r2}) + 2b_s a U_s =$$

$$[0.5\pi\ (B1^2 + B2^2) + A\ (B1 + B2)] \cdot U \qquad (2.38)$$

$$a + b_{r1} + b_{r2} = A + B1 + B2 \qquad (2.39)$$

$$B1/B2 = b_{r1}/b_{r2} \qquad (2.40)$$

where U_{r1}, U_{r2}, U_s and U are the plume velocities corresponding to the half round jets with radii b_{r1} and b_{r2}, the slot jet with half width b_s, and the overall merged plume defined by B1, B2 and A, respectively.

Equation (2.38) describes the redistribution of the volume flux from the calculated merged plume to the proposed modified plume. Equation (2.39) maintains the same plume length between the calculated and modified plumes. Equation (2.40) keeps the same ratios of the radii of the two half round plumes between calculated and modified plumes.

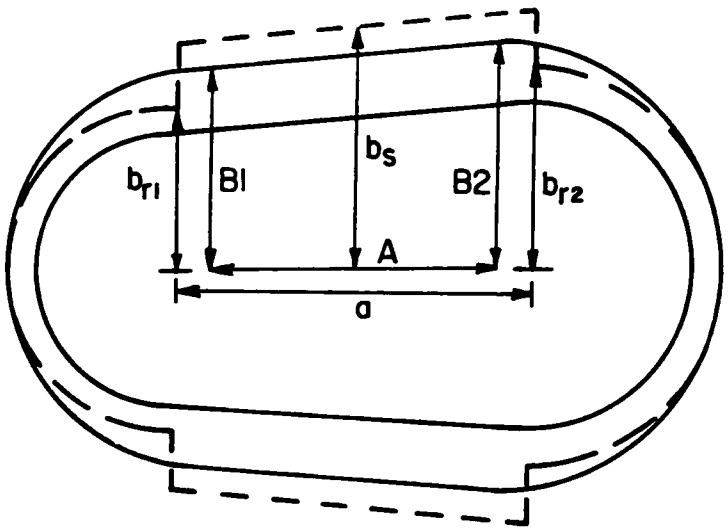


Figure 2.5 Modified Merged Plume Shape

After the modified plume shape is determined, the half width, BY and the half height, BXZ of the merged plume, indicated in Figure 2.3, can be determined by the following equations for the purpose of checking plume merging at the next step:

$$
\begin{aligned}
BY &= 0.5x\ (A \cdot \cos\phi + B1 + B2) && \text{for } \cos\phi \neq 0 \\
&= B1 && \text{for } \cos\phi = 0 \text{ and } B1 \geq B2 \\
&= B2 && \text{for } \cos\phi = 0 \text{ and } B2 > B1 \\
BXZ &= 0.5x\ (A \cdot \sin\phi + B1 + B2) && \text{for } \sin\phi \neq 0 \\
&= B1 && \text{for } \sin\phi = 0 \text{ and } B1 \geq B2 \\
&= B2 && \text{for } \sin\phi = 0 \text{ and } B2 > B1
\end{aligned}
\tag{2.41}
$$

Due to the uneven change of B1, B2 and A for each integration step, the y-coordinate of the plume centroid also needs to be readjusted. The amount of adjustment Δy noted in Figure 2.6 is

$$
\Delta y = \left[\frac{A_j + B1_j + B2_j}{2} \times \frac{A_{j+1}}{A_j} + B2_{j+1} - \frac{A_{j+1} + B1_{j+1} + B2_{j+1}}{2} \right] \cdot |\cos\phi|
$$

$$
= 0.5x|\cos\phi| x \left[(B1_j - B2_j) x \frac{A_{j+1}}{A_j} + B2_{j+1} - B1_{j+1} \right]
$$

where j and j+1 refer to the calculation steps.

With the modified merged plume cross-sectional shape, the entrainment and drag force can be determined and the conservation equations integrated. During the calculation, barring further merging, the length of the slot jet A generally will be reduced and the radii of the two ending round plumes will be increased. Finally, when A diminishes to zero, the shape of the merged plume cross-section becomes practically

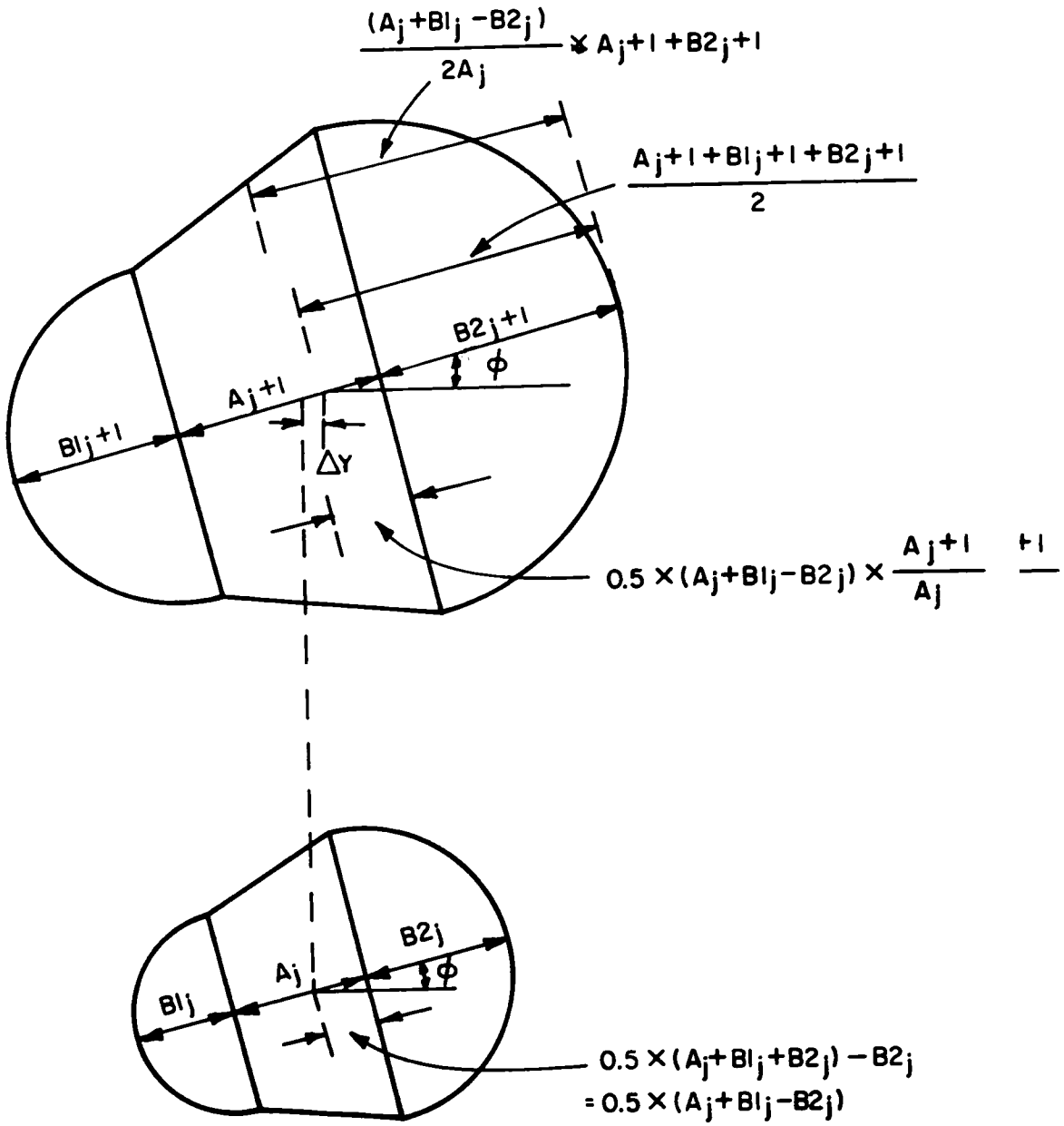


Figure 2.6 Correction of Δy for the Merged Plume

round. At that point, a round plume is again adopted to carry through the final stage of plume calculation.

CHAPTER 3

COMPUTER PROGRAM

The governing equations for predicting the dynamic behavior of multiple cooling tower plumes were presented in Chapter 2. No analytical solution can be obtained due to their complexity as well as the arbitrary ambient conditions in the governing equations. Therefore, a computer program written in Fortran IV language was developed to solve these equations. A standard fourth order Runge-Kutta method was employed in the solution. The inputs to the program include tower exit conditions, ambient conditions, tower configuration, entrainment and drag coefficients, and some control parameters. The basic routine of the computer program begins with inputting data, setting initial conditions (subroutine SETIC) and calculating the first plume (from the tower with the smallest value of x) by setting an indicator IND(I) = 1 for i^{th} individual round plume (subroutines RUNGS and DERIVR). As the calculation continues, the subroutines CHKNWP, ALIGN and PLMERG are called to check for the appearance of any new plumes, to align the existing plumes at approximately the same x-coordinate, and to check for the merging among the existing plumes, respectively, along the direction of the plume trajectory. If new plumes appear (whenever x exceeds the x-location of downstream tower exits), the results for such new plumes are calculated stepwise until the stage is reached to necessitate the checking of the merging criterion. If the plumes merge, the indicator of the ith and the jth plumes are changed to IND(I) = 2 and IND(J) = 0 (J>I). In the subroutine RESETI, the fluxes of the merged plumes are added together, and the initial conditions for the merged plumes are

reset. The subroutines DERIVR and DERIVS are called to calculate the plume half widths and velocities of the round and slot jets in order to determine the shape of the modified merged plume. Then, subroutine DERIVE is used to calculate the dynamic properties of the modified merged plume. The calculation stops when the integration step number is equal to the desired (input) step number. The outputs include the input information, and the calculated plume properties such as temperature, excess temperature, moisture, excess moisture, half width and trajectory at visible, merging and final stages of the plumes. The detailed listings and examples of the input and output are presented in Appendix A. The general structure of the computer program is described by the flow chart shown in Figure 3.1. Some important variables in the text and program are compiled and listed in Appendix B. The complete computer program is presented in Appendix C.

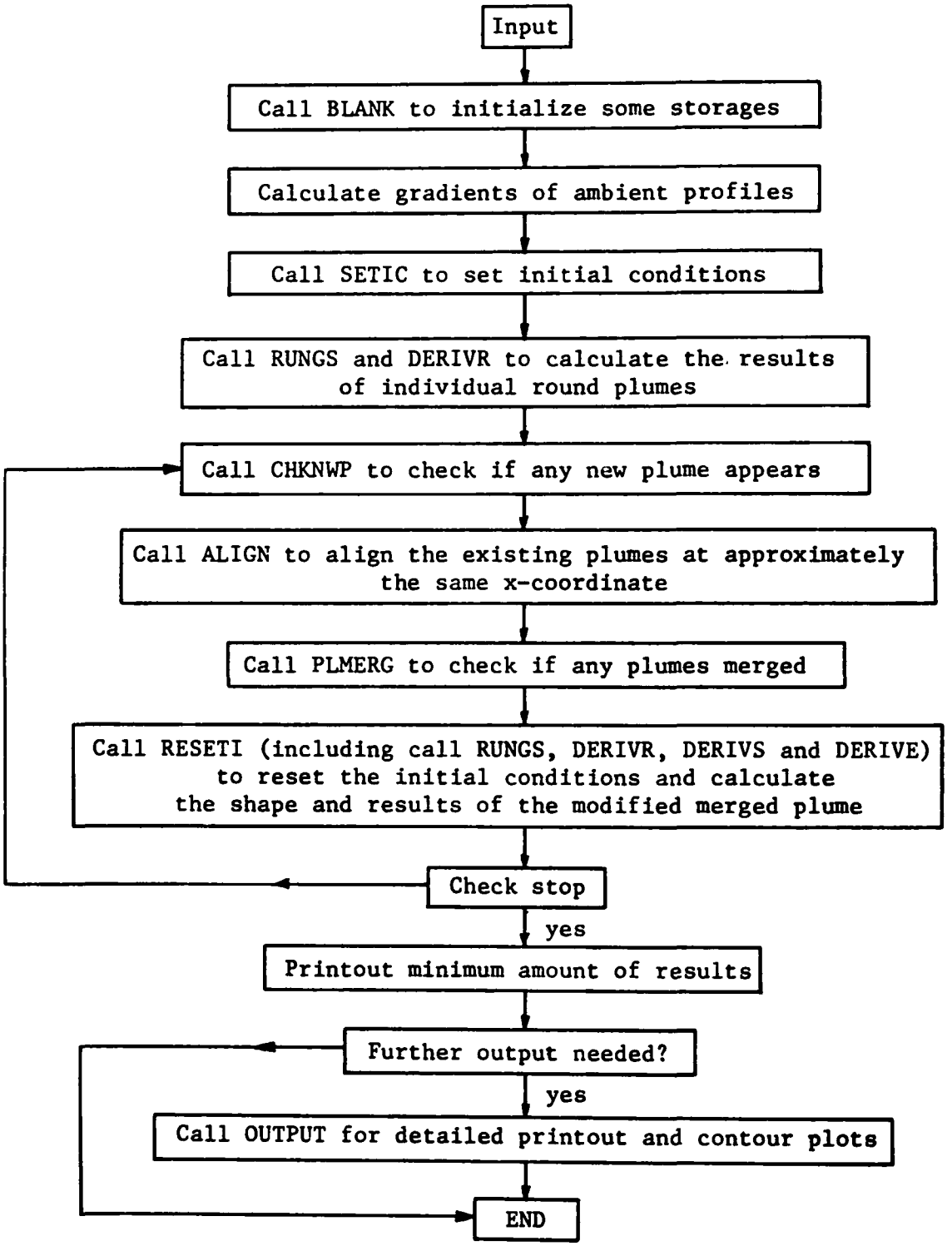


Figure 3.1 Flow Chart of the Computer Program

CHAPTER 4

RESULTS, COMPARISONS AND DISCUSSIONS

In this chapter, four example cases are presented. The results of the present theory are also compared with the laboratory results of Fan (1967), Chan et al. (1974), and field data from TVA (Carpenter et al., 1968).

In the example runs, a line array of four cooling towers and a round array of five cooling towers are considered. For the cases with the line array, three wind directions (i.e. 0°, 90°, and 135° with respect to the tower array) are chosen. The input data cards are shown in Table 4.1, which include the number of towers, the desired number of calculation steps, control parameters, tower configuration, ambient levels, temperature profile, humidity profile, wind velocity profile, tower exit conditions, coefficients of contour plots and heading of plots. Normally, the outputs consist only of the input information, the results at the merging points, and those at the beginning and ending points of the visible phases of plumes. However, detailed printouts and/or contour plots can also be provided by the program upon request. The contour plots of excess temperature, humidity and liquid phase moisture for these examples are shown in Figures 4.1 through 4.12. The plots represent the distribution of the highest values projected onto the X-Z plane. Detailed explanations of the input and output parameters are presented in Appendix A.

Three sets of data from Fan (1967) for a single jet, one set from Chan et al. (1974) for six towers and two sets from Carpenter et al. (1968) for a single tower and multiple towers are chosen for comparison with the model.

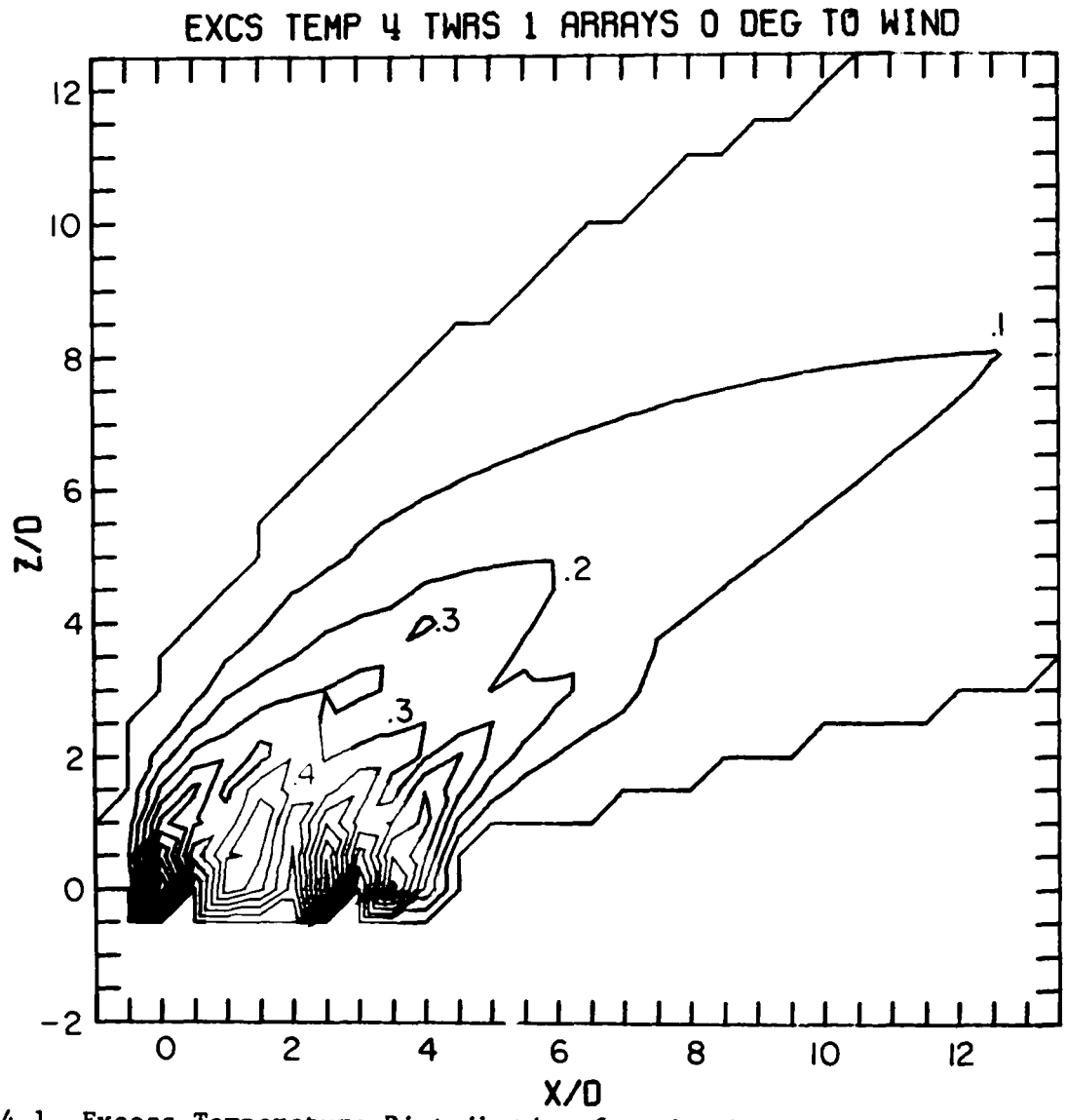


Figure 4.1 Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction

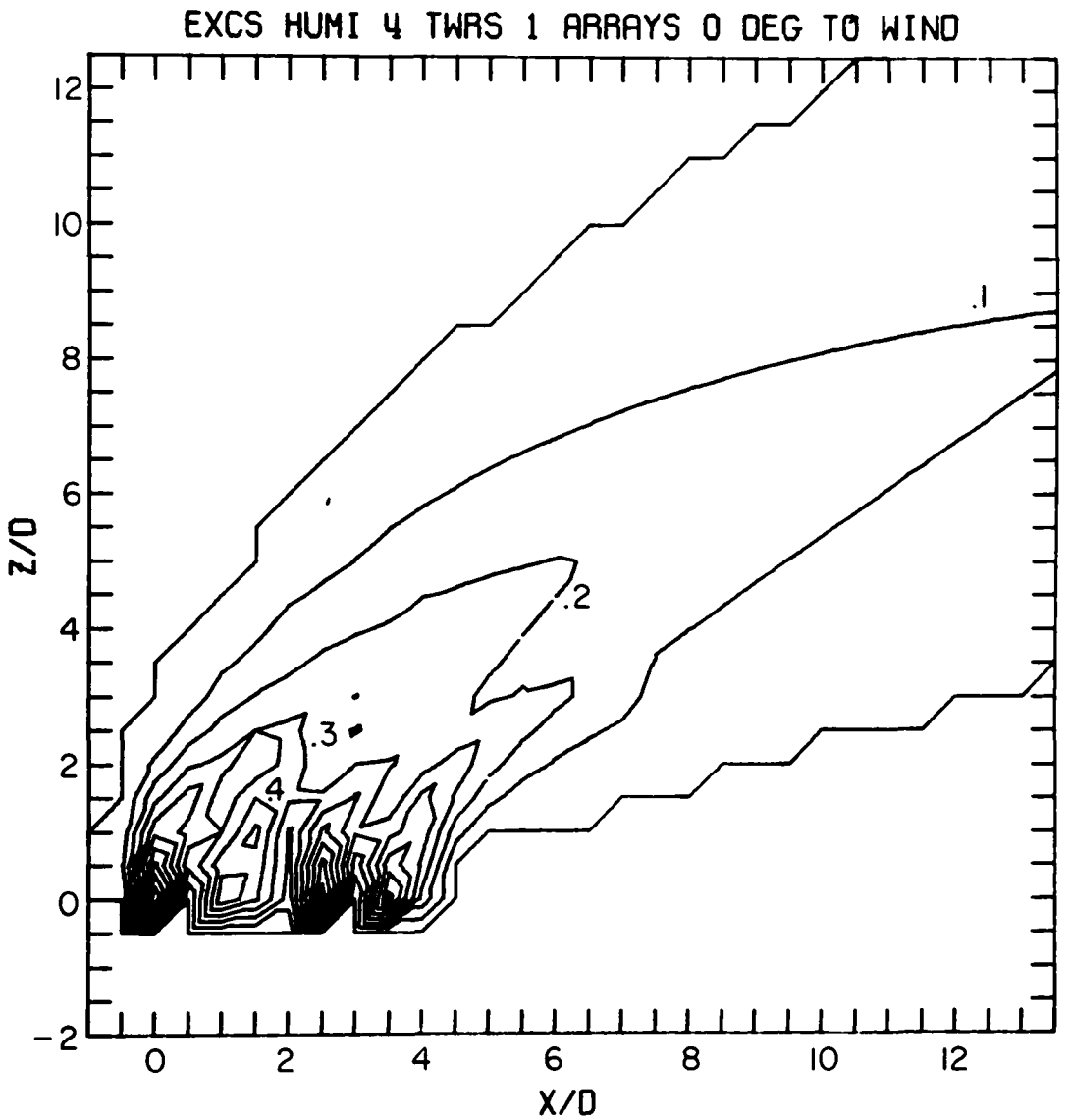


Figure 4.2 Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction

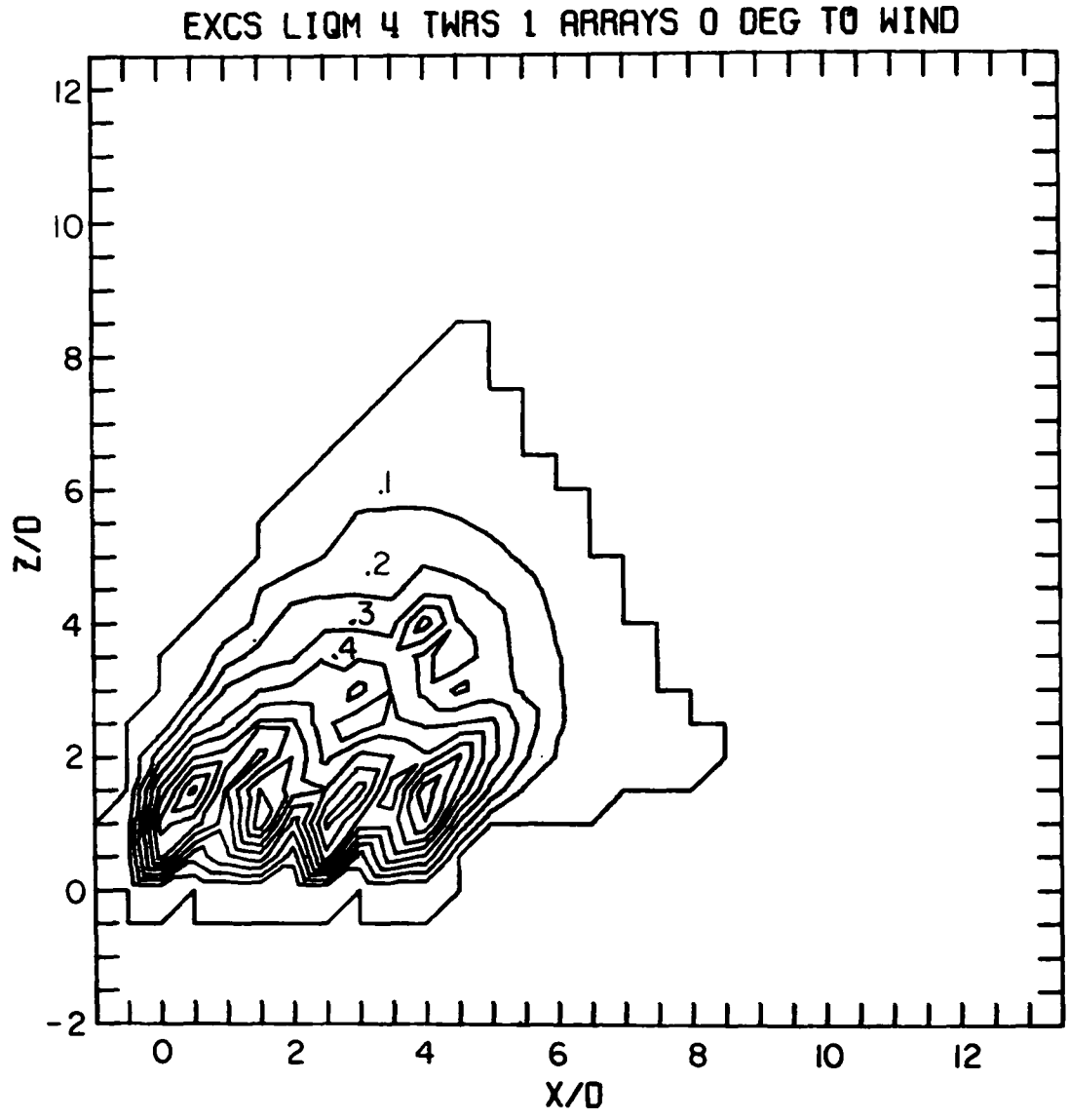


Figure 4.3 Excess Liquid Phase Moisture Distribution for the Case of 4 Towers in Linear Array and 0° to Wind Direction

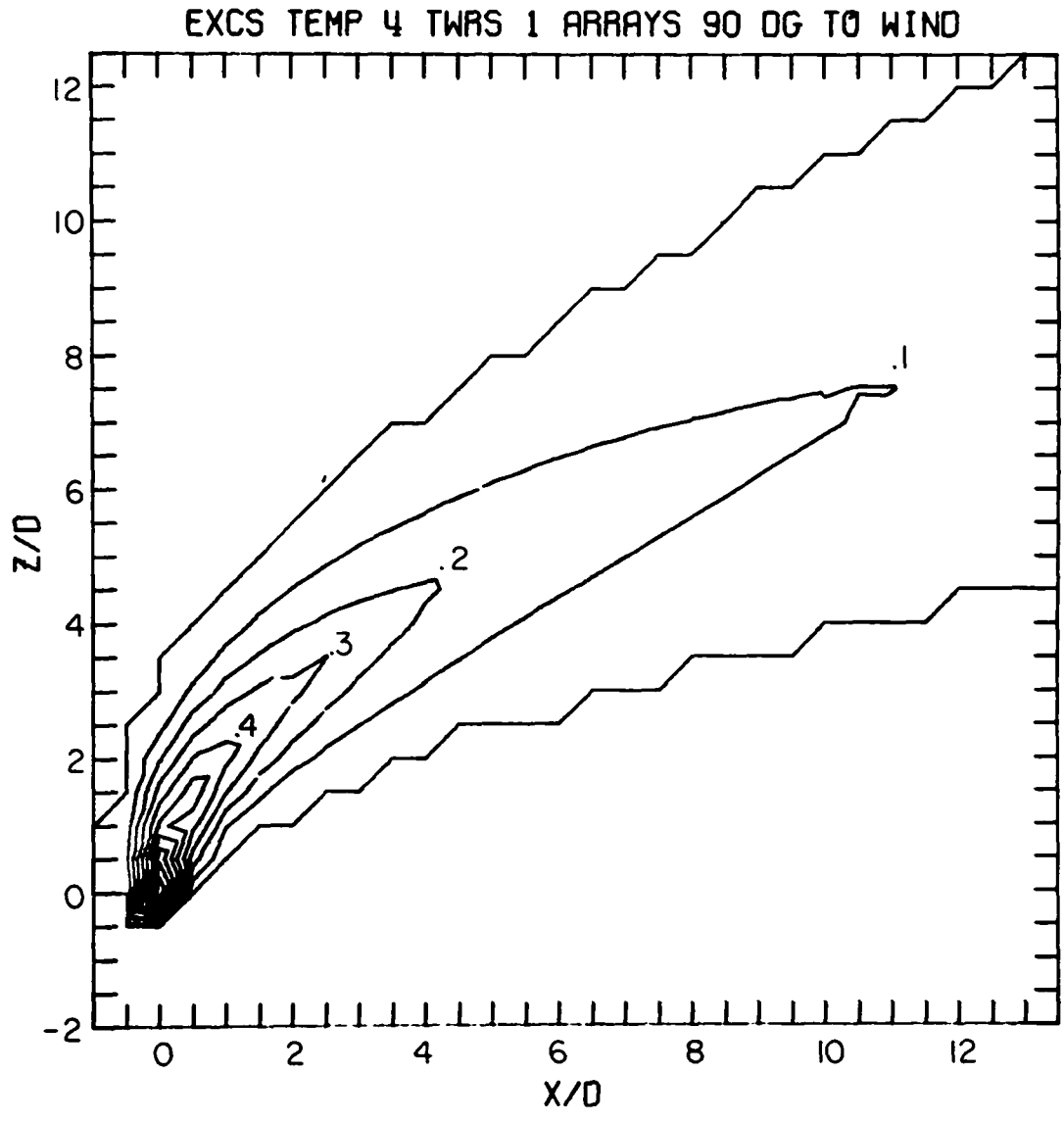


Figure 4.4 Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction

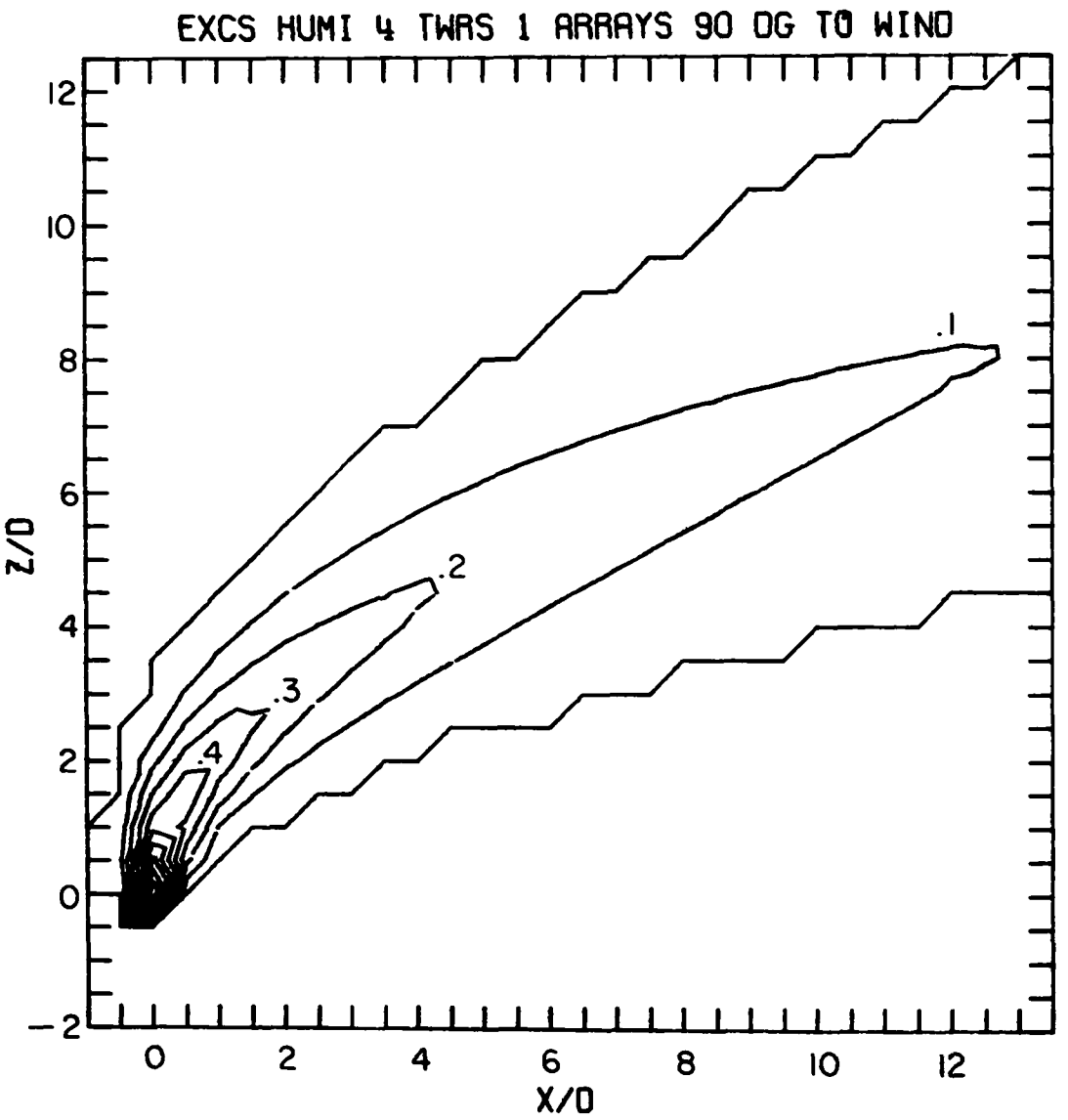


Figure 4.5 Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction

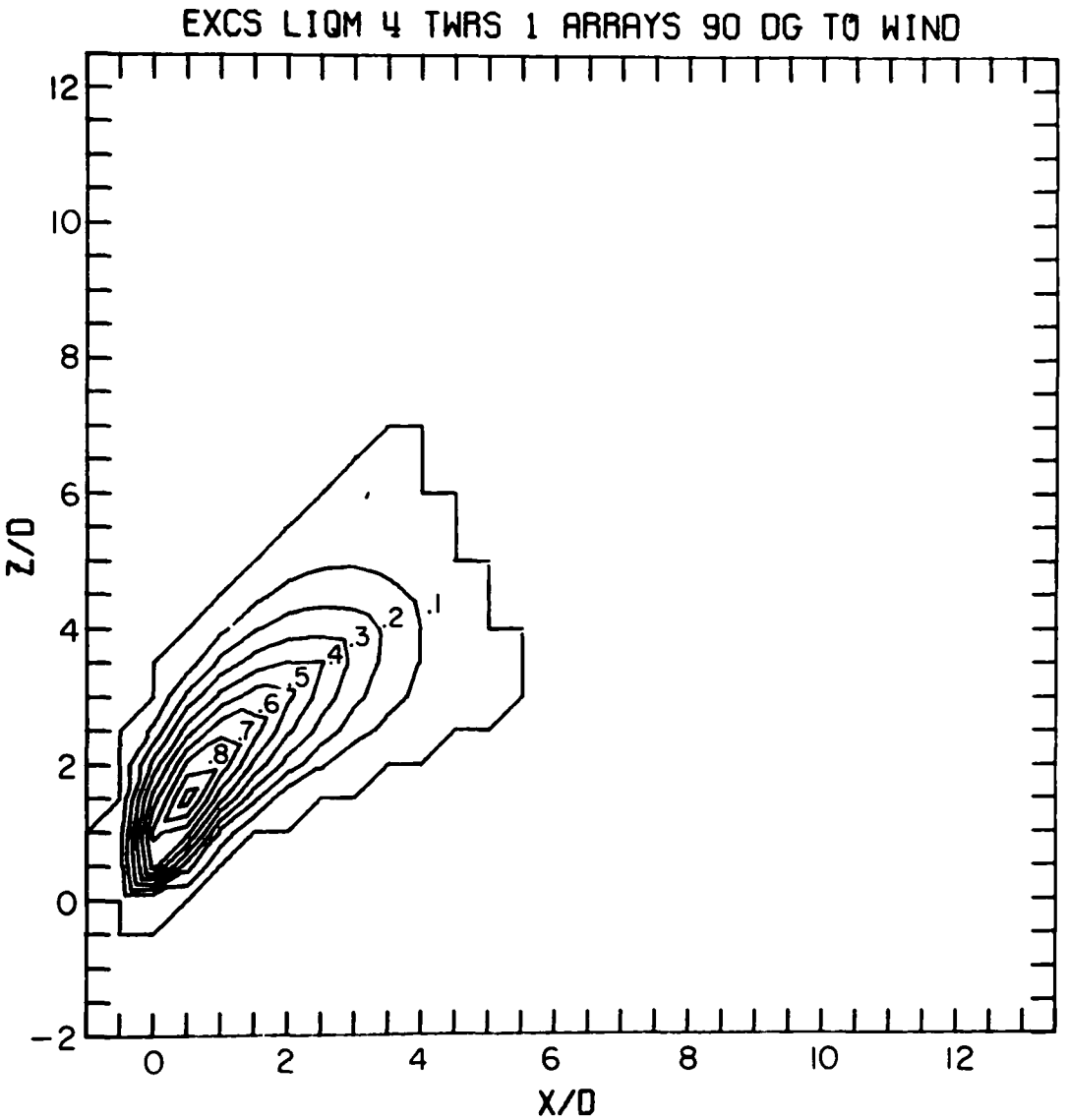


Figure 4.6 Excess Liquid Phase Moisture Distribution for the Case of 4 Towers in Linear Array and 90° to Wind Direction

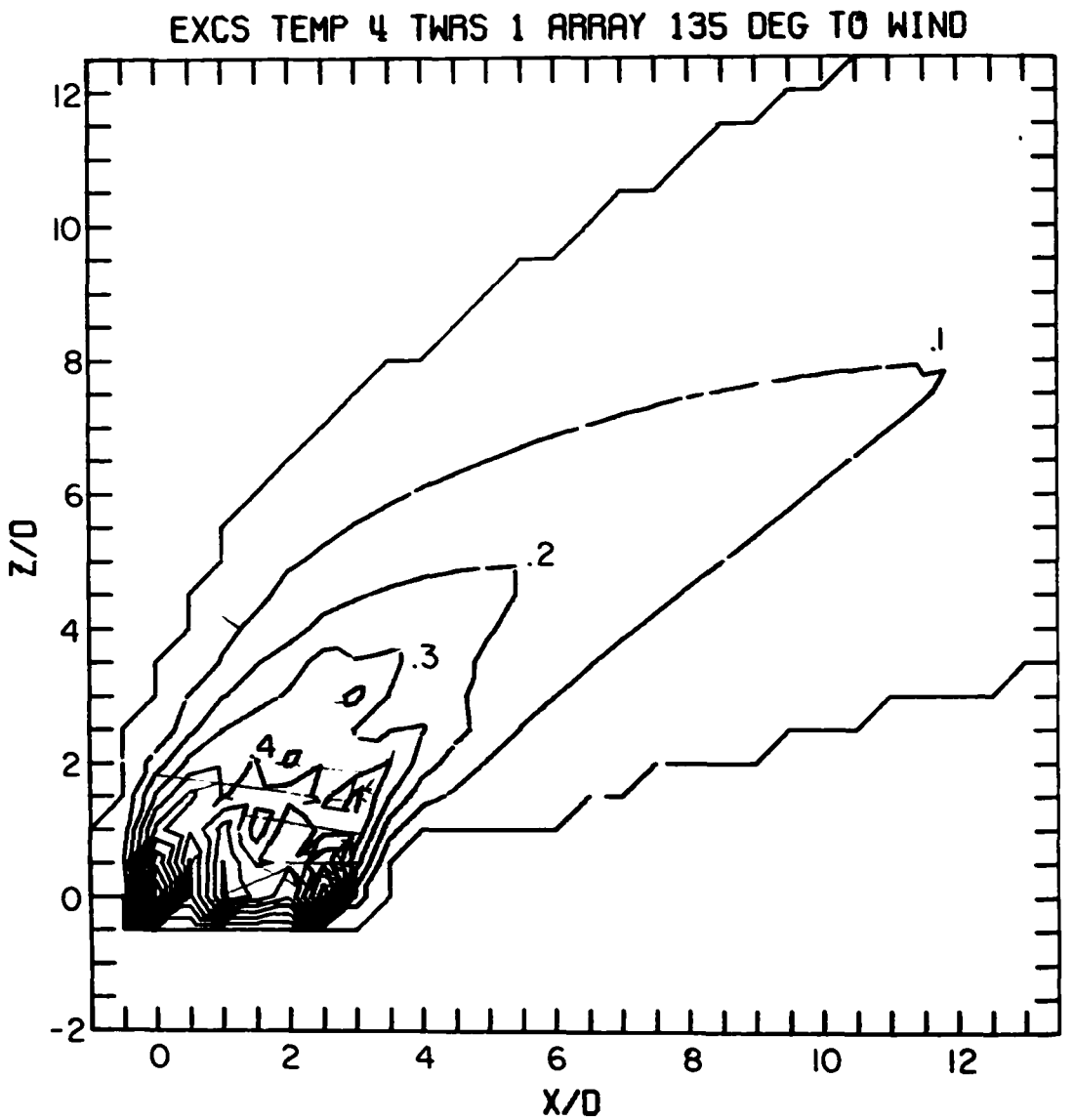


Figure 4.7 Excess Temperature Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction

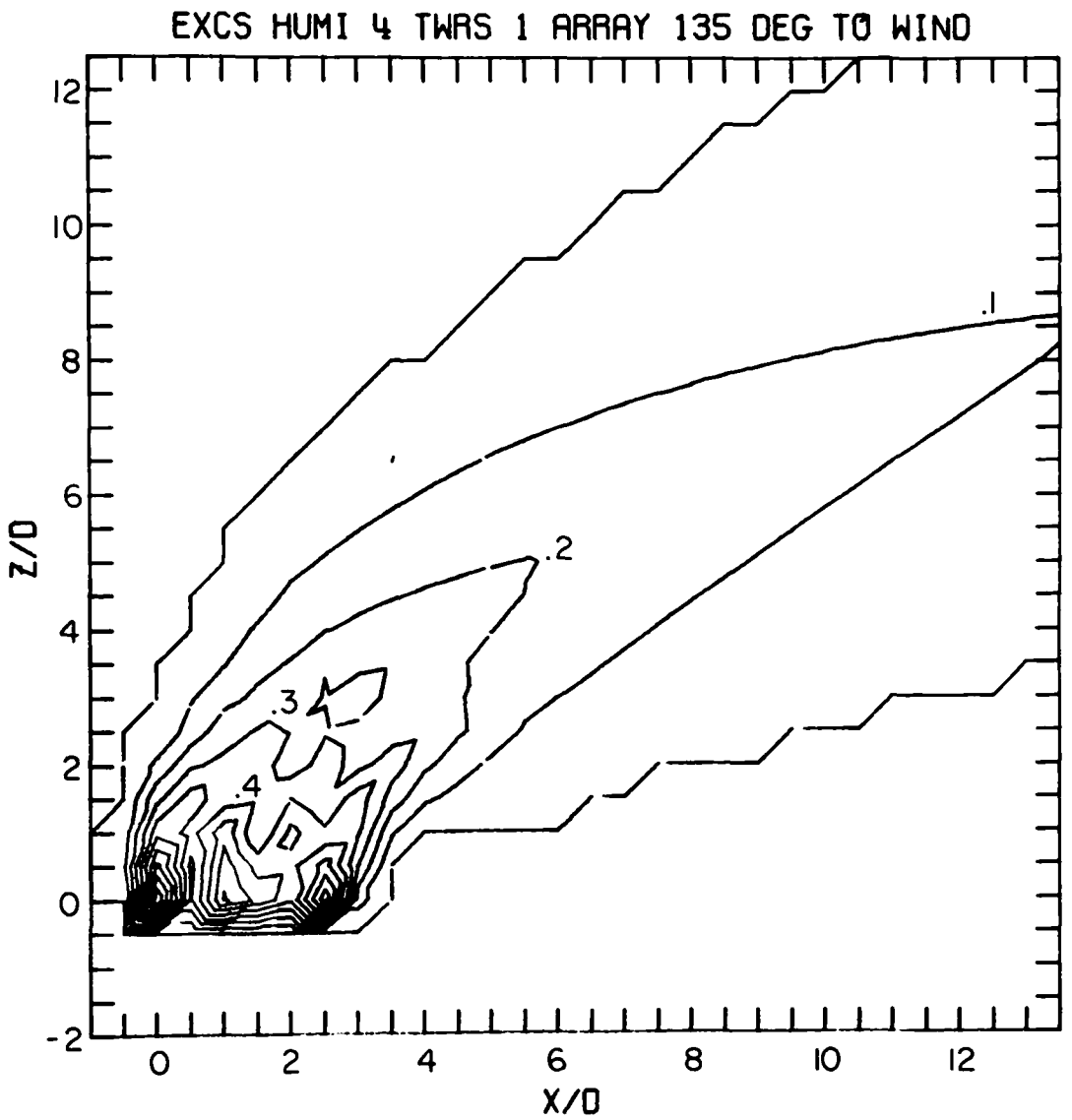


Figure 4.8 Excess Humidity Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction

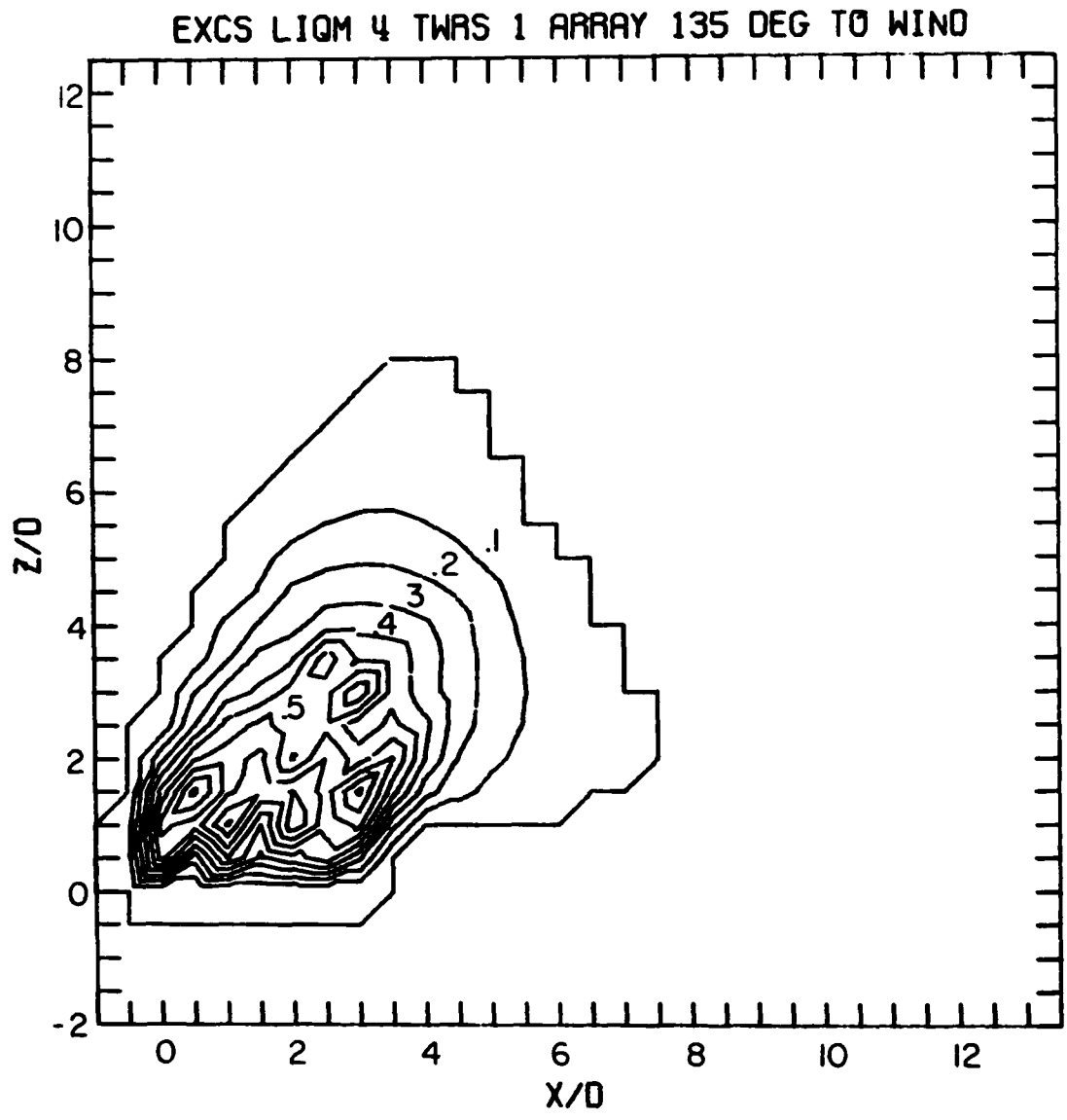


Figure 4.9 Excess Liquid Phase Moisture Distribution for the Case of 4 Towers in Linear Array and 135° to Wind Direction

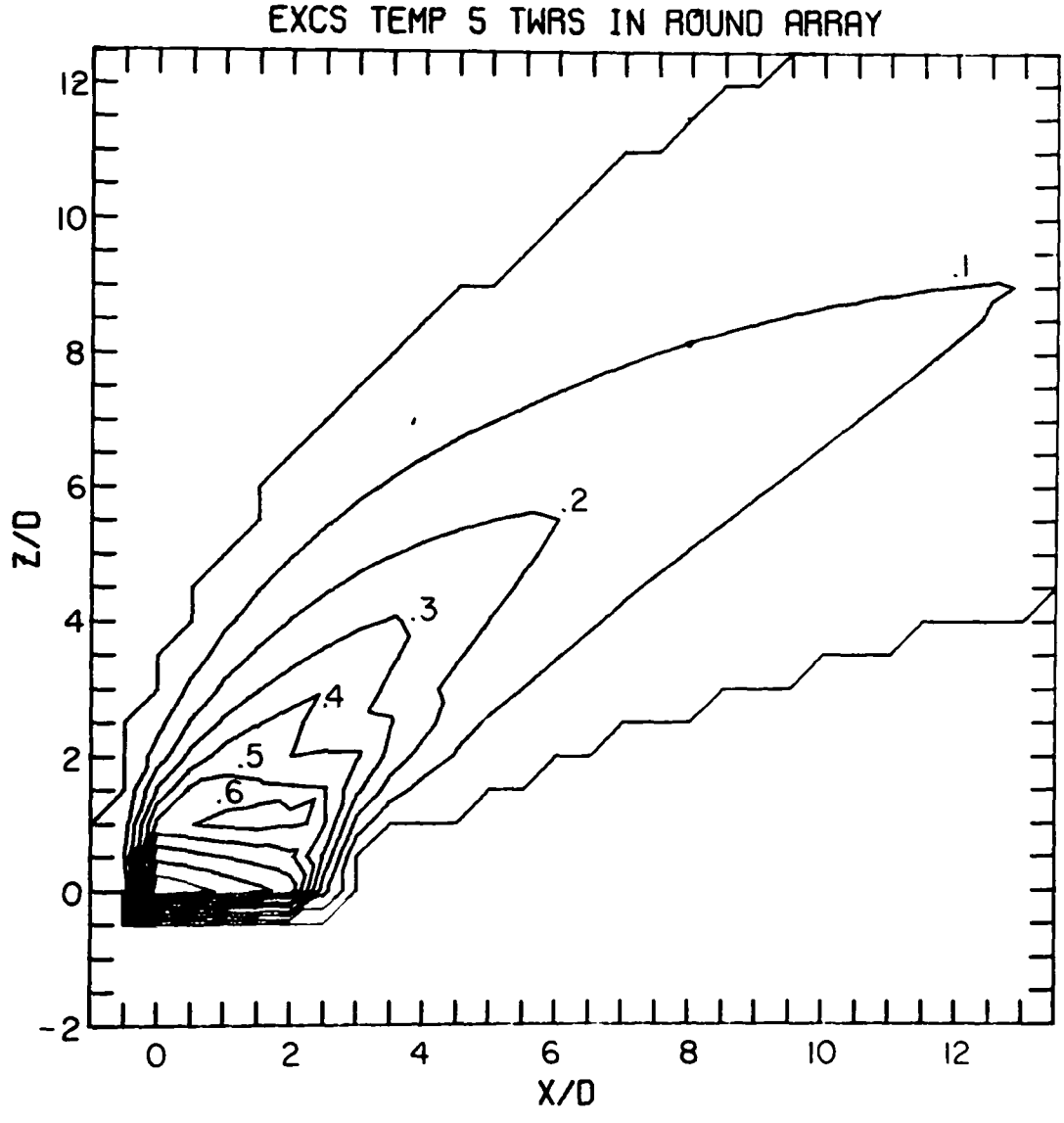


Figure 4.10 Excess Temperature Distribution for the Case of 5 Towers in Round Array

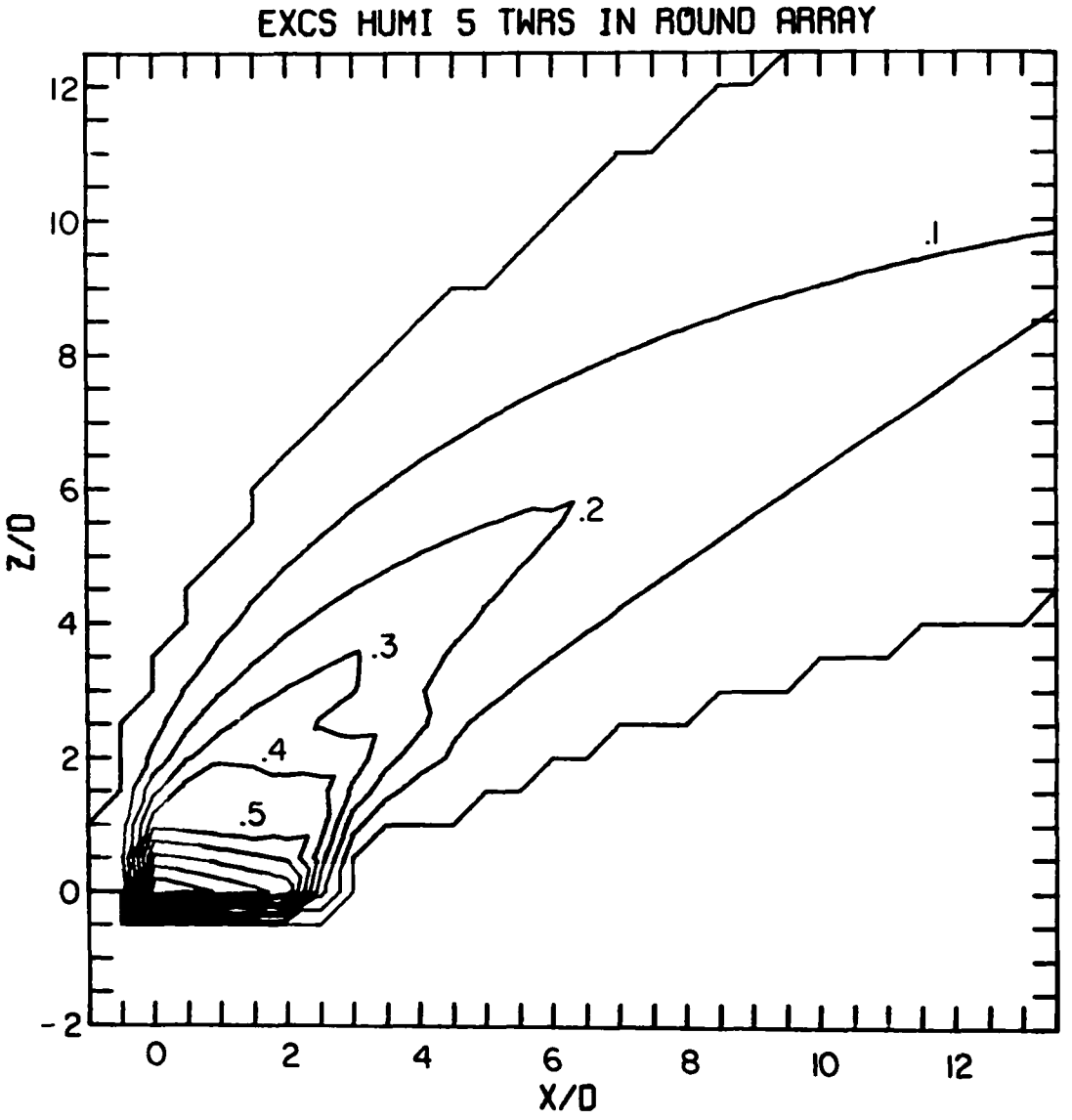


Figure 4.11 Excess Humidity Distribution for the Case of 5 Towers in Round Array

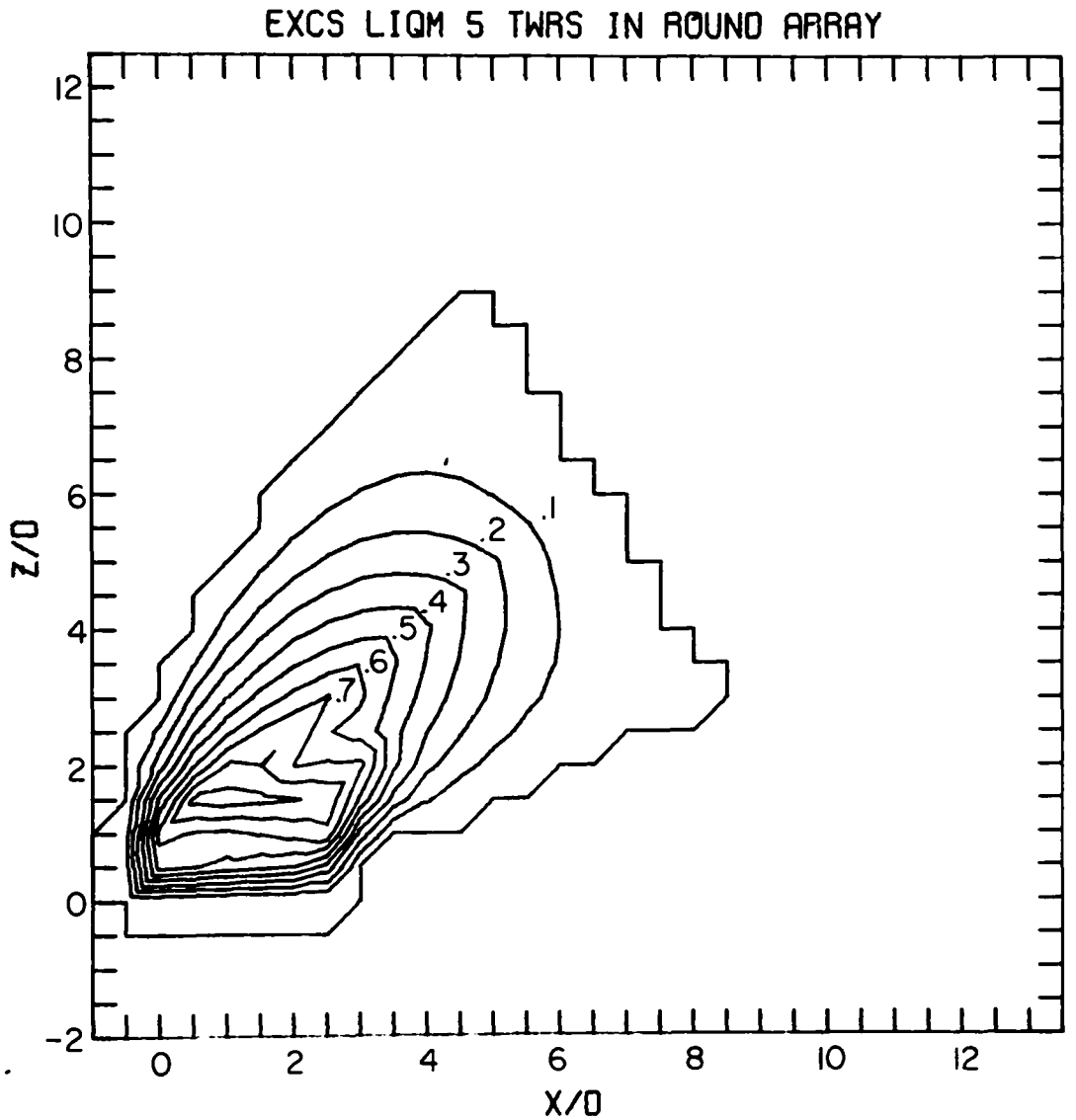
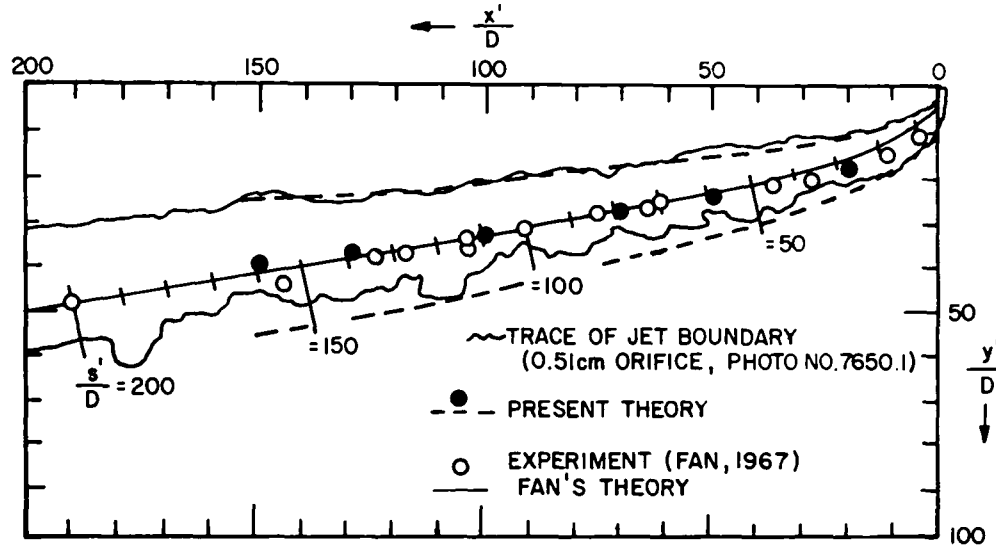


Figure 4.12 Excess Liquid Phase Moisture Distribution for the Case of 5 Towers in Round Array

The input data cards for these cases are shown in Tables 4.2 through 4.5. The ambient conditions for the data from Fan and Chan et al. are uniform. The velocity and temperature at the tower exit and ambient are chosen to satisfy the given values of densimetric Froude number F and velocity ratio K. The predicted results of dilution, plume trajectory and width for Fan's cases are shown in Figures 4.13, 4.14 and 4.15, and are compared with his experimental results. The comparisons are generally good. The predicted excess temperature distribution for the six tower case from Chan et al. is shown in Figure 4.16, together with the experimental results. In this case the six towers are in one line array and the ambient flow to it is normal. The contour plot is for the distribution of values in the central x-z plane. It seems that the present model tends to overpredict the excess temperature. The main reason might be because of the neglect of the effect of the mixing in the plume wake zone in the present model. However it should also be noted that the experimental results of Chan et al. may have been influenced by the blockage of the flow by the model towers due to the finite width of the experimental flume.

The field results from TVA at the Paradise power plant include two cases. One is for a single tower in a stable ambient (TVA-11, potential temperature gradient $\frac{\partial\theta}{\partial z} = 0.59$ °k/100m, $0 < \frac{\partial\theta}{\partial z} \leq 1.0$ °k/m). The other is for two towers in an ambient with a temperature inversion (TVA-14, $\frac{\partial\theta}{\partial z} = 1.42$ °k/100m > 1.0 °k/m). Since only the average temperature gradient and average wind velocities at a few levels were available only rough estimates of ambient temperature and wind velocity profiles were constructed based on the limited data.



F=20 k=8 60(d)

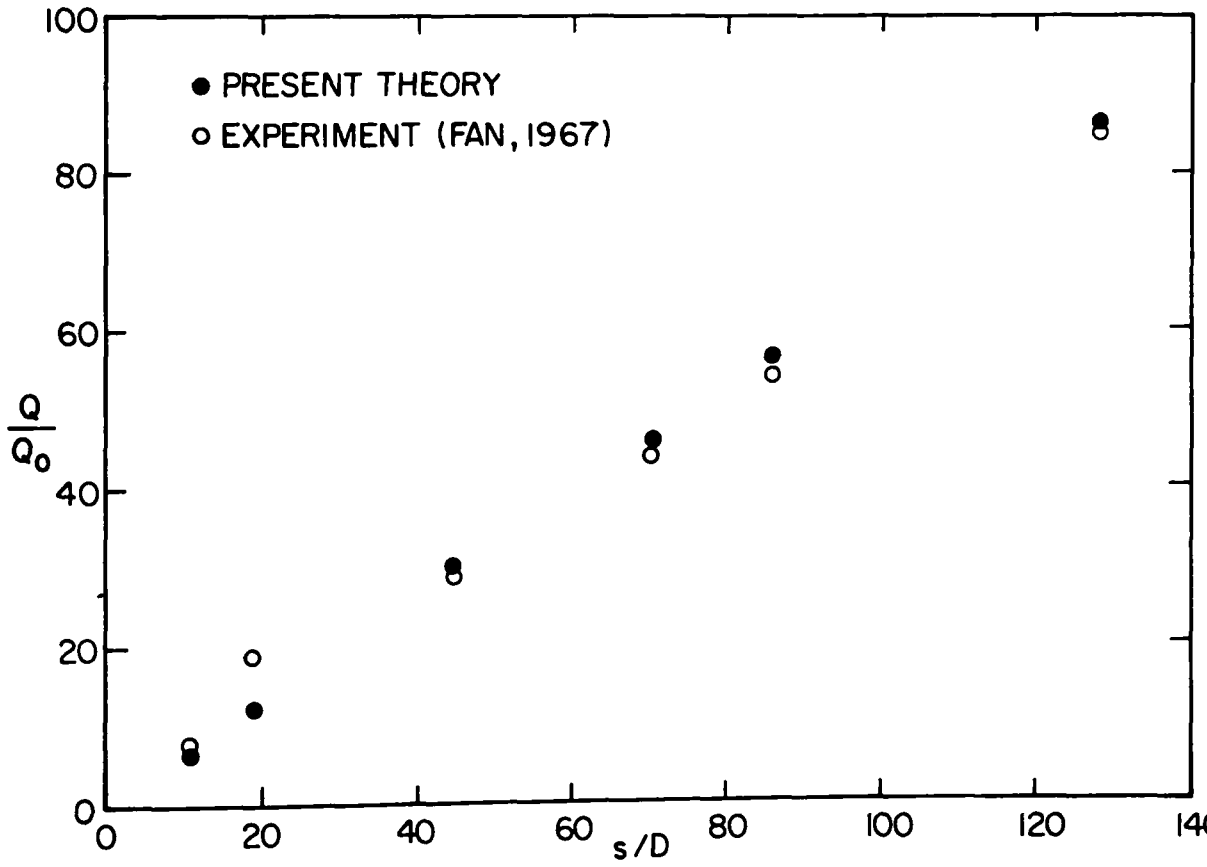
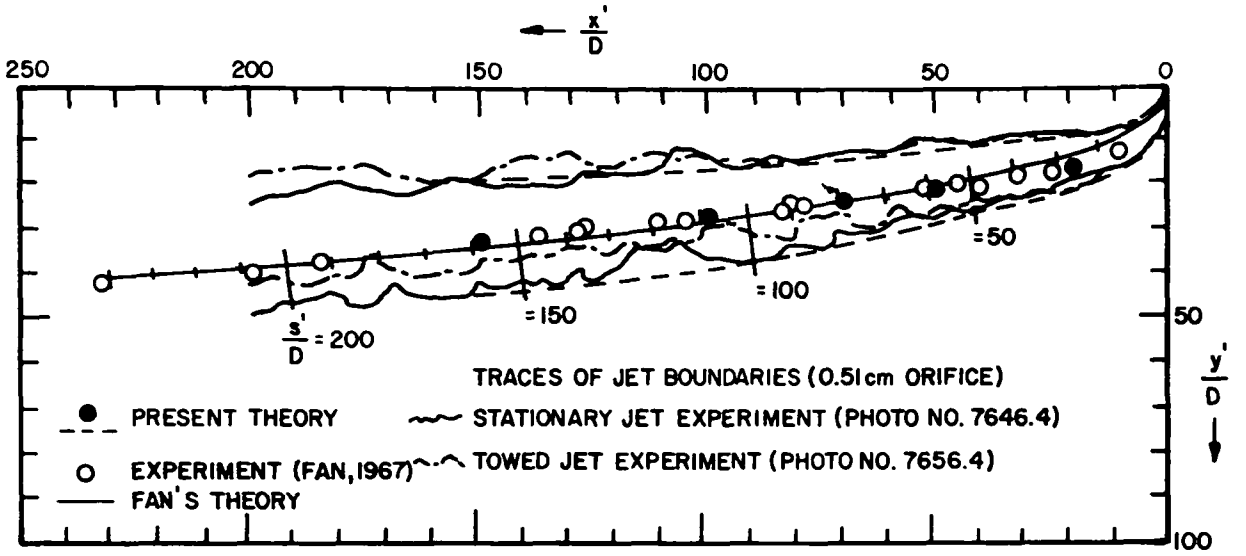


Figure 4.13 Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for F = 20 and K = 8



F=40 k=8 60(g)

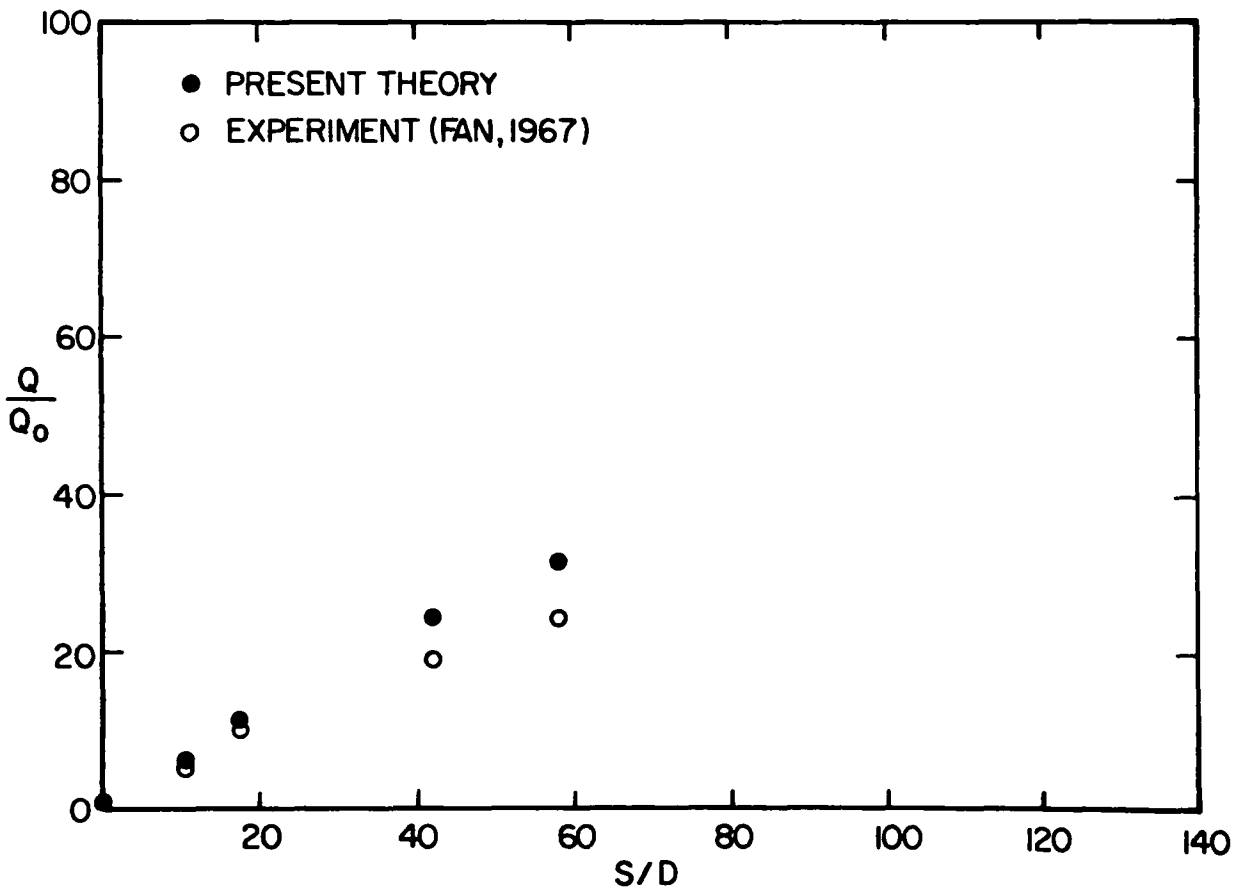
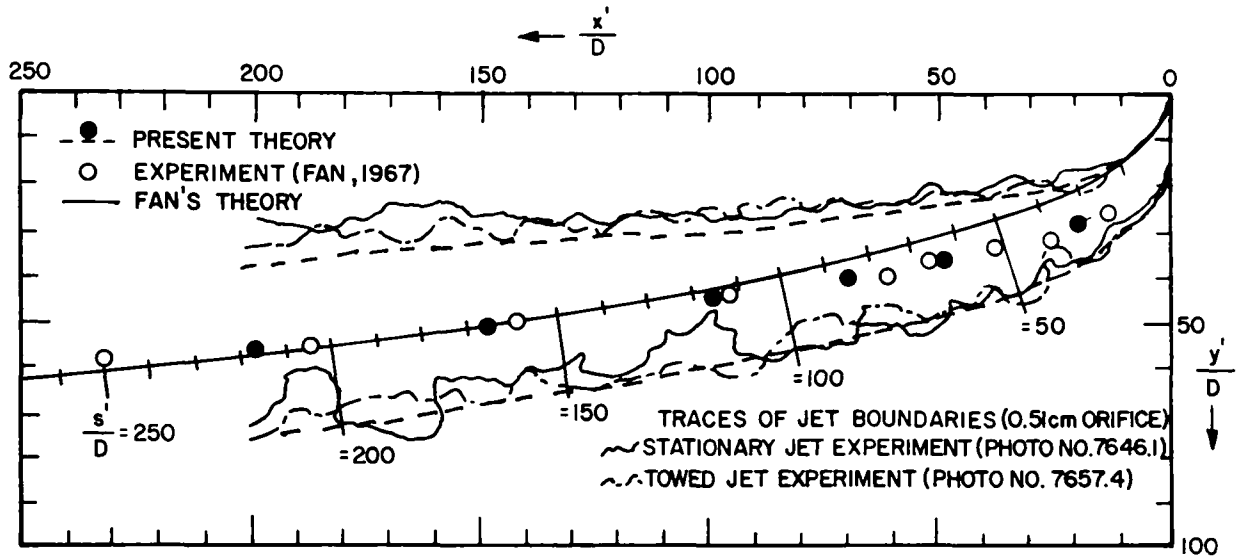


Figure 4.14 Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for F = 40 and K = 8



F=80 k=16 60(j)

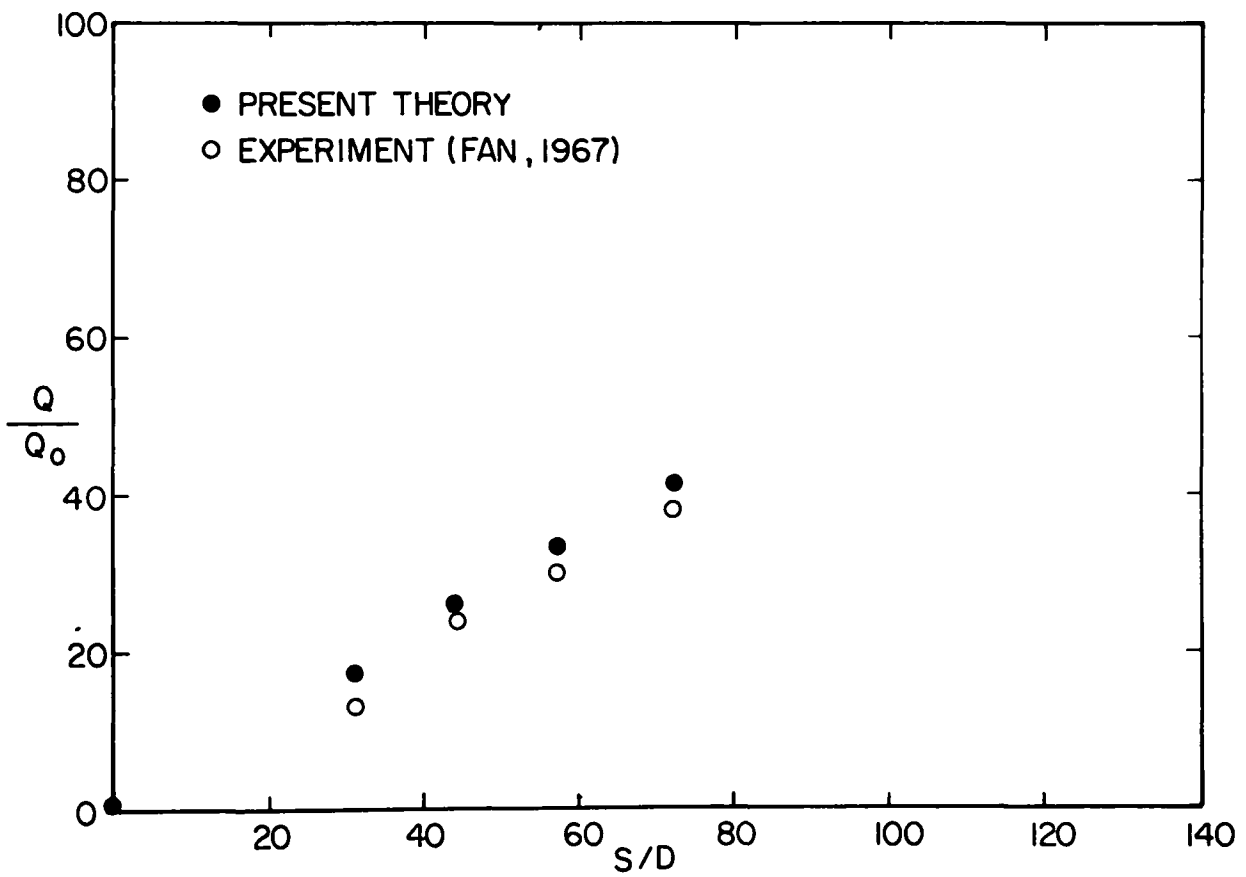


Figure 4.15 Comparisons of Plume Trajectory, Width and Dilution Between the Present Theory and Fan's (1967) Experiments for F = 80 and k = 16

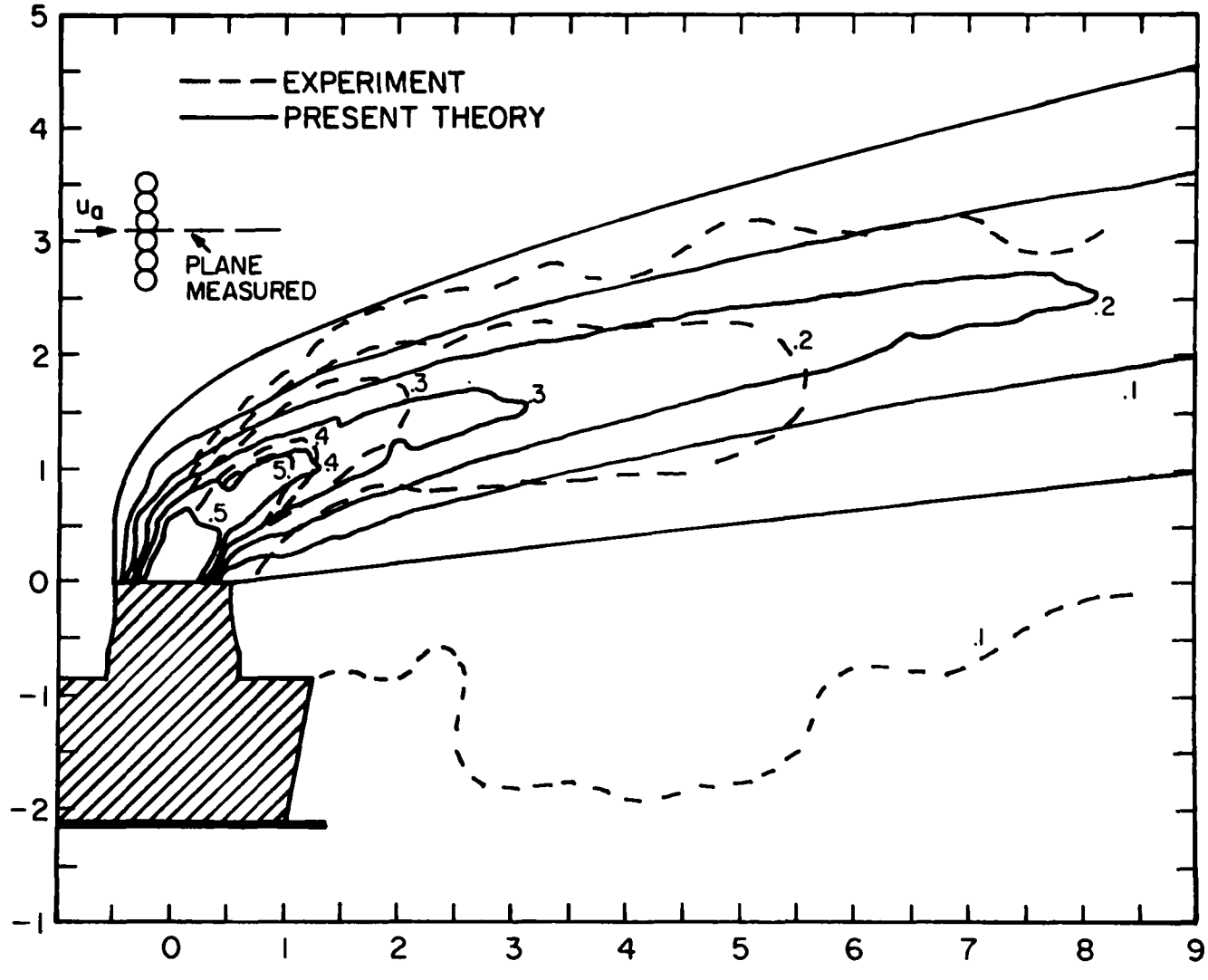


Figure 4.16 Comparisons of Plume Excess Temperature Between the Present Theory and Chan et al.'s (1974) Experiments for F = 4 and K = 1.02

Three ambient relative humidity profiles (100%, 70%, 0%) associated with the relative temperature profiles were generated and tested. The exit plume humidities were assumed 100% (saturated) except for one dry plume case which is 0% for ambient and exit humidities. The input data cards are presented in Tables 4.4 and 4.5. The predicted results and the comparisons are shown in Figures 4.17 and 4.18. From the variations of plume trajectory for different ambient humidity conditions, the effect of the ambient humidity can be seen to be quite significant. Similar conclusions could be drawn for the effect of ambient temperature and wind velocity. The present model overpredicts the plume trajectories for TVA's cases. This could be due to the incomplete information of the ambient conditions and the neglect of drift in the tower initial conditions. Adequate ambient and source conditions are mandatory for proper model validation.

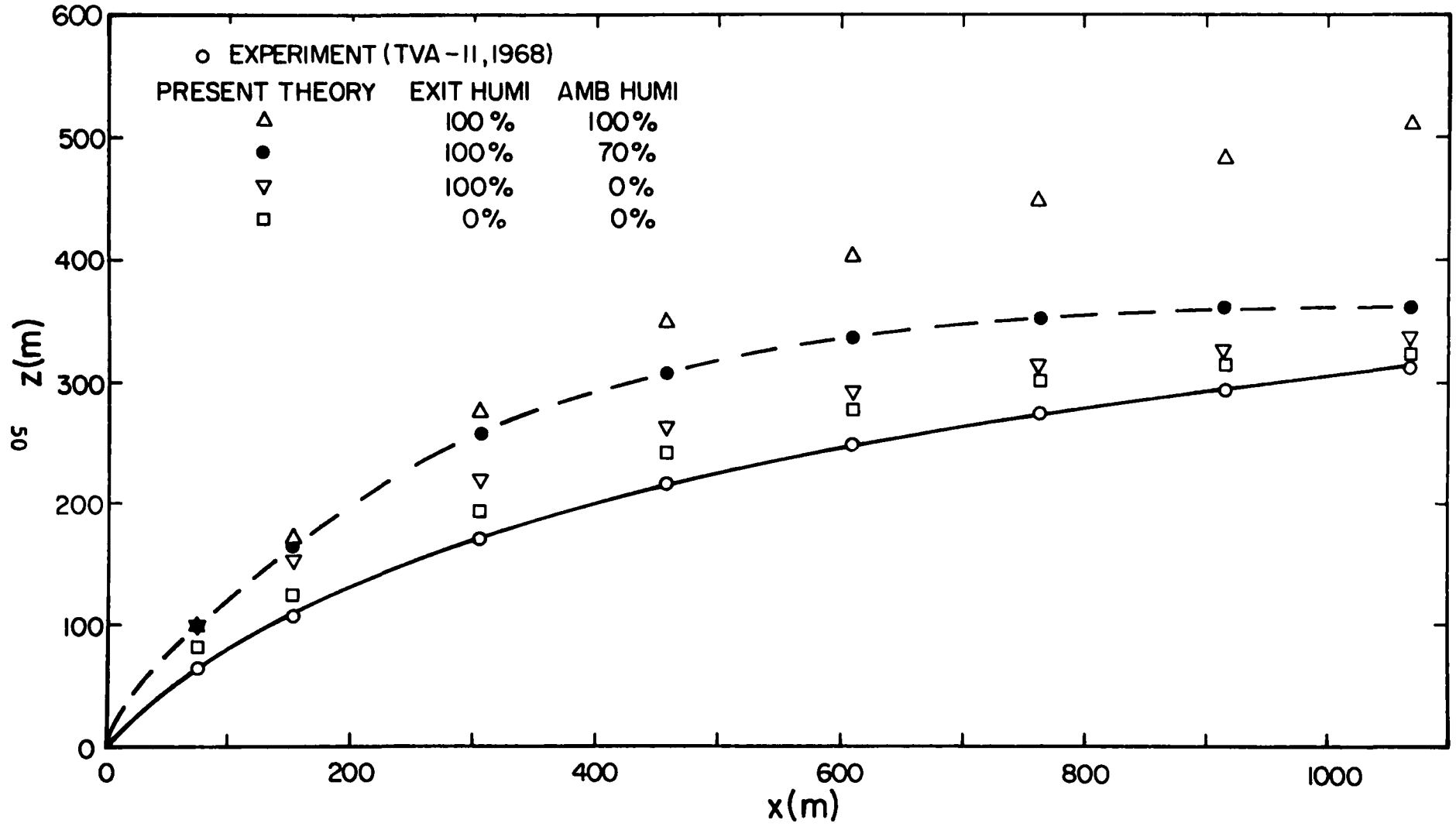


Figure 4.17 Comparisons of Plume Trajectories Between the Present Theory and TVA (1968, TVA-11, single tower) Field Data in a Stable Atmospheric Condition ($\partial\theta/\partial z$=0.59°K/100 m)

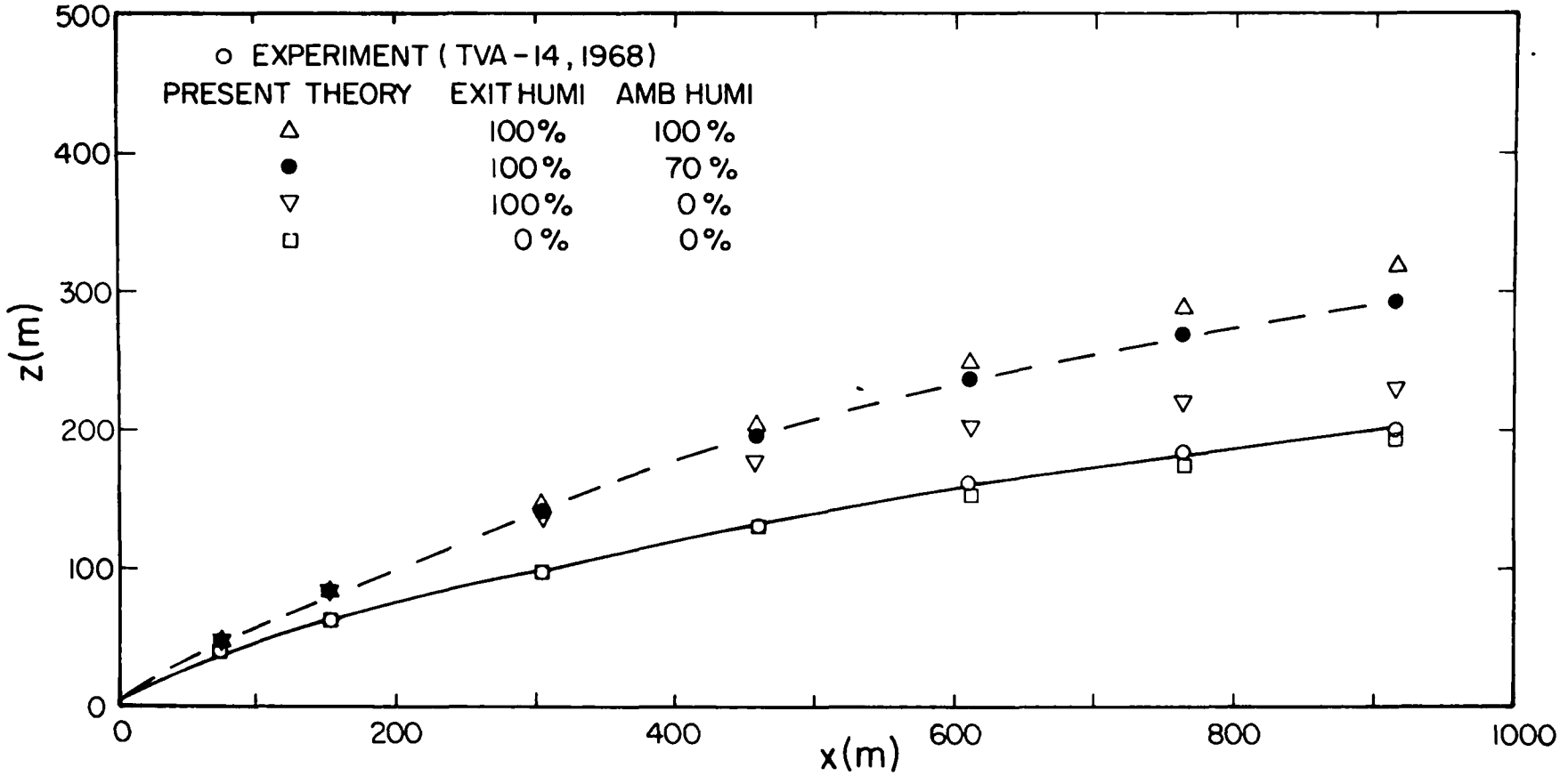


Figure 4.18 Comparisons of Plume Trajectories Between the Present Theory and TVA (1968, TVA, two towers) Field Data in an Atmosphere with an Inversion ($\partial\theta/\partial z$=1.42°K/100 m)

Table 4.1 Input Data Cards for Example Cases (Different Wind Directions to a Line Array (3 cases) and Round Array (one case) of Towers)

```
CASE (1)  4 TOWERS IN ONE ARRAY   0 DEGREES TO WIND
    4 120  30  30  11
    0   0   0   3  10   0   1   1   1   1   1
     .00000  11.45000  22.90000  34.35000
     .00000    .00000    .00000    .00000
     .00000 100.00000 200.00000
   10.50000  10.30000  10.10000
   70.00000  70.00000  70.00000
    4.10000   5.22504   5.76969   4.10000   5.22504   5.76969   4.10000   5.22504
    5.76969   4.10000   5.22504   5.76969
    9.44880  10.26800  31.90000    .02821    .00000
    5.00000   5.00000   0   0   0   0
 EXCS TEMP 4 TWRS 1 ARRAYS 0 DEG TO WIND Z/D                    X/D
 EXCS HUMI 4 TWRS 1 ARRAYS 0 DEG TO WIND Z/D                    X/D
 EXCS LIQM 4 TWRS 1 ARRAYS 0 DEG TO WIND Z/D                    X/D

CASE (2)  4 TOWERS IN ONE ARRAY  90 DEGREES TO WIND
    4 120  30  30  11
    0   0   0   3  10   0   1   1   1   1   1
     .00000    .00000    .00000    .00000
     .00000  11.45000  22.90000  34.35000
     .00000 100.00000 200.00000
   10.50000  10.30000  10.10000
   70.00000  70.00000  70.00000
    4.10000   5.22504   5.76969   4.10000   5.22504   5.76969   4.10000   5.22504
    5.76969   4.10000   5.22504   5.76969
    9.44880  10.26800  31.90000    .02821    .00000
    5.00000   5.00000   0   0   0   0
 EXCS TEMP 4 TWRS 1 ARRAYS 90 DG TO WIND Z/D                    X/D
 EXCS HUMI 4 TWRS 1 ARRAYS 90 DG TO WIND Z/D                    X/D
 EXCS LIQM 4 TWRS 1 ARRAYS 90 DG TO WIND Z/D                    X/D

CASE (3)  4 TOWERS IN ONE ARRAY 135 DEGREES TO WIND
    4 120  30  30  11
    0   0   0   3  10   0   1   1   1   1   1
     .00000   8.10000  16.19000  24.29000
     .00000   8.10000  16.19000  24.29000
     .00000 100.00000 200.00000
   10.50000  10.30000  10.10000
   70.00000  70.00000  70.00000
    4.10000   5.22504   5.76969   4.10000   5.22504   5.76969   4.10000   5.22504
    5.76969   4.10000   5.22504   5.76969
    9.44880  10.26800  31.90000    .02821    .00000
    5.00000   5.00000   0   0   0   0
 EXCS TEMP 4 TWRS 1 ARRAY 135 DEG TO WINDZ/D                    X/D
 EXCS HUMI 4 TWRS 1 ARRAY 135 DEG TO WINDZ/D                    X/D
 EXCS LIQM 4 TWRS 1 ARRAY 135 DEG TO WINDZ/D                    X/D
CASE (4)  5 TOWERS IN ROUND ARRAY
    5 100  30  30  11
    0   0   0   3  10   0   0   1   1   1   1
     .00000   5.00000  10.00000  15.00000  20.00000
   10.00000    .00000  20.00000   2.00000  12.00000
     .00000 100.00000 200.00000
   10.50000  10.30000  10.10000
   70.00000  70.00000  70.00000
    4.10000   5.22504   5.76969   4.10000   5.22504   5.76969   4.10000   5.22504
    5.76969   4.10000   5.22504   5.76969   4.10000   5.22504   5.76969
    9.44880  10.26800  31.90000    .02821    .00000
    5.00000   5.00000   0   0   0   0
 EXCS TEMP 5 TWRS IN ROUND ARRAY          Z/D                    X/D
 EXCS HUMI 5 TWRS IN ROUND ARRAY          Z/D                    X/D
 EXCS LIQM 5 TWRS IN ROUND ARRAY          Z/D                    X/D
```

Table 4.2 Input Data Cards for Three Cases of Fan's (1967) Experiments with F = 20, K = 8; F = 40, K = 8; and F = 80, K = 16

```
CASE (1)  60(D)  F=20  K=8

  1 350   1   1   1
  0   0   0   2   1   0   0   0   0   0   0
    .0
    .0
    .00000  -50.00000
  31.87000   31.87000
    .00000     .00000
    .13700     .13700
    .00760   -1.10000  20.00000    .00000    .00000
```

```
CASE (2)  60(G)  F=40  K=8

  1 350   1   1   1
  0   0   0   2   1   0   0   0   0   0   0
    .0
    .0
    .00000  -50.00000
  26.57000   26.57000
    .00000     .00000
    .20400     .20400
    .00760   -1.63000  20.00000    .00000    .00000
```

```
CASE (3)  60(J)  F=80  K=16

  1 350   1   1   1
  0   0   0   2   1   0   0   0   0   0   0
    .0
    .0
    .00000  -50.00000
  23.31000   23.31000
    .00000     .00000
    .14600     .14600
    .00760   -2.32000  20.00000    .00000    .00000
```

Table 4.3 Input Data Cards for Chan et al.'s (1974) Experiment with F = 4, K = 1.02

```
Case (1) 6 Towers in One Array 90 Degrees to Wind F=4, K=1.02

 6 100   21  17  11
 0   0    1   2   0   0   1  1   0   0  1
   .00000     .00000    .00000   .00000   .00000   .00000
   .00000     .06501    .13003   .19504   .26006   .32507
   .00000  900.00000
 25.00000   25.00000
   .00000     .00000
   .37621     .37621    .37621   .37621   .37621   .37621   .37621   .37621
   .37621     .37621    .37621   .37621
   .05690     .38374  30.00000   .00000   .00000
   .50000     .50000   1.00000  3.00000
  6.31250    5.06250   0   0   0   0
EXCS TEMP 6 TWRS 1 ARRAY 90 DEG TO WIND Z/D          X/D A3=0.3536 CD=1.5
```

Table 4.4 Input Data Cards for TVA (1968, TVA-11, single tower) Field Data in a Stable Atmospheric Condition ($\partial\theta/\partial z$=0.59°K/100 m)

```
CASE (1)  100% EXIT HUMI & 100% AMB HUMI

    1 300   1   1   1
    0   0   0   8   1   0   0   0   0   0   0
     .00000
     .00000
     .00000 100.00000 150.00000 200.00000 250.00000 300.00000 350.00000 400.00000
   20.00000  20.16000  20.24000  20.32000  20.40000  20.48000  20.56000  20.64000
  100.00000 100.00000 100.00000 100.00000 100.00000 100.00000 100.00000 100.00000
    4.10000   4.10000   4.10000   4.70000   5.30000   5.90000   6.50000   7.10000
    7.90000  17.10000 139.00000    .67883    .00000

CASE (2)  100% EXIT HUMI &  70% AMB HUMI

    1 300   1   1   1
    0   0   0   8   1   0   0   0   0   0   0
     .00000
     .00000
     .00000 100.00000 150.00000 200.00000 250.00000 300.00000 350.00000 400.00000
   20.00000  19.61000  19.42000  19.23000  19.04000  18.84000  18.65000  18.46000
   70.00000  70.00000  70.00000  70.00000  70.00000  70.00000  70.00000  70.00000
    4.10000   4.10000   4.10000   4.70000   5.30000   5.90000   6.50000   7.10000
    7.90000  17.10000 139.00000    .67883    .00000

CASE (3)  100% EXIT HUMI &   0% AMB HUMI

    1 300   1   1   1
    0   0   0   8   1   0   0   0   0   0   0
     .00000
     .00000
     .00000 100.00000 150.00000 200.00000 250.00000 300.00000 350.00000 400.00000
   20.00000  19.61000  19.42000  19.23000  19.04000  18.84000  18.65000  18.46000
     .00000    .00000    .00000    .00000    .00000    .00000    .00000    .00000
    4.10000   4.10000   4.10000   4.70000   5.30000   5.90000   6.50000   7.10000
    7.90000  17.10000 139.00000    .67883    .00000

CASE (4)    0% EXIT HUMI &   0% AMB HUMI

    1 300   1   1   1
    0   0   0   8   1   0   0   0   0   0   0
     .00000
     .00000
     .00000 100.00000 150.00000 200.00000 250.00000 300.00000 350.00000 400.00000
   20.00000  19.61000  19.42000  19.23000  19.04000  18.84000  18.65000  18.46000
     .00000    .00000    .00000    .00000    .00000    .00000    .00000    .00000
    4.10000   4.10000   4.10000   4.70000   5.30000   5.90000   6.50000   7.10000
    7.90000  17.10000 139.00000    .00000    .00000
```

Table 4.5 Input Data Cards for TVA (1968, TVA-14, two towers) Field Data in an Atmosphere with an Inversion ($\partial\theta/\partial z$=1.42°K/100 m)

```
CASE (1)  100% EXIT HUMI & 100% AMB HUMI

     2 300   1   1   1
     0   0   0   6   1   0   1   0   0   0   0
      .00000  29.06000
      .00000  54.65000
      .00000  50.00000 100.00000 150.00000 200.00000 250.00000
     7.00000   7.43000   7.86000   8.29000   8.72000   9.15000
   100.00000 100.00000 100.00000 100.00000 100.00000 100.00000
     8.60000   8.80000   9.10000  10.50000  11.60000  12.60000   8.60000   8.80000
     9.10000  10.50000  11.60000  12.60000
     7.90000  20.20000 149.00000    .73951    .00000

CASE (2)  100% EXIT HUMI &  70% AMB HUMI

     2 300   1   1   1
     0   0   0   6   1   0   1   0   0   0   0
      .00000  29.06000
      .00000  54.65000
      .00000  50.00000 100.00000 150.00000 200.00000 250.00000
     7.00000   7.22000   7.44000   7.67000   7.89000   8.11000
    70.00000  70.00000  70.00000  70.00000  70.00000  70.00000
     8.60000   8.80000   9.10000  10.50000  11.60000  12.60000   8.60000   8.80000
     9.10000  10.50000  11.60000  12.60000
     7.90000  20.20000 149.00000    .73951    .00000

CASE (3)  100% EXIT HUMI &   0% AMB HUMI

     2 300   1   1   1
     0   0   0   6   1   0   1   0   0   0   0
      .00000  29.06000
      .00000  54.65000
      .00000  50.00000 100.00000 150.00000 200.00000 250.00000
     7.00000   7.22000   7.44000   7.67000   7.89000   8.11000
      .00000    .00000    .00000    .00000    .00000    .00000
     8.60000   8.80000   9.10000  10.50000  11.60000  12.60000   8.60000   8.80000
     9.10000  10.50000  11.60000  12.60000
     7.90000  20.20000 149.00000    .73951    .00000

CASE (4)   0% EXIT HUMI &   0% AMB HUMI

     2 300   1   1   1
     0   0   0   6   1   0   1       0   0   0
      .00000  29.06000
      .00000  54.65000
      .00000  50.00000 100.00000 150.00000 200.00000 250.00000
     7.00000   7.22000   7.44000   7.67000   7.89000   8.11000
      .00000    .00000    .00000    .00000    .00000    .00000
     8.60000   8.80000   9.10000  10.50000  11.60000  12.60000   8.60000   8.80000
     9.10000  10.50000  11.60000  12.60000
     7.90000  20.20000 149.00000    .00000    .00000
```

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, a mathematical model and corresponding computer program have been developed for the prediction of plume behavior from multiple cooling towers. Some comparisons between the predictions based on the present model and the measured results from laboratories and the field are made in order to test the model. The following conclusions and recommendations are made based on this study.

(1) The model is developed for arbitrary vertical profiles of ambient temperature, humidity, wind velocity, and arbitrary tower arrangement. The velocity defect for the downstream towers due to the effect of the upstream towers and plumes can be included by specifying different ambient velocity profiles for each plume. A general expression for the velocity defect of the downstream towers might be developed in the future.

(2) The temperature range for which this model is valid is -50°C to 140°C, because of the accuracy associated with the calculation of the saturation humidity.

(3) A set of suggested values of entrainment and drag coefficients have been incorporated in the computer program. Because of the rapid merging and usually rapid bending over of the plumes, the coefficients a_3, α_s and C_d are the most important ones. Better estimates of their values are needed such as by further experimental study or field program.

(4) The merging criteria and processes (defined in this model by equations (2.38) (2.39) and (2.40)) could also be improved when further

research results on plume interaction are available.

(5) The blockage and recirculation effects in the wake zone of the towers and plumes have not been incorporated in the present model. Future effort could be made to include these effects.

(6) Based on comparisons between model and laboratory results (Fan, and Chan et al.), good predictions of dry plume behavior can be obtained. In order to verify the model for actual cooling tower plumes, a more complete set of experimental data (including the plume width, trajectory, dilution and detailed ambient profiles of temperature, humidity and wind velocity) are required. Therefore, a complete set of field measurement are strongly recommended for validation of the model.

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APPENDIX A

COMPUTER PROGRAM

The computer program based on the model and listed in Appendix C was tested on an IBM 370/158. The detailed input and output information are listed in this Appendix. The input ambient wind velocity profiles (AU(NP,MG)) for each tower are designed to allow consideration of the velocity defect in the wake of upstream towers (i.e., the tower array parallel to the ambient wind direction). In addition, some suggested input values are listed below for reference:

NS = 300

NX = 40

NY = 40

NCONT = 11

IX(3) = IX(6) = IX(11) =0

In this Appendix, the input sequence as well as the input and output variables are tabulated, explained and related to the symbols used in the text of this report.

INPUT SEQUENCE

Symbol	Parameter	Format	Subroutine
NP,NS,NX,NY,NCONT		5I4	CTPS
(IX(I),I=1,11)		11I4	MTP
(CX(I),I=1,NP)		8F10.5	MTP
(CY(I),I=1,NP)		8F10.5	MTP
(AZ(I),I=1,MG)		8F10.5	MTP
(AT(I),I=1,MG)		8F10.5	MTP
(AH(I),I=1,MG)		8F10.5	MTP
((AU(I,J),J=1,MG),I=1,NP)		8F10.5	MTP
DI(1),UO(1), TO(1),HO(1),WO(1)	IX(1)=0+	8F10.5	MTP
(DI(I),I=1,NP)	IX(1)=1*	8F10.5	MTP
(UO(I),I=1,NP)	IX(1)=1*	8F10.5	MTP
(TO(I),I=1,NP)	IX(1)=1*	8F10.5	MTP
(HO(I),I=1,NP)	IX(1)=1*	8F10.5	MTP
(WO(I),I=1,NP)	IX(1)=1*	8F10.5	MTP
A1,A2,A3,A4,CD,TURBF	IX(2)=1*	8F10.5	MTP
DX,DZ,XO,ZO	IX(3)=1*	4F10.5	OUTPUT
WIDTH, HITE,MORE,NOMAP,ICENT NOTICK	IX(11)=1*	2F10.5 4I4	OUTPUT
(HEDN(k),k=1,10),(LABY(L),L=1,5),(LABX(M),M=1,5)	IX(8)=1*	20A4	OUTPUT
(HEDN(k),k=1,10),(LABY(L),L=1,5),(LABX(M),M=1,5)	IX(9)=1*	20A4	OUTPUT
(HEDN(k),k=1,10),(LABY(L),L=1,5),(LABX(M),M=1,5)	IX(10)=1*	20A4	OUTPUT

+ Skip card if IX(1)=1

* Skip card if the corresponding IX(I)=0, (I=1,2,3,11,8,9,10)

EXPLANATION OF THE INPUT SYMBOLS

In Program	In Text	Remarks	
NP		Total number of towers	
NS		Desired number of calculation steps	
NX, NY [CONTA(NX,NY)]		Horizontal and vertical grid sizes, respectively (for contour plot)	
NCONT [CONTB(NCONT)]		Desired contour levels for plotting	
IX(1)		IX(1)=0	Same exit conditions of all the plumes (Input one card only)
		IX(1)=1	Different exit conditions of the plumes
IX(2)		IX(2)=0	No input card of entrainment and drag coefficients is needed
		IX(2)=1	Input the desired entrainment and drag coefficients
IX(3)		IX(3)=0	No input card of DX, DZ, XO and ZO is needed
		IX(3)=1	Input the desired values of DX, DZ, XO and ZO
		IX(3)=-1	No plot needed
IX(4)		MG	Number of vertical levels for ambient conditions
IX(5)		INRPR	Interval of detailed printout for plume 1
IX(6)		IPNT=0	For contour plot (always use IPNT=0)
IX(7)		LC=0	For cluster array (round array) of towers
		LC=1	For line or random array of towers
IX(8)		IX(8)=0	No contour map plotted for plume excess temperature
		IX(8)=1	Contour map plotted for plume excess temperature
IX(9)		IX(9)=0	No contour map plotted for plume excess humidity
		IX(9)=1	Contour map plotted for plume excess humidity
IX(10)		IX(10)=0	No contour map plotted for plume excess liquid moisture
		IX(10)=1	Contour map plotted for plume excess liquid moisture
IX(11)		IX(11)=0	No input card of WIDTH, HITE, MORE, NOMAP, ICENT, and NOTICK is needed
		IX(11)=1	Input the desired values of WIDTH, HITE, MORE, NOMAP, ICENT and NOTICK

In Program	In Text	Remarks
CX(NP)	x	x-coordinates of towers (in m)
CY(NP)	y	y-coordinates of towers (in m)
AZ(MG)	z	Ambient levels (in m)
AT(MG)	ta	Ambient temperature profile corresponding to AZ(I) (in °C)
AH(MG)	q_a	Ambient relative humidty profile corresponding to AZ(I) (in percentage of the saturation humidity)
AU(NP,MG)	U_a	Ambient wind velocity profile corresponding to AZ(I) for each tower (in m/sec)
DI(NP)	D_o	Diameter of each tower (in m)
UO(NP)	U_o	Exit velocity of each plume (in m/sec)
TO(NP)	t_o	Exit temperature of each plume (in °C)
HO(NP)	q_o	Exit specific humidity of each plume (in kg/kg)
WO(NP)	σ_o	Exit liquid phase moisture of each plume (in kg/kg)
A1,A2,A3 and A4	a_1, a_2, a_3 and a_4	Entrainment coefficients (Default: A1=0.0806, A2=0.4775, A3=0.3536, A4=0.)
CD	C_d	Drag coefficient (Default: CD=1.5)
TURBF	U'_a	Intensity of ambient turbulent fluctuations (in percentage, decimal; Default: TURBF=0.)
DX,DZ		Increments of grid size in x and z directions, respectively (Normalized by the diameter of the first tower; Default:DX=0.5, DZ=0.5)
XO,ZO		Location of the center of the top of the first tower in the grid (Normalized by the diameter of the first tower; Default:XO=1, ZO=2.)
WIDTH,HITE		Width and height of contour map, respectively (Inches; Default: 8", 8")
MORE		MORE=1 Do not finish off the map (Default: MORE=0)
NOMAP		NOMAP=1 Do not force grid to be square (Default:NOMAP=0)
ICENT		ICENT=1 Do not center the title (Default: ICENT=0)
NOTICK		NOCITK=1 Do not draw tick marks (Default: NOTICK=0)

In Program	In Text	Remarks
HEDN(10)		40 characters to plot as title on top (Default: Blank)
LABY(5)		20 characters to plot as label on vertical left (Default: Blank)
LABX(5)		20 characters to plot as label on horizontal bottom (Default: Blank)

EXPLANATIONS OF THE OUTPUT SYMBOLS

In Program	In Text	Remarks
EXIT,COEF,TWLC,AMBL, INPR,IPNT,LC,ETPL, EHPL,EMPL,COPL		Correspond to IX(1) to IX(11) respectively
A1,A2,A3,A4,CD, TURBF	a_1, a_2, a_3, a_4, C_d, U_a'	Same as input symbols
NTHP		The Nth plume
CX,CY [(CX(I),CY(I)]		Same as input symbols
DIA,VELO,TEMP,HUMI, LPMO [DI(I),UO(I), HO(I)WO(I)]	D_o, U_o, t_o, q_o, σ_o	Tower diameter, exit values of plume velocity, temperature, specific humidity and liquid phase moisture, respectively
NSTEP*		The Nth step of calculation referred to each tower
X,Y,Z [PX(NP,NS),PY(NP,NS), PZ(NP,NS)]	x,y,z	The horizontal, lateral and vertical coordinates of plume center
PTEMP,PHUMI,PLQDMOIST [PT(NP,NS),PH(NP,NS), PW(NP,NS)]	t_p, q_p, σ_p	Plume temperature, specific humidity and liquid phase moisture respectively
EXCEST, EXCESH [PET(NP,NS),PEH (NP,NS)]	Δt, Δq	Excess plume temperature and specific humidity
PCROSEC [BXZ(I)]	HT/2	Half height of plume cross-section
SLOTLEN[A(I)]	A	Finite length of slot jet of the merged plume
PANGLE[PCOS(NP,NS) PSIN(NP,NS)]	θ	The angle between the tangent of plume trajectory and the horizontal line
DILUTN [PDIL(NP,NS)]	Q/Q_o	Plume dilution
PVELO [PU(NP,NS)]	U_p	Plume velocity

* NSTEP refers to the number of calculation step of plume 1 when each plume first appeared

APPENDIX B

EXPLANATION OF THE IMPORTANT SYMBOLS IN THE PROGRAM MTP

In Program	In Text	Remarks
PX(NP,NS)	x	*
PY(NP,NS)	y	*
PZ(NP,NS)	z	*
PS(NP,NS)	s	*
PCOS(NP,NS)	$\cos\theta$	*
PSIN(NP,NS)	$\sin\theta$	*
PQ(NP,NS)	Q	*
PMX(NP,NS)	M_x	*
PMZ(NP,NS)	M_z	*
PF(NP,NS)	F	*
PG(NP,NS)	G	*
PH(NP,NS)	H	*
PW(NP,NS)	W	*
PT(NP,NS)	T	*
PET(NP,NS)	$t_p - t_a$	Excess temperature
PEH(NP,NS)	$q_p - q_a$	Excess humidity
PAN(NP,NS)	θ	*
PU(NP,NS)	U	Net plume velocity
PENT(NP,NS)	E	*
PA(NP,NS)	A	*
PB(NP,NS)	b or (B1+B2)/2	Average plume width
PC(NP,NS)	BXZ	*
PDIL(NP,NS)	Q/Q_o	Plume dilution
CONTA(NX,NY)		Normalized PET,PEH & PW (or PEW)
CONTB(NCONT)		Contour levels
IND(I)		Indication of the status of each plume
	IND(I)=5	Plume which has not been started
	IND(I)=1	Single plume
	IND(I)=2	Merged plume
	IND(I)=3	All plumes are merged
IS(I)		Beginning step number for each plume
MP(I)		Merged plume pair
MS(I)		Merged plume step numbers associated with MP(I)
A(I)	A	*
B1(I)	B1	*
B2(I)	B2	*
BXZ(I)	BXZ	*
BY(I)	BY	*
PMCOS(I)	$\cos\phi$	*
PMSIN(I)	$\sin\phi$	*
DW(I)	$2\cdot BY$	*
NBV(I)		Beginning step number for visible plume
NEV(I)		Ending step number for visible plume
PAI	π	3.1415926
GRA	g	*
A1	a_1	*
A2	a_2	*
A3	a_3	*
A4	a_4	*

In Program	In Text		Remarks
CD	C_d		*
TURBF	U_a		*
UC	U_p		*
B			Plume width
TP	t_p		*
HP	q_p		*
WP	σ_p		*
ET	$t_p - t_a$		Excess temperature
EH	$q_p - q_a$		Excess humidity
MG			Elevation level
CFRL	Fr_{LC}		*
ALV	L_v		*
CPA	C_{pa}		*
ANG	θ		*
ITHP			i^{th} plume
ENTRAN	E		*
IQ		<3	All the plumes have not been completely merged
		=3	All the plumes have merged
		>3	All the plumes have merged and become a round plume again
IL			Number of merged pairs
IK			Plume step number
KE(I)			Ending step number of each plume
Y(I)	Y(1)=Q		*
	Y(2)=Mcosθ		*
	Y(3)=Msinθ		*
	Y(4)=G		*
	Y(5)=F		*
	Y(6)=x		*
	Y(7)=z		*
YP(I)			Derivatives of Y(I) with respect to s
YR1(I),YR2(I), & YS(I)			Y(I) associated with the two half round plumes and the central slot plume for the merged plume
YR1P(I),YR2P(I), & YSP(I)			YP(I) associated with the two half round plumes and the central slot plume for the merged plume

* Refer to "List of Symbols"

APPENDIX C

LISTING OF PROGRAM

```
0001          DIMENSION IA(3),I(26)
        C     NP=NUMBER OF PLUME,NS=NUMBER OF CALCULATION STEP, NX,NY=DESIRED
        C     GRID OF CONTOUR PLOT, NCCNT=DESIRED CONTOUR LEVELS
0002        3 READ(5,2,END=9) NP,NS,NX,NY,NCONT
0003        2 FORMAT(5I4)
0004          N4=MAXO(NX,NY)
0005          NTOTAL=NP*NS
0006          IA(2)=NTOTAL*23+NX*NY+NCCNT+N4
0007          CALL GETVEC(IA)
0008          I(1)=IA(3)
0009          DO 1 J=2,24
0010        1 I(J)=I(J-1)+NTOTAL
0011          I(25)=I(24)+NX*NY
0012          I(26)=I(25)+NCONT
0013          CALL MTP(IA(I(1)),IA(I(2)),IA(I(3)),IA(I(4)),IA(I(5)),IA(I(6)),
             1IA(I(7)),IA(I(8)),IA(I(9)),IA(I(10)),IA(I(11)),IA(I(12)),IA(I(13))
             2,IA(I(14)),IA(I(15)),IA(I(16)),IA(I(17)),IA(I(18)),IA(I(19)),
             3IA(I(20)),IA(I(21)),IA(I(22)),IA(I(23)),IA(I(24)),IA(I(25)),
             4IA(I(26)),NP,NS,NX,NY,NCCNT,N4)
0014          CALL FREEUP(IA)
0015          GO TO 3
0016        9 STOP
0017          END
```

```
0001          SUBROUTINE MTP(PX,PZ,PQ,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,PU,PS,PB,PA,
             1PT,PET,PH,PEH,PW,PAN,PDIL,PY,PC,CONTA,CONTB,CONTC,NP,NS,NX,NY,
             2NCONT,N4)
0002          EXTERNAL DERIVE,DERIVS,DERIVF
0003          DOUBLE PRECISION AQ,BQ,CQ,DQ
0004          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE2/MP(30),MS(30),IIP(30)
             2       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(30,30),
             A               AUG(30,30)
             3       /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             4               PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             5       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             6               MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             7       /CONST2/IL,NII,IK,NI,NIP1
             8       /CONST3/AQ,BQ,CQ,DQ
             9       /CONTUU/WIDTH,HITE,MORE,NOMAP,ICENT,NOTICK,HEDN(10),
             *               LABY(5),LABX(5)
             B       /STORE5/DI(30),UO(30),TO(30),HC(30),WO(30)
0005          DIMENSION PX(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),PMZ(NP,NS),
             1PB(NP,NS),PU(NP,NS),PF(NP,NS),PG(NP,NS),PCOS(NP,NS),PSIN(NP,NS),
             2PENT(NP,NS),PH(NP,NS),PW(NP,NS),PEH(NP,NS),CX(30),CY(30),KE(30),
             3PT(NP,NS),PS(NP,NS),PA(NP,NS),PET(NP,NS),PAN(NP,NS),PY(NP,NS),
             4Y(8),YP(8),YS(8),YSP(8),YR1(8),YR1P(8),YR2(8),YR2P(8),PDIL(NP,NS
             5CONTA(NX,NY),CONTB(NCONT),CONTC(N4),IX(12),MGPA2(30),MGST1(30),
             6PC(NP,NS),LCHK(30),AHP(30)
        C     INITIALIZE STORAGES
0006          CALL BLANK(PX,PZ,PQ,PMX,PMZ,PB,PU,PF,PG,PCOS,PSIN,PENT,PT,PS,PA,
             1PET,PEH,PAN,PY,PDIL,PH,PW,PC,NP,NS,NX,NY,NCONT,N4,CONTA,CONTB,
             2CONTC,MGPA2,MGST1,DX,DZ,XO,ZC,IPNT,KE,LCHK,AHP)
        C     INPUT CONTROL PARAMETERS
0007          READ(5,2) (IX(I),I=1,11)
0008          MG=IX(4)
0009          INTPR=IX(5)
0010          IPNT=IX(6)
0011          LC=IX(7)
        C     INPUT TOWER CONFIGURATION
0012          READ(5,1) (CX(I),I=1,NP)
0013          READ(5,1) (CY(I),I=1,NP)
        C     INPUT AMBIENT CONDITIONS
0014          READ(5,1) (AZ(I),I=1,MG)
0015          READ(5,1) (AT(I),I=1,MG)
0016          READ(5,1) (AHP(I),I=1,MG)
0017          READ(5,1) ((AU(I,J),J=1,MG),I=1,NP)
0018          IF(IX(1) .GT. 0) GO TO 34
        C     INPUT TOWER EXIT CONDITIONS;DI=DIA. UC=VELO., TO=TEMP., HO=HUMID
        C     WO=LIQUID PHASE MOISTURE
0019          READ(5,1)DI(1),UC(1),TO(1),HC(1),WO(1)
0020          DO 24 I=2,NP
0021          DI(I)=DI(1)
0022          UC(I)=UC(1)
0023          TO(I)=TO(1)
0024          HO(I)=HC(1)
0025       24 WC(I)=WC(1)
0026          GO TO 35
0027       34 READ(5,1) (DI(I),I=1,NP)
0028          READ(5,1) (UO(I),I=1,NP)
```

```
0029          READ(5,1) (TO(I),I=1,NP)
0030          READ(5,1) (HO(I),I=1,NP)
0031          READ(5,1) (WO(I),I=1,NP)
0032       35 IF(IX(2) .LE. 0) GO TO 32
        C     INPUT COEFFICIENTS OF ENTRAINMENT AND DRAG ;TURBF=TURB. FLUCT.
        C     TURBF=%(IN DECIMAL) OF AMBIENT WIND VELOCITY
0033          READ(5,1)A1,A2,A3,A4,CD,TURBF
0034          CFRL=A2/(0.116-A1)
0035        1 FORMAT(8F10.5)
0036        2 FORMAT(12I4)
0037       32 WRITE(6,555)
0038      555 FORMAT(1H1)
0039          WRITE(6,3)
0040        3 FORMAT(1X,'UNITS OF THE VARIABLES')
0041          WRITE(6,4)
0042        4 FORMAT(1X,'LENGTH:M,  TEMP:C,  MOISTURE:KG/KG,  VELO:M/SEC,  ANGL
             1:DEG')
0043          WRITE(6,50)NP,NS,NX,NY,NCONT
0044          WRITE(6,49)
0045          WRITE(6,36)
0046          WRITE(6,48) (IX(J),J=1,11)
0047       50 FORMAT(1X,'NO. OF TOWERS=',I4,'  NO. OF CALCULATION STEPS=',I4,
             1'  GRID SIZE (X,Y)=',I4,'  X',I4,'  CONTOUR LEVELS=',I4//)
0048       49 FORMAT(1X,'CONTROL PARAMETERS')
0049       36 FORMAT(' EXIT  COEF  TWLC  AMBL  INPR  IPNT   LC   ETPL  EMPL  '
             1'EMPL  COPL')
0050       48 FORMAT(1X,11(I4,2X)//)
0051          WRITE(6,5)
0052        5 FORMAT(1X,'COEFFICIENTS OF ENTRAINMENT AND DRAG')
0053          WRITE(6,6)A1,A2,A3,A4,CD,TURBF
0054        6 FORMAT(1X,'A1=',F8.5,5X,'A2=',F8.5,5X,'A3=',F8.5,5X,'A4=',F8.5,5
             1'CD=',F8.5,5X,'TURBF=',F8.5//)
0055          WRITE(6,7)
0056        7 FORMAT(1X,'AMBIENT PROFILES')
0057          WRITE(6,8)
0058        8 FORMAT(3X,'HEIGHT',7X,'TEMP',12X,'HUMIDITY',9X,'VELOCITY')
0059          DO 556 I=1,MG
0060          TK=AT(I)+273.16
0061          T=1.-373.16/TK
0062          EST=EXP((13.3185-(1.976+(0.6445+0.1229*T)*T)*T)*T)
0063          ES=0.622*1013.25*EST
0064          FSH=ES/(1013.25+ES)
0065      556 AH(I)=AHP(I)*0.01*FSH
0066          DO 9 I=1,MG
0067        9 WRITE(6,10)AZ(I),AT(I),AH(I),AHP(I),AU(1,I)
0068       10 FORMAT(1X,2(F10.5,2X),F10.6,1X,'(',F6.2,'%)',2X,F10.5)
0069          WRITE(6,11)
0070       11 FORMAT(/)
0071          WRITE(6,12)
0072       12 FORMAT(1X,'TOWER CONFIGURATION AND EXIT CONDITIONS')
0073          WRITE(6,18)
0074       18 FORMAT(2X,'NTHP',6X,'CX',8X,'CY',8X,'CIA',4X,'VELO',6X,'TEMP',9)
             1'HUMI',9X,'LPMO')
0075          DO 17 I=1,NP
0076       17 WRITE(6,13)I,CX(I),CY(I),DI(I),UO(I),TO(I),HO(I),WO(I)
0077       13 FORMAT(1X,I5,3X,F7.2,3X,F7.2,3X,F6.2,3X,F6.2,3X,F8.3,3X,F12.8,3)
```

```
                 1F12.8)
0078             WRITE(6,242)
           C     CALCULATION OF TEMPERATURE,HUMIDITY AND VELOCITY GRADIENTS
0079             MG1=MG-1
0080             DO 14 I=1,MG1
0081             II=I+1
0082             DV=AZ(II)-AZ(I)
0083             ATG(I)=(AT(II)-AT(I))/DV
0084          14 AHG(I)=(AH(II)-AH(I))/DV
0085             DO 47 J=1,NP
0086             DO 47 I=1,MG1
0087             II=I+1
0088             DV=AZ(II)-AZ(I)
0089          47 AUG(J,I)=(AU(J,II)-AU(J,I))/DV
0090             DO 148 I=1,NP
0091             DO2=DI(I)/2.
0092             BXZ(I)=DO2
0093             BY(I)=DO2
0094             B1(I)=DO2
0095         148 B2(I)=DO2
0096             WRITE(6,15)
0097          15 FORMAT(1X,'PLUME    1  APPEARS AT NSTEP=   1',//)
           C     SET INITIAL CONDITIONS,
0098             TP=TO(1)
0099             ALV=FALV(TP)
0100             CALL SETIC(Y,ITHP,CX)
           C     INTEGRATION BY RUNGE-KUTTA METHOD
0101             L=0
0102             S=0.
0103             IKT=1
0104             DS=DI(ITHP)/20.
0105             GO TO 598
0106          86 IF(NIP1 .GT. NP) GO TO 19
           C     CHECK IF ANY NEW PLUME APPEARS
0107             CALL CHKNWP(PX,PZ,PQ,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,PU,PS,PB,PA,PT,
                1PET,PH,PEH,PW,PAN,PY,PDIL,PC,CX,NP,NS,DERIVR,CY,KE)
0108          19 IF(NII-1)16,105,105
0109         357 IKT=IK+NOVIK(1)
0110             ITHP=1
0111             ALV=FALV(TP)
0112             DS=0.1*PB(1,IKT-1)
0113         598 CALL RUNGS(S,DS,Z,Y,YP,L,DERIVR)
0114             B1(1)=B
0115             B2(1)=B
0116             BXZ(1)=B
0117             BY(1)=B
           C     SOLUTIONS FOR SINGLE PLUME
0118             CALL SOLUTN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PCOS,PSIN
                1PT,PET,PH,PEH,PW,PAN,PDIL,PC,CY,Y,YP,S,ITHP,IKT,NP,NS)
0119             GO TO 78
           C     CHECK IF ANY NEW PLUME MERGING OCCURS
0120         105 CALL ALIGN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PC,PCOS,
                1PSIN,PT,PET,PH,PEH,PW,PAN,PDIL,CY,Y,YP,YS,YSP,YR1,YR1P,YR2,YR2P,
                2DERIVE,DERIVS,DERIVR,S,LC,NP,NS,KE)
0121             CALL PLMERG(PX,PY,PZ,PT,PET,PH,PEH,PW,PA,PB,PAN,PDIL,PCOS,PSIN,
                1CY,NP,NS,KE,MGPA2,MGST1,PC,LCHK,PU)
```

```
0122          16 DO 23 I=1,NI
0123             ITHP=I
0124             IKT=IK+NOVIK(I)-IS(I)+1
0125             IF(IND(I) .LT.1) GO TO 23
0126             DS=0.1*PB(I,IKT-1)
           C     RESET INITIAL CONDITIONS AND CALCULATE PLUME PROPERTIES FOR SINGLE
           C     AND MERGED PLUMES
0127             CALL RESETI(I,IKT,DS,S,NP,NS,CY,Y,YP,YS,YSP,YR1,YR1P,YR2,YR2P,
                1DERIVE,DERIVS,DERIVR,PX,PZ,PQ,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,PU,PB,
                2PA,PT,PET,PEH,PW,LC)
           C     SOLUTIONS OF PLUMES INCLUDING SINGLE & MERGED PLUMES
0128             CALL SOLUTN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PCOS,PSIN,
                1PT,PET,PH,PEH,PW,PAN,PDIL,PC,CY,Y,YP,S,I,IKT,NP,NS)
0129          23 CONTINUE
0130             IL=0
0131          78 DO 77 I=1,NP
0132             IF((IK+NOVIK(I)) .LT. NS) GO TO 77
0133             IND(I)=0
0134          77 CONTINUE
0135             DO 75 I=1,NP
0136             IF(IND(I) .GT. 0) GO TO 79
0137          75 CONTINUE
0138             GO TO 80
0139          79 IK=IK+1
0140             IF(IQ-3)86,16,397
0141          80 DO 81 I=1,NP
0142             IF(KE(I) .LE. 0) GO TO 82
0143             IF(LCHK(I) .LT. 1)GO TO 81
0144             KE(I)=KE(I)+1
0145             J=KE(I)
0146             K=MGPA2(I)
0147             L=MGST1(I)+1
0148             PX(I,J)=PX(K,L)
0149             PZ(I,J)=PZ(K,L)
0150             PB(I,J)=PB(K,L)
0151             PC(I,J)=PC(K,L)
0152             PCOS(I,J)=PCOS(K,L)
0153             PSIN(I,J)=PSIN(K,L)
0154             PET(I,J)=PET(K,L)
0155             PEH(I,J)=PEH(K,L)
0156             PW(I,J)=PW(K,L)
0157             GO TO 81
0158          82 KE(I)=NS
0159          81 CONTINUE
0160             WRITE(6,808)
0161         808 FORMAT(1X,'RESULTS OF THE VISIBLE PLUMES')
0162             WRITE(6,225)
0163             CH=0.
0164             DO 807 I=1,NP
0165             KEN=KE(I)
0166             DO 803 J=1,KEN
0167             IF(PW(I,J).GT.0.)GO TO 802
0168             IF(NCV(I).EQ.0)GO TO 803
0169             NEV(I)=J
0170             NCV(I)=0
0171             CH=2.
```

```
0172          WRITE(6,809)J,I,PX(I,J),PZ(I,J),PY(I,J),PT(I,J),PET(I,J),PH(I,J),
             1PEH(I,J),PW(I,J),PB(I,J),PC(I,J),PA(I,J),PAN(I,J),PDIL(I,J),
             2PU(I,J)
0173      809 FORMAT(1X,2(I5,1X),3(F8.2,1X),2(F7.2,1X),3(F8.5,1X),6(F7.2,1X),/)
0174          GO TO 803
0175      802 IF(NCV(I).NE.0)GO TO 803
0176          NBV(I)=J
0177          NCV(I)=1
0178          CH=1.
0179          WRITE(6,241)J,I,PX(I,J),PZ(I,J),PY(I,J),PT(I,J),PET(I,J),PH(I,J),
             1PEH(I,J),PW(I,J),PB(I,J),PC(I,J),PA(I,J),PAN(I,J),PDIL(I,J),
             2PU(I,J)
0180      241 FORMAT(1X,2(I5,1X),3(F8.2,1X),2(F7.2,1X),3(F8.5,1X),6(F7.2,1X))
0181      803 CONTINUE
0182          IF(CH-1.) 804,805,807
0183      804 WRITE(6,233)I
0184      233 FORMAT(1X,'NO VISIBLE PART OF PLUME FOR PLUME',I4/)
0185          GO TO 807
0186      805 WRITE(6,243)I,J
0187      243 FORMAT(1X,'PLUME',I4,' STILL VISIBLE AT THE TERMINATION STEP',I4/)
0188      807 CONTINUE
0189          WRITE(6,242)
0190      242 FORMAT(//)
0191          WRITE(6,224)
0192      224 FORMAT(1X,'RESULTS AT THE LAST STEP OF CALCULATION')
0193          WRITE(6,225)
0194      225 FORMAT(1X,'NSTEP   NTHP    X         Z         Y       PTEMP   EXCEST
             1,'  PHUMI   EXCESH PLODMOIST PAVHFWD PCROSEC SLOTLEN  PANGLE  ',
             2'DILUTN  PVELO')
0195          NTHP=1
0196          WRITE(6,226)NS,NTHP,PX(1,NS),PZ(1,NS),PY(1,NS),PT(1,NS),PET(1,NS)
             1PH(1,NS),PEH(1,NS),PW(1,NS),PB(1,NS),PC(1,NS),PA(1,NS),PAN(1,NS),
             2PDIL(1,NS),PU(1,NS)
0197      226 FORMAT(1X,2(I5,1X),3(F8.2,1X),2(F7.2,1X),3(F8.5,1X),6(F7.2,1X),//
0198          CALL OUTPUT(PX,PY,PZ,PT,PET,PH,PEH,PW,PA,PC,PAN,PDIL,PSIN,PCOS,
             1CONTA,CONTB,CONTC,KE,INTPR,IPNT,NX,NY,NCONT,N4,NP,NS,IX,DX,DZ,XO,
             2ZC,PB,PS,PU)
0199          RETURN
0200          END
```

```
0001          SUBROUTINE BLANK(PX,PZ,PQ,PMX,PMZ,PB,PU,PF,PG,PCOS,PSIN,PENT,
             1PT,PS,PA,PET,PEH,PAN,PY,PDIL,PH,PW,PC,NP,NS,NX,NY,NCONT,N4,CONTA,
             2CONTB,CONTC,MGPA2,MGST1,DX,DZ,XO,ZC,IPNT,KE,LCHK,AHP)
0002          DOUBLE PRECISION AQ,BQ,CQ,DQ
0003          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE2/MP(30),MS(30),IIP(30)
             2       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(30,30),
             A                AUG(30,30)
             3       /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             4                PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             5       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             6                MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             7       /CONST2/IL,NII,IK,NI,NIP1
             8       /STORE5/DI(30),UO(30),TO(30),HC(30),WO(30)
             9       /CONST3/AQ,BQ,CQ,DQ
0004          DIMENSION PX(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),PMZ(NP,NS),
             1PB(NP,NS),PU(NP,NS),PF(NP,NS),PG(NP,NS),PCOS(NP,NS),PSIN(NP,NS),
             2PENT(NP,NS),PT(NP,NS),PS(NP,NS),PA(NP,NS),PET(NP,NS),PEH(NP,NS),
             3PAN(NP,NS),PH(NP,NS),PW(NP,NS),PY(NP,NS),PDIL(NP,NS),CONTA(NX,NY),
             4CONTB(NCONT),CONTC(N4),MGPA2(30),MGST1(30),PC(NP,NS),KE(30),
             5LCHK(30),AHP(30)
0005          DO 4 I=1,AP
0006          MGPA2(I)=0
0007          MGST1(I)=0
0008          IS(I)=C
0009          LCHK(I)=0
0010          A(I)=0.
0011          NBV(I)=0
0012          NEV(I)=0
0013          ACV(I)=0
0014          DW(I)=C.
0015          PMSIN(I)=0.
0016          PMCCS(I)=0.
0017          IND(I)=5
0018          MP(I)=0
0019          MS(I)=0
0020          IIP(I)=0
0021          IADT(I)=0
0022        4 NOVIK(I)=0
0023          DO 1 I=1,NP
0024          DO 1 J=1,NS
0025          PX(I,J)=0.
0026          PZ(I,J)=0.
0027          PQ(I,J)=0.
0028          PMX(I,J)=0.
0029          PMZ(I,J)=0.
0030          PF(I,J)=0.
0031          PG(I,J)=0.
0032          PC(I,J)=0.
0033          PB(I,J)=0.
0034          PCOS(I,J)=0.
0035          PSIN(I,J)=0.
0036          PU(I,J)=0.
0037          PENT(I,J)=0.
0038          PET(I,J)=0.
0039          PEH(I,J)=0.
```

```
0040          PT(I,J)=0.
0041          PS(I,J)=0.
0042          PA(I,J)=0.
0043          PH(I,J)=0.
0044          PY(I,J)=0.
0045          PAN(I,J)=0.
0046          PDIL(I,J)=C.
0047        1 PW(I,J)=0.
0048          DO 2 I=1,NX
0049          DO 2 J=1,NY
0050        2 CCNTA(I,J)=0.
0051          DO 3 I=1,NCONT
0052        3 CONTB(I)=0.
0053          DO 5 I=1,N4
0054        5 CONTC(I)=0.
0055          DO 6 I=1,30
0056          DC 6 J=1,30
0057          AUG(I,J)=0.
0058        6 AU(I,J)=0.
0059          DO 7 I=1,30
0060          KE(I)=0
0061          AZ(I)=0.
0062          AT(I)=0.
0063          AHP(I)=0.
0064          AH(I)=0.
0065          ATG(I)=0.
0066        7 AHG(I)=0.
0067          AC=0.000009153132
0068          BQ=0.0002112502
0069          CQ=0.003660244
0070          DQ=0.009494118
0071          CPA=1.005
0072          PAI=3.14159265
0073          GRA=9.8066
0074          A1=0.0806
0075          A2=0.6753
0076          A3=0.3536
0077          A4=0.
0078          CD=1.5
0079          TLRBF=0.
0080          DX=0.5
0081          DZ=0.5
0082          XO=1.
0083          ZO=2.
0084          IPNT=0
0085          CFRL=A2/(0.116-A1)
0086          IL=0
0087          NII=0
0088          IK=1
0089          IQ=1
0090          NI=1
0091          NIP1=2
0092          ITHP=1
0093          IND(1)=1
0094          IS(1)=1
0095          RETURN
0096          END
```

```
0001          FUNCTION FALV(TC)
        C     TO DETERMINE LATEN HEAT. ALV
0002          IF(TC .LT. 0.) GO TO 1
0003          FALV=(597.31-0.57*TC)*4.1868
0004          GO TO 2
0005        1 FALV=(677.01+0.622*TC)*4.1868
0006        2 RETURN
0007          END
```

```
0001          SUBROUTINE SETIC(Y,I,CX)
0002          COMMON /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             1              MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             2       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(30,30),
             *              AUG(30,30)
             3       /STORE5/DI(30),UO(30),TO(30),HO(30),WO(30)
0003          DIMENSION Y(8),CX(30)
0004          Y(1)=PAI*DI(I)*DI(I)*ABS(UO(I))/4.
0005          Y(2)=0.
0006          Y(3)=Y(1)*UO(I)
0007          Y(4)=Y(1)*(TO(I)-AT(1)-WO(I)*ALV/CPA)
0008          Y(5)=Y(1)*(HO(I)-AH(1)+WO(I))
0009          Y(6)=CX(I)
0010          Y(7)=0.
0011          RETURN
0012          END
```

```
0001          SUBROUTINE RUNGS(X,H,N,Y,YPRIME,INDEX,DERIV)
0002          DIMENSION Y(8),YPRIME(8),Z(8),W1(8),W2(8),W3(8),W4(8)
        C     RUNGS-RUNGE-KUTTA SOLUTICN OF SET OF FIRST ORDER O.D.E. FORTRAN I
        C     DIMENSICNS MUST BE SET FCR EACH PRCGRAM
        C     X    INDEPENDENT VARIABLE
        C     H    INCREMENT DELTA X,MAY BE CHANGED IN VALUE
        C     N    NUMBER OF ECUATICNS
        C     Y    DEPENDENT VARIABLE BLOCK    ONE DIMENSIONAL ARRAY
        C     YPRIME   DERIVATIVE BLOCK    ONE DIMENSIONAL ARRAY
        C     THE PROGRAMMER MUST SUPPLY INITIAL VALUES OF Y(1) TO Y(N)
        C     INDEX   IS A VARIABLE WHICH SHOULD BE SET TO ZERO BEFORE EACH
        C     INITIAL ENTRY TO THE SUBROUTINE, I.E., TO SOLVE A DIFFERENT
        C     SET OF EQUATICNS OR TO START WITH NEW INITIAL CONDITIONS.
        C     THE PROGRAMMER MUST WRITE A SUBROUTINE CALLED DERIVE WHICH
        C     CCMPUTES THE CERIVATIVES AND STORES THEM
        C     THE ARGUMENT LIST IS SUBROUTINE DERIVE(X,N,Y,YPRIME)
0003          IF(INDEX) 5,5,1
0004        1 DO 2 I=1,N
0005          W1(I)=H*YPRIME(I)
0006        2 Z(I)=Y(I)+(W1(I)*.5)
0007          A=X+0.5*H
0008          CALL DERIV(A,N,Z,YPRIME)
0009          DC 3 I=1,N
0010          W2(I)=H*YPRIME(I)
0011        3 Z(I)=Y(I)+.5*W2(I)
0012          A=X+0.5*H
0013          CALL DERIV(A,N,Z,YPRIME)
0014          CO 4 I=1,N
0015          W3(I)=H*YPRIME(I)
0016        4 Z(I)=Y(I)+W3(I)
0017          A=X+H
0018          CALL DERIV(A,N,Z,YPRIME)
0019          DO 7 I=1,N
0020          W4(I)=H*YPRIME(I)
0021        7 Y(I)=Y(I)+(((2.*(W2(I)+W3(I)))+W1(I)+W4(I))/6.)
0022          X=X+H
0023          CALL DERIV(X,N,Y,YPRIME)
0024          GO TO 6
0025        5 CALL DEPIV(X,N,Y,YPRIME)
0026          INDEX=1
0027        6 RETURN
0028          END
```

```
0001          SUBROUTINE DERIVR(S,N,Y,YP)
0002          DOUBLE PRECISICN AQ,BC,CC,DQ
0003          COMMON /STORE1/INE(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(3 C,30),
             A               ALG(30,30)
             3       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             4               MG,MG1,CFRL,ALV,CPA,ANG,IC,ITHP,ENTRAN
             5       /CCNST3/AC,BQ,CQ,DQ
             6       /STORE5/DI(30),UO(30),TO(30),HO(30),WO(30)
0004          DIMENSION Y(8),YP(8)
        C     DETERMINE AMBIENT CONDITIONS
0005          TPK=TP+273.16
0006          TOK=TO(ITHP)+273.16
0007          DO 88 I=2,MG
0008          IF(Y(7) .GT. AZ(I)) GC TO 88
0009          II=I-1
0010          DZZ=Y(7)-AZ(II)
0011          TA=AT(II)+ATG(II)*DZZ
0012          HA=AH(II)+AHG(II)*DZZ
0013          UA=AU(ITHP,II)+AUG(ITHP,II)*DZZ
0014          TG=ATG(II)
0015          HG=AHG(II)
0016          GO TO 90
0017       88 CONTINUE
0018          DZ1=Y(7)-AZ(MG1)
0019          TA=AT(MG1)+ATG(MG1)*DZ1
0020          HA=AH(MG1)+AHG(MG1)*DZ1
0021          UA=AU(ITHP,MG1)+AUG(ITHP,MG1)*DZ1
0022          HG=AHG(MG1)
0023          TG=ATG(MG1)
0024       90 TAK=TA+273.16
0025          UP=UA*TURBF
        C     DETERMINE MOMENTUM,TRAJECTCRY AND VELOCITY CF PLUME
0026          PM=SQRT(Y(2)*Y(2)+Y(3)*Y(3))
0027          PCOS=Y(2)/PM
0028          PSIN=Y(3)/PM
0029          IF(PCOS .NE. 0.) GO TC 86
0030          ANG=90.
0031          GO TO 85
0032       86 ANG=ATAN(PSIN/PCCS)*180./PAI
0033       85 SIGN=1.
0034          IF(PSIN .LT. 0.) SIGN=-1.
0035          APSIN=ABS(PSIN)
0036          SY=PSIN*Y(1)
0037          UC=PM/Y(1)
0038          U=UC-UA*PCOS
0039          SPM=SQRT(PAI*PM)
0040          B=Y(1)/SPM
0041          USU=UC*PAI*B*B
0042          PMC=CD*B*UA*UA*PSIN*PSIN
0043          Y4=Y(4)/USU
0044          Y5=Y(5)/USU
0045          C1=ALV/CPA
0046          C2=Y4+TA+C1*(Y5+HA)
0047          C3=Y5+HA
        C     TO ASSUME THE PLUME IS SATURATED AND CALCULATE THE SATURATED PLU
```

```
          C     HUMIDITY AND TEMPERATURE
0048            CALL ITER(TPK,HP,EST,C1,C2)
          C     TO DETERMINE THE PLUME LIQUID PHASE MOISTURE
0049            WP=C3-HP
0050            IF(WP .GT. 0.) GO TO 79
          C     DRY PLUME
0051            WP=0.
0052            HP=C3
0053            TP=TA+Y4
0054            TPK=TP+273.16
0055            GO TO 178
          C     WET PLUME
0056         79 TP=TPK-273.16
0057        178 ET=TP-TA
0058            EH=HP-HA
          C     TO DETERMINE ADIABATIC LAPSE RATE
0059            GAMA=FGAMA(TAK,HA)
          C     DETERMINE PLUME ENTRAINMENT
0060            RT=TPK/TAK
0061            PER=2.*PAI*B
0062            IF(RT .EQ. 1.) GO TO 99
0063            FRL=UC*UC*TPK/(GRA*TCK*ABS(RT-1.)*B)
0064            IF(FRL .GT. CFRL) GO TO 9
0065            A12=0.116
0066            GO TO 10
0067          9 A12=A1+A2*APSIN/FRL
0068            GO TO 10
0069         99 A12=A1
0070         10 ENTRAN=PER*(A12*ABS(U)+A3*UA*APSIN*PCOS+A4*UP)
          C     EQUATIONS OF CONSERVATION OF VOLUME,MOM.,ENERGE AND MOIST. FLUXES
0071            YP(1)=ENTRAN*RT
0072            YP(2)=(UA*ENTRAN+PMC*APSIN)*RT
0073            YP(3)=(RT-1.-WP)*GRA*LSL/UC-SIGN*PMC*PCOS*RT
0074            YP(4)=-(TG+GAMA)*SY
0075            YP(5)=-HG*SY
0076            YP(6)=PCOS
0077            YP(7)=PSIN
0078            RETURN
0079            END
```

```
0001          SUBROUTINE DERIVS(S,N,Y,YP)
0002          DOUBLE PRECISION AQ,BQ,CQ,DQ
0003          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(30,30),
             A               ALG(30,30)
             3       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WF,
             4               MG,MG1,CFRL,ALV,CPA,ANG,IC,ITHP,ENTRAN
             5       /CONST3/AQ,BQ,CQ,DQ
             6       /STORE5/DI(30),UC(30),TO(30),HO(30),WO(30)
0004          DIMENSION Y(8),YP(8)
0005          TPK=TP+273.16
        C     DETERMINE AMBIENT CONDITIONS
0006          TOK=TO(ITHP)+273.16
0007          DO 88 I=2,MG
0008          IF(Y(7) .GT. AZ(I)) GO TO 88
0009          II=I-1
0010          DZZ=Y(7)-AZ(II)
0011          TA=AT(II)+ATG(II)*DZZ
0012          HA=AH(II)+AHG(II)*DZZ
0013          UA=AU(ITHP,II)+AUG(ITHP,II)*DZZ
0014          TG=ATG(II)
0015          HG=AHG(II)
0016          GO TO 90
0017       88 CONTINUE
0018          DZ1=Y(7)-AZ(MG1)
0019          TA=AT(MG1)+ATG(MG1)*DZ1
0020          HA=AH(MG1)+AHG(MG1)*DZ1
0021          UA=AU(ITHP,MG1)+AUG(ITHP,MG1)*DZ1
0022          TG=ATG(MG1)
0023          HG=AHG(MG1)
0024       90 TAK=TA+273.16
0025          UP=UA*TURBF
        C     DETERMINE MOMENTUM,TRAJECTORY AND VELOCITY OF PLUME
0026          PM=SQRT(Y(2)*Y(2)+Y(3)*Y(3))
0027          PCOS=Y(2)/PM
0028          PSIN=Y(3)/PM
0029       85 SIGN=1.
0030          IF(PSIN .LT. 0.) SIGN=-1.
0031          APSIN=ABS(PSIN)
0032          SY=PSIN*Y(1)
0033          UC=PM/Y(1)
0034          U=UC-UA*PCOS
0035          B=Y(1)*Y(1)/(2.*PM)
0036          USU=2.*B*UC
0037          PMC=CD*UA*UA*PSIN*PSIN*0.5
0038          Y4=Y(4)/USU
0039          Y5=Y(5)/USU
0040          C1=ALV/CPA
0041          C2=Y4+TA+C1*(Y5+HA)
0042          C3=Y5+HA
        C     TO ASSUME THE PLUME IS SATURATED AND CALCULATE THE SATURATED PLUME
        C     HUMIDITY AND TEMPERATURE
0043          CALL ITER(TPK,HP,EST,C1,C2)
        C     TO DETERMINE THE PLUME LIQUID PHASE MOISTURE
0044          WP=C3-HP
0045          IF(WP .GT. 0.) GO TO 79
```

```
C     DRY PLUME
      WP=0.
      HP=C3
      TP=TA+Y4
      TPK=TP+273.16
      GO TO 178
C     WET PLUME
   79 TP=TPK-273.16
  178 ET=TP-TA
      EH=HP-HA
C     TO DETERMINE ADIABATIC LAPSE RATE
      GAMA=FGAMA(TAK,PA)
C     DETERMINE PLUME ENTRAINMENT
      TPK=TP+273.16
      RT=TPK/TAK
      ENTRAN=2.*(0.198*ABS(U)+A3*UA*APSIN*PCOS+A4*UP)
C     EQUATICNS OF CCNSERVATICN OF VOLUME,MOM.,ENERGE AND MOIST. FLUXES
      YP(1)=ENTRAN*RT
      YP(2)=(UA*ENTRAN+PMC*APSIN)*RT
      YP(3)=(RT-1.-WP)*GRA*LSL/UC-SIGN*PMC*PCOS*RT
      YP(4)=-(TG+GAMA)*SY
      YP(5)=-HG*SY
      YP(6)=PCCS
      YP(7)=PSIN
      RETURN
      END
```

```
0001          SUBROUTINE DERIVE(S,N,Y,YP)
0002          DOUBLE PRECISION AQ,BQ,CQ,DQ
0003          COMMON /STORE1/INC(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE3/AH(30),AT(30),AZ(30),AHG(30),ATG(30),AU(30,30),
             A               AUG(30,30)
             2       /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             3               PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             4       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HF,EH,WP,
             5               MG,MG1,CFRL,ALV,CPA,ANG,IC,ITHP,ENTRAN
             6       /CONST3/AQ,BQ,CQ,DQ
             7       /STORE5/DI(30),UC(30),TO(30),HO(30),WO(30)
0004          DIMENSION Y(8),YP(8)
0005          TPK=TP+273.16
        C     DETERMINE AMBIENT CONDITIONS
0006          TOK=TO(ITHP)+273.16
0007          DO 88 I=2,MG
0008          IF(Y(7) .GT. AZ(I)) GO TO 88
0009          II=I-1
0010          DZZ=Y(7)-AZ(II)
0011          TA=AT(II)+ATG(II)*DZZ
0012          HA=AH(II)+AHG(II)*DZZ
0013          UA=AU(ITHP,II)+AUG(ITHP,II)*DZZ
0014          TG=ATG(II)
0015          HG=AHG(II)
0016          GO TO 90
0017       88 CONTINUE
0018          DZ1=Y(7)-AZ(MG1)
0019          TA=AT(MG1)+ATG(MG1)*DZ1
0020          HA=AH(MG1)+AHG(MG1)*DZ1
0021          UA=AU(ITHP,MG1)+AUG(ITHP,MG1)*DZ1
0022          TG=ATG(MG1)
0023          HG=AHG(MG1)
0024       90 TAK=TA+273.16
0025          UP=UA*TURBF
        C     DETERMINE MOMENTUM,TRAJECTORY AND VELOCITY OF PLUME
0026          PM=SQRT(Y(2)*Y(2)+Y(3)*Y(3))
0027          PCOS=Y(2)/PM
0028          PSIN=Y(3)/PM
0029          IF(PCOS .NE. 0.) GO TO 86
0030          ANG=90.
0031          GO TO 85
0032       86 ANG=ATAN(PSIN/PCOS)*180./PAI
0033       85 SIGN=1.
0034          IF(PSIN .LT. 0.) SIGN=-1.
0035          APSIN=ABS(PSIN)
0036          SY=PSIN*Y(1)
0037          UC=PM/Y(1)
0038          U=UC-UA*PCOS
0039          USU=UC*(A(ITHP)*(B1(ITHP)+B2(ITHP))+0.5*PAI*(B1(ITHP)*B1(ITHP)+
             1B2(ITHP)*B2(ITHP)))
0040          PMC=0.5*CD*UA*UA*PSIN*PSIN*DW(ITHP)
0041          Y4=Y(4)/USU
0042          Y5=Y(5)/USU
0043          C1=ALV/CPA
0044          C2=Y4+TA+C1*(Y5+HA)
0045          C3=Y5+HA
```

```
            C     TO ASSUME THE PLUME IS SATURATED AND CALCULATE THE SATURATED PLUM
            C     HUMIDITY AND TEMPERATURE
 0046             CALL ITER(TPK,HP,EST,C1,C2)
            C     TO DETERMINE THE PLUME LIQUID PHASE MOISTURE
 0047             WP=C3-HP
 0048             IF(WP .GT. 0.) GO TO 79
            C     DRY PLUME
 0049             WP=0.
 0050             HP=C3
 0051             TP=TA+Y4
 0052             TPK=TP+273.16
 0053             GO TO 178
            C     WET PLUME
 0054          79 TP=TPK-273.16
 0055         178 ET=TP-TA
 0056             EH=HP-HA
            C     TO DETERMINE ADIABATIC LAPSE RATE
 0057             GAMA=FGAMA(TAK,HA)
            C     DETERMINE PLUME ENTRAINMENT
 0058             TPK=TP+273.16
 0059             RT=TPK/TAK
 0060             PER=2.*A(ITHP)
 0061             A12=0.198
 0062             IF(RT .EQ. 1.) GO TO 99
 0063             FRC=UC*UC*TPK/(GRA*TCK*ABS(RT-1.))
 0064             FRL=FRC/B1(ITHP)
 0065             IF(FRL .GT. CFRL) GO TO 106
 0066             B12=0.116
 0067             GO TO 108
 0068         106 B12=A1+A2*APSIN/FRL
 0069         108 FRL=FRC/B2(ITHP)
 0070             IF(FRL .GT. CFRL) GO TO 104
 0071             C12=0.116
 0072             GO TO 107
 0073         104 C12=A1+A2*APSIN/FRL
 0074             GO TO 107
 0075          99 B12=A1
 0076             C12=A1
            C     ENTRAINMENT OF TWO HALF ROUND ENDING PLUMES
 0077         107 ENTR=PAI*(ABS(U)*(B1(ITHP)*B12+B2(ITHP)*C12)+(B1(ITHP)+B2(ITHP))
                 1*(A3*UA*APSIN*PCOS+A4*UP))
            C     ENTRAINMENT OF TWO HALF ROUND PLUMES AND SLOT JET
 0078             ENTRAN=PER*(A12*ABS(U)+A3*UA*APSIN*PCOS+A4*UP)+ENTR
            C     EQUATIONS OF CONSERVATION OF VOLUME,MOM.,ENERGE AND MOIST. FLUXES
 0079             YP(1)=ENTRAN*RT
 0080             YP(2)=(UA*ENTRAN+PMC*APSIN)*RT
 0081             YP(3)=(RT-1.-WP)*GRA*LSL/UC-SIGN*PMC*PCOS*RT
 0082             YP(4)=-(TG+GAMA)*SY
 0083             YP(5)=-HG*SY
 0084             YP(6)=PCOS
 0085             YP(7)=PSIN
 0086             RETURN
 0087             END
```

```
0001          SUBROUTINE PHI(I,JR,M,CY,PZ,NP,NS,IKQ,IKP)
0002          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
            1        /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
            2                 PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
0003          DIMENSION PZ(NP,NS),CY(30)
        C     TO CALCULATE THE ANGLE OF THE INCLINATION OF MERGED PLUME (PHI)
0004          IJR=INDT(JR)
0005          IM=INDT(M)
0006          IF(IJR .NE. IM) GO TO 1
0007          IF(IJR .EQ. 1 .AND. IM .EQ. 1) GO TO 2
0008          IF(JR .EQ. M) GO TO 6
0009          IF(IJR .EQ. 2 .AND. IM .EQ. 2) GO TO 4
0010        2 DY=ABS(CY(JR)-CY(M))
0011          DZ=ABS(PZ(JR,IKP)-PZ(M,IKQ))
0012          DS=SQRT(DY*DY+DZ*DZ)
0013          PMCOS(I)=DY/DS
0014          PMSIN(I)=DZ/DS
0015          GO TO 5
0016        1 IF(IJR .NE. 1) GO TO 6
0017        7 PMCOS(I)=PMCOS(M)
0018          PMSIN(I)=PMSIN(M)
0019          GO TO 5
0020        6 PMCOS(I)=PMCOS(JR)
0021          PMSIN(I)=PMSIN(JR)
0022          GO TO 5
0023        4 COSS=PMCOS(JR)*PMCOS(M)+PMSIN(JR)*PMSIN(M)
0024          PMCOS(I)=SQRT(0.5*(1.+COSS))
0025          PMSIN(I)=SQRT(0.5*(1.-COSS))
0026        5 RETURN
0027          END
```

```
0001          SUBROUTINE ITER(TPK,HP,EST,C1,C2)
0002        1 TS=373.16/TPK
0003          T=1.-TS
0004          EST=1013.25*EXP((13.3185-(1.976+(0.6445+0.1299*T)*T)*T)*T)
0005          ES=0.622*EST
0006          HP=ES/(1013.25+ES)
0007          FTPK=C2-C1*HP+273.16-TPK
0008          IF(ABS(FTPK) .LT. 0.01) RETURN
0009          DST=(13.3185-(3.952+(1.9335+0.5196*T)*T)*T)*TS/TPK
0010          FTPKD=-1.+C1*HP*DST*(HP-1.)
0011          TPK=TPK-FTPK/FTPKD
0012          GO TO 1
0013          END
```

```
0001          FUNCTION FGAMA(TAK,HA)
        C     TO DETERMINE ADIABATIC LAPSE RATE
0002          T=1.-373.16/TAK
0003          EST=EXP((13.3185-(1.976+(0.6445+0.1229*T)*T)*T)*T)
0004          ES=0.622*1013.25*EST
0005          HAS=0.99*ES/(1013.25+ES)
0006          IF(HA .GE. HAS) GO TO 1
        C     DRY ADIABATIC LAPSE RATE
0007          FGAMA=0.00976
0008          GO TO 2
0009        1 RESP=EST/TAK
        C     SATURATED ADIABATIC LAPSE RATE
0010          FGAMA=0.00976*(1.+5420.*RESP)/(1.+839000.*RESP/TAK)
0011        2 RETURN
0012          END
```

```
0001          SUBROUTINE SOLUTN(PX,PY,PZ,PG,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PCOS,
             1PSIN,PT,PET,PH,PEH,PW,PAN,PDIL,PC,CY,Y,YP,S,I,J,NP,NS)
0002          COMMON /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             1              PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             2        /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             3              MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             4        /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
0003          DIMENSION PX(NP,NS),PY(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),
             1PMZ(NP,NS),PG(NP,NS),PF(NP,NS),PU(NP,NS),PENT(NP,NS),PS(NP,NS),
             2PA(NP,NS),PB(NP,NS),PCOS(NP,NS),PSIN(NP,NS),PT(NP,NS),PET(NP,NS),
             3PH(NP,NS),PEH(NP,NS),PW(NP,NS),PAN(NP,NS),PDIL(NP,NS),CY(30),Y(8),
             4YP(8),PC(NP,NS)
0004          PX(I,J)=Y(6)
0005          PZ(I,J)=Y(7)
0006          PY(I,J)=CY(I)
0007          PQ(I,J)=Y(1)
0008          PMX(I,J)=Y(2)
0009          PMZ(I,J)=Y(3)
0010          PG(I,J)=Y(4)
0011          PF(I,J)=Y(5)
0012          PU(I,J)=UC
0013          PENT(I,J)=ENTRAN
0014          PS(I,J)=S
0015          PA(I,J)=A(I)
0016          PC(I,J)=BXZ(I)
0017          PB(I,J)=B
0018          PCOS(I,J)=YP(6)
0019          PSIN(I,J)=YP(7)
0020          PT(I,J)=TP
0021          PET(I,J)=ET
0022          PH(I,J)=HP
0023          PEH(I,J)=EH
0024          PW(I,J)=WP
0025          PAN(I,J)=ANG
0026          PDIL(I,J)=Y(1)/PQ(I,1)
0027          RETURN
0028          END
```

```
0001          SUBROUTINE CHKNWP(PX,PZ,PQ,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,PU,PS,PB,
             1PA,PT,PET,PH,PEH,PW,PAN,PY,PDIL,PC,CX,NP,NS,DERIVR,CY,KE)
0002          EXTERNAL DERIVR
0003          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             2               PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             3       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             4               MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             5       /CONST2/IL,NII,IK,NI,NIP1
             6       /STORE5/DI(30),UO(30),TO(30),HC(30),WO(30)
0004          DIMENSION PX(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),PMZ(NP,NS),
             1PB(NP,NS),PU(NP,NS),PF(NP,NS),PG(NP,NS),PCOS(NP,NS),PSIN(NP,NS),
             2PENT(NP,NS),PA(NP,NS),PT(NP,NS),CX(30),Y(8),YP(8),PS(NP,NS),
             3PH(NP,NS),PW(NP,NS),PET(NP,NS),PEH(NP,NS),PAN(NP,NS),PY(NP,NS),
             4PDIL(NP,NS),CY(30),KE(30),PC(NP,NS)
        C     CHECK IF ANY NEW PLUME APPEARS
0005          IKK=IK+NOVIK(1)-IS(1)
0006          IF(PX(1,IKK) .LT. CX(NIP1)) GO TO 19
0007          NIPP=NIP1
0008          DO 22 J=NIPP,NP
0009          DS=DI(J)/20.
0010          IF(ABS(CX(NIPP)-CX(J)) .GE. DS) GO TO 22
0011          NI=NI+1
0012          WRITE(6,40)J,IKK
0013       40 FORMAT(1X,'PLUME',2X,I3,'  APPEARS AT NSTEP=',I5//)
0014          NII=1
0015          IS(J)=IKK
0016          NOVIK(J)=NOVIK(1)
0017          NIP1=J+1
0018          IND(J)=1
0019          IKS=1
        C     SET INITIAL CONDITIONS
0020          TP=TO(J)
0021          ALV=FALV(TP)
0022          CALL SETIC(Y,J,CX)
0023          L=0
0024          S=0.
0025          ITHP=J
0026       30 CALL RUNGS(S,DS,7,Y,YP,L,DERIVR)
0027          BXZ(J)=B
        C     SOLUTIONS FOR UNMERGED SINGLE ROUND PLUME
0028          CALL SOLUTN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PCOS,PSIN,
             1PT,PET,PH,PEH,PW,PAN,PDIL,PC,CY,Y,YP,S,J,IKS,NP,NS)
        C     CHECKING THE CRITERION FOR STOPPING THE CALCULATION OF THE NEW
        C     ISSUED SINGLE PLUME
0029          IF(PZ(J,IKS) .GE. PZ(1,IKK)) GO TO 23
0030          IF(IKS .GE. NS) GO TO 22
0031          IKS=IKS+1
0032          DS=B*0.1
0033          ALV=FALV(TP)
0034          GO TO 30
0035       23 KE(J)=IKS
0036       22 CONTINUE
0037       19 RETURN
0038          END
```

```
0001          SUBROUTINE ALIGN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PC,
             1PCOS,PSIN,PT,PET,PH,PEH,PW,PAN,PDIL,CY,Y,YP,YS,YSP,YR1,YR1P,YR2,
             2YR2P,DERIVE,DERIVS,DERIVR,S,LC,NF,NS,KE)
0002          EXTERNAL DERIVE,DERIVS,DERIVR
0003          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             2               MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             3       /CONST2/IL,NIL,IK,NI,NIP1
             4       /STORE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             5               PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
0004          DIMENSION PX(NP,NS),PY(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),
             1PMZ(NP,NS),PG(NP,NS),PF(NP,NS),PU(NP,NS),PENT(NP,NS),PS(NP,NS),
             2PA(NP,NS),PB(NP,NS),PC(NP,NS),PCOS(NP,NS),PSIN(NP,NS),PT(NP,NS),
             3PET(NP,NS),PH(NP,NS),PEH(NP,NS),PW(NP,NS),PAN(NP,NS),PDIL(NP,NS),
             4CY(30),Y(8),YP(8),YS(8),YSP(8),YR1(8),YR1P(8),YR2(8),YR2P(8),
             5KE(30)
0005          I1=IK+NOVIK(1)-1
0006          PXMAX=PX(1,I1)
0007          DO 1 I=1,NI
0008          IM=IK+NOVIK(I)-IS(I)
0009          IF(PXMAX .LT. PX(I,IM)) PXMAX=PX(I,IM)
0010        1 CONTINUE
0011          DO 2 I=1,NI
0012          IF(IND(I) .LT. 1) GO TO 2
0013          IM=IK+NOVIK(I)-IS(I)
0014       11 IF(IM .GE. NS) GO TO 2
0015          DS=PB(I,IM)*0.1
0016          IF((PXMAX-PX(I,IM)-DS) .LT. 0.) GO TO 2
0017          IM=IM+1
0018          IF(IND(I) .GT. 1) GO TO 8
0019          IF(IM .GT. KE(I)) GO TO 8
0020          B1(I)=PB(I,IM)
0021          B2(I)=PB(I,IM)
0022          BXZ(I)=PB(I,IM)
0023          BY(I)=PB(I,IM)
0024          PC(I,IM)=PB(I,IM)
0025          GO TO 9
0026        8 ITHP=I
0027          IKT=IM
0028          CALL RESET1(I,IKT,DS,S,NP,NS,CY,Y,YP,YS,YSP,YR1,YR1P,YR2,YR2P,
             1DERIVE,DERIVS,DERIVR,PX,PZ,PC,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,PU,PB,
             2PA,PT,PET,PEH,PW,LC)
0029          CALL SOLUTN(PX,PY,PZ,PQ,PMX,PMZ,PG,PF,PU,PENT,PS,PA,PB,PCOS,PSIN,
             1PT,PET,PH,PEH,PW,PAN,PDIL,PC,CY,Y,YP,S,I,IKT,NP,NS)
0030        9 NOVIK(I)=NOVIK(I)+1
0031          GO TO 11
0032        2 CONTINUE
0033          RETURN
0034          END
```

```
0001          SUBROUTINE PLMERG(PX,PY,PZ,PT,PET,PH,PEH,PW,PA,PB,PAN,PDIL,PCOS,
             1PSIN,CY,NP,NS,KE,MGPA2,MGST1,PC,LCHK,PU)
0002          COMMON /STCRE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE2/MP(30),MS(30),IIP(30)
             2       /STCRE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             3               PMSIN(30),DW(30),NBV(30),NEV(30),NCV(30)
             4       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TURBF,UC,B,TP,ET,HP,EH,WP,
             5               MG,MG1,CFRL,ALV,CPA,ANG,IQ,ITHP,ENTRAN
             6       /CONST2/IL,NII,IK,NI,NIP1
0003          DIMENSION PX(NP,NS),PZ(NP,NS),PB(NP,NS),PCOS(NP,NS),PXI(30),
             1PYI(30),PZI(30),PBI(30),PCOSI(30),CY(30),IRE(30),PSIN(NP,NS),
             2PSINI(30),KE(30),PY(NP,NS),PT(NP,NS),PET(NP,NS),PH(NP,NS),
             3PEH(NP,NS),PW(NP,NS),PA(NP,NS),PAN(NP,NS),PDIL(NP,NS),MGPA2(30),
             4MGST1(30),PC(NP,NS),B1I(30),B2I(30),BXZI(30),BYI(30),AI(30),
             5LCHK(30),PU(NP,NS)
        C     REARRANGE THE TRAJECTORIES OF THE EXISTING PLUMES
0004          NJ=0
0005          DO 101 I=1,NI
0006          IF(IND(I)-1)101,102,102
0007      102 ISC=IK+NOVIK(I)-IS(I)
0008          NJ=NJ+1
0009          PXI(NJ)=PX(I,ISC)
0010          PYI(NJ)=CY(I)
0011          PZI(NJ)=PZ(I,ISC)
0012          PBI(NJ)=PB(I,ISC)
0013          PCOSI(NJ)=PCOS(I,ISC)
0014          PSINI(NJ)=PSIN(I,ISC)
0015          AI(NJ)=A(I)
0016          B1I(NJ)=B1(I)
0017          B2I(NJ)=B2(I)
0018          BXZI(NJ)=BXZ(I)
0019          BYI(NJ)=BY(I)
0020          IRE(NJ)=I
0021      101 CONTINUE
        C     CHECK PLUME MERGING
0022          IL=0
0023          NI1=NJ-1
0024          DO 103 I=1,NI1
0025          J1=I+1
0026          DO 103 J=J1,NJ
0027          PYD=ABS(PYI(I)-PYI(J))
0028          PZD=ABS(PZI(I)-PZI(J))
0029          PYZ=SQRT(PZD*PZD+PYD*PYD)
0030          SR=BXZI(I)*PCOSI(I)+BXZI(J)*PCOSI(J)
0031          SR2=BYI(I)+BYI(J)
0032          IF(SR-PZD)103,10,10
0033       10 IF(SR2-PYD)103,104,104
0034      104 IF(AI(I) .EQ. 0. .AND. AI(J) .EQ. 0.) GO TO 1
0035          GO TO 106
0036        1 AREA1=0.5*PAI*(B1I(I)*B1I(I)+B1I(J)*B1I(J))
0037          AREA2=PYZ*(B1I(I)+B1I(J))
0038          IF(AREA1-AREA2) 103,106,106
0039      106 IL=IL+1
        C     RECORD THE PAIRS OF THE MERGED PLUMES
0040          MP(IL)=IRE(I)
0041          MS(IL)=IRE(J)
```

```
0042              II=IRE(I)
0043              JJ=IRE(J)
0044              INDT(JJ)=IND(JJ)
0045              INDT(II)=IND(II)
            C     RESET IND(II)=2,IND(JJ)=0 FOR JJ>II WHEN PLUMES II AND JJ MERGED
0046              IND(JJ)=0
0047              IIP(JJ)=IK+NOVIK(JJ)-IS(JJ)
0048              IF(IND(II)-1) 103,111,113
0049          111 IND(II)=2
0050          113 IIP(II)=IK+NOVIK(II)-IS(II)
0051          103 CONTINUE
0052              IF(IL-1)16,107,205
0053          205 K=1
0054          206 II=K+1
0055              DO 200 I=II,IL
0056              IF(MS(K).NE.MS(I))GO TO 200
0057              IF(MP(I)-MP(K))204,200,203
0058          203 IF(IND(I).EQ.0)GO TO 200
0059              IND(I)=0
0060              IIP(I)=IK+NOVIK(I)-IS(I)
0061              GO TO 200
0062          204 IF(IND(K).EQ.0)GO TO 200
0063              IND(K)=0
0064              IIP(K)=IK+NOVIK(K)-IS(K)
0065          200 CONTINUE
0066              K=K+1
0067              IF(K.LT.IL)GO TO 206
            C     PLUME MERGING OCCURS
0068          107 WRITE(6,108)
0069          108 FORMAT(1X,'RESULTS OF THE PAIRS OF MERGED PLUMES AT MERGING PLACE'
                 1)
0070              WRITE(6,112)
0071          112 FORMAT(1X,'NSTEP   NTHP    X        Z        Y       PTEMP  EXCEST'
                 1,'  PHUMI    EXCESH PLODMCIST PAVHFWD PCROSEC SLOTLEN  PANGLE  ',
                 2'DILUTN  PVELO')
0072              DO 109 I=1,IL
0073              INDX=1
0074              LP=MP(I)
0075              LS=MS(I)
0076              MT=IIP(LP)
0077              NT=IIP(LS)
0078              MGPA2(LS)=LP
0079              MGST1(LS)=MT
0080              IF(KE(LS) .GT. NT) GO TO 116
0081              LCHK(LS)=1
0082              KE(LS)=NT
0083          116 WRITE(6,110)MT,LP,PX(LP,MT),PZ(LP,MT),PY(LP,MT),PT(LP,MT),
                 1PET(LP,MT),PH(LP,MT),PEH(LP,MT),PW(LP,MT),PB(LP,MT),PC(LP,MT),
                 2PA(LP,MT),PAN(LP,MT),PDIL(LP,MT),PU(LP,MT)
0084          110 FORMAT(1X,2(I5,1X),3(F8.2,1X),2(F7.2,1X),3(F8.5,1X),6(F7.2,1X))
0085              IF(INDX-1)117,117,118
0086          117 INDX=2
0087              LP=LS
0088              MT=NT
0089              GO TO 116
0090          118 WRITE(6,119)
```

```
0091          119 FORMAT(/)
0092          105 CONTINUE
0093              DO 777 I=2,NI
0094              IF(IND(I)-1) 777,779,779
0095          777 CONTINUE
0096              NII=0
0097              ITHP=1
0098          779 DO 400 I=2,NP
0099              IF(IND(I))16,400,16
0100          400 CONTINUE
            C     ALL THE PLUMES ARE MERGED WHEN IND(I)=C FOR 1<I<NP+1
0101              IND(1)=3
0102              IQ=3
0103              NI=1
0104              ITHP=1
0105           16 RETURN
0106              END
```

```
0001          SUBROUTINE RESETI(I,IKT,DS,S,NP,NS,CY,Y,YP,YS,YSP,YR1,YR1P,YR2,
             1YR2P,DERIVE,DERIVS,DERIVR,PX,PZ,PQ,PMX,PMZ,PG,PF,PCOS,PSIN,PENT,
             2PU,PB,PA,PT,PET,PEH,PW,LC)
0002          EXTERNAL DERIVE,DERIVS,DERIVR
0003          COMMON /STCRE1/INC(30),INDT(30),NOVIK(30),IS(30)
             1       /STORE2/MP(30),MS(30),IIP(30)
             2       /STCRE4/A(30),B1(30),B2(30),BXZ(30),BY(30),PMCOS(30),
             3               PMSIN(30),CW(30),NBV(30),NEV(30),NCV(30)
             4       /CONST1/PAI,GRA,A1,A2,A3,A4,CD,TUREF,UC,B,TP,ET,HF,EH,WP,
             5               MG,MG1,CFRL,ALV,CPA,ANG,IG,ITHP,ENTRAN
             6       /CONST2/IL,NII,IK,NI,NIP1
0004          DIMENSION FX(NP,NS),PZ(NP,NS),PQ(NP,NS),PMX(NP,NS),PMZ(NP,NS),
             1PB(NP,NS),PF(NP,NS),PG(NP,NS),PENT(NP,NS),IRP(30),COS(30),Y(8),
             2YP(8),CY(30),PT(NP,NS),PET(NP,NS),PU(NP,NS),YS(8),YSP(8),
             3PA(NP,NS),PCOS(NP,NS),PSIN(NP,NS),YR1(8),YR1P(8),YR2(8),YR2P(8),
             4PEH(NP,NS),PW(NP,NS),IH(30)
0005          IK1=IKT-1
0006          Y(1)=PQ(I,IK1)
0007          Y(2)=PMX(I,IK1)
0008          Y(3)=PMZ(I,IK1)
0009          Y(4)=PG(I,IK1)
0010          Y(5)=PF(I,IK1)
0011          Y(6)=PX(I,IK1)
0012          Y(7)=PZ(I,IK1)
0013          APT=PT(I,IK1)
0014          IF(IND(I)-2)29,30,30
0015       30 IF(IL)32,32,33
        C     RESET INITIAL CONDITIONS WHEN ANY NEW PLUME MERGING OCCURS
0016       33 IRP(1)=I
0017          IJK=1
0018          MM=1
0019          JR=I
0020          M=I
0021          JRZ=I
0022          MZ=I
0023          CYMANI=CY(I)+BY(I)
0024          CYMINI=CY(I)-BY(I)
0025          PZMANI=PZ(I,IK1)+BXZ(I)
0026          PZMINI=PZ(I,IK1)-BXZ(I)
0027          CYMAN=CYMANI
0028          CYMIN=CYMINI
0029          PZMAN=PZMANI
0030          PZMIN=PZMINI
0031       60 DO 34 J=1,IL
0032          IF(IRP(MM)-MP(J))34,35,34
0033       35 JJ=MS(J)
0034          DO 86 NR=1,IJK
0035          IF(JJ-IRP(NR))86,34,86
0036       86 CONTINUE
        C     SUMMING UP VOLUME,MOMENTUM,ENERGY AND MOISTURE FLUXES OF THE
        C     MERGED PLUMES
0037          IKP=IK+NCV(JJ)-IS(JJ)
0038          Y(1)=Y(1)+PQ(JJ,IKP)
0039          Y(2)=Y(2)+PMX(JJ,IKP)
0040          Y(3)=Y(3)+PMZ(JJ,IKP)
0041          Y(4)=Y(4)+PG(JJ,IKP)
```

```
0042          Y(5)=Y(5)+PF(JJ,IKP)
0043          PQ(I,1)=PQ(I,1)+PQ(JJ,1)
0044          APT=APT+PT(JJ,IKP)
0045          IJK=IJK+1
0046          IRP(IJK)=JJ
0047          CYMANC=CY(JJ)+BY(JJ)
0048          CYMINC=CY(JJ)-BY(JJ)
0049          PZMANC=PZ(JJ,IKP)+BXZ(JJ)
0050          PZMINC=PZ(JJ,IKP)-BXZ(JJ)
0051          IF(INDT(JJ) .GT. 1) GO TO 401
0052          IF(INDT(I)-2) 401,400,401
0053      400 IF(IH(I) .GT. 2) GO TO 404
0054          IF(CYMANI .GE. CYMANC .AND. CYMINI .LE. CYMINC) GO TO 34
0055          GO TO 401
0056      404 IF(PZMANI .GE. PZMANC .AND. PZMINI .LE. PZMINC) GO TO 34
0057      401 IF(CYMAN .GE. CYMANC) GO TO 244
0058          CYMAN=CYMANC
0059          JR=JJ
0060      244 IF(CYMIN .LE. CYMINC) GO TO 28
0061          CYMIN=CYMINC
0062          M=JJ
0063       28 IF(PZMAN .GE. PZMANC) GO TO 26
0064          PZMAN=PZMANC
0065          JRZ=JJ
0066       26 IF(PZMIN .LE. PZMINC) GO TO 34
0067          PZMIN=PZMINC
0068          MZ=JJ
0069       34 CONTINUE
0070          IF(MM-IJK) 58,59,59
0071       58 MM=MM+1
0072          GO TO 60
0073       59 IF(MM-1) 32,32,859
0074      859 APT=APT/FLCAT(IJK)
0075          Y(7)=0.5*(PZMAN+PZMIN)
        C     LC=0 MEANS CLUSTER OF TOWERS; LC=1 MEANS LINE TOWER ARRAY
0076          IF(LC-1)575,572,575
0077      575 CY(I)=0.5*(CYMAN+CYMIN)
0078          GO TO 571
0079      572 IKQ=IK+NCVIK(M)-IS(M)
0080          IKP=IK+NCVIK(JR)-IS(JR)
0081          DCYAI=CYMAN-CYMIN
0082          DPZAI=PZMAN-PZMIN
0083          IF(DCYAI .LT. DPZAI) GO TO 402
0084          IF((CYMAN-CYMIN) .LT. (PZMAN-PZMIN)) GO TO 402
0085          IF(CY(M) .EQ. CY(JR)) GO TO 407
0086          CYDZ=ABS(PZ(M,IKQ)-PZ(JR,IKP))
        C     TO CALCULATE THE ANGLE OF THE INCLINATION OF MERGED PLUME (PHI)
0087          CALL PHI(I,JR,M,CY,PZ,NF,NS,IKQ,IKP)
0088          IF(CYDZ.NE.0.)GO TO 408
0089          IH(I)=2
0090          GO TO 409
0091      408 IH(I)=1
0092      409 B1(I)=PB(M,IKQ)
0093          B2(I)=PB(JR,IKP)
0094          IF(PMCOS(I) .EQ. 0.) GO TO 988
0095          A(I)=(DCYAI-B1(I)-B2(I))/PMCOS(I)
```

```
0096              GO TO 573
0097          988 A(I)=DPZAI-B1(I)-B2(I)
0098              GO TO 573
0099          402 JR=JRZ
0100              M=MZ
0101              IKQ=IK+NOVIK(M)-IS(M)
0102              IKP=IK+NCVIK(JR)-IS(JR)
0103              IF(PZ(JR,IKP) .EQ. PZ(M,IKQ)) GO TO 407
0104              PZY=ABS(CY(JR)-CY(M))
            C     TO CALCULATE THE ANGLE OF THE INCLINATION OF MERGED PLUME (PHI)
0105              CALL PHI(I,JR,M,CY,PZ,NF,NS,IKQ,IKP)
0106              IF(PZY.NE.0.)GO TO 431
0107              IH(I)=3
0108              GO TO 432
0109          431 IH(I)=1
0110          432 B1(I)=PB(M,IKQ)
0111              B2(I)=PB(JR,IKP)
0112              IF(PMSIN(I) .EQ. 0.) GO TO 989
0113              A(I)=(DPZAI-B1(I)-B2(I))/PMSIN(I)
0114              GO TO 573
0115          989 A(I)=DCYAI-B1(I)-B2(I)
0116              GO TO 573
0117          407 A(I)=A(JR)
0118              B1(I)=B1(JR)
0119              B2(I)=B2(JR)
0120              PMCOS(I)=PMCOS(JR)
0121              PMSIN(I)=PMSIN(JR)
0122              IH(I)=IH(JR)
0123          573 CY(I)=0.5*(CYMAN+CYMIN)
0124              IF(A(I) .EQ. 0.)GO TO 38
0125              GO TO 574
0126           32 IF(LC-1)571,570,571
0127          571 IF(IND(I)-3)29,41,29
0128          570 IF(A(I))38,38,39
0129           38 A(I)=0.
0130              IF(IND(I)-3)40,41,40
0131           41 IQ=4
0132              IND(I)=4
0133              GO TO 29
0134           40 IND(I)=1
0135              GO TO 29
0136           39 JR=I
0137              IKP=IK1
0138              M=I
0139              IKQ=IK1
            C     RESET I.C. FOR THE HALF ROUND PLUME
0140          574 BBB=PAI*B1(I)*B1(I)*ABS(PU(M,IKQ))
0141              ALV1=FALV(PT(M,IKQ))
0142              ALV2=FALV(PT(JR,IKP))
0143              YR1(1)=BBB
0144              YR1(2)=BBB*PU(M,IKQ)*PCCS(M,IKQ)
0145              YR1(3)=BBB*PU(M,IKQ)*PSIN(M,IKQ)
0146              YR1(4)=BBB*(PET(M,IKQ)-ALV1*PW(M,IKQ))
0147              YR1(5)=BBB*(PEH(M,IKQ)+PW(M,IKQ))
0148              YR1(6)=PX(M,IKQ)
0149              YR1(7)=PZ(M,IKQ)
```

```
      C     RESET I.C. FOR THE HALF ROUND PLUME
0150        BBB=PAI*B2(I)*B2(I)*ABS(PU(JR,IKP))
0151        YR2(1)=BBB
0152        YR2(2)=BBB*PU(JR,IKP)*PCOS(JR,IKP)
0153        YR2(3)=BBB*PU(JR,IKP)*PSIN(JR,IKP)
0154        YR2(4)=BBB*(PET(JR,IKP)-ALV2*PW(JR,IKP))
0155        YR2(5)=BBB*(PEH(JR,IKP)+PW(JR,IKP))
0156        YR2(6)=PX(JR,IKP)
0157        YR2(7)=PZ(JR,IKP)
      C     RESET I.C. FOR THE CENTRAL SLOT JET
0158        YS(1)=(Y(1)-0.5*(YR1(1)+YR2(1)))/A(I)
0159        YS(2)=(Y(2)-0.5*(YR1(2)+YR2(2)))/A(I)
0160        YS(3)=(Y(3)-0.5*(YR1(3)+YR2(3)))/A(I)
0161        YS(4)=(Y(4)-0.5*(YR1(4)+YR2(4)))/A(I)
0162        YS(5)=(Y(5)-0.5*(YR1(5)+YR2(5)))/A(I)
0163        YS(6)=Y(6)
0164        YS(7)=Y(7)
      C     CALCULATE NEW HALF WIDTH AND VELO. OF THE HALF ROUND PLUME
0165        L=0
0166        ALV=ALV1
0167        CALL RUNGS(S,DS,5,YR1,YR1P,L,DERIVR)
0168        CALL RUNGS(S,DS,5,YR1,YR1P,L,DERIVR)
0169        BR1=B
0170        UR1=UC
0171        S=S-DS
      C     CALCULATE NEW HALF WIDTH AND VELO. OF THE HALF ROUND PLUME
0172        L=0
0173        ALV=ALV2
0174        CALL RUNGS(S,DS,5,YR2,YR2P,L,DERIVR)
0175        CALL RUNGS(S,DS,5,YR2,YR2P,L,DERIVR)
0176        BR2=B
0177        UR2=UC
0178        S=S-DS
      C     CALCULATE NEW HALF WIDTH AND VELO. OF THE SLOT JET
0179        L=0
0180        ALV=FALV(APT)
0181        CALL RUNGS(S,DS,5,YS,YSF,L,DERIVS)
0182        CALL RUNGS(S,DS,5,YS,YSF,L,DERIVS)
0183        BS=B
0184        US=UC
0185        S=S-DS
      C     CALCULATE MERGED PLUME WITH THE MODIFIED PLUME SHAPE DETERMINED C
      C     THE PREVIOUS STEP
0186        L=0
0187        CALL RUNGS(S,DS,7,Y,YP,L,DERIVE)
0188        CALL RUNGS(S,DS,7,Y,YF,L,DERIVE)
      C     DETERMINE B1,B2 AND A OF THE MODIFIED PLUME SHAPE FOR CALCULATING
      C     ENTRAINMENT AND DRAG FOR NEXT STEP
0189        UU=UC
0190        W=A(I)
0191        CB1=BR2/BR1
0192        CB2=W+BR1+BR2
0193        CB3=(1.5707963*(BR1*BR1*UR1+BR2*BR2*UR2)+2.*BS*W*US)/UU
0194        CB4=1.+CB1
0195        AP1=1.5707963*(1.+CB1*CB1)-CB4*CB4
0196        BP1=CB2*CB4
```

```
0197              CP1=-CB3
0198              B1P=B1(I)
0199              B2P=B2(I)
0200              AP=A(I)
            C     THE DETERMINED B1,B2 AND A
0201              B1(I)=(-BP1+SQRT(BP1*BP1-4.*AP1*CP1))/(2.*AP1)
0202              B2(I)=CB1*B1(I)
0203              A(I)=CB2-CB4*B1(I)
0204              B=(B1(I)+B2(I))*0.5
0205              IF(A(I))418,418,419
0206          418 A(I)=0.
0207              IF(IND(I)-3) 420,421,420
0208          421 IQ=4
0209              IND(I)=4
0210              GO TO 31
0211          420 IND(I)=1
0212              GO TO 31
0213          419 DY=0.5*(B2(I)-B1(I)+(B1P-B2P)*A(I)/AP)*ABS(PMCOS(I))
0214              CY(I)=CY(I)+DY
            C     DETERMINE SOME LENGTH SCALES FOR THE USE OF MERGING CRITERION
0215              AL=0.5*(B1(I)+B2(I))
0216              ALC=AL+0.5*PMCOS(I)*A(I)
0217              ALS=AL+0.5*PMSIN(I)*A(I)
0218              LQ=IH(I)
0219              GO TO (411,412,413),LC
0220          411 BY(I)=ALC
0221              BXZ(I)=ALS
0222              GO TO 416
0223          412 BY(I)=ALC
0224              BXZ(I)=AMAX1(B1(I),B2(I))
0225              GO TO 416
0226          413 BXZ(I)=ALS
0227              BY(I)=AMAX1(B1(I),B2(I))
0228          416 DW(I)=2.*BY(I)
0229              GO TO 31
            C     CALCULATE SINGLE ROUND FLUME
0230           29 L=0
0231              ALV=FALV(PT(I,IK1))
0232              CALL RUNGS(S,DS,7,Y,YF,L,DERIVR)
0233              CALL RUNGS(S,DS,7,Y,YF,L,DERIVR)
0234              B1(I)=B
0235              B2(I)=B
0236              BXZ(I)=B
0237              BY(I)=B
0238           31 RETURN
0239              END
```

```
0001          SUBROUTINE OUTPUT(PX,PY,PZ,PT,PET,PH,PEH,PW,PA,PC,PAN,PDIL,PSIN,
             1PCOS,CONTA,CONTB,CONTC,KE,INTPR,IFNT,NX,NY,NCONT,N4,NP,NS,IX,DX,
             2DZ,XO,ZO,PB,PS,PU)
0002          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
             1       /CONTUU/WIDTH,HITE,MORE,NOMAP,ICENT,NOTICK,HEDN(10),
             2              LABY(5),LABX(5)
             3       /STORE5/DI(30),UO(30),TO(30),HO(30),WO(30)
0003          DIMENSION PX(NP,NS),PY(NP,NS),PZ(NP,NS),PT(NP,NS),PET(NP,NS),
             1PH(NP,NS),PEH(NP,NS),PW(NP,NS),PA(NP,NS),PC(NP,NS),PAN(NP,NS),
             2PDIL(NP,NS),PSIN(NP,NS),PCOS(NP,NS),CONTA(NX,NY),CONTB(NCONT),
             3CONTC(N4),KE(30),IX(12),PB(NP,NS),PS(NP,NS),PU(NP,NS)
0004          IF(INTPR .LE. 0) GO TO 10
0005          WRITE(6,1)
0006        1 FORMAT(1X,'DETAILED RESULTS OF PLUME 1')
0007          WRITE(6,2)
0008        2 FORMAT(1X,'NSTEP  NTIP    X       Z       Y     PTEMP  EXCEST
             1,'  PHUMI    EXCESH PLQDMOIST PAVHFWQ PCRCSEC SLOTLEN  PANGLE  ',
             2'DILUTN  PVELO')
0009          I=1
0010          DO 3 J=1,NS,INTPR
0011        3 WRITE(6,241)J,I,PX(I,J),PZ(I,J),PY(I,J),PT(I,J),PET(I,J),PH(I,J),
             1PEH(I,J),PW(I,J),PB(I,J),PC(I,J),PA(I,J),PAN(I,J),PDIL(I,J),
             2PU(I,J)
0012      241 FORMAT(1X,2(I5,1X),3(F8.2,1X),2(F7.2,1X),3(F8.5,1X),6(F7.2,1X))
0013       10 IF(IX(3))15,21,20
0014       20 READ(5,22)DX,DZ,XO,ZO
0015       22 FORMAT(4F10.5)
0016       21 IF(IX(11) .LE. 0) GO TO 26
0017          READ(5,28)WIDTH,HITE,MORE,NOMAP,ICENT,NOTICK
0018       28 FORMAT(2F10.5,4I4)
0019          NCONB=-NCONT
0020       26 PETO=PMAX(PET,NP,NS,KE)
0021          PEHC=PMAX(PEH,NP,NS,KE)
0022          PEWO=PMAX(PW,NP,NS,KE)
0023          IF(PETO .GT. 0.) GO TO 14
0024          IX(8)=0
0025          PETO=1.
0026          WRITE(6,40)
0027       40 FORMAT(1X,'NO EXCESS TEMP PLOT DUE TO ZERO OR NEGATIVE EXCESS',
             1' TEMPERATURE')
0028       14 IF(PEHC .GT. 0.) GO TO 42
0029          IX(9)=0
0030          PEHC=1.
0031          WRITE(6,43)
0032       43 FORMAT(1X,'NO EXCESS HUMI PLOT DUE TO ZERO OR NEGATIVE EXCESS',
             1' HUMIDITY')
0033       42 IF(PEWO .GT. 0.) GO TO 47
0034          IX(10)=0
0035          PEWO=1.
0036          WRITE(6,46)
0037       46 FORMAT(1X,'NO EXCESS LIQUID PHASE MOISTURE PLOT DUE TO ZERO OR',
             1' NEGATIVE EXCESS LIQUID PHASE MOISTURE')
        C     DETERMINE GRID DISTRIBUTION
0038       47 DO 11 I=1,NP
0039          DO 11 J=1,NS
0040          PX(I,J)=PX(I,J)/EI(1)
```

```
0041          PZ(I,J)=PZ(I,J)/DI(1)
0042          PB(I,J)=PB(I,J)/DI(1)
0043          PC(I,J)=PC(I,J)/DI(1)
0044          PS(I,J)=PS(I,J)/DI(1)
0045          PW(I,J)=PW(I,J)/PEWO
0046          PEH(I,J)=PEH(I,J)/PEHC
0047       11 PET(I,J)=PET(I,J)/PETC
0048          I=8
0049          IF(IX(I) .LE. 0) GO TO 5
0050          CALL GRD2(CONTA,DX,DZ,PX,PZ,PC,PET,PCOS,PSIN,NP,NS,KE,XO,ZO,NX,NY)
0051          WRITE(6,31)
0052       31 FORMAT(1X,'EXCESS TEMPERATURE PLOT',//)
0053          GO TO 37
0054        8 CALL GRD2(CONTA,DX,DZ,PX,PZ,PC,PEH,PCOS,PSIN,NP,NS,KE,XO,ZO,NX,NY)
0055          WRITE(6,32)
0056       32 FORMAT(1X,'EXCESS SPECIFIC HUMIDITY PLOT',//)
0057          GO TO 37
0058        9 CALL GRD2(CONTA,DX,DZ,PX,PZ,PC,PW,PCOS,PSIN,NP,NS,KE,XO,ZO,NX,NY)
0059          WRITE(6,33)
0060       33 FORMAT(1X,'EXCESS LIQUID PHASE MOISTURE PLOT',//)
0061       37 READ(5,30) (HEDN(K),K=1,10),(LABY(L),L=1,5),(LABX(M),M=1,5)
0062       30 FORMAT(20A4)
0063        7 CALL CONTU(CONTA,CONTE,CONTC,NX,NY,NCONB,IFAT)
0064        5 I=I+1
0065          IF(I-10)16,17,15
0066       16 IF(IX(I))5,5,8
0067       17 IF(IX(I))5,5,9
0068       15 RETURN
0069          END
```

```
0001          FUNCTION PMAX(PT,NP,NS,KE)
0002          DIMENSION PT(NP,NS),KE(30)
0003          PMAX=PT(1,1)
0004          DO 1 I=1,NP
0005          K=KE(I)
0006          DO 1 J=1,K
0007          IF(PT(I,J) .GT. PMAX) PMAX=PT(I,J)
0008        1 CONTINUE
0009          RETURN
0010          END
```

```
0001          SUBROUTINE GRD2(A,DX,DZ,PX,PZ,PB,PG,PCOS,PSIN,NP,NS,KE,XO,ZO,ID,
             1JD)
0002          COMMON /STORE1/IND(30),INDT(30),NOVIK(30),IS(30)
0003          DIMENSICN A(ID,JD),RM(5),C(5),IC(4),PX(NP,NS),PZ(NP,NS),PG(NP,NS)
             1PB(NP,NS),PCOS(NP,NS),PSIN(NP,NS),KE(30)
0004          DO 210 I=1,ID
0005          CO 210 J=1,JD
0006      210 A(I,J)=0.
0007          CO 1 N=1,NP
0008          DC 1 I=1,NS
0009          PX(N,I)=PX(N,I)+XO
0010        1 PZ(N,I)=PZ(N,I)+ZO
0011          KX=1
0012          DO 2 N=1,NP
0013          KY=KE(N)-1
0014          IF(KX .GE. KY) GO TO 2
0015          RM(1)=0.
0016          C(1)=PZ(N,KX)
0017          IC(1)=(PX(N,KX)-PB(N,KX))/DX+1.0005
0018          IC1=PX(N,KX)/DX+1.0005
0019          IC(2)=(PX(N,KX)+PB(N,KX))/DX+1.0005
0020          DO 2 K=KX,KY
0021          PB2S=PB(N,K+1)*PSIN(N,K+1)
0022          IC(3)=(PX(N,K+1)-PB2S)/DX+1.0005
0023          IC2=PX(N,K+1)/DX+1.0005
0024          IC(4)=(PX(N,K+1)+PB2S)/DX+1.0005
0025          PB2C=PB(N,K+1)*PCOS(N,K+1)
0026          PB1C=PB(N,K)*PCCS(N,K)
0027          PB1S=PB(N,K)*PSIN(N,K)
0028          DZZ=PZ(N,K+1)-PZ(N,K)
0029          DXX=PX(N,K+1)-PX(N,K)
0030          DPBC=PB2C-PB1C
0031          DPBS=PB2S-PB1S
0032          DS=SQRT(DZZ*DZZ+DXX*DXX)
0033          DB=PB(N,K+1)-PB(N,K)
0034          DG=PG(N,K)-PG(N,K+1)
0035          IF(PSIN(N,K+1) .LT. C.) GO TO 101
0036          IF(IC(1)-IC(3)) 103,104,105
0037      105 IL=IC(3)+1
0038          GO TO 112
0039      104 IL=IC(3)+1
0040          GO TO 113
0041      103 IL=IC(1)+1
0042      112 RM(3)=(DZZ+DPBC)/(DXX-DPBS)
0043          C(3)=PZ(N,K+1)+PB2C-(PX(N,K+1)-PB2S)*RM(3)
0044      113 DXPB=DXX+DPBS
0045          IF(DXPB .EQ. 0.) GO TO 20
0046          RM(4)=(DZZ-DPBC)/DXPB
0047          C(4)=PZ(N,K+1)-PB2C-(PX(N,K+1)+PB2S)*RM(4)
0048       20 IF(PSIN(N,K+1) .EQ. 0.) GO TO 109
0049          RM(2)=-PCCS(N,K+1)/PSIN(N,K+1)
0050          C(2)=PZ(N,K+1)-PX(N,K+1)*RM(2)
0051      109 IR=IC(4)
0052          IF(IL .GT. IR) GO TO 99
0053          DO 12 I=IL,IR
0054          IF(I .GT. ID) GO TO 12
```

```
      IF(I .LT. 1) GO TO 12
      X=DX*FLOAT(I-1)
      IF(I .GT. IC(3)) GO TO 7
      ZU=RM(3)*X+C(3)
      GO TO 8
    7 ZU=RM(2)*X+C(2)
    8 JU=ZU/DZ+1.0001
      IF(I .GT. IC(2)) GO TO 10
      IF(I .GT. IC(1)) GO TO 115
      ZL=RM(3)*X+C(3)
      GO TO 11
  115 ZL=RM(1)*X+C(1)
      GO TO 11
   10 ZL=RM(4)*X+C(4)
   11 IF((ZL-DZ*FLOAT(JU-1)) .GT. 0.) GO TO 12
      JL=ZL/DZ+1.9999
      IF(JU .LT. JL) GO TO 12
      CALL PD2(A,PX,PZ,PB,PG,PCOS,PSIN,RM,C,NP,NS,N,JL,JU,DB,DG,DZ,X,
     1DXX,DZZ,I,K,ID,JD)
   12 CONTINUE
      GO TO 99
  101 IF(IC(2)-IC(4)) 121,122,123
  122 IL=IC(2)+1
      GO TO 124
  123 IL=IC(4)+1
      GO TO 125
  121 IL=IC(2)+1
  125 RM(4)=(DZZ-DPBC)/(DXX+DPBS)
      C(4)=PZ(N,K+1)-PB2C-(PX(N,K+1)+PB2S)*RM(4)
  124 DXDP=DXX-DPBS
      IF(DXDP .EQ. 0.) GO TO 21
      RM(3)=(DZZ+DPBC)/DXDP
      C(3)=PZ(N,K+1)+PB2C-(PX(N,K+1)-PB2S)*RM(3)
   21 RM(2)=-PCOS(N,K+1)/PSIN(N,K+1)
      C(2)=PZ(N,K+1)-PX(N,K+1)*RM(2)
      IR=IC(3)
      IF(IL .GT. IR) GO TO 99
      DO 128 I=IL,IR
      IF(I .GT. ID) GO TO 128
      IF(I .LT. 1) GO TO 128
      X=DX*FLOAT(I-1)
      IF(I .GT. IC(1)) GO TO 130
      IF(I .GT. IC(2)) GO TO 132
      ZU=RM(4)*X+C(4)
      GO TO 133
  132 ZU=RM(1)*X+C(1)
      GO TO 133
  130 ZU=RM(3)*X+C(3)
  133 JU=ZU/DZ+1.0001
      IF(I .GT. IC(4)) GO TO 135
      ZL=RM(4)*X+C(4)
      GO TO 136
  135 ZL=RM(2)*X+C(2)
  136 IF((ZL-DZ*FLOAT(JU-1)) .GT. 0.) GO TO 128
      JL=ZL/DZ+1.9999
      IF(JU .LT. JL) GO TO 128
```

```
0110          CALL PD2(A,PX,PZ,PB,PG,PCOS,PSIN,RM,C,NP,NS,N,JL,JU,DB,DG,DZ,X,
             1DXX,DZZ,I,K,ID,JD)
0111      128 CONTINUE
0112       99 RM(1)=RM(2)
0113          C(1)=C(2)
0114          IC(1)=IC(3)
0115          IC(2)=IC(4)
0116          IC1=IC2
0117        2 CONTINUE
0118          CH=1.
0119          IP=1
0120          IW=20
0121      171 IF(ID .GT. IW) GO TO 172
0122          IW=ID
0123          CH=0.
0124      172 WRITE(6,178)
0125      178 FORMAT(1H1)
0126          DO 662 J=1,JD
0127          L=JD+1-J
0128      662 WRITE(6,3) (A(I,L),I=IP,IW)
0129        3 FORMAT(1X,20(F5.2,1X))
0130          IF(CH .EQ. 0.) GO TO 173
0131          IP=IP+20
0132          IW=IW+20
0133          GO TO 171
0134      173 DO 310 N=1,NP
0135          DO 310 I=1,NS
0136          PX(N,I)=PX(N,I)-XO
0137      310 PZ(N,I)=PZ(N,I)-ZO
0138          RETURN
0139          END
```

```
0001          SUBROUTINE PD2(A,PX,PZ,PB,PG,PCOS,PSIN,RM,C,NP,NS,N,JL,JU,DB,DG,
             1DZ,X,DXX,DZZ,I,K,ID,JD)
0002          DIMENSION A(ID,JD),PX(NP,NS),PZ(NP,NS),PB(NP,NS),PG(NP,NS),
             1PCOS(NP,NS),PSIN(NP,NS),RM(5),C(5)
0003          DO 1 J=JL,JU
0004          IF(J .GT. JD) GO TO 1
0005          IF(J .LT. 1) GO TO 1
0006          Z=DZ*FLOAT(J-1)
0007          PDX=PX(N,K)-PX(N,K+1)
0008          IF(PDX .NE. 0.) GO TO 5
0009          XK1=X
0010          XK=X
0011          ZK1=RM(2)*XK1+C(2)
0012          ZK=RM(1)*XK+C(1)
0013          GO TO 7
0014        5 RM(5)=DZZ/DXX
0015          C(5)=PZ(N,K+1)-PX(N,K+1)*RM(5)
0016          CP=Z-X*RM(5)
0017          IF(PSIN(N,K+1) .EQ. 0.) GO TO 3
0018          XK1=(C(2)-CP)/(RM(5)-RM(2))
0019          GO TO 4
0020        3 XK1=PX(N,K+1)
0021        4 ZK1=RM(5)*XK1+CP
0022        7 DXK1=XK1-X
0023          DZK1=ZK1-Z
0024          DSB=SQRT(DXK1*DXK1+DZK1*DZK1)
0025          IF(PSIN(N,K) .EQ. 0.) GO TO 9
0026          IF(PDX .EQ. 0.) GO TO 10
0027          XK=(C(1)-CP)/(RM(5)-RM(1))
0028          GO TO 11
0029        9 XK=PX(N,K)
0030       11 ZK=RM(5)*XK+CP
0031       10 DXK=XK-XK1
0032          DZK=ZK-ZK1
0033          DSP=SQRT(DXK*DXK+DZK*DZK)
0034          RDSBP=DSB/DSP
0035          XPC=PX(N,K+1)-RDSBP*DXX
0036          ZPC=PZ(N,K+1)-RDSBP*DZZ
0037          DXPC=X-XPC
0038          DZPC=Z-ZPC
0039          DSC=SQRT(DXPC*DXPC+DZPC*DZPC)
0040          B=PB(N,K+1)-RDSBP*DB
0041          AN=(1.-DSC/B)*(PG(N,K+1)+RDSBP*DG)
0042          IF(AN .GT. A(I,J)) A(I,J)=AN
0043        1 CONTINUE
0044          RETURN
0045          END
```

```
0001          SUBROUTINE CONTU(A,B,C,ISET,LIM,NN,IPNT)
0002          DIMENSION A(ISET,1),B(1),C(1)
0003          COMMON/CONTUU/WIT,HITE,KEY(4),HEDN(20),
            * XNIN,XNAX,YNIN,YNAX,XOFF,YOFF,XSIZ ,YSIZ ,NCONT ,IFLAG
0004          COMMON/LBLCOM/ITEST,SLBL,STTL,SSCL,STICKL
0005          IF(IPNT.LT.0) GOTO 999
0006          IF(IPNT.GT.0) GOTO 888
0007          IF(NN.EQ.0) NN=-10
0008          NCONT=IABS(NN)
0009          MAX=MAX0(LIM,ISET)
0010          DO 2 I=1,LIM
0011        2 CALL MAXMIN(A(1,I),ISET,C(I),C(LIM+I))
0012          CALL MAXMIN(C,LIM*2,YMAX1,YMIN1)
0013          CALL SCALE(YMAX1,YMIN1,TOP,BOT,NCONT,IERR)
0014          IF(IERR.NE.0)  GOTO 1000
0015          CALL MAXMIN(B,NCONT,BMAX,BMIN)
0016          IF(BMAX.LT.YMIN1.OR.BMIN.GT.YMAX1) GOTO 4
0017          IF(NN.GT.0) GOTO 1
0018        4 DELTA=(TOP-BOT)/NCONT
0019          B(1)=BOT
0020          DO 3 I=2,NCONT
0021        3 B(I)=B(I-1)+DELTA
0022        1 IF(IFLAG.NE.0) GOTO 6
0023          ISET1=ISET-1
0024          LIM1=LIM-1
0025          YSIZE=HITE
0026          XSIZE=WIT
0027          XMIN=1.
0028          YMIN=1.
0029          XMAX=ISET
0030          YMAX=LIM
0031          YNAX=YMAX
0032          YNIN=YMIN
0033          XNAX=XMAX
0034          XNIN=XMIN
0035          IF(KEY(2).EQ.1) GOTO 10
0036          DX=XMAX-XMIN
0037          DY=YMAX-YMIN
0038          IF(DX.GT.DY) GOTO 11
0039          DUM=XSIZE
0040          XSIZE=YSIZE
0041          YSIZE=DUM
0042       11 YSIZE=AMIN1(YSIZE,26.)
0043          DX=AMIN1(XSIZE/DX,YSIZE/DY)
0044          XSIZE=DX*(XMAX-XMIN)
0045          YSIZE=DX*(YMAX-YMIN)
0046       10 XBIG=1.3*XSIZE
0047          IF(XBIG.LT.15.) XBIG=15.
0048          IF(XBIG.GT.50.) CALL SYSXMX(XBIG)
0049          YBIG=10.
0050          IF(YSIZE.LE.10.) GOTO 12
0051          YBIG=29.
0052          CALL SYSPSZ(1)
0053       12 YOFF=0.5*IFIX(YBIG-YSIZE)
0054          XOFF=0.5*IFIX(XBIG-XSIZE)+0.5
0055          XD=XSIZE/(XMAX-XMIN)
```

```
0056          YD=YSIZE/(YMAX-YMIN)
0057          XTOFF=0.1
0058          IF(YSIZE.GT.10.) XTOFF=YSIZE*.01
0059          IF(YSIZE.LT.5..AND.XSIZE.LT.7.5) XTOFF=YSIZE*.02
0060          XTOFF=AMAX1(XTOFF,.05)
0061          ITEST=1
0062          SLBL=1.1*XTOFF
0063          STTL=1.2*XTOFF
0064          SSCL=XTOFF
0065          STICKL=STTL
0066          IF(KEY(4).NE.0) STICKL=0
0067          SYMS=0.8*XTOFF
0068          YT     =YOFF+YSIZE+XTOFF
0069          IF(YT+STTL.GT.YBIG) YT=YOFF+YSIZE-XTOFF-XTOFF-STTL
0070          XSIZ=XSIZE
0071          YSIZ=YSIZE
0072          IF(LIM.GT.ISET) XSIZ=XSIZ*LIM1/ISET1
0073          IF(ISET.GT.LIM) YSIZ=YSIZ*ISET1/LIM1
0074          CALL LABEL(XOFF,YSIZE+YOFF,XMIN,XMAX,XSIZE,-ISET1,' ',-1,0)
0075          CALL LABEL(XSIZE+XOFF,YOFF,YMIN,YMAX,YSIZE,-LIM1 ,' ',-1,1)
0076          CALL FINDMT(HEDN(16),MT16,20)
0077          CALL FINDMT(HEDN(11),MT  ,20)
0078          CALL LABEL(XOFF,YOFF,XMAX,XMIN,XSIZE,-ISET1,HEDN(16),MT16,0)
0079          CALL LABEL(XOFF,YOFF,YMAX,YMIN,YSIZE,-LIM1,HEDN(11),MT,1)
0080          CALL FINDMT(HEDN,MT,40)
0081          IF(MT.EQ.0) GOTO 6
0082          XBEGIN=XOFF+XTOFF
0083          IF(KEY(3).EQ.0)XBEGIN=XOFF+.5*XSIZE+(.1-.4286*MT)*STTL
0084          CALL SYSSYM(XBEGIN     ,YT,STTL,HEDN,MT,0.)
0085        6 IDUM1=1
0086          IDUM2=IDUM1+MAX
0087          IDUM3=IDUM2+MAX
0088          IDUM4=IDUM3+MAX
0089          CALL TOPO(A,B,C(IDUM1),C(IDUM2),C(IDUM3),C(IDUM4),LIM,ISET)
0090          WRITE(6,100)                    (B(I),I=1,NCONT)
0091      100 FORMAT(' ++ CONTU LEVELS ',8G13.5/(1X1P10G13.5))
0092          IFLAG=1
0093          IF(KEY(1).NE.0) RETURN
0094       50 CALL SYSPLT(0.,0.,999)
0095          IFLAG=0
0096          RETURN
0097     1000 WRITE(6,1001) YMIN1,YMAX1,NCONT
0098     1001 FORMAT(' ** TROUBLES **   MIN,MAX,NCONTOUR = ',2G13.5,I5)
0099          RETURN
0100      888 IDUM1=IPNT
0101          DO 88 I=1,ISET
0102          XBIG=XOFF+(B(I)-XMIN)*XD
0103          YBIG=YOFF+(A(I,1)-YMIN)*YD
0104       88 CALL SYSSYM(XBIG,YBIG,SYMS,IDUM1,-1,0)
0105          RETURN
0106      999 XBIG=XOFF+(B(1)-XMIN)*XD
0107          YBIG=YOFF+(A(1,1)-YMIN)*YD
0108          CALL SYSPLT(XBIG,YBIG,3)
0109          IDUM1=MAX0(LIM,1)
0110          DO 99 I=1,ISET,IDUM1
0111          XBIG=XOFF+(B(I)-XMIN)*XD
0112          YBIG=YOFF+(A(I,1)-YMIN)*YD
0113       99 CALL SYSPLT(XBIG,YBIG,2)
0114          RETURN
0115          END
```

```
0001          BLOCK DATA
0002          COMMON/CONTUU/WIT,HITE,KEY(4),HEDN(20),STUFF(9),IFLAG
0003          DATA WIT,HITE,KEY,HEDN/8.,8.      ,4*0,20*1H /
0004          DATA IFLAG/0/
0005          END
```

```
0001          SUBROUTINE TOPO(     V,CNTR,RA,RB,X,Y,M,N)
0002          DIMENSION V(  N ,1),CNTR(1),RA(1),RB(1),X(1),Y(1)
0003          COMMON/CONTUU/SKUPO(26),
             *              XMIN,XMAX,YMIN,YMAX,XOFF,YOFF,XSIZ ,YSIZ ,NCONT
0004           SX=XMAX-XMIN
0005           SY=YMAX-YMIN
0006          SMAX=AMAX1(SX,SY)
0007          SMAX1=1./SMAX
0008           SS=SX*SMAX1
0009          SYS=SY*SMAX1
0010          SSS=0.5*SYS
0011          Y1 = SY*SMAX1- .001
0012          X2 = SX*SMAX1- .001
0013          YCONV=SMAX1
0014           DELTAX=N-1
0015           DELTAX=(XMAX-XMIN)/DELTAX
0016           X(1) = 0.
0017          RB(1) = V(1,1)
0018          DO 27 J=2,N
0019           RB(J)=V(J,1)
0020       27  X(J)=X(J-1)+DELTAX
0021           DELTAY=M-1
0022           DELTAY=(YMAX-YMIN)/DELTAY
0023           Y(1) = 0.
0024          DO 28 J=2,M
0025       28  Y(J)=Y(J-1)+DELTAY
0026          DO 118  K=2,M
0027           DO 30 J=1,N
0028           RA(J)=RB(J)
0029       30 RB (J)=V(J,K)
0030          DO 118  J=2,N
0031       35 ASSIGN 112 TO L
0032          RR=RA(J)
0033          XX=X(J)
0034          YY=Y(K-1)
0035       37 RL=RR
0036          XL=XX
0037          YL=YY
0038       39 IF(RL.LT.RA(J-1)) GOTO 41
0039       40 IF(RL-RB(J))42,50 ,50
0040       41 RL=RA(J-1)
0041          XL=X (J-1)
0042          YL= Y(K-1)
0043          GO TO 40
0044       42 RL=RB(J)
0045          XL=X (J)
0046          YL=Y(K)
0047       50 RS=RR
0048          XS=XX
0049          YS=YY
0050          IF(RS.GT.RA(J-1)) GOTO 53
0051       52 IF(RS-RB(J)) 60,60,54
0052       53 RS=RA(J-1)
0053          XS=X (J-1)
0054          YS =Y(K-1)
0055          GO TO 52
```

```
0056          54 RS=RB(J)
0057             XS=X (J)
0058             YS=Y (K)
0059          60 RM=RR
0060             XM=XX
0061             YM=YY
0062              IF (RM-RS) 62,2062,61
0063       2062   IF (XM.EQ.XS .AND. YM.EQ.YS) GO TO 62
0064        61    IF (RM-RL) 70,2065,62
0065       2065   IF(XM.EQ.XL .AND. YM.EQ.YL) GO TO 62
0066              GO TO 70
0067          62 RM=RA(J-1)
0068             XM=X (J-1)
0069             YM=Y (K-1)
0070              IF (RM-RS) 64,2063,63
0071       2063   IF (XM.EQ.XS .AND.YM.EQ.YS) GO TO 64
0072        63    IF (RM-RL) 70,2064,64
0073       2064   IF (XM.EQ.XL .AND. YM.EQ.YL) GO TO 64
0074              GO TO 70
0075          64 RM = RB(J)
0076             XM=X (J)
0077             YM=Y (K)
0078          70 YCS=YS*YCONV
0079             YCM=YM*YCCNV
0080             YCL=YL*YCONV
0081          71 YS=YS-YMAX+YMIN
0082             YM=YM-YMAX+YMIN
0083             YL=YL-YMAX+YMIN
0084          72  XCS=XS*SMAX1
0085              XCM=XM*SMAX1
0086              XCL=XL*SMAX1
0087             NC=1
0088             RC=CNTR(1)
0089          80 IF(NC.GT.NCONT) GOTO110
0090             IF ( RC .NE. RM ) GO TO 91
0091          81 IF ( RM .NE. RS ) GO TO 91
0092          82 IF ( RL .EQ. RM ) GO TO 100
0093          91 IF(RC.LT.RS) GOTO 100
0094             IF(RC-RM)96,93,94
0095          93 XPA=XCM
0096             YPA=YCM
0097             GO TO 99
0098          94 IF(RC-RL)106,103,110
0099          96 Q = (RC-RS)/(RM-RS)
0100          97 XPA = XCS-Q*(XCS-XCM)
0101             YPA = YCS-Q*(YCS-YCM)
0102          99 Q = (RC-RS)/(RL-RS)
0103             XPB = XCS-Q*(XCS-XCL)
0104             YPB = YCS-Q*(YCS-YCL)
0105             IF(RC)10115,10116,10116
0106      10115 XPB1=0.5*(XPA+XPB)
0107             YPB1=0.5*(YPA+YPB)
0108             IF(ABS (XPA-XPB1)-.001)5001,5002,5002
0109       5001 IF(ABS (YPA-YPB1)-.001)100,5002,5002
0110       5002 CALL PLOTZ(XPA,YPA,XPB1,YPB1)
0111             GO TO 100
```

```
0112        10116 IF(ABS (XPA-XPB)-.001)5003,5004,5004
0113         5003 IF(ABS (YPA-YPB)-.001)100,5004,5004
0114         5004 CALL   PLOTZ(XPA,YPA,XPB,YPB)
0115          100 RC=CNTR(NC+1)
0116              NC=NC+1
0117              GO TO 80
0118          103 XPA = XCL
0119              YPA = YCL
0120              GO TO 99
0121          106 Q=(RC-RM)/(RL-RM)
0122              XPA=XCM-Q*(XCM-XCL)
0123              YPA=YCM-Q*(YCM-YCL)
0124              GO TO 99
0125          110  GO TO L,(112,118)
0126          112  ASSIGN 118 TO L
0127              RR   =RB(J-1)
0128              XX   =X (J-1)
0129              YY   =Y (K)
0130              GO TO 37
0131          118 CONTINUE
0132               RETURN
0133               END
```

```
0001          SUBROUTINE PLOTZ(X1,Y1,X2,Y2)
0002          INTEGER EC
0003          LOGICAL*1 LXS
0004          DIMENSION X(2),Y(2),LXS(1)
0005          COMMON/CONTUU/SKIUP(26),
             *              XMIN,XMAX,YMIN,YMAX,XOFF,YOFF,XSIZE,YSIZE,NCONT
0006          X(1)=XSIZE *X1+XOFF
0007          X(2)=XSIZE *X2+XOFF
0008          Y(1)=YSIZE *Y1+YOFF
0009          Y(2)=YSIZE *Y2+YOFF
0010          CALL SYSPLT(X(1),Y(1),3)
0011          CALL SYSPLT(X(2),Y(2),2)
0012          RETURN
0013          ENTRY FINDMT(LXS,MT,NBT)
0014          MT=NBT
0015          DO 44 J=1,NBT
0016          IF(EC(LXS(MT),' ').EQ.0) RETURN
0017       44 MT=MT-1
0018          RETURN
0019           END
```

```
 LOC  OBJECT CODE   ADDR1 ADDR2  STMT   SOURCE STATEMENT                                          ASM 0200 10.13 08/03/77

                           0000F     2 X15      EQU   15                                                                  11
                           00000     3 X0       EQU   0                                                                   12
                           00001     4 X1       EQU   1                                                                   13
                           00002     5 X2       EQU   2                                                                   14
                           00003     6 X3       EQU   3                                                                   15
                           00004     7 X4       EQU   4                                                                   16
                                     8          ENTRY FREEUP                  FREE A DYNAMIC ARRAY.                         23
0C0000                               9 GETVEC   CSECT
                                    10          SAVE  (14,4),,*               SAVE REGISTERS.
0C0000 47F0 F00C      0000C         11+         B     12(0,15)                        BRANCH AROUND ID        00860000
000004 06                           12+         DC    AL1(6)                                                  00880000
000005 C7C5E3E5C5C3                 13+         DC    CL6'GETVEC'                     IDENTIFIER              00900000
00000B 00
0C000C 90E4 D00C      0000C         14+         STM   14,4,12(13)                     SAVE REGISTERS          01180000
000010 184F                         15          LR    X4,X15                  SET UP A BASE REGISTER.                55
                           00000    16          USING GETVEC,X4          #X4                                           56
000012 1821                         17          LR    X2,X1                   (X2)= A(PARAMETER LIST).               57
000014 5830 2000      00000         18          L     X3,0(,X2)               (X3)= A(ARRAY ANCHOR).
                           00000    19          USING ANCHOR,X3          #X3                                           59
000018 5800 3004      00004         20          L     X0,DIMEN                (X0)= DIMENSION OF ARRAY.              60
00001C 8800 0002      00002         21          SLA   X0,2                    (X0)= LENGTH OF ARRAY IN BYTES.        61
000020 5000 3000      00000         22          ST    X0,LENGTH
                                    23          GETMAIN R,LV=(0)        (X1)= A(ARRAY).                                62
0C0024 4510 4028      00028         24+         BAL   1,*+4                           INDICATE GETMAIN        68800001
000028 0A0A                         25+         SVC   10                              ISSUE GETMAIN SVC       69000001
0C002A 5010 3004      00004         26          ST    X1,LENGTH+4
00002E 4130 3000      00000         27          LA    X3,0(,X3)               (X3)= A(ANCHOR(1)).                    65
000032 1813                         28          SR    X1,X3                   (X1)= A(ARRAY(1)) - A(ANCHOR(1)).      66
000034 8A10 0002      00002         29          SRA   X1,2                    CONVERT TO ARRAY INDEX WITH            67
000038 4110 1001      00001         30          LA    X1,1(,X1)               RESPECT TO THE ANCHOR:          *      68
                                                                            ARRAY(1) = ANCHOR(INDEX).              69
00003C 5010 3008      00008         31          ST    X1,INDEX                PLANT INDEX IN ARRAY ANCHOR.           70
                                    32          DROP  X3                 #X3                                           71
                                    33          RETURN (14,4),T,RC=0    RETURN TO CALLER.
000040 98E4 D00C      0000C         34+         LM    14,4,12(13)                     RESTORE THE REGISTERS   00260000
000044 92FF D00C      0000C         35+         MVI   12(13),X'FF'                    SET RETURN INDICATION   00640000
000048 41F0 0000      00000         36+         LA    15,0(0,0)                       LOAD RETURN CODE        00700000
00004C 07FE                         37+         BR    14                              RETURN                  00800000
                                    38 FREEUP   SAVE  (14,4),,*               SAVE REGISTERS.                       124
00004E 47F0 F00C      0000C         39+FREEUP   B     12(0,15)                        BRANCH AROUND ID        00860000
000052 06                           40+         DC    AL1(6)                                                  00880000
0C0053 C6D9C5C5E4D7                 41+         DC    CL6'FREEUP'                     IDENTIFIER              00900000
000059 00
00005A 90E4 D00C      0000C         42+         STM   14,4,12(13)                     SAVE REGISTERS          01180000
0C005E 184F                         43          LR    X4,X15                  SET UP A BASE REGISTER.               125
                           0004E    44          USING FREEUP,X4          #X4                                           126
000060 1821                         45          LR    X2,X1                   (X2)= A(PARAMETER LIST).               127
000062 5830 2000      00000         46          L     X3,0(,X2)               (X3)= A(ARRAY ANCHOR).
                           00000    47          USING ANCHOR,X3          #X3                                           129
0C0066 9801 3000      00000         48          LM    X0,X1,LENGTH            (X0,X1)= FREEMAIN PARAMETERS.          130
                                    49          DROP  X3                 #X3                                           131
                                    50          FREEMAIN R,LV=(0),A=(1)         RELEASE THE CORE.                      132
0C006A 4111 0000      00000         51+         LA    1,0(1)                          CLEAR THE HIGH ORDER BYTE 03130018
00006E 0A0A                         52+         SVC   10                      ISSUE FREEMAIN SVC              03140018
                                    53          RETURN (14,4),T,RC=0            RETURN TO CALLER.
```

ASM 0200 10.13 08/03/77

```
 LOC  OBJECT CODE    ADDR1 ADDR2  STMT   SOURCE STATEMENT
000070 98E4 000C     0000C          54+          LM    14,4,12(13)          RESTORE THE REGISTERS  00260000
000074 92FF 000C     0000C          55+          MVI   12(13),X'FF'         SET RETURN INDICATION  00640000
000078 41F0 0000     00000          56+          LA    15,0(0,0)            LOAD RETURN CODE       00700000
00007C 07FE                         57+          BR    14                   RETURN                 00800000
000000                              58 ANCHOR    DSECT                                                465
000000                              59           DS    F      UNUSED WORD.                            469
000004                              60 DIMEN     DS    F      BITS/ROW OR # OF FULLWORDS.             470
000008                     00000    61           ORG   ANCHOR                                         475
000000                              62 LENGTH    DS    2F     LENGTH OF THE ARRAY, BYTES.             476
000008                              63 INCR      DS    F      BYTES BETWEEN ROWS IN A BIT      *      480
                                                                ARRAY.                                481
                           00008    64 INDEX     EQU   INCR   INDEX FROM START OF ANCHOR TO    *      482
                                                                START OF ARRAY FOR FULLWORD      *      483
                                                                ARRAYS.                               484
                                    65           END                                                  486
```

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-78-102	2.	3. RECIPIENT'S ACCESSION NO.
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16. ABSTRACT

A mathematical model is developed for the prediction of plume properties such as excess plume temperature, humidity and liquid phase moisture (water droplet), plume trajectory, width, and dilution at the merging locations and the beginning and ending points of the visible part of the plumes. Detailed printout and contour plots of excess temperature and moisture distribution can also be obtained if desired.

Based on comparison with laboratory data this model gives good predictions for the case of dry plumes (no moisture involved). It should be noted that several empirical coefficients are as yet not accurately known. Verification of this model for the wet plume (such as for prototype cooling tower plumes) and the determination of the values for these empirical coefficients to be used in prototype applications must await detailed comparison with field data.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Cooling Towers Plumes Mechanical Draft Merging Thermal Pollution Cooling Water	Mathematical Model	13B

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