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USER'S GUIDE FOR PAL 2.0

A GAUSSIAN-PLUME ALGORITHM

FOR POINT, AREA, AND LINE SOURCES

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

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FOR POINT, AREA, AND LINE SOURCES

by

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NOTICE

AFFILIATION

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PREFACE

The User's Guide for PAL 2.0 was written so that one need not understand the mathematical formulation to apply the model. However, we strongly recommend that the user carefully read Sections 2, 3, 7, and 8, which give valuable insight into the model's flexibility and limitations, and the assignment of values to input parameters.

While attempts are made to thoroughly check out computer programs with a wide variety of data, errors are found occasionally, In case there is a need to correct, revise, or update this model, revisions will be distributed in the same manner as this report. If your copy was obtained by purchase or special order, you may obtain revisions as they are issued by completing the mailing form on the last page of this report.

Comments and suggestions regarding this document should be directed to Chief, Environmental Applications Branch, Meteorology and Assessment Division, (Mail Drop 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 PAL 2.0 will be contained (along with other dispersion models) in futrue 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 PAL 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 PAL 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 PAL 2.0 will be referred to as PAL. PAL 2.0 represents a significant modification to the original PAL model, (Petersen, 1978). 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 PAL. 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.

ABSTRACT

PAL is an acronym for the Point, Area, and Line source algorithm. PAL is a method of estimating short-term dispersion using Gaussian-plume steady-state assumptions. The algorithm can be used for estimating concentrations of non-reactive pollutants at 99 receptors for averaging times of from 1 to 24 hours, and for a limited number of point, area, and line sources (99 of each type).

Calculations are performed for each hour. The hourly meteorological data required are wind direction, wind speed, stability class, and mixing height. Single values of each of these four parameters are assumed representative for the area modeled. The Pasquill-Gifford or McElroy-Pooler dispersion curves are used to characterize dispersion.

This algorithm is not intended for application to entire urban areas but is intended, rather, to assess the impact on air quality, on scales of tens to hundreds of meters, of portions of urban areas such as shopping centers, large parking areas, and airports. Level terrain is assumed.

The Gaussian point source equation estimates concentrations from point sources after determining the effective height of emission and the upwind and crosswind distance of the source from the receptor.

Numerical integration of the Gaussian point source equation is used to determine concentrations from the four types of line sources. Subroutines are included that estimate concentrations for multiplelane line and curved path sources, special line sources (line sources with endpoints at different heights above ground), and special curved path sources.

Integration over the area source which includes edge effects from the source region is done by considering finite line sources perpendicular to the wind at intervals upwind from the receptor. The crosswind integration is done analytically; integration upwind is done numerically by successive approximations.

The PAL model can treat deposition of both gaseous and suspended particulate pollutants in the plume since gravitational settling and dry deposition of the particles are explicitly accounted for. The analytical diffusion-deposition expressions (Rao, 1982) listed in this report are easy to apply and, in the limit when pollutant settling and deposition velocities are zero, they reduce to the usual Gaussian plume diffusion algorithms.

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SYMBOLS & ABBREVIATIONS

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

- a - acceleration of the vehicle (l/t^2)
- d - diameter of particle (l)
- D - total line source length (l)
- D_f - surface deposition flux ($m/l^2\ t$)
- EF - emission factor (m/veh l)
- f_p - point source dispersion function
- f_c - dispersion function corrected for finite length of line source
- f - dispersion function for area sources
- h - building height (l)
- H - effective height of source emission (l)
- H_b - width of building (l)
- l - length of line (l)
- L - mixing height of inversion, top of unstable layer (l)
- N - eddy reflection number
- Q - point source emission rate (m/t)
- q_l - line source emission rate (m/t l)
- q_A - area emission rate (m/l^2)
- t - total time of travel (t)
- t_p - time of travel to a point (t)
- TV - traffic volume (veh/t)
- U - mean wind speed (l/t)
- V_d - dry deposition velocity of pollutant (l/t)
- V_L - average vehicle length (l)
- V_S - minimum vehicle speed (l/t)
- V_p - vehicle speed at a given point (l/t)
- V_f - final vehicle speed (l/t)
- V_o - initial vehicle speed (l/t)
- W - gravitational settling velocity of pollutant particles (l/t)
- X - upwind distance from a receptor to a point on a line source (l)
- X_f - total distance of travel (l)
- X_p - distance to travel to any point, P (l)
- Y - crosswind distance from a receptor to a point on a line source (l)
- Y_A - crosswind distance of a point from the receptor (l)
- Y_B - crosswind distance of a point from the receptor (l)
- z - receptor height above ground (l)
- ρ - radius of circle (l)
- χ_p - concentration from a single point (m/l^3)
- ϕ - azimuth from circle center to intersection (radians)
- μ - dynamic viscosity of air
- σ_y - standard deviation of plume concentration distribution in the lateral (l)
- σ_z - standard deviation of plume concentration distribution in the vertical (l)
- θ - wind direction

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Bruce Turner, who was responsible for much of the development of the PAL model; to John Irwin and Alan Huber for their helpful discussions and review. Much credit for PAL 2.0 also belongs to Dr. Shankar Rao and TRC for their development of PAL-DS and PALU respectively. Portions of this text were excerpted from the PAL and PAL-DS user's guides.

EXECUTIVE SUMMARY

The Point Area Line source computer algorithm is designed to simulate dispersion from continuous releases of six source types. The algorithm is based upon Gaussian plume assumptions including a vertically uniform wind direction field and no chemical reactions. PAL can provide concentration estimates at up to 99 receptor locations.

The model requires hourly input of wind direction and speed, stability class, mixing height and ambient air temperature. Source parameters include physical stack height above ground, stack top inside diameter, stack gas temperature, exit velocity and pollutant emission rate. Line source information include number of lanes of traffic, vehicle speeds and line source emission rates.

PAL 2.0 incorporates two major enhancements from previous versions of PAL. Rao (1982) provided an analytical solution of a gradient- transfer model for dry deposition of gaseous and particulate pollutants which was included in a version of PAL called PAL-DS. The deposition and gravitational settling algorithm are included in PAL 2.0. The other major enhancement is the inclusion of urban diffusion coefficients.

Features of the PAL computer code include:

- Wind speed extrapolated to release heights,
- Removal through gravitational settling and deposition,
- Optional control to include average concentrations,
- Optional control to include diurnal variation in emissions, and
- Optional control to include urban diffusion coefficients.

SECTION 1
INTRODUCTION

PAL is a multisource Gaussian-Plume atmospheric dispersion algorithm for estimating concentrations of non-reactive pollutants. Concentration estimates are based on hourly meteorology, and averages can be computed for averaging time from 1 to 24 hours. Six source types are included in PAL: point, area, two types of line sources, and two types of curved path sources. As many as 99 sources may be included under each source type. PAL is not intended as an urban-wide model but may be applied to estimate the contribution of part of an urban area to the concentration. Portions of urban areas assessed by PAL for impact on air quality are:

- o Industrial complexes
- o Sports stadiums
- o Parking lots
- o Shopping areas
- o Airports

At the heart of PAL is the Gaussian-Plume point source equation (Gifford, 1960). The equation is used directly in the computations for point, line, and curved path sources, and in a modified form for area sources. A unique feature of PAL is the computational technique for estimating the concentration from area sources. This technique incorporates edge effects and is theoretically more accurate than the methods used in the Climatological Dispersion Model (CDM) (Busse and Zimmerman, 1973) and the Air Quality Display Model (AQDM) (Martin, 1971). The horizontal line source algorithm is similar to the Highway Air Pollution Model (HIWAY) (Zimmerman and Thompson, 1975). Input source types also include two types of curved paths, one of which considers variation of emissions along the path. PAL will also estimate concentrations from a line source which has a variation in emission along the source. This line source may be slanted or elevated relative to the ground. PAL offers considerable flexibility to the user. Any or all of the six source subroutines may be utilized. The user also has the options of employing an hourly variation to emission rates and of allowing the wind speed to change with height. Concentration estimates can be made at up to 99 user specified receptor locations.

Rao (1982) gave analytical solutions of a gradient-transfer model for dry deposition of gaseous and particulate pollutants from a plume. These new diffusion-deposition algorithms were presented as analytical extensions of the Gaussian plume diffusion algorithms currently used in EPA models under various atmospheric stability and mixing conditions. The analytical gradient-transfer model treats gravitational settling and dry deposition of pollutant in a physically realistic and straightforward manner, and it is subject to the same basic assumptions and limitations associated with all Gaussian plume-type models.

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 and project directors who wish to evaluate the applicability of the model to their needs. Sections 5, 6, 9, and 10 are directed toward dispersion meteorologists or engineers who are required to become familiar with the details of the model. Finally, Sections 7 through 10 are directed toward persons responsible for implementing and executing the program.

SECTION 2

DATA-REQUIREMENTS CHECKLIST

The PAL algorithm can consider six types of sources. In any single execution, any combination of these six source types can be used. However, the maximum number of input sources for any given type cannot exceed 99. PAL requires data on user options, sources, meteorology and receptors. The user must indicate whether the following options are to be employed:

- o Integration accuracy for area and line sources,
- o Wind increase with height,
- o Control for average concentrations,
- o Option for diurnal variations in emissions,
- o Option for urban diffusion coefficients, and
- o Option for deposition and gravitational settling.

The treatment of point sources in PAL is similar to that in many other air quality simulation models. In order to calculate plume rise, the stack gas temperature in combination with stack gas volume flow, or stack inside diameter and stack gas velocity are required. Point source information consists of the following for each source:

- o Point source strength (g sec^{-1}),
- o Physical stack height (m),
- o Stack gas temperature (°K),
- o Stack gas velocity (m sec^{-1}),
- o Stack inside top diameter (m),
- o Stack gas volume flow (m^3 sec^{-1}),
- o East coordinator of stack (km),
- o North coordinate of stack (km), and
- o Initial dispersion parameters (m).

In PAL, the shape of area sources may be squares or rectangles. Boundaries must be oriented north-south and east-west. There are no special restrictions about source size. A unique feature of PAL is that negative area source strengths can be considered in order to account for smaller areas with no emission within larger area sources. Area source information consists of the following for each source:

- Area source strength (g $sec^{-1}m^{-2}$),
- Area source height (m) (assumed to be effective height.),
- East coordinate of south-west corner (km) and,
- North coordinate of south-west corner (km).

Four types of line sources can be considered in PAL. All require similar input data. Curved path sources require coordinates of three points to define the path. Special line and path sources require information on vehicle speed and size. Line source information consist of the following:

- Line source strength (g $sec^{-1}m^{-1}$),
- Line source height (m),
- Number of lanes if multilane (dimensionless),
- East coordinate of point A (km),
- North coordinate of point A (km),
- East coordinate of point B (km),
- North coordinate of point B (km),
- Initial speed of vehicles (m sec^{-1}) (at point A),
- Final speed of vehicles (m sec^{-1}) (at point B),
- Initial dispersion parameters (m),
- Gross estimate of vehicle size (m) and
- Vehicle volume (Veh/hr).

Receptors may be located at any position relative to the air pollutant sources. However, common sense should be used so that receptors are not positioned in the center of lanes of traffic, etc. The data required for each receptor consist of the east and north coordinates of the receptor and the height of the receptor above ground level. The height of a receptor is the distance of that receptor above the local ground level, not the height of the ground above some reference plane. The three receptor parameters are:

- o East coordinate of receptor (km),
- o North coordinate pf receptor (km), and
- o Height of receptor above ground (m).

The input of meteorological data for each simulated hour, up to 24 hours, follows all required source and receptor data. Care should be taken to ensure that the meteorological data are representative of the source-receptor locality. Available airport data may not be representative of an urban or suburban site. Wind speed and direction are especially sensitive to the local environment especially in the vicinity of buildings. Depending upon the nature of the problem being considered, special instrumentation may be established in the field in order to gather representative meteorological data.

Mixing height will frequently be of little importance if source-receptor distances are small. Mixing height is the top of the unstable or neutral layer near the ground. Therefore, mixing height is not used if the lowest atmospheric layer is stable. Mixing height is usually more nearly the same over larger areas than wind speed or wind direction. However, urban influences may cause the existance of a neutral layer at the surface and a mixing height at night compared to stable conditions for this period in the rural area.

The ambient air temperature is used only for the calculation of plume rise for the point sources.

Since a meteorological data card is read for each simulated hour, some additional optional data related to diurnal emission rates are included with the meteorological data. If the option is employed to vary the emission rates of the sources, a dimensionless factor for each source type is read in for each hour. The computations for each source are then multiplied by this factor using the individual emissions previously read. For example, if information indicates that for this hour the emissions from all point sources are about half the emission rates previously read in, the factor would be 0.5. Or, if the emissions are thought to be about 30 percent higher for this hour, the factor would be 1.30.

The meteorological and diurnal factor input parameters follow:

- Wind direction (deg),
- Wind speed (m sec^{-1}),
- Pasquill stability class (dimensionless),
- Mixing height (m),
- Ambient air temperature (°K),
- Diurnal variation for point sources (dimensionless),
- Diurnal variation for area sources (dimensionless),
- Diurnal variation for horizontal line sources (dimensionless),
- Diurnal variation for curved sources (dimensionless),
- Diurnal variation for specialized line sources (dimensionless), and
- Diurnal variation for specialized curved sources (dimensionless).

SECTION 3

FEATURES AND LIMITATIONS

The analysis power available to the user of PAL cannot be appreciated unless two features of the model are understood. One feature of the model concerns the handling of the wind speed. While the user is specifying the kinds of source types which will later be input in the problem, the user also specifies whether the wind speed varies as a function of height. The wind speed can be held constant or can be varied as a function of height and stability class. The manner in which the wind speed is handled within PAL is specified for each source type, allowing considerable flexibility.

A second feature of the model concerns how the emission rates from the various input sources are determined. Unlike some multisource models, such as the Real-Time Air-Quality Model (RAM) (Novak and Turner, 1976), the emissions data for each source type is input into the model only once and is not initialized for each hour of meteorology. However, as each hour of meteorology is input, the user can specifv, independently for each source type, the fractional amount of the initial input emission rate to be applied. For instance, say we had specified the maximum sulfur dioxide (SO_2) emission rate for a situation in which we had only point and area sources. From insight into the situation, we might know that the point sources contribute most during the daylight hours from factory emissions, and that the area sources contribute most during the nighttime hours from home heating. We could model the above hypothetical situation by appropriately varying the emission factors, individually for each source type, for each hour of a 24-hour period. The wind speed feature and the emission rate feature are extremely powerful when considered with the various restarting options of the program.

PAL, as other Gaussian models, is subject to Gaussian dispersion assumptions, such as conservation of mass, steady state atmospheric conditions, and relatively flat terrain. Complex aerodynamic effects, like downwash from buildings, are not considered in PAL. However, enhanced dispersion can be simulated by modifying the dispersion parameters to account for initial mixing caused by buildings. The detail which PAL considers, such as edge effects from area sources and the finite length of line sources, generally prohibits the application of PAL to an entire urban area due to excessive computer cost. Also, since meteorological data are entered hour by hour, a normal run for PAL would be to simulate a period of 1 to 24 hours. Calculations for more than several 24-hour periods would also be costly. The principal use of PAL is to estimate the increase in pollutant concentration over that due to other sources not included in the PAL computation.

PAL treats gravitational settling and dry deposition of pollutants in a physically realistic manner, and is subject to the same basic assumptions and limitations associated with Gaussian plume models. The equations used in PAL are the same as those used in PAL-DS (Rao, 1982).

In Gaussian models concentration estimates are inversely proportional to the wind speed. Besides the unreasonably high concentration estimates calculated during very low speed conditions due to this inverse relationship, there are other modeling difficulties associated with low wind speeds. Wind directions may be extremely variable. Thus, the hour average wind direction used in the model may well not be a true representation of the wind direction during the hour. The dispersion parameters used in PAL do not account for this kind of variability in the wind. Because of the extreme variability of the wind direction, actual concentrations might well be much lower than model estimates. Gaussian models also assume that there is no build-up of pollutant from hour to hour. That is, the concentration estimate made for a particular hour is independent of the concentration estimate made for the meteorology of the previous hour. However, during low wind speed conditions, pollutant build-up may occur, particularly for an urban area or a section of an urban area. A reasonable lower limit of wind speed to use as input into PAL is 1.0 m sec^{-1}.

Care must also be exercised when computing high average concentration estimates to compare with air quality standards, say for example 8 hours. It would be unrealistic to assume that a combination of wind direction, wind speed, and stability class would persist during an 8-hour period. The persistence of the above variables can be obtained from meteorological records and should be used accordingly in the model.

PAL is designed to make estimates over relatively level terrain. Receptor height should <u>not</u> be used in an attempt to simulate topographic differences. The height of the receptor is the height of that receptor above the local ground level, not the height of the ground above some reference plane.

The Pasquill-Gifford horizontal dispersion parameter values used in PAL are strictly applicable only to concentration estimates with a 3-minute averaging time (Pasquill, 1976). An increase would be expected in horizontal dispersion for averaging times of 1 hour. As on-site measurements of turbulence statistics become more routinely available and the state-of-the-art in dispersion modeling improves, PAL could be easily modified to incorporate such advances. The dispersion parameters in PAL are applicable for rural or urban environments depending on the value of IURB on card type 4.

Finally, PAL does not require any tape drives or external files for storage. Storage requirements are approximately 49K words. The example problem 1 (Section 6) used 21.6 seconds of computer time on the UNIVAC 1110.

SECTION 4
BASIS FOR PAL

The following assumptions are made: 1) Dispersion from points, and area and line elements result in Gaussian distributions in both the horizontal and vertical directions through the dispersing plume from that point or element, and therefore steady-state Gaussian plume equations can be used for point sources and the integration of these equations for line and area sources. 2) Concentration estimates may be made for each hourly period using the mean meteorological conditions appropriate for each hour. 3) The total concentration at a receptor is the sum of the concentrations estimated from all point and area sources, that is, concentrations are additive.

POINT SOURCES

The basis for the point source calculations is the point source form of the Gaussian diffusion equation. A computation is made for each source-receptor pair. The upwind distance of a source from an individual receptor is first calculated. If this distance is negative, indicating that the source is downwind of the receptor, no calculation for this source-receptor pair is needed. For positive upwind distances, the crosswind distance of the source from the receptor is also determined. Plume rise for each source is calculated once for each hourly simulation period. The plume rise is added to the physical stack height to give effective height of emission. The dispersion equation is then evaluated. The standard deviations of plume spreading are determined as functions of the Pasquill stability class and of the source-receptor distance. As each concentration from a point source at a receptor is calculated, it is added to the accumulated concentrations from point sources for that particular hour.

AREA SOURCES

The calculation of concentrations from area sources is simulated by a number of finite crosswind line sources. If all four corners of the area source have positive upwind distances from the receptor, an integration will be performed starting from the corner of minimum distance to the corner of maximum distance. If some but not all of the corners have a negative upwind distance, then the integration will be performed from an upwind distance of zero to the greatest distance. If all four corners have negative distances from the receptor, this indicates the entire area source is downwind of the receptor position. A number of crosswind (that is, perpendicular to the upwind direction) line sources at various distances from the minimum to the maximum distance are considered. Concentrations for each of these distances are calculated using the infinite line source form of the Gaussian equation. This concentration from an infinite line source is corrected for the finite extent of each individual line by considering the distance in units of σ_y of each end of the line from the upwind azimuth line through the receptor. The fraction of the area under a Gaussian curve between these limits determines the correction. An integration is performed using the concentration contribution from a number of lines and considering the distance between lines. This integration is the first estimate of the concentration from the area source. A second estimate is made by using the first estimate with additional calculations made for lines lying half-way between all the previously calculated lines. This second estimate is compared with the first and if the second falls within a set criteria the second estimate is taken as the final concentration. If the second estimate is not within the criteria, additional calculations are made, each time choosing additional lines lying half-way between lines of the previous total set.

LINE SOURCES

The calculation of concentrations from line sources is done by an integration of the point source equation in the same manner as in Zimmerman and Thompson (1975). Distances to the end points of the lines are determined in terms of upwind and crosswind distances. The line source is limited to those parts of the line which contribute concentrations to the receptor. Calculations are made for a number of points on the line, and, assuming linear change in concentration between these points, an estimate of the concentration from the line is determined. This first estimate is then compared to a second estimate, made by taking additional points between the existing ones and then assuming linear changes of concentrations between each of the adjacent points. The second estimate is compared to the first, and if it falls within a set criteria, the second estimate is taken as the concentration. If the second estimate is not within the criteria, third and subsequent estimates may be required by taking additional points. Estimates for curved sources are determined similarly by evaluating for locations on the curve and integrating. For the specilized line and curved sources, provisions are included to determine the height and emission rate for each location evaluated.

SECTION 5

TECHNICAL DESCRIPTION

These expressions are used in the discussions that follow:

$$g_1 = \exp\left(-0.5\, y^2/\sigma_y^2\right)$$

$$g_2 = \exp\left[-0.5(z-H)^2/\sigma_z^2\right] + \exp\left[-0.5(z+H)^2/\sigma_z^2\right]$$

$$g_3 = \sum_{N=-\infty}^{\infty} \left\{ \exp\left[-0.5(z-H+2NL)^2/\sigma_z^2\right] + \exp\left[-0.5(z+H+2NL)^2/\sigma_z^2\right]\right\}$$

(This infinite series converges rapidly, and evaluation with the integer, N, varying from -4 to +4 is usually sufficient.)

Where: H = effective height of emission (m),
- L = mixing height, the top of the unstable layer (m),
- y = crosswind distance (m),
- z = receptor height above ground (m),
- σ_y = standard deviation of plume concentration distribution in the lateral (m), and
- σ_z = standard deviation of plume concentration distribution in the vertical (m).

POINT SOURCE COMPUTATION

The upwind distance, X, and the crosswind distance, Y, of a point source from a receptor (see Figure 1) are given by:

$$X = (S_p - S_r)\cos\theta + (R_p - R_r)\sin\theta \qquad (1)$$

$$Y = (S_p - S_r)\sin\theta - (R_p - R_r)\cos\theta \qquad (2)$$

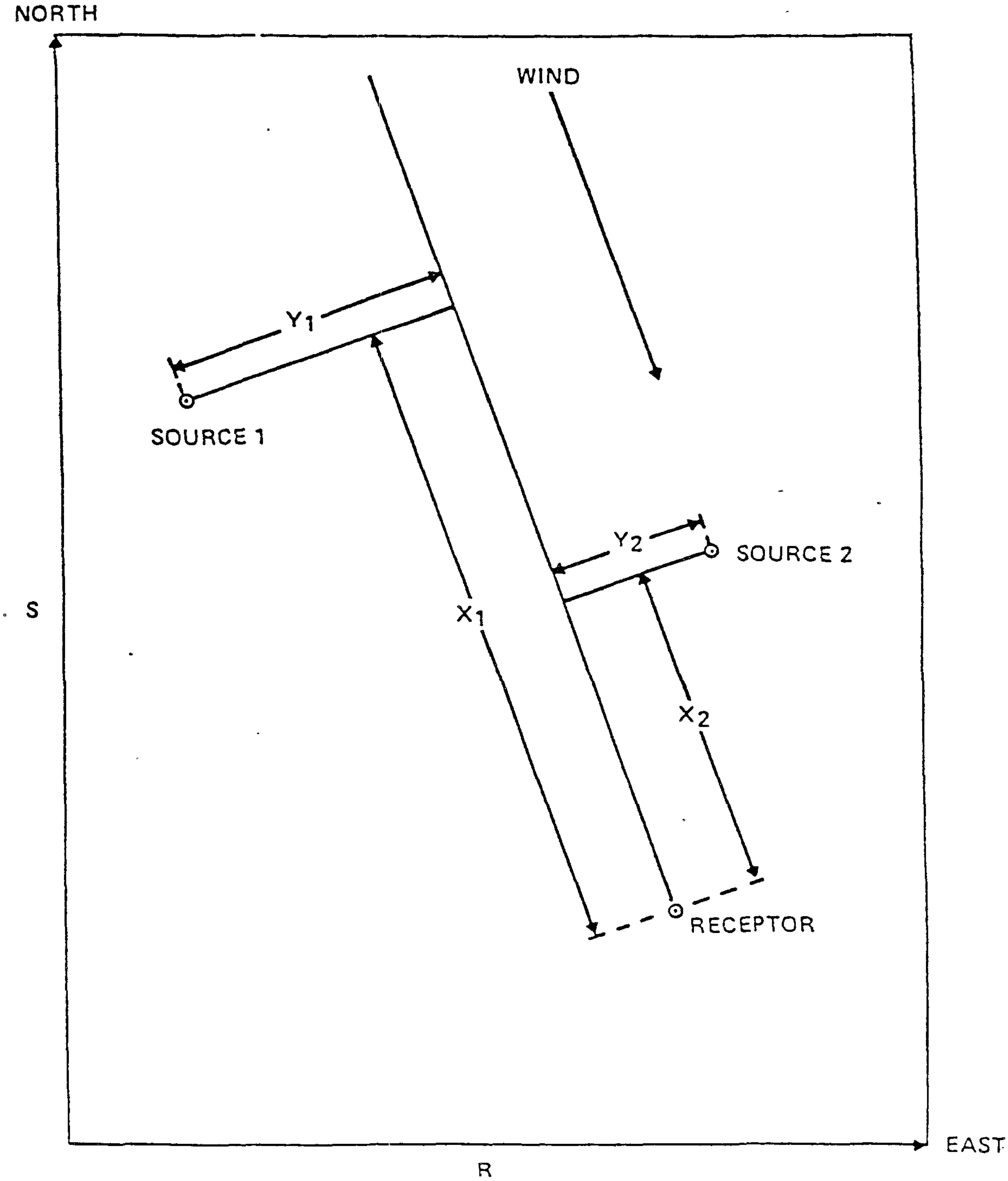

Figure 1. Upwind and crosswind distances of point sources from a receptor.

where R_p, S_p are the coordinates of the point source; R_r, S_r are the coordinates of the receptor, and θ is the wind direction (the direction from which the wind blows). The units of x and y will be the same as those of the coordinate system R, S. Frequently a conversion is required in order to express x and y in meters or kilometers.

The contribution to the concentration, χ_p, from a single point source to a receptor is given by one of the three following equations where χ_p is in g m^{-3}, Q is point source emission rate in g sec^{-1}, u is wind speed in m sec^{-1}, and σ_y and σ_z are evaluated for the upwind distance x, and the stability class.

For stable conditions or unlimited mixing:

$$\chi_p = Q\ g_1\ g_2/(2\pi\sigma_y\sigma_z u) \qquad (3)$$

In unstable or neutral conditions and if σ_z is greater than 1.6 times the mixing height, L, the distribution below the mixing height is uniform with height provided that both the effective height, H, and the receptor height, z, are below the mixing height:

$$\chi_p = Q\ g_1/[\sigma_y L u(2\pi)^{1/2}] \qquad (4)$$

(If H or z is above the mixing height, $\chi_p = 0$.)

In all other unstable or neutral conditions, that is, if σ_z is less than 1.6 times the mixing height:

$$\chi_p = Q\ g_1\ g_3/(2\pi\sigma_y\sigma_z u) \qquad (5)$$

AREA SOURCE COMPUTATIONS

Equation (1) is used to determine the upwind distance, X, of a corner of the area source with coordinates R_p, S_p from a receptor with coordinates R_r, S_r.

By evaluating X for the four corners of the area source, the maximum and minimum upward distances of the area source from the receptor are determined (see Figure 2). If the X's are negative for all four corners, indicating the entire area source is downwind, no calculation is performed. If the minimum x is negative, the minimum considered is zero, as no computations need to be performed for that portion of the area source downwind of the receptor.)

For a given upwind distance, X, from a receptor at point R_r, S_r, the north coordinate, S_L, of the intersection of a crosswind line with a north-south boundary given by $R = R_b$ is:

$$S_L = \frac{-(R_b - R_r)\sin\theta}{\cos\theta} + S_r \tag{6}$$

The coordinates of this intersection are then R_b, S_L.

Similarly, for a given upwind distance, X, from a receptor at R_r, S_r, the east coordinate, R_L, of the intersection of a crosswind line with an east-west boundary given by $S = S_b$ is:

$$R_L = \frac{x - (S_b - S_r)\cos\theta}{\sin\theta} + R_r \tag{7}$$

The coordinates of this intersection are then R_L, S_b.

Using the above relationships and special tests for $\sin\theta = 0$ and $\cos\theta = 0$, along with the equations for the four boundaries of the area source, the two intersetions (A and B) of the crosswind line and the boundaries of the area source can be found.

The two crosswind distances, Y_A and Y_B, of these points from the receptor can be found using Equation (2).

Assuming that the distances Y_A and Y_B are in km, the number of standard deviations in the Gaussian distribution of these points from the upwind azimuth

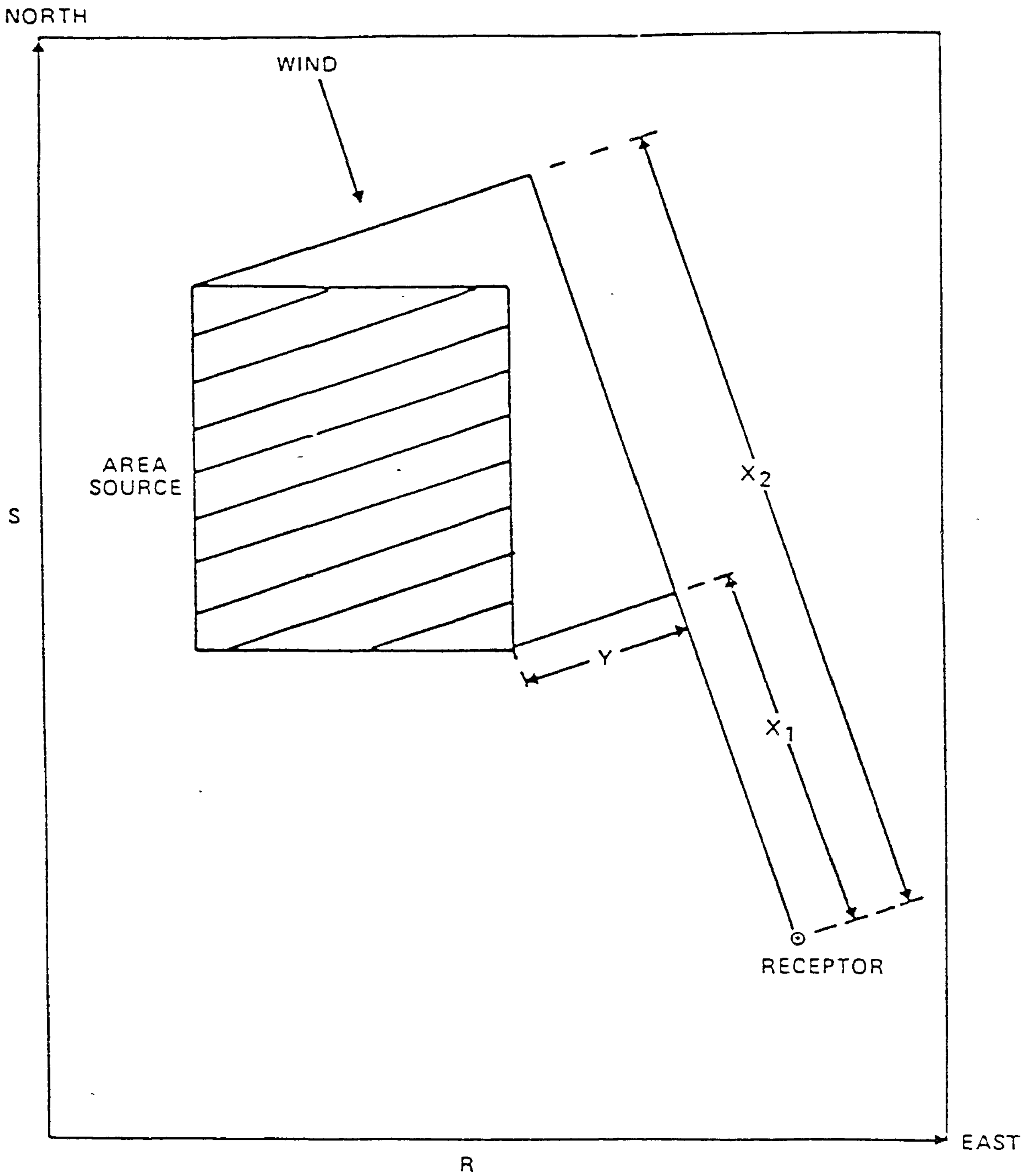

Figure 2. Minimum, X_1, and maximum, X_2, upwind distances of crosswind line sources related to an area source from a receptor.

through the receptor are given by:

$$s_A = (1000\ Y_A)\ /\ \sigma_y \qquad (8)$$

$$s_B = (1000\ Y_B)\ /\ \sigma_y \qquad (9)$$

where σ_y is in meters and is determined for the distance X and the atmospheric stability. s_A and s_B can be used to determine the fractional portion of the area under a Gaussian curve between these limits. In PAL this is accomplished by interpolating between values in a table. The values in the table are from -3.8 s to 3.8 s at intervals of 0.1 s.

To account for the finite length of the line source, the fraction determined above is used to correct the calculation for a crosswind line source, infinite in extent.

The first estimate, C_1, for the concentration, χ_A, from an area source is given by:

$$C_1 = \frac{q_A}{U}\left[\frac{f_c(X_{min})}{2} + \frac{f_c(X_{max})}{2} + \sum_{i=1}^{9} f_c\ (X_{min} + i\ \Delta\ X)\right]\Delta\ X. \qquad (10)$$

where q_A is area emission rate (g sec^{-1} m^{-2}),
U is mean wind speed (m sec^{-1}),
f_c is defined below, and
$\Delta X = (X_{max} + X_{min})\ /10$

The second estimate, C_2, for the concentration, χ_A, from an area source is given by:

$$C_2 = \frac{C_1}{2} + \frac{q_A\ \Delta X}{2U}\sum_{j=1}^{10} f_c\ (X_{min} - \Delta X/2 + j\ \Delta X) \qquad (11)$$

The second estimate is compared with the first estimate and if the ratio of the two are within a set criteria, $\chi_A = C_2$. If not, a third estimate is made, by evaluating f_c for additional lines, then comparing with the second estimate. The notation f_c means each f as defined below is corrected for the finite length of each line. The following defines the function, f, which is related to the concentration contribution from an infinite crosswind line source.

For stable conditions or unlimited mixing:

$$f = g_2 / [\ \sigma_z\ (2\pi)^{1/2}\ ] \tag{12}$$

where g_2 was defined before.

In unstable or neutral conditions and if σ_z is greater than 1.6 times the mixing height, L, the distribution below the mixing height is uniform with height provided that both the effective height, H, and the receptor height, z, are below the mixing height:

$$f = 1/L \tag{13}$$

(If H or z is above the mixing height, f = 0.)

In all other unstable or neutral conditions, that is if σ_z is less than 1.6 times the mixing height:

$$f = g_3 / [\ \sigma_z (2\pi)^{1/2}\ ] \tag{14}$$

LINE SOURCE COMPUTATIONS

The line source and receptor relationships are shown in Figure 3. Points A and B are the beginning and ending points of the line. X and Y are the

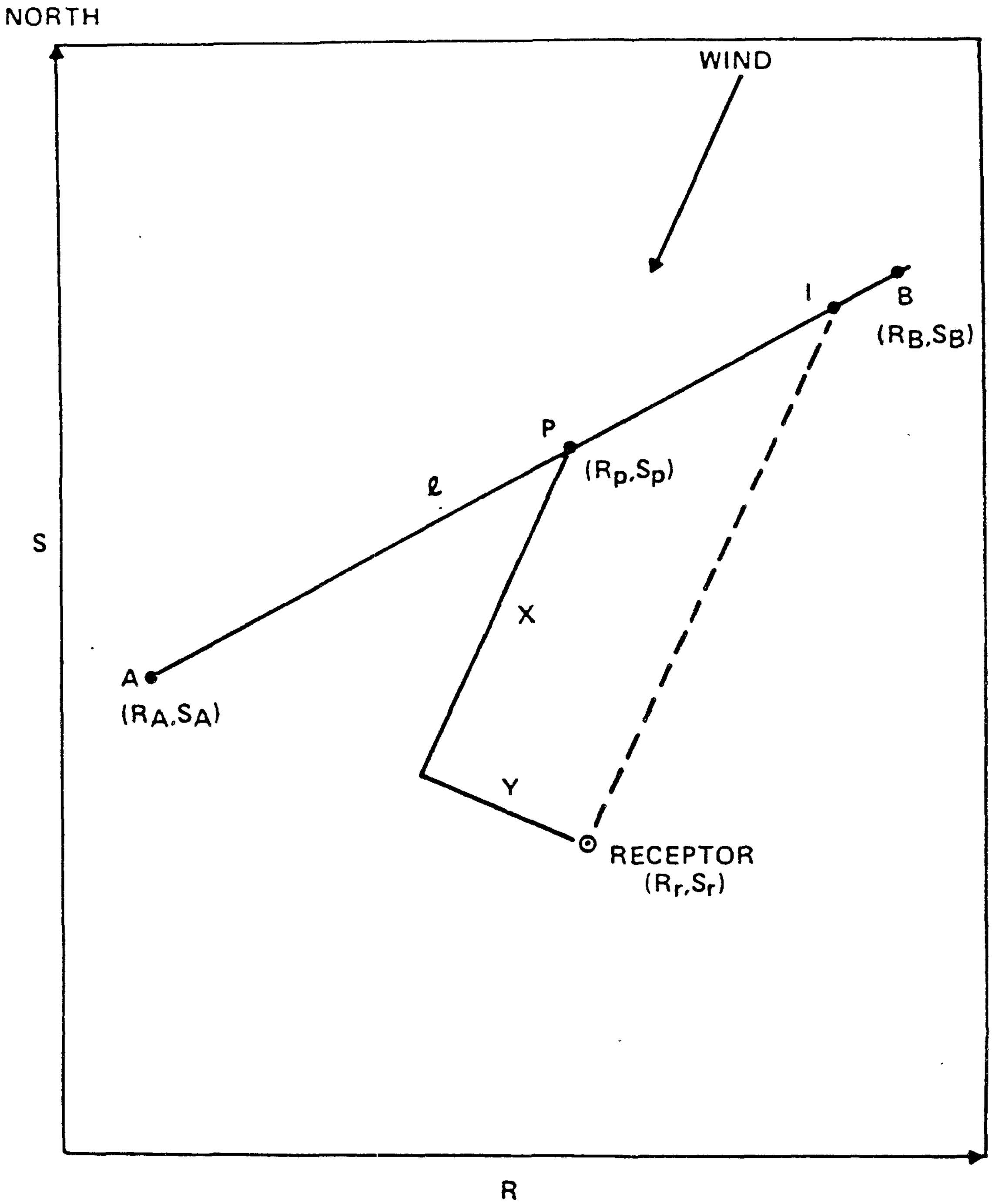

Figure 3. Line source and receptor relationships.

upwind and crosswind distances from a receptor to a point on the line source. X and Y are given by Equations (1) and (2).

R_p and S_p are the coordinates of any point on the line and are functions of length, ℓ, along the line and total length of the line, D:

$$R_p = \frac{\ell}{D} (R_B - R_A) + R_A \qquad (15)$$

$$S_p = \frac{\ell}{D} (S_B - S_A) + S_A \qquad (16)$$

Since R_p and S_p are functions of ℓ (see Figure 1), X and Y are also functions of ℓ .

The upwind distances, X, of the receptor to points A and B are calculated. If both of these X's are negative, then the line source is downwind of the receptor and the concentrations at the receptor due to the line source is zero. If either or both X's are positive, it is determined if there is a point on the line source directly upwind of the receptor. The equation for the line source is:

$$(R - R_A) \;/\; (S - S_A) = (R_B - R_A) \;/\; (S_B - S_A) \qquad (17)$$

The equation of the line through the receptor in the upwind direction is:

$$R - R_r = (S - S_r) \tan \theta \qquad (18)$$

Solve these two equations simultaneously for R and S by letting:

$$m = (R_B - R_A) \;/\; (S_B - S_A).$$

$$S = \frac{m\, S_A - S_r \tan \theta + R_r - R_A}{m - \tan \theta} \qquad (19)$$

and $$R = (S - S_r) \tan \theta + R_r \tag{20}$$

The resulting intersection R, S (see point I, Figure 3) must be tested to see if it is upwind of the receptor by testing for positive X using Equation (1), and if it lies on the line source between points A and B. If both of these conditions are met, the line source is considered to be made up of two segments: The first segment from point A to the intersection point, and the second segment from the intersection point to point B. The point directly upwind has a significant contribution to the concentration at the receptor. The line is broken into two segments so that this point will be considered in the integration estimate that follows. If there are two segments to the line source, the total concentration is given by the sum of the two concentrations from the segments.

The concentration from a line source is then given by the following equation.

$$\chi = \frac{q_\ell}{U} \int_o^D f_p \, d\ell \tag{21}$$

where:

q_ℓ = line source emission rate (g $sec^{-1} m^{-1}$),
U = wind speed (m sec^{-1})
D = line source length (m), and
f_p = point source dispersion function.

The point source dispersion function is given by one of the three following equations where σ_y and σ_z are evaluated for the upwind distance, X, and the stability class.

For stable conditions, or unlimited mixing:

$$f_p = \frac{g_1 g_2}{2\pi\ \sigma_y\ \sigma_z} \tag{22}$$

where g_1 and g_2 have been previously defined.

In unstable or neutral conditions, if σ_z is greater than 1.6 times the mixing height, L (meters), the distribution below the mixing height is uniform with height regardless of source or receptor height, provided both are less than the mixing height.

$$f_p = \frac{g_1}{\sigma_y\ L\ (2\pi)^{1/2}} \tag{23}$$

In all other unstable or neutral conditions:

$$f_p = \frac{g_1 g_3}{2\pi\ \sigma_y\ \sigma_z} \tag{24}$$

It should be noted that in PAL, initial σ_y's and σ_z's, such as to account for intial dispersion in the turbulent wake behind vehicles, are input values. The virtual distance for the given stability class is calculated within the algorithm. These virtual distances are added to the physical distances prior to determining σ_y and σ_z for each concentration computation.

The integral, Equation 21, is evaluated using the trapezoidal rule by making first estimate, C_1, given by:

$$C_1 = \frac{q_\ell\ \Delta\ell}{U} \left\{ \frac{1}{2} \left[f_p(o) + f_p\ (10\Delta\ell) \right] + \sum_{i=1}^{9} f_p\ (i\Delta\ell) \right\} \tag{25}$$

where $\Delta\ell$ = D/10, and f_p is defined above. For each of the 11 evaluations of f_p, the upwind distance, X, of the point on the line from the receptor is determined as a function of $\Delta\ell$, and X is used to determine σ_z and σ_y in the function f_p. Portions of the line where f_p equals zero are eliminated and the line is redefined. Then Equation (25) is again evaluated.

A second estimate, C_2, is determined from:

$$C_2 = \frac{C_1}{2} + \frac{q_\ell \Delta\ell}{2u} \left[\sum_{j=1}^{10} f_p(-\Delta\ell/2 + j\Delta\ell) \right] \qquad (26)$$

A calculation is made of $(C_2 - C_1)/C_2$. If this value is within a set criteria, $\chi = C_2$. If not within the criteria, a third estimate is made by evaluating f_p for additional points midway between those points previously calculated and assuming linear concentration change between adjacent points (trapezoidal rule). This is continued until the approximation to the integral converges, that is, until two successive estimates are within the criteria. The last estimate is the concentration, χ, from this line source.

For line source with an intersection point upwind from the receptor, the contribution from the second segment must also be determined. If the point directly upwind was not used to break the line into two segments, and the entire line source is considered as one segment, it is possible for the entire portion of the line that contributes significantly to the concentration to be between two of the eleven points, and thus an erroneous concentration of zero would result.

For line sources with multiple lanes, the integral would be evaluated for each lane and the concentration summed to represent the total concentration at that receptor from the line source.

CURVED SOURCE COMPUTATIONS

Figure 4 shows the curved source and receptor relationships. Points A and C are the end points of the curved path. Point B is an arbitrary point on the curve between A and C. The curve is assumed to be of constant radius.

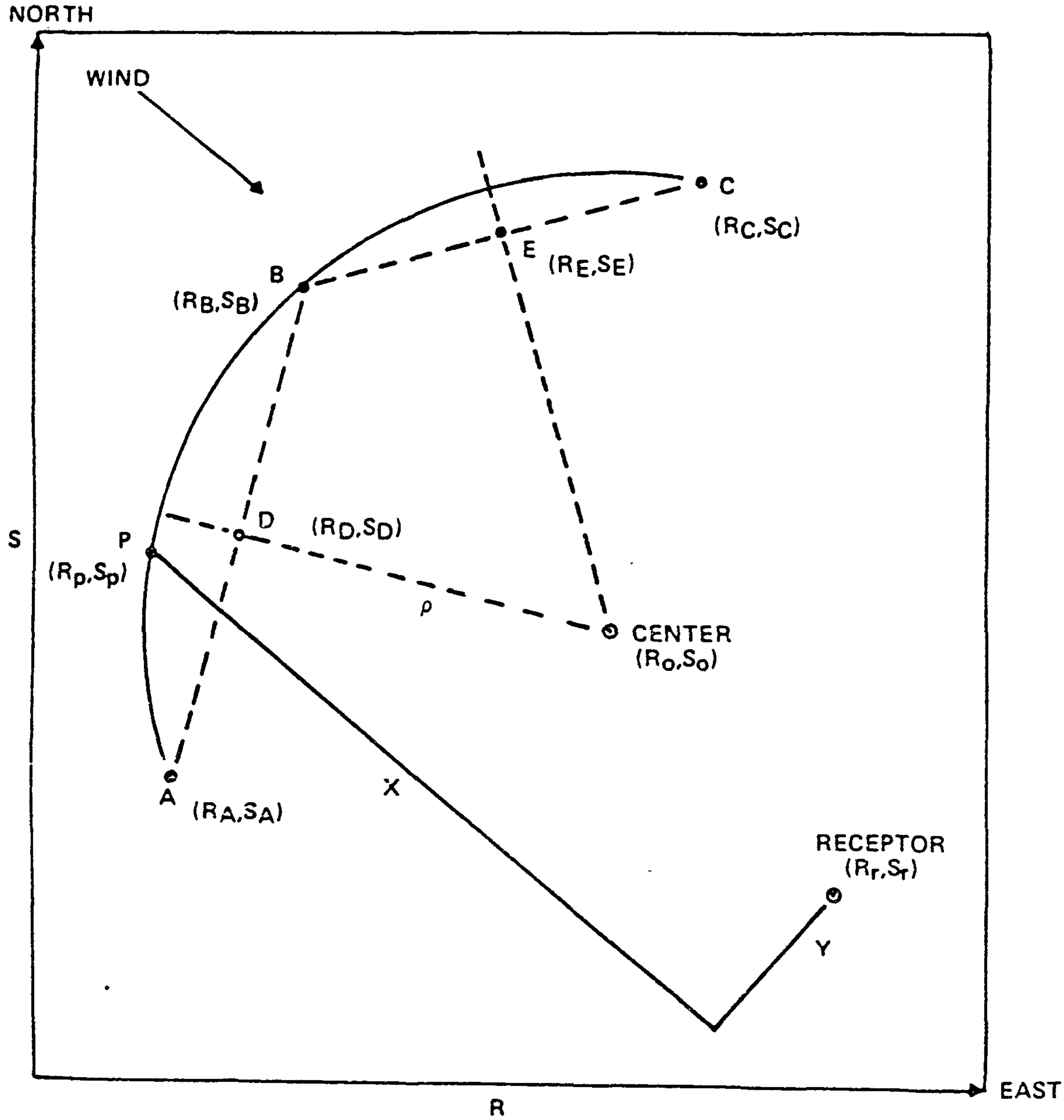

Figure 4. Curved source and receptor relationships.

The radius of the circle, of which the curve is a part, is determined in the following way: The coordinates of point D midway between A and B on a chord are found by averaging the R and S coordinates of A and B. Similarly, the coordinates of point E midway between B and C on a chord are found. The perpendicular bisector of a chord of a circle will pass through the center of a circle. Also, the slope of the perpendicuar bisector is the negative reciprocal of the slope of the chord. The slope of chord AB is:

$$(R_B - R_A) / (S_B - S_A)$$

and the slope of chord BC is:

$$(R_c - R_B) / (S_c - S_B)$$

The slope of the bisector through D, call this m_1, is:

$$- (S_B - S_A) / (R_B - R_A) = m_1$$

The slope of the bisector through E, call this m_2, is:

$$- (S_C - S_B) / (R_C - R_B) = m_2$$

The resulting equation of the bisector through D is:

$$R_o - R_D = m_1 (S_o - S_D) \qquad (27)$$

and the equation of the bisector through E is:

$$R_o - R_E = m_2 (S_o - S_E) \qquad (28)$$

R_o and S_o can be determined from these two equations, for example:

$$S_o = (m_1 S_D - m_2 S_E - R_D + R_E) / (m_1 - m_2) \qquad (29)$$

$$\text{and } R_o = m_1 (S_o - S_D) + R_D \qquad (30)$$

The radius of the circle can be determined from the coordinates of the center (R_o, S_o) and any one of the three points on the curve, for example:

$$\rho = \sqrt{(S_A - S_o)^2 + (R_A - R_o)^2} \tag{31}$$

In order to provide a proper estimate of the concentrations from the curved source at a receptor, it is desirable to determine if a line in the upwind direction from the receptor intersects the curve. The equation of the line through the receptor in the direction of the upwind azimuth is:

$$R - R_r = (S - S_r) \tan \theta \tag{32}$$

The equation of the circle of which the curve is a part is:

$$\rho^2 = (S - S_o)^2 + (R - R_o)^2 \tag{33}$$

The two possible intersections of the line and the circle are found by solving a quadratic equation for one of the two variables, for example, of the form:

$$a R^2 + b R + c = 0 \tag{34}$$

where $a = 1 + \cot^2\theta$ (35)

$$b = -2 R_r \cot^2\theta + 2 S_r \cot\theta - 2 S_o \cot\theta - 2 R_o \tag{36}$$

$$\text{and } c = {R_r}^2 \cot^2\theta - 2 R_r S_r \cot\theta - 2 R_r S_o \cot\theta - 2 S_o S_r + {S_r}^2 + {S_o}^2 + {R_o}^2 - \rho^2 \tag{37}$$

Two possible values of R are found from:

$$R = \frac{-b \pm \sqrt{b^2-4ac}}{2a} \tag{38}$$

If b^2-4ac is negative, R has imaginary roots and there is no intersection of the circle and the line. If b^2-4ac is zero, the line is tangent to the circle and there is one intersection. If b^2-4ac is positive there are two intersections and both roots of the equation are found. If one or two values of R are found, then one or two values of S are found from:

$$S = (R-R_r) \cot\theta + S_r \tag{39}$$

If one or more intersections were found for the line and circle, the upwind distance of this (these) point(s) from the receptor can be determined using Equation (1). If this value is negative, indicating the point is downwind from the receptor, it need not be considered further. However, for a point with a positive x, it must be determined if this intersection on the circle is also on the curve, that is, between points A and C.

The direction from the center of the circle (R_o, S_o) to a point (R_p, S_p) on the circle is:

$$\phi = \tan^{-1} [(R_p-R_o) / (S_p - S_o)] \tag{40}$$

The directed azimuth from the circle's center to any intersection and to points A, B, and C can then be found. With some logic to consider the crossover point (from 360° to 0°), it can be determined if the ϕ for the intersection is within the range of ϕ swept out by the curve.

After determining if any intersections are on the curve, the curve is considered in three pieces if there are two intersections, two if there is one intersection, and as a single curve if there are no intersections. The computation is done very similarly to that for line sources. Whereas the length along the line is used to make calculations at intervals for the line source, the variation of the azimuth from the center of the circle, ϕ, is used for the curved source. The coordinates of a point on the curve for which the concentration contribution is being evaluated are found from:

$$R_p = R_o + \rho \sin \phi \tag{41}$$

$$S_p = S_o + \rho \sin \phi \tag{42}$$

The upwind and crosswind distances, x and y, of a given point on the curve with coordinates (R_p, S_p) for the receptor (R_r, S_r) are calculated as previously using Equations (1) and (2). The same point source dispersion function, f_p as given in the "Line Source Computations" section is used.

SPECIAL PATH SOURCES

The slant (or special line) and special curved path source calculations are made in a similar way as the line source and curved source calculations, respectively. Unlike Equation 21, the concentration from special sources is given by

$$\chi = \frac{1}{U} \int_o^D q_\ell \, f_p \, d\,\ell \tag{43}$$

where q_ℓ is now no longer a constant but varies along the source. This section will describe how q_ℓ is calculated for special sources.

The acceleration of the vehicles is assumed constant and equal to

$$a = \frac{V_f - V_o}{t} \tag{44}$$

where a = acceleration of the vehicles,
V_o = initial vehicle speed at point A (see Figures 3 and 4),
V_f = final vehicle speed at B or C (see Figures 3 and 4), and
t = total time of travel.

The vehicle speed at any point "P" on the source is given by

$$V_p = at_p + V_o \tag{45}$$

where v_p = vehicle speed at P, and
t_p = time of travel to P.

The vehicle acceleration can also be expressed as

$$a = \frac{V_f^2 - V_o^2}{2X_f} \tag{46}$$

where X_f = total distance of travel.

The distance of travel to any point "P" can be expressed as

$$X_p = \frac{1}{2} a\, t_p^2 + V_o\, t_p \tag{47}$$

where X_p = distance of travel to P.

Solving for t_p in Equation 47 and substituting in Equation 45,

$$V_p = \left[V_o^2 + \frac{x_p}{X_f} (V_f^2 - V_o^2)\right]^{1/2} \tag{48}$$

The emission rate q_ℓ [g/(sec m)] is now given by

$$q_\ell = \frac{\text{TV (veh/hr) EF [g/(sec veh)]}}{3600 \text{ (sec/hr) } V_p \text{ (m/sec)}} \tag{49}$$

where TV = traffic volume.

The emission rate is inversely proportional to V_p. In order to ensure that q_ℓ will not approach infinity as V_p goes to zero, a simple tecnhique is used to set a minimum vehicle speed. The minimum speed (V_s) is calcualted using the traffic volume and a gross estimate of average vehicle length (VL).

$$V_s = \frac{\text{TV (veh/hr)} \quad \text{VL (m/veh)}}{3600 \quad \text{(sec/hr)}} \tag{50}$$

V_s is then in m/sec and physically it is the slowest speed the vehicles could be going and still maintain the traffic volume. If V_p is less than V_s, then V_p is set equal to V_s.

For most applications this change in vehicle speed will have negligible effect on the concentration estimates.

SETTLING AND DRY DEPOSITION

The analytical expressions for atmospheric concentration of a gaseous or suspended particulate pollutant, subject to deposition and/or gravitational settling, in a plume released from an elevated continuous point source are given by Rao (1982). These algorithms are based on a gradient-transfer (K-theory) model. Details of the model and the solutions can be found in that reference. Here we only list the plume diffusion-deposition algorithms applicable to the PAL model under various stability and mixing conditions.

The expressions to be used in the discussions that follow are

$$g_1 = \exp\,(-\hat{y}^2) \tag{51}$$

$$g_2' = \exp\{-2\hat{W}(\hat{z} - \hat{H})\hat{x} - \hat{W}^2\,\hat{x}^2\}$$

$$[\exp\{-(\hat{z} - \hat{H})^2\} + \exp\{-(\hat{z} + \hat{H})^2\}$$

$$(1 - 4\sqrt{\pi}\,\hat{V}_1\,x\,\exp\,\{\xi^2\}\,\text{erfc}\,\{\xi\}\,)] \tag{52}$$

$$g_3' = \sum_{N=-\infty}^{\infty} \Big[\exp\{-2\hat{W} (\hat{z} - \hat{H}_1) \hat{x} - \hat{W}^2 \hat{x}^2\}$$

$$[\exp\{-(\hat{z} - \hat{H}_1)^2\} + \exp\{-(\hat{z} + \hat{H}_1)^2\}$$

$$(1 - 4\sqrt{\pi}\, \hat{V}_1 \hat{x} \exp\{\xi_1^2\} \operatorname{erfc} \xi_1)]\Big] \qquad (53)$$

<u>For $\hat{V}_2 = 0$,</u>

$$g_4' = (1 + 2\hat{x}_1^2) \operatorname{erfc}(\hat{x}_1) - (2\hat{x}_1/\sqrt{\pi}) \exp(-\hat{x}_1^2) \qquad (54)$$

<u>For $\hat{V}_2 \neq 0$,</u>

$$g_4' = (\hat{V}_1/\hat{V}_2) \cdot \exp(4\hat{V}_d \hat{V}_2 \hat{x}^2) \operatorname{erfc}(2\hat{V}_1 \hat{x})$$

$$- (\hat{W}/2\hat{V}_2) \cdot \operatorname{erfc}(\hat{W} \hat{x}) \qquad (55)$$

In the above, g_2', g_3', and g_4' are the modifications of the nondimensional functions g_2, g_3, and g_4 defined previously. Though g_4 was not explicitly defined, it can be easily seen that $g_4 = 1$. The capped quantities denote the nondimensional variables defined below.

$\hat{H} = H/\sqrt{2}\,\sigma_z$	$\hat{H}_1 = H_1/\sqrt{2}\,\sigma_z$
$\hat{L} = L/\sqrt{2}\,\sigma_z$	$\hat{V}_d = V_d/U$
$\hat{V}_1 = \hat{V}_d - \hat{W}/2$	$\hat{V}_2 = \hat{V}_d - \hat{W}$
$\hat{W} = W/U$	$\hat{x} = x/\sqrt{2}\,\sigma_z$
$\hat{y} = y/\sqrt{2}\,\sigma_z$	$\hat{z} = z/\sqrt{2}\,\sigma_z$
$\xi = \hat{z} + \hat{H} + 2\hat{V}_1 \hat{x}$	$\xi_1 = \hat{z} + \hat{H}_1 + 2\hat{V}_1 \hat{x}$

where

H = effective height of source emission,

H_1 = H + 2 N L,

L = mixing depth or height of inversion lid,

N = eddy reflection number,

U = mean wind speed,

V_d = dry deposition velocity of pollutant,

W = gravitational settling velocity of pollutant particles,

X = horizontal upwind distance of source from receptor,

Y, z = horizontal crosswind and vertical coordinates of receptor, and

σ_y, σ_z = Gaussian plume dispersion parameters in y and z directions

In the limit of $\hat{W} = \hat{V}_d = 0$, the expressions for g_2', g_3', and g_4' reduce to the expressions for g_2, g_3, g_4.

Depending on the atmospheric stability and mixing conditions, the contribution to the receptor concentration, χ_p, due to a single point source is given by one of the following equations.

For stable conditions or unlimited mixing,

$$\chi_p = \frac{Q}{U} \frac{g_1}{L_y} \cdot \frac{g_2'}{L_z} \tag{57}$$

For unstable or neutral conditions, with $\sigma_z < 1.6$ L,

$$\chi_p = \frac{Q}{U} \cdot \frac{g_1}{L_y} \cdot \frac{g_3'}{L_z} \tag{58}$$

For unstable or neutral conditions, with uniform vertical mixing ($\sigma_z > 1.6$L),

$$\chi_p = \frac{Q}{U} \cdot \frac{g_1}{L_y} \cdot \frac{g_4'}{L} \tag{59}$$

In the above,

$$L_y = \sqrt{2\pi}\ \sigma_y, \qquad L_z = \sqrt{2\pi}\ \sigma_z, \tag{60}$$

L is the mixing depth, and Q is the point source emission rate; σ_y and σ_z are evaluated for the given distance x and the atmospheric stability class. Equations 57 to 59 are directly used in the computations for point, line, and curved path sources.

The equations given above are used in modified form for area sources. Integration over the area source which includes edge effects from the source region is done by considering finite line sources perpendicular to the mean wind at intervals upwind from the receptor. The concentration due to a finite line source is obtained by correcting the function f related to the concentration contribution to a receptor from an infinite crosswind line source. Depending on the atmospheric stability and mixing conditions, the function f is given by one of the following equations:

For stable conditions or unlimited mixing,

$$f = g_2'/L_z \tag{61}$$

For unstable or neutral conditions, with $\sigma_z < 1.6$ L,

$$f = g_3'/L_z \tag{62}$$

For unstable or neutral conditions, with uniform vertical mixing ($\sigma_z > 1.6$ L),

$$f = g_4'/L \tag{63}$$

In the above, L is the mixing depth and L_z is defined in Equation 60.

Surface Deposition Flux

The surface deposition flux D_f is calculated directly from the ground-level concentration as

$$D_f(x,y) = V_d \cdot \chi(x,y,0) \tag{64}$$

This is the amount of pollutant deposited per unit time per unit surface area. D_f is usually expressed as kg/km^2-hour. In the PAL program, the deposition flux is calculated only at ground-level receptors; these are defined as the receptors which are not higher than 1 meter above local ground-level elevation.

SETTLING AND DEPOSITION VELOCITIES

The values of the settling and deposition velocities primarily depend on the particle diameter d. 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 nongravitational effects. In this case, $W = 0$ but $V_d > 0$. For small particles ($d = 0.1\sim50$ 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 in a dust storm, for example. The first four types of model parameters given above are widely used in atmospheric disperison 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 models. A more complete discussion of these model parameters is given by Rao (1982).

SECTION 6
EXAMPLE PROBLEMS

In this section, problems are provided to illustrate different modeling scenarios and to demonstrate several unique features of PAL. Details concerning input and output of the example problems are discussed in Section 10 after the reader has become familiar with PAL input data preparation.

EXAMPLE 1

This example problem demonstrates the basic use of PAL. The sources path and receptor locations are shown in Figure 5: one point source, two area sources, three line sources, one curved path source, and two special line sources. This example is intended to be a simplified model of an airport; none of the emissions and physical dimensions should be considered realistic. Also, not all of the sources of emissions, such as taxiways, are included in this example problem. Notice that the two area sources are overlayed. In this paricular example the hatched area represents a building with no emissions and the other area source is a parking lot with its associated emissions. The area source strength for the building is the same as that for the parking lot but negative in sign. The effect of the negative area source strength is to make the concentration from the building equal to zero. Also, using the negative area source strength reduces the number of area source inputs from three to two in this case. The point source is an incinerator. Line sources one and two are fourlane highways with a fourlane curved path source in between. Line source three is a two-lane entrance road. The special line sources are active runways.

This example consists of two, three-hour meteorology periods. Each period has a unique set of meteorology shown in Table 1. During the first three hours a transition from neutral (stability class 4) to unstable (stability class 2) atmospheric stability is simulated. Also, the height of the mixed depth layer increases from 500 m to 1100 m. During the second three-hour period the major change is the increase in wind speed during the second hour.

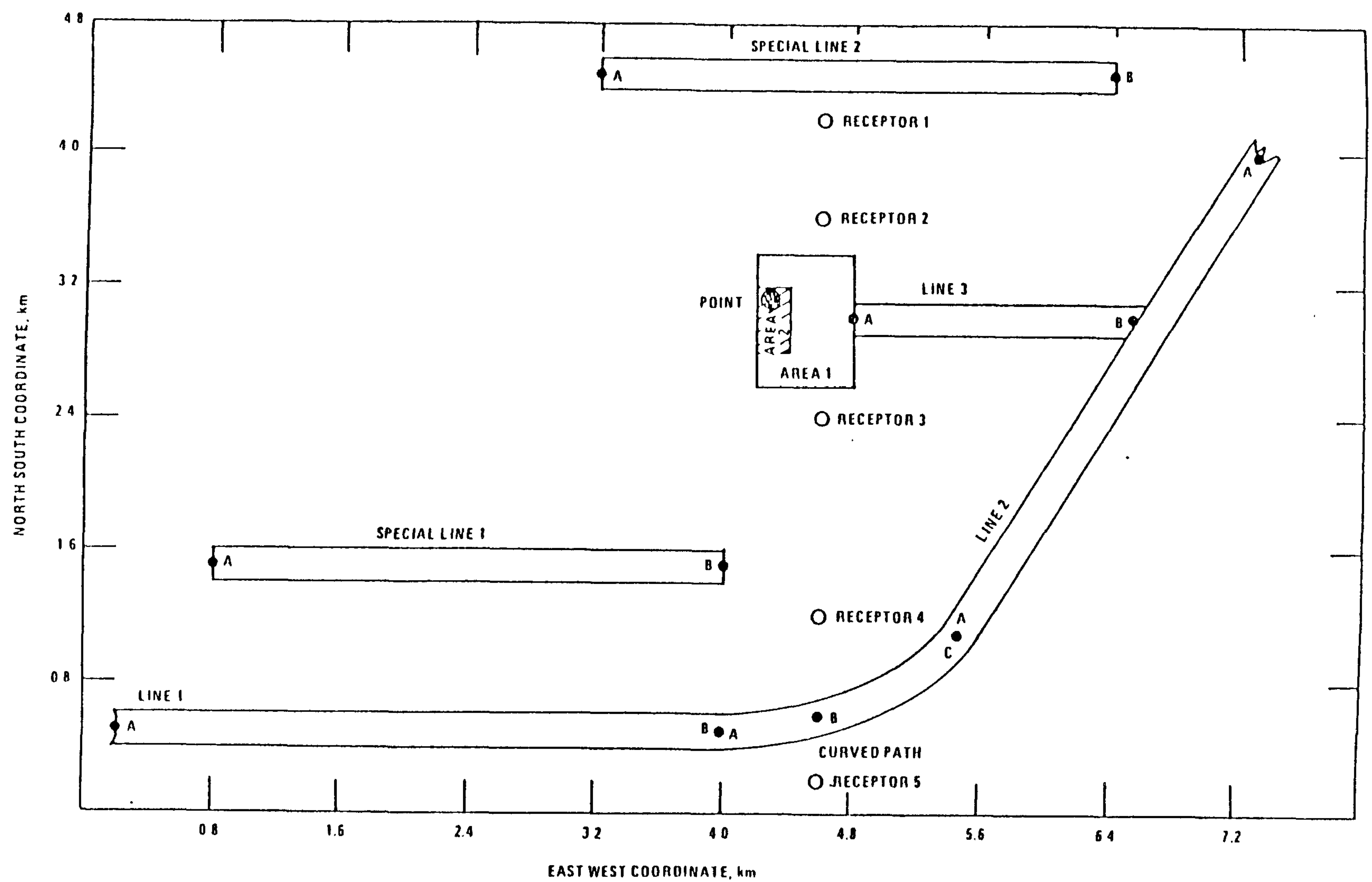

Figure 5. Source types included in Example Problem 1.

TABLE 1. METEOROLOGICAL DATA FOR EXAMPLE 1

Meteorology Period 1

Hour	Wind Angle (Deg)	Wind Speed (m/sec)	Stability Class	Mixing Ht. (m)	Ambient Air Temp (Deg-K)
1	0	2	4	500	285
2	350	2.5	3	900	289
3	345	3.0	2	1100	294
Meteorology Period 2					
1	30	3.0	4	1000	290
2	45	6.1	4	1000	300
3	50	3.8	3	1000	298

TABLE 2. SOURCE STRENGTHS FOR THE FIVE SOURCE TYPES IN EXAMPLE 1.

	Point	Areas	Horizontal Lines				Curved Horizontal Path				Slant or Vertical Lines
			(Lane) (1)	(2)	(3)	(4)	(Lane) (1)	(2)	(3)	(4)	
(No.)	g/sec	g/sec-m^2	g/sec-m				g/sec-m				g/sec
1	5.	.0002	.0001	.0002	.0009	.0010	.001	.002	.0009	.001	30.
2		-.0002	.0018	.0018	.0009	.0007					10.
3			.0002	.0020							

Five of the six possible source types are included in this problem. Table 2 illustrates their individual source strenghts. These strengths remain constant throughout both meteorology periods.

PAL computes the contribution to the concentration at each receptor for each source type. This output is produced for each hour of simulation. The average concentration for each of the two three-hour meteorology periods is also displayed as a part of the output and is summarized here in Table 3. During the first three hours area source 1 has a major impact at receptors 3, 4, and 5. Maximum line source contributions are about an order of magnitude lower. During the second 3 hours major impact occurs from the area source and special line source.

TABLE 3. THREE-HOUR AVERAGE CONCENTRATION ($\mu g/m^3$) FOR BOTH 3-HOUR METEOROLOGY PERIODS.

Receptor No.	From Points	From Areas	From Hor. Lines	From Cur. Lines	From Spec. Lines	From Spec. Paths	Total Conc.
			First 3-Hour Meteorology Period				
1	0	0	0	0	140.6	0	140.6
2	0	0	0	0	65.0	0	65.0
3	10.5	1890.	<1	0	37.7	0	1938.2
4	12.3	527.9	<1	0	29.1	0	569.9
5	7.6	310.7	1.1	76.8	26.4	0	422.7
			Second 3-Hour Meteorology Period				
1	0	0	<1	0	102.7	0	102.7
2	0	0	<1	0	43.2	0	43.2
3	0	264.8	32.7	0	12.9	0	310.4
4	0	0	30.4	<1	3.0	0	33.3
5	0	0	21.5	51.9	<1	0	73.6

EXAMPLE 2

Example 2 is intended to illustrate all six types of sources available in PAL. It does not pretend to represent a realistic situation. The locations of the sources and receptors are presented in Figure 6. Some of the receptors are above ground-level. The pollutant is assumed to be total suspended particulate (TSP) matter with a deposition velocity V_d equal to the gravitational settling velocity W of 10 cm/sec. The meteorology was held constant for four hours, except for the wind direction. The wind was allowed to blow from a different quadrant each hour. Wind direction for periods 1-4 were 315, 45, 135, and 225 degrees. The wind speed was 4 m/sec, the atmosphere was slightly unstable with a 1000 m mixing height. The horizontal line sources used consist of two lines, each with two lanes. All four lanes have the same emission rate. The curved horizontal path sources used also consist of two lanes, each having the same emission rate. Listed below are the individual source strengths for each source type.

Source Type	Source Strength
Point	10. (G/sec)
Area	.05 (G/sec-m^2)
Horizontal Lines	.001 (G/sec-m)
Curved Horizontal Paths	.001 (G/sec-m)
Slant or Vertical Line	10. (G/sec)
Special Path	8. (G/sec)

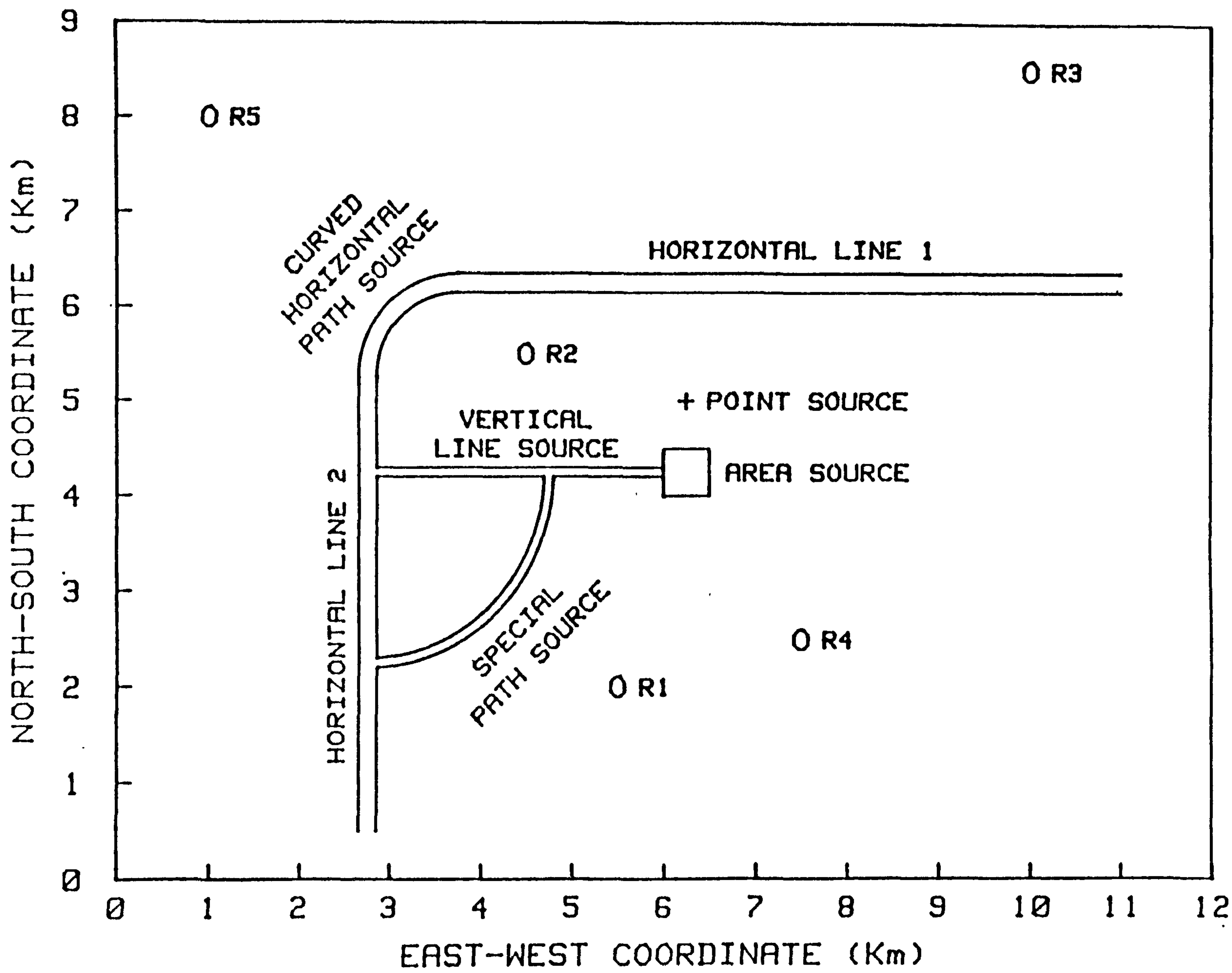

Figure 6. Schematic diagram of sources and receptors in Example Problem 2.

Example two differs from problem I in that the concentrations at the receptors are affected by gravitational settling and deposition loss of the pollutant. In this example, no average concentrations are calculated. The concentrations for each receptor within each of the four hours are computed along with deposition flux quantities. Deposition fluxes are computed only for surface receptors. Figure 12 in Section 10 shows the output from the model run.

SECTION 7

COMPUTER ASPECTS OF THE MODEL

The general framework of PAL is discussed in this section. It 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 PAL, the structure of the computer subroutines and the computer functions, and a brief description of each subroutine and function are included in this section.

GENERAL FLOW OF THE MODEL

Figure 7 depicts the general flow of the model. The main routine reads the following types of information.

- o integration accuracy for area and line sources,
- o options to be employed concerning wind speed changes with height and variation of emission factors,
- o source types to be used,
- o options for urban coefficients,
- o control for average concentration,
- o options for deposition or gravitational settling,
- o source types and characteristics,
- o receptor coordinates,
- o meteorological data, and
- o options for diurnal variation in emissions.

Up to a maximum of 99 sources of each type or any combination of the source types may be used.

Figure 8 shows the structure of the subroutines and functions. "PAL" is the main routine; it reads input data and stores the appropriate data in common with the six major subroutines. All input data for each hour are read before execution begins on any source type. A brief description of the main program, subroutines and functions follows.

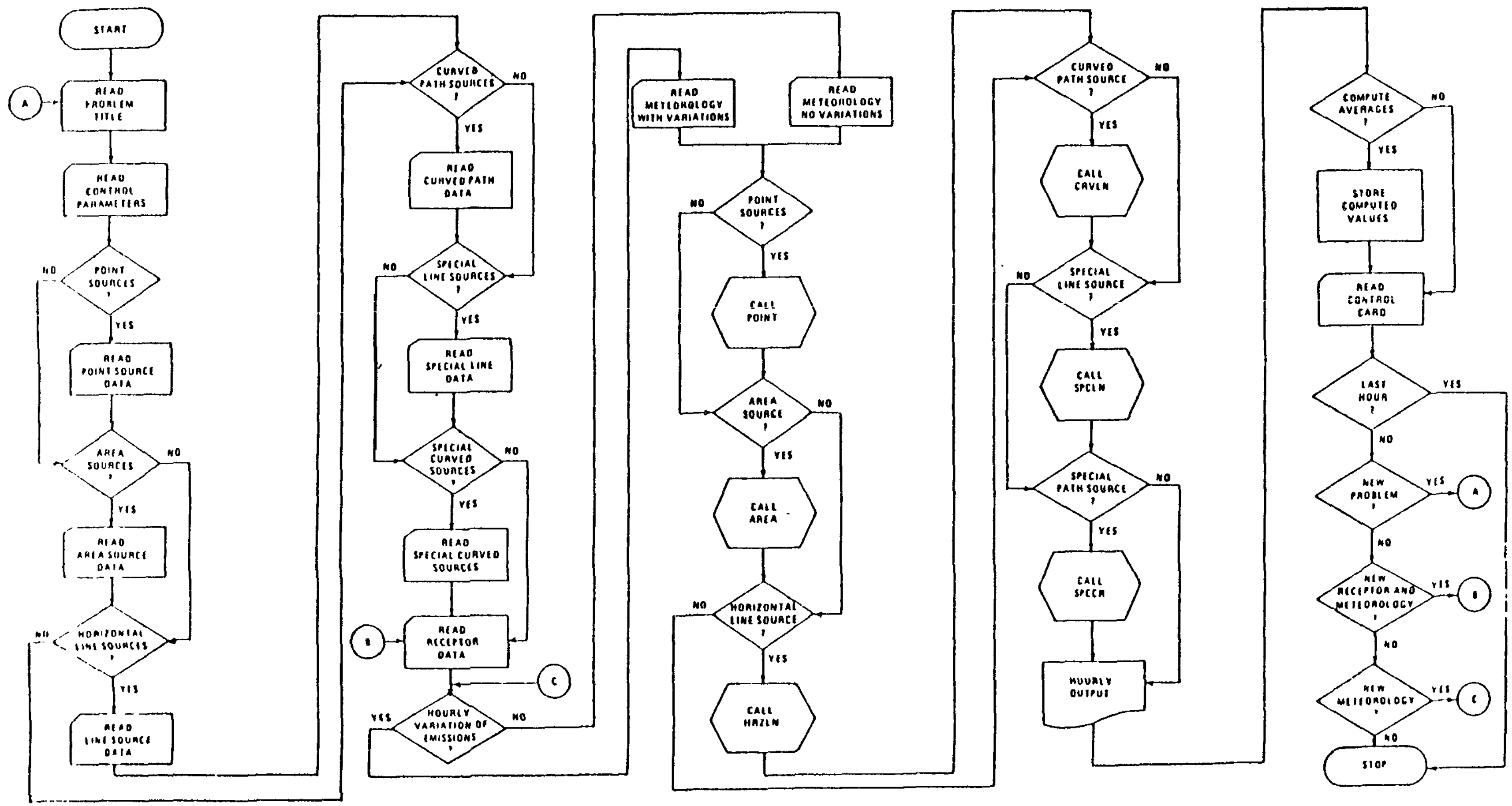

Figure 7. General flow diagram for PAL.

```
                      | WIND
                      | XVY
                      | XVZ
      | POINT ----    | FPLUME      | URBNYZ
      |               | XPLUME      |   or
      |               | RCONCP  --| PGSIG
      |               |   or
      |               | RCONPD  --| URBNYZ
      |                           |   or
      |                           | PGSIG
      |               | WIND      | ARGCHK
      |               | URBNYZ    | EXPO
      |               |   or
      |               | PGSIG
      | AREA -----    | RCONCA
      |               |   or      | EXPO
      |               | RCONAD  --| ARGCHK
      |
      |               | WIND
      |               | XVY                                     | URBNYZ
      |               | XVZ                   | DIFANG          |  or
      | HRZLN ----    | INTEGL ---   F ----| RCONCP  ----| PGSIG
      |               |           | URBNYZ  |   or
      |               | RCONCP  --|   or    | RCONPD  ----| URBNYZ
      |               |   or      | PGSIG                   |   or
      |               |                                     | PGSIG
      |               | RCONPD--  | URBNYZ or PGSIG          | ARGCHK
      |                           | ARGCHK                  | EXPO
      |               | WIND      | EXPO
      |               | XVY
      |               | XVZ
      |               | ANGARC                                  | URBNYZ
PAL-|               | DIFANG                | DIFANG          |  or
      | CRVLN ----    | INTEGL ---   F ----| RCONCP  ----| PGSIG
      |               | CURLIN    | URBNYZ  |   or
      |               | RCONCP  --|   or    | RCONPD  ----| URBNYZ
      |               |   or      | PGSIG                   |   or
      |               |                                     | PGSIG
      |               | RCONPD--  | URBNYZ or PGSIG          | ARGCHK
      |                           | ARGCHK                  | EXPO
      |                           | EXPO
      |               | WIND
      |               | XVY                                     | URBNYZ
      |               | XVZ                   | DIFANG          |  or
      | SPCLN ----    | INTEGL ---   F ----| RCONCP  ----| PGSIG
      |               |           | URBNYZ  |   or
      |               | RCONCP  --|   or    | RCONPD  ----| URBNYZ
      |               |   or      | PGSIG                   |   or
      |               |                                     | PGSIG
      |               | RCONPD--  | URBNYZ or PGSIG          | ARGCHK
      |                           | ARGCHK                  | EXPO
      |                           | EXPO
      |               | WIND
      |               | XVY
      |               | XVZ                                     | URBNYZ
      |               | ANGARC                | DIFANG          |  or
      | SPCCR ----    | INTEGL ---   F ----| RCONCP  ----| PGSIG
                      | CURLIN    | URBNYZ  |   or
                      | RCONCP  --|   or    | RCONPD  ----| URBNYZ
                      |   or      | PGSIG                   |   or
                      |                                     | PGSIG
                      | RCONPD--  | URBNYZ or PGSIG          | ARGCHK
                                  | ARGCHK                  | EXPO
                                  | EXPO
```

Figure 8. Structure of subroutine and functions in PAL program.

DESCRIPTION OF SUBROUTINES AND FUNCTIONS

Each subroutine and function of PAL is briefly described in the following pages.

PAL - PAL is the main program that reads in all input data. Source input data cards include point, area, horizontal line, special line, horizontal curved path, and special curved path sources. Subroutines are called for each source type. Any combination, or all, of the above subroutines can be called by PAL. Input data cards for receptor location and hourly meteorology are required and not optional input as the above. PAL prints out all input data and concentration estimates.

POINT - This subroutine is called by PAL and makes concentration estimates for point sources. POINT calls subroutines XPLUME and FPLUME for plume rise calculation. Subroutine RCONCP is called by POINT to estimate the relative concentration for a receptor at a given downwind and crosswind distance.

AREA - This subroutine is called by PAL and makes concentration estimates from area sources. AREA calls RCONCA, which calculates the relative concentration for a receptor downwind of an infinite line source. PGSIG is also called by AREA to determine sigma y (σ_y) and sigma z (σ_z) for a given stability class and downwind distance. The concentration from area sources is approximated by numerical integration in the upwind direction of the concentration from infinite crosswind line sources corrected for finite length.

HRZLN - This subroutine is called by PAL and makes concentration estimates for multilane horizontal line sources. Functions XVY and XVZ are called by HRZLN to calculate the virtual distance necessary to account for initial crosswind and vertical dispersion, which is specified by the user. Subroutines RCONCP, called by HRZLN, estimates the relative concentration for a receptor at a given downwind and crosswind distance.

CRVLN - This subroutine is called by PAL and makes concentration estimates from multilane horizontal curved path sources. CRVLN calls two subroutines, CURLIN and RCONCP. CURLIN calculates the coordinates, if any, of the intersection points of the curved path and the upwind projection from the receptor coordinates. Subroutine RCONCP and functions XVY and XVZ are called by CRVLN and have the same function as they do in HRZLN. The shape of the curved path is approximated by an arc from a circle, determined from the three points on the curved path specified by the user.

SPCLN - This subroutine is called by PAL and makes concentration estimates from special line sources. SPCLN calls subroutine RCONCP and functions XVY and XVZ, which are used in the same manner as in HRZLN. The line sources do not have to be horizontal and emissions per unit length are allowed to vary.

SPCCR - This subroutine is called by PAL and makes concentraion estimates from special curved path sources. Subroutines CURLIN and RCONCP and functions XVY, XVZ, DIFANG and ANGARC are called by SPCCR and are used in the same manner as in CRVLN. The special curved path sources must be horizontal but will allow emissions per unit length to vary along the curved path.

XPLUME - This subroutine is called by POINT and calculates the plume rise at a given downwind distance x.

FPLUME - This subroutine is called by POINT and calculates the final plume rise.

RCONCP - This subroutine is called by POINT, HRZLN, CRVLN, SPCLN, and SPCCR. RCONCP calls PGSIS. RCONCP determines the relative concentration at a receptor from a point source at a given upwind and crosswind distance.

PGSIG - This subroutine is called by RCONCP and calculates σ_y and σ_z for a given stability and downwind distance.

RCONCA - This subroutine is called by AREA and calculates the relative concentration normalized for wind speed for a receptor downwind of a crosswind infinite line source.

CURLIN - This subroutine is called by CRVLN and SPCCR. CURLIN determines the coordinates of the intersetion points, if any, of a curved path source and the line in the direction of the wind through the receptor coordinates.

XVY - This function is called by POINT, HRZLN, CRVLN, SPCLN, and SPCCR. XVY calculates the virtual distance necessary to account for the initial crosswind dispersion.

XYZ - This function is called by POINT, HRZLN, CRVLN, SPCLN, and SPCCR. XVZ calculates the virtual distance necessary to account for the initial vertical dispersion.

DIFANG - This function is called by CRVLN and SPCCR. DIFANG determines the angular difference between two angles.

ANGARC - This function is called by CRVLN and SPCCR. ANGARC determines the angle specified by a given slope. The resulting angle is between 0 and 360 degrees.

WIND - This subroutine causes wind speed to be constant with height below and above minimum and maximum above-ground heights. It also allows wind speed to be no lower than a user input minimum speed.

URBNYZ - This subroutine incorporates Briggs urban (McElroy-Pooler) dispersion coefficients. Calculates urban sigmas from the stability and downwind distances.

F - This function, called by INTEGL, calculates the concentration of a single point source on a special line source, a horizontal line source, a curved path source, or a special curved path source, depending on the option chosen.

INTEGL - This subroutine calculates the approximate value of a definite integral, and a relative error-bound for that value. The integration algorithm is an application of the Richardson extrapolation to the composite trapezoidal rule.

RCONAD - This subroutine, called by AREA, calculates $\chi U/Q$, the relative concentration normalized for wind speed, at any downwind receptor location due to the dispersion and deposition of gaseous or particulate pollutants from a crosswind infinite line source.

RCONPD - This subroutine, called by POINT and F, calculates $\chi U/Q$, the relative concentration normalized for wind speed, at any downwind receptor location due to the dispersion and deposition of gaseous or particulate pollutants from a continuous point source.

ARGCHK - This subroutine, called by RCONAD and RCONPD, limits the arguments of $\exp(p^2)\cdot\mathrm{erfc}(p)$ arising in the deposition algorithms to avoid overflow/underflow errors in the program.

EXPO - This subroutine, called by RCONAD and RCONPD, calculates and returns $q = e^p$, if p is given. EXPO checks and limits the argument p to avoid overflow/underflow errors in the program.

SECTION 8

PREPARATION OF INPUT DATA

The sequence of input data cards is shown in Figure 9. The formats for the input data cards are shown in Table 4. All input data are in free format, except card 1 which is an alphanumeric 20A4 format. While the free format is very easy to use, care should be taken to make sure every variable is given a value in the correct order. Each variable should be separated by a comma or blank. A complete description of the free format can be found in any Fortran reference manual. Integer variable names begin with the letters I - N. Those input cards which are optional are noted below the card type number. A brief description of each input parameter is given in Table 4 with the appropriate units. The metric system of units is used in PAL. Horizontal coordinates of sources are given in units of kilometers. Temperatures are given in units of degrees kelvin. Emission rates are given in mgs units (meter-gram-second).

Input data cards for source types, receptor locations, and hourly meteorology have, as a first variable, an integer called ICARD. If ICARD equals one, more cards of this type are expected. If ICARD equals two, then the last card of this type is expected. At card type 13 the program will terminate if KTL = 0. Three other options are also available:

- o To start a new problem giving all the input information.
- o To leave all sources the same but input new information on receptors and meteorology.
- o To input new information on meteorology.

There are two other options available to the user, IDEP and IURB. If IDEP = 1, deposition effects are ignored. If IDEP = 2, deposition effects are considered using the specified values (in centimeters/sec) of pollutant settling and deposition velocities W and VD, respectively. If IURB = 1, Pasquill-Gillford dispersion curves are used for rural dispersion. If IURB = 2, Briggs urban (McElroy-Pooler) dispersion curves are used for urban dispersion.

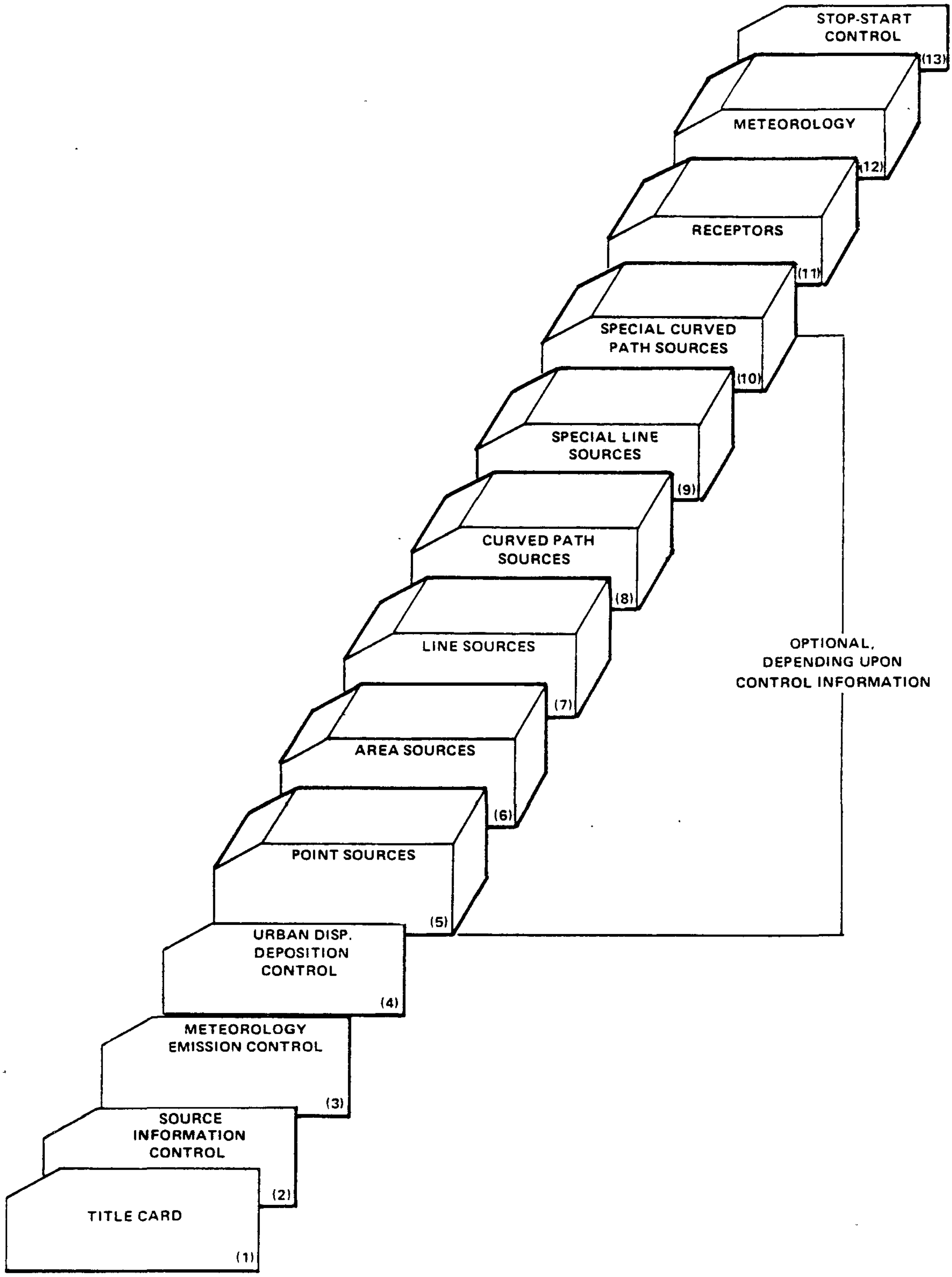

Figure 9. Input data deck for the PAL model. Card type numbers are in parentheses.

TABLE 4. DESCRIPTION OF INPUT DATA

CARD TYPE 1	20A4 FORMAT ALPHANUMERIC TITLE TO IDENTIFY OUTPUT	
CARD TYPE 2	PINA, PINL, IQP, IQA, IQLH, IQLC, IQLS, IQAC	
PINA	TEST FOR AREA INTEGRATION ACCURACY. PINA IS IN DECIMAL FORM.	(DIMENSIONLESS)
PINL	TEST FOR LINE INTEGRATION ACCURACY. PINA IS IN DECIMAL FORM.	(DIMENSIONLESS)
IQP	CONTROL FOR POINT SOURCES. IF IQP = 1, NO POINT SOURCES. IF IQP = 2, UP TO 99 POINT SOURCES CAN BE INCLUDED.	(DIMENSIONLESS)
IQA	CONTROL FOR AREA SOURCES. USED THE SAME AS IQP.	(DIMENSIONLESS)
IQLH	CONTROL FOR LINE SOURCE. USED THE SAME AS IQP.	(DIMENSIONLESS)
IQLC	CONTROL FOR CURVED PATH SOURCES. USED THE SAME AS IQP.	(DIMENSIONLESS)
IQLS	CONTROL FOR SLANT LINE SOURCES. USED THE SAME AS IQP.	(DIMENSIONLESS)
IQAC	CONTROL FOR SPECIAL PATH SOURCES. USED THE SAME AS IQP.	(DIMENSIONLESS)
CARD TYPE 3	IUZP, IUZA, IUZH, IUZC, IUZS, IUZE, IAVG, IDRNL	
IUZP	WIND INCREASE WITH HEIGHT FOR POINT SOURCES. IF IUZP = 1, NO CHANGE OF WIND SPEED WITH HEIGHT. IF IUZP = 2, CHANGE OF WIND SPEED WITH HEIGHT IN EFFECT.	(DIMENSIONLESS)
IUZA	WIND INCREASE WITH HEIGHT FOR AREA SOURCES. USED THE SAME AS IUZP.	(DIMENSIONLESS)
IUZH	WIND INCREASE WITH HEIGHT FOR HORIZONTAL LINES. USED THE SAME AS IUZP.	(DIMENSIONLESS)
IUZC	WIND INCREASE WITH HEIGHT FOR CURVED PATH SOURCES. USED THE SAME AS IUZP.	(DIMENSIONLESS)

TABLE 4. (CONTINUED)

IUZS	WIND INCREASE WITH HEIGHT FOR SLANT LINE SOURCES. USED THE SAME AS IUZP.	(DIMENSIONLESS)
IUZE	WIND INCREASE OF HEIGHT FOR SPECIAL PATH SOURCES. USED THE SAME AS IUZP.	(DIMENSIONLESS)
IAVG	CONTROL FOR AVERAGE CONCENTRATIONS. IF IAVG = 1, NO AVERAGES ARE CALCULATED. IF IAVG = 2, AVERAGE CONCENTRATIONS CAN BE CALCULATED UP TO 24 HOURS.	(DIMENSIONLESS)
IDRNL	CONTROL FOR EMISSION FACTORS. IF IDRNL = 1, NO HOURLY VARIATION ON EMISSIONS. IF IDRNL = 2, HOURLY VARIATIONS IN EMISSIONS CAN BE INCLUDED.	(DIMENSIONLESS)
CARD TYPE 4	IURB, IDEP, W, VD, UHGT, HMIN, HMAX, UMIN	
IURB	CONTROL FOR URBAN OPTION. IF IURB = 1, PASQUILL-GIFFORD DISPERSION COEFFICIENTS ARE USED. IF IURB = 2, BRIGGS URBAN (MCELROY-POOLER) DISPERSION COEFFICIENTS ARE USED.	(DIMENSIONLESS)
IDEP	IF IDEP = 1, GRAVITATIONAL SETTLING AND/OR DEPOSITION LOSS OF POLLUTANT IGNORED. IF IDEP = 2, GRAVITATIONAL SETTLING AND/OR DEPOSITION LOSS OF POLLUTANT INCLUDED.	(DIMENSIONLESS)
W	POLLUTANT SETTLING VELOCITY.	(CM/SEC)
VD	POLLUTANT DEPOSITION VELOCITY.	(CM/SEC)
UHGT	THE HEIGHT APPLICABLE TO THE WIND MEASUREMENT.	(M)
HMIN	WIND CONSTANT BELOW THIS HEIGHT.	(M)
HMAX	WIND CONSTANT ABOVE THIS HEIGHT.	(M)
UMIN	MINIMUM WIND SPEED. IF FOUND BELOW THIS VALUE, SET TO THIS VALUE.	(M/S)
CARD TYPE 5	ICARD, QP, HPP, TSP, VSP, DP, VFP, RQP, SQP, SYOP, SZOP CARD 3 IS OPTIONAL. (POINT SOURCES)	

TABLE 4. (CONTINUED)

ICARD	IF ICARD = 1, MORE DATA CARDS ARE EXPECTED. IF ICARD = 2, LAST DATA CARD OF THIS TYPE.	(DIMENSIONLESS)
QP	POINT SOURCE STRENGTH.	(G/SEC)
HPP	PHYSICAL STACK HEIGHT.	(M)
TSP	STACK GAS TEMPERATURE.	(DEG K)
VSP	STACK GAS VELOCITY. (VSP IS DISREGARDED IF VFP IS GREATER THAN ZERO)	(M/SEC)
DP	STACK INSIDE DIAMETER. (DP IS DISREGARDED IF VFP IS GREATER THAN ZERO)	(M)
VFP	STACK GAS VOLUME FLOW.	(M**3/SEC)
RQP	EAST COORDINATE OF STACK.	(KM)
SQP	NORTH COORDINATE OF STACK.	(KM)
SYOP	INITIAL SIGMA Y.	(M)
SZOP	INITIAL SIGMA Z.	(M)
CARD TYPE 6	ICARD, QA, HQ, RQ, SQ, DEST, DNOR CARD 4 IS OPTIONAL. (AREA SOURCES)	
ICARD	USED THE SAME AS IN THE POINT SOURCES.	(DIMENSIONLESS)
QA	AREA SOURCE STRENGTH.	(G/SEC-M**2)
HQ	AREA SOURCE HEIGHT.	(M)
RQ	EAST COORDINATE OF S.W. CORNER.	(KM)
SO	NORTH COORDINATE OF S.W. CORNER.	(KM)

TABLE 4. (CONTINUED)

DEST	EAST-WEST SIZE.	(KM)
DNOR	NORTH-SOUTH SIZE.	(KM)
CARD TYPE 7	ICARD, HLN, NL, RAQ, SAQ, RBQ, SBQ, SYO, SZO, WT, WM, QLT CARD 7 IS OPTIONAL. (HORIZONTAL LINE SOURCES)	
ICARD	USED THE SAME AS IN THE POINT SOURCES.	(DIMENSIONLESS)
HLN	HEIGHT OF THE LINE SOURCE.	(M)
NL	NUMBER OF LANES. (1 LANE OR AN EVEN NUMBER OF LANES)	(DIMENSIONLESS)
RAQ	EAST COORDINATE OF POINT A. (SEE FIGURE 3)	(KM)
SAQ	NORTH COORDINATE OF POINT A.	(KM)
RBQ	EAST COORDINATE OF POINT B.	(KM)
SBQ	NORTH COORDINATE OF POINT B.	(KM)
SYO	INITIAL SIGMA Y.	(M)
SZO	INITIAL SIGMA Z.	(M)
WT	TOTAL WIDTH OF LINE SOURCE.	(M)
WM	WIDTH OF THE MEDIAN.	(M)
QLT	LINE SOURCE EMISSION RATE, ONE FOR EACH LANE. ORDERING OF EMISSION RATES ARE FROM LEFT TO RIGHT WHEN LOOKING FROM POINT A TO POINT B.	(G/SEC-M)
CARD TYPE 8	ICARD, HLNS, NL, RBQS, SBQS, RMQS, SMQS, REOS, SEQS, SIYO, SIZO, WT, WM, QLTS CARD 8 IS OPTIONAL. (CURVED PATH SOURCES)	
ICARD	USED THE SAME AS IN THE POINT SOURCES.	(DIMENSIONLESS)

TABLE 4. (CONTINUED)

HLNS	HEIGHT OF CURVED PATH SOURCE.	(M)
NL	NUMBER OF LANES. (1 LANE OR AN EVEN NUMBER OF LANES)	(DIMENSIONLESS)
RBQS	EAST COORDINATE OF POINT A. (SEE FIGURE 4)	(KM)
SBQS	NORTH COORDINATE OF POINT A.	(KM)
RMQS	EAST COORDINATE OF POINT B.	(KM)
SMQS	NORTH COORDINATE OF POINT B.	(KM)
REQS	EAST COORDINATE OF POINT C.	(KM)
SEQS	NORTH COORDINATE OF POINT C.	(KM)
SIYO	INITIAL SIGMA Y.	(M)
SIZO	INITIAL SIGMA Z.	(M)
WT	TOTAL WIDTH OF PATH SOURCE.	(M)
WM	WIDTH OF MEDIAN.	(M)
QLTS	CURVED PATH SOURCE EMISSION RATE, ONE FOR EACH LANE. ORDERING OF EMISSION RATES ARE FROM OUTSIDE LANE TO INSIDE.	(G/SEC-M)
CARD TYPE 9	ICARD, QLS, HAS, HBS, RAS, SAS, RBS, SBS, SPDI, SPDF, SYOS, SZOS, TVSL, VSSL CARD 9 IS OPTIONAL. (SPECIAL LINE SOURCES)	
ICARD	USED THE SAME AS IN THE POINT SOUCES.	(DIMENSIONLESS)
QLS	LINE SOURCE STRENGTH, ONE LANE ONLY.	(G/SEC)
HAS	HEIGHT OF POINT A.	(M)
HBS	HEIGHT OF POINT B.	(M)

TABLE 4. (CONTINUED)

RAS	EAST COORDINATE OF POINT A.	(KM)
SAS	NORTH COORDINATE OF POINT A.	(KM)
RBS	EAST COORDINATE OF POINT B.	(KM)
SBS	NORTH COORDINATE OF POINT B.	(KM)
SPDI	VEHICLE SPEED AT POINT A.	(M/SEC)
SPDF	VEHICLE SPEED AT POINT B.	(M/SEC)
SYOS	INITIAL SIGMA Y.	(M)
SZOS	INITIAL SIGMA Z.	(M)
TVSL	VEHICLE VOLUME.	(VEH/HR)
VSSL	GROSS ESTIMATE OF VEHICLE SIZE.	(M)
CARD TYPE 10	ICARD QLNA, HCL, RBQA, SBQA, RMQA, SMQA, REQA, SEQA, SPEI, SPEF, SIYA, SIZA, TVCL, VSCL. CARD 10 IS OPTIONAL. (SPECIAL CURVED PATH SOURCES)	
ICARD	USED THE SAME AS IN THE POINT SOURCES.	(DIMENSIONLESS)
QLNA	PATH SOURCE STRENGTH, ONE LANE ONLY.	(G/SEC)
HCL	PATH SOURCE HEIGHT.	(M)
RBQA	EAST COORDINATE OF POINT A.	(KM)
SBQA	NORTH COORDINATE OF POINT A.	(KM)
RMQA	EAST COORDINATE OF POINT B.	(KM)
SMQA	NORTH COORDINATE OF POINT B.	(KM)

TABLE 4. (CONTINUED)

REQA	EAST COORDINATE OF POINT C.	(KM)
SEQA	NORTH COORDINATE OF POINT C.	(KM)
SPEI	VEHICLE SPEED AT POINT A.	(M/SEC)
SPEF	VEHICLE SPEED AT POINT C.	(M/SEC)
SIYA	INITIAL SIGMA Y.	(M)
SIZA	INITIAL SIGMA Z.	(M)
TVCL	VEHICLE VOLUME.	(VEH/HR)
VSCL	GROSS ESTIMATE OF VEHICLE SIZE.	(M)
CARD TYPE 11	ICARD, RR, SR, ZR	
ICARD	USED THE SAME AS IN THE POINT SOURCES	(DIMENSIONLESS)
RR	EAST COORDINATE OF RECEPTOR.	(KM)
SR	NORTH COORDINATR OF RECEPTOR.	(KM)
ZR	HEIGHT OF RECEPTOR.	(M)
CARD TYPE 12	ICARD, WTHET, WU, MKST, WHL, WTA, DVP, DVA, DVH, DVS, DDVH, DVHA	
ICARD	USED THE SAME AS IN THE POINT SOURCES. UP TO 24 HOURS OF METEOROLOGY CAN BE INPUT.	(DIMENSIONLESS)
WTHET	WIND DIRECTION.	(DEG AZIMUTH)
WU	WIND SPEED.	(M/SEC)
MKST	STABILITY CLASS.	(DIMENSIONLESS)

TABLE 4. (CONTINUED)

WHL	MIXING HEIGHT.	(M)
WTA	AMBIENT AIR SURFACE TEMPERATURE.	(DEG K)
DVP	HOURLY VARIATION OF EMISSIONS FOR POINT SOURCES.	(DIMENSIONLESS)
DVA	HOURLY VARIATION OF EMISSIONS FOR AREA SOURCES.	(DIMENSIONLESS)
DVH	HOURLY VARIATION OF EMISSIONS FOR LINE SOURCES.	(DIMENSIONLESS)
DVS	HOURLY VARIATION OF EMISSIONS FOR SPECIAL LINE SOURCES.	(DIMENSIONLESS)
DDVH	HOURLY VARIATION OF EMISSIONS FOR CURVED PATH SOURCES.	(DIMENSIONLESS)
DVHA	HOURLY VARIATION OF EMISSIONS FOR SPECIAL PATH SOURCES. IF IDRNL = 1, (CARD 3) NO HOURLY INFORMATION NEEDED. IF IDRNL = 2, THE HOURLY VARIATION OF EMISSIONS ARE GIVEN AS THE RATIO OF THAT EMITTED DURING THIS HOUR TO THE INPUT EMISSION. IF THE SAME AS THE INPUT, THE VALUE IS 1.00	(DIMENSIONLESS)
CARD TYPE 13	KTL	
KTL	IF KTL = 0, PROGRAM TERMINATES. IF KTL = 1, START NEW PROBLEM. IF KTL = 2, READ NEW RECEPTOR AND METEOROLOGY DATA. IF KTL = 3, READ NEW METEOROLOGY DATA.	(DIMENSIONLESS)

Table 4 should be helpful in organizing data for input into PAL. However, there are several variables that may need further explanation. The balance of this section will be concerned with explaining the use of these input variables and should aid the user in assigning values to them.

POINT SOURCES

In the point source subroutine (POINT) the stack gas velocity (VSP) and stack inside diameter (DP) are ignored if the stack gas volume flow (VFP) is greater than zero. However, VSP and DP must still be specified with dummy values since the free format requires values for all variables. If there are no point sources in a particular run, then the ambient air temperature (WTA) from the meteorology input card type 12 is ignored. If WTA equals zero, then a value of 293°K is assumed in the program.

In subroutine POINT the initial dispersion parameters SYOP and SZOP allow for initial dispersion in the horizontal and vertical, respectively. For a tall stack these parameters would generally have little influence on downwind concentrations. The initial disperion parameters would be helpful in accounting for the initial mixing of a plume in the building wake. Due to the complex turbulence in the building wake, plume dispersion is best modeled using physical models. However, there are some simple cases where the initial dispersion parameters would be applicable. The values suggested for SYOP and SZOP in this report should be considered preliminary in nature. It is beyond the scope of this report to undertake a detailed discussion of aerodynamic effects in the wake of a building. Some pertinent points are discussed below concerning the circumstances in which aerodynamic effects are a problem and where SYOP and SZOP might be useful.

For a squat building, whose width is $\geq$ its height, a sufficient stack height and exit velocity for the effluent to escape the influence of the building is given by the familiar 2 1/2 times rule. The rule simply states that if the stack height is greater than 2 1/2 h (where h is the building height) and the exit velocity of the plume is greater than 1.5 u (where u is the mean wind speed), then the plume will escape from the influence of the building. Stack height always refers to the height of the stack above the ground. For a tall building, whose height is greater than its width, the 2 1/2 rule can be relaxed. Briggs (1973) suggested that a sufficient stack height would be the building height plus 1.5 times the smaller of either the building height, or the maximum width of the building perpendicular to the wind direction. If the criteria in either one of the above rules are met, then the stack can be considered a tall one, and building influences may be ignored.

In a wind tunnel study, for a squat building, whose width was twice its height, Huber and Snyder (1976) suggested that the plume was strongly affected by the recirculating flow in the wake "cavity" region behind the building during the following conditions: (1) When the stack height was $\leq$ 1.2 h and (2) When the exit velocity was $\leq$ 1.5 u. The buoyancy of the plume is generally not a factor in the initial plume capture within the "cavity" region. If the above criteria are met, then SYOP and SZOP can be used to model the initial mixing. Huber (1984) suggests that appropriate initial dispersion parameters might be

$$\sigma_{yo} = .35\ H_b$$
$$\sigma_{zo} = 0.7\ h$$

where: H_b is the width of the building and h is the building height.

These findings are applicable for cubical or squat buildings. For a building much wider than it is tall, it would be expected that σ_{yo} would reach a maximum. Concentrations very close to the building are extremely sensitive to the shape and orientation of the building with respect to the location of the source. Concentration estimates using the above initial dispersion parameters are more likely applicable for distances beyond ten building heights downwind. The last case that remains is a most difficult one: either the stack is not tall enough or the exit velocity of the plume not great enough for the plume to escape the influence of the building, but the plume is not totally affected by the building wake. The plume may be totally or partially captured in the displacement zone where it may be brought near the ground at some distance downwind. In such cases, physical models should be used to examine plume dispersion. More research is needed to determine the extent of the displacement zone and cavity behind a variety of shapes of buildings. The above initial dispersion parameters are intended to provide some guidance until more complete analyses can be obtained.

AREA SOURCES

It is not mandatory that variables DEST and DNOR on card type 6 have the same dimensions. Area sources can be either squares or rectangles. A special feature in PAL allows for the area source to be negative. The advantage of this feature is demonstrated in the example problem 1 in Section 6.

LINE SOURCES

In all of the line and curved path source subroutines the height of emissions must be specified. The variables HLN, HLNS, and HCL on card types 7, 8, and 10, respectively, represent the height of the line or curved path above the surrounding terrain. For a highway it is not the height of the highway above the surrounding terrain, but the height of the emissions above the highway. It is assumed that the height of the highway and surrounding terrain are nearly the same.

A uniform emission rate, q_ℓ, must be specified for each line source in subroutines HRZLN and CRVLN. For vehicles this line-source emission rate can be found if the emission factor, EF(g veh^{-1} mi^{-1}), and the traffic volume, TV(veh hr^{-1}), are known.

$$q_\ell \text{ (g sec}^{-1}\text{ m}^{-1}) = \frac{\text{EF(g veh mi}^{-1}\text{) TV(veh hr}^{-1})}{1609.3 \text{ (m mi}^{-1}) \text{ 3600 (sec hr}^{-1})}$$

$$= 1.726 \times 10^{-7} \text{ (EF) (TV)}$$

A value of the emission factor for automobiles can be obtained from supplement No. 5 for Compilation of Air Pollutant Emission Factors (EPA 1975). If the special line or special path sources are used, both of which allow the emission rate to vary, the user must specify the traffic volume (veh hr^{-1}) and the emission factor (g sec^{-1}) since these parameters are used internally to derive the variable emission rate as a function of location along the source. The emission factors for aircraft, where traffic volumes are low, should be 1-hour average values. PAL is not intended to predict peak concentrations that are likely to occur from aircraft emissions but rather is intended to estimate the average concentration over a 1-hour time period. The variables VSSL and VSCL on card types 9 and 10 respectively, are a rough estimate of the length of the vehicles being considered.

METEOROLOGY

The stability of the atmosphere (MKST) is specified on card type 12. The atmospheric stability is used to estimate the horizontal and vertical dispersion parameters, σ_y, σ_z. The dispersion parameters were developed from data most applicable to open country (Pasquill, 1961). When PAL is used in urban areas (IURB on card type 4 should be 2) the dispersion parameters suggested by McElroy-Pooler (1968) are used and account for the increase in the roughness elements and the generally more unstable air over urban environments.

The wind-increase-with-height option allows the user to either specify the wind speed (constant for all heights) or to use the option and let the program estimate the wind speed for different heights. To account for an increase of wind with height a power law of the form

$$u_{(z)} = u_o \ (z/z_o)^p$$

is used in PAL. Irwin (1977) suggested a theoretical variation of the wind profile power law exponent as a function of surface roughness and stability. The exponents given in Table 5 are appropriate for a surface roughness typical of urban areas.

TABLE 5. EXPONENTS FOR WIND PROFILE

Stability class	Rural Exponent (p)	Urban Exponent (p)
A	.07	.15
B	.07	.15
C	.10	.20
D	.15	.25
E	.35	.30
F	.55	.30

On card type 4 of the input data, UHGT is the height applicable to the wind speed, generally anemometer height. This variable is only used if the wind increase with height option is used for one or more of the source types. However, if the option is not used, a value for UHGT is required due to the free format input. The usual anemometer height for airport data is in the range of 7-10 meters.

SECTION 9
SENSITIVITY ANALYSIS

The area source and four line source algorithms estimate the concentration at each receptor through an interative process. The convergence criteria are specified by the user through the PINA and PINL values. In the past we have recommended a value of 0.02 (2%) for these values but no sensitivity test were performed to establish the sensitivity of CPU time and concentration estimates to the PINA and PINL values. A brief description of the sensitivity of CPU time and concentration estimates for PINA, PINL values from 0.001 to 0.1 are provided in this section. A 1 km area source and two line sources were considered in this sensitivity test. The line sources differed only in their length. One was 100 km while the other was 1 km. Receptor distances varied from 2 m to 10 km downwind of the source. Wind direction, atmospheric stability, and source receptor geometry all effect the number of iteration necessary for convergence.

Table 6 shows the percentage difference in CPU time for three wind direction and two source types. The percentage difference was computed between the PINA (PINL) values 0.001 and 0.1. Table 6 as well as other computations not shown indicate the run time is more sensitive for the line source algorithm. The PINA value can be assigned a very small value without the sacrifice of excessive run time.

The sensitivity of concentration estimates are shown in Figure 10. The percentage difference versus the PINA (PINL) values are plotted for three wind direction orientations and three stability classes (P-G classes A, D, and F). The percentage difference was computed for the nearest receptor since it was the most sensitive. This figure clearly shows the sensitivity to wind direction, stability and source receptor geometry. It is difficult to generalize these results since a slight change in wind direction or source receptor geometry could significantly change the results.

TABLE 6. PERCENTAGE DIFFERENCE IN CPU TIME FOR PINL (PINA) VALUES OF 0.001. and 0.1. Difference [(CPU 0.001 - CPU 0.1)/CPU 0.001] *100

Wind Direction	Area Source	Long Line Source
Perpendicular	14.5	1.36
Oblique	14.6	26.9
Parallel	9.1	22.1

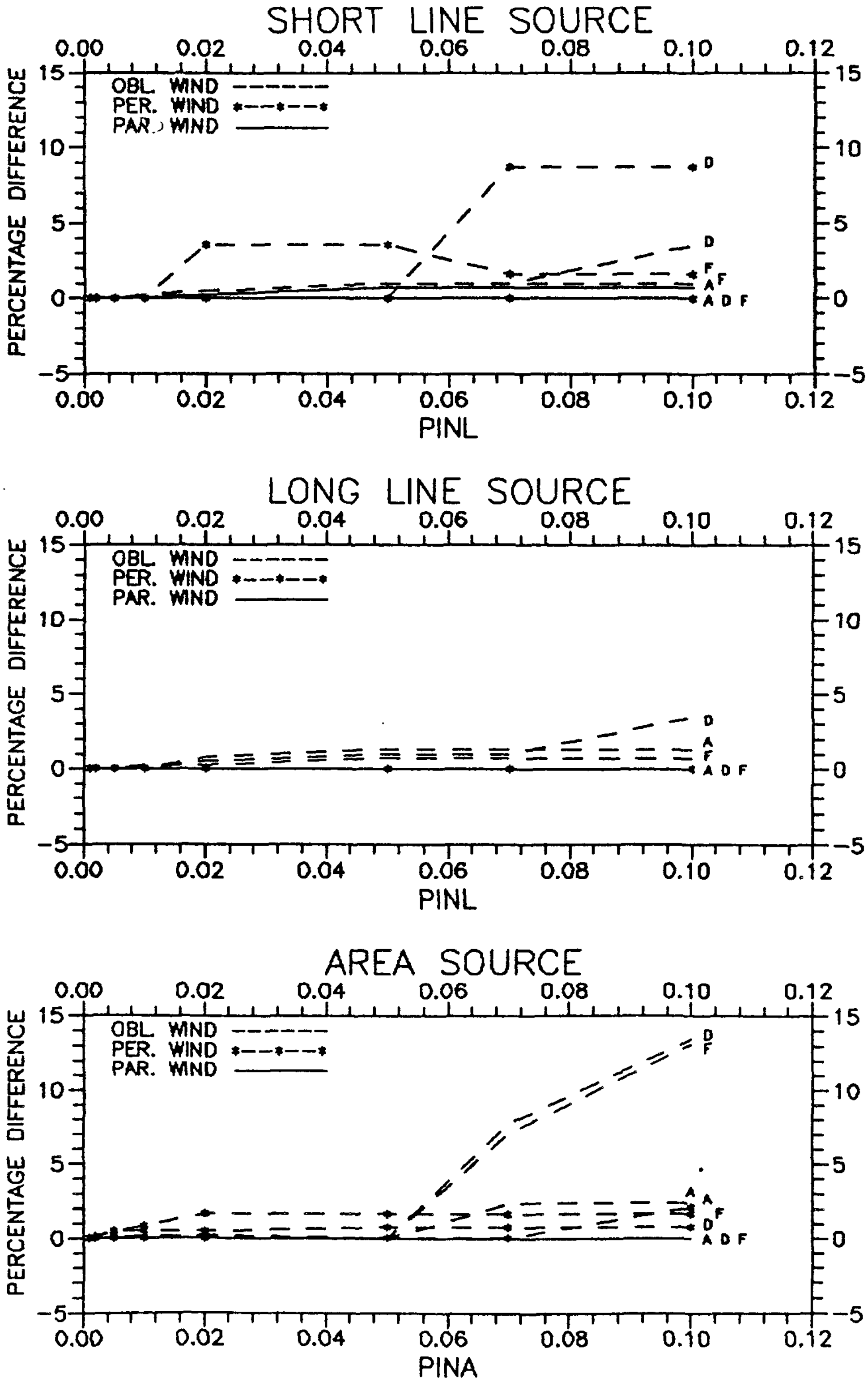

Figure 10. Percentage difference in concentration versus integration accuracy. The P-G stability for each simulation is indicated by A, D, or F.

SECTION 10

EXECUTION OF THE MODEL AND INTERPRETATION OF OUTPUT

PAL produces an error free compile on the UNIVAC 1110 computer. The code should be transportable to other systems with little or no change. The output of PAL has eleven parts, two 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 options beginning with the urban (IURB) option and the user designated PINA (area integration accuracy) and PINL (line integration accuracy) values. Following the option list, the levels of constant wind are printed along with the minimum wind value. If the user has exercised the option for deposition the output prints a statement confirming the choice along with its corresponding velocity values next. The rural or urban wind profile exponents are then listed with either their default or user specified values. The next output section is the source type, then all receptor information is listed followed by a printing of the current meteorology conditions. Finally, a table of total concentrations is output giving totals for each receptor for all meteorological periods.

The optional outputs available to the user include concentration averages and deposition flux tables. If the option for concentration averages is used, a table listing average concentrations for each source type is printed out for each set of meteorology. Average concentrations are indicated by zeros in the column entitled "Hour". If the deposition option is exercised, the output prints a listing of deposition fluxes for each receptor for all meteorology periods.

A job stream on the UNIVAC 1110 system might have the following form:

```
@RUN, R/R 12 JOB-ID, ETC
@SYM PRINT $., 1, PR
@ASG, A PAL.
@XQT PAL.
```

The input and output listing of example problems 1 and 2 of section 6 are presented in this section. The sample test data for example 1 is as follows:

TABLE 7. INPUT DATA FOR EXAMPLE PROBLEM 1

CARD TYPE	
1	EXAMPLE PROBLEM FOR PAL
2	0.02,0.02,2,2,2,2,2,1
3	1,1,1,1,1,1,2,1
4	1,1,0.0,0.0,5.,10.,200.,1
5	2,5.0,10.0,320.,0.,0.,12.,4.26,3.14,1.,1.
6	1,0.0002,0.,4.2,2.6,0.6,0.8
6	2,-0.0002,0.,4.2,2.8,0.2,0.4
7	1,0.,4,0.2,0.5,4.0,0.5,3.0,1.5,16.,0.,0.0001,0.002,0.0009,0.001
7	1,0.,4,5.45,1.3,7.3,4.,3.,1.5,16.,0.,0.0018,0.0018,0.0009,0.0007
7	2,0.,2,4.8,3.,6.52,3.,3.,1.5,8.,0.,0.002,0.002
8	2,0.,4,4.,0.5,4.6,0.58,5.45,1.3,3.,1.5,16.,0.,0.001,0.002,0.0009,0.001
9	1,30.,3.,3.,3.2,4.5,6.4,4.5,0.,80.,15.,6.,60.,30.
9	2,10.,3.,3.,0.8,1.5,4.,1.5,80.,0.,15.,6.,60.,30.
11	1,4.6,4.2,1.
11	1,4.6,3.6,1.
11	1,4.6,2.4,1.
11	1,4.6,1.2,1.
11	2,4.6,0.2,1.
12	1,0.,2.,4,500.,285.
12	1,350.,2.5,3,900.,289.
12	2,345.,3.,2,1100.,294.
13	3
12	1,30.,3.,4,1000.,290.
12	1,45.,6.1,4,1000.,300.
12	2,50.,3.8,3,1000.,298.
13	0

The numbers in the left hand column of table 4 are the input card type numbers. For a complete description of each input card type see Table 1. In this example there is no input card type 10, since there are no special curved path sources. Table 5 is a computer listing of the output for example 1. Sources included are indicated by "YES's" under the column titles "Sources Included" in the options list. Average concentrations are calculated for two 3-hour meteorology periods. The hourly variations in emissions option is not used in this problem. Concentrations at the receptors are in units of gm^{-3}.

Figure 11. Computer listing of output for example problem 1.

```
                PAL-2.0 (DATE 86087)
                AN AIR QUALITY DISPERSION MODEL IN
                SECTION 3.  NON-GUIDELINE MODELS.
                IN UNAMAP (VERSION 6) JUL 86
                SOURCE: UNAMAP FILE ON EPA'S UNIVAC 1110, RTP,NC.

EXAMPLE PROBLEM FOR PAL                                               DATE 86077

URBAN OPTION (IURB) = 1 (1 - PASQUILL-GIFFORD DISPERSION CURVES, 2 - BRIGGS/MCELROY-POOLER DISPERSION CURVES)


PINA =    0.02000 PINL =    0.02000

             SOURCE     WIND INCREASE
            INCLUDED    WITH  HEIGHT

   POINT       YES            NO

   AREA        YES            NO

HORIZONTAL
LINE SOURCE    YES            NO

    CURVE
PATH SOURCE    YES            NO

  SPECIAL
LINE SOURCE    YES            NO

  SPECIAL
PATH SOURCE     NO            NO          AVERAGE     YES   DIURNAL    NO     HEIGHT AT WIND SPEED    5.0 METERS
WIND CONSTANT BELOW 10.0 METERS AND ABOVE 200.0 METERS. MINIMUM WIND SPEED SET TO:  1.0M/S.
 WIND PROFILE EXPONENTS FOR STABILITY CLASSES (A-F)     0.07   0.07   0.10   0.15   0.35   0.55


***P O I N T   S O U R C E S***
      NO.    POINT    PHYSICAL   STACK     STACK     STACK    VOLUME       COORDINATES        INITIAL SIGMAS
            SOURCE     HEIGHT    TEMP       GAS    DIAMETER    FLOW      EAST      NORTH        Y          Z
           STRENGTH   (METERS)  (DEG-K)  VELOCITY  (METERS)  (CU M/SEC)  (KM)      (KM)        (M)        (M)
            (G/SEC)                       (M/SEC)

      1        5.00      10.0     320.0     0.00      0.00     12.00     4.260     3.140       1.0        1.0
```

Figure 11. (Continued)

AREA SOURCES

NO.	AREA SOURCE STRENGTH (G/SEC-M**2)	AREA SOURCE HEIGHT (METERS)	COORDINATES SW-CORNER EAST (KM)	COORDINATES SW-CORNER NORTH (KM)	AREA SIZE EAST-WEST (KM)	AREA SIZE NORTH-SOUTH (KM)
1	0.00020000	0.0	4.200	2.600	0.600	0.800
2	-.00020000	0.0	4.200	2.800	0.200	0.400

HORIZONTAL LINE SOURCES

NO.	LINE SOURCE STRENGTH (G/SEC-M)	LINE SOURCE HEIGHT (METERS)	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)	NO. OF LANES	TOTAL WIDTH (METERS)	MEDIAN WIDTH (METERS)
1	0.00010000	0.0	0.200	0.506	4.000	0.506	3.00	1.50	4.	16.0	0.0
2	0.00200000	0.0	0.200	0.502	4.000	0.502	3.00	1.50			
3	0.00090000	0.0	0.200	0.498	4.000	0.498	3.00	1.50			
4	0.00100000	0.0	0.200	0.494	4.000	0.494	3.00	1.50			
5	0.00180000	0.0	5.445	1.303	7.295	4.003	3.00	1.50	4.	16.0	0.0
6	0.00180000	0.0	5.448	1.301	7.298	4.001	3.00	1.50			
7	0.00090000	0.0	5.452	1.299	7.302	3.999	3.00	1.50			
8	0.00070000	0.0	5.455	1.297	7.305	3.997	3.00	1.50			
9	0.00200000	0.0	4.800	3.002	6.520	3.002	3.00	1.50	2.	8.0	0.0
10	0.00200000	0.0	4.800	2.998	6.520	2.998	3.00	1.50			

CURVED HORIZONTAL PATH SOURCES

NO.	PATH SOURCE STRENGTH (G/SEC-M)	PATH SOURCE HEIGHT (METERS)	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	POINT C EAST (KM)	POINT C NORTH (KM)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)	NO. OF LANES	TOTAL WIDTH (METERS)	MEDIAN WIDTH (METERS)
1	0.00100000	0.000	4.000	0.500	4.600	0.580	5.450	1.300	3.00	1.50	4	16.00	0.00

SOURCE STRENGTH FOR THE REMAINING LANES

LANE	SOURCE STRENGTH
2	0.00200000
3	0.00090000
4	0.00100000

Figure 11. (Continued)

SLANT OR VERTICAL LINE SOURCES*

NO.	SOURCE STRENGTH (G/SEC)	SOURCE HEIGHT (METERS) POINT A	POINT B	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	INITIAL SPEED (M/SEC)	FINAL SPEED (M/SEC)	INITIAL SIGMAS Y (M)	Z (M)	TRAFFIC VOLUME (VEH/HR)	VEH. SIZE (M)
1	30.00	3.0	3.0	3.200	4.500	6.400	4.500	0.000	80.000	15.00	6.00	60.	30.0
2	10.00	3.0	3.0	0.800	1.500	4.000	1.500	80.000	0.000	15.00	6.00	60.	30.0

RECEPTORS*

NO.	RREC(KM)	SREC(KM)	Z (M)
1	4.600	4.200	1.0
2	4.600	3.600	1.0
3	4.600	2.400	1.0
4	4.600	1.200	1.0
5	4.600	0.200	1.0

METEOROLOGY*

NO.	THETA(DEG)	U (M/SEC)	KST	HL (M)	T (DEG-K)	DIURNAL VARIATIONS (FRACTIONS OF GIVEN Q) POINT	AREA	HORIZONAL LINE	CURVED PATH	SPECIAL LINE	SPECIAL PATH
1.	0.	2.0	4	500.	285.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2.	350.	2.5	3	900.	289.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3.	345.	3.0	2	1100.	294.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

CONCENTRATIONS AT RECEPTORS*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
1	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	2.268E-04	0.000E-01	2.268E-04
1	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	1.145E-04	0.000E-01	1.145E-04
1	3	4.600	2.400	1.00	1.233E-13	3.455E-03	3.169E-10	0.000E-01	7.016E-05	0.000E-01	3.526E-03
1	4	4.600	1.200	1.00	2.274E-06	1.272E-03	1.525E-06	0.000E-01	5.378E-05	0.000E-01	1.330E-03
1	5	4.600	0.200	1.00	9.673E-06	8.203E-04	3.233E-06	1.335E-04	4.635E-05	0.000E-01	1.013E-03

Figure 11. (Continued)

CONCENTRATIONS AT RECEPTORS*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
2	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	1.218E-04	0.000E-01	1.218E-04
2	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	5.366E-05	0.000E-01	5.366E-05
2	3	4.600	2.400	1.00	5.868E-06	1.510E-03	2.310E-11	0.000E-01	2.886E-05	0.000E-01	1.545E-03
2	4	4.600	1.200	1.00	2.797E-05	2.387E-04	1.867E-08	0.000E-01	2.329E-05	0.000E-01	2.900E-04
2	5	4.600	0.200	1.00	1.119E-05	8.272E-05	3.221E-08	6.213E-05	2.206E-05	0.000E-01	1.781E-04

CONCENTRATIONS AT RECEPTORS*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
3	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	7.318E-05	0.000E-01	7.318E-05
3	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	2.682E-05	0.000E-01	2.682E-05
3	3	4.600	2.400	1.00	2.570E-05	7.042E-04	7.501E-10	0.000E-01	1.405E-05	0.000E-01	7.440E-04
3	4	4.600	1.200	1.00	6.731E-06	5.882E-05	1.992E-08	0.000E-01	1.018E-05	0.000E-01	7.575E-05
3	5	4.600	0.200	1.00	2.070E-06	1.713E-05	2.031E-08	3.482E-05	1.090E-05	0.000E-01	6.495E-05

AVERAGE CONCENTRATIONS FOR 3 HOURS.

CONCENTRATIONS AT RECEPTORS*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
0	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	1.406E-04	0.000E-01	1.406E-04
0	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	6.501E-05	0.000E-01	6.501E-05
0	3	4.600	2.400	1.00	1.052E-05	1.890E-03	3.633E-10	0.000E-01	3.769E-05	0.000E-01	1.938E-03
0	4	4.600	1.200	1.00	1.232E-05	5.233E-04	5.212E-07	0.000E-01	2.908E-05	0.000E-01	5.653E-04
0	5	4.600	0.200	1.00	7.643E-06	3.067E-04	1.095E-06	7.681E-05	2.644E-05	0.000E-01	4.187E-04

Figure 11. (Continued)

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

NO.	THETA(DEG)	U (M/SEC)	KST	HL (M)	T (DEG-K)	DIURNAL VARIATIONS (FRACTIONS OF GIVEN Q) POINT	AREA	HORIZONAL LINE	CURVED PATH	SPECIAL LINE	SPECIAL PATH
1.	30.	3.0	4	1000.	290.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2.	45.	6.1	4	1000.	300.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3.	50.	3.8	3	1000.	298.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
1	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	1.521E-04	0.000E-01	1.521E-04
1	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	6.940E-05	0.000E-01	6.940E-05
1	3	4.600	2.400	1.00	0.000E-01	7.377E-04	4.976E-05	0.000E-01	3.601E-05	0.000E-01	8.235E-04
1	4	4.600	1.200	1.00	0.000E-01	0.000E-01	2.370E-05	0.000E-01	8.903E-06	0.000E-01	3.260E-05
1	5	4.600	0.200	1.00	0.000E-01	0.000E-01	5.627E-05	1.345E-04	3.888E-07	0.000E-01	1.912E-04

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
2	1	4.600	4.200	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	7.824E-05	0.000E-01	7.824E-05
2	2	4.600	3.600	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	3.398E-05	0.000E-01	3.398E-05
2	3	4.600	2.400	1.00	0.000E-01	3.868E-05	2.547E-05	0.000E-01	2.100E-06	0.000E-01	6.625E-05
2	4	4.600	1.200	1.00	0.000E-01	0.000E-01	3.913E-05	0.000E-01	2.186E-11	0.000E-01	3.913E-05
2	5	4.600	0.200	1.00	0.000E-01	0.000E-01	6.310E-06	1.567E-05	1.730E-16	0.000E-01	2.198E-05

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
3	1	4.600	4.200	1.00	0.000E-01	0.000E-01	6.488E-29	0.000E-01	7.790E-05	0.000E-01	7.790E-05
3	2	4.600	3.600	1.00	0.000E-01	0.000E-01	8.653E-16	0.000E-01	2.626E-05	0.000E-01	2.626E-05
3	3	4.600	2.400	1.00	0.000E-01	1.797E-05	2.296E-05	0.000E-01	5.102E-07	0.000E-01	4.144E-05
3	4	4.600	1.200	1.00	0.000E-01	0.000E-01	2.822E-05	2.150E-14	1.261E-10	0.000E-01	2.822E-05
3	5	4.600	0.200	1.00	0.000E-01	0.000E-01	2.048E-06	5.608E-06	7.018E-14	0.000E-01	7.656E-06

Figure 11. (Continued)

AVERAGE CONCENTRATIONS FOR 3 HOURS.

CONCENTRATIONS AT RECEPTORS*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
0	1	4.600	4.200	1.00	0.000E-01	0.000E-01	2.163E-29	0.000E-01	1.027E-04	0.000E-01	1.027E-04
0	2	4.600	3.600	1.00	0.000E-01	0.000E-01	2.884E-16	0.000E-01	4.321E-05	0.000E-01	4.321E-05
0	3	4.600	2.400	1.00	0.000E-01	2.648E-04	3.273E-05	0.000E-01	1.287E-05	0.000E-01	3.104E-04
0	4	4.600	1.200	1.00	0.000E-01	0.000E-01	3.035E-05	7.168E-15	2.968E-06	0.000E-01	3.332E-05
0	5	4.600	0.200	1.00	0.000E-01	0.000E-01	2.154E-05	5.192E-05	1.296E-07	0.000E-01	7.360E-05

Table 8 lists the input data cards for example problem 2. Figure 12 is a computer listing of the output. As in the previous problem, the output begins with a listing of all the input parameters and options used. All source types are included here. The output continues with the same format except that deposition flux tables are listed in kg/km^2-hour following the concentration tables. Also, no average concentrations are printed. It should be noted that calculated concentrations are less when including the effects of deposition loss as compared to those of the similar case not considering deposition loss.

TABLE 8. INPUT DATA FOR EXAMPLE PROBLEM 2

CARD TYPE	
1	TEST OF PAL USING ALL SOURCE TYPES FOR TSP
2	.02,.02,2,2,2,2,2,2
3	1,1,1,1,1,1,1,1
4	1,2,10.,10.,5.,10.,200.,1.
5	2,10.,50.,310.,0.0,0.0,12.,6.25,5.,3.,2.
6	2,.05,1.,6.,4.,.5,.5
7	1,.5,2,3.75,6.25,11.,6.25,3.,2.,10.,0.0,.001,.001
7	2,.5,2,2.75,.5,2.75,5.25,3.,2.,10.,0.0,.001,.001
8	2,.5,2,2.75,5.25,3.04,5.96,3.75,6.25,3.,2.,10.,0.0,.001,.001
9	2,10.,.2,10.,2.752,4.25,6.,4.25,40.,40.,3.,1.5,60.,5.
10	2,8.,.5,2.75,2.25,4.27,2.73,4.75,4.25,50.,50.,2.,1.5,40.,5.
11	1,5.5,2.,1.
11	1,4.5,5.5,8.
11	1,10.,8.5,1.
11	1,7.5,2.5,5.
11	2,1.,8.,1.
12	1,315.,4.,3,1000.,280.
12	1,45.,4.,3,1000.,280.
12	1,135.,4.,3,1000.,280.
12	2,225.,4.,3,1000.,280.
13	0

Figure 12. Computer listing of output for example problem 2.

```
          PAL-2.0 (DATE 86087)
          AN AIR QUALITY DISPERSION MODEL IN
          SECTION 3.  NON-GUIDELINE MODELS.
          IN UNAMAP (VERSION 6) JUL 86
          SOURCE: UNAMAP FILE ON EPA'S UNIVAC 1110, RTP,NC.

TEST OF PAL USING ALL SOURCE TYPES FOR TSP                                DATE 86077

URBAN OPTION (IURB) = 1 (1 - PASQUILL-GIFFORD DISPERSION CURVES, 2 - BRIGGS/MCELROY-POOLER DISPERSION CURVES)

PINA =   0.02000 PINL =   0.02000

              SOURCE    WIND INCREASE
             INCLUDED   WITH  HEIGHT

   POINT       YES           NO

   AREA        YES           NO

HORIZONTAL
LINE SOURCE    YES           NO

   CURVE
PATH SOURCE    YES           NO

  SPECIAL
LINE SOURCE    YES           NO

  SPECIAL
PATH SOURCE    YES           NO        AVERAGE     NO   DIURNAL    NO     HEIGHT AT WIND SPEED    5.0 METERS
WIND CONSTANT BELOW 10.0 METERS AND ABOVE 200.0 METERS. MINIMUM WIND SPEED SET TO:  1.0M/S.

GRAVITATIONAL SETTLING AND/OR DEPOSITION LOSS OF POLLUTANT CONSIDERED
POLLUTANT SETTLING VELOCITY = 10.00 CM/SEC     POLLUTANT DEPOSITION VELOCITY = 10.00 CM/SEC

 WIND PROFILE EXPONENTS FOR STABILITY CLASSES (A-F)     0.07   0.07   0.10   0.15   0.35   0.55
```

*** P O I N T   S O U R C E S ***

NO.	POINT SOURCE STRENGTH (G/SEC)	PHYSICAL HEIGHT (METERS)	STACK TEMP (DEG-K)	STACK GAS VELOCITY (M/SEC)	STACK DIAMETER (METERS)	VOLUME FLOW (CU M/SEC)	COORDINATES EAST (KM)	COORDINATES NORTH (KM)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)
1	10.00	50.0	310.0	0.00	0.00	12.00	6.250	5.000	3.0	2.0

Figure 12. (Continued)

AREA SOURCES*

NO.	AREA SOURCE STRENGTH (G/SEC-M**2)	AREA SOURCE HEIGHT (METERS)	COORDINATES SW-CORNER EAST (KM)	COORDINATES SW-CORNER NORTH (KM)	AREA SIZE EAST-WEST (KM)	AREA SIZE NORTH-SOUTH (KM)
1	0.05000000	1.0	6.000	4.000	0.500	0.500

HORIZONTAL LINE SOURCES*

NO.	LINE SOURCE STRENGTH (G/SEC-M)	LINE SOURCE HEIGHT (METERS)	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)	NO. OF LANES	TOTAL WIDTH (METERS)	MEDIAN WIDTH (METERS)
									2.	10.0	0.0
1	0.00100000	0.5	3.750	6.253	11.000	6.253	3.00	2.00			
2	0.00100000	0.5	3.750	6.247	11.000	6.247	3.00	2.00			
									2.	10.0	0.0
3	0.00100000	0.5	2.747	0.500	2.747	5.250	3.00	2.00			
4	0.00100000	0.5	2.753	0.500	2.753	5.250	3.00	2.00			

CURVED HORIZONTAL PATH SOURCES *

NO.	PATH SOURCE STRENGTH (G/SEC-M)	PATH SOURCE HEIGHT (METERS)	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	POINT C EAST (KM)	POINT C NORTH (KM)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)	NO. OF LANES	TOTAL WIDTH (METERS)	MEDIAN WIDTH (METERS)
1	0.00100000	0.500	2.750	5.250	3.040	5.960	3.750	6.250	3.00	2.00	2	10.00	0.00

SOURCE STRENGTH FOR THE REMAINING LANES

LANE	SOURCE STRENGTH
2	0.00100000

SLANT OR VERTICAL LINE SOURCES*

NO.	SOURCE STRENGTH (G/SEC)	SOURCE HEIGHT (METERS) POINT A	SOURCE HEIGHT (METERS) POINT B	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	INITIAL SPEED (M/SEC)	FINAL SPEED (M/SEC)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS Z (M)	TRAFFIC VOLUME (VEH/HR)	VEH. SIZE (M)
1	10.00	0.2	10.0	2.752	4.250	6.000	4.250	40.000	40.000	3.00	1.50	60.	5.0

SPECIAL PATH SOURCES *

NO.	SOURCE STRENGTH (G/SEC)	SOURCE HEIGHT (METERS)	POINT A EAST (KM)	POINT A NORTH (KM)	POINT B EAST (KM)	POINT B NORTH (KM)	POINT C EAST (KM)	POINT C NORTH (KM)	INITIAL SPEED (M/SEC)	FINAL SPEED (M/SEC)	INITIAL SIGMAS Y (M)	INITIAL SIGMAS 0 (M)	TRAFFIC VOLUME (VEH/HR)	VEH. SIZE (M)
1	8.00	0.5	2.750	2.250	4.270	2.730	4.750	4.250	50.000	50.000	2.000	1.500	40.	5.0

Figure 12. (Continued)

R E C E P T O R S*

NO.	RREC(KM)	SREC(KM)	Z (M)
1	5.500	2.000	1.0
2	4.500	5.500	8.0
3	10.000	8.500	1.0
4	7.500	2.500	5.0
5	1.000	8.000	1.0

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

DIURNAL VARIATIONS (FRACTIONS OF GIVEN Q)

NO.	THETA(DEG)	U (M/SEC)	KST	HL (M)	T (DEG-K)	POINT	AREA	HORIZONAL LINE	CURVED PATH	SPECIAL LINE	SPECIAL PATH
1.	315.	4.0	3	1000.	280.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2.	45.	4.0	3	1000.	280.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3.	135.	4.0	3	1000.	280.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4.	225.	4.0	3	1000.	280.	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

NOTE: CONCENTRATIONS ARE AFFECTED BY GRAVITATIONAL SETTLING AND/OR DEPOSITION LOSS OF POLLUTANT.

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
1	1	5.500	2.000	1.00	0.000E-01	0.000E-01	1.155E-06	1.994E-07	3.088E-06	2.405E-06	6.847E-06
1	2	4.500	5.500	8.00	0.000E-01	0.000E-01	2.425E-06	2.165E-06	0.000E-01	0.000E-01	4.590E-06
1	3	10.000	8.500	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
1	4	7.500	2.500	5.00	2.989E-08	6.702E-03	5.221E-07	4.034E-07	3.731E-06	1.142E-08	6.707E-03
1	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
2	1	5.500	2.000	1.00	2.904E-14	1.025E-06	8.566E-07	0.000E-01	1.583E-16	0.000E-01	1.882E-06
2	2	4.500	5.500	8.00	0.000E-01	0.000E-01	4.830E-06	0.000E-01	0.000E-01	0.000E-01	4.830E-06
2	3	10.000	8.500	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
2	4	7.500	2.500	5.00	0.000E-01	0.000E-01	3.634E-07	0.000E-01	0.000E-01	0.000E-01	3.634E-07
2	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

Figure 12. (Continued)

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
3	1	5.500	2.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
3	2	4.500	5.500	8.00	7.464E-12	6.690E-03	0.000E-01	0.000E-01	5.502E-06	1.321E-15	6.696E-03
3	3	10.000	8.500	1.00	0.000E-01	0.000E-01	5.570E-11	0.000E-01	0.000E-01	0.000E-01	5.570E-11
3	4	7.500	2.500	5.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
3	5	1.000	8.000	1.00	2.313E-08	4.723E-04	3.569E-08	1.374E-06	2.094E-06	4.169E-07	4.762E-04

C O N C E N T R A T I O N S A T R E C E P T O R S*

CONCENTRATIONS IN GRAMS PER CUBIC METER

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
4	1	5.500	2.000	1.00	0.000E-01	0.000E-01	1.190E-09	0.000E-01	0.000E-01	0.000E-01	1.190E-09
4	2	4.500	5.500	8.00	0.000E-01	0.000E-01	2.165E-06	1.433E-19	6.036E-06	5.495E-10	8.201E-06
4	3	10.000	8.500	1.00	3.678E-06	2.652E-03	2.101E-06	2.304E-12	1.234E-06	7.682E-07	2.659E-03
4	4	7.500	2.500	5.00	0.000E-01	0.000E-01	2.029E-12	0.000E-01	0.000E-01	1.569E-26	2.029E-12
4	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

D E P O S I T I O N F L U X A T G R O U N D L E V E L R E C E P T O R S

DEPOSITION FLUXES IN KILOGRAMS PER SQUARE KILOMETER PER HOUR

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
1	1	5.500	2.000	1.00	0.000E-01	0.000E-01	4.157E-01	7.179E-02	1.112E+00	8.659E-01	2.465E+00
1	3	10.000	8.500	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
1	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

D E P O S I T I O N F L U X A T G R O U N D L E V E L R E C E P T O R S

DEPOSITION FLUXES IN KILOGRAMS PER SQUARE KILOMETER PER HOUR

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
2	1	5.500	2.000	1.00	1.045E-08	3.692E-01	3.084E-01	0.000E-01	5.699E-11	0.000E-01	6.776E-01
2	3	10.000	8.500	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
2	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

Figure 12. (Continued)

D E P O S I T I O N   F L U X   A T   G R O U N D   L E V E L   R E C E P T O R S

DEPOSITION FLUXES IN KILOGRAMS PER SQUARE KILOMETER PER HOUR

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
3	1	5.500	2.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01
3	3	10.000	8.500	1.00	0.000E-01	0.000E-01	2.005E-05	0.000E-01	0.000E-01	0.000E-01	2.005E-05
3	5	1.000	8.000	1.00	8.326E-03	1.700E+02	1.285E-02	4.947E-01	7.537E-01	1.501E-01	1.714E+02

D E P O S I T I O N   F L U X   A T   G R O U N D   L E V E L   R E C E P T O R S

DEPOSITION FLUXES IN KILOGRAMS PER SQUARE KILOMETER PER HOUR

HOUR	RECEPTOR NO.	RECEPTOR COORDINATES EAST	NORTH	HEIGHT	FROM POINTS	FROM AREAS	FROM HORIZONAL LINES	FROM CURVED PATHS	FROM SPECIAL LINES	FROM SPECIAL PATHS	TOTAL
4	1	5.500	2.000	1.00	0.000E-01	0.000E-01	4.284E-04	0.000E-01	0.000E-01	0.000E-01	4.284E-04
4	3	10.000	8.500	1.00	1.324E+00	9.546E+02	7.562E-01	8.295E-07	4.444E-01	2.765E-01	9.574E+02
4	5	1.000	8.000	1.00	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01	0.000E-01

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APPENDIX

SETTLING AND DEPOSITION VELOCITIES

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

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

$$W = \frac{d^2 \, g \, \rho}{18 \, \mu}$$

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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