180
11/2

44.2326

TIME-SHARING ISOPLETH-AREA PROGRAM

Richard F. King

ARGONNE NATIONAL LABORATORY

CENTER FOR ENVIRONMENTAL STUDIES

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Atomic Energy Commission, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	Kansas State University	The Ohio State University
Carnegie-Mellon University	The University of Kansas	Ohio University
Case Western Reserve University	Loyola University	The Pennsylvania State University
The University of Chicago	Marquette University	Purdue University
University of Cincinnati	Michigan State University	Saint Louis University
Illinois Institute of Technology	The University of Michigan	Southern Illinois University
University of Illinois	University of Minnesota	The University of Texas at Austin
Indiana University	University of Missouri	Washington University
Iowa State University	Northwestern University	Wayne State University
The University of Iowa	University of Notre Dame	The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

Printed in the United States of America
Available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.95

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

TIME-SHARING ISOPLETH-AREA PROGRAM

by

Richard F. King

Center for Environmental Studies

September 1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	5
1. INTRODUCTION	5
2. USING THE TIME-SHARING PROGRAM.	6
2.1 Typical Program Run	9
2.2 Costs.	13
3. APPLICATION OF THE PROGRAM.	14
4. DETERMINING EFFECTIVE STACK HEIGHT; MEAN WIND SPEED, AND MIXING HEIGHT	14
4.1 Effective Stack Height.	14
4.2 Mean Wind Speed.	16
4.3 Mixing-layer Height	17
5. THEORY AND LIMITATIONS OF THE PLUME AND PUFF MODELS	17
5.1 Basic Equation and Theory	17
5.2 Ground-level Reflection	18
5.3 Mixing-height Assumption	18
5.4 Theory of the Puff Model.	19
5.5 Accuracy of Atmospheric Dispersion Estimates	21
APPENDIX: Source-program Listing for PLETHS, Isopleth Area at Ground Level for Single Source	23
REFERENCES:	35

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TIME-SHARING ISOPLETH-AREA PROGRAM

by

Richard F. King

ABSTRACT

The time-sharing computer program discussed in this report provides an immediate estimate of the location and extent of downwind pollution concentration resulting from a single source. Stack height, weather conditions, and source emission rate are to be typed in at a teletype terminal connected by dataphone to the computer. The program calculates and describes high-pollution areas enclosed by isopleths of constant pollutant concentration. To do so, it uses the plume and the puff models for atmospheric dispersion.

Concentrations and isopleths may be calculated for any gas or any airborne particulate matter.

A typical program run is shown, as well as a source-statement listing of the entire program.

1. INTRODUCTION

This report describes a time-sharing computer program for determining ground-level areas of high pollutant concentration downwind of a single source of emission. These elliptical areas, also called "footprints," are enclosed by isopleths of constant concentration. They are produced by continuous pollutant emissions from one smoke stack or ground source, or from a closely associated group of single sources.

Concentrations for each point of a square grid are calculated by means of the plume model for atmospheric dispersion or (for low wind speeds) the puff model, both described in Sec. 5 below. Grid points are one-half mile apart, with the grid axis pointed downwind. Since pollutant concentrations are functions of source strength, effective stack height, mixing height, and wind speed, the user must provide these as teletype terminal input data. He also indicates cloud conditions, date, and time (or, optionally, the atmospheric stability class). These are utilized by the program to determine the stability class and in turn the horizontal and vertical dispersion coefficients for each downwind distance.

Most of the analysis and programming for the time-sharing program was accomplished several years ago, and formed the basis for the isopleth-area code and tables described in Ref. 1. That report should be referred to for details not covered here. The isopleth-area code also formed "the nucleus of the PUFF program."² The PUFF code associated with the APICS system³ performs the single-source calculations for all of the point sources in the system, and synthesizes the data in a time-dependent calculation to model urban air quality." (From the Introduction in Ref. 1.)

The present effort modifies this isopleth-area code to allow immediate time-sharing computation and output for just the particular source strength(s) and isopleth level(s) designated. In addition, a previously written subroutine that determines the Turner stability class described in Ref. 4 is invoked upon request. These five stability classifications depend on the amount of solar radiation (as determined from date and time), but modified by the cloud conditions and the wind speed. They are 1 or B--unstable, 2 or C--slightly unstable, 3 or D--neutral, 4 or E--slightly stable, and 5 or F--stable.

The time-sharing program can be used to determine the location and regional extent of high pollution levels from one source, or to estimate the combined, additive effects of emissions from a number of neighboring sources upon a given point. Accurate forecasts of wind speed and direction, together with mixing height and cloud conditions, and knowledge of source strengths are necessary, of course, for successful prediction of pollution levels.

Calculations can be performed for any (nonreacting) gas or particulate matter. The resulting concentrations and isopleths are in parts per million (for gases of given molecular weight) or in micrograms per cubic meter (for any pollutant).

The particular advantage of the time-sharing computer program is that isopleths can be calculated for any combination of source strength and isopleth level, as well as any combination of wind speed, stability, and other meteorological conditions. Any book of tables must be limited to a relatively small set of cases. Even Ref. 1, which considers only conditions that could be applicable to air pollution episodes, forms a book almost an inch and one-half thick.

2. USING THE TIME-SHARING PROGRAM

This program is written in the (General Electric) GE-400 time-sharing FORTRAN language, and is adapted from the Isopleth-area Tables routine (Ref. 1, Appendix) originally done in FORTRAN IV for the IBM 360.

Both the FORTRAN source code (PLETHS) and the binary or object code (PLETH) presently reside in the General Services Administration (GSA) Time-Sharing System in Atlanta, Georgia. Code lengths are: source, about 22,407 bytes; object, about 12,969 bytes. There are three bytes per 24-bit word. The source-program listing is included in the appendix of this report.

Any government-related facility with a time-sharing teletype terminal having a dataphone may subscribe to the GSA Computer Time-Sharing Service by contacting

Federal ADP Resources Staff
General Services Administration
1776 Peachtree Street, N.W., Room 556
Atlanta, Georgia 30309
Telephone FTS 404 526-5772/5348.

("Government-related" means being a federal establishment or having a federal government contract of some kind.) GSA procedures, costs, and so forth are subject to revision, of course, but subscribers may currently (9/72) gain access to the time-sharing isopleth area program by telephoning (for example) one of the Federal Telephone Service numbers

FTS Atlanta: 404 526-4351

FTS Washington, D.C.: 202 755-2000

from a time-sharing teletype terminal. After logging the time started and receiving proper identification, the system will print

TYPE OLD OR NEW:

To get the isopleth-area program, respond by entering

OLD: PLETH, N014

from the keyboard. (N014 is the user number under which the program has been filed.) The computer gets the program, and says

READY

To execute the program, type

RUN

on the teletype keyboard. In each case, the user records his response by hitting the RETURN key.

The program starts with a printed descriptive segment, which may be omitted at the user's option. This description is some 24 lines long and lists

input, output, and options; it is reproduced in the typical program run of Sec. 2.1. All input is in the so-called free-field format, which simply means that the user need not concern himself with field widths and number types.

The user then types a single line of identification, which in turn is reproduced by the program.

There is now an option: to have concentrations and isopleths in micrograms per cubic meter, the user types a zero; for parts per million, he types the molecular weight of the gaseous pollutant.

Another option follows: The user may insert the stability class number (1, 2, 3, 4, or 5), keep the old class, or allow the program to compute it. For this computation, the user provides the month (given as a number 1 through 12), day (a number 1 through 31), and hour in standard time (1 through 24). He also gives the ground wind speed (in miles per hour), cloud cover (as a decimal fraction from 0 through 1.0), and ceiling (in feet). These are to be given as simple lists, separated by commas and transmitted to the program by pressing the RETURN key.

The next request is for mixing height (in feet). As input progresses, all parameters (including Turner stability class) are printed out on the teletype.

In a manner similar to that in Ref. 1, a table is constructed for each designated isopleth level (in parts per million or micrograms per cubic meter). The difference here is that only one line at a time is computed and printed for each specified source strength (Q), effective stack height (EFFHT), and mean wind speed (WIND). The table lists EFFHT in feet, WIND in miles per hour, Q in pounds per hour of pollutant, calculated isopleth area (AREA) in square miles, distance to the area's leading edge (DLE) in miles, length of the area (LGTH) in miles, width (WDTH) in miles, maximum grid point concentration (CHIMAX) in parts per million (PPM) or micrograms per cubic meter (MMG/M³), and distance to the maximum concentration (DCM) in miles.

Fig. 1. A Single-source Ground-level Isopleth.
ANL Neg. No. 190-189 Rev. 1.

The calculated isopleth area may be visualized as in Fig. 1, which is a reproduction of Fig. 2.1 in Ref. 1.

Sets of source strength, effective stack height, and mean wind speed are requested and given, one set at a time, until the user chooses to start a new table at another isopleth level. He does this by ignoring the next request for source strength, effective stack height, and mean wind speed. Instead of these, he types a

zero or blank, or just hits the RETURN key. In a similar way, he can ignore an isopleth request and so go to another case (a different mixing height or stability class) or terminate the program.

Finally, the Time-Sharing Service lists running time in seconds, input/output time in seconds, and time of logging off.

2.1 Typical Program Run

Listed below is a copy of the teletype terminal output for an example program run by user N015, using the binary (object) program PLETH filed under user N014. Each query by the program is denoted by a question mark; user responses are indicated in this report by underlining.

A 200-ft-tall smoke stack is considered in the example. Increase of wind speed with height, and effective stack height have been determined according to the prescriptions of Sec. 4 below. The pollutant is sulfur dioxide, whose molecular weight is 64.06.

GSA 440 TIME-SHARING

ON AT - 14:38 PN:22 TTY:22

USER ID-- N015
 PASSWØRD
88888?

TYPE ØLD ØR NEW:ØLD:PLETH,N014

READY
RUN

PLETH 14:38 ATL WED 09/06/72

SINGLE-SØRCE ISØPLETH AREA PRØGRAM, PLETH.
 TØ ØMIT DESCRIPTION, TYPE-IN A NEGATIVE NUMBER ØR ZERO.
 FØR DESCRIPTION, TYPE-IN ANY PØSITIVE NUMBER.
 ? 3

DESCRIPTION ØF SINGLE-SØRCE ISØPLETH AREA
 PRØGRAM, PLETH. (SØRCE PRØGRAM VERSION---PLETHS).
 GIVEN FØLLØWING DATA ENTERED AT TIME-SHARING TERMINAL---
 TIME(MØNTH,DAY,HØUR) AND WEATHER CØNDITIØNS(GRØUND
 WIND SPEED,CLØUD CØVER,CEILING,MIXING HEIGHT).
 PRØGRAM CØMPUTES(CØN REQUEST) TURNER ATMØSPHERIC
 STABILITY CLASS---1 ØR B-UNSTABLE,2 ØR C-SLIGHTLY
 UNSTABLE,3 ØR D-NEUTRAL,4 ØR E-SLIGHTLY STABLE,
 5 ØR F-STABLE. IT THEN CALLS FØR DESIRED GRØUND

ISOPLETH LEVEL, AND COMPUTES DOWNWIND CONCENTRATIONS ABOVE THIS LEVEL FOR EACH GIVEN SOURCE STRENGTH(Q), EFFECTIVE STACK HEIGHT(EFFHT), AND MEAN WIND SPEED (WIND), USING PLUME OR PUFF DISPERSION MODEL.

OUTPUT AT TERMINAL LISTS EFFHT, WIND, Q, AREA WITHIN DESIGNATED ISOPLETH(AREA), DISTANCE TO LEADING EDGE OF AREA(DLE), LENGTH(LGTH) AND WIDTH(WDTH) OF AREA, MAXIMUM CONCENTRATION(CHIMAX), AND DISTANCE TO CHIMAX(DCM). ISOPLETHS, IN PARTS/MILLION OR MICROGRAMS/CUBIC METER, ARE FOR ANY GIVEN (NON-REACTING) POLLUTANT. TO GO TO ANOTHER ISOPLETH LEVEL, IGNORE SOURCE STRENGTH REQUEST AND TYPE-IN A ZERO OR BLANK, OR JUST HIT RETURN KEY. TO END CURRENT CASE, IGNORE ISOPLETH LEVEL REQUEST AND TYPE-IN A ZERO OR BLANK, OR JUST HIT RETURN KEY.

TYPE-IN ONE IDENTIFYING LINE (FOR EXAMPLE: USER, NAME OF POLLUTANT).
? S02, CASE 43

S02, CASE 43

FOR CONCENTRATIONS CHI IN MICROGRAMS/CUBIC METER (MMG/M3), TYPE-IN A ZERO. FOR CHI IN PARTS/MILLION (PPM), TYPE-IN MOLECULAR WEIGHT(MW) OF GASEOUS POLLUTANT.
? 64.06

MOLECULAR WEIGHT= 64.06

FOR STABILITY COMPUTATION, TYPE-IN A ZERO.
TO KEEP OLD STABILITY CLASS, TYPE-IN ANY NEGATIVE NUMBER.
TO INSERT STABILITY CLASS, TYPE IT IN AS 1,2,3,4, OR 5.
? 0

TYPE-IN MONTH(1-12), DAY(1-31), HOUR(1-24)
? 7,2,13

TYPE-IN GROUND WIND SPEED(MPH), CLOUD COVER(0-1.0), CEILING(FT)
? 5,0,20000

MONTH= 7, DAY= 2, HOUR=13
GROUND WIND SPEED= 5.0 MPH, CLOUD COVER=0.0, CEILING=20000. FT

TYPE-IN MIXING HEIGHT(FT)

? 750

TURNER STABILITY CLASS=B-UNSTABLE

MIXING HEIGHT= 750.0 FT

TYPE-IN ISOPLETH LEVEL WANTED(PPM)

? .02

ISOPLETH LEVEL= 0.020 PPM

EFFHT	WIND	Q	AREA	DLE	LGTH	WDTH	CHIMAX	DCM
FT	MPH	LB/HR	SQ MI	MI	MI	MI	PPM	MI

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
? 201,7.3,100

201.0	7.3	100.	0.0	0.0	0.0	0.0	0.00	0.0
-------	-----	------	-----	-----	-----	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
? 204,7.3,1000

204.0	7.3	1000.	1.7	0.2	3.5	0.5	0.17	0.5
-------	-----	-------	-----	-----	-----	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
? 206,7.3,2500

206.0	7.3	2500.	18.7	0.2	10.5	2.5	0.41	0.5
-------	-----	-------	------	-----	------	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
? 208,7.3,5000

208.0	7.3	5000.	76.2	0.2	22.5	4.5	0.83	0.5
-------	-----	-------	------	-----	------	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
? 0

TYPE-IN ISOPLETH LEVEL WANTED (PPM)

? .1

ISOPLETH LEVEL= 0.100 PPM

EFFHT	WIND	Q	AREA	DLE	LGTH	WDTH	CHIMAX	DCM
FT	MPH	LB/HR	SQ MI	MI	MI	MI	PPM	MI

TYPE-IN EFFECTIVE STACK HEIGHT (FT),
MEAN WIND SPEED (MPH), SOURCE STRENGTH (LB/HR OF POLLUTANT)
? 213, 7.4, 12000

213.0	7.4	12000.	16.5	0.2	10.0	2.5	1.95	0.5
-------	-----	--------	------	-----	------	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT (FT),
MEAN WIND SPEED (MPH), SOURCE STRENGTH (LB/HR OF POLLUTANT)
? 202, 7.3, 400

202.0	7.3	400.	0.0	0.0	0.0	0.0	0.00	0.0
-------	-----	------	-----	-----	-----	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT (FT),
MEAN WIND SPEED (MPH), SOURCE STRENGTH (LB/HR OF POLLUTANT)
? 215, 7.4, 16000

215.0	7.4	16000.	27.7	0.2	13.5	2.5	2.59	0.5
-------	-----	--------	------	-----	------	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT (FT),
MEAN WIND SPEED (MPH), SOURCE STRENGTH (LB/HR OF POLLUTANT)
? 0

TYPE-IN ISOPLETH LEVEL WANTED (PPM)

? .25

ISOPLETH LEVEL= 0.250 PPM

EFFHT	WIND	Q	AREA	DLE	LGTH	WDTH	CHIMAX	DCM
FT	MPH	LB/HR	SQ MI	MI	MI	MI	PPM	MI

TYPE-IN EFFECTIVE STACK HEIGHT (FT),
MEAN WIND SPEED (MPH), SOURCE STRENGTH (LB/HR OF POLLUTANT)
? 215, 7.4, 15000

215.0	7.4	15000.	3.2	0.2	4.5	1.5	2.43	0.5
-------	-----	--------	-----	-----	-----	-----	------	-----

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
 MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
 ? 219,7.4,26000

219.0 7.4 26000. 11.2 0.2 8.5 1.5 4.19 0.5

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
 MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
 ? 238,7.5,100000

238.0 7.5 100000. 189.5 0.2 37.0 6.5 15.51 0.5

TYPE-IN EFFECTIVE STACK HEIGHT(FT),
 MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)
 ?

TYPE-IN ISOPLETH LEVEL WANTED(PPM)
 ?

END OF CURRENT CASE. FOR NEXT CASE, TYPE-IN ANY
 POSITIVE NUMBER. IF FINISHED, TYPE-IN A ZERO OR BLANK.
 ? 0

END OF ISOPLETH AREA PROGRAM.
 STOP

RUNNING TIME: 11.6 SECS I/O TIME : 19.1 SECS

READY
BYE

OFF AT 14:52

2.2 Costs

For the example shown, approximate costs were 76.8¢ for processing and input/output time (30.7 sec @ 2.5¢ per second) and 151.2¢ for terminal connect time (14 min @ 10.8¢ per minute), or about 22.8¢ per source entry. In addition, FTS telephone costs (@ 14¢ per minute) would be about 19.6¢ per source. The program description, which takes about 140 sec of terminal time, would normally be omitted by a frequent user.

Since large isopleth areas require more computation, they result in somewhat higher costs. Very low wind speeds (less than 2 mph) may increase costs substantially because of the integration time required in the Puff Model (Sec. 5.4). The fixed input/output, terminal connect, and telephone costs usually dominate computation costs, however.

3. APPLICATION OF THE PROGRAM

As with the isopleth-area tables, this time-sharing program can be helpful in choosing optimal control strategies during an air pollution episode. For with it, under the prevailing or forecast weather conditions, relative contributions of known emission sources to high pollution areas can be determined. Responsible control agencies may then take appropriate corrective action.

When an accident or spill occurs, a nominal source strength can be used to determine downwind isopleth areas. Then any relevant available air-quality reading may be used to normalize isopleth levels and thus estimate the extent of the danger.

Recall that the time-sharing program can be used to produce isopleths for any airborne pollutant. Hence, even if the pollutant does not behave as a gas, the computed isopleths can be very useful to "bracket" a situation. Conservative estimates can often be helpful in planning an emergency control strategy.

4. DETERMINING EFFECTIVE STACK HEIGHT, MEAN WIND SPEED, AND MIXING HEIGHT

These input parameters, to be supplied by the user, may be calculated according to the prescription of Secs. 2.4-2.6 of Ref. 1; slight changes in numbering and notation have been made for conformity with the present report.

4.1 Effective Stack Height

"The effective stack height H is the height above ground which best defines the centerline of the plume. The plume is assumed to originate as a point source at an altitude H feet above ground at the location of the stack. If aerodynamic downwash causes the plume to break up and mix rapidly downward in the vicinity of the stack, H may be set equal to the actual, physical stack height H_s . Otherwise the plume rise ΔH is added to the physical stack height H_s , so that:

$$H = H_s + \Delta H$$

where ΔH is estimated as described below:

"Smoke plume rise calculations and curves ... are based on a plume rise formula derived from observations at TVA stations and other power plants by Carson and Moses.⁵ The momentum term in their original formulation is omitted in the following equation since its contribution is generally considered negligible compared to thermal buoyancy.

$$\Delta H \text{ (feet)} = K Q_s^{1/2} / U \quad (1)$$

where

ΔH = plume rise (feet)

Q_s = heat emission rate from stack (Btu/hr)

U = wind speed (miles per hour) at the height of the stack

K = .870 (unstable), .354 (slightly unstable, neutral), .222 (slightly stable, stable).

The wind speed at the stack height is estimated by multiplying the measured wind speed near the ground by a factor depending upon the height of the stack, H_s , and the stability class." This is discussed in Sec. 4.2.

"There are four restrictions which should be placed on the use of (Eq. 1):

1. Mixing-layer Height (H_m , defined in Sec. 4.3):
 - a. The effective stack height, H , cannot be greater than the mixing-layer height, H_m , if the stack is beneath the mixing layer; i.e., $H \leq H_m$ if $H_s < H_m$.
 - b. If the physical stack height H_s is greater than H_m during the day assume that the effluent does not reach the ground.
2. Low Wind Speeds (U):

If U is estimated to be less than 4 miles per hour, use the value 4 mph in (Eq. 1).
3. Stability Class and the Coefficient K :

If the physical stack height (H_s) is equal to or greater than 500 feet, use $K = .354$ (neutral) even though the stability index indicates unstable conditions.

"The first two restrictions (1a and 1b) are based on the assumption of an impenetrable atmospheric layer (lid) at height H_m ... However, it is appropriate to note that the effluent from a stack which emits its plume just beneath the lid will probably penetrate into the stable layer rather than obey the assumption of perfect reflection off of the lid. Unfortunately, there is no widely accepted way to model this situation at present.

"Restriction 2 limits the minimum wind speed to be used in (Eq. 1). This reflects the fact that the equation is an empirical one in which the parameters n and m in an equation of the form of $\Delta H = K Q^n U^m$ were found by multiple linear regression. A comparison of (Eq. 1) with TVA data⁶ indicates good agreement down to wind speeds of about 6 mph. Below

this, the $(1/U)$ factor in the equation causes an overestimation of the plume rise. An arbitrary restriction on a minimum value of U in (Eq. 1) has therefore been made.

"Restriction 3 occurs because the vertical variation of temperature (lapse rate) at heights greater than 500 feet is rarely characterized by an unstable (superadiabatic) lapse rate even though unstable conditions may exist in the first few hundred feet above ground."

The heat emission rate from the stack (Q_s , Btu/hr) in Eq. 1 may be estimated as follows: Assume that Q_s is a fixed percentage of the total heat-generation rate (heating rate of the fuel times the fuel-use rate). "The percentage depends on the type and efficiency of the burning and heat exchange equipment but may be categorized as follows:

power plant - 12%

large industrial, commercial - 20%

small industrial, commercial and residential - 35%."

4.2 Mean Wind Speed

To calculate the plume rise by Eq. 1, the wind at the physical height H_s should be used. For isopleth calculations, however, the wind speed should be that at the effective stack height H . Call this the mean wind speed.

"In each case, the desired value for the wind speed will usually be greater than that measured at a local point (typically at 30 to 100 feet above ground), since stack heights are generally greater than the height at which airport wind measurements are made." The following equation provides a correction term for altitudes up to 1000 feet:

$$U_2 = U_1 (Z_2/Z_1)^P, \quad (2)$$

where U_i is the wind speed at height Z_i ($i = 1, 2$) and the exponent p is dependent on the stability class:⁷

$$p = .5 \text{ (stable),}$$

$$P = .2 \text{ (slightly stable, neutral, slightly unstable, unstable).}$$

"The experimental data in the reference cited indicated a slightly more uniform vertical wind speed profile for unstable than for neutral conditions. For our purposes, the distinction is negligible. However, this correction can be important in some cases, since the factor $(1/U)$ in the plume rise equation (Eq. 1) has a critical influence on ground level pollution concentration."

4.3 Mixing-layer Height

"The mixing layer defines a maximum altitude through which pollutants can be diluted... . The height of the mixing layer, H_m , should be measured locally once or twice a day by balloon or helicopter, especially during an air pollution incident. A staff meteorologist can then estimate the current value of H_m as the altitude of the intersection of a dry adiabat projected from the local surface temperature with a plot of the most recent sounding. When vertical soundings cannot be made locally, it may be necessary to approximate the local sounding by interpolating between soundings at other rawinsonde stations that are in the same air system."

5. THEORY AND LIMITATIONS OF THE PLUME AND PUFF MODELS

This section is an abbreviated and modified version of Sec. 4 of Ref. 1.

The theoretical model of smoke plume diffusion discussed here is the basis for the time-sharing isopleth-area program of this report as well as the tables of Ref. 1. In the calculations, units are converted from meters, meters per second, and micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) to miles or feet, miles per hour, or parts per million, as appropriate.

5.1 Basic Equation and Theory

For wind speeds greater than or equal to 2 miles per hour, a model based on a steady-state Gaussian plume has been used to calculate concentrations.* "In a Cartesian coordinate system with the z-axis vertical and horizontal axes rotated so that the x-axis coincides with the downwind direction, the basic kernel describing the concentration X at receptor point x, y, z due to a steady emission from the point $x = 0, y = 0, z = H$ in an infinite medium is:

$$X(x, y, z/H) = \frac{Q}{2\pi U \sigma_y \sigma_z} \exp \left[-0.5 \left\{ \left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{z-H}{\sigma_z} \right)^2 \right\} \right], \quad (3)$$

where

Q = pollutant emission rate (micrograms per second)

U = mean wind speed (meters/sec)

σ_y = crosswind dispersion coefficient (meters), a function of downwind distance, x

*This speed is 4 mph for the Isopleth-area Tables. In the time-sharing program, a mean wind speed typed in as 0 is arbitrarily set to the value 1 mph.

σ_z = vertical dispersion coefficient (meters), a function of downwind distance, x

y = crosswind distance (meters),

z = height of receptor (meters)

H = effective height of emission (meters)

χ = pollutant concentration ($\mu\text{g}/\text{m}^3$)."

The dispersion coefficients, σ_y and σ_z (see Figs. 3-2 and 3-3 of Ref. 4), are functions of the downwind distance, x , and are parameterized according to five classes of atmospheric stability in this report. "The dispersion coefficients shown in (Ref. 4) are based on a sampling or averaging time of about 10 minutes. The smallest time increment of interest in determining the onset of an episode and in defining strategies is 1 hour. Thus, for use in (Eq. 3), the values of σ_y and σ_z have been multiplied by the factor $(60 \text{ min}/10 \text{ min})^2 = 1.43$."

"The units of χ are $\mu\text{g}/\text{m}^3$. To convert ($\mu\text{g}/\text{m}^3$) of SO_2 [say] to parts per million (ppm) at standard temperature (32°F) and pressure (1 atmosphere), divide by 2854. A further correction for the actual temperature is not warranted considering the uncertainties inherent in the assumed form of the dispersion equation and in the experimentally determined values of σ_y and σ_z ."

5.2 Ground-level Reflection

"The assumption that the pollutant is not absorbed when it makes contact with the ground or with buildings can be approximated by a model based on perfect reflection at the ground. In (the model), two infinite medium sources (Eq. 3) are superimposed: the actual source at effective height H and an image source H meters below the reflecting (ground) plane."

5.3 Mixing-height Assumption

"A stable layer existing at height H_m above an unstable or neutral zone inhibits vertical diffusion and acts as a lid. This phenomenon can be approximated by assuming the existence of a reflecting plane at height H_m , so that in a manner analogous to reflection at ground level, an image source is introduced above the lid plane at height $2H_m - H$.

"The problem is now complicated by the existence of two reflecting planes, ground and lid. As anyone who has stood between two mirrors knows, the result is describable by introducing multiple (infinite) pairs of reflections at increasing distances from the true source... .

"The mathematical representation of the concentration of pollutants trapped between two reflecting planes is therefore represented by pairs of

images which become important with increasing downwind distance. Eventually the vertical distribution of pollutants is approximately uniform and a modified version of (Eq. 3) can be employed:

$$\chi(x, y) = \frac{Q}{\sqrt{2\pi} \sigma_y U H_m} \exp[-.5(y/\sigma_y)^2] \quad (4)$$

where

H_m = height of mixing layer (meters).

"The transition from multiple images (Eq. 3) to the uniform distribution can be made smoothly after three pairs of image sources have been introduced and at a downwind distance x_u defined by

$$2.15 \sigma_z(x_u) = (4H_m - H). \quad (5)$$

The right-hand side of Eq. 5 is the height above ground of an image representing the mixing-height reflection of the ground-level reflection of the original mixing-height reflection.

5.4 Theory of the Puff Model

Mean wind speeds of less than 2 mph invoke the puff model, described below, for calculating concentrations:

"An assumption inherent in the formulation of the plume model is that upwind-downwind diffusion in the direction of transport be neglected.⁴ This implies that downwind advection with the mean wind dominates upwind and downwind turbulent diffusion. This assumption also leads to the $(1/U)$ factor in the standard equation (Eq. 3), and, while there is no practical meaning to a zero wind speed, the use of the plume model under conditions of extremely low wind speed is questionable.

"An alternative to the plume formulation is the puff model, which introduces the parameter σ_x , an upwind-downwind diffusion coefficient.⁹⁻¹² This model is based on an instantaneous release of pollutant at a rate $Q \mu\text{g/sec}$ for an interval Δ seconds. The center of the puff will move downwind (along the + x-axis) with the mean wind speed $U \text{ m/sec}$. Diffusion about the center is described by a Gaussian distribution with coefficients σ_x , σ_y , and σ_z . In accord with this description, the basic equation for a puff released at position $x = 0$, $y = 0$, $z = H$ and time $t = 0$ and observed at position x , y , z and time $t = T$ in an infinite medium is:

$$\chi(x, y, z, T) = \frac{Q\Delta}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \left[\exp - .5 \left\{ \left(\frac{x - UT}{\sigma_x} \right)^2 + \left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{z - H}{\sigma_z} \right)^2 \right\} \right] \quad (6)$$

where

σ_x = along-wind diffusion, a function of the downwind travel of the puff (UT)

T = lifetime of the puff

Other quantities are the same as in (Eq. 3) except that σ_y and σ_z are now functions of UT, the location of the center of the puff, rather than x, the distance to the dose point.

"In order to calculate the concentration at x,y,z due to a steady emission Q, (Eq. 6) must be integrated:

$$X(x,y,z) = \int_0^{\infty} dT \frac{Q}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left[-0.5 \left\{ \left(\frac{x - UT}{\sigma_x} \right)^2 + \left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{z - H}{\sigma_z} \right)^2 \right\} \right] \quad (7)$$

where

$$\sigma_x = \sigma_x(UT)$$

$$\sigma_y = \sigma_y(UT)$$

$$\sigma_z = \sigma_z(UT)$$

mks units.

"The integration must be performed numerically; however, it can be approximated by an integral over finite limits. Consider the example U = 1.5 meters/sec, x = 30 km. The travel time from source to receptor is thus 3×10^4 meters / (1.5 m/sec) = 20,000 sec or 5.6 hours. Now a puff one hour old will have traveled only 5.4 km and therefore will not contribute significantly to a dose point 24.6 km (30 km - 5.4 km) away; a puff that is 10 hours old will be too far downwind of the dose point. Thus, for this example, the limits in the integral can quite reasonably be set at

$$\int_{1 \times 3600 \text{ sec}}^{9 \times 3600 \text{ sec}} \quad \text{instead of} \quad \int_0^{\infty}$$

In practice, when the travel time to the source is N hours, the numerical integration is performed over a ten-hour period surrounding the hour N; i.e.,

$$\int_{(N-5) \times 3600 \text{ sec}}^{(N+5) \times 3600 \text{ sec}}$$

The assumption $\sigma_x = \sigma_y$ is used in Eq. 7 to generate isopleth areas "for wind speeds less than 2 mph.* Since these are also the coefficients for the plume model, the two approaches (plume and puff) merge when downwind advection dominates upwind-downwind dispersion. ... At 2 mph, the centerline concentrations predicted by the two models are in close agreement although variations in the crosswind direction are significant... . Introduction of upwind-downwind dispersion...tends to widen the plume and thereby raise crosswind concentrations near the source.

"The assumption $\sigma_x = \sigma_y$ results in a circular puff (Eq. 6) moving downwind at speed U. Although not strictly correct, it is convenient to consider σ_x as the superposition of two components: (1) horizontal turbulence due to eddies of a scale smaller than the puff size, and (2) upwind/downwind elongation due to vertical shear. Thus, while the assumption $\sigma_x = \sigma_y$ may be reasonable for unstable and neutral conditions of atmospheric stability, it may be inappropriate in situations where the effect of wind shear is magnified by the existence of a stable atmosphere which inhibits vertical mixing.¹¹ Cramer⁸ suggests an algorithm for incorporating wind shear in the puff formulation for stable atmospheric conditions. However, this modification has not been employed in forming the isopleth-area tables" or the time-sharing isopleth program.

"Equation (6) is written for an infinite medium as in the basic plume equation (Eq. 3). In the puff model, the procedure for incorporating the effects of reflections at the ground and at a stable layer aloft is exactly the same as that described for the plume model (in Secs. 5.2 and 5.3). Multiple images are introduced, and eventually the vertical distribution becomes uniform. For the case of uniform mixing between the ground and a lid at height H_m , the denominator (in Eq. 4) becomes $(2\pi\sigma_x\sigma_yH_m)$."

5.5 Accuracy of Atmospheric Dispersion Estimates

"The following quotation from the Workbook by Turner⁴ discusses the accuracy of the plume model based on his experience in developing urban air pollution models for Nashville, Tenn., and St. Louis, Mo.:

'Because of a multitude of scientific and technical limitations the diffusion computation method presented in this manual may provide best estimates but not infallible predictions. In the unstable and stable cases, severalfold errors in estimate of σ_z can occur for the longer travel distances. In some cases the σ_z may be expected to be correct within a factor of 2, however. These are: (1) all stabilities for distance of travel out to a few hundred meters; (2) neutral to moderately unstable conditions for distances out to a few kilometers; and (3) unstable conditions in the lower

*4 mph for the Isopleth-area Tables.

1000 meters of the atmosphere with a marked inversion above for distances out to 10 km or more. Uncertainties in the estimates of σ_y are in general less than those of σ_z . The ground-level center-line concentrations for these three cases (where σ_z can be expected to be within a factor of 2) should be correct within a factor of 3, including errors in σ_y and u ...

"For purposes of developing control strategies during air pollution episodes, the relative contributions at ground level of different controllable sources are as important as the actual or absolute values of these concentrations. These relative contributions can often be estimated with greater confidence than the actual values. For example, if the estimate of σ_y is 50% high, it will influence somewhat uniformly the estimated dispersion from all plants. In contrast, if a lid exists at 700 feet instead of the estimated 1500 feet, it will greatly affect the ground level contribution from a 400-foot stack but have little effect on that from a 75-foot stack."

APPENDIX

Source-program Listing for PLETHS,
Isopleth Area at Ground Level for Single Source

```

PLETHS      18:06  ATL TUE   09/05/72

100$SAV
110C          LABEL OBJECT PROGRAM PLETH
120$NDM
130C          DELETE LINE NUMBERS FOR RUN-TIME INPUT REQUESTS
140C
150C          ISOPLETH AREA AT GROUND LEVEL FOR SINGLE SOURCE, PLETHS
160C
170          REAL MW
180          COMMON H,DELH,Q,MW
190          COMMON WS,C0V,CEIL,HMIX,J
200          COMMON XSTART,XSTOP,YMAX,SQMI
210          COMMON X,Y,Z,NF
220          COMMON NL0W,NHIGH
230          DIMENSION ITITLE(23)
240          DIMENSION QU0T(2),TSTAB(20)
250          DATA QU0T/" ","+"/
260          DATA TSTAB/"B-UNSTABLE",
270&          "C-SLIGHTLY UNSTABLE", "D-NEUTRAL",
280&          "E-SLIGHTLY STABLE", "F-STABLE",
290          DX=.5
300          DY=.5
310          Z=0.
320          DELH=0.
330          PRINT,1H0,"SINGLE-SOURCE ISOPLETH AREA PROGRAM, PLETH.",
340&          "TO OMIT DESCRIPTION, TYPE-IN A NEGATIVE NUMBER OR ZERO.",
350&          "FOR DESCRIPTION, TYPE-IN ANY POSITIVE NUMBER."
360          READ,DESC
370          IF(DESC)3,3,7
380          7 PRINT,1H0,"DESCRIPTION OF SINGLE-SOURCE ISOPLETH AREA",
390&          "PROGRAM, PLETH. (SOURCE PROGRAM VERSION---PLETHS).",
400&          "GIVEN FOLLOWING DATA ENTERED AT TIME-SHARING TERMINAL---",
410&          "  TIME(MONTH,DAY,HOUR) AND WEATHER CONDITIONS(GROUND",
420&          "  WIND SPEED,CLOUD COVER,CEILING,MIXING HEIGHT).",
430&          "PROGRAM COMPUTES(ON REQUEST) TURNER ATMOSPHERIC",
440&          "  STABILITY CLASS---1 OR B-UNSTABLE,2 OR C-SLIGHTLY",
450&          "  UNSTABLE,3 OR D-NEUTRAL,4 OR E-SLIGHTLY STABLE,",
460&          "  5 OR F-STABLE. IT THEN CALLS FOR DESIRED GROUND",
470&          "  ISOPLETH LEVEL, AND COMPUTES DOWNWIND CONCENTRATIONS",
480&          "  ABOVE THIS LEVEL FOR EACH GIVEN SOURCE STRENGTH(Q)",
490&          "  EFFECTIVE STACK HEIGHT(EFFHT), AND MEAN WIND SPEED",
500&          "  (WIND), USING PLUME OR PUFF DISPERSION MODEL.",
510&          "OUTPUT AT TERMINAL LISTS EFFHT, WIND, Q, AREA WITHIN",
520&          "  DESIGNATED ISOPLETH(AREA), DISTANCE TO LEADING EDGE",
530&          "  OF AREA(DLE), LENGTH(LGTH) AND WIDTH(WDTH) OF AREA",
540&          "  MAXIMUM CONCENTRATION(CHIMAX), AND DISTANCE",
550&          "  TO CHIMAX(DCM).",
560&          "ISOPLETHS, IN PARTS/MILLION OR MICROGRAMS/CUBIC METER",
570&          "  ARE FOR ANY GIVEN (NON-REACTING) POLLUTANT.",
580&          "TO GO TO ANOTHER ISOPLETH LEVEL, IGNORE SOURCE",
590&          "  STRENGTH REQUEST AND TYPE-IN A ZERO OR BLANK, OR",
600&          "  JUST HIT RETURN KEY. TO END CURRENT CASE, IGNORE",
610&          "  ISOPLETH LEVEL REQUEST AND TYPE-IN A ZERO OR BLANK",
620&          "  OR JUST HIT RETURN KEY."

```

```

630      3 PRINT,1H0,"TYPE-IN ONE IDENTIFYING LINE (FOR EXAMPLE: USER,"
640&      "NAME OF POLLUTANT)."
```

```

650      READ 70,ITITLE
660      PRINT 72,ITITLE
670      PRINT,1H0,"FOR CONCENTRATIONS CHI IN MICROGRAMS/CUBIC METER",
680&      "(MMG/M3), TYPE-IN A ZERO. FOR CHI IN PARTS/MILLION(PPM),"
690&      "TYPE-IN MOLECULAR WEIGHT(MW) OF GASEOUS POLLUTANT."
```

```

700      READ,MW
710      IF(MW)8,8,2
720      2 PRINT 71,MW
730      8 PRINT,1H0,"FOR STABILITY COMPUTATION, TYPE-IN A ZERO.",
740&      "TO KEEP OLD STABILITY CLASS,TYPE-IN ANY NEGATIVE NUMBER.",
750&      "TO INSERT STABILITY CLASS, TYPE IT IN AS 1,2,3,4,OR 5."
```

```

760      READ,TSB
770      IF(TSB)6,5,4
780      5 PRINT,1H0,"TYPE-IN MONTH(1-12),DAY(1-31),HOUR(1-24)"
790      READ,MONTH,NDAY,NHOUR
800      PRINT,1H0,"TYPE-IN GROUND WIND SPEED(MPH),CLOUD",
810&      "COVER(0-1.0),CEILING(FT)"
820      READ,WS,COV,CEIL
830      PRINT 60,MONTH,NDAY,NHOUR
840      PRINT 63,WS,COV,CEIL
850C      COMPUTE TURNER STABILITY CLASS
860      CALL STAB(MONTH,NDAY,NHOUR,COV,CEIL,WS,J)
870      GO TO 6
880      4 J=TSB
890      6 KD=4*J-3
900      LD=4*J
910      PRINT,1H0,"TYPE-IN MIXING HEIGHT(FT)"
920      READ,HMIX
930      PRINT 65,(TSTAB(JD),JD=KD,LD)
940      PRINT 67,HMIX
950      10 XIS0=-1.0
960      IF(MW)30,30,31
970      30 PRINT,1H0,"TYPE-IN ISOPLETH LEVEL WANTED(MMG/M3)"
980      GO TO 32
990      31 PRINT,1H0,"TYPE-IN ISOPLETH LEVEL WANTED(PPM)"
1000     32 READ,XIS0
1010     IF(XIS0)11,11,12
1020     11 GO TO 500
1030     12 IF(MW)13,13,14
1040     13 PRINT 68,XIS0
1050     GO TO 18
1060     14 PRINT 69,XIS0
1070     18 PRINT 50
1080     IF(MW)40,40,41
1090     40 PRINT 51
1100     GO TO 15
1110     41 PRINT 52
1120     15 Q=-1.0
1130     PRINT,1H0,"TYPE-IN EFFECTIVE STACK HEIGHT(FT).",
1140&     "MEAN WIND SPEED(MPH), SOURCE STRENGTH(LB/HR OF POLLUTANT)"
1150     READ,H,WS,Q
1160     IF(Q)16,16,17
1170     16 GO TO 300
1180     17 IF(H.GT.HMIX) GO TO 400
1190     PIS0=XIS0
1200     IF(WS.LT.2) GO TO 20
1210     CALL XYAREA(DX,DY,Z,PIS0,CHIMAX,DCM)
1220     GO TO 21
```

```

1230 20 IF(WS.GE.1) G0 T0 205
1240 WS=1.0
1250 205 CALL XYISO(DX,DY,Z,PISO,CHIMAX,DCM)
1260 21 END=XSTOP
1270 DLE=XSTART
1280 XDIM=XSTOP-XSTART
1290 YDIM=2.*YMAX
1300 AREA=SQMI
1310 CMAX=CHIMAX
1320 DIST=DCM
1330 IF(AREA.EQ.0.) G0 T0 85
1340 G0 T0 80
1350 85 END=0.
1360 DLE=0.
1370 XDIM=0.
1380 YDIM=0.
1390 CMAX=0.
1400 DIST=0.
1410 80 HH=QUOT(1)
1420 IF(END.GE.49.) G0 T0 95
1430 G0 T0 90
1440 95 AREA=(50.-DLE)*YDIM
1450 XDIM=50.
1460 HH=QUOT(2)
1470 90 IF(MW)91,91,92
1480 91 PRINT 54,H,WS,Q,AREA,DLE,XDIM,HH,YDIM,CMAX,DIST
1490 G0 T0 93
1500 92 PRINT 55,H,WS,Q,AREA,DLE,XDIM,HH,YDIM,CMAX,DIST
1510 93 CONTINUE
1520C PROCESS NEXT SOURCE STRENGTH
1530 200 G0 T0 15
1540C PROCESS NEXT ISOPLETH
1550 300 G0 T0 10
1560 400 PRINT,1H0,"STACK ABOVE MIXING HEIGHT. NO GROUND ISOPLETHS."
1570 G0 T0 15
1580 500 CASE=-1.0
1590 PRINT,1H0,"END OF CURRENT CASE. FOR NEXT CASE, TYPE-IN ANY",
1600& "POSITIVE NUMBER. IF FINISHED, TYPE-IN A ZERO OR BLANK."
1610 READ,CASE
1620 IF(CASE)501,501,502
1630 502 PRINT,1H0,"NEXT CASE."
1640 G0 T0 8
1650 501 PRINT,1H0,"END OF ISOPLETH AREA PROGRAM."
1660 STOP
1670 50 FORMAT(1H0,2X,"EFFHT",2X,"WIND",4X,"Q",5X,
1680& " AREA DLE LGTH WDTH CHIMAX DCM")
1690 51 FORMAT(1H ,3X,"FT",4X,"MPH",3X,"LB/HR",2X,
1700& " SQ MI MI MI MI MMG/M3 MI")
1710 52 FORMAT(1H ,3X,"FT",4X,"MPH",3X,"LB/HR",2X,
1720& " SQ MI MI MI MI PPM MI")
1730 54 FORMAT(1H ,F7.1,1X,F5.1,1X,F7.0,F7.1,F5.1,2X,F4.1,A1,F5.1,
1740& F8.0,F6.1)
1750 55 FORMAT(1H ,F7.1,1X,F5.1,1X,F7.0,F7.1,F5.1,2X,F4.1,A1,F5.1,
1760& F8.2,F6.1)
1770 60 FORMAT(4X,"MONTH=",I2," ",DAY=",I2," ",HOUR=",I2)
1780 63 FORMAT(1H ,3X,"GROUND WIND SPEED=",F5.1," MPH, ",
1790& "CLOUD COVER=",F3.1," ",CEILING=",F6.0," FT")
1800 65 FORMAT(1H0,3X,"TURNER STABILITY CLASS=",4A6)
1810 67 FORMAT(1H ,3X,"MIXING HEIGHT=",F7.1," FT")

```



```

1820 68 FORMAT(1H0,3X,"ISOPLETH LEVEL=",F6.1," MICROGM/CU.METER")
1830 69 FORMAT(1H0,3X,"ISOPLETH LEVEL=",F6.3," PPM")
1840 70 FORMAT(23A3)
1850 72 FORMAT(1H ,23A3)
1860 71 FORMAT(1H ,3X,"MOLECULAR WEIGHT=",F6.2)
1870 END
1880C
1890 SUBROUTINE XYAREA(DELX,DELY,ZZ,PISO,CHIMAX,DIST)
1900 REAL MW
1910 DIMENSION YY(50),CHI(50),D(3),XC(3)
1920 COMMON H,DELH,Q,MW
1930 COMMON WS,C0V,CEIL,HMIX,J
1940 COMMON XSTART,XSTOP,YMAX,SQMI
1950 COMMON X,Y,Z,NF
1960 COMMON NL0W,NHIGH
1970 FACT=1./(5280.*2.15)
1980 D(1)=(2.*HMIX-H)*FACT
1990 D(2)=(2.*HMIX+H)*FACT
2000 D(3)=(4.*HMIX-H)*FACT
2010 NF=0
2020C CALCULATE DISTANCES AT WHICH NEW IMAGES BECOME IMPORTANT
2030 D0 36 N=1,3
2040 G0 T0 (31,32,33,34,35),J
2050C B STABILITY
2060 31 XC(N)=(D(N)/(110.*.000889))**(1/1.09)
2070 G0 T0 36
2080C C STABILITY
2090 32 XC(N)=(D(N)/(60.*.000889))**(1/.92)
2100 G0 T0 36
2110C D STABILITY
2120 33 XC(N)=(D(N)/(33.*.000889))**(1/.61)
2130 G0 T0 36
2140C E STABILITY
2150 34 XC(N)=(D(N)/(21.5*.000889))**(1/.56)
2160 G0 T0 36
2170C F STABILITY
2180 35 XC(N)=(D(N)/(14.*.000889))**(1/.53)
2190 36 CONTINUE
2200 Z=ZZ
2210 XSTART=0.
2220 XSTOP=0.
2230 CHIMAX=0.
2240 YMAX=0.
2250 SQMI=0.
2260 YY(1)=0.
2270 D0 20 JK=2,50
2280 YY(JK)=YY(JK-1)+DELY
2290 20 CONTINUE
2300 X=0.
2310 D0 80 I=1,101
2320 X=X+DELX
2330 IF (X.GE.XC(1)) NF=1
2340 IF (X.GE.XC(2)) NF=2
2350 IF (X.GE.XC(3)) NF=3
2360 NY=0
2370 D0 40 JK=1,50
2380 Y=YY(JK)
2390 T=X/WS
2400C SIGMAS ARE BASED ON DOWNWIND DISTANCE. T IS A DUMMY.
2410 IF(MW)60,60,59

```

```

2420 60 CHI(JK)=Q*TRANSS(T)*.10882
2430 G0 T0 58
2440 59 CHI(JK)=Q*TRANSS(T)*.0024391/MW
2450 58 IF(CHI(JK).LT.PIS0) G0 T0 50
2460 NY=NY+1
2470 40 C0NTINUE
2480 50 C0NTINUE
2490 IF(NY.EQ.0) G0T0 70
2500 IF(XSTART.EQ.0.) XSTART=X
2510 YMAX=AMAX1(YMAX,YY(NY))
2520 IF(CHI(1)-CHIMAX)10,11,11
2530 11 CHIMAX=CHI(1)
2540 DIST=X
2550 10 C0NTINUE
2560 SQMI=SQMI+(2*NY-1)*DELX*DELY
2570 G0 T0 80
2580 70 C0NTINUE
2590 IF(XSTART.EQ.0.) G0T0 80
2600 XSTOP=X-DELX
2610 G0 T0 85
2620 80 C0NTINUE
2630 IF(XSTOP.EQ.0.) XSTOP=X
2640 85 C0NTINUE
2650 YMAX=YMAX+DELY*.5
2660 XSTOP=XSTOP+DELX*.5
2670 IF(XSTART.EQ.0.) XSTART=DELX*.5
2680 XSTART=XSTART-DELX*.5
2690 RETURN
2700 END
2710C
2720 FUNCTION TRANSS(T)
2730C GROUND LEVEL CONCENTRATIONS ONLY
2740C CONSIDERS REFLECTIONS FROM GROUND AND LID
2750 REAL MW
2760 COMMON H,DELH,Q,MW
2770 COMMON WS,C0V,CEIL,HMIX,J
2780 COMMON XSTART,XSTOP,YMAX,SQMI
2790 COMMON X,Y,Z,NF
2800 COMMON NL0W,NHIGH
2810 TRANSC=0.
2820 TRANSD=0.
2830 TRANSE=0.
2840 TRANSF=0.
2850 ZKEEP=Z
2860 EFFHGT=H+DELH
2870 IF(EFFHGT.GT.HMIX) DELH=HMIX-H
2880 IF(NF.EQ.0)G0 T0 5
2890 IF(NF.EQ.1)G0 T0 6
2900 IF(NF.EQ.2)G0 T0 7
2910 IF(NF.EQ.3)G0 T0 10
2920 7 Z=((2.*HMIX+H+DELH)/5280.)-ZKEEP
2930 TRANSE=TPLUME(T)
2940 Z=((4.*HMIX-H-DELH)/5280.)-ZKEEP
2950 TRANSF=TPLUME(T)
2960 6 Z=((2.*HMIX-H-DELH)/5280.)-ZKEEP
2970 TRANSC=TPLUME(T)
2980 Z=((2.*HMIX+H+DELH)/5280.)-ZKEEP
2990 TRANSD=TPLUME(T)
3000 5 Z=(H+DELH)/5280.-ZKEEP
3010 TRANSA=2.*TPLUME(T)
3020 Z=(2.*HMIX-(H+DELH))/5280.-ZKEEP

```

```

3030      TRANSB=TPLUME(T)
3040      TRANSS=TRANSA+TRANSB+TRANSC+TRANSD+TRANSE+TRANSF
3050      Z=ZKEEP
3060      RETURN
3070  10  SY=SIGY(X,J)
3080      HM=HMIX/5280.
3090      B0T=SQRT(6.283)*SY*HM*WS
3100      EXP0N=(-.5*(Y/SY)**2)
3110      IF(ABS(EXP0N).GT.20.)G0 T0 20
3120      T0P=EXP(EXP0N)
3130      TRANSS=T0P/B0T
3140      RETURN
3150  20  TRANSS=0.
3160      RETURN
3170      END
3180C
3190      FUNCTION TPLUME(T)
3200      REAL MW
3210      COMMON H,DELH,Q,MW
3220      COMMON WS,C0V,CEIL,HMIX,J
3230      COMMON XSTART,XSTOP,YMAX,SQMI
3240      COMMON X,Y,Z
3250      COMMON NL0W,NHIGH
3260      DATA C0EF/6.283/
3270      SY=SIGY(X,J)
3280      SZ=SIGZ(X,J)
3290      T1=0.
3300      T2=Y/SY
3310      T3=Z/SZ
3320      EXP0N=-(T1*T1+T2*T2+T3*T3)*.5
3330      IF(ABS(EXP0N).GT.20) G0T0 2
3340      T0P=EXP(EXP0N)
3350      B0T=C0EF*WS*SY*SZ
3360      FT=T0P/B0T
3370      G0 T0 5
3380  2  CONTINUE
3390      FT=0.
3400  5  CONTINUE
3410      TPLUME=FT
3420      RETURN
3430      END
3440C
3450      FUNCTION SIGY(X,J)
3460C      DISPERSION COEFFICIENTS BASED ON TURNER WORKBOOK
3470C      J=1,2,3,4,5 ARE CLASSES B,C,D,E,F
3480C      X AND SIGY ARE IN MILES
3490      DIMENSION A(5),B(5)
3500      DATA A/155.,100.,68.,50.,34./, B/.91,.92,.93,.90,.93/
3510      XX=X*1.609
3520      SIGY=A(J)*XX**B(J)
3530      SIGY=SIGY*.000889
3540C      .000889=(1/1609.)*(6**.2)
3550C      HERE THE SIGMAS GIVEN IN THE TURNER WORKBOOK FOR
3560C      TEN-MINUTE SAMPLINGS ARE SCALED TO 1 HOUR AVERAGES
3570C      BY A FACTOR 1.43
3580      RETURN
3590      END

```

```

3600C
3610      FUNCTION SIGZ(X,J)
3620C      DISPERSION COEFFICIENT BASED ON TURNER WORKBOOK
3630C      J=1,2,3,4,5 ARE CLASSES B,C,D,E,F
3640C      X AND SIGZ ARE IN MILES
3650      DIMENSION A(3,5),B(3,5)
3660      DATA A/110.,110.,110.,60.,60.,60.,33.,33.,40.,21.5,
3670&      21.5,36.,14.,14.,23.5/
3680      DATA B/1.,1.09,1.09,.92,.92,.92,.80,.61,.53,.77,.56,
3690&      .35,.78,.53,.30/
3700C      A(I,J),B(I,J). I=1,2,3 FOR X IN (0.,1.),(1.,10.),(10.,100.)
3710      XX=X*1.609
3720      I=1
3730      IF(XX.GT.1.)I=2
3740      IF(XX.GT.10.)I=3
3750      SIGZ=A(I,J)*XX*B(I,J)*.000889
3760C      .000889=(1/1609)*(60/10)**.2
3770      RETURN
3780      END
3790C
3800      SUBROUTINE XYISO(DELX,DELY,ZZ,PISO,CHIMAX,DIST)
3810      DIMENSION YY(50),CHI(50),D(3),XC(3)
3820      REAL MW
3830      COMMON H,DELH,Q,MW
3840      COMMON WS,C0V,CEIL,HMIX,J
3850      COMMON XSTART,XSTOP,YMAX,SQMI
3860      COMMON X,Y,Z,NF
3870      COMMON NL0W,NHIGH
3880      DATA NCUT/1/,NHOURS/4/
3890      FACT=1./(5280.*2.15)
3900      D(1)=(2.*HMIX-H)*FACT
3910      D(2)=(2.*HMIX+H)*FACT
3920      D(3)=(4.*HMIX-H)*FACT
3930      NF=0
3940C      CALCULATE DISTANCES AT WHICH NEW IMAGES BECOME IMPORTANT
3950      D0 36 N=1,3
3960      G0 T0 (31,32,33,34,35),J
3970C      B STABILITY
3980      31 XC(N)=(D(N)/(110.*.000889))**(1/1.09)
3990      G0 T0 36
4000C      C STABILITY
4010      32 XC(N)=(D(N)/(60.*.000889))**(1/.92)
4020      G0 T0 36
4030C      D STABILITY
4040      33 XC(N)=(D(N)/(33.*.000889))**(1/.61)
4050      G0 T0 36
4060C      E STABILITY
4070      34 XC(N)=(D(N)/(21.5*.000889))**(1/.56)
4080      G0 T0 36
4090C      F STABILITY
4100      35 XC(N)=(D(N)/(14.*.000889))**(1/.53)
4110      36 CONTINUE
4120      Z=ZZ
4130      XSTART=0.
4140      CHIMAX=0.
4150      XSTOP=0.
4160      YMAX=0.
4170      SQMI=0.
4180      YY(1)=0.
4190      D0 20 JK=2,50
4200      YY(JK)=YY(JK-1)+DELY

```

```

4210 20 CONTINUE
4220 X=0.
4230 D0 80 I=1,101
4240 X=X+DELX
4250 IF(X.GE.XC(1)) NF=1
4260 IF(X.GE.XC(2)) NF=2
4270 IF(X.GE.XC(3)) NF=3
4280 NTMAX=X/WS
4290 NTWIDE=NCUT-NTMAX/NHOURS
4300 IF(NTWIDE.LT.0)NTWIDE=0
4310 NL0W=NTMAX-NTWIDE
4320 NHIGH=NTMAX+1+NTWIDE
4330 NY=0
4340 D0 40 JK=1,50
4350 Y=YY(JK)
4360 IF(MW)60,60,59
4370 60 CHI(JK)=Q*TRANSX(NTMAX)*.10882
4380 G0 T0 58
4390 59 CHI(JK)=Q*TRANSX(NTMAX)*.0024391/MW
4400 58 IF(CHI(JK).LT.PIS0) G0 T0 50
4410 NY=NY+1
4420 40 CONTINUE
4430 50 CONTINUE
4440 IF(NY.EQ.0)G0T0 70
4450 IF(XSTART.EQ.0.)XSTART=X
4460 YMAX=AMAX1(YMAX,YY(NY))
4470 IF(CHI(1)-CHIMAX)10,11,11
4480 11 CHIMAX=CHI(1)
4490 DIST=X
4500 10 CONTINUE
4510 SQMI=SQMI+(2*NY-1)*DELX*DELY
4520 G0 T0 80
4530 70 CONTINUE
4540 IF(XSTART.EQ.0.)G0T0 80
4550 XST0P=X-DELX
4560 G0T0 85
4570 80 CONTINUE
4580 IF(XST0P.EQ.0.)XST0P=X
4590 85 CONTINUE
4600 YMAX=YMAX+DELY*.5
4610 XST0P=XST0P+DELX*.5
4620 IF(XSTART.EQ.0.) XSTART=DELX*.5
4630 XSTART=XSTART-DELX*.5
4640 RETURN
4650 END
4660C
4670 FUNCTION TRANSX(M)
4680 SUM=0.
4690 N1=M-5
4700 N2=M+5
4710 IF(M.LE.5) N1=1
4720 D0 10 N=N1,N2
4730 ADD=TRAN(N)
4740 SUM=SUM+ADD
4750 10 CONTINUE
4760 TRANSX=SUM
4770 RETURN
4780 END

```

```

4790C
4800      FUNCTION TRAN(N)
4810C      CUTOFF ON N
4820C      GROUND-LEVEL CONCENTRATIONS ONLY
4830      REAL MW
4840      COMMON H,DELH,Q,MW
4850      COMMON WS,C0V,CEIL,HMIX,J
4860      COMMON XSTART,XSTOP,YMAX,SQMI
4870      COMMON X,Y,Z,NF
4880      COMMON NL0W,NHIGH
4890      EXTERNAL KERN
4900      ADD1=0.
4910      ADD2=0.
4920      ADD3=0.
4930      ADD4=0.
4940      ADD5=0.
4950      ADD6=0.
4960      ADD7=0.
4970      A=N-1
4980      B=N
4990      ZKEEP=Z
5000      Z=(H+DELH)/5280.-ZKEEP
5010      IF(N.LT.NL0W.OR.N.GT.NHIGH)G0T0 10
5020      CALL INTEG1(KERN,A,B,.05,1.,.1,ADD1)
5030      G0T0 20
5040 10 CONTINUE
5050      CALL KERN(N-.5,ADD1)
5060 20 CONTINUE
5070      IF(NF.EQ.3) G0T0 99
5080      ADD2=ADD1
5090      Z=(HMIX+HMIX-(H+DELH))/5280.-ZKEEP
5100      IF(N.LT.NL0W.OR.N.GT.NHIGH)G0T0 30
5110      CALL INTEG1(KERN,A,B,.05,1.,.1,ADD3)
5120      G0T0 40
5130 30 CONTINUE
5140      CALL KERN(N-.5,ADD3)
5150 40 CONTINUE
5160      HX=H+DELH
5170      SZ=SIGZ(X,J)
5180      XL1=((2.*HMIX-HX)/SZ)**2
5190      XL2=((2.*HMIX+HX)/SZ)**2
5200      XL3=((4.*HMIX-HX)/SZ)**2
5210      ADD4=ADD3
5220      ADD5=ADD3*EXP(.5*(XL1-XL2))
5230C      PUFF MODEL APPROXIMATION. MULTIPLE IMAGES NOT INTEGRATED
5240 99 TRAN=ADD1+ADD2+ADD3+ADD4+ADD5+ADD6+ADD7
5250      Z=ZKEEP
5260      RETURN
5270      END
5280C
5290      SUBROUTINE INTEG1(FFUNC,XL,XU,DXINT,AMAG,EPS,VALU)
5300C      ROUTINE TO EVALUATE INTEGRAL OF F(X) BETWEEN LIMITS
5310C      XL AND XU BY VARIABLE SIMPSON RULE
5320      VALU=0.
5330      XZER0=XL
5340      DX=DXINT
5350      CALL FFUNC(XZER0,FZER0)
5360 10 CONTINUE
5370      IF(XU-(XZER0+4.*DX))20,30,30

```

```

5380 20 CONTINUE
5390 DX=(XU-XZER0)/4.
5400 30 CONTINUE
5410 CALL FFUNC(XZER0+DX,F1)
5420 CALL FFUNC(XZER0+2.*DX,F2)
5430 CALL FFUNC(XZER0+3.*DX,F3)
5440 CALL FFUNC(XZER0+4.*DX,F4)
5450 S1=2.*DX*(FZER0+4.*F2+F4)/3.
5460 S2=DX*(FZER0+4.*F1+2.*F2+4.*F3+F4)/3.
5470 RATIO=ABS(S2-S1)/(AMAX1(ABS(S2),AMAG*1.E-4)*EPS)
5480 IF(RATIO-1.)60,40,40
5490 40 CONTINUE
5500C CYCLE REJECTED. REDUCE DX AND TRY AGAIN.
5510 DX=DX/1.5
5520 G0 T0 30
5530 60 CONTINUE
5540C CYCLE ACCEPTED
5550 ADD=S2+(S2-S1)/15.
5560 VALU=VALU+ADD
5570 XZER0=XZER0+4.*DX
5580 FZER0=F4
5590 IF(XZER0-XU)80,70,70
5600 70 CONTINUE
5610 RETURN
5620 80 CONTINUE
5630 IF(RATIO-.5)100,90,90
5640 90 CONTINUE
5650 DX=DX/1.5
5660 G0 T0 10
5670 100 CONTINUE
5680 IF(RATIO-.01)110,10,10
5690 110 DX=DX*1.5
5700 G0 T0 10
5710 END
5720C
5730 SUBROUTINE KERN(T,FT)
5740 REAL MW
5750 COMMON H,DELH,Q,MW
5760 COMMON WS,C0V,CEIL,HMIX,J
5770 COMMON XSTART,XSTOP,YMAX,SQMI
5780 COMMON X,Y,Z,NF
5790 COMMON NL0W,NHIGH
5800 DATA C0EF/15.750/
5810 IF(T.EQ.0.)G0T0 10
5820 QQ=WS*T
5830 SY=SIGY(QQ,J)
5840 SX=SY
5850 SZ=SIGZ(QQ,J)
5860 T1=(X-WS*T)/SX
5870 T2=Y/SY
5880 T3=Z/SZ
5890 IF(NF.EQ.3) T3=0.
5900 EXP0N=-(T1*T1+T2*T2+T3*T3)*.5
5910 IF(ABS(EXP0N).GT.20)G0 T0 10
5920 T0P=EXP(EXP0N)
5930 B0T=C0EF*SX*SY*SZ
5940 IF(NF.EQ.3) B0T=6.283*(HMIX/5280.)*SX*SY
5950 FT=T0P/B0T
5960 RETURN

```



```

5970 10 CONTINUE
5980 FT=0.
5990 RETURN
6000 END
6010C
6020 SUBROUTINE STAB(M0,NDAY,NHR,C0V,CEIL,WS,NCLASS)
6030C CALCULATES TURNER STABILITY CLASSIFICATION FOR EACH HOUR.
6040C IDENTIFIES SUNRISE AND SUNSET AND TWO HOURS EITHER SIDE.
6050C J=1,2,3,4,5 ARE CLASSES B,C,D,E,F, RESPECTIVELY
6060 WSM=WS
6070 WS=WSM*5280./6050.2
6080C CALCULATE JULIAN DAY
6090 J=30.42*(M0-1)+NDAY
6100C CALCULATE DECLINATION OF SUN IN DEGREES
6110 DECL=23.27*SIN(.0172*(J-80))
6120C CALCULATE SUNRISE AND SUNSET HOURS
6130 IF(DECL.GE.20.)GOTO 11
6140 IF(DECL.GE.0.)GOTO 12
6150 IF(DECL.GE.-15.)GOTO 13
6160 GOTO 14
6170 11 NSR=4
6180 NSS=19
6190 GOTO 20
6200 12 NSR=5
6210 NSS=18
6220 GOTO 20
6230 13 NSR=6
6240 NSS=17
6250 GOTO 20
6260 14 NSR=7
6270 NSS=16
6280 20 CONTINUE
6290 KRISE=3
6300 KSET=3
6310 IF(NHR.GT.(NSR+2).AND.NHR.LT.(NSS-2))GOTO 200
6320C G0 FOR DAYTIME
6330 IF(NHR.LT.(NSR-2).OR.NHR.GT.(NSS+2))GOTO 100
6340C G0 FOR NIGHTTIME
6350 IF(NHR.GT.12)GOTO 40
6360C G0 FOR SUNSET
6370 KRISE=NHR-NSR
6380 GOTO 50
6390 40 KSET=NHR-NSS
6400 50 CONTINUE
6410 IF(NHR.GT.NSR.AND.NHR.LT.NSS)GOTO 200
6420C G0 FOR DAY NEAR START OR END
6430C NIGHT FOLLOWS
6440 100 IF(C0V.GE..95.AND.CEIL.LE.7000.)GOTO 110
6450 IF(C0V.LE..4)GOTO 120
6460 NRAD=-1
6470 GOTO 300
6480 110 NRAD=0
6490 GOTO 300
6500 120 NRAD=-2
6510 GOTO 300
6520C DAYTIME FOLLOWS
6530 200 NSUN=IABS(12-NHR)
6540 IF(C0V.GE..95.AND.CEIL.LT.7000.)GOTO 290
6550C CALCULATE ANGLE OF SUN IN DEGREES
6560 DECL=DECL*.01745

```

```

6570      HRANG=NSUN*.2654
6580      ALP=57.29*ASIN(.670*SIN(DECL)+.743*COS(DECL)*COS(HRANG))
6590C      TURNER TABLE A-2
6600      IF(ALP.GT.60.)GOTO 211
6610      IF(ALP.GT.35.)GOTO 212
6620      IF(ALP.GT.15.)GOTO 213
6630      NRAD=1
6640      GOTO 220
6650 211 NRAD=4
6660      GOTO 220
6670 212 NRAD=3
6680      GOTO 220
6690 213 NRAD=2
6700 220 IF(COV.LT..51)GOTO 300
6710      IF(CEIL.LT.7000.)NRAD=NRAD-2
6720      IF(CEIL.GE.7000..AND.CEIL.LT.16000.)NRAD=NRAD-1
6730      IF(COV.GT..99)NRAD=NRAD-1
6740      IF(NRAD.LT.1)NRAD=1
6750      GOTO 300
6760 290 NRAD=0
6770 300 CONTINUE
6780C      TURNER TABLE A-1
6790      NCLASS=4
6800      NR=NRAD+3
6810      GOTO(310,320,330,340,350,360,370),NR
6820 310 IF(WS.LE.10.5)NCLASS=5
6830      GOTO 380
6840 320 IF(WS.LE.6.5)NCLASS=5
6850 330 GOTO 380
6860 340 IF(WS.LE.3.5)NCLASS=3
6870      GOTO 380
6880 350 NCLASS=3
6890      IF(WS.LE.3.5)NCLASS=2
6900      IF(WS.GE.9.5)NCLASS=4
6910      GOTO 380
6920 360 IF(WS.LE.7.5)GOTO 362
6930      NCLASS=3
6940      IF(WS.GE.11.5)NCLASS=4
6950      GOTO 380
6960 362 NCLASS=2
6970      IF(WS.LE.1.5)NCLASS=1
6980      GOTO 380
6990 370 NCLASS=2
7000      IF(WS.LE.5.5)NCLASS=1
7010      IF(WS.GE.9.5)NCLASS=3
7020      GOTO 380
7030 380 CONTINUE
7040      WS=WSM
7050      RETURN
7060      END
7070      FUNCTION ASIN(T)
7080      DATA A0/1.5707963050/,A1/-0.2145988016/,A2/0.0889789874/
7090      DATA A3/-0.0501743046/,A4/0.0308918810/,A5/-0.0170881256/
7100      DATA A6/0.0066700901/,A7/-0.0012624911/
7110      F1=((((((A7*T+A6)*T+A5)*T+A4)*T+A3)*T+A2)*T+A1)*T+A0
7120      F2=SQRT(1.0-T)
7130      ASIN=3.1415926536/2-F2*F1
7140      RETURN
7150      END

```

REFERENCES

1. L. A. Conley, E. J. Croke, A. S. Kennedy, R. F. King, J. E. Norco, J. J. Roberts, A. D. Rossin, and T. D. Wolsko, *Isopleth-area Tables*, ANL/ES-8 (Oct 1971).
2. *Chicago Air Pollution Systems Analysis Program: Final Report*, J. J. Roberts, Ed., ANL/ES-CC-009 (Feb 1971).
3. A. S. Cohen, E. J. Croke, A. Hurter, J. E. Norco, and J. J. Roberts, *Long-range Planning in Air Resource Management*, ANL/ES-CC-008 (Jan 1971).
4. D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*, U.S. Dept. of Health, Education, and Welfare, U.S. Public Health Service Publ. No. 999-AP-26 (Revised 1970).
5. J. E. Carson and H. Moses, "The Validity of Currently Popular Plume Rise Formulas," in *Proc. USAEC Meteorological Information Meeting, Held at Chalk River Nuclear Laboratories, September 11-14, 1967*, AECL-2787, pp. 1-20.
6. S. G. Carpenter, J. A. Frizzola, M. E. Smith, J. M. Leavitt, and F. W. Thomas, *Report on Full-Scale Study of Plume Rise at Large Electric Generating Stations*, Paper No. 67-82, 60th Annual Air Pollution Control Association Annual Meeting, Cleveland, Ohio, June 11-16, 1967.
7. G. A. DeMarrais, *Wind-Speed Profile at Brookhaven National Laboratory*, J. Meteorol. 16, 181-190 (Apr 1959).
8. H. E. Cramer, G. M. DeSanto, R. K. Dumbauld, P. Morgenstern, and R. N. Swanson, *Meteorological Prediction Techniques and Data System*, Geophysics Corp. of America, Bedford, Mass., GCA Tech. Report No. 64-3-G, p. 34 (Mar 10, 1964).
9. F. Pasquill, *Atmospheric Diffusion*, D. Van Nostrand Co., Ltd., London, pp. 179-204.
10. H. E. Cramer and R. K. Dumbauld, *Experimental Designs for Dosage Predictions in CB Field Tests*, Geophysics Corp. of America, Bedford, Mass., GCA Tech. Report No. 68-17-G.
11. E. J. Croke, J. E. Carson, D. F. Gatz, H. Moses, F. L. Clark, A. S. Kennedy, J. A. Gregory, J. J. Roberts, R. P. Carter, and D. B. Turner, *City of Chicago Air Pollution System Model: Second Quarterly Progress Report*, ANL/ES-CC-002 (May 1968).
12. E. J. Croke, J. E. Carson, D. F. Gatz, H. Moses, A. S. Kennedy, J. E. Norco, J. J. Roberts, K. G. Croke, J. B. Anderson, D. M. Nelson, J. E. Ash, R. P. Carter, D. Parsons, J. W. Lin, and R. J. Votruba, *Chicago Air Pollution Systems Analysis Program: Fourth Quarterly Progress Report*, ANL/ES-CC-004 (Mar 1969).