EPA/600/8-86/024
July 1986

INPUFF 2.0 - A MULTIPLE SOURCE GAUSSIAN PUFF DISPERSION ALGORITHM
User's Guide

by

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AFFILIATION

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PREFACE

One area of research within the Meteorology and Assessment Division is development, evaluation, validation, and application of models for air quality simulation, photochemistry, and meteorology. The models must be able to describe air quality and atmospheric processes affecting the dispersion of airborne pollutants on scales ranging from local to global. Within the Division, the Environmental Operations Branch adapts and evaluates new and existing meteorological dispersion models and statistical technique models, tailors effective models for recurring user application, and makes these models available through EPA's UNAMAP system.

INPUFF 2.0 is an integrated puff model with a wide range of applications and flexibility. It is designed to model semi-instantaneous or continuous point sources over a spatially and temporally variable wind field. A software plotting package is also provided to display concentration versus time plots for each receptor and the puff trajectories after each simulation time.

Although attempts are made to thoroughly check computer programs with a wide variety of input data, errors are occasionally found. Revisions may be obtained as they are issued by completing and returning the form on the last page of this guide.

The first four sections of this document are directed to managers and project directors who wish to evaluate the applicability of the model to their needs. Sections 5, 6, 9, and 11 are directed to engineers, meteorologists, and other scientists who are required to become familiar with the details of the model. Finally, Sections 7 through 11 are directed to persons responsible for implementing and executing the program.

Comments and suggestions regarding this publication should be directed to:

Chief, Environmental Operations Branch
Meteorology and Assessment Division (MD-80)
Environmental Protection Agency
Research Triangle Park, NC 27711.

Technical questions regarding use of the model may be asked by calling (919) 541-4564. Users within the Federal Government may call FTS 629-4564. Copies of the user's guide are available from the National Technical Information Service (NTIS), Springfield, VA 22161.

The magnetic tape containing FORTRAN source code for INPUFF will be contained (along with other dispersion models) in future versions of the UNAMAP library, which may be ordered from Computer Products, NTIS, Springfield, VA 22161 (phone number: (703) 487-4763).

This user's guide is intended to be a living document that is updated as changes are required. Each page of the User's Guide to INPUFF 2.0 has a month and year typed in the lower right hand corner. Future revisions to this document will be indicated in the preface, and every page that is changed due to the revision will have a new date printed in the lower right hand corner. The current version number of INPUFF and the date associated with it will be given in the preface of the user's guide. The version number is also maintained in the source code allowing the user to confirm that his user's guide and source code are current.

Throughout the rest of this document INPUFF 2.0 will be referred to as INPUFF. INPUFF 2.0 represents a significant modification to the original INPUFF model, (Petersen et al., 1984). In the past such a modification to one of our air quality models would have been accompanied with a change in the name of the model. However, the following convention will be used for INPUFF. Major modifications to the model will be indicated by a change in the version number. Minor modifications will be reflected by a change in the update number. The version and update numbers are separated by a "." and appear after the name of the model.

INPUFF 2.0 has been updated to version 2.1. The update to version 2.1 only affects concentration estimates if buoyancy induced dispersion option is true.

INPUFF 2.1 has been updated to version 2.2. The update to version 2.2 only affects concentration estimates if the deposition and settling option is true. Concentration estimates in the sample problems remain unaffected. Page 26 in the user's guide dated 5-86 has been replaced by one dated 1-88.

ABSTRACT

INPUFF is a Gaussian INtegrated PUFF model. The Gaussian puff diffusion equation is used to compute the contribution to the concentration at each receptor from each puff every time step. Computations in INPUFF can be made for a single or multiple point sources at up to 100 receptor locations. In practice, however, the number of receptors should be kept to a minimum. In the default mode, the model assumes a homogeneous wind field. However, the user has the option of specifying the wind field for each meteorological period at up to 100 user-defined grid locations. Three dispersion algorithms are utilized within INPUFF for dispersion downwind of the source. These include Pasquill's scheme as discussed by Turner (1970) and a dispersion algorithm discussed by Irwin (1983), which is a synthesis of Draxler's (1976) and Cramer's (1976) ideas. The third dispersion scheme is used for long travel times in which the growth of the puff becomes proportional to the square root of travel time. Optionally the user can incorporate his own subroutines for dispersion and plume rise. Removal is incorporated through deposition and gravitational settling algorithms (Rao, 1982). A software plotting package is provided to display concentration versus time for a given receptor and the puff trajectories after each simulation time.

CONTENTS

FIGURES

TABLES

SYMBOLS AND ABBREVIATIONS

Dimensions are abbreviated as follows:
m = mass, l = length, t = time, K = temperature

C	--	pollutant concentration (m/l^3)
d	--	stack inside diameter (l)
F	--	buoyancy flux parameter (l^4/t^3)
f_y	--	nondimensional function of travel time for horizontal dispersion
f_z	--	nondimensional function of travel time for vertical dispersion
g	--	acceleration due to gravity (l/t^2)
H	--	effective height of plume (l)
h	--	stack height above ground (l)
h'	--	stack height adjusted for stack downwash (l)
L	--	mixing layer depth (l)
Q	--	emission rate (m/t)
r	--	radial distance from center of puff (l)
s	--	stability parameter (t^{-2})
t	--	travel time (t)
T	--	ambient air temperature (K)
T_s	--	stack gas temperature (K)
u	--	wind speed at stack top (l/t)
v_s	--	stack gas exit velocity (l/t)
x	--	downwind distance (l)
x_f	--	distance to final rise (l)
x^*	--	distance at which atmospheric turbulence begins to dominate entrainment (l)
y	--	crosswind distance (l)
z	--	height above ground (l)
Δh	--	plume rise (l)
ΔT	--	temperature difference between ambient air and stack gas (K)
$(\Delta T)_c$	--	temperature difference for crossover from momentum to buoyancy-dominated plume (K)
$\partial\theta/\partial z$	--	vertical potential temperature gradient of a layer of air (K/l)
π	--	pi, 3.14159
σ_a	--	standard deviation of the horizontal wind angle (radians)
σ_e	--	standard deviation of the vertical wind angle (radians)
σ_r	--	horizontal dispersion parameter (l)
σ_{ro}	--	initial horizontal dispersion (l)
σ_v	--	standard deviation of the horizontal crosswind component of the wind (l/t)
σ_w	--	standard deviation of the vertical component of the wind (l/t)
σ_x	--	dispersion parameter in the downwind direction (l)
σ_y	--	lateral dispersion parameter (l)
σ_z	--	vertical dispersion parameter (l)
σ_{zo}	--	initial vertical dispersion (l)
σ_{ze}	--	effective vertical dispersion (l)
W	--	settling velocity (l/t)
V_d	--	deposition velocity (l/t)

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. D. Bruce Turner, Mr. John S. Irwin, and Dr. Shankar Rao for helpful comments regarding aspects of the work presented here. Much appreciation and credit for this document belong to; Joseph A. Catalano, Thomas Chico, and Tsanying S. Yuen of Aerocomp Inc. Their effort in the development and writing of the original user's guide to INPUFF is greatly appreciated. Portions of this text were excerpted from the CRSTER, MPTER, and PTPLU user's guides.

EXECUTIVE SUMMARY

The INPUFF (INtegrated PUFF) computer code is designed to simulate dispersion from semi-instantaneous or continuous point sources over a spatially and temporally variable wind field. The algorithm is based upon Gaussian puff assumptions including a vertically uniform wind direction field and no chemical reactions. INPUFF can estimate concentrations from multiple point sources at up to 100 receptors.

INPUFF utilizes three distinct dispersion algorithms. For short travel time dispersion, the user has the option of using either the Pasquill-Gifford (P-G) scheme (Turner, 1970) or the on-site scheme (Irwin, 1983). The third dispersion algorithm was designed for use in conjunction with the P-G or on-site schemes. It is used for long travel times where the growth of the puff is assumed proportional to the square root of travel time.

Features of the INPUFF computer code include:

* Optional stack downwash,
* Optional buoyancy induced dispersion,
* Wind speed extrapolated to release height,
* Temporally variable source characteristics,
* Temporally and spatially variable wind field (user-supplied),
* Consideration of terrain effects through user-supplied wind field,
* Consideration of moving source,
* Optional user-supplied subroutine for selecting dispersion coefficients,
* Optional user-supplied subroutine for estimating plume rise, and
* Removal through gravitational settling and deposition.

In addition, a software plotting package has been provided to display concentration versus time for a given receptor and the puff trajectories after each simulation time.

A simple sensitivity analysis of two user options is provided in Section 9. Tips on minimizing computer costs without sacrificing accuracy are also suggested.

SECTION 1
INTRODUCTION

INPUFF is a Gaussian integrated puff model with a wide range of applications. The implied modeling scale is from tens of meters to tens of kilometers. The model is capable of addressing the accidental release of a substance over several minutes, or of modeling the more typical continuous plume from a stack. Several requests to the Meteorology Division for assistance in modeling the air quality downwind of incineration ships prompted the development of an integrated puff model. INPUFF is, therefore, capable of simulating moving point sources as well as stationary sources.

Computations in INPUFF can be made for multiple point sources at up to 100 receptor locations. In practice, however, the number of receptor locations should be kept to a minimum to avoid excessive run time. INPUFF is primarily designed to model a single event during which one meteorological transition period may occur, such as, going from afternoon to evening conditions. Up to 144 separate meteorological periods of the same length may be used to characterize the meteorology during the event; this provides a time resolution that ranges from minutes to an hour. The user has the option of specifying the wind field for each meteorological period at up to 100 grid locations or allowing the model to default to a homogeneous wind field.

Three dispersion algorithms are used within INPUFF for dispersion downwind of the source. The user may select the Pasquill-Gifford (P-G) scheme (Turner, 1970) or the on-site scheme (Irwin, 1983) for short travel time dispersion. The on-site scheme, so named because it requires specification of the variances of the vertical and lateral wind direction, is a synthesis of work performed by Draxler (1976) and Cramer (1976). The long travel time scheme is the third dispersion algorithm in which the growth of the puff becomes proportional to the square root of time. Optionally, the user can incorporate his own subroutine for estimating atmospheric dispersion.

INPUFF utilizes the deposition algorithms given by Rao (1982). In the limit when pollutant settling and dry deposition velocities are zero, these expressions reduce to the Gaussian diffusion algorithms.

A software plotting package has also been provided to display concentrations versus time for a given receptor and the puff trajectories after each simulation period.

This document is divided into three parts, each directed to a different audience: managers, dispersion meteorologists, and computer specialists. The first four sections are aimed at managers who wish to evaluate the applicability of the model to their needs. Sections 5, 6, 9, and 11 are directed toward dispersion meteorologists or engineers who are required to become familiar with the details of the model. Finally, Sections 7 through 11 are directed toward persons responsible for implementing and executing the program. A detailed description of the plume rise algorithm, and a discussion on settling and deposition velocities are included in the appendices.

SECTION 2
DATA-REQUIREMENTS CHECKLIST

INPUFF requires data on user options, grid dimensions, sources, meteorology, receptors, and plotter control. The user must indicate whether the following options are to be employed:

* Stack-tip downwash,
* Source update,
* User-supplied wind field,
* Intermediate concentration output,
* Puff information output,
* Buoyancy induced dispersion,
* User-supplied dispersion algorithm, and
* User-supplied plume rise algorithm.

The dimension of the modeling grid must be specified. If the user-supplied wind field option is implemented, then the dimension of the meteorological grid along with the size of each grid rectangle must also be indicated. It is recommended that both grids be given a common origin. If a puff travels outside the modeling region, it is deleted from further consideration. If it travels outside the meteorological grid, but is still within the modeling region, the wind at the nearest grid point to the puff is used to advect it further.

Information on the source includes the following:

* Location (km),
* Emission rate (g/sec),
* Physical stack height (m),
* Stack gas temperature (K),

* Stack diameter (m),
* Stack gas velocity (m/sec),
* Stack gas volume flow (m^3/sec),
* Initial dispersion parameters (m), and
* Deposition and gravitational settling velocities (cm/sec).

Also, the direction and speed of the source, if it is moving, must be provided as input.

The meteorological data needed for the computations are as follows:

* Wind direction (deg),
* Wind speed (m/sec),
* Mixing height (m),
* Stability class (dimensionless),
* Standard deviation of elevation angle (radians),
* Standard deviation of azimuth angle (radians),
* Ambient air temperature (K), and
* Anemometer height (m).

The user has the option of updating the meteorological information after each meteorological time period. The location and height of each receptor must be indicated. If dispersion is characterized by the on-site scheme, then the standard deviations of the azimuth and elevation angles are required.

The following information is required by the plot routines:

* Type of plot desired,
* Location of concentration versus time plots, and
* Plotting grid.

The plot routines were developed on a UNIVAC 1110 and use CALCOMP plotting software.

SECTION 3
FEATURES AND LIMITATIONS

Several requests to the Environmental Operations Branch for assistance in modeling the air quality downwind of incineration ships stimulated the development of INPUFF, a model capable of simulating a moving point source in a spatially variable wind field. The model also possesses the following features which increase its flexibility and range of application:

* Optional stack-tip downwash,
* Wind speed extrapolated to release height,
* Temporally variable source characteristics,
* Temporally and spatially variable wind field,
* Up to 100 receptors,
* Some consideration of terrain effects through the wind field,
* Optional buoyancy induced dispersion,
* Optional deposition and settling,
* Optional user-supplied dispersion parameters,
* Optional user-supplied plume rise, and
* Optional graphics display.

The implied modeling scale is from tens of meters to tens of kilometers. INPUFF is capable of addressing the accidental release of a substance over a short time period, or of modeling the more typical continuous plume from a stack.

Although INPUFF has several advantages over its continuous plume counterparts, it still retains several limitations, including:

* Wind direction constant with height,
* No consideration of chemical reactions,
* No explicit treatment of complex terrain,
* No consideration of building wake or cavity effects.

SECTION 4
BASIS FOR INPUFF

GAUSSIAN PUFF METHODOLOGY

A graphical representation of the INPUFF model is given in Figure 1. Here the first puff (the puff with the longest trajectory) was first exposed to east-southeast winds, followed by slightly stronger winds from the south and the south-southeast. The second puff was released at the time the winds shifted from east-southeast to south. The third puff was released when winds were from the south-southeast. The stability conditions need not be equal for the various time steps, though in the figure, stability is shown to be fairly constant with time (i.e., the rate of puff growth is constant over the time frame). INPUFF assumes $\sigma_x = \sigma_y$, thus puffs remain circular throughout their lifetime. Puffs A, B, and C represent the location of the three emitted puffs at time t_3.

In Gaussian-puff algorithms, source emissions are treated as a series of puffs emitted into the atmosphere. Constant conditions of wind and atmospheric stability are assumed during a time interval. The diffusion parameters are functions of travel time. During each time step, the puff centers are determined by the trajectory and the in-puff distributions are assumed to be Gaussian. Thus, each puff has a center and a volume which are determined separately by the mean wind, atmospheric stability, and travel time.

PLUME RISE

Plume rise is calculated using the methods of Briggs (see Section 5). Although plume rise from point sources is usually dominated by buoyancy, plume rise due to momentum is also

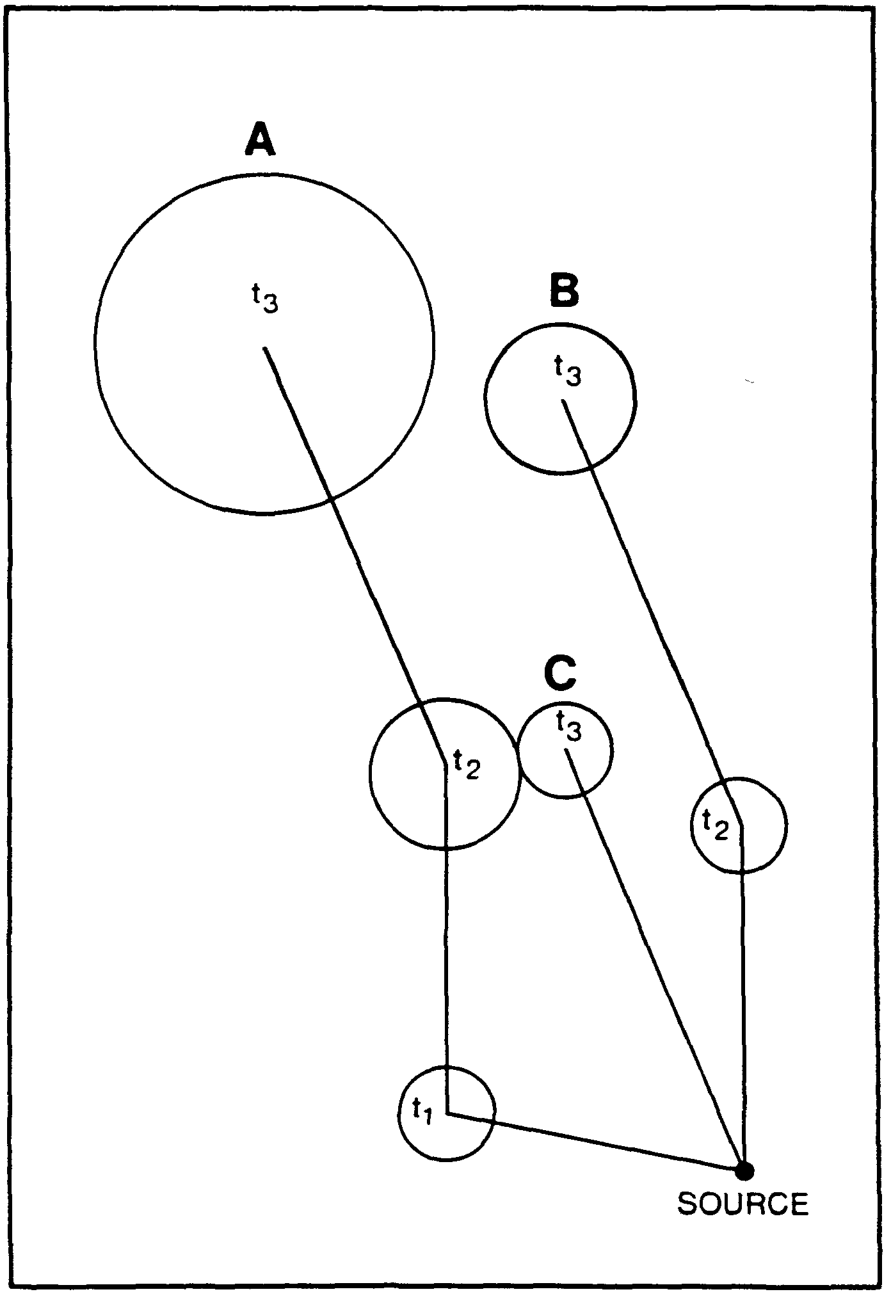

Figure 1. Gaussian puff model.

considered. Building downwash, and gradual plume rise are not treated by INPUFF.

Stack-tip downwash (optional) can be considered using the methods of Briggs. In such an analysis, a height increment is deducted from the physical stack height before momentum or buoyancy rise is determined. Use of this option primarily affects computations from stacks having small ratios of exit velocity to wind speed.

DISPERSION ALGORITHMS

Three dispersion algorithms are used within INPUFF for dispersion downwind of the source:

* P-G scheme as discussed by Turner (1970),
* On-site scheme formulated by Irwin (1983), and
* Long travel time scheme.

The user has the option of choosing either the P-G or the on-site algorithm (for short travel time dispersion) and specifying when the long travel time dispersion parameters are to be implemented. Optionally, a user-supplied subroutine to estimate dispersion can be used.

Dispersion downwind of a source, as characterized by the P-G scheme, is a function of stability class and downwind distance. Stability categories are commonly specified in terms of wind speed and solar radiation. The on-site dispersion algorithm is a synthesis of Draxler's (1976) and Cramer's (1976) ideas and requires specification of the variances of the vertical and lateral wind directions. The third dispersion scheme is used in conjunction with the other two and is for long travel times in which the growth of the puff is proportional to the square root of time.

SETTLING AND DRY DEPOSITION

Rao (1982) gave analytical solutions of a gradient-transfer model for dry deposition of pollutants from a plume. His solutions treat gravitational settling and dry deposition of pollutants in a physically realistic manner, and are subject to the same basic assumptions and limitations associated with Gaussian plume models. His equations for deposition and settling were incorporated in several EPA air quality models including PAL-DS (Rao and Snodgrass, 1982). The equations used in INPUFF are the same as those used in PAL-DS except they are cast in terms of travel time instead of wind speed and downwind distance.

SECTION 5
TECHNICAL DESCRIPTION

This section presents the mathematical formulation of the Gaussian-puff model.

GAUSSIAN PUFF EQUATIONS

The concentration, C, of a pollutant at x, y, z from an instantaneous puff release with an effective emission height, H, is given by the following equation:

$$C(x,y,z,H) = \frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_z\sigma_y} \exp\left[\frac{-1}{2}\left(\frac{x-ut}{\sigma_x}\right)^2\right] \exp\left[\frac{-1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

$$\left\{\exp\left[\frac{-1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \exp\left[\frac{-1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

Since each puff is free to move in response to changing wind speed, u, and is not constrained to a single centerline, the diffusion parameters are given as functions of travel time, t, rather than of downwind distance.

Following the puff and assuming σ_x equals σ_y, expresed as σ_r, where $r = (x-ut)^2 + y^2$, the puff equation can be rewritten as follows:

$$C(r,z,H) = \frac{Q}{(2\pi)^{3/2}\sigma_r^2\sigma_z} \exp\left[\frac{-1}{2}\left(\frac{r}{\sigma_r}\right)^2\right] \left\{\exp\left[\frac{-1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \exp\left[\frac{-1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\right\} \quad (2)$$

when σ_z becomes larger than eight tenths of the mixed depth layer, L, the puff is assumed to be well mixed and the concentration equation is expressed as,

$$C(r,z,H) = \frac{Q}{2\pi\sigma_r^2 L} \exp\left[\frac{-1}{2}\left(\frac{r}{\sigma_r}\right)^2\right] \quad \text{for } \sigma_z > 0.8L. \qquad (3)$$

The total contribution from all the puffs is summed at each receptor after each time step.

Although a Gaussian-puff model, such as INPUFF, is useful in estimating pollution dispersion under unsteady and nonuniform flow, it has several limitations:

(1) Pollution dispersion within the puff is assumed to be Gaussian and meteorological conditions within a time step are assumed to be spatially and temporally uniform. These assumptions may cause significant error in estimating concentrations, especially at long travel distances.

(2) The diffused material is assumed to be stable over a long period of time. Chemical reactions and other nonlinear processes are not handled by INPUFF.

(3) Data for puff diffusion are sparse and there is no ordering of the sigma curves by stability; therefore, many Gaussian puff models use plume sigma's. However, similarity theory for puff diffusion (Batchelor, 1952) suggests that there is a region in which puff growth is greater than plume growth. For downwind distances where travel time is larger than sampling time, the use of plume sigma's in a puff model may be inappropriate. However, as long as the variations in meteorological conditions are not simulated to any finer resolution than 3 to 10 minute periods, the use of plume characterizations of dispersion may still be reasonable.

(4) As mentioned, the primary purpose of the integrated puff model is to simulate a continuous plume. Plume diffusion formulas apply to continuous plumes, where the sampling time is long compared to the travel time from source to receptor. Since INPUFF uses the plume characteristics of σ_y and σ_z, one would expect that the concentration estimates from INPUFF would yield the best agreement with observations if the travel time was short compared to the sample duration of the concentration estimates. Since this assumption is violated, the model estimates relate more to the average of many realizations of the same experiment, recognizing that the correspondence of any one experiment may differ greatly in comparison to the average obtained from many experiments.

(5) Given the complex nature of the wind field, sampling the flow so that it can be completely defined from a mathematical point of view is impossible. There can always be any number of solutions which could stem from one initial state, while satisfying all other requirements.

The most important difference between Gaussian-plume models and INPUFF is that INPUFF can handle changing meteorological conditions, whereas typical Gaussian-plume models assume spatial and temporal uniformity in the meteorology.

PLUME RISE

Plume rise from point sources is calculated using the methods of Briggs (1969, 1971, 1973, and 1975). These equations are based on the assumption that plume rise depends on the inverse of the mean wind speed and is directly proportional to the two-thirds power of the downwind distance from the source, with different equations specified for neutral or unstable conditions and for stable conditions. Only the final rise equations are summarized below. The reader is referred to Appendix A for the details of the formulation.

For unstable or neutral atmospheric conditions, the downwind distance of final plume rise is

$$x_f = 3.5x^*,$$

where

$$x^* = 14F^{5/8} \qquad \text{for } F < 55\ m^4/sec^3$$

and

$$x^* = 34F^{2/5} \qquad \text{for } F \geq 55\ m^4/sec^3.$$

The final plume rise under these conditions is

$$H = h' + [1.6F^{1/3}\ (3.5x^*)^{2/3}/u(h)]. \qquad (4)$$

For stable atmospheric conditions, the downwind distance of final plume rise is

$$x_f = 0.0020715u(h)s^{-1/2}$$

where

$$s = g(\partial\theta/\partial z)/T.$$

Plume rise is

$$H = h' + 2.6\{F/[u(h)s]\}^{1/3} \quad \text{for windy conditions} \qquad (5)$$

and

$$H = h' + 4F^{1/4}s^{-3/8} \qquad \text{for near-calm conditions.} \qquad (6)$$

The lower of the two values obtained from the above two equations (5 and 6) is taken as the final effective height. Definitions and units of variables mentioned in this section are summarized in Table 1.

TABLE 1. DEFINITION OF VARIABLES USED IN PLUME RISE EQUATIONS

Symbol	Definition	Units
F	Buoyancy flux parameter	m^4/sec^3
g	Acceleration due to gravity	m/sec^2
H	Effective height of plume	m
h'	Stack height adjusted for stack downwash	m
s	Stability parameter	sec^{-2}
T	Ambient air temperature	K
u(h)	Wind speed at stack top	m/sec
xf	Distance to final rise	m
x*	Distance at which atmospheric turbulence begins to dominate entrainment	m

DISPERSION ALGORITHMS

The primary purpose of the integrated puff model is to simulate a continuous or semi-continuous plume for varying meteorological conditions. The vertical and lateral dispersion parameters for continuous plume dispersion models are used in INPUFF. Under steady meteorological conditions, the output concentrations of INPUFF should, all other factors such as plume rise being equal, approximate the results calculated by a Gaussian-plume model such as PAL-DS. To demonstrate this, concentration estimates of INPUFF and PAL-DS are compared. The meteorology used in this comparison is as follows:

* Wind speed -- 5 m/sec,
* Wind direction -- 180°,
* Mixing height -- 5000 m, and
* Stability class -- E.

INPUFF was executed for a 2-hour simulation to bring about steady-state conditions.

Table 2 summarizes the results. The last column shows the percent difference in the computed concentrations for the two models. Although they differ by 25% at receptors close to the source, the percent difference decreases to less than 1% near the maximum concentrations. The results show that INPUFF can indeed simulate a continuous plume.

TABLE 2. COMPARISON OF INPUFF AND PAL-DS. DIFFERENCE(%) = [(INPUFF - PAL-DS)/PAL-DS]*100

Downwind distance (km)	Concentration ($\mu g/m^3$) INPUFF	PAL	Difference (%)
0.2	0.01	0.008	25.00
0.3	1.23	1.13	8.85
0.5	11.99	11.82	1.44
0.7	20.10	20.13	-0.15
0.9	22.10	22.29	-0.85
1.0	22.08	22.08	0.
2.0	13.25	13.30	-0.38
3.0	8.44	8.48	-0.47
5.0	4.51	4.52	-0.22
7.0	2.92	2.94	-0.68
10.0	1.85	1.84	0.54
20.0	0.75	0.75	0.

Three dispersion algorithms are incorporated within the model to account for initial dispersion, short travel time dispersion, and long travel time dispersion. The initial dispersion algorithm handles the finite size of the release through the use of initial dispersion parameters. Once the puff leaves the source its growth is determined by one of two short travel time dispersion algorithms; The Pasquill-Gifford scheme which characterizes dispersion as a function of downwind distance and the on-site scheme which characterizes dispersion as a function of travel time. For long travel time, a dispersion algorithm that allows the puff to grow as a function of the square root of time can be used.

Initial Dispersion

The initial dispersion of the plume at the source is modeled by specifying the initial horizontal and vertical dispersion parameters, σ_{ro} and σ_{zo}. For tall stacks these parameters, generally, have little influence on downwind concentrations. However, if the source is large enough or close enough to the ground, then initial size is important in determining ground level concentrations near the source. For a source near the ground, the initial horizontal dispersion can be calculated by dividing the initial horizontal dimension of the source by 4.3, and the initial vertical dispersion parameter is derived by dividing the initial height of the source by 2.15. This method of accounting for the initial size of near ground level release gives reasonable concentration estimates at downwind distances greater than about five times the initial horizontal dimension of the source.

Buoyancy Induced Dispersion

The buoyancy-induced dispersion feature is offered because emitted plumes undergo a certain amount of growth during the plume rise phase, due to the turbulent motions associated with the conditions of plume release and the turbulent entrainment of ambient air. Pasquill (1976) suggests that this induced dispersion, σ_{zo}, can be approximated by $\Delta H/3.5$, and the effective dispersion can be determined by adding variances, i.e.,

$$\sigma_{ze} = (\sigma_{zo}^2 + \sigma_z^2)^{1/2}$$

where σ_{ze} is the effective dispersion and σ_z is the dispersion due to ambient turbulence levels. At the distance of final rise and beyond, σ_{zo} is a constant using ΔH of final rise. At distances closer to the source, the ΔH used to determine σ_{zo} is itself determined using gradual rise.

Since in the initial growth phases of release the plume is nearly symmetrical about its centerline, buoyancy-induced dispersion in the horizontal direction equal to that in the vertical is used, $\sigma_{yo} = \Delta H/3.5$. This expression is combined with that for dispersion due to ambient turbulence in the same manner as is shown above for the vertical.

In general, buoyancy-induced dispersion will have little effect upon maximum concentrations unless the stack height is small compared to the plume rise. Also, it is most effective in simulating concentrations near plume centerlines close to the source, where treating the emission as a point source confines the plume to a volume much smaller than the actual plume. It should be clarified here that the buoyancy-induced dispersion close to the source is calculated using the gradual rise in INPUFF, even though gradual plume rise is not being used to determine the effective plume height.

Short Travel Time Dispersion

Dispersion downwind of the source can be characterized by the P-G scheme, which is a function of stability class and downwind distance, or by the on-site scheme, which is a function of travel time.

Pasquill-Gifford Scheme

The P-G values, which are applicable for areas characterized as rural, are used in the model. However, for neutral atmospheric conditions two dispersion curves as suggested by Pasquill (1961) are incorporated into the model. Dispersion curves D1 and D2 are appropriate for adiabatic and subadiabatic conditions, respectively. The D2 curve is used in Turner (1970) for neutral conditions. From a practical point of view, since temperature soundings may not be available we refer to the D1 and D2 curves as D-day and

D-night. P-G stability classes are numerical inputs to the puff model. Stability classes A through D-day are specified by 1-4, and classes D-night through F are specified by 5-7, respectively.

On-site Meteorology Scheme

The sigma-curves of the P-G scheme above are based on data of near-ground level releases and short-range dispersion studies. These data are used to extrapolate the P-G curves to high release heights and far receptor distances. In view of this, INPUFF has an option of using on-site meteorological data to estimate dispersion. This scheme is a result of the recommendations of the American Meteorological Society's workshop on stability classification schemes and sigma curves (Hanna et al., 1977). Irwin (1983) proposed characterizing σ_y and σ_z in a manner similar to Cramer (1976) and Draxler (1976). The standard deviation of the crosswind concentration distribution, σ_y, is

$$\sigma_y = \sigma_v t f_y \qquad (7)$$

where σ_v is the standard deviation of the horizontal crosswind component of the wind, t is the downstream travel time of the pollutant, and f_y is a nondimensional function of travel time. The standard deviation of the vertical concentration distribution, σ_z, for an elevated source, when σ_z is less than the source height, is

$$\sigma_z = \sigma_V t f_z, \qquad (8)$$

where σ_w the standard deviation of the vertical component of the wind, and f_z is a nondimensional function, primarily dependent upon travel time. The nondimensional functions f_y and f_z were characterized by Irwin (1983) as

$$f_y = 1./[1 + 0.9(t/1000)^{1/2}], \tag{9}$$

$$f_z = 1, \qquad \text{for unstable conditions}$$

and

$$f_z = 1./[1 + 0.9(t/50)^{1/2}] \quad \text{for stable conditions.} \tag{10}$$

Besides the P-G stability class, the scheme requires σ_v and σ_w, which are assumed to be typical of conditions at final plume height. For small angles, $\sigma_v = \sigma_a u$ and $\sigma_w = \sigma_e u$ where u is the wind speed at measurement height and σ_a and σ_e are the standard deviations of the horizontal and vertical wind angle, respectively. The puff model requires σ_a and σ_e as data input and computes σ_v and σ_w.

Long Travel Time Dispersion

That the dispersion parameters used in INPUFF satisfy the diffusion theory developed by Taylor (1921) is desirable. Taylor showed that for an ensemble average of particle displacements during stationary and homogeneous conditions, the dispersion parameters can be written as,

$$\sigma_{y,z}^2 = \overline{2(vw)'^2} \int_0^{T_d} \int_0^{t} R(\tau)\,d\tau\,dt, \tag{11}$$

where $R(\tau)$ is the Lagrangian autocorrelation of the appropriate component of the wind velocity fluctuation; $\overline{(vw)'^2}$ are the variances of the lateral or vertical components of the wind velocity, respectively; and Td is the diffusion time. For horizontal and vertical diffusions, $\overline{v'^2}$ and $\overline{w'^2}$ are used respectively instead of $\overline{(v'w')^2}$. The autocorrection starts at 1 and approaches 0 for large diffusion time. Therefore, from Eq. 11, while the growth of the puff is linear with time near the source, the growth becomes proportional to the square root of time at large distances. In the model, after the puff has attained a specified horizontal dimension, the algorithm automatically goes to a long travel time growth rate proportional to the square root of time. The size of the puff at that time is specified by the user. For example, the user may decide that when σ_r for the puff is greater than 1000 meters the long travel time dispersion parameters should by utilized. A very large SYMAX value results in the long travel time code not being executed.

MIXING HEIGHT

Depending on the stack height, plume rise, and height of the mixing layer, the puffs can be above or below the mixed depth layer, L. If the puffs are above L then there are two cases that govern their growth. Initially the puffs are allowed to grow according to the P-G, F curve, or if the on-site scheme is used, the puffs are restricted to a vertical growth rate characterized by σ_w=0.01m/sec. After the puffs attain a given size of σ_r (not actual puff size) specified by the user, the horizontal growth rate is specified by the $\sqrt{t}$.

When the puffs are below L, then there are four cases that must be considered. Cases one and two are puffs which are not well mixed vertically and whose growth rates are characterized by the short travel time sigmas or by $\sqrt{t}$. Cases three and four are puffs that are well mixed vertically and whose growth for σ_r is for short travel times or according to $\sqrt{t}$. During the modeling simulation, every puff is given a key to indicate whether it is above or below L and whether its growth rate is characterized by the short travel time sigmas or by $\sqrt{t}$.

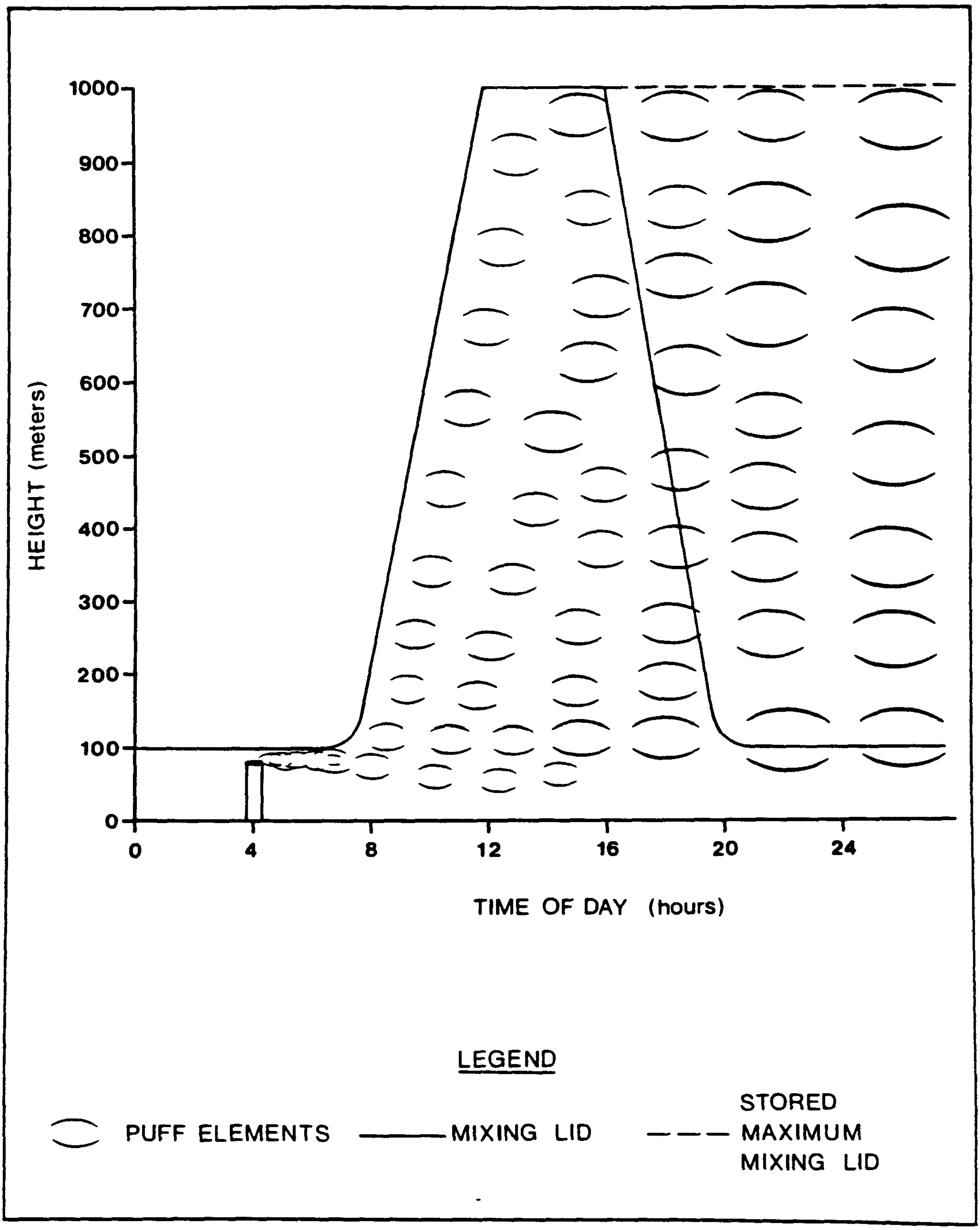

Figure 2. Effect of variable mixing height on puff dispersion.

In the modeling design, puffs are allowed to change their dispersion keys. When the height of L becomes greater than the puff height, the puffs are allowed to grow at the rate characterized by surface measurements. Normally this is a neutral or unstable situation. This transition period is likely to occur in the morning hours. In the afternoon, despite the decay of active mixing, a puff remains well mixed through the maximum mixing lid as shown in Figure 2. The maximum height of L is stored for each puff and is never allowed to decrease. This method assures that concentration does not increase with downwind distance or travel time, so as to violate the second law of thermodynamics.

ATMOSPHERIC STABILITY

As discussed earlier, short travel time dispersion can be characterized by two schemes, the P-G scheme and the on-site scheme. The P-G scheme uses the empirical P-G curves and stability classification to estimate dispersion coefficients (Turner, 1970), whereas the on-site scheme relates diffusion directly to turbulence. If on-site meteorological data are not available, only the widely used P-G scheme can be adopted. If on-site meteorological data are available, either scheme can be used.

INPUFF's on-site scheme adopts Irwin's algorithm (1983) in characterizing σ_y and σ_z. This scheme essentially requires information on the standard deviations of horizontal (σ_a) andverticl (σ_e) wind fluctuations and wind speed at measurement height. Stability is classified as stable or unstable from the near-surface data for temperature difference, Richardson Number, or stability parameter.

SETTLING AND DRY DEPOSITION

The analytical solutions for atmospheric concentration of a gaseous or suspended particulate pollutant, incorporating dry deposition and gravitational settling were given by Rao (1982). That document provides a review of deposition models and the details of the derivation of the equations used in INPUFF. In this user's guide we only list the final equations used in INPUFF for unlimited and well mixed conditions.

For unlimited mixing,

$$C(r,z,H) = \frac{Q}{(2\pi)^{3/2}\sigma_r^2\sigma_z} \exp\left[\frac{-1}{2}\left(\frac{r}{\sigma_r}\right)^2\right] \exp\left[\frac{-Wt\,(z-H)}{\sigma_z^2} - \frac{1}{2}\left(\frac{Wt}{\sigma_z}\right)^2\right]$$

$$\left\{ \exp\left[\frac{-1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[\frac{-1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] - \frac{(2\pi)^{1/2}V_1 2t}{\sigma_z}\right.$$

$$\left. \exp\left[\frac{V_1 2t(z+H)}{\sigma_z^2} + \frac{1}{2}\left(\frac{2tV_1}{\sigma_z}\right)^2\right] \operatorname{erfc}\left[\frac{z+H}{\sqrt{2}\sigma_z} + \frac{2V_1 t}{\sqrt{2}\sigma_z}\right]\right\} \qquad (12)$$

where

$$V_1 = V_d - 1/2\ W$$

and V_d and W are the deposition and gravitational settling velocities respectively. Travel time is indicated by t.

For uniform vertical mixing. When the settling and deposition velocities are equal:

$$C(r,z,H) = \frac{Q}{2\pi\sigma_r^2 L} \exp\left[\frac{-1}{2}\left(\frac{r}{\sigma_r}\right)^2\right]\left[1 + \left(\frac{V_d t}{\sigma_z}\right)^2\right.$$

$$\left. \operatorname{erfc}\left(\frac{V_d t}{\sqrt{2}\sigma_z}\right) - \frac{2V_d t}{\sqrt{2\pi}\sigma_z} \exp\left[-\left(\frac{V_d t}{\sqrt{2}\sigma_z}\right)^2\right]\right] \qquad (13)$$

When the settling and deposition velocities are not equal:

$$C(r,z,H) = \frac{Q}{2\pi\sigma_r^2 L} \exp\left[\frac{-1}{2}\left(\frac{r}{\sigma_r}\right)^2\right] \frac{V_1}{V_2} \exp\left[\frac{2V_dV_2t^2}{\sigma_z^2}\right]$$

$$\operatorname{erfc}\left[\frac{V_1 t\sqrt{2}}{\sigma_z}\right] - \frac{W}{2V_2} \operatorname{erfc}\left[\frac{Wt}{\sqrt{2}\sigma_z}\right] \qquad (14)$$

Where, V_2 is $V_d - W$

The above equations reduce to the Gaussian puff equations for V_d and $W = 0$. Appendix B provides information on assigning settling and deposition velocities.

GRIDDING SCHEMES

To utilize gridded wind data INPUFF requires a meteorological preprocessor to compute wind speed and direction at each grid square. The user is required to specify the format of the meteorological data file. The coordinate and size of each grid square, as well as the extent of the meteorological region, must be defined in the input. The modeling region need not be the same as the meteorological region. If the meteorological region is smaller than the modeling region and the puffs travel outside of the meteorological region, then they are advected according to the wind speed and direction at the closest grid point. If the meteorological region is larger than the modeling region and the puffs travel outside the modeling region, they are eliminated from further consideration. The source must stay within the modeling region; otherwise, all puffs are eliminated.

To improve the spatial resolution of the concentration pattern, receptors in INPUFF are specified by the user. The resolution of the receptors can be more detailed than that of the meteorological grid. The receptors may be placed independent of the meteorological grid. Figure 3 illustrates a possible arrangement of the modeling region, meteorological grid, and receptor locations. In this example the receptors are concentrated along part of the puff trajectory with a spatial resolution two times finer than the meteorological grid.

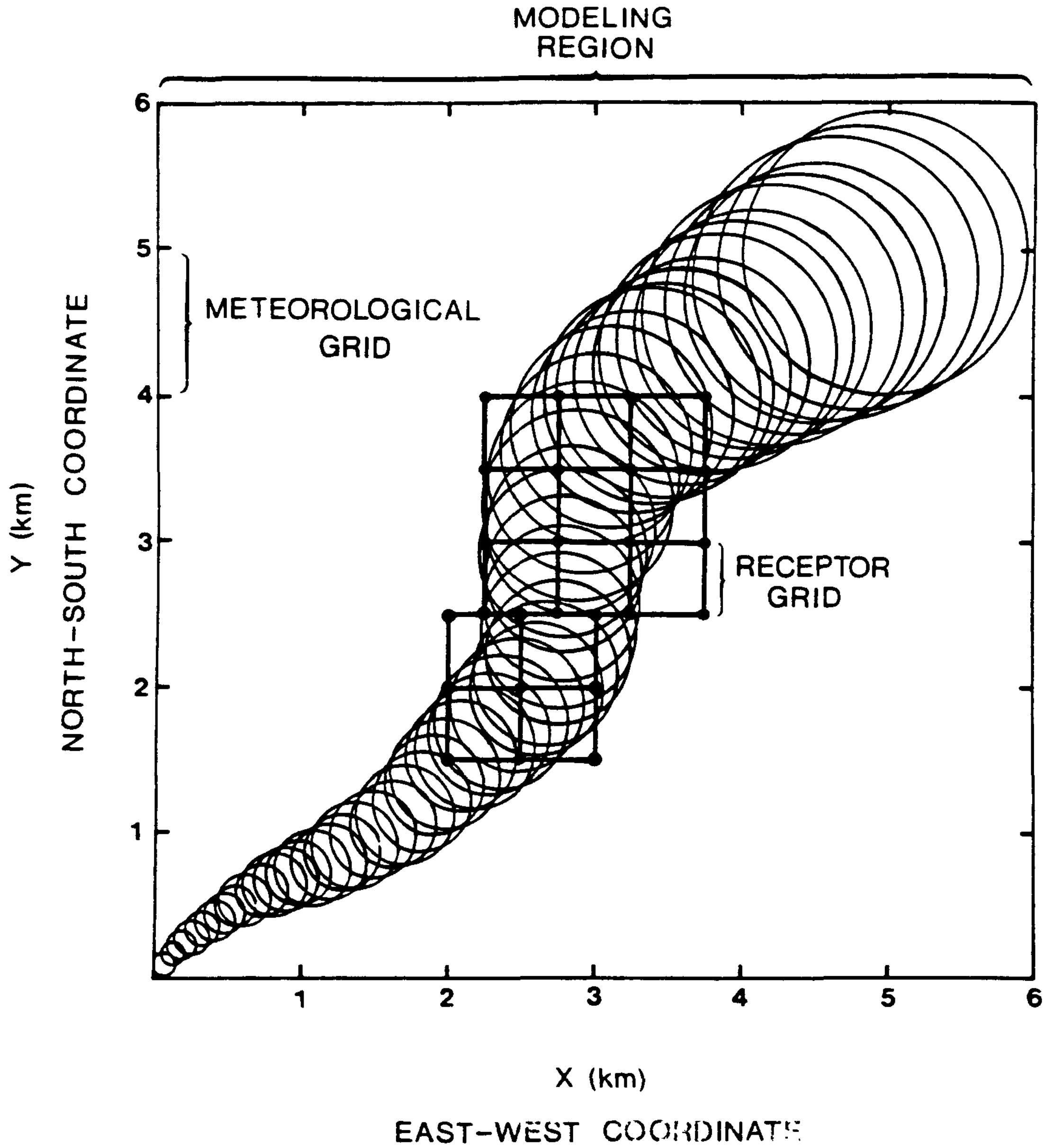

Figure 3. A possible arrangement of modeling and receptor grids.

SECTION 6
EXAMPLE PROBLEMS

In this section, problems are provided to illustrate different modeling scenarios and to demonstrate several unique features of INPUFF. Details concerning input and output of the first two example problems are discussed in Section 11 after the reader has become familiar with INPUFF input data preparation.

EXAMPLE 1 -- MOVING SOURCE

This example uses a unique feature of INPUFF that allows the source to move at a constant speed and direction over a specified time. Figure 4 shows the source path and receptor locations. The source is initially southwest of the receptors and travels due east for twenty minutes remaining south of all receptors. Southerly winds at 3.5 m/sec are observed and the atmosphere is slightly unstable. Twenty minutes into the simulation the source assumes a northeast heading. Atmospheric conditions become neutral, wind speed increases to 4 m/sec, and wind direction changes slightly from 180° to 170°. The stack parameters of the source are as follows:

* Emission rate -- 600 g/sec,
* Stack height -- 30 m,
* Stack gas temperature -- 390 K,
* Stack gas velocity -- 15 m/sec, and
* Stack diameter -- 2 m.

The impact at the receptors is outlined in Table 3. As shown in the table, INPUFF provides average concentrations for each meteorological time period and for the total simulation time. As expected, impact is greatest at the western receptors (1, 2, 5, and 6) during the first meteorological period and to the eastern receptors (3, 4, 7, and 8) during the second meteorological period.

TABLE 3. COMPUTED CONCENTRATIONS FOR EXAMPLE 1

Receptor number	Concentrations ($\mu g/m^3$)		
	0-20 min. ave.	20-40 min. ave.	40 min ave.
1	135	<1	68
2	167	8	87
3	22	123	72
4	<1	13	7
5	180	<1	90
6	221	2	111
7	4	177	90
8	<1	13	6

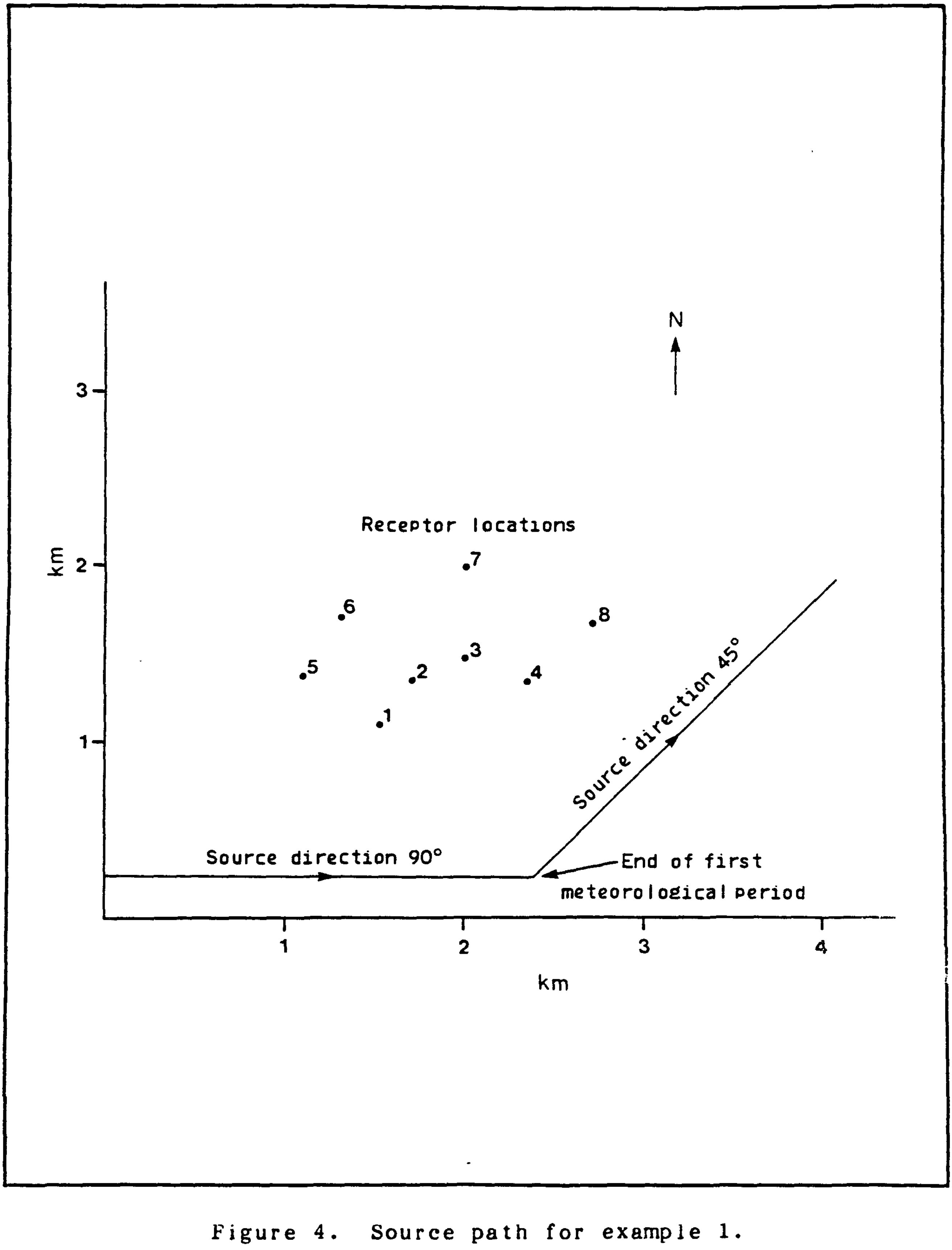

Figure 4. Source path for example 1.

The input stream and output listing for this problem are provided in Section 11. The plotting features of the model are also demonstrated in Section 11.

EXAMPLE 2 -- LOW LEVEL SOURCE WITH LOW WIND SPEED CONDITIONS

This problem illustrates the model simulation of a low level release during conditions of light and variable winds. Another feature highlighted in the problem is that of temporally variable source characteristics.

Twelve periods of 10-minute duration are used to simulate a 2-hour release. Both meteorology and source characteristics are updated every 10 minutes. The wind speeds are light at 0.5 m/sec, and wind direction fluctuates from 145° to 210°. On-site dispersion measurements of σ_a and σ_e are available and are used in the simulation. Values of other pertinent meteorological parameters are listed below:

* Mixing height -- 5000 m,
* σ_a -- 0.393 radians,
* σ_e -- 0.035 radians, and
* Temperature -- 290 K.

The source-receptor geometry shown in Figure 5 was chosen based on the observed southeast to south-southwest winds. Receptors are located along two radial arcs approximately 0.5 km and 1.0 km from the source. Figure 6 shows how the source strength decays with time. Initially the emission rate is 825 g/sec, but by the 12th period it has dropped to 12 g/sec.

Average concentrations at each receptor for the simulation time are listed in Table 4. As expected, impacts are greatest at receptors (3 and 8) due north of the source.

TABLE 4. COMPUTED CONCENTRATIONS FOR EXAMPLE 2

Receptor number	2-hour average concentrations ($\mu g/m^3$)
1	5
2	253
3	2268
4	132
5	1
6	<1
7	96
8	10460
9	17
10	<1

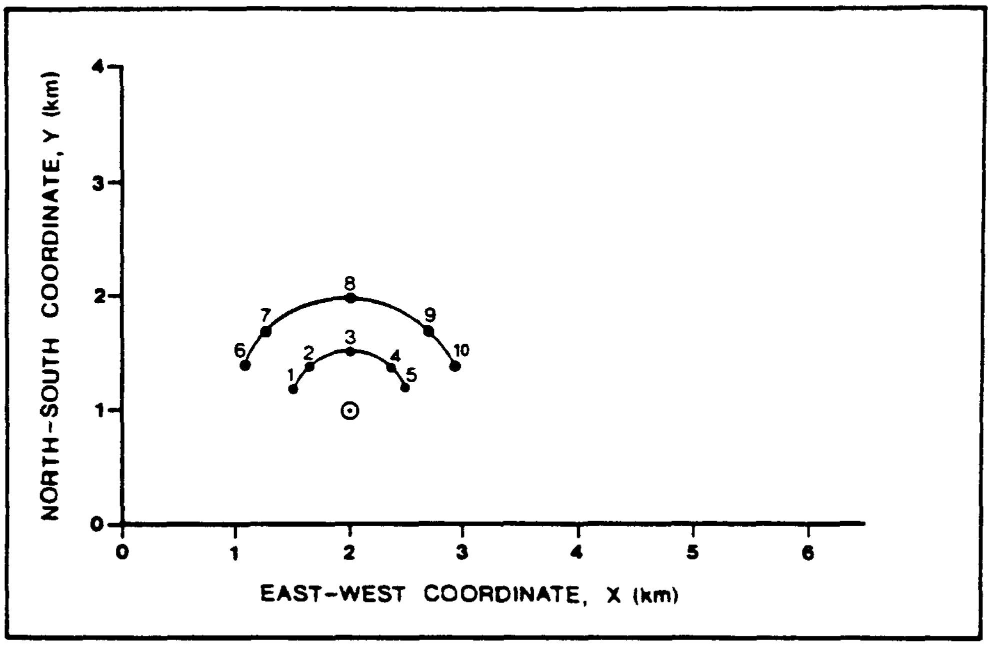

Figure 5. Source-receptor geometry for example 2.

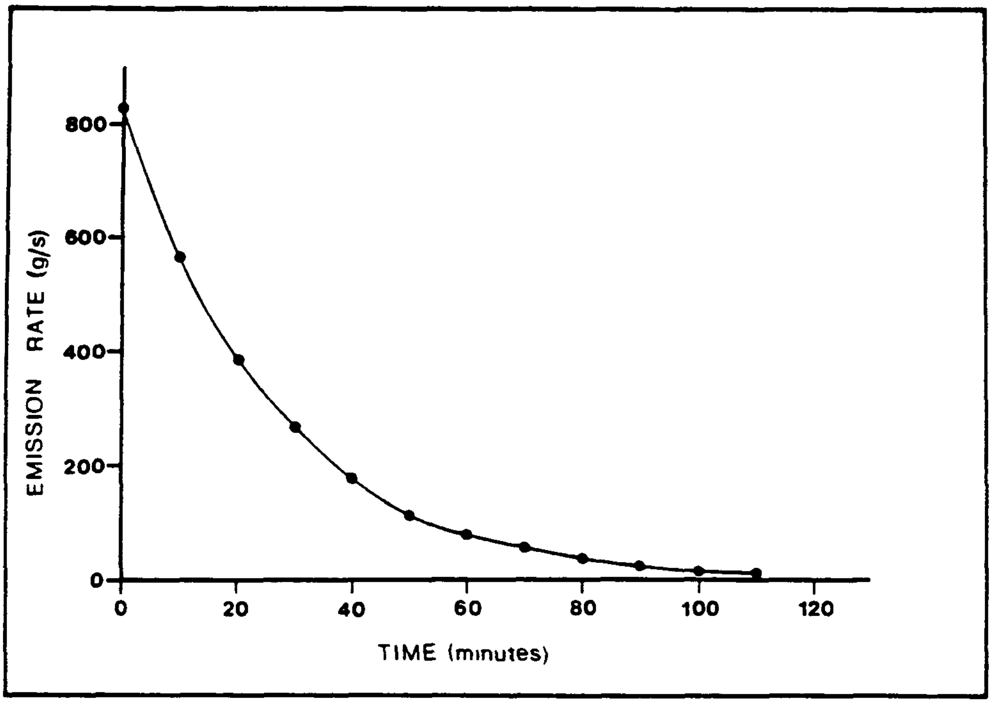

Figure 6. Emission rate versus time plot for example 2.

The input stream and abridged output listing for this problem are provided in Section 11. The plotting features of the model are also shown there.

EXAMPLE 3 -- MULTIPLE SOURCE WITH DEPOSITION

The user-specified depositional settling option is exercised in this example. Characteristics of the sources are as follows:

* Source strength -- 1 g/sec,
* Stack height -- 30 m,
* Stack gas temperature -- 293,
* Stack gas velocity -- 0.0,
* Stack diameter -- 1.0.

The depositiion/settling velocities for sources one through three are 0.0, 5.0, and 10.0 cm/sec.

The hourly meteorological data remain the same through the run. In effect the results are comparable to Figure 1, page 33 in Rao (1982). That figure has been reproduced here (Figure 7) to demonstrate that INPUFF gives essentially the same result as PAL-DS for the same input conditions. The greatest differences occur for short travel distances with excellent agreement between the two models for travel distances at and beyond distance to maximum concentrations.

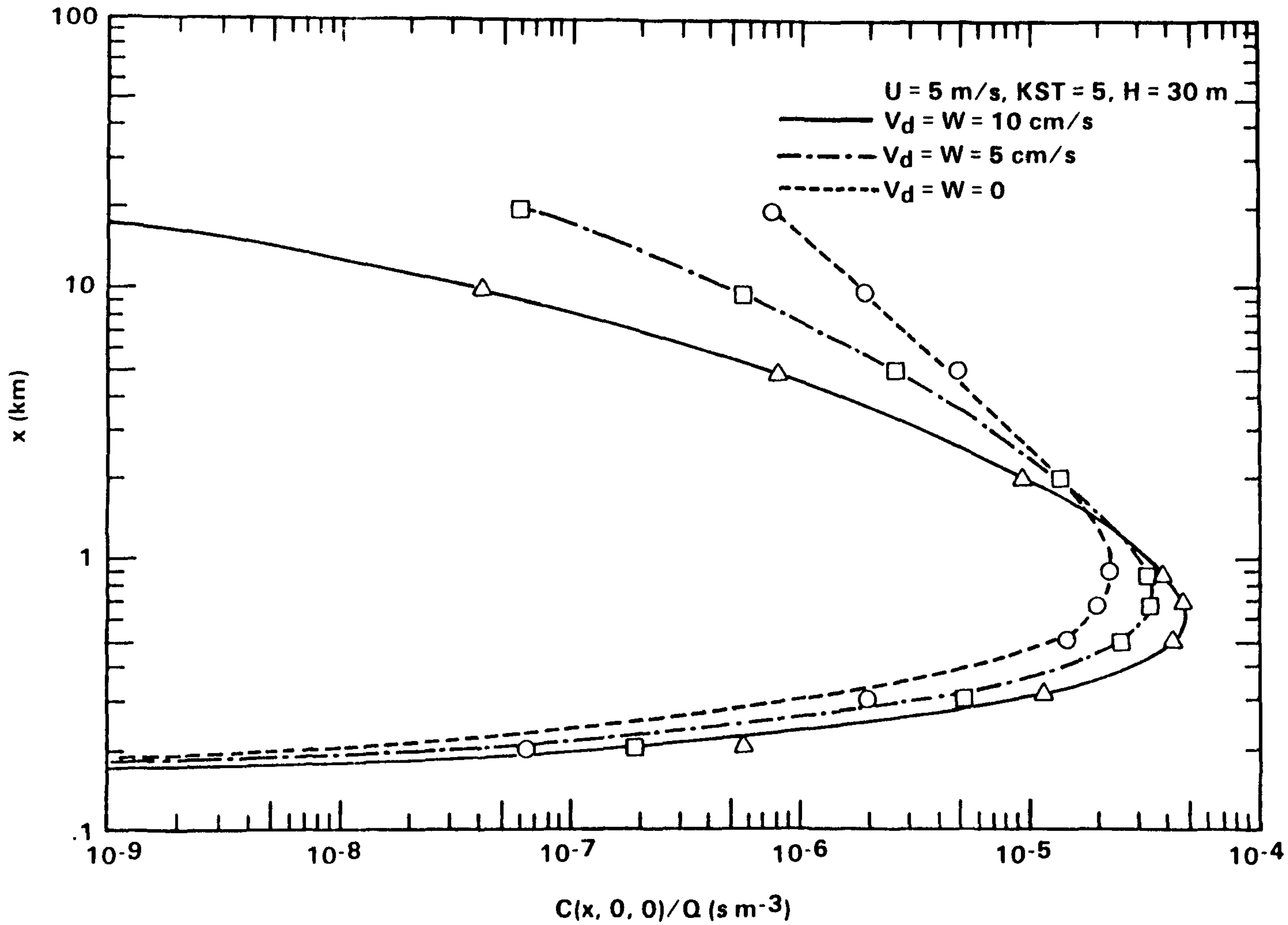

Figure 7. Variation of plume-centerline surface concentration. INPUFF estimates indicated by symbols.

SECTION 7
COMPUTER ASPECTS OF THE MODEL

INPUFF

This section discusses the general framework of INPUFF. The section is intended to give the reader a general knowledge of the computer program, rather than a detailed description of each subroutine. The general flow of INPUFF, the structure of the computer subroutines and functions, and a brief description of each subroutine and function are included.

The following types of information are needed by the model:

* Options to be exercised during program execution,
* Simulation information and puff characteristics,
* Specifications of the modeling region,
* Source characteristics,
* Receptor coordinates, and
* Meteorological data.

INPUFF is a multiple source model that permits source characteristics to be updated at time steps evenly divisible into the meteorological period. The meteorology during the modeling exercise can be specified by up to 144 equal length meteorological periods. Concentration estimates can be made for 100 locations.

Figure 8 shows the structure of the subroutines and functions. INPUFF is the main routine that initializes the puffs and stores the appropriate data in common with the other subroutines. Subroutines that begin with the letter "R" read input data. A brief description of the main program, subroutines, and functions follows.

```
           |---- CMBRMV
           |
           |---- CONCEN -  ERFC
           |
           |---- RMODEL -  ERROR
           |
           |             |- ERROR
           |---- RSOURC- |
           |             |- IGCDIV
           |
           |---- RSRATE -  ERROR
           |
           |             |- PLMRS
           |---- CMPRIS- |- USRPRS
           |             |- UFACTR
           |
           |             |- USRVRT - USRSIG
           |             |- USRSIG
           |---- CALSTP- |- SIGJSY
           |             |- SIGPGY
           |             |- VTIMY
           |             |- VTIMZ
           |
           |             |- USRVRT - USRSIG
           |             |- VTIMY
           |---- MODPUF- |- VTIMZ
           |             |- XVY
INPUFF --  |             |- XVZ
           |
           |---- RWINDS -  ERROR
           |
           |---- UFACTR
           |
           |---- ERROR
           |
           |---- ADVECT
           |
           |---- PLMRS
           |
           |---- USRPRS
           |
           |             |- USRVRT - USRSIG
           |             |- XVY
           |---- ADDPUF- |- XVZ
           |             |- VTIMY
           |             |- VTIMZ
           |
           |             |- USRSIG
           |             |- SIGJSY
           |---- PROCES- |- SIGJSZ
                         |- SIGLTY
                         |- SIGPGY
                         |- SIGPGZ
```

Figure 8. Structure of INPUFF.

PROGRAM MODULES

INPUFF -- INPUFF is the main program that performs puff initialization. The following subroutines and functions are called by INPUFF: PLMRS, CMBRMV, CONCEN, RMODEL, RSOURC, RSRATE, CMPRIS, CALSTP, MODPUF, RWINDS, UFACTR, ERROR, ADVECT, USRPRS, ADDPUF, and PROCES. INPUFF prints out the input data and the concentration estimates at each receptor for each time period.

ADDPUF -- ADDPUF assigns most of the characteristics of a new puff. Subroutines USRVRT and USRSIG and functions XVY, XVZ, VTIMY, and VTIMZ are called by ADDPUF.

ADVECT -- This subroutine is called by INPUFF if the user-supplied wind field option is exercised (i.e., LADT = TRUE). ADVECT reads the gridded wind field data from unit 21, and computes the appropriate wind speed and direction for each puff.

CALSTP -- This routine is called only if the input value for ISTEP is negative. The puff release rate and criteria for puff combination are determined in CALSTP. Subroutines USRVRT, and USRSIG and functions SIGJSY, SIGPGY, VTIMY, and XVY are called by CALSTP.

CMBRMV -- This subroutine combines and removes puffs.

CMPRIS -- This routine calculates the components of the wind and source motion (if source is moving). CMPRIS calls subroutines PLMRS, USRPRS, and function UFACTR.

CONCEN -- This subroutine is called by INPUFF and computes the concentration from each puff for each receptor location. The equations for deposition and gravitational settling are in this routine. CONCEN only calls function ERFC.

EFRC -- This function calculates the complimentary error function of X, using Rational Chebyshev approximations.

ERROR -- This routine produces error messages.

IGCDIV -- This function determines the greatest common divisor between two arguments.

MODPUF -- MODPUF updates KEYP values and virtual distances (times) as necessary for existing puffs. MODPUF calls subroutines USRVRT and USRSIG and functions VTIMY, VTIMZ, XVY, and XVZ.

PLMRS -- This routine calculates final plume rise using the methods outlined by Briggs (1975).

PROCES -- Called directly by INPUFF, the major functions of PROCES are to: determine which dispersion routine is called for each puff, assign dispersion keys (KEYP) for each puff, and account for the effect of the mixed depth layer for each puff. PROCES calls subroutine USRSIG, and functions SIGJSY, SIGJSZ, SIGLTY, SIGPGY, and SIGPGZ.

RMODEL -- This routine reads in all of the "one time only" input data and opens all external files. Subroutine ERROR is called by RMODEL.

RSOURC -- This routine reads in source related input data. Subroutine ERROR and function IGCDIV are called by RSOURC.

RSRATE -- This routine reads in source emission rate and other related data that may vary during the course of a model run. RSRATE only calls subroutine ERROR.

RWINDS -- Subroutine RWINDS is called if LADT is true. Wind speed and direction are read in for each grid square from unit 21.

SIGJSY -- This function computes sigma Y based on travel time (Irwin 1982).

SIGJSZ -- This function computes sigma Z based on travel time (Irwin 1982).

SIGLTY -- Sigma Y for long travel time is computed in this function. Growth is proportional to the square root of time.

SIGPGY -- This routine computes sigma Y using the P-G curves.

SIGPGZ -- This routine computes sigma Z using the P-G curves.

UFACTR -- This function computes the adjustment to the wind speed based on the "Power law" exponents.

USRPRS -- This routine is a user-supplied subroutine for plume rise.

USRSIG -- This routine is a user-supplied subroutine for dispersion parameters.

USRVRT -- The virtual times or distances for the user-supplied sigmas are computed by USRVRT. Subroutine USRSIG is called by USRVRT.

VTIMY -- This function calculates the virtual time, corresponding to the SIGJSY function.

VTIMZ -- This function calculates the virtual time, corresponding to the SIGJSZ function.

XVY -- This function calculates the virtual distance necessary to account for the initial crosswind dispersion using the P-G scheme.

XVZ -- This function calculates the virtual distance necessary to account for the initial vertical dispersion using the P-G scheme.

The table below shows the input/output units used by the model.

TABLE 5. INPUT/OUTPUT UNITS USED BY THE MODEL

Unit number	Mode	Contents
5	Input	Program control and input data
6 (IW)	Output	Output listing
21	Input	User-supplied wind field
22*	Output/input	Input data for plotting software

* Output from the main routine and input for plotting routine.

PLOT POSTPROCESSOR

The plot routine reads the following types of information:

* Type of plots desired,
* Location of concentration versus time plots, and
* Plotting grid.

The above information is read from unit 5. The following information, generated by the main routine if LP22 = T (see Table 6), is read from unit 22:

* Number of meteorological periods,
* Length of each meteorological period,
* Total simulation time,
* Location of each receptor,
* Computed concentrations at each receptor, and
* Location of each puff and its sigma values.

The plot routines were developed on a UNIVAC 1110 and call CALCOMP plotting software. They are provided primarily as an example of the utility of the data in unit 22. The main program calls two subroutines which actually do the plotting. These are PLTCON, which generates concentration versus time plots at specified receptor locations, and PLTTRJ, which plots puff trajectories and receptor locations. The input data for the plot routines are shown in Table 7 and are described in the next section.

SECTION 8

INPUT DATA PREPARATION

RECORD INPUT SEQUENCE FOR INPUFF

There are twelve record types that are read by INPUFF. Ten of these are free format input, and two are alphanumeric. While the free format is very easy to use, care should be taken to ensure that every variable is given a value in the correct order. Each variable should be separated by a comma or blank space and should conform to the variable name type. Two of the twelve input records are optional, depending on the options exercised on record 2. Records 1 through 7 are read in subroutine RMODEL. Records 8 through 11 are read in subroutine RSOURC. And finally record 12 is read in subroutine RSRATE. A brief description of each input parameter is given in Table 6 with the appropriate units; the metric system of units is used throughout the model. Thus horizontal coordinates of source and receptor locations are in kilometers, temperatures in degrees kelvin, and emission rates in grams per second. Under the "Format" column of Table 6, AN refers to alphanumeric, FF represents free format. Standard notation for real and integer variables are used. Logical variables are indicated in the "Units" column.

TABLE 6. RECORD INPUT SEQUENCE FOR INPUFF

Variable	Format	Record type & Variable description	Units
Record 1			
ALP	AN	80-character title to describe output	--

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
Record 2			
IW	FF	Unit number for write statements	--
LADT	FF	Does user supply a wind field?	(logical)
LP22	FF	Unit 22 output desired?	(logical)
KEYDSP	FF	Dispersion option KEYDSP = 1 For PG (distance dependent) sigma curves KEYDSP = 2 For Irwin, et. al. (time dependent) sigma curves KEYDSP = 3 For user specified distance dependent sigma curves KEYDSP = 4 For user specified time dependent sigma curves	--
SYMAX	FF	Maximum size of sigma Y before going to SIGLTY function; If very large then the use of SIGLTY is effectively prevented	(m)
LPCC	FF	Option to print out puff information each ITIME desired?	(logical)
LPIC	FF	Option to print out intermediate concentrations desired?	(logical)

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
Record 3			
XGRDSW	FF	East-west coordinate of S.W. corner of model region	(km)
YGRDSW	FF	North-south coordinate of S.W. corner of model region	(km)
XSIZE	FF	East-west size of model region	(km)
YSIZE	FF	North-south size of model region	(km)
Record 4			
NTIME	FF	Number of periods of simulation	--
ITIME	FF	Simulation time (length of a meteorological period)	(seconds)
NSOURC	FF	Number of sources for this run	--
NREC	FF	Number of receptors	--
Record 5 (Read NREC times)			
XREC	FF	X coordinate of receptor	(km)
YREC	FF	Y coordinate of receptor	(km)
ZREC	FF	Z coordinate of receptor	(m)

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
TWO OPTIONAL RECORD TYPES FOLLOW:			
Record 6 -- Optional			
If LADT is TRUE then read this record.			
FRMAT	AN	Format of unit 21 Met. Data Subroutine RWINDS reads unit 21	--
Record 7 -- Optional			
If LADT is TRUE then read this record.			
XSWC	FF	East-west coordinate of the S.W. corner of meteorological region	--
YSWC	FF	North-south coordinate of the S.W. corner of meteorological region	--
NUMX	FF	Number of grid squares in east-west direction	--
NUMY	FF	Number of grid squares in north-south direction	--
DGX	FF	East-west width of grid square	(km)
DGY	FF	North-south width of grid square	(km)

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
Record types 8 through 12 all occur under the control of a source loop and are executed NSOURC times:			
Record 8			
LDWSH	FF	Stack downwash option desired?	(logical)
LBID	FF	Buoyancy induced dispersion option desired?	(logical)
LDEPS	FF	Deposition and settling option desired?	(logical)
LUPLRS	FF	User plume rise option desired?	(logical)
LCMBPF	FF	Does user want puff combinations? if so, the frequency of puff combinations is set automatically	(logical)
Record 9			
ISTEP	FF	Time between puff releases (used internally as MSTEP, in millisec). If ISTEP is negative, a value for MSTEP will be computed based on the stability class, wind speed, and minimum distance from source to receptor (CDIS). If positive, ISTEP must divide evenly into ITIME, ISUPDT, and ISAMPL.	(seconds)

(continued)

TABLE 6. (continued)

Variable	Format	Record type & Variable description	Units
ISAMPL	FF	"Sampling" time for concentrations (used if LPIC is TRUE. Also used to assign value for ISTEP). ISAMPL must divide evenly into ITIME.	(seconds)
ISTRTC	FF	Time to start concentration calculations	(seconds)
SDCMBN	FF	Fraction of crosswind dispersion for puff combination; If SDCMBN is negative and ISTEP is negative, SDCMBN is calculated based on MSTEP, relative speed of wind vs. source movement, and sigma Y at the closest receptor; If SDCMBN is negative and ISTEP is positive, SDCMBN is set to 1.0	--
ANHGT	FF	Anemometer height	(m)

Record type 10 is within a meteorological period loop, which in turn is within the source loop. It is executed NTIME times for every source.

Variable	Format	Record type & Variable description	Units
Record 10			
WDIR	FF	Wind direction	(degrees)
WSPD	FF	Wind speed	(m/sec)

(continued)

TABLE 6. (continued)

Variable	Format	Record type & Variable description	Units
HL	FF	Mixing height	(m)
KST	FF	Stability class...please note!!! 1=Pasquill's A, 2=B, 3=C, 4=D-Day, 5=D-Night, 6=E, 7=F	--
SGPH	FF	Sigma phi, standard deviation of elevation angle	(radians)

(continued)

Variable	Format	Record type & Variable description	Units
SGTH	FF	Sigma theta, standard deviation of azimuth angle	(radians)
TEMP	FF	Air temperature	(K)
CDIS	FF	Minimum distance source to receptor	(km)

Record type 11 is within the source loop only, and is executed immediately after the met data (rec. type 10) for the source have been read and checked.

Variable	Format	Record type & Variable description	Units
Record 11			
XSORC	FF	X Coordinate of source	(km)
YSORC	FF	Y Coordinate of source	(km)
NSRCDS	FF	Number of source emissions records	--

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
		If ISUPDT is zero or negative, this should be 1, otherwise NTIME*ITIME should equal NSRCDS*ISUPDT.	
ISUPDT	FF	Time between source emissions updates (used internally as MSUPDT, in millisec.). If no updating, ISUPDT should be zero or negative or equal to NTIME*ITIME. If updating, ISTEP (if positive) must evenly divide into ISUPDT. Also, either ITIME must be a multiple of ISUPDT (but ITIME must be no more than 100 times ISUPDT); or ISUPDT must be a multiple of ITIME.	(seconds)
DV	FF	Deposition velocity	(cm/sec)
SVV	FF	Settling velocity	(cm/sec)

Notes on DV and SVV:

Setting both DV=0. and SVV=0. is equivalent to a no deposition case.
For deposition to occur, SVV should be less than or equal to DV.
For deposition of gases and very small particles, SVV=0.
For deposition of small particles, SVV is less than DV.
For deposition of medium and large particles, SVV=DV.
Re-entrainment of particles is implied if SVV is greater then DV.

(continued)

TABLE 6. (Continued)

Variable	Format	Record type & Variable description	Units
Record type 12 is effectively within a source emissions period loop, which in turn is within the source loop. It is executed NSRCDS times for each source. This is the last data type for unit 5.			
Record 12			
QP	FF	Emission rate	(g/sec)
HPP	FF	Height of release	(m)
TSP	FF	Stack gas temperature	(K)
DP	FF	Stack diameter	(m)
VSP	FF	Stack gas velocity	(m/sec)
VFP	FF	Stack gas volume flow	(M**3/sec)
SYOP	FF	Initial sigma Y	(m)
SZOP	FF	Initial sigma Z	(m)
SDIR	FF	Source direction	(degrees)
SSPD	FF	Source speed	(m/sec)

Most of the input data are straightforward and typical of the kind of information required for Gaussian models. However, there are some input variables which are unique to this code and require additional explanation to ensure proper assignment of values.

Record 2

If KEYDSP is equal to 3 or 4 subroutine USRSIG must be included at the time the program is linked. This subroutine is provided so the user can incorporate his own characterization of dispersion. Dispersion can be characterized as a function of downwind distance or travel time. The appropriate value of KEYDSP (3 or 4) must be specified. A sample subroutine USRSIG is included in the code. The user's version must retain the same calling arguments.

SYMAX is the maximum size of sigma Y for any puff before the program calls SIGLTY to compute the dispersion parameters. SYMAX can be assigned any size (in meters) depending on how soon the user wants the model to compute the dispersion parameters as a function of the square root of time. If it is desired not to call SIGLTY, then a very large value of SYMAX should be assigned.

Record 4

The data req ested on record 4 give the program information regarding the modeling design. NTIME is the number of meteorological periods simulated in a run. ITIME is the time period associated with the meteorological data. For example, if the meteorological data are recorded in 20-minute averages and the user wants to make a 3-hour simulation, then NTIME = 9 and ITIME = 1200 seconds. Any number of sources may be simulated in a given execution of INPUFF. However, run time is approximately proportional to the number of sources. The number of receptors, NREC, must not exceed 100.

Records 6 and 7

Records 6 and 7 are read if LADT is TRUE. The information on record 7 defines the coordinates of the SW corner of the gridded region and the size of each grid square. Wind speed and direction are read in for each grid square, a row at a time, from west to east (left to right). Rows are read from south to north (bottom to top). There are a few caveats associated with using gridded meteorological data. The source must stay within the defined region. The meteorological region defined on record 7 need not be the same as the modeling region defined on record 3, but it is best if the southwest corner of both have the same coordinates. If the meteorological region is smaller than the modeling region and the puffs travel outside of the meteorological region, then they will be advected according to the closest wind speed and direction grid location. If the meteorological region is larger than the modeling region and the puffs travel outside the modeling region, they will be eliminated from further consideration. Record 6 requires the user to input the format of his meteorological data file. This file has to be assigned to unit 21, and is read by subroutine RWINDS according to the format specified on record 6. If the option to specify the wind field is exercised, then the meteorological data read on record 10 must be appropriate for the grid square that contains the source. Record 10 must be supplied whether or not the wind field option is exercised.

Record 8

An alternate plume rise algorithm can be utilized in INPUFF by setting LUPLRS to TRUE. The user may incorporate any plume rise algorithm appropriate to his modeling exercise. The subroutine name must remain USRPRS with the same calling arguments. Meteorology and source information are provided in common blocks. A sample plume rise program is provided in INPUFF to compute the plume rise from a forest fire.

For most applications LCMBPF should be TRUE. If it is false no puff combinations or removal will occur, resulting in excessive run time and possible program termination.

Record 9

The data requested on record 9 give the program additional information regarding the modeling design. ISTEP is the time interval between puff releases. If ISTEP is assigned a negative value the model computes ISTEP based on the stability class, wind speed, and minimum distance from source to receptor. The minimum value that can be assigned to ISTEP is 1 second. However, if ISTEP is negative the model may calculate a puff release rate faster than one every second. When assigning ISTEP for a moving source, be sure to take into account the path of the source when computing the minimum distance between source and receptor (CDIS), specified on record 10. ISTEP should always be divisible into ITIME, ISUPDT and ISAMPL, which is the time interval at which intermediate concentration values are printed out. ISUPDT is the time interval at which source characteristics are updated. For example, if ITIME = 1200 and ISAMPL = 300, then four 5-minute average concentration tables are printed (if LPIC = T) as well as the 20-minute average concentration table.

The next two input parameters, ISTRTC and SDCMBN, are used to reduce computing time. ISTRTC is the time when concentration calculations are to begin. For most cases ISTRTC is assigned a value of zero. However, if the minimum source-receptor distance is large and requires a substantial amount of travel time for the puffs to reach the receptor, a value for ISTRTC can be assigned which would advect the puffs downwind but would delay the concentration calculations until the current time equaled ISTRTC.

The parameter SDCMBN controls when puff combinations take place. Combinations occur only for adjacent puffs in the release sequence which have the same dispersion key. A puff can have one of six possible dispersion keys: (1) puff is below the mixing height and using short travel time dispersion; (2) puff is using long travel time dispersion; (3) puff is above the mixing height; (4) puff is well mixed and using either P-G or on-site dispersion; (5) puff is above the mixing height and using long travel time dispersion; and (6) puff is well mixed and using long travel time dispersion. For instance, suppose two puffs are adjacent in time and have identical dispersion keys. If SDCMBN is 1 then the puffs combine when their centers are within one sigma Y of each other (sigma Y of the younger puff is used for the test). If SDCMBN equals 2, then the puffs combine when their centers are within 2 sigma Y of each other. A value of SDCMBN equal to 0 results in no puff combinations. SDCMBN can be assigned any value; however, in practice, SDCMBN equal to 1 is a reasonable value for puff combination. If SDCMBN is negative INPUFF will assign a value for SDCMBN.

Upon combining puffs, the position, displacement, and travel time are combined based on the weighted (based on total mass within puff) average between the two puffs. The puff sigmas are calculated according to the weighted geometric means. The mass is summed.

Record 10

With the exception of stability class (KST) the variables on this record are typical of many air quality models. As mentioned in Section 5, INPUFF considers seven stability categories with the inclusion of D-day and D-night. Thus stability classes A through D-day are specified by 1-4, and classes D-night through F are specified by 5-7, respectively.

Record 11

The input parameters NSRCDS and ISUPDT must be correctly specified. If no updates to the source characterization are desired, then ISUPDT should be zero or negative and NSRCDS should be assigned a value of one. If you would like to update some aspect of the source characterization, such as emission rate, then ISUPDT must be positive. If ISTEP is positive, ISUPDT should be specified such that ISTEP divides evenly into ISUPDT. The following condition must also be true. ISUPDT must be a multiple of or evenly divided into ITIME. The source can be updated up to 100 times during any meteorological period. For example, if ITIME is 3600 seconds and you want to update the source every five minutes, then NSRCDS=12 and ISUPDT=300. If there were three meteorological periods (NTIME=3) then NSRCDS=36 and ISUPDT remains the same.

INPUT DATA FOR PLOT POSTPROCESSOR

The input data for the plot postprocessor, assigned on four input records, are read using free format (indicated by an FF in Table 7). Table 7 shows the input parameters for each record with the appropriate units. The main routine of the plotting package reads the input data and the information generated on unit 22 by the main routine of the puff model. There are two plots which are optional output in the execution of the plotting routine. One is a plot of concentration versus time and the other is a plot of the puff trajectory at the end of each meteorological period. Either one or both of the plots may be requested during a given simulation.

TABLE 7. RECORD INPUT SEQUENCE FOR PLOT POSTPROCESSOR

Record type & Variable	Format	Variable description	Units
Record 1			
IPLT	FF	Plotting options: 1 = plot concentration versus time 2 = plot puff trajectory 3 = plot both	--
Record 2			
IYR	FF	Order of magnitude of concentration to be plotted on the y-axis. (Default value is 6)	--
NUMR	FF	Number of receptors for which concentration versus time is plotted	--
ITPT	FF	Number of periods for which concentration versus time is plotted. ITPT must be evenly divisible into NTIME. (If ITPT > 999, all periods are plotted together.)	--
XSI	FF	Length of x-axis	in
YSI	FF	Length of y-axis	in

(continued)

TABLE 7. (Continued)

Record type & Variable	Format	Variable description	Units
Record 3			
IREC	FF	Receptor number for concentration versus time plots. (NUMR integers are read on this record.)	--
Record 4			
XMIN	FF	East-west coordinate of SW corner of plotting grid	km
YMIN	FF	North-south coordinate of SW corner of plotting grid	km
XSIZE	FF	East-west size of plotting grid	km
YSIZE	FF	North-south size of plotting grid	km
AXL	FF	Length of x-axis	in
AYL	FF	Length of y-axis	in

On record 2, NUMR is the number of receptor locations that a plot of concentration versus time is generated. The actual receptor numbers are read on record type 3. For example, if the user has made concentration estimates at ten locations and wishes to see the concentration versus time plots for receptors 1, 3, and 8, then NUMR = 3 and the array on record 3 is assigned the values 1, 3, and 8. The third parameter on record 2 is ITPT. This parameter allows the user to combine meteorological periods for the concentration versus time plots. If ITPT = 1, then a concentration versus time plot is generated each ITIME for all receptors specified on record type 3. However, for ease in observing the time variations in concentrations, the periods can be combined. For example, if NTIME = 3 and ITIME = 3600 (i.e., a 3-hour simulation) and a plot of concentration versus time is desired for the entire 3 hours, ITPT should be set to greater than 999. ITPT must be evenly divisible into NTIME, or be greater than 999.

SECTION 9
SENSITIVITY ANALYSIS

This section presents a simple analysis designed to acquaint the user with the magnitude of changes expected in pollutant concentrations and CPU time when certain model inputs are varied. A near surface released was used as a basis for this analysis.

PUFF COMBINATION -- SDCMBN

Integrated puff models are by their nature computationally time consuming. To minimize computational time required in the model, the puffs are combined or deleted, or in certain situations no computation is made. For instance, if a puff is not close to a receptor no computations may take place. The parameter SDCMBN controls the rate of puff combinations. If the value of SDCMBN is 1, then the puffs combine when their centers are within one lateral standard deviation of each other.

As noted in Figure 9, CPU time increases rapidly as SDCMBN approaches zero due to increased number of puffs. Execution time for SDCMBN equal to 0.2 is more than three times longer than for an SDCMBN of 1. CPU time levels off for SDCMBN greater than 1. Increasing SDCMBN from 1 to 3 results in only a 50% reduction in execution time.

The sensitivity of ground level center line concentrations to SDCMBN is shown in Table 8. Varying SDCMBN from 0 to 3 has little effect on concentrations. However, shifting the wind direction can increase the percentage difference. This result, in conjunction with decreased computer costs with increasing SDCMBN (see Figure 9), suggests that SDCMBN equal to 1 is a reasonable value for puff combination.

TABLE 8. PERCENT CHANGE IN CONCENTRATIONS USING DIFFERENT SDCMBN VALUES*

Downwind distance (km)	SDCMBN				
	0.4	0.6	1.0	2.0	3.0
0.5	0	0	0	+2	0
1.0	0	0	0	-2	0
2.0	0	0	0	0	+1
3.0	0	0	0	0	-1
5.0	0	0	0	0	0
10.0	0	0	0	0	0
20.0	0	0	0	0	+3
30.0	0	0	0	0	0
50.0	0	0	0	0	+2

* Concentrations were compared with those computed with SDCMBN equal to 0.2.

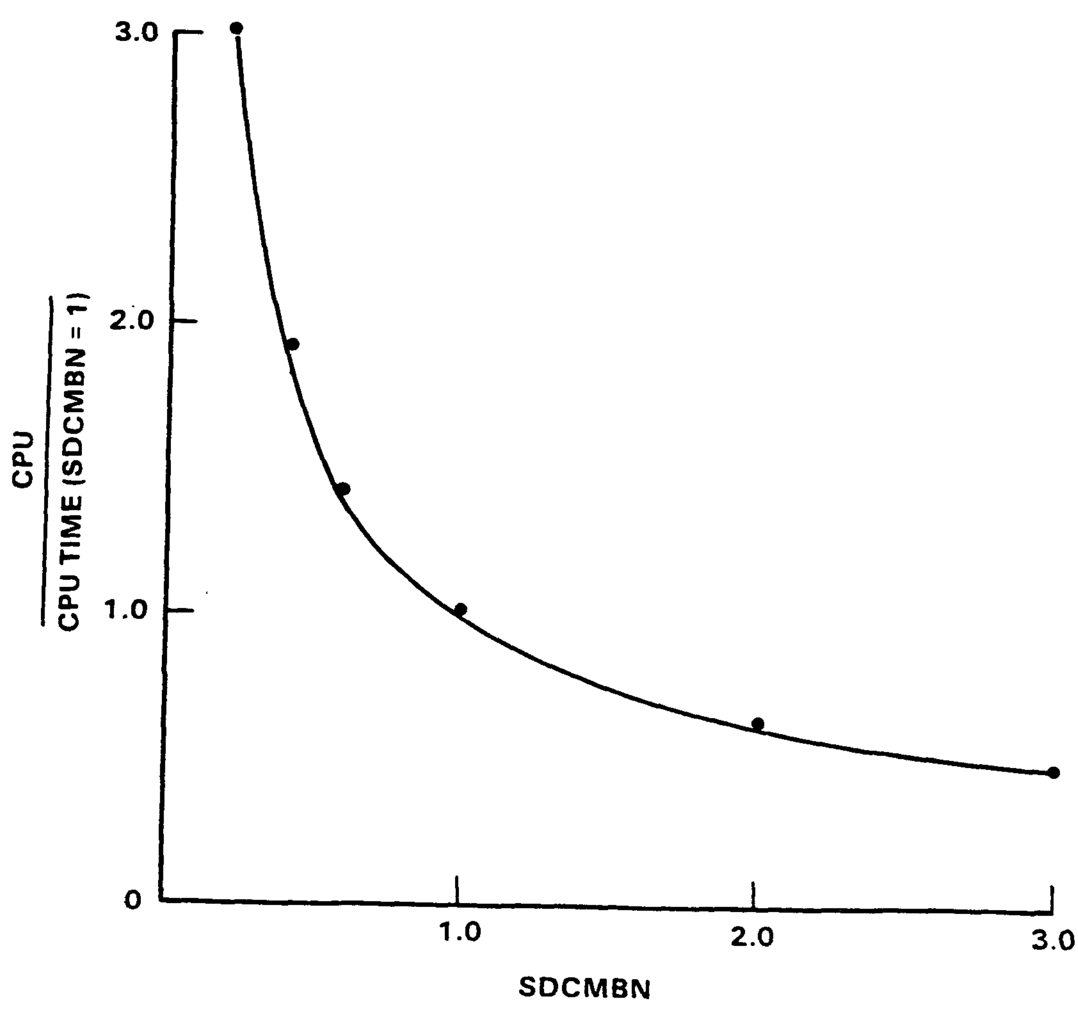

Figure 9. Sensitivity of CPU time to SDCMBN.

SIZE OF MODELING REGION

By defining the modeling region carefully, the user may save substantial computer costs as illustrated in Figure 10. For example, it makes little sense to extend the modeling region 50 kilometers downstream of the source when all the receptors are within 5 kilometers. INPUFF keeps track of all puffs in the modeling region regardless of their distance from a particular receptor. It might, nevertheless, be useful to have a large modeling region under some circumstances, such as in a dramatic wind shift situation that blows puffs back over the receptors.

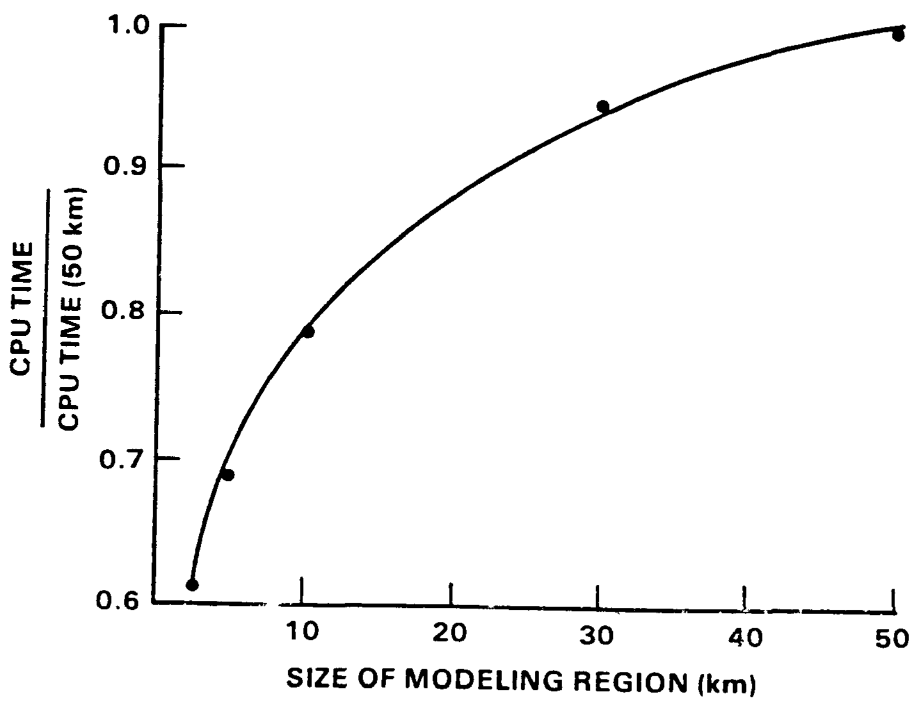

Figure 10. Sensitivity of CPU time to size of modeling region.

SECTION 10

EXECUTION OF THE MODEL AND SAMPLE TEST

INPUFF produces an error-free compile on IBM MVS and UNIVAC EXEC 8 computers with comparable execution results. The code conforms to American National Standard FORTRAN, ANSI /X3.9-1978, and should be transportable to other systems with little or no change. Sample job streams are presented below.

Sample test data for model verification are as follows:

```
INPUFF VERIFICATION RUN
6,F,F,1,1000.,F,F
0.,0.,25.,40.
2,3600,1,7
 0.5,20.,0.
 1.0,20.,0.
 2.0,20.,0.
 3.0,20.,0.
 5.0,20.,0.
10.0,20.,0.
20.0,20.,0.
T,F,F,F,T
-1,3600,0,1.,10.
270. 3. 1500. 4 .112 .175 290. .5
270. 3. 1500. 4 .112 .175 290. .5
0.,20.,1,7200,0.,0.
2750.,165.,425.,4.5,38.,0.,1.5,1.5,0.,0.
```

A job stream for a UNIVAC EXEC 8 system might have the following form:

```
 @ RUN,R/R JOB-ID,ETC
 @ ASG,A MODELS*LOAD.
```

```
@ ASG,A WINDS   )
@ USE 21,WINDS  |  Not needed for
@ ASG,R PLOT    |  verification run
@ USE 22,PLOT   )
@ XQT MODELS*LOAD.INPUFF
  (input records shown above)
@ FIN
```

The following is a sample job stream for an IBM system under OS or MVS. Units 21 and 22 are assumed to have been preallocated.

```
//JOBID     JOB  (PROJ,ACCT,OTHER),CLASS=A,TIME=1
//XINPUFF   EXEC PGM=INPUFF,TIME=(,30)
//STEPLIB   DD   DSN=USER.MODELS.LOAD,DISP=SHR
//FT21F001  DD   DSN=USER.WINDS.DATA,DISP=SHR)  Not needed for
//FT22F001  DD   DSN=USER.PLOT.DATA,DISP=SHR )  verification run
//FT06F001  DD   SYSOUT=A
//FT05F001  DD   *
(input records shown above)
/*
//
```

A sample job stream for a CDC system under Scope 3.14 may look as follows:

```
XX,T05,P4.
USER,HALE,EPA.
PROJECT,*PRJ*XX.
ATTACH,LIB,MODELSLIB,ID=XX.
ATTACH,TAPE21,WINDS,ID=XX.)  Not needed for
ATTACH,TAPE22,PLOT,ID=XX. )  verification run
LIBRARY,LIB.
INPUFF.
*
(input records shown above)
*
```

Figure 11 provides the output for the sample test. Users may verify the proper execution of the program by comparing their results with those given in the figure.

```
                 INPUFF 2.0  MULTIPLE SOURCE INTEGRATED PUFF MODEL (DATED 86128)
                   AN AIR QUALITY DISPERSION MODEL IN
                   SECTION 2. NON-GUIDELINE MODELS,
                   IN UNAMAP (VERSION 6) JUL 86.
                   SOURCE: UNAMAP FILE ON EPA'S UNIVAC 1110, RTP, NC.


INPUFF VERIFICATION RUN


M O D E L   O P T I O N S          A "T" INDICATES THAT
                          THE OPTION HAS BEEN EXERCISED

USER SUPPLIED WIND FIELD       F
UNIT 22 OUTPUT OPTION          F
PRINT PUFF INFORMATION         F
INTERMEDIATE CONCENTRATIONS    F

DISPERSION CALCULATED USING PASQUILL-GIFFORD (DISTANCE DEPENDENT) SIGMA CURVES,
WITH TRANSITION TO DRAXLER'S LONG RANGE TRANSPORT SIGMA-Y AT SYMAX =     1000.0 METERS.
```

Figure 11. Output for the sample test.

```
            B E G I N  A N A L Y S I S  O F  S O U R C E  N U M B E R   1

S O U R C E  O P T I O N S        A "T" INDICATES THAT
                             THE OPTION HAS BEEN EXERCISED

STACK DOWNWASH                T
BUOYANCY INDUCED DISPERSION   F
DEPOSITION AND SETTLING       F
USER PLUME RISE               F
PERFORM PUFF COMBINATIONS     T


I N P U T   P A R A M E T E R S

SOURCE UPDATE INTERVAL =   7200 SECONDS.   (-1 INDICATES NO UPDATE)
START CONCENTRATION CALCULATIONS AT TIME =      0 SECONDS.
ANEMOMETER HEIGHT =  10.0 METERS.
```

Figure 11. (continued)

*** INFORMATION FOR SOURCE NUMBER 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 0 SECONDS EAST (KM)	NORTH (KM)
.275E+04	165.00	425.000	38.000	4.500	0.000	0.000	20.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	558.22	1.5	1.5	0.00	0.00

*** METEOROLOGY ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
270.0	3.000	1500.	0.150	4	4.702	290.0	0.1750	0.1120

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
0	3600	3600	15.000	0.50	1.000

3600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 0 TO 3600 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
0.500	20.000	0.000	0.000E-01
1.000	20.000	0.000	0.000E-01
2.000	20.000	0.000	9.075E-20
3.000	20.000	0.000	8.477E-13
5.000	20.000	0.000	7.620E-08
10.000	20.000	0.000	1.845E-05
20.000	20.000	0.000	3.588E-11

Figure 11. (continued)

*** I N F O R M A T I O N F O R S O U R C E N U M B E R 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 3600 SECONDS EAST (KM)	NORTH (KM)
.275E+04	165.00	425.000	38.000	4.500	0.000	0.000	20.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	558.22	1.5	1.5	0.00	0.00

*** M E T E O R O L O G Y ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
270.0	3.000	1500.	0.150	4	4.702	290.0	0.1750	0.1120

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
3600	7200	3600	15.000	0.50	1.000

3600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 3600 TO 7200 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
0.500	20.000	0.000	0.000E-01
1.000	20.000	0.000	0.000E-01
2.000	20.000	0.000	1.064E-19
3.000	20.000	0.000	1.060E-12
5.000	20.000	0.000	1.111E-07
10.000	20.000	0.000	4.695E-05
20.000	20.000	0.000	1.333E-04

Figure 11. (continued)

* *

2.00 HR AVG. CONCENTRATION AT RECEPTORS FOR ALL SIMULATION PERIODS
DUE TO SOURCE NUMBER 1

RECEPTORS			
X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
0.500	20.000	0.000	0.000E-01
1.000	20.000	0.000	0.000E-01
2.000	20.000	0.000	9.859E-20
3.000	20.000	0.000	9.540E-13
5.000	20.000	0.000	9.365E-08
10.000	20.000	0.000	3.270E-05
20.000	20.000	0.000	6.667E-05

Figure 11. (continued)

SECTION 11
INTERPRETATION OF OUTPUT

The output of INPUFF has eleven parts, three of which are optional. The output begins with printing the title of the run, which can be up to 80 characters in length. The next printed information is a list of model options, followed by a list of the source options and input. Next are the source data followed by a printout of meteorological conditions used in the execution of the model for the current simulation period. These are followed by five pieces of information regarding how INPUFF simulates the release, including: simulation period, simulation time, puff release rate, minimum source-receptor distance, and dispersion type. The next two output sections are optional. If LPIC = T, then intermediate concentrations are written every ISAMPL seconds. The time period for which the averages are appropriate is printed in the first line of the intermediate concentration output. If LPCC = T, then information on each puff is printed each ITIME in addition to average concentrations at each receptor. A table of average concentrations is output giving averages for each receptor for all meteorological periods. This output is repeated for all sources. Finally a table of average concentrations for all sources is provided.

There is one other optional output available to the user. If LP22 = T, then information is written to unit 22, which can be used later for plotting purposes.

The input stream and output listing of example problems 1 and 2 of Section 6 are presented in the next two sections. The reader is referred to the earlier section for the physical description of each problem. Intricacies of the input data are discussed and the output listing is annotated for ease of interpretation.

EXAMPLE 1 -- MOVING SOURCE

This example demonstrates an unique feature of INPUFF that allows the source to move at a constant speed and direction over a specified time. In this example, the source is changing speed and direction at the same frequentcy as the meteorology. Table 9 lists the input data; outputs of the example problem are given in Figure 12. Since LPCC =T, the output includes puff information printed for each ITIME.

TABLE 9. INPUT DATA FOR EXAMPLE 1

Record	Record Type
EXAMPLE 1 MOVING SOURCE	1
6,F,F,1,1000.,T,F	2
0.,0.,25.,15.	3
2,1200,1,8	4
1.54,1.19,0.	5
1.65,1.35,0.	5
2.,1.5,0.	5
2.35,1.35,0.	5
1.08,1.38,0.	5
1.3,1.7,0.	5
2.,2.,0.	5
2.7,1.7,0.	5
T,F,F,F,T	8
-1,60,0,.75,10.	9
180. 3.5 3000. 3 .074 .105 290. .5	10
170. 4.0 3000. 4 .047 .067 288. .5	10
0.,2,2,1200,0.,0.	11
600.,30.,390.,2.,15.,0.,1.,1.,90.,2.	12
600.,30.,390.,2.,15.,0.,1.,1.,45.,2	12

Note that the source information is updated every 20 minutes for two periods. If, however, the source speed and direction were changing every 5 minutes, NSRCDS would be equal to 8 and ISUPDT would equal 300. There would be 8 source information records (record type 12).

The information printed for each puff includes: puff number and coordinates, time of puff release, total mass of the puff, sigmas and travel distance for the puff, and its dispersion key.

Because the puffs combine as they travel downwind, each puff's characteristics are adjusted each time it combines with another puff. For example, puff 1 has a total mass of 72,000 grams. Since the source strength is 600 g/sec and the puff release rate is 20 seconds, this represents the combination of six puffs. All the parameters are affected by puff combinations except the dispersion key (KEYP). Puffs with different KEYP values do not combine.

Plots of concentration versus time for each of the eight receptors are shown in Figure 13. The coordinates of each receptor are printed at the top of each plot. The input data used in the execution of the plot programs are very short and are shown below.

Input Data Records	Data
1	1
2	-1, 8, 2, 5., 5.
3	1, 2, 3, 4, 5, 6, 7, 8

```
INPUFF 2.0   MULTIPLE SOURCE INTEGRATED PUFF MODEL (DATED 86128)
  AN AIR QUALITY DISPERSION MODEL IN
  SECTION 2. NON-GUIDELINE MODELS,
  IN UNAMAP (VERSION 6) JUL 86.
  SOURCE: UNAMAP FILE ON EPA'S UNIVAC 1110, RTP, NC.


EXAMPLE 1    MOVING SOURCE
```
Run title

```
INPUFF 2.0    MULTIPLE SOURCE INTEGRATED PUFF MODEL

M O D E L  O P T I O N S          A "T" INDICATES THAT
                          THE OPTION HAS BEEN EXERCISED

USER SUPPLIED WIND FIELD        F
UNIT 22 OUTPUT OPTION           F
PRINT PUFF INFORMATION          T
INTERMEDIATE CONCENTRATIONS     F

DISPERSION CALCULATED USING PASQUILL-GIFFORD (DISTANCE DEPENDENT) SIGMA CURVES,
WITH TRANSITION TO DRAXLER'S LONG RANGE TRANSPORT SIGMA-Y AT SYMAX =    1000.0 METERS.


          B E G I N  A N A L Y S I S  O F  S O U R C E  N U M B E R   1

S O U R C E  O P T I O N S          A "T" INDICATES THAT
                          THE OPTION HAS BEEN EXERCISED

STACK DOWNWASH                  T
BUOYANCY INDUCED DISPERSION     F
DEPOSITION AND SETTLING         F
USER PLUME RISE                 F
PERFORM PUFF COMBINATIONS       T
```
Options and input parameters exercised by the user

```
I N P U T   P A R A M E T E R S

SOURCE UPDATE INTERVAL =   1200 SECONDS.   (-1 INDICATES NO UPDATE)
START CONCENTRATION CALCULATIONS AT TIME =      0 SECONDS.
ANEMOMETER HEIGHT =  10.0 METERS.
```

Figure 12. Annotated output of example 1.

*** I N F O R M A T I O N F O R S O U R C E N U M B E R 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 0 SECONDS EAST (KM)	NORTH (KM)
.600E+03	30.00	390.000	15.000	2.000	0.000	0.000	0.200

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (M) (R)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
2.000	90.0	113.47	1.0	1.0	0.00	0.00

*** M E T E O R O L O G Y ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
180.0	3.500	3000.	0.100	3	4.462	290.0	0.1050	0.0740

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
0	1200	1200 ←*ITIME*	20.000 ←*ISTEP*	0.50 ←*CDIS*	0.750

puff location

PUFF#	X (M)	Y (M)	Z (M)	TIME (MILLISEC)	TOTAL Q (GRAMS)	SY (M)	SZ (M)	TRAV. D. (KM)	KEYP
1	139.998	5242.374	113.471	70000	72000.00	445.491	269.076	5.042	1
2	359.998	4751.523	113.471	180000	60000.00	406.437	245.068	4.552	1
3	539.998	4349.918	113.471	270000	48000.00	374.129	225.262	4.150	1
.									
.									
.									
29	2319.999	378.492	113.471	1160000	12000.00	21.965	13.362	0.178	1
30	2359.999	289.246	113.471	1180000	12000.00	11.953	7.468	0.089	1
31	2399.999	200.001	113.471	1200000	12000.00	1.000	1.000	0.000	1

Figure 12. (continued)

1200 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 0 TO 1200 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	1.353E-04
1.650	1.350	0.000	1.667E-04
2.000	1.500	0.000	2.165E-05
2.350	1.350	0.000	1.211E-08
1.080	1.380	0.000	1.803E-04
1.300	1.700	0.000	2.208E-04
2.000	2.000	0.000	3.692E-06
2.700	1.700	0.000	0.000E-01

Average concentrations at each receptor are printed at the end of each meteorological period.

*** I N F O R M A T I O N F O R S O U R C E N U M B E R 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 1200 SECONDS EAST (KM)	NORTH (KM)
.600E+03	30.00	390.000	15.000	2.000	0.000	2.400	0.200

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
2.000	45.0	100.17	1.0	1.0	0.00	0.00

Next meteorological period. Source parameters and meteorology are different from the previous period.

*** M E T E O R O L O G Y ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
170.0	4.000	3000.	0.150	4	5.652	288.0	0.0670	0.0470

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
1200	2400	1200	12.000	0.50	0.750

Figure 12. (continued)

PUFF#	X (M)	Y (M)	Z (M)	TIME (MILLISEC)	TOTAL Q (GRAMS)	SY (M)	SZ (M)	TRAV. D. (KM)	KEYP
1	202.338	9154.611	113.471	690000	96000.00	557.316	249.356	9.058	1
2	502.338	8485.274	113.471	840000	84000.00	508.543	219.018	8.388	1
3	742.338	7949.803	113.471	960000	60000.00	468.597	195.082	7.853	1
.									
.									
.									
45	4039.568	1996.691	100.167	2376000	7200.00	11.662	6.484	0.136	1
46	4068.315	1946.873	100.167	2388000	7200.00	6.552	3.967	0.068	1
47	4097.062	1897.055	100.167	2400000	7200.00	1.000	1.000	0.000	1

1200 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 1200 TO 2400 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	1.129E-07
1.650	1.350	0.000	7.536E-06
2.000	1.500	0.000	1.231E-04
2.350	1.350	0.000	1.310E-05
1.080	1.380	0.000	3.230E-10
1.300	1.700	0.000	1.912E-06
2.000	2.000	0.000	1.771E-04
2.700	1.700	0.000	1.284E-05

Average concentrations for the second meteorological period.

Length of simulation time

****

0.67 HR AVG. CONCENTRATION AT RECEPTORS FOR ALL SIMULATION PERIODS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	6.769E-05
1.650	1.350	0.000	8.711E-05
2.000	1.500	0.000	7.237E-05
2.350	1.350	0.000	6.555E-06
1.080	1.380	0.000	9.016E-05
1.300	1.700	0.000	1.114E-04
2.000	2.000	0.000	9.040E-05
2.700	1.700	0.000	6.421E-06

Average concentrations at each receptor over the modeling period.

Figure 12. (continued)

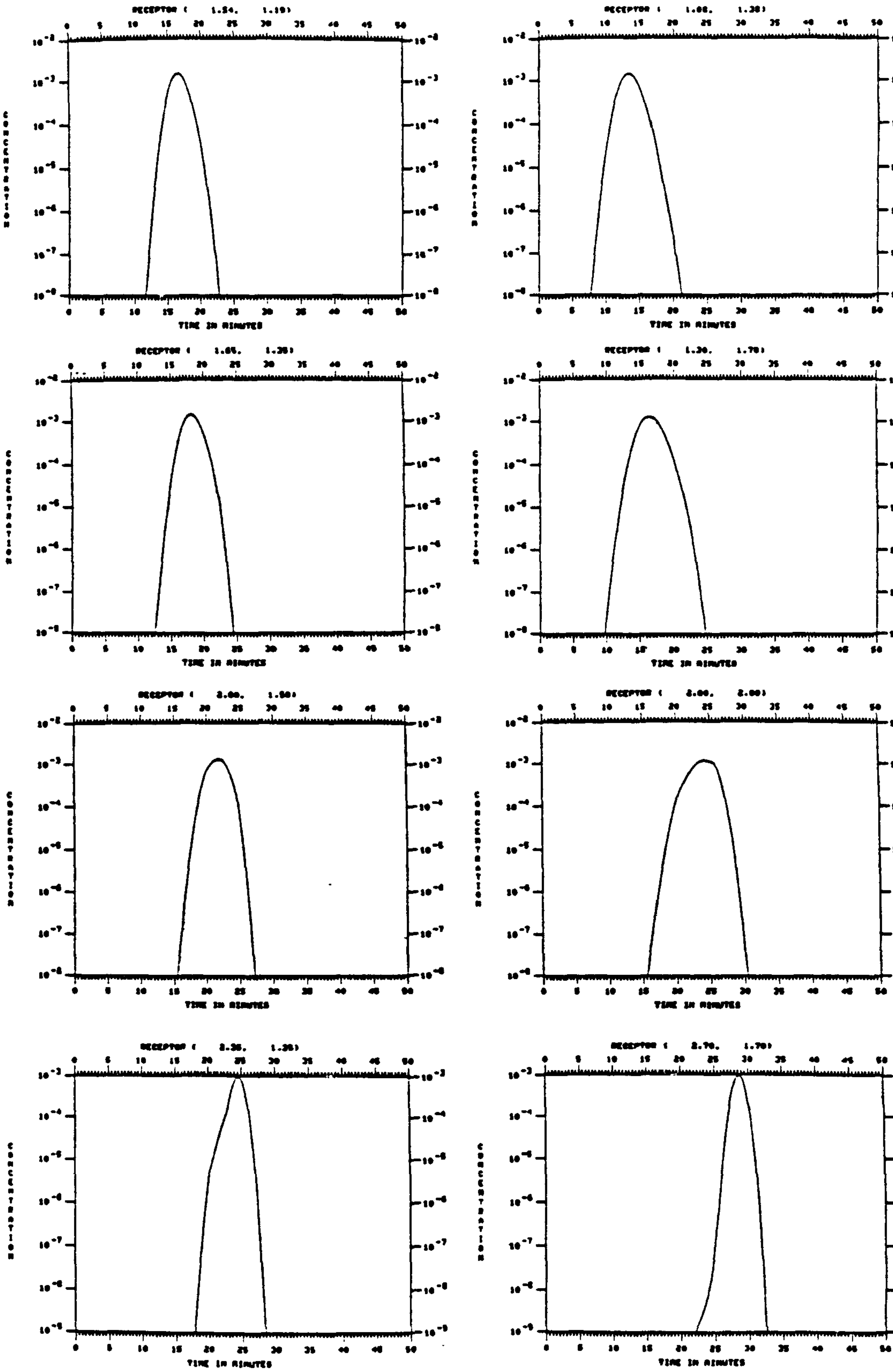

Figure 13. Concentration versus time plots for example 1.

EXAMPLE 2 -- LOW LEVEL SOURCE WITH LOW WIND SPEED CONDITIONS

This problem illustrates the model simulation for a low level release during conditions of light and variable winds. The input data stream is shown in Table 10 and the abridged output in Figure 14. A very important difference between this example and the previous example is that for this example KEYDSP on record 2 has been assigned a value of 2. Dispersion downwind of the source is no longer characterized by travel distance but by travel time using the on-site dispersion scheme. The values assigned to σ_a and σ_e are not used in the P-G characterization of dispersion. However, in the on-site scheme, σ_y and σ_z are functions of σ_a and σ_e.

In this example, twelve simulation periods of 10-minute duration are used to simulate the 2-hour release. The atmosphere is stable with large fluctuations in the wind direction. σ_a has been assigned a large value, typical of low wind speed conditions. The strength of the source is decaying with time; initially the source strength is 825 g/sec, but by the 12th period it has dropped to 12 g/sec.

In this simulation, average concentrations at each receptor are printed every 10 minutes. The puff locations at the end of each 10 minute period are plotted in Figure 15. The input data for the plot program are shown below:

Input Data Record	Data
1	2
2	0., 0., 5., 5., 5., 5.

Circles drawn around the centers of the puff positions have a radius equal to σ_r.

TABLE 10. INPUT DATA FOR EXAMPLE 2

Record	Record type
EXAMPLE 2 LOW LEVEL SOURCE LOW WIND SPEED	1
6,F,F,2,1000.,F,F	2
0.,0.,25.,15.	3
12,600,1,10	4
1.54,1.19,0.	5
1.65,1.35,0.	5
2.,1.5,0.	5
2.35,1.35,0.	5
2.46,1.19,0.	5
1.08,1.38,0.	5
1.3,1.7,0.	5
2.,2.,0.	5
2.7,1.7,0.	5
2.92,1.38,0.	5
F,F,F,F,T	8
-1,300,0,1.,10.	9
180. .5 5000. 6 .035 .393 290. .5	10
210. .5 5000. 6 .035 .393 290. .5	10
175. .5 5000. 6 .035 .393 290. .5	10
145. .5 5000. 6 .035 .393 290. .5	10
155. .5 5000. 6 .035 .393 290. .5	10
210. .5 5000. 6 .035 .393 290. .5	10
200. .5 5000. 6 .035 .393 290. .5	10
182. .5 5000. 6 .035 .393 290. .5	10
170. .5 5000. 6 .035 .393 290. .5	10
195. .5 5000. 6 .035 .393 290. .5	10
185. .5 5000. 6 .035 .393 290. .5	10
195. .5 5000. 6 .035 .393 290. .5	10
2.,1.,12,600,0.,0.	11
825.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
562.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
383.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
261.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
178.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
121.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
83.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
56.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
38.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
26.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
18.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12
12.,3.,290.,.5,10.,0.,1.,1.,0.,0.	12

```
               INPUFF 2.0   MULTIPLE SOURCE INTEGRATED PUFF MODEL (DATED 86128)
                 AN AIR QUALITY DISPERSION MODEL IN
                 SECTION 2. NON-GUIDELINE MODELS,
                 IN UNAMAP (VERSION 6) JUL 86.
                 SOURCE: UNAMAP FILE ON EPA'S UNIVAC 1110, RTP, NC.


    EXAMPLE 2    LOW LEVEL SOURCE LOW WIND SPEED


               INPUFF 2.0    MULTIPLE SOURCE INTEGRATED PUFF MODEL

M O D E L   O P T I O N S          A "T" INDICATES THAT
                           THE OPTION HAS BEEN EXERCISED

USER SUPPLIED WIND FIELD        F
UNIT 22 OUTPUT OPTION           F
PRINT PUFF INFORMATION          F
INTERMEDIATE CONCENTRATIONS     F

DISPERSION CALCULATED USING IRWIN, ET. AL. (TIME DEPENDENT) SIGMA CURVES,
WITH TRANSITION TO DRAXLER'S LONG RANGE TRANSPORT SIGMA-Y AT SYMAX =    1000.0 METERS.


                B E G I N   A N A L Y S I S   O F   S O U R C E   N U M B E R   1

S O U R C E   O P T I O N S         A "T" INDICATES THAT
                             THE OPTION HAS BEEN EXERCISED

STACK DOWNWASH                  F
BUOYANCY INDUCED DISPERSION     F
DEPOSITION AND SETTLING         F
USER PLUME RISE                 F
PERFORM PUFF COMBINATIONS       T


I N P U T   P A R A M E T E R S

SOURCE UPDATE INTERVAL =    600 SECONDS.   (-1 INDICATES NO UPDATE)
START CONCENTRATION CALCULATIONS AT TIME =      0 SECONDS.
ANEMOMETER HEIGHT =  10.0 METERS.
```

Figure 14. Annotated output of example 2.

*** I N F O R M A T I O N   F O R   S O U R C E   N U M B E R   1   ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 0 SECONDS EAST (KM)	NORTH (KM)
.825E+03	3.00	290.000	10.000	0.500	0.000	2.000	1.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	12.33	1.0	1.0	0.00	0.00

*** M E T E O R O L O G Y ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
180.0	0.500	5000.	0.350	6	0.538	290.0	0.3930	0.0350

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
0	600	600	150.000	0.50	1.000

600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 0 TO 600 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	0.000E-01
1.650	1.350	0.000	0.000E-01
2.000	1.500	0.000	1.025E-09
2.350	1.350	0.000	0.000E-01
2.460	1.190	0.000	0.000E-01
1.080	1.380	0.000	0.000E-01
1.300	1.700	0.000	0.000E-01
2.000	2.000	0.000	0.000E-01
2.700	1.700	0.000	0.000E-01
2.920	1.380	0.000	0.000E-01

Figure 14. (continued)

*** INFORMATION FOR SOURCE NUMBER 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 600 SECONDS EAST (KM)	NORTH (KM)
.562E+03	3.00	290.000	10.000	0.500	0.000	2.000	1.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	12.33	1.0	1.0	0.00	0.00

*** METEOROLOGY ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
210.0	0.500	5000.	0.350	6	0.538	290.0	0.3930	0.0350

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
600	1200	600	150.000	0.50	1.000

600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 600 TO 1200 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	0.000E-01
1.650	1.350	0.000	3.022E-08
2.000	1.500	0.000	8.054E-04
2.350	1.350	0.000	2.110E-04
2.460	1.190	0.000	1.214E-06
1.080	1.380	0.000	0.000E-01
1.300	1.700	0.000	0.000E-01
2.000	2.000	0.000	6.353E-08
2.700	1.700	0.000	5.249E-09
2.920	1.380	0.000	0.000E-01

Figure 14. (continued)

*** I N F O R M A T I O N F O R S O U R C E N U M B E R 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 1200 SECONDS EAST (KM)	NORTH (KM)
.383E+03	3.00	290.000	10.000	0.500	0.000	2.000	1.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	12.33	1.0	1.0	0.00	0.00

*** M E T E O R O L O G Y ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
175.0	0.500	5000.	0.350	6	0.538	290.0	0.3930	0.0350

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
1200	1800	600	150.000	0.50	1.000

600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 1200 TO 1800 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	3.225E-09
1.650	1.350	0.000	2.005E-06
2.000	1.500	0.000	6.034E-03
2.350	1.350	0.000	6.528E-04
2.460	1.190	0.000	4.198E-06
1.080	1.380	0.000	0.000E-01
1.300	1.700	0.000	2.225E-09
2.000	2.000	0.000	1.531E-03
2.700	1.700	0.000	6.928E-06
2.920	1.380	0.000	4.182E-10

Output is abridged. The following meteorological periods are missing from the sample output:

1800 to 2400 sec,
2400 to 3000 sec,
3000 to 3600 sec,
3600 to 4200 sec,
4200 to 4800 sec,
4800 to 5400 sec,
5400 to 6000 sec, and
6000 to 6600 sec.

(Eight meteorology periods have been deleted from output listing)

Figure 14. (continued)

*** INFORMATION FOR SOURCE NUMBER 1 ***

SOURCE STRENGTH (G/SEC)	STACK HEIGHT (M)	STACK TEMP. (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (M)	VOLUME FLOW (M**3/SEC)	COORD. AT TIME 6600 SECONDS EAST (KM)	NORTH (KM)
.120E+02	3.00	290.000	10.000	0.500	0.000	2.000	1.000

SOURCE SPEED (M/SEC)	SOURCE DIRECTION (DEG)	PLUME HEIGHT (M)	INITIAL SIGMAS (R) (M)	(Z)	DEPOSITION VELOCITY (CM/SEC)	SETTLING VELOCITY (CM/SEC)
0.000	0.0	12.33	1.0	1.0	0.00	0.00

Source strength has decayed to 12 g/sec from an original value of 825 g/sec.

*** METEOROLOGY ***

WIND DIR. (DEG)	WIND SPD. (M/SEC)	MIXING HGT. (M)	PROF.EP (DIMEN)	STABILITY (CLASS)	U PLUME (M/SEC)	TEMP (K)	SIGMA TH. (RAD.)	SIGMA PH. (RAD.)
195.0	0.500	5000.	0.350	6	0.538	290.0	0.3930	0.0350

SIMULATION PERIOD START (SEC)	STOP (SEC)	SIMULATION TIME (SEC)	PUFF RELEASE RATE (SEC)	SOURCE RECEPTOR DISTANCE (KM)	PUFF COMB. CRITERION (SIGMAS)
6600	7200	600	150.000	0.50	1.000

600 SEC AVG. CONCENTRATION AT RECEPTORS FOR SIMULATION PERIOD 6600 TO 7200 SECONDS
DUE TO SOURCE NUMBER 1

RECEPTORS X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	5.131E-10
1.650	1.350	0.000	1.620E-07
2.000	1.500	0.000	2.718E-04
2.350	1.350	0.000	1.032E-05
2.460	1.190	0.000	5.629E-08
1.080	1.380	0.000	0.000E-01
1.300	1.700	0.000	7.123E-08
2.000	2.000	0.000	2.102E-03
2.700	1.700	0.000	5.161E-06
2.920	1.380	0.000	1.074E-09

Figure 14. (continued)

* *
2.00 HR AVG. CONCENTRATION AT RECEPTORS FOR ALL SIMULATION PERIODS
DUE TO SOURCE NUMBER 1

RECEPTORS			
X (KM)	Y (KM)	Z (M)	CONCENTRATION (G/M**3)
1.540	1.190	0.000	5.101E-06
1.650	1.350	0.000	2.546E-04
2.000	1.500	0.000	2.277E-03
2.350	1.350	0.000	1.329E-04
2.460	1.190	0.000	1.133E-06
1.080	1.380	0.000	5.812E-08
1.300	1.700	0.000	9.711E-05
2.000	2.000	0.000	1.048E-02
2.700	1.700	0.000	1.717E-05
2.920	1.380	0.000	5.186E-09

Figure 14. (continued)

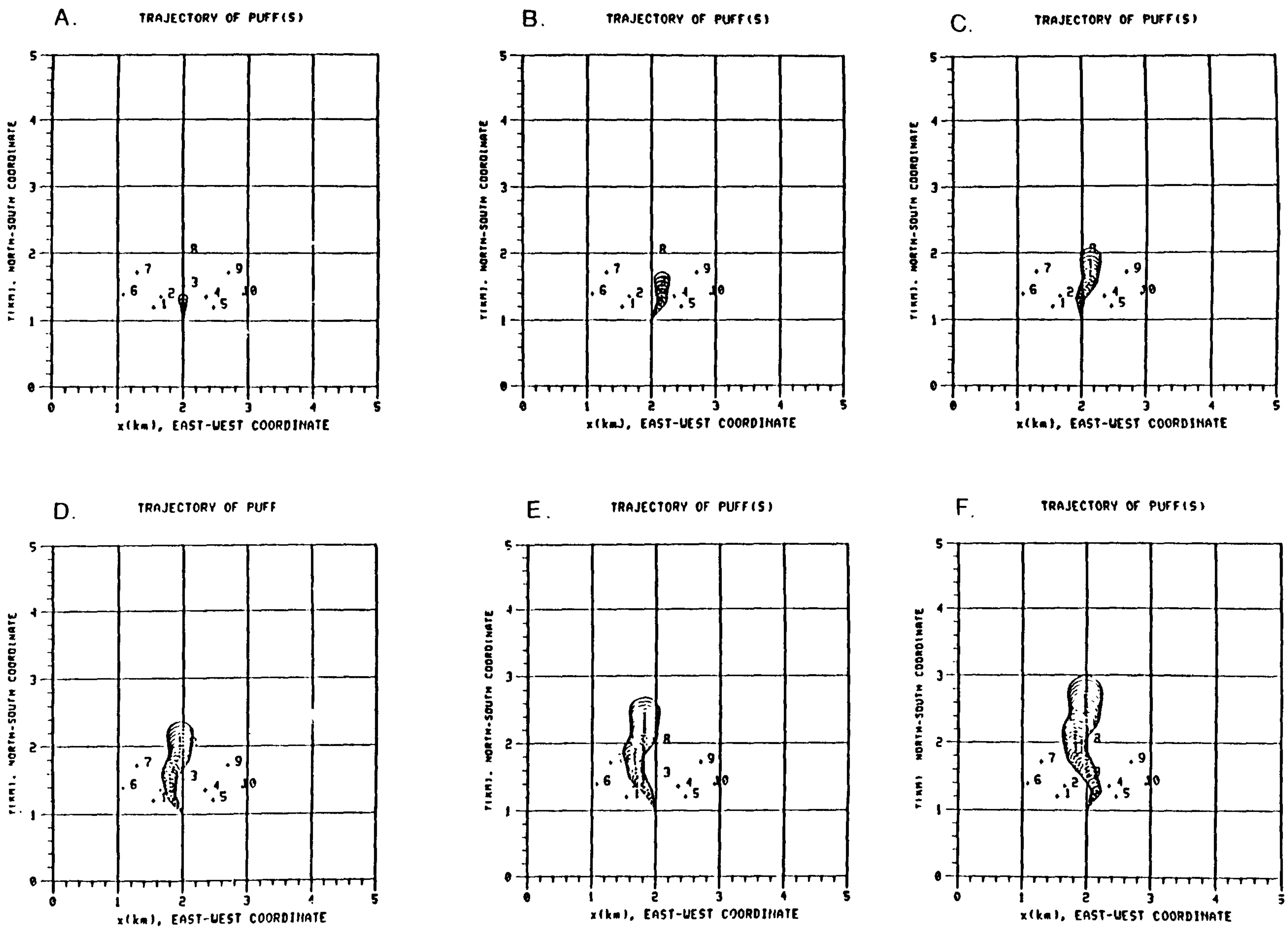

Figure 15. Puff locations at the end of each simulation period.
A - L represents 10-minute intervals

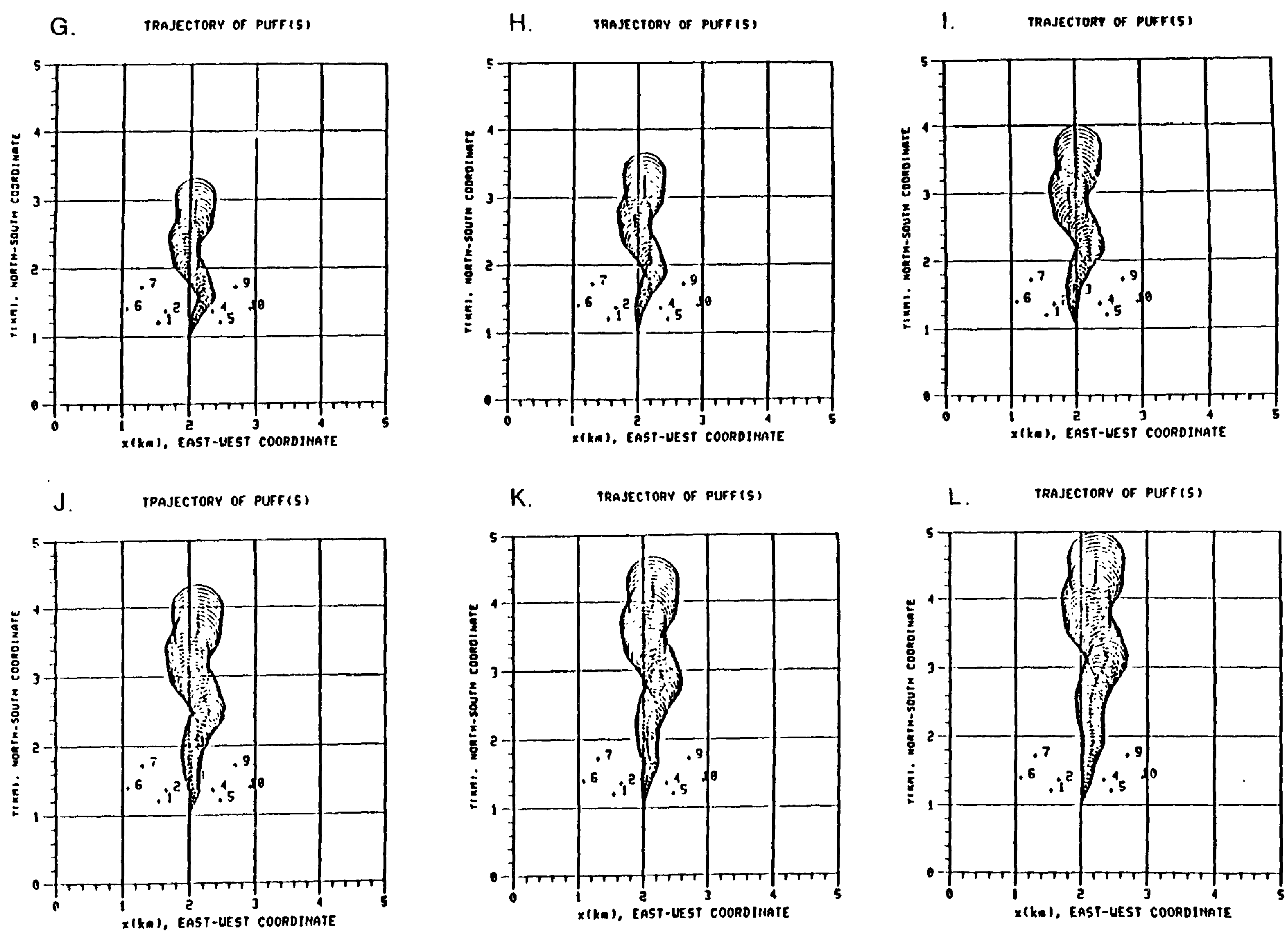

Figure 15. (continued)

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APPENDIX A
PLUME RISE

The use of the methods of Briggs to estimate plume rise and effective height of emission are discussed below. In all calculations, it is assumed that actual or estimated wind speed at stack top, u(h), is available.

STACK DOWNWASH

To consider stack downwash, the physical stack height is modified following Briggs (1973, p. 4). The h' is found from

$$h' = h + 2\{[v_s/u(h)] - 1.5\}d \qquad \text{for} \quad v_s < 1.5u(h), \qquad \text{(A-1)}$$

$$h' = h \qquad \text{for} \quad v_s \geq 1.5u(h),$$

where h is physical stack height (meters), v_s is stack gas velocity (meters per second), and d is inside stack-top diameter (meters). The h' is used throughout the plume height computation. If stack downwash is not considered, h' = h in the equations.

BUOYANCY FLUX

For most plume rise calculations, the value of the Briggs buoyancy flux parameter, F (m^4/s^3), is needed. The following equation is equivalent to Briggs' Eq. 12 (1975, p. 63):

$$F = (gv_s,d^2\Delta T)/(4T_s), \qquad \text{(A-2)}$$

where $\Delta T = T_s - T$, T_s is stack gas temperature (degrees kelvin), and T is ambient air temperature (degrees kelvin).

UNSTABLE OR NEUTRAL: CROSSOVER BETWEEN MOMENTUM AND BUOYANCY

For cases with stack gas temperature greater than or equal to ambient air temperature, it must be determined whether the plume rise is dominated by momentum or buoyancy. The crossover temperature difference $(\Delta T)_c$ is determined for (1) F less than 55 and (2) F greater than or equal to 55. If the difference between stack gas temperature and ambient air temperature, ΔT, exceeds or equals the $(\Delta T)_c$, plume rise is assumed to be buoyancy dominated; if the difference is less than $(\Delta T)_c$, plume rise is assumed to be momentum dominated (see below).

The crossover temperature difference is found by setting Briggs' Eq. 5.2 (1969, p. 59) equal to the combination of Briggs' Eqs. 6 and 7 (1971, p. 1031) and solving for ΔT. For F less than 55,

$$(\Delta T)_c = 0.0297 v_s^{1/3} T_s/d^{2/3}. \qquad \text{(A-3)}$$

For F equal to or greater than 55,

$$(\Delta T)_c = 0.00575 v_s^{2/3} T_s/d^{1/3}. \qquad \text{(A-4)}$$

UNSTABLE OR NEUTRAL: BUOYANCY RISE

For situations where ΔT exceeds or is equal to $(\Delta T)_c$ as determined above, buoyancy is assumed to dominate. The distance to final rise x_f (in kilometers) is determined from the equivalent of Briggs' Eq. 7 (1971, p. 1031), and the distance to final rise is assumed to be 3.5x*, where x* is the distance at which atmospheric turbulence begins to dominate entrainment. For F less than 55,

$$x_f = 0.049 F^{5/8}. \qquad \text{(A-5)}$$

For F equal to or greater than 55,

$$x_f = 0.119F^{2/5}. \tag{A-6}$$

The plume height, H (in meters), is determined from the equivalent of the combination of Briggs' Eqs. 6 and 7 (1971, p. 1031). For F less than 55,

$$H = h' + 21.425F^{3/4}/u(h), \tag{A-7}$$

and for F equal to or greater than 55,

$$H = h' + 38.71F^{3/5}/u(h). \tag{A-8}$$

UNSTABLE OR NEUTRAL: MOMENTUM RISE

For situations where the stack gas temperature is less than the ambient air temperature, it is assumed that the plume rise is dominated by momentum. Also, if ΔT is less than $(\Delta T)_c$ from Eq. A-3 or A-4, it is assumed that the plume rise is dominated by momentum. The plume height is calculated from Briggs' Eq. 5.2 (1969, p. 59):

$$H = h' + 3dv_s/u(h). \tag{A-9}$$

Briggs (1969) suggests that this equation is most applicable when v_s/u is greater than 4. Since momentum rise occurs quite close to the point of release, the distance to final rise is set equal to zero.

STABILITY PARAMETER

For stable situations, the stability parameter s is calculated from the following equation (Briggs, 1971, p. 1031):

$$s = g(\partial\theta/\partial_z)/T. \quad \text{(A-10)}$$

As an approximation, for stability class E, $\partial\theta/\partial z$ is taken as 0.02 K/m, and for stability class F, $\partial\theta/\partial z$ is taken as 0.035 K/m.

STABLE: CROSSOVER BETWEEN MOMENTUM AND BUOYANCY

For cases with stack gas temperature greater than or equal to ambient air temperature, it must be determined whether the plume rise is dominated by momentum or buoyancy. The crossover temperature difference $(\Delta T)_c$ is found by setting Briggs' Eq. 59 (1975, p. 96) equal to Briggs' Eq. 4.28 (1969, p. 59), and solving for ΔT. The result is

$$(\Delta T)_c = 0.019582 v_s \; T \; s^{1/2}. \quad \text{(A-11)}$$

If the difference between stack gas temperature and ambient air temperature (ΔT) exceeds or equals $(\Delta T)_c$, the plume rise is assumed to be buoyancy dominated; if ΔT is less than $(\Delta T)_c$, the plume rise is assumed to be momentum dominated.

STABLE: BUOYANCY RISE

For situations where ΔT is greater than or equal to $(\Delta T)_c$, buoyancy is assumed to dominate. The distance to final rise (in kilometers) is determined by the equivalent of a combination of Briggs' Eqs. 48 and 59 (1975, p. 96):

$$x_f = 0.0020715 u(h) s^{-1/2}. \quad \text{(A-12)}$$

The plume height is determined by the equivalent of Briggs' Eq. 59 (1975, p. 96):

$$H = h' + 2.6 \{F/[u(h)s]\}^{1/3}. \quad \text{(A-13)}$$

The stable buoyancy rise for calm conditions (Briggs, 1975, pp. 81-82) is also evaluated:

$$H = h' + 4F^{1/4}s^{-3/8}. \qquad \text{(A-14)}$$

The lower of the two values obtained from Eqs. A-13 and A-14 is taken as the final effective height.

By setting Eqs. A-13 and A-14 equal to each other and solving for u(h), one can determine the wind speed that yields the same plume rise for the wind conditions (A-13) as does the equation for calm conditions (A-14). This wind speed is

$$u(h) = (2.6/4)^3 F^{1/4} s^{1/8}$$

$$= 0.2746 F^{1/4} s^{1/8}. \qquad \text{(A-15)}$$

For wind speed less than or equal to this value, Eq. A-14 should be used for plume rise; for wind speeds greater than this value, Eq. A-13 should be used.

STABLE: MOMENTUM RISE

When the stack gas temperature is less than the ambient air temperature, it is assumed that the plume rise is dominated by momentum. If ΔT is less than $(\Delta T)_c$ as determined by Eq. A-11, it is also assumed that the plume rise is dominated by momentum. The plume height is calculated from Briggs' Eq. 4.28 (1969, p. 59):

$$H = h' + 1.5\{(v_s^2\ d^2 T)/[4T_s u(h)]\}^{1/3}\ s^{-1/6}. \qquad \text{(A-16)}$$

The equation for unstable or neutral momentum rise (A-9) is also evaluated. The lower result of these two equations is used as the resulting plume height.

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APPENDIX B
SETTLING AND DEPOSITION VELOCITIES

This appendix is a reproduction of Appendix B in Rao, (1982).

APPENDIX B

SETTLING AND DEPOSITION VELOCITIES

For a monodisperse particulate cloud, the individual particles have a constant gravitational settling velocity. This terminal velocity is given by Stokes' equation (Fuchs, 1964):

$$W = \frac{d^2 \, g \, \rho}{18 \, \mu} \qquad \text{(B-1)}$$

where d is the diameter of the particle, g is acceleration due to gravity, ρ is density of particles, and μ is the dynamic viscosity of air. For d > 100 µm, the terminal fall velocity is sufficiently great that turbulence in the wake of the particle cannot be neglected, and the viscous drag force F_d on the particle is greater than given by the Stokes' law, $F_d = 3\pi d \mu W$. For a particle with d = 400 µm, the actual value of W is about one-third the value given by Eq. (B-1). Stokes' expression for the drag force describes the effects of collisions between air molecules and a particle, assuming air to be a continuum. This assumption is not valid for very small particles, since the mean free path between molecular collisions is comparable to the particle size; under these conditions "slippage" occurs, and the particles undergo Brownian motion and diffusion, which give a terminal velocity greater than that predicted by Eq. (B-1). A discussion of the slip correction factor for the Stokes' equation can be found in Fuchs (1964) and Cadle (1975).

The values for the terminal gravitational settling velocities for different particulate materials are given in a tabular form by Lapple (1961) based on particle diameter and Reynolds number. These values, which account for the deviations from Stokes' equation discussed above, are given for spherical particles with a specific gravity of 2.0 in air at 25°C and 1 atm. pressure. This table has been reprinted in Sheely et al (1969) and Stern (1976).

The dry deposition pollutant-removal mechanisms at the earth's surface include gravitational settling, turbulent and Brownian diffusion, chemical absorption, inertial impaction, thermal, and electrical effects. Some of the deposited particles may be re-released into the atmosphere by mechanical resuspension. Following the concept introduced by Chamberlain (1953), particle removal rates from a polluted atmosphere to the surface are usually described by dry deposition velocities which vary with particle size, surface properties (including surface roughness (z_o) and moisture), and meteorological conditions. The latter include wind speed and direction, friction velocity (u_*), and thermal stratification of the atmosphere. Deposition velocities for a wide variety of substances and surface and atmospheric conditions may be obtained directly from the literature (e.g., McMahon and Denison, 1979; Sehmel, 1980). Sehmel and Hodgson (1974) gave plots relating deposition velocity (V_d) to d, z_o, u_*, and the Monin-Obukhov stability length.

Considerable care needs to be exercised in choosing a representative deposition velocity since it is a function of many factors and can vary by two orders of magnitude for particles. Generally, V_d should be defined relative to the height above the surface at which the concentration measurement is made. The particle deposition velocity is approximately a linear function of wind speed and friction velocity, and its minimum value occurs in the particle diameter range 0.1 - 1 μm.

In the trivial case of $W = V_d = 0$, settling and deposition effects are negligible. For very small particles ($d < 0.1$ μm), gravitational settling can be neglected, and dry deposition occurs primarily due to the nongravitational effects mentioned above. In this case, $W = 0$ and $V_d > 0$. For small particles ($d = 0.1$~50 μm), $0 < W < V_d$; deposition is enhanced here beyond that due to gravitational settling, primarily due to increased turbulent transfer resulting from surface roughness. For larger particles ($d > 50$ μm), it is generally assumed that $V_d = W > 0$, since gravitational settling is the dominant deposition mechanism. When $W > V_d > 0$, re-entrainment of the deposited particles from the surface back into the atmosphere is implied as, for example, in a dust storm. The first four sets of model parameters given above are widely used in atmospheric dispersion and deposition of particulate material. The deposition of gases is a special case of the particulate problem with $W = 0$. Thus, one has to carefully select the values of W and V_d for use in the model.

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