NOAA TM ERL ARL-42

NOAA Technical Memorandum ERL ARL-42

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

A Program for Evaluating Atmospheric Dispersion From a Nuclear Power Station

JERROLD F. SAGENDORF

Air Resources
Laboratory
IDAHO FALLS,
IDAHO
May 1974

ENVIRONMENTAL RESEARCH LABORATORIES

AIR RESOURCES LABORATORIES

IMPORTANT NOTICE

Technical Memoranda are used to insure prompt dissemination of special studies which, though of interest to the scientific community, may not be ready for formal publication. Since these papers may later be published in a modified form to include more recent information or research results, abstracting, citing, or reproducing this paper in the open literature is not encouraged. Contact the author for additional information on the subject matter discussed in this Memorandum.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Technical Memorandum ERL ARL-42

A PROGRAM FOR EVALUATING ATMOSPHERIC DISPERSION FROM A NUCLEAR POWER STATION

Jerrold F. Sagendorf

Air Resources Laboratory
Idaho Falls, Idaho
May 1974

DISCLAIMER

The Environmental Research Laboratories do not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to the Environmental Research Laboratories or to this publication furnished by the Environmental Research Laboratories in any advertising or sales promotion which would indicate or imply that the Environmental Research Laboratories approve, recommend, or endorse any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this Environmental Research Laboratories publication.

CONTENTS

A PROGRAM FOR EVALUATING ATMOSPHERIC DISPERSION FROM A NUCLEAR POWER STATION

Jerrold F. Sagendorf

A computer code (SEP for Site Evaluation Program) is described. The program uses a joint frequency distribution of winds and stability classes to evaluate the atmospheric dispersion potential near a nuclear power station. The code includes models for short-term and long-term effluent releases. A description of the input parameters is included.

1. INTRODUCTION

This report describes a computer code developed for the Directorate of Licensing of the Atomic Energy Commission to evaluate atmospheric dispersion characteristics of potential sites for nuclear power stations. To do this, concentrations of effluents normalized by the source strength of the power plant are calculated. These atmospheric dilution factors are calculated for hourly and annual periods using data describing the power plant site and meteorology of the area.

2. INPUT DATA

A complete description of the input data necessary to run the program is given in appendix A. These data include a joint frequency distribution of wind speed and stability classes for each directional sector, the distances to the site boundary in each sector, the minimum distance to a site boundary, the distance to the nearest population center, and the cross section and height of the reactor building. If the site has a stack, the exit velocity of the effluent, the height and diameter of the stack, and the distances and elevations of significant terrain features for each sector must also be provided.

3. MACHINE REQUIREMENTS

The program is written in FORTRAN IV and uses 250 K memory on an IBM 360/75 computer. Computing time varies depending on the options used and the size of the joint frequency distribution. A typical run using all the options and calculating both the surface and the stack effluent releases takes less than 1 min of computing time.

Plotting is done on an FR-80 microfilm system. The plotting routines are separate from the calculating routines, so that the program can be run where an FR-80 is not available. In this case, core requirements would also be reduced.

4. DESIGN BASIS ACCIDENT MODEL

To evaluate the potential severity of an accident, atmospheric dilution factors are calculated for each hour in a year of "typical" weather conditions. One can then see the value of χ/Q (effluent concentration/source strength) that could be exceeded any given percent of the time. The calculations use the following equations:

$$\chi/Q = [U(\pi\sigma_y\sigma_z + CA)]^{-1} \quad (1a)$$

$$\chi/Q = (3U\pi\sigma_y\sigma_z)^{-1} \quad (1b)$$

$$\chi/Q = \exp[-\tfrac{1}{2}(h_e/\sigma_z)^2](U\pi\sigma_y\sigma_z)^{-1} \quad (2)$$

χ = effluent concentration (m^{-3})
Q = source strength (sec^{-1})
U = upper limit of the wind speed class ($m\ sec^{-1}$)
σ_y = horizontal standard deviation of material in the plume (m)
σ_z = vertical standard deviation of material in the plume (m)
h_e = effective stack height (m)
C = building wake constant (C = 0.5)
A = cross section of the reactor building (m^2)

For a ground-level release, the results of (1a) and (1b) are compared and the larger value is used. Equation (1b) represents the limit allowed for building wake dilution. Values of χ/Q are calculated for all combinations of wind speed and stability classes using distances obtained in three different ways: (1) the distance to the nearest site boundary, (2) the distance to the nearest population center, and (3) the actual distance to the site boundary in each sector. In each case, the values of χ/Q are ordered from greatest to least, and the cumulative frequency is obtained from the joint frequency distribution. Finally a curve is fit to the χ/Q versus cumulative frequency data points, and the data points and curves are plotted on log-normal plots.

If a stack release is considered, (2) is used and the same procedures followed as for a ground release. In this case, however, the maximum value of χ/Q may occur at some distance beyond the considered distance. Because of this, calculations are made for a number of distances, and the maximum value of χ/Q at or beyond the considered distance is the one used.

5. ANNUAL AVERAGE MODEL

In this model, a long-term continuous release is assumed in order to evaluate the impact of a power plant under normal operating conditions. The equations used are

$$\left(\frac{\chi}{Q}\right)_{ave} = \frac{(2/\pi)^{1/2}}{r\theta} \sum \frac{f \exp\left[-\frac{1}{2}\left(\frac{h_e}{\sigma_z}\right)^2\right]}{\bar{U}(\sigma_z^2 + CD_z^2/\pi)^{1/2}} \qquad (3a)$$

$$\frac{\chi}{Q}_{ave} = \frac{(2/\pi)^{1/2}}{r\theta\sqrt{3}} \sum \frac{f \exp\left[-\frac{1}{2}\left(\frac{h_e}{\sigma_z}\right)^2\right]}{\bar{U}\ \sigma_z} \qquad (3b)$$

$\left(\frac{\chi}{Q}\right)_{ave}$ = annual average effluent concentration normalized by source strength

$\bar{U}$ = average wind speed in the given wind speed class (m sec^{-1})

σ_z = vertical standard deviation of material in the plume (m)

f = joint probability of stability, wind speed, and wind direction

C = building wake constant ($C = 0.5$)

D_Z = height of the building (m)

r = distance at which calculation is being made (m)

θ = sector width in radians.

Equation (3b) reflects the maximum allowable building wake dilution. The results of (3a) and (3b) are compared, and the larger value is used. Values of $(\chi/Q)_{ave}$ are calculated for the site boundary and a number of distances out to 80 km for each sector. Each sector is divided into segments, and an average value of χ/Q is determined for the segments as follows:

$$(\chi/Q)_{seg} = \frac{R_1(\chi/Q)_{R_1} + r_1(\chi/Q)_r + \cdots + r_n(\chi/Q)r_n + R_2(\chi/Q)R_2}{R_1 + r_2 + \cdots r_n + R_2} \quad (4)$$

$(\chi/Q)_{seg}$ = average value of $(\chi/10)_{ave}$ for the segment

$(\chi/Q)_r$ = $(\chi/Q)_{ave}$ calculated at distance r

R_1, R_2 = segment boundaries

$r_1 \cdots r_2$ = selected radii between R_1 and R_2.

The program has the option to assume mixing occurs between adjacent sectors. This option smoothes the values of $(\chi/Q)_{seg}$ as follows:

$$\overline{(\chi/Q)_K} = \tfrac{1}{4}[(\chi/Q)_{K-1} + 2(\chi/Q)_K + (\chi/Q)_{K+1}] \quad (5)$$

$\overline{(\chi/Q)_K}$ = the smoothed value of $(\chi/Q)_{seg}$ in the K^{th} sector

$(\chi/Q)_K$ = $(\chi/Q)_{seg}$ in the K^{th} sector.

A second option that is also available averages all values of $(\chi/Q)_{seg}$ at each radii.

Note that the program can calculate values for a ground, an elevated, or a mixed release. For a mixed release, the origin is assumed to be at the reactor building; values obtained from an elevated release are interpolated into the appropriate radii surrounding the reactor.

6. CALMS

Note that in (1a), (1b), (2), (3a), and (3b) wind speed appears as a factor in the denominator. This causes obvious difficulties in making calculations for calm periods.

The procedure used in the model is to assign a "direction" to each calm period according to the directional distribution for the lowest wind speed class. This is done separately for the calms in each stability category. In the rare instance that a stability category has calms but no occurrence of a lowest wind speed class, the calms are distributed evenly among all sectors. The calms are then added to the lowest wind speed class in the proper sector and stability category. The program also has the option of making the calms a separate wind speed class by assigning them some wind speed value and distributing them to the sectors in the same manner as above.

7. EFFECTIVE STACK HEIGHT

For elevated releases for both the accident and annual average models, effective stack height is determined from

$$h_e = h_s + h_{pr} - h_t \tag{6}$$

h_e = effective stack height (m)

h_s = physical stack height (m)

h_{pr} = plume rise (m)

h_t = terrain height (m).

The program interpolates linearly between terrain data points to obtain the terrain height at any given location.

Plume rise is calculated using formulas from Briggs (1969). The program will calculate plume rise caused by either momentum or buoyancy, depending on the heat emission rate (Q_h) that is put into the program as data. Nuclear power stations generally have cold plumes, so the heat emission rate is read in as zero, and the plume rise is calculated from the momentum equations. For neutral or unstable conditions, we have

$$h_{pr} = 1.44 \left(\frac{W_0}{U}\right)^{2/3} \left(\frac{X}{D}\right)^{1/3} D \qquad (7)$$

h_{pr} = plume rise (m)
W_0 = exit velocity (m sec^{-1})
X = distance (m)
U = wind speed (m sec^{-1})
D = internal stack diameter (m).

When the exit velocity is less than 1.5 times the wind speed, a correction (Briggs, 1973; private communication) for downwash is subtracted from (7)

$$C = 3\left(1.5 - \frac{W_0}{U}\right) D \qquad (8)$$

where C is the value to be subtracted, and the other terms are defined as in (7). The result from (7), corrected by (8) if necessary, is compared with

$$h_{pr} = 3\left(\frac{W_0}{U}\right) D, \qquad (9)$$

and the more conservative value is used.

For stable conditions, the results from (7) or (9) are compared with the results from the following two equations

$$h_{pr} = 4\left(\frac{F_m}{S}\right)^{1/4} \qquad (10)$$

$$h_{pr} = 1.5\left(\frac{F_m}{U}\right)^{1/3} S^{-1/6}, \qquad (11)$$

and the smallest value of h_{pr} is used. In (10) and (11), F_m is the momentum flux parameter and S is a stability parameter. They are defined as

$$F_m = W_0^2 \left(\frac{D}{2}\right)^2 \tag{12}$$

$$S = \frac{g}{T} \frac{\partial\theta}{\partial z} \tag{13}$$

g = acceleration of gravity (m sec^{-2})

T = ambient air temperature (deg K)

$\partial\theta/\partial z$ = vertical potential temperature gradient (deg K m^{-1}).

For the purposes of the program, S was defined as 8.7 x 10^{-4} for E stability, 1.75 x 10^{-3} for F stability, and 2.45 x 10^{-3} for G stability.

If plume rise is to be calculated for a buoyant plume, the value of Q_h (in cal sec^{-1}) is read in as data. Plume rise to distances less than some distance X* is given by

$$h_{pr} = 1.6F^{1/3} U^{-1} X^{2/3} \tag{14}$$

$$F = 4.3 \times 10^{-3} \left[\frac{ft/sec^3}{cal/sec}\right] Q_h. \tag{15}$$

For neutral and unstable conditions,

$$X^* = 0.5 F^{2/5} h_s^{3/5} \quad (h_s < 1000 \text{ ft}) \tag{16}$$

$$X^* = 33 F^{2/5} \quad (h_s > 1000 \text{ ft})$$

where h_s is the stack height. At distances beyond X*, plume rise under unstable and neutral conditions is calculated by

$$h_{pr} = \frac{1.6 F^{1/3} X^{*2/3} \left[\frac{2}{5} + \frac{16}{25}\left(\frac{X}{X^*}\right) + \frac{11}{5}\left(\frac{X}{X^*}\right)^2\right]}{U \left(1 + \frac{4X}{5X^*}\right)^2} . \tag{17}$$

At $X = 5X^*$, the plume is assumed to reach its maximum height. In stable conditions, (14) holds to a distance $X = 24US^{-\frac{1}{2}}$ after which the plume rise is given by

$$h_{pr} = 2.9(F/US)^{1/3} \quad (18)$$

where S is given by (13) and the same values are used as for momentum.

One other option available is simply to ignore plume rise.

8. OUTPUT

The output includes a printout of the maximum wind speed in each class and the frequency of occurrence of the wind speed class. Also printed out are the values of wind speed occurring at any desired increment of frequency, as determined by fitting a curve to the wind speed and cumulative frequency data point. A plot of the data points and the curve is also optionally available.

Similar tables and plots are included for the accident χ/Q calculations, and for the stack releases the plots and tables of the exponential term are included as well. For the annual average model, tables of annual average χ/Q versus distance and average values of χ/Q for each segment are printed out. If the site has a stack, the average effective stack height for each segment is printed out. Also included are the values of $(\chi/Q)_{ave}$ at the site boundaries and the average wind speed in each sector. Plots of $(\chi/Q)_{ave}$ versus distance for each sector and contour maps of $(\chi/Q)_{ave}$ for an 80 km radius around the site are optionally available.

9. REFERENCE

Briggs, G. A. (1969): Plume Rise, USAEC Report TID-15075. Available from Clearinghouse for Federal Scientific and Technical Information National Bureau of Standards, U. S. Dept. of Commerce, Springfield, Virginia 22151.

Appendix A: Input Data for Program

Card Type	Columns	Variable Name	Format	Description
1	1-14	KØPT	14I1	KØPT is the option array. 1 = do, 0 = bypass
1	1	KØPT(1)	I1	Design basic accident calculations
1	2	KØPT(2)	I1	Annual average calculations
1	3	KØPT(3)	I1	Ground-level release
1	4	KØPT(4)	I1	Stack release
1	5	KØPT(5)	I1	Printout input data
1	6	KØPT(6)	I1	Plot results on microfilm
1	7	KØPT(7)	I1	Printout individual X/Q calculations
1	8	KØPT(8)	I1	Calculate plume rise
1	9	KØPT(9)	I1	Use running mean smoothing on annual average sectors.
1	10	KØPT(10)	I1	Calculate sector averages as a function of distance.
1	11	KØPT(11)	I1	Mixed release calculations. (Submit data for ground-level release ahead of that for a stack and assign an internal storage device to unit 8.)
1	12	KØPT(12)	I1	Adjust wind speed classes
1	13	KØPT(13)	I1	Include calms as a separate wind speed class
1	14	KØPT(14)	I1	Use 30° sectors for north, south, east and west and 20° sectors for all other directions.
2	1-80	TITLA	20A4	Title for the minimum boundary case
3	1-80	TITLB	20A4	Title for the low population zone case
4	1-80	TITLC	20A4	Title for the variable boundary case
5	1-80	TITLD	20A4	General title for the site
6	1-80	TITLE	20A4	Title for the mixed release case. Include only if KØPT(4) = 1.
7	1-5	NVEL	I5	The number of velocity categories
7	6-10	NSTA	I5	The number of stability categories
7	11-15	NDIR	I5	The number of directional sectors (16 or 18).
7	16-20	NDIS	I5	The number of distances for which terrain heights are given
7	21-25	NHRS	I5	The number of hours from which the joint frequency distribution was obtained. If the joint frequency distribution is given in percent set NHRS = 1. If NHRS is read in as a negative number, it will be set to 1000000.

Appendix A: Input Data for Program - Continued

Card Type	Columns	Variable Name	Format	Description
7	26-30	INC(S)	I5	The increment in percent for which the accident results are printed out.
8	1-10	C	F10.0	The constant in the building wake term. (0.5)
8	11-20	A	F10.0	The cross section of the reactor building (m^2)
8	21-30	D	F10.0	The building height
8	31-40	HS	F10.0	The stack height (m)
8	41-50	Q	F10.0	The heat emission rate (calories sec^{-1}).
8	51-60	W	F10.0	The stack exit velocity (meter sec).
8	61-70	DIA	F10.0	The stack diameter (m).
9	1-10	DLPZ	F10.0	The low population zone (LPZ) distance (m). (DLPZ $\leq$ 1 allows you to skip LPZ calculations.)
9	11-10	BDYMIN	F10.0	The minimum site boundary distance (m).
10	1-5	GAMA	F5.0	The bearing (°) from the reactor to the stack.
10	6-10	SEP	F5.0	The distance (m) from the reactor to the stack.
10	11-15	QR	F5.0	The fraction of the source strength assumed from the reactor.
10	16-20	QS	F5.0	The fraction of the source strength assumed from the stack.
10	21-25	UCS	F5.0	The value to multiply the stable wind speed classes by.
10	26-30	UCU	F5.0	The value to multiply the unstable wind speed classes by. If the wind speed classes do not need adjusting KØPT(12) = 0 and USC = UCU = 1.
11	1-3	CALM(I) I=1,NSTA	7F5.0	The number of hours or percent of calm for each stability category. If calms are already included in the joint frequency distribution read these values in as zero.
12	1-80	FREQ(K,I,J) K=1,NDRI I=1,NVEL J=1,NSTA	16F5.0	The joint frequency distribution in either hours or percent of time. The values for up to 16 sections are read in on each card for each combination of wind speed class and stability class. If 18 directional sectors are used, the remaining two values are read in a second card. The loop to read these values cycles first on direction (starting with north and continuing clockwise), then on wind speed class, and finally on stability class.

Appendix A: Input Data for Program - Continued

Card Type	Columns	Variable Name	Format	Description
13	1-80	BDY(K) K=1,NDIR	8F10.0	The distance (m) to the site boundary in each directional sector. The values are read in eight to a card, beginning with the boundary to the south and proceeding clockwise until all sector boundaries are read in.
14	1-80	DIST(K,I) K=1,NDIR I=1,NDIS	8F10.0	The distances (m) at which the terrain heights are given. These values are read in eight to a card as for BDY above, except that NDIS distances are allowed. These cards are not read in for ground releases (i.e., if KØPT(4) = 0).
15	1-80	HT(K,I) K=1,NDIR I=1,NDIS	16F5.0	The terrain heights (m) corresponding to the distances in the DIST array above. These values are read in the same order as DIST, except there are 16 values to a card. They are also skipped if KØPT(4) = 0.
16	1-35	CØR(J) J=1,NSTA	7F5.0	An array of correction factors that may be applied to the joint frequency distribution. A different factor is possible for each stability class. If no corrections are needed, read in CØR(1) as a negative value.
17	1-5	UCØR	F5.0	A correction factor that may be applied to the wind speed classes. UCØR < 0 No corrections will be made. UCØR > 100 The wind speed classes will be converted from miles/hour to m/sec.
17	6-75	UMAX(I) I=1,NVEL	14F5.0	The maximum wind speed in each wind speed class. The values may be in either miles/hour or m/sec. If given in miles/hour set UCØR to a value greater than 100.

Note: Card type 6 (TITLE) is read in only if KØPT(4) = 1. If no mixed release calculations are made, it may be included as a blank card.
Card types 14 and 15 (DIST and HT) are skipped if KØPT(4) = 0.

Appendix B: List of Subroutines

ANNUAL	–	Annual average model
CHIQ	–	Design basis accident model
CONV	–	Used in transforming data points to the log-probability graphs
DATPLT	–	Plots the log-probability plots
CORECT	–	Used if the wind speeds must be adjusted
GAUSS	–	Integrates by Gaussian method to determine area under a normal curve
INVERS	–	Matrix inversion routine used in least-square curve fitting
ISOLIN	–	Plots contour maps of annual average χ/Q
LOGPLT	–	Plots χ/Q distance on a log-log graph
LSTSQR	–	Fits curves by least-squares method
MAIN	–	Reads input data
ORDER	–	Orders data from greatest to least
OUTPUT	–	Handles output for design basis accident case
POLYN	–	Computes σ_y and σ_z
RISE	–	Calculates plume rise
REVORD	–	Orders data from least to greatest
SHIFT	–	Interpolates annual average χ/Q values from the stack to radii around the reactor
SPCOUT	–	Handles output for wind speed vs cumulative frequency for cases where the wind speeds must be adjusted.

USCOMM - ERL