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CONCENTRIC CYLINDER SET MODEL FOR ESTIMATING DOSE FROM GAMMA-EM--ETC(U)
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AFRRI TECHNICAL REPORT

Concentric cylinder set model for estimating dose from gamma-emitting cloud

J. M. Arras

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFRRI-TR81-1	2. GOVT ACCESSION NO. AD-A100 390	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CONCENTRIC CYLINDER SET MODEL FOR ESTIMATING DOSE FROM GAMMA-EMITTING CLOUD		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. M. Arras		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Armed Forces Radiobiology Research Institute (AFRRI) Defense Nuclear Agency Bethesda, Maryland 20014		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NWED QAXM 97822
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency (DNA) Washington, D.C. 20305		12. REPORT DATE March 1981 13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The concentric cylinder set (CCS) cloud gamma dose model has been developed to estimate external gamma doses from elevated radioactive clouds. The primary application of this model is for stack releases by small radiological research facilities, including release during changing meteorological conditions or over irregular terrain.

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S/N 0102-014-6601

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20. ABSTRACT (continued)

The CCS model is applied with elementary calculation procedures, using only the tables and working curves included here. Calculation procedures are provided for dose estimates based on simple plumes and irregular clouds. Sample calculations are provided for evaluating doses from irregular clouds.

The CCS model has been compared to both published models, where the latter could be applied, and field measurements have been made during stack releases of argon-41, with satisfactory results. CCS model dose estimates provide substantial information on environmental surveillance for a wide range of release conditions, with little expenditure of time or money.

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CONTENTS

1.0 BACKGROUND INFORMATION

1.1 Introduction

When radioactive material is released to the atmosphere, estimates of radiation doses received by persons downwind are generally made by use of standard atmospheric dispersion equations (ref. 1, pp. 97-116). This procedure is adequate as a means of estimating inhalation doses, but it may result in very large errors when evaluating external gamma doses from radioactive clouds (2). Therefore, a number of cloud gamma dose models have been developed (3, 4).

Most published cloud gamma dose models were developed as part of computer codes used to estimate doses resulting from releases by nuclear power reactors. Such models may, when applied to small radiological research facilities, yield estimates with large and unpredictable errors. The model described in this study was developed to provide dose estimates for such releases. This model, which uses exposure rate source geometries consisting of concentric sets of hollow cylinders, has been designated the concentric cylinder set (CCS) model. A more detailed discussion of the background of the CCS model has been presented elsewhere (ref. 5, pp. 2-7, 13-19).

1.2 Purpose

The CCS cloud gamma dose model was developed solely for the purpose of providing external gamma dose estimates for a variety of radioactive cloud geometries. The CCS model may be applied to the simple plume geometries and long-term "average" meteorological conditions postulated in most models. However, the primary purpose of developing the CCS model is to estimate doses from irregular clouds.

An irregular cloud may possess any of the following characteristics: (a) finite size, (b) more than one plume centerline, (c) more than one plume orientation, (d) not accurately described with single-valued "effective" meteorological parameters, (e) widely varying concentrations of radioactivity within one gamma ray mean free path of the receptor, (f) plumes resulting from widely varying release rates, and (g) receptors at downwind distances where entrainment of released gases has not yet been completed.

1.3 Model Comparisons

The CCS model has been compared to a number of published cloud gamma dose models for those conditions to which the published models can be applied (ref. 5, pp. 78-88). Comparison was also made between calculated (CCS model) exposure rates and those obtained by measurements taken during the same stack releases (ref. 5, pp. 113-117). The CCS model generally agreed with published models to within 30% when identical input parameters could be used. The model generally agreed with field measurements within a factor of 2.

A point-by-point model was developed solely as a comparison model. The point-by-point model is basically a computer code derived from theoretical cloud gamma dose equations, without the special assumptions used in developing the CCS model (6). Only a few sets of release conditions were evaluated in this comparison, due to the large amount of machine time required for this model. Comparison to the CCS model showed consistent agreement within 20%.

2.0 BASIC MODEL

2.1 General Description

The concentric cylinder set model requires little expenditure of money or man-hours. It is not a computer code and requires no computer for its application. The model is flexible, due to its modular data sets and absence of any decision making in the model proper. All information needed to apply the model is provided in this report, except for specific radioactive source data. Values for source gamma energies and half-lives may be obtained from standard references (7).

A number of assumptions have been made in developing the CCS model, particularly in its application to irregular clouds. These assumptions, which have been discussed elsewhere (ref. 5, pp. 57, 58, 92), may be summarized as follows:

(a) Any radioactive cloud may be considered, for purposes of external radiation dose evaluation, to consist of a few (generally less than 20) smaller source volumes. Each source volume may be described by a set of single-valued meteorological and geometric parameters.

(b) A Gaussian diffusion model (8) may be used to approximate the internal source distribution of each source volume, or plume segment. This condition holds, even if the segment has undergone changes in direction during the period of its travel from release point to exposure of a receptor. This assumption is acceptable for external gamma dose estimates but not for internal dose estimates.

(c) Assumptions generally used in cloud gamma dose models (ref. 1, pp. 337-355) (9) may be used for the CCS model when used to evaluate both simple plumes and irregular clouds, with proper adjustments.

2.2 Simple Plume Geometry

The most useful application for the CCS model is the evaluation of doses from irregular clouds. However, application to simple plumes provides a better background for learning to apply the model, and will be discussed first. Figure 1A is a side view of an idealized simple elevated plume, as represented in the CCS model. The plume is represented by a train of end-to-end concentric sets of hollow cylinders. A perspective of several cylinder sets is shown in Figure 1B. The plume centerline is taken as the +X coordinate in standard dispersion calculations.

Each cylinder set has a Gaussian source distribution. The maximum cylinder radius included in the dose summations is denoted s_{max}, and is equal to 3σ, where σ is magnitude of the dispersion coefficient (ref. 1, pp. 100-105). Although this parameter increases monotonically and continuously in standard dispersion calculations, it is treated as a step-function in the CCS model.

The minimum distance between the receptor and the plume centerline is designated the centerline-receptor distance, denoted by a. The length of a set of cylinders is denoted by L. If a receptor is located directly below the plume centerline, then $a = H$, the effective stack height. Since the CCS model represents a theoretically

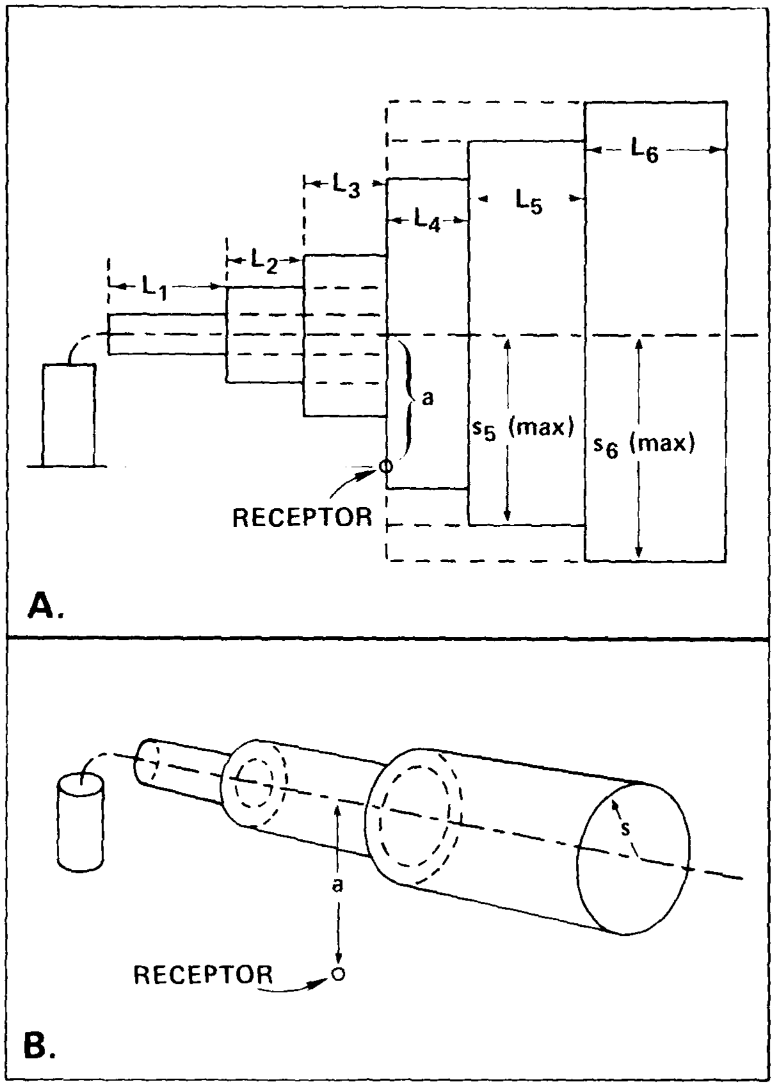

Figure 1. Concentric cylinder set geometry. (A) Regular plume geometry, showing net cylinder sets. (B) Perspective of concentric cylinder sets

conical geometry by a set of end-to-end cylinders, the two geometries become identical only as the cylinder lengths approach zero. In practice, however, the gamma doses associated with the two geometries are nearly equal for the conditions used in this report.

2.3 Basic Concentric Cylinder Set Equation

The basic CCS exposure rate module is based on the use of a hollow cylinder as the smallest separate source element. An integral solution exists for the fluence rate from such a source geometry (ref. 10, pp. 397-415). If attenuation is assumed to have a lesser effect on the exposure, the solution can be used to approximate the expected exposure rate. In the equation below used to develop the exposure rate curves, integration is applied over the cylinder internal angle and summation over the other dimensions (cylinder length and radii).

The exposure rate module equation for exposure rate is:

$$E.R. = \frac{\Gamma Q' F C A}{\sigma^2 \bar{u}} \sum_{j=1}^{3\sigma} s_j \Delta s \sum_{i=1}^{L} \frac{(1 + k\mu r_{ij}) \exp(-\mu r_{ij} - s_j^2/2\sigma^2)}{\sqrt{(s_j^2 + a^2 + \ell_i^2)^2 - 4 s_j^2 a^2}} \Delta \ell, \text{ with:}$$

E.R. = exposure rate at receptor, mR/h

L = length of each cylinder in the set, m

Q' = radioactivity release rate, mCi/s

s_j = radius of the j^{th} cylinder in the set, m

Γ = point source gamma exposure rate constant, R-m^2/Ci - h

ℓ_i = distance along the cylinder axis, to i^{th} increment, m

$\bar{u}$ = average, or effective, wind speed, m/s

σ^2 = product of dispersion coefficients, m^2, with $\sigma^2 = \sqrt{\sigma_y \sigma_z}$

k = gamma buildup constant in air, no units

μ = gamma attenuation coefficient in air, m^{-1}

a = centerline-receptor distance, m

F = radioactive decay correction factor, no units

C = cylinder eccentricity correction factor, no units

A = air-ground scattered gamma correction factor, no units

r_{ij} = distance between receptor and cloud volume corresponding to ℓ_i, s_j, m

$\Delta\ell$ = increment of cylinder length, along axis, m, and

Δs = increment of cylinder radius in a set, m.

2.4 Dispersion Coefficient

Meteorological parameters can be obtained by use of a wind speed- and direction-recording system and by visual observation of the sky. Values of the dispersion coefficient, σ, are provided in Figure 2. They should be applied with care in order not to be used outside the limiting conditions of their applicability (11).

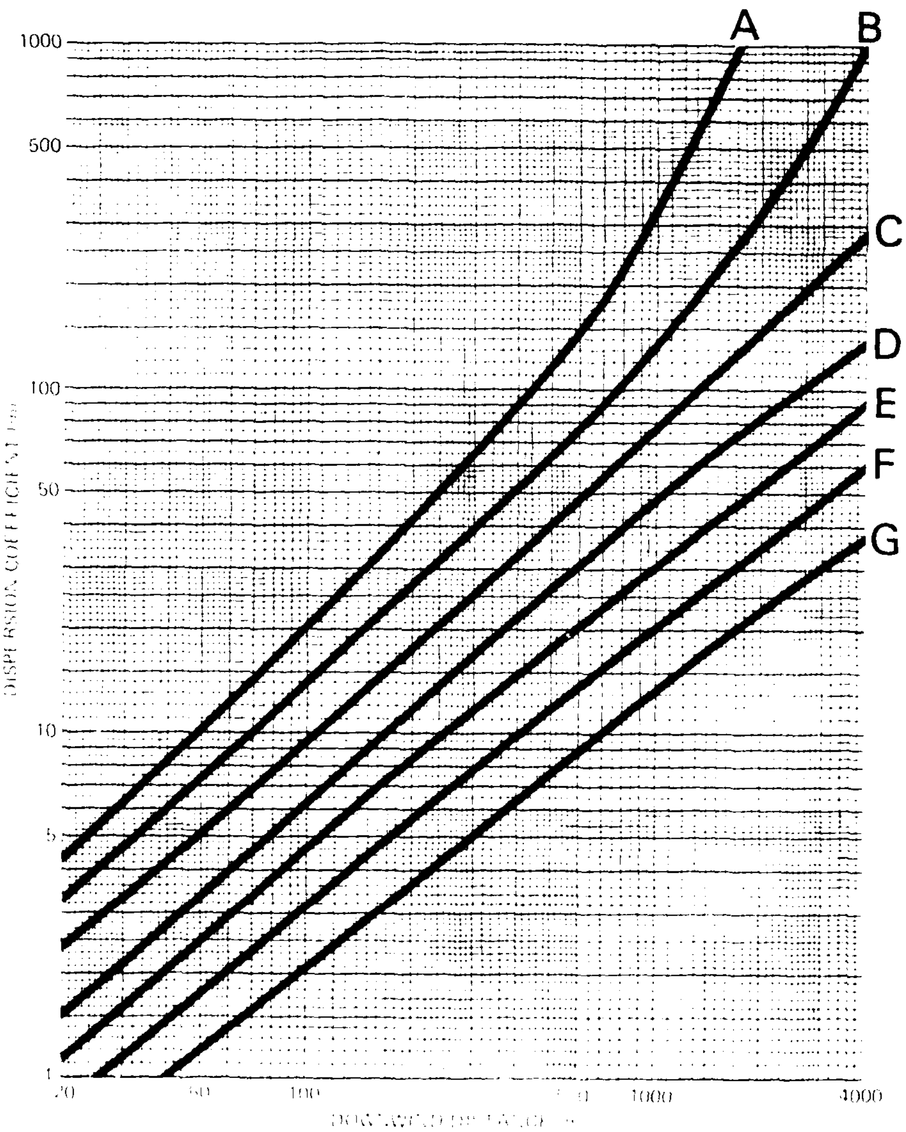

Figure 2. Dispersion coefficients (σ) (diffusion parameters) as function of meteorological stability category and downwind distance. Meteorological stability categories: A, extremely unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, moderately stable; G, extremely stable

Stability classes (or types) chosen for this study are listed in the legend for Figure 2. They are recommended by the U.S. Nuclear Regulatory Commission (USNRC). Type D should be used for all heavily overcast conditions. The appropriate classes can be ascertained by referring to Table 1, modified as necessary from standard references (12).

Table 1. Categories* of Meteorological Stability

	Daytime Brightness			Nighttime Cloudiness	
Surface Wind Speed (m/s)	Strong	Moderate	Slight	50% or More	40% or Less
<2	A	A-B	B	(F) †	(F-G)
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

* Categories taken from references 11 and 12

† Parentheses indicate that these were not included in original typing scheme.

3.0 APPLICATION

3.1 Cylinder Eccentricity

In the basic CCS equation, a circular cylinder geometry is assumed; this corresponds to isotropic diffusion in the yz-plane. This assumption, while not consistent with observed diffusion patterns, generally results in acceptably small errors when used only for external gamma dose estimates. However, there are cases in which the resulting error may be significant. So it is necessary to include a correction factor, C, for cylinder eccentricity.

Figure 3A qualitatively illustrates the effect of cylinder eccentricity on source-receptor geometry. Table 2 lists values of the ratios of crosswind-to-vertical dispersion coefficients for the range of conditions for which the CCS model might be needed. Table 3 lists correction factors. Correction factors for cylinder eccentricity exposure rate were obtained by FORTRAN summation over cylinder set volumes. Values of C are listed for the following parameter values: ratio of σ_y/σ_z, ratio of σ/a, ratio of L/a, and values of the angle ϕ, which is the angle between the line a and the vertical. For a ground level receptor and with $\sigma_y > \sigma_z$, C is always less than 1.0, and can be ignored for conservatism.

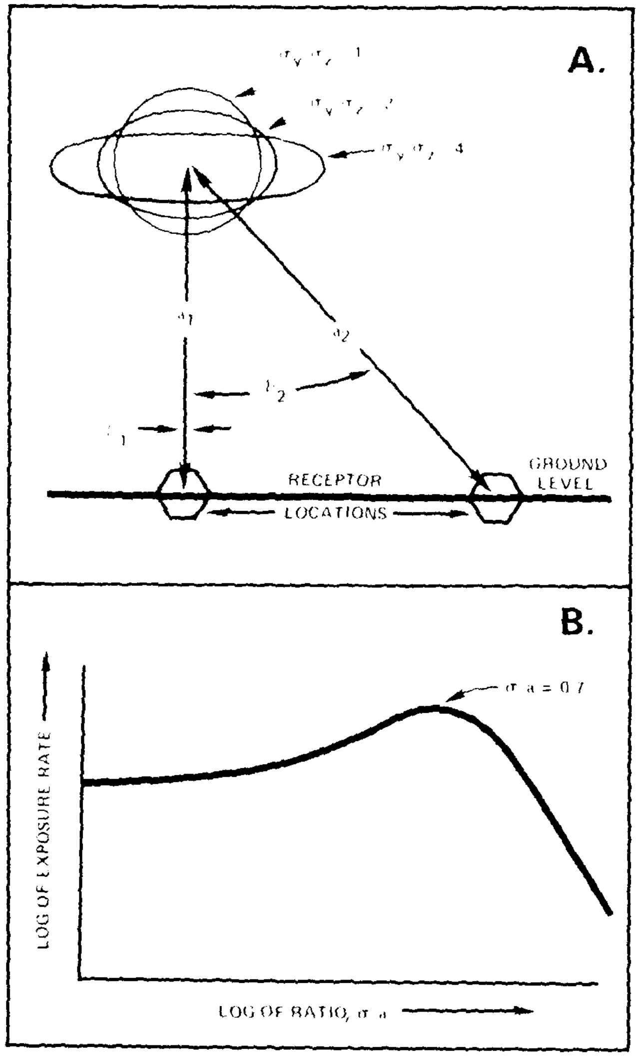

Figure 3. Dispersion coefficient ratios. (A) Geometry of cylinder set eccentricity. (B) Relative exposure rate as function of ratio of dispersion coefficient to centerline-receptor distance

Table 2. Ratios of Anisotropic Diffusion

Ratio σ_y/σ_z, with $\sigma = \sqrt{\sigma_y \sigma_z}$ (in meters) equal to:

Stability Category	1	2	5	10	20	40	70	100	150	200
A	–	–	2.4	2.2	2.0	1.7	1.4	1.1	0.8	0.6
B	–	–	1.8	1.8	1.8	1.7	1.6	1.5	1.3	1.2
C	–	1.6	1.6	1.7	1.7	1.8	1.7	1.7	1.7	–
D	–	1.6	1.7	1.8	1.9	2.1	2.5	2.8	4.2	–
E	–	1.6	1.7	1.9	2.1	2.5	3.2	3.8	4.8	–
F	1.5	1.6	1.9	2.1	2.4	3.1	4.3	5.4	–	–
G *	1.7	2.0	2.4	2.7	3.2	4.3	6.4	–	–	–

* Ratios based on coefficients taken from references 5 and 12; other ratios based on coefficients taken from one reference.

Table 3. Correction Factors for Cylinder Eccentricity

Φ (o)	σ/a	L/a	Factor, C, for σ_y/σ_z = 0.5	1.0	2.5	4.0	6.5	Φ (o)	σ/a	L/a	Factor, C, for σ_y/σ_z = 0.5	1.0	2.5	4.0	6.5
0	0.25	< 1	1.4	1	0.8	0.6	0.5	45	0.25	< 1	1.0	1	0.9	0.8	0.7
		1-2	1.2	1	0.8	0.7	0.6			1-2	1.0	1	0.9	0.8	0.7
		> 2	1.2	1	0.8	0.7	0.6			> 2	1.0	1	0.9	0.8	0.7
	0.75	< 1	1.2	1	0.6	0.4	0.3		0.75	< 1	0.8	1	0.9	0.6	0.4
		1-2	1.1	1	0.7	0.5	0.4			1-2	0.8	1	0.9	0.7	0.5
		> 2	1.1	1	0.7	0.6	0.4			> 2	0.8	1	0.9	0.7	0.5
	1.25	< 1	1.0	1	0.8	0.6	0.5		1.25	< 1	0.9	1	0.9	0.8	0.6
		1-2	1.0	1	0.9	0.7	0.6			1-2	0.9	1	1.0	0.8	0.7
		> 2	1.0	1	0.9	0.7	0.6			> 2	0.9	1	1.0	0.9	0.7
	1.75	< 1	0.9	1	0.9	0.8	0.6		1.75	< 1	0.9	1	1.0	0.9	0.7
		1-2	0.9	1	0.9	0.8	0.7			1-2	0.9	1	1.0	0.9	0.8
		> 2	0.9	1	0.9	0.9	0.7			> 2	0.9	1	1.0	0.9	0.8
	2.25	< 1	0.9	1	0.9	0.8	0.7		2.25	< 1	0.9	1	1.0	0.9	0.8
		1-2	0.9	1	1.0	0.9	0.8			1-2	0.9	1	1.0	1.0	0.9
		> 2	0.9	1	1.0	0.9	0.8			> 2	0.9	1	1.0	1.0	0.9
	2.75	< 1	0.9	1	1.0	0.9	0.8		2.75	< 1	0.9	1	1.0	1.0	0.9
		1-2	0.9	1	1.0	1.0	0.9			1-2	0.9	1	1.0	1.0	0.9
		> 2	0.9	1	1.0	1.0	0.9			> 2	0.9	1	1.0	1.0	0.9
30	0.25	< 1	1.1	1	0.8	0.7	0.6	90	0.25	< 1	0.8	1	1.1	1.0	0.9
		1-2	1.1	1	0.9	0.7	0.6			1-2	0.9	1	1.1	1.0	0.9
		> 2	1.1	1	0.9	0.8	0.6			> 2	0.9	1	1.0	1.0	0.9
	0.75	< 1	1.0	1	0.6	0.4	0.3		0.75	< 1	0.6	1	1.3	1.4	1.4
		1-2	1.0	1	0.7	0.5	0.4			1-2	0.7	1	1.3	1.2	1.2
		> 2	1.0	1	0.7	0.5	0.4			> 2	0.7	1	1.2	1.2	1.2
	1.25	< 1	1.0	1	0.9	0.7	0.5		1.25	< 1	0.8	1	1.2	1.1	1.1
		1-2	1.0	1	0.9	0.7	0.5			1-2	0.8	1	1.1	1.1	1.1
		> 2	1.0	1	0.9	0.7	0.6			> 2	0.8	1	1.1	1.1	1.0
	1.75	< 1	0.9	1	0.9	0.8	0.6		1.75	< 1	0.8	1	1.1	1.1	1.1
		1-2	0.9	1	0.9	0.8	0.7			1-2	0.8	1	1.1	1.1	1.0
		> 2	0.9	1	1.0	0.9	0.7			> 2	0.8	1	1.1	1.1	1.0
	2.25	< 1	0.9	1	1.0	0.9	0.8		2.25	< 1	0.9	1	1.1	1.1	1.0
		1-2	0.9	1	1.0	0.9	0.8			1-2	0.9	1	1.1	1.1	1.0
		> 2	0.9	1	1.0	0.9	0.8			> 2	0.8	1	1.1	1.1	1.0
	2.75	< 1	0.9	1	1.0	0.9	0.8		2.75	< 1	0.9	1	1.1	1.1	1.0
		1-2	0.9	1	1.0	1.0	0.9			1-2	0.9	1	1.1	1.1	1.0
		> 2	0.9	1	1.0	1.0	0.9			> 2	0.9	1	1.1	1.1	1.0

$$C = \frac{\text{Exposure rate from elliptical cylinder set}}{\text{Exposure rate from circular cylinder set}}$$

Φ = Angle between receptor-centerline shortest distance line and vertical

3.2 Concentric Cylinder Set Exposure Rates

Each summation of the basic equation presented above yields a single exposure rate value, scaled to values of unity for the following parameters: Γ, the exposure rate constant; Q', the release rate; and $\bar{u}$, the wind speed. To obtain corrected exposure rates, it is necessary to multiply the exposure rate values from the curves by the appropriate values of the factor $\Gamma Q'/\bar{u}$.

Figure 3B shows typical relative ground-level exposure rates for increasing values of the ratio σ/a, which generally corresponds to increasing downwind distance for a given set of conditions. This figure is provided as an aid to understanding, and is not to be used in calculations. Figures 4 through 8 provide the basic uncorrected exposure rate data to be used in calculations. The figures correspond to values of σ/a equal to 0.3, 0.5, 0.7, 1.1, and 1.9. FORTRAN summations used to obtain the data for these figures indicate that the maximum exposure rate occurs for $\sigma/a \simeq 0.7$, slightly less than the maximum point indicated by differentiation of the dispersion equation, 0.707.

The ranges of parameters included in Figures 4 through 8 are: $5 \text{ m} \leq L \leq 360 \text{ m}$; E = 0.2, 0.5, and 2.0 MeV, for a = 5, 20, 50, and 90 m; E = 0.5 MeV, for a = 10, 30, 40, 70, 120, and 150 m. All exposure rates are given in microroentgens per hour. Interpolation between curves and figures may be necessary in some cases. Direct interpolation is often acceptable; if a more sophisticated method is needed, the Lagrange Interpolation Formula gives good results (13).

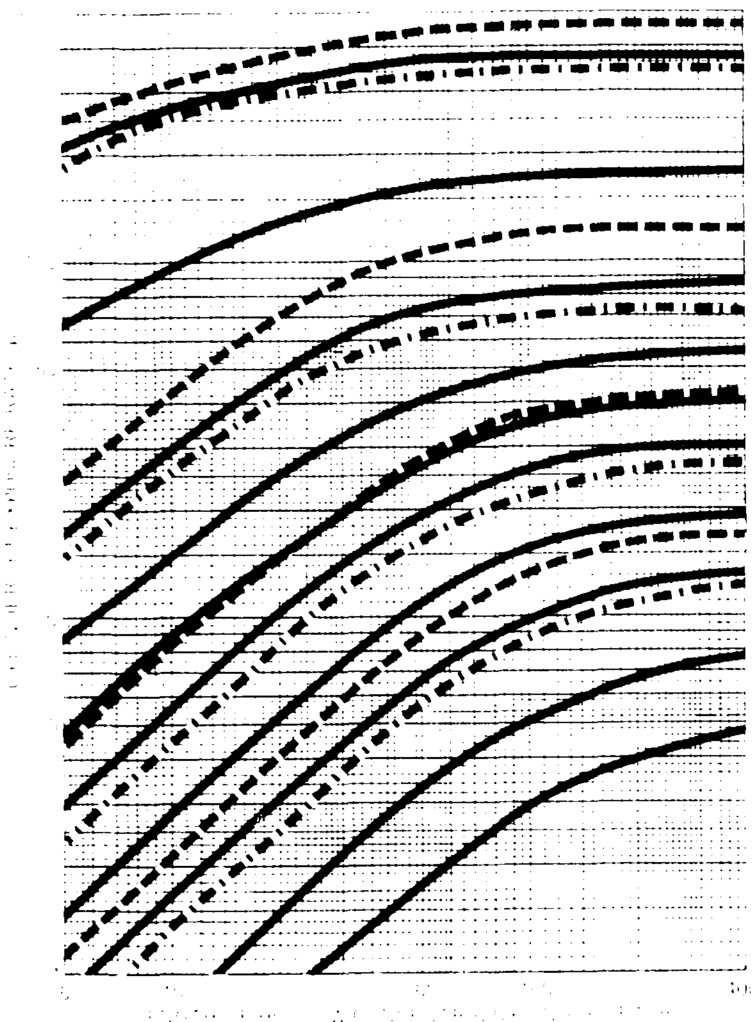

Figure 4. Cylinder set exposure rates, scaled ... 0.3

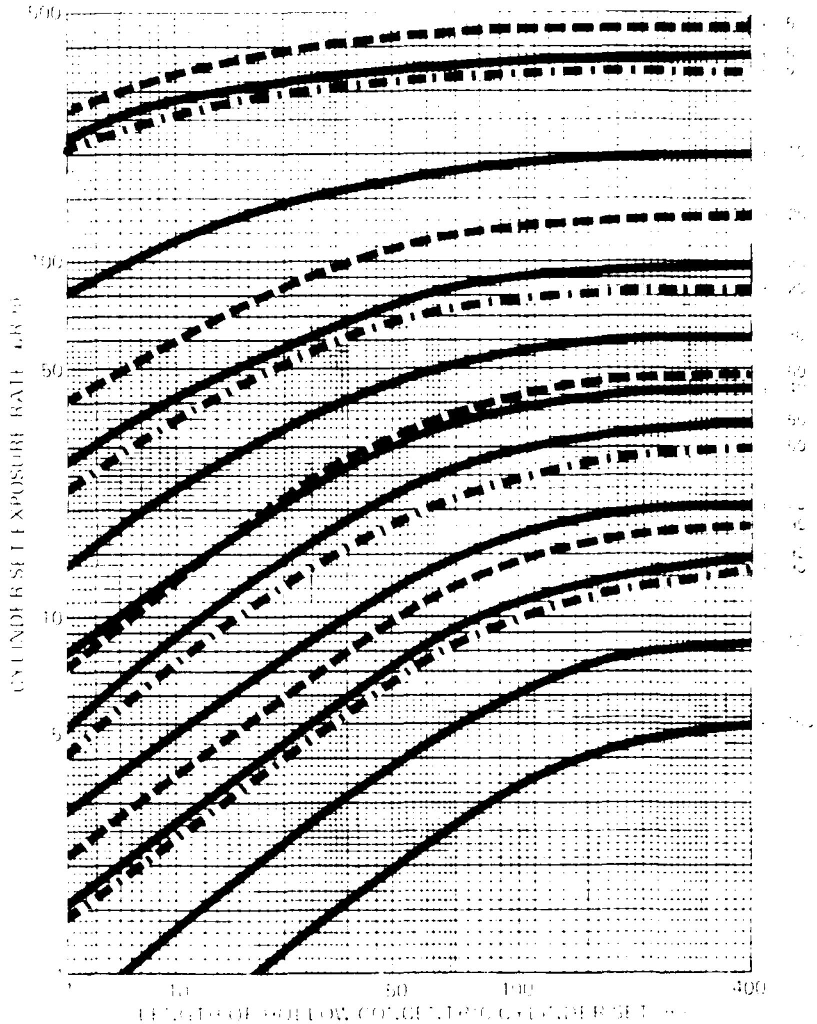

Figure 5. Cylinder set exposure rates, scaled σ a = 0.5

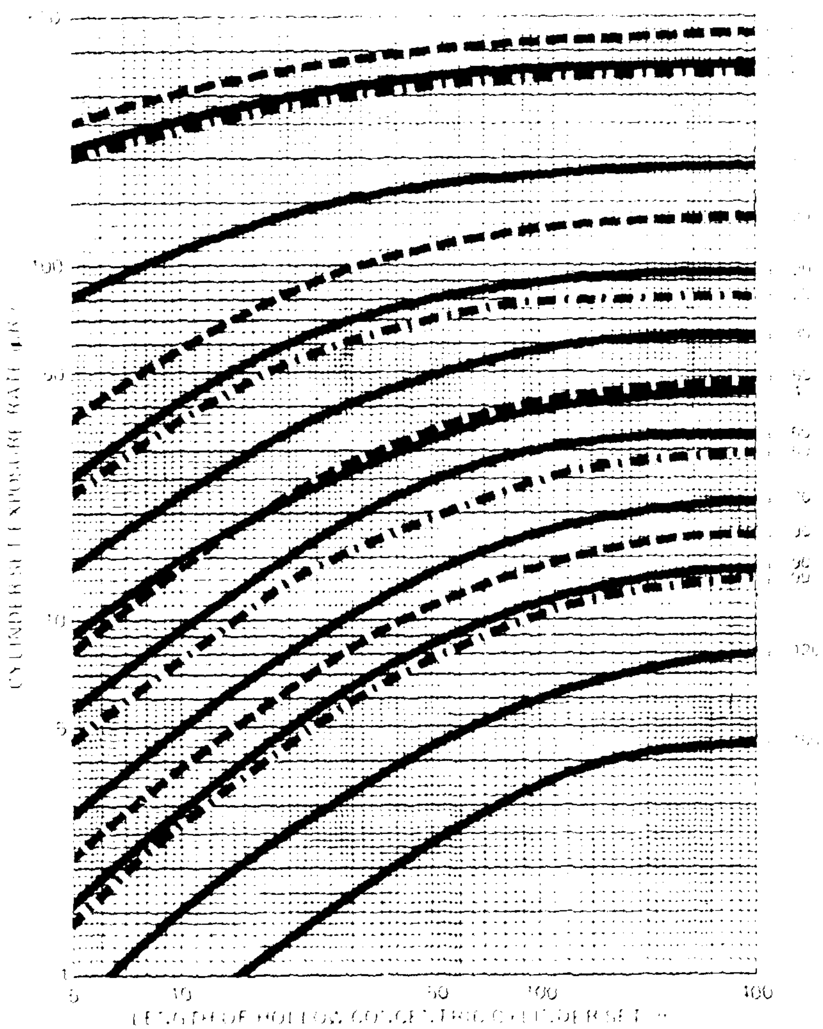

Figure 6. Cylinder set exposure rates, scaled $\theta/a = 0.7$

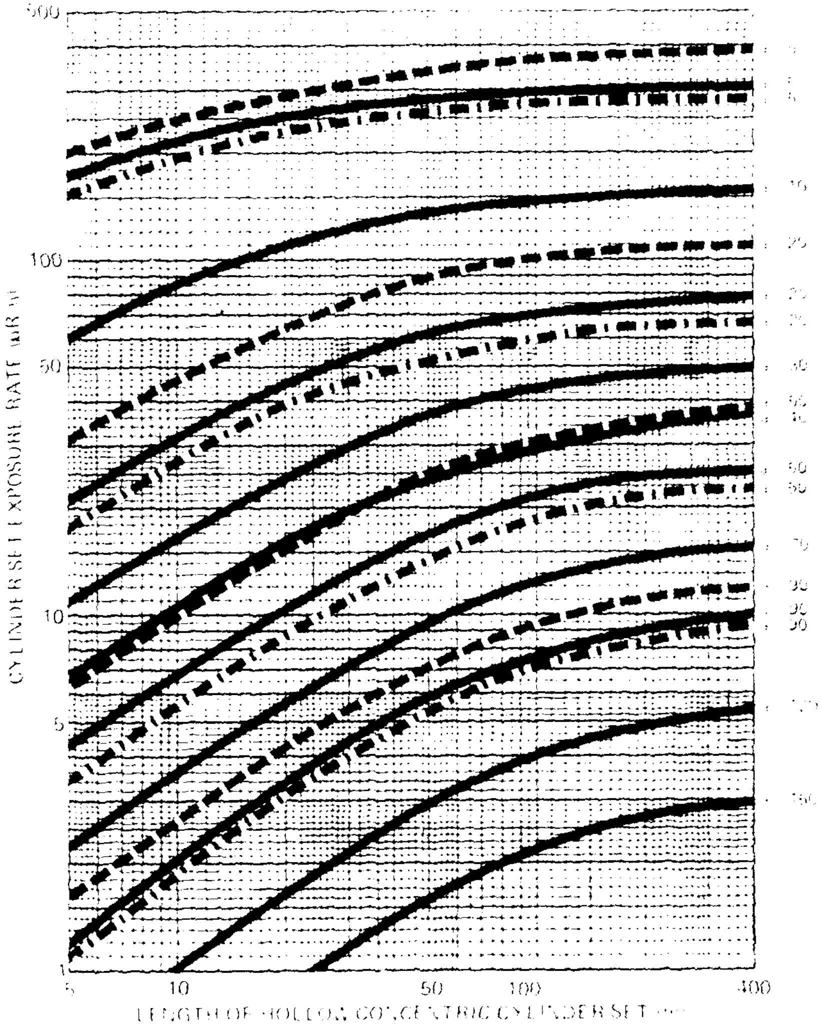

Figure 7. Cylinder set exposure rates, scaled $\theta/a = 1.1$

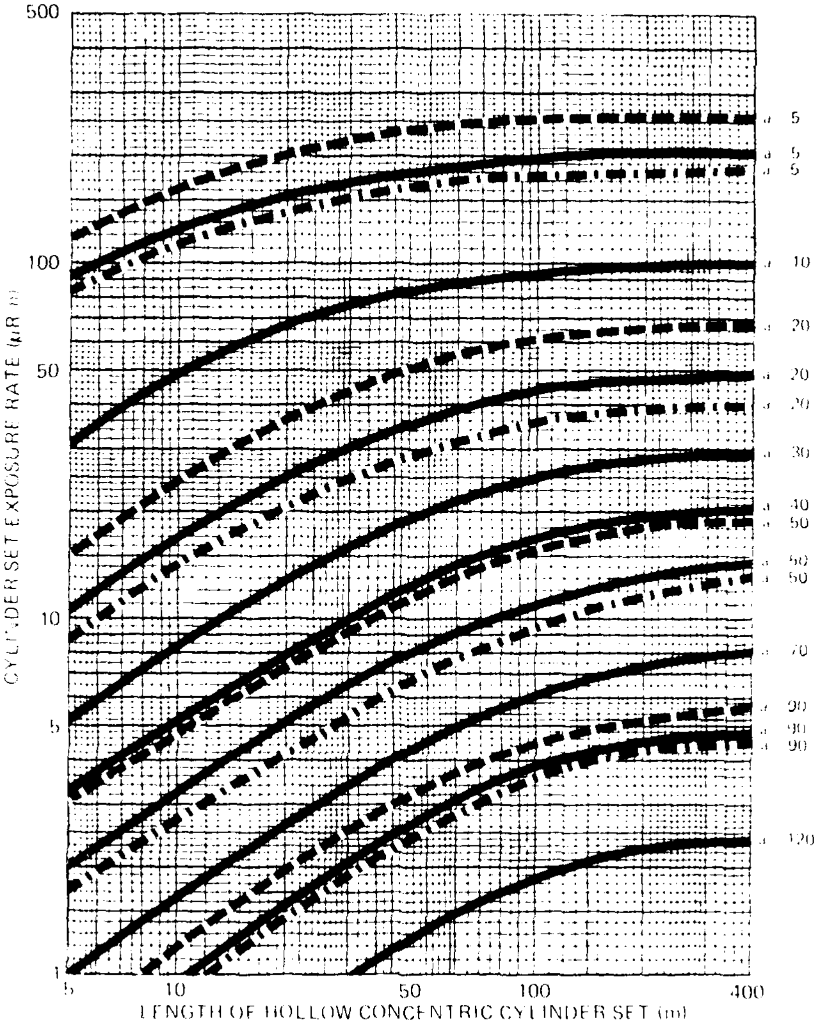

Figure 8. Cylinder set exposure rates, scaled σ/a = 1.9

E = 0.2 MeV - - - -, E = 0.5 MeV ———, E = 2.0 MeV —·—·

Scaled for all curves

σ = dispersion coefficient, m; a = centerline receptor distance, m

Γ = 1 R - m² Ci - h   Q′ = 1 mCi/s   ū = 1 m/s

3.3 Net Cylinder Set Procedure

The basic CCS equation applies only to that cylinder set that includes the receptor in the plane of its base. However, the correction for other receptor locations is straightforward (ref. 10, p. 369), and may be accomplished by use of a net cylinder set procedure. The steps in the procedure are as follows:

(a) Obtain the exposure rate for a set extending from the plane of the far base of the CCS to the parallel plane including the receptor. The corresponding exposure rate, from this total CCS, is denoted ER(T).

(b) Obtain the exposure rate for the CCS extending from th plane of the near base of the CCS to the parallel plane including the receptor. The corresponding exposure rate, from this subtrahend CCS, is denoted ER(S).

(c) Subtract ER(S) from ER(T) to obtain the exposure rate from the CCS that is to be evaluated: i.e., the net CCS. This exposure rate is denoted ER(N).

Values for correction factors, meteorological parameters, and geometric parameters other than cylinder length should be those appropriate to the net CCS, for all three sets used in the net cylinder set procedure. This is an exact calculation procedure, not an approximation.

3.4 Application to Simple Plumes

The calculation procedure for exposure rates applicable to simple plumes is presented in Table 4. The number of cylinder sets listed, including both total and subtrahend sets, is sufficient to represent any simple plume.

The radioactive decay factor, F, can be obtained by the relationship $F = \exp(-\lambda x/\bar{u})$, with λ the radioactive decay constant, s^{-1}; x, the total path length traveled, m; and $\bar{u}$ the wind speed, m/s. The eccentricity correction factor, C, has been discussed above. The air-ground interface scattered radiation correction, A, will be discussed in detail in the discussion of irregular clouds. The correction used for simple plumes is not as complicated. In general, a correction factor of 1.2 is conservative for any simple plume, but not overly conservative.

Table 4. Worksheet Format for Simple Plume Calculation

Cyl. Set No.	Length of Set, L (m)	CCS Type: T, S, N	Effective X (m) *	Disp. Coeff., σ (m)	Exposure Rate † (μR/h)	Radio. Decay, F	Eccen- tricity, C	Air-Gr. Scatter, A	Corrected Exposure Rate ‡ (μR/h)
1	330	T	R - 210	σ_1	$+ER_1$	F_1	—	A_1	$+ER_1F_1A_1$
2	90	S	R - 210	σ_1	$-ER_2$	F_1	—	A_1	$-ER_2F_1A_1$
3	90	T	R - 60	σ_2	$+ER_3$	F_2	C_1	A_2	$+ER_3F_2A_2C_1$
4	30	S	R - 60	σ_2	$-ER_4$	F_2	C_1	A_2	$-ER_4F_2A_2C_1$
5	30	T	R - 20	σ_3	$+ER_5$	F_3	C_2	A_3	$+ER_5F_3A_3C_2$
6	10	S	R - 20	σ_3	$-ER_6$	F_3	C_2	A_3	$-ER_6F_3A_3C_2$
7	10	N	R - 5	σ_4	$+ER_7$	F_4	C_3	A_4	$+ER_7F_4A_4C_3$
8	10	N	R + 5	σ_5	$+ER_8$	F_5	C_4	A_5	$+ER_8F_5A_5C_4$
9	10	S	R + 20	σ_6	$-ER_9$	F_6	C_5	A_6	$-ER_9F_6A_6C_5$
10	30	T	R + 20	σ_6	$+ER_{10}$	F_6	C_5	A_6	$+ER_{10}F_6A_6C_5$
11	30	S	R + 60	σ_7	$-ER_{11}$	F_7	C_6	A_7	$-ER_{11}F_7A_7C_6$
12	90	T	R + 60	σ_7	$+ER_{12}$	F_7	C_6	A_7	$+ER_{12}F_7A_7C_6$
13	90	S	R + 210	σ_8	$-ER_{13}$	F_8	—	A_8	$-ER_{13}F_8A_8$
14	330	T	R + 210	σ_8	$+ER_{14}$	F_8	—	A_8	$+ER_{14}F_8A_8$
							Total ER = sum of ER's:		....

* R = X coordinate (downwind distance) of receptor

† Multiplied by single scaling factor term, $\Gamma Q'/\bar{u}$, applicable to exposure conditions; + and - indicate that exposure rate value will be added to or subtracted from sum of CCS exposure rate values.

‡ Total plume exposure rate is "sum" of 14 corrected exposure rates. Each subscript number represents single value of parameter.

4.0 IRREGULAR CLOUDS

4.1 Irregular Cloud Applications

The estimation of doses from irregular clouds involves assumptions not required for evaluating simple plumes (ref. 5, pp. 89-92). It is assumed that the source geometry of any plume segment can be described by use of a plume trajectory model (14). Segment parameters are therefore calculated as reflecting the plume segment path history from release point to exposure of the receptor. Figure 9 shows plume segment path trajectories (Figure 9A) and calculated parameters corresponding to those trajectories (Figure 9B).

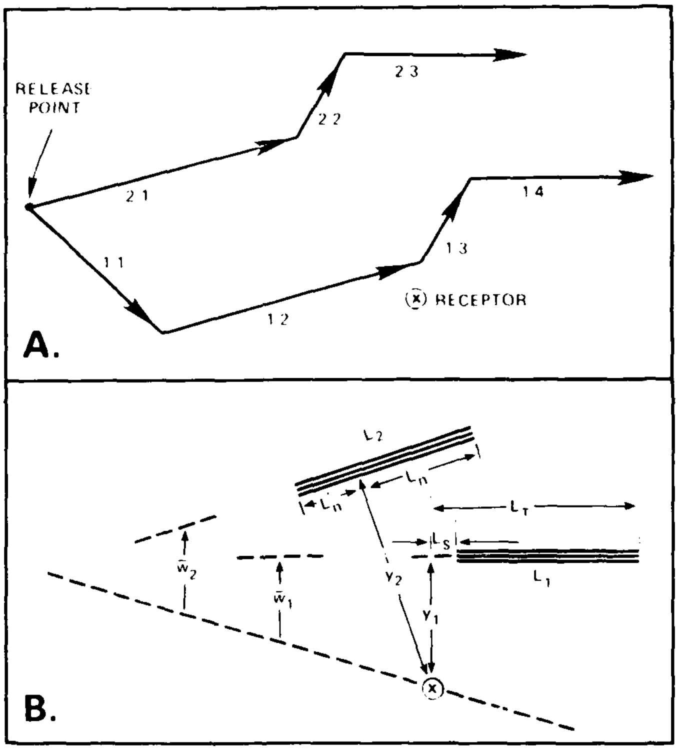

Figure 9. Irregular cloud parameters. (A) Trajectories of released air parcels (m-n = n^{th} trajectory of path length of m^{th} air parcel released). (B) Cloud segment parameters.

Figure 10A represents the source-receptor geometry of plume segments in an irregular cloud. Evaluations can be made by visually inspecting exposure rate curves for (a) bending plume geometry effect, (b) correction for anisotropic diffusion, and (c) variation in effective stack height. The effect of bending plume geometry is not significant unless a plume changes direction sharply within a distance of the receptor small enough that, for that plume segment, the relationship $L \gtrsim a$ holds. Even in this case, the correction will generally be on the order of 10%. A conservative dose estimate can be obtained by using overlapping plume segments in the calculational model.

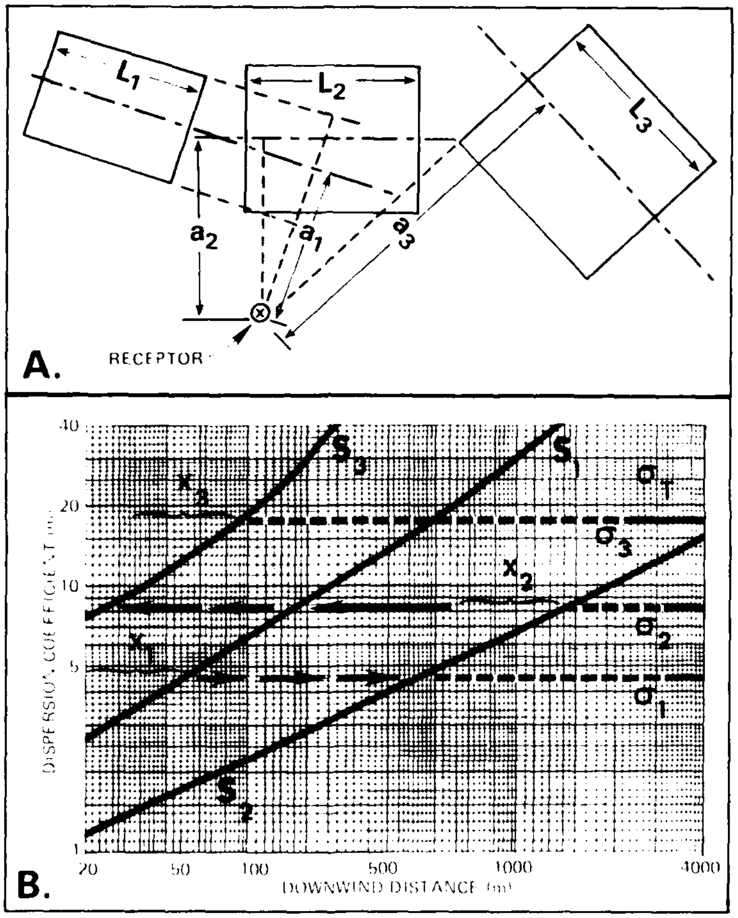

Figure 10. Techniques of irregular plume geometry. (A) Determination of cylinder set length, L, and receptor-centerline distance, a, for irregular plume segments. (B) Calculation of effective total dispersion coefficient for release made under varying meteorological conditions

Crosswind anisotropic diffusion errors will be relatively small, and the portion of the segment closest to the receptor may be used to assign a dispersion coefficient to the entire segment without excessive conservatism. Variable stack height adjustments can be made by using different values of a for each plume segment, if necessary.

4.2 Calculation of Effective Parameters

Several input parameters applicable to irregular cloud volumes are calculated as functions of the path length traveled by a particular volume or plume segment. The total path length consists of a series of partial lengths, or traverses. The calculation of parameters is based, in some cases, on distance-weighted averages, taken over the sum of traverses, not the actual downwind distance of the receptor.

Figure 10B illustrates the method of obtaining dispersion coefficient values; it involves incrementing over the sum of traverses. Adjacent traverses with the same meteorological stability type applying to them may be treated as one large traverse, for this calculation only. It should be noted that the minimum value of σ for a particular traverse is equal to the maximum value for the nearest upwind traverse. Equations used to calculate effective parameter values are presented below. In these summations, the plume segment released last will have traveled the shortest distance and will correspond to i = 1, or some other minimum value of i. The earliest segment released will correspond to i = n, or some other maximum value of i.

4.3 Equations Used to Calculate Effective Parameters

The following equations are used to calculate the effective parameters that require a technique more complicated than for evaluation of simple plumes. All equations apply to the n^{th} traverse of a plume segment, and therefore include summed values from the entire plume segment path history of that traverse.

Total path length, m: $$X_T = \sum_{i=1}^{n} X_i$$

Effective wind speed, m/s: $$\overline{u} = \frac{\sum_{i=1}^{n} (u_i \cdot X_i)}{\sum_{i=1}^{n} X_i}$$

Effective wind direction (*): $$\overline{w} = \frac{\sum_{i=1}^{n} (w_i \cdot X_i)}{\sum_{i=1}^{n} X_i}$$

*Determines effective angle of segment centerline. Use any angular units, but be consistent.

Incremented dispersion coefficient, m: $\sigma_T = \sum_{i=1}^{n} (\sigma_{x_i^+, S_i} - \sigma_{x_i^-, S_i})$

with: $x_i = x_i^+ - x_i^-$ and: $\sigma_{x_i^+, S_i} = \sigma_{x_{i+1}^-, S_{i+1}}$

Maximum postulated segment length, m: $L_n \leq x_n - x_{n-1} = u_n \cdot t_n$

Definition of symbols:

x = distance from release point to a point downwind, m
X = length of a traverse, m
S = Gifford-Pasquill stability type, not a parameter
σ = increment or sum of dispersion coefficient, m
u = wind speed, m/s
w = wind direction, angular units
x^+ = maximum downwind distance in a traverse, m
x^- = minimum downwind distance in a traverse, m
t = length of time applicable to a plume segment (release period with constant conditions), s
L = length of a plume segment, or CCS, m

4.4 Air-Ground Scatter Correction

The ratio of exposure rate at the air-ground interface to that expected in an infinite medium can be estimated, for irregular clouds, by use of an "image" source technique (15). Data presented below have been extracted from this published technique and extrapolated to a wide range of energies using other published data (ref. 10, pp. 233-245). The technique is strictly meant to be applied only to point sources but is applicable to small cloud volumes located some distance from the receptor. This condition represents those cases in which the technique is needed, since estimates made for large cloud volumes located closer to the receptor can be made sufficiently accurate by using a simpler method applicable to simple plumes, such as assuming a 10% increase in the exposure rate.

To apply the technique, postulate an "image" source located at a position in the ground medium equivalent geometrically to that of the real source (cloud volume) in the air medium. Assume that the receptor is located on a plane parallel to that of the air-ground interface. Refer to Figure 11. Let h_1 and h_2 be the minimum distances from the receptor plane to the real and image sources, respectively. Let r_1 and r_2 be the distances from the receptor to the sources. Then the angle Ψ = Arcsin (h_1/r_1) is as shown in Figure 11.

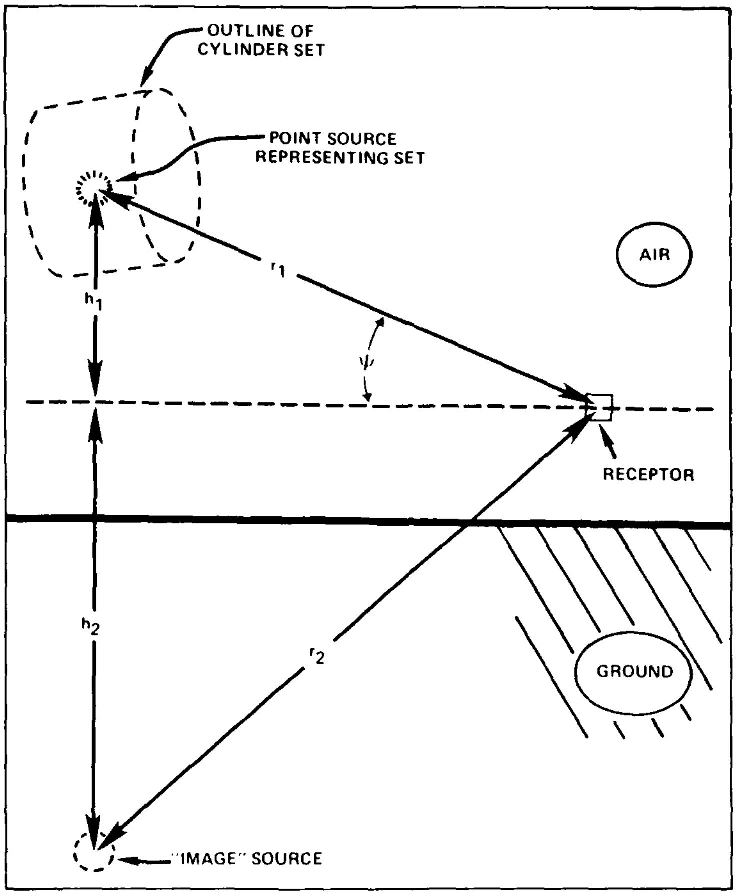

Figure 11. "Image" source geometry

The ratio of interface-to-infinite medium exposure rates is designated the air-ground scatter correction factor, A. The basic formula for calculating A is:

$$A = 1 - \frac{(B_{\mu r_2} - 1)\, r_1^2}{(B_{\mu r_1})\, r_2^2}\, e^{\mu(r_1 - r_2)} \cdot S_A + \frac{(B_{\mu r_2})\, r_1^2}{(B_{\mu r_1})\, r_2^2}\, e^{\mu(r_1 - r_2)} \cdot S_G$$

where $B_{\mu r}$ is the infinite medium exposure rate buildup factor, μr is the number of mean free paths between source and receptor, and S_A and S_G are "air" and "ground" image source strengths, respectively. Values for these terms are given in Table 5. Subscripts 1 and 2 in the formula refer to distances between receptor and real and image sources, respectively.

Table 5. Parameters S_A and S_G* of "Image" Source Strength

Gamma Energy (MeV)	Ψ = 0°		Ψ = 15°		Ψ = 30°		Ψ = 60°		Ψ = 90°	
	S_A	S_G	S_A	S_G	S_A	S_G	S_A	S_G	S_A	S_G
0.20	0.51	0.00	0.29	0.26	0.22	0.23	0.14	0.27	0.13	0.22
0.50	0.50	0.00	0.27	0.15	0.20	0.20	0.13	0.20	0.12	0.19
0.66	0.49	0.00	0.26	0.14	0.19	0.18	0.12	0.18	0.11	0.17
1.00	0.49	0.02	0.23	0.12	0.16	0.14	0.10	0.14	0.19	0.13
1.25	0.49	0.03	0.22	0.12	0.15	0.12	0.10	0.12	0.18	0.11
2.00	0.48	0.04	0.20	0.09	0.13	0.09	0.08	0.10	0.06	0.09

* S_A and S_G are terms for "image" source strength (ref. 15) for air and ground scatter contributions, respectively.

For a receptor located at ground level, a simplification is possible, reducing the calculation of A to the form below. To assist in calculations made with the image source technique, attenuation parameters are given in Table 6. Alternative references may be used if desired. For a ground level receptor, use:

$$A = 1 - (1 - \frac{1}{B_{\mu r_1}}) \cdot S_A + S_G$$

Table 6. Attenuation Parameters for Scatter Correction

Gamma Energy (MeV)	Attenuation Coefficient $\mu(m^{-1})$	Exposure Rate Buildup Factor, B (μr); r = 10 m	20 m	40 m	70 m	100 m	140 m	200 m
0.20	0.0158	1.55	2.11	3.22	4.88	6.54	8.76	12.08
0.50	0.0112	1.20	1.41	1.81	2.42	3.03	3.84	5.05
0.66	0.0099	1.16	1.32	1.64	2.12	2.60	3.25	4.21
1.00	0.0082	1.11	1.21	1.42	1.74	2.11	2.47	3.10
1.25	0.0073	1.09	1.17	1.34	1.59	1.85	2.19	2.69
2.00	0.0057	1.05	1.10	1.20	1.36	1.51	1.71	2.02

Interpolation may be used for intermediate values of r, or values of B obtained from standard references may be substituted.

5.0 VARIABLE RELEASES: CALCULATION EXAMPLE

5.1 Background Information

Postulate a release made over a period of 50 s with a constant release rate and variable meteorological conditions, as shown in Table 7. For calculation purposes, the release is arbitrarily divided into ten plume segments, with each corresponding to a parcel of gases released during a 5-s interval.

A gamma level exposure rate estimate is taken at 5 s after the end of release for a location 100 m from the release point and directly south (180°) of it. The elevations of release point and receptor correspond to a physical stack height of 20 m.

The effective stack height for the various stability types can be calculated by use of the following: $H = (20 + k/u)$ m, with u the wind speed in m/s and k a constant corresponding to stability, with values of 8 for type B conditions, 4 for type C, and 1.2 for type D. The wind speed and direction assigned to a plume segment are for the period between release and dose estimation.

5.2 Plume Segment Parameters

Using the procedure described previously, calculate geometric and other parameters for each of the ten segments. Geometric parameters less directly related to meteorological conditions are listed in Table 8. Among the parameters calculated for Tables 7 and 8 are: (a) incremented σ, dispersion coefficient; (b) effective w, wind direction; (c) effective u, wind speed; (d) H, effective stack height; (e) x, plume segment downwind distance; (f) y, receptor-centerline horizontal distance; (g) a, receptor-centerline distance; (h) L_T, L_S, and L_N--the total, subtrahend, and net cylinder set lengths, respectively; and (i) the ratio of σ to a.

The length of a subtrahend CCS is taken as the smallest difference between the downwind distances of the receptor and the CCS. In this example, the relationship used to calculate x is: $x_i = \cos \bar{w}_i \cdot \Sigma X_i$. The horizontal receptor-centerline distance, y, is taken at the receptor location, not that corresponding to the CCS. In this example, $y_i = \sin \bar{w}_i \cdot 100$.

5.3 Calculation Specifications

Inspection of the data in Table 8 and reference to the CCS method permit the use of the following assumptions: (a) If radioactive decay is insignificant, the contribution from segments 7-10 can be ignored without underestimating the exposure rate by more than about 5%. This assumption requires the evaluation of both $|x_i - 100|$ and a. (b) For all cloud gamma dose equations of the types estimated by the CCS method, the exposure rate for all $\sigma/a < 0.35$ can be taken as equal to that for $\sigma/a = 0.35$. (c) In this example it was assumed that $E = 0.5$ MeV, $\Gamma = 0.4$ R - m^2/Ci - h, and Q', the release rate, is 0.3 mCi/s. (d) Correction factors, F, A, and C, are taken as a product equal to 1.0. Based on the above assumptions, the correction and scaling factor for a plume segment is equal to $0.12/\bar{u}$, and represents the product $\Gamma \cdot Q' \cdot F \cdot A \cdot C/\bar{u}$. Table 9 summarizes the exposure rate calculation parameters.

Table 7. Meteorological and Calculated Parameters for a Variable Release

	Plume Segment Number									
	1	2	3	4	5	6	7	8	9	10
Release Interval, s	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
Wind Speed (u), m/s	2	3	4	3	5	3	4	2	3	2
Wind Direction (W), degrees	155	170	165	180	190	175	160	145	165	175
Stability Type	B	C	D	C	D	C	D	B	C	B
Traverse Length (X), m	10	15	20	15	25	15	20	10	15	10
ΣX (traverse sum), m	155	145	130	110	95	70	55	35	25	10
Incremented σ, m	14.1	12.3	11.0	9.9	8.7	7.1	5.6	4.6	3.2	1.7
$w_i = 180° - W_i$, degrees	15	10	15	0	-10	15	20	35	15	5
$\Sigma\, w_iX_i$, degrees - m	1600	1450	1300	1000	1000	1250	1025	625	275	50
$\Sigma\, u_iX_i$, m^2/s	525	505	460	380	335	210	165	85	65	20
$\bar{w}$ (effective w), degrees	10	10	10	9	11	18	19	18	11	5
$\bar{u}$ (effective u), m/s	3.4	3.5	3.5	3.5	3.5	3.0	3.0	2.4	2.6	2.0
Stack Height, H, m	24.0	21.3	20.3	21.3	20.2	21.1	20.3	24.0	21.3	24.0

Table 8. Geometric Parameters of Plume Segment

	Plume Segment Number									
	1	2	3	4	5	6	7	8	9	10
Downwind Distance (X_i), *m*	153	143	128	109	93	67	52	33	25	10
Horizontal R-C (y_i), *m*	17	17	17	16	20	31	33	31	20	9
R-C Distance (*a*), *m*	29	27	27	27	28	38	39	39	29	26
Subtrahend, L_S, *m*	53	43	28	9	7	33	48	67	75	90
Net, L_N, *m*	10	15	20	15	25	15	20	10	15	10
Total, L_T, m	63	58	48	24	32	48	68	77	90	100
y/a Ratio, no units	0.49	0.46	0.41	0.37	0.31	0.19	0.14	0.12	0.11	0.07

Table 9. Calculation of Exposure Rate

Plume Segment No.	Ratio, y/a	CCS Lengths, m L_T	CCS Lengths, m L_S	a, m	Scaled Exp. Rate, μR/h ER(T)	Scaled Exp. Rate, μR/h ER(S)	Scaled Exp. Rate, μR/h ER(N)	Corr.* Factor	Corrected E.R., μR/h
1	0.49	63	53	29	53	51	2	0.060	0.12
2	0.46	58	43	27	54	50	4	0.046	0.19
3	0.41	48	28	27	48	38	10	0.050	0.50
4	0.37	24	9	27	33	15	18	0.040	0.72
5	0.31	32	7	28	38	13	25	0.040	1.00
6	0.30	48	33	38	30	25	5	0.034	0.17
									2.70

*7Q'FAC/u

5.4 Exposure Rate Estimate

Assuming that the total exposure rate is about 5% greater than that obtained from the sum in Table 9, the correct exposure rate can be taken as about 2.85 μR/h. From this, the maximum expected unrestricted area exposure rate can be taken as not more than 25% greater than the above value, corresponding to a location at which $y/a \approx 0.7$. The maximum exposure rate is therefore estimated as about 3.55 μR/h, and the total exposure from the 50-s release is less than 0.05 μR. Note that the 25% assumption is valid only for short downwind distances; at very great distances (e.g., *more than 500 m), this assumption might* lead to an underestimate of maximum exposure rate.

SUMMARY

The concentric cylinder set (CCS) cloud gamma dose model has been developed to estimate external gamma doses from elevated radioactive clouds. The primary application of this model is for stack releases by small radiological research facilities, including release during changing meteorological conditions or over irregular terrain.

The CCS model is applied with elementary calculation procedures, using only the tables and working curves included here. Calculation procedures are provided for dose estimates based on simple plumes and irregular clouds. Sample calculations are provided for evaluating doses from irregular clouds.

The CCS model has been compared to both published models, where the latter could be applied, and field measurements have been made during stack releases of argon-41, with satisfactory results. CCS model dose estimates provide substantial information on environmental surveillance for a wide range of release conditions, with little expenditure of time or money.

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