A.4 ESTIMATION OF GROUND-LEVEL RADIATION DOSES FROM RELEASE OF AIRBORNE RADIOACTIVE MATERIALS[1]

ABSTRACT

A method of estimating ground-level radiation doses corresponding to a release of airborne radioactive materials is described. The method considers external dose from both beta and gamma sources, internal dose from inhalation of ground level concentrations of the material and external dose as a result of fallout from the cloud.

The method relates quantity released (in curies) to a dose for various meteorological conditions, types of materials released, and for short-term or prolonged release periods.

The method assumes that normal Gaussian diffusion equations describe the dispersion of the cloud. Situations where topographic or nearby manmade structures could have significant effects on the cloud are not considered. Special calculations should be used for such situations.

1.0 INTRODUCTION

The calculation of ground-level radiation doses from a cloud of airborne materials such as assumed in reactor accident analysis may be divided into two general parts. The first part involves the atmospheric transport and dilution of the cloud by the wind. This results in a calculated integrated air concentration[2] in the cloud at some dose point of interest. The second part of the analysis is the conversion of air concentration to radiation dose of interest.

The sources of radiation usually considered in reactor accident analysis are (a) the noble gases and their external whole-body dose effect, (b) the halogens and the resulting thyroid dose from inhalation, (c) volatile solids (cesium, rubidium, selenium, arsenic, antimony, molybdenum, and tellurium) resulting in lung dose from inhalation, and (d) bone dose from inhalation of the nonvolatile solids (all others). The whole-body dose from fallout of materials is also usually calculated.

Various meteorological conditions are generally examined in such analyses to give a spectrum of radiological effects during the poor diffusion conditions of inversion and the better diffusion conditions of lapse or unstable. For example, very stable and moderately stable, each at a wind speed of 1 m/sec (2 mph), neutral conditions at wind speeds of 1 and 5 m/sec (10 mph), and unstable conditions at wind speeds of 1 and 5 m/sec may be used.

2.0 ATMOSPHERIC DIFFUSION MODEL

In the calculation of the transport and dilution of an airborne cloud, the time period of release of the cloud is very significant. This is so, primarily because the wind does not tend to remain fixed direction-wise, but rather it meanders and fluctuates to a considerable extent. Thus, if a cloud is formed during a long release period, portions of it will tend to be transported in different directions. On the other hand, if the cloud is formed from an explosive release or "puff" it will all tend to be transported in the same direction. This variability of the wind refers principally to the horizontal changes as opposed to vertical changes, since the former is often very significant while the latter is much more subdued.

A means of describing dilution for a cloud released over a long period of time (say several hours) has been suggested by Simpson[3]. If the total release is viewed as successive shorter term releases (but not puffs) during which the average wind direction is reasonably constant (although short-term fluctuations may exist) then the dilution of these shorter-term releases may be calculated with presently available methods. The net dilution at any given point would then be the sum of the dilution for each incremental cloud transported in the various average directions (some additional discussion is given on this point under Section 4.0, Application of Methods).

The calculation of the dilution or integrated air concentration in a cloud for a unit release of material transported in a given direction is usually described by the Gaussian equation[4]:

$$(X)=\left(\frac{Q_0}{(2\pi)(\sigma_y)(\sigma_z)(\bar{\mu}_h)}\right)\exp\left[-\left(\frac{z^2}{2\sigma_z^2}\right)-\left(\frac{y^2}{2\sigma_y^2}\right)\right]\left[\frac{Q}{Q_0}\right] \qquad \text{(D-1)}$$

where:

(X) = Integrated air concentration (Ci-sec/m3 or µCi-sec/cc);

Q = Quantity released (Ci);

$\bar{\mu}_h$ = Average wind speed at height of release or effective height if cloud rise occurs (m/sec);

σ = Standard deviation of cloud width in horizontal y-direction and vertical z-direction (m);

t = Time after release (sec) and is equal to the downward distance divided by the average wind speed $X \div \bar{\mu}_h$;

Q/Q_0 = Correction for cloud depletion due to deposition and is the fraction of initial amount released which is present at downwind distance x (x = $\bar{\mu}_h t$);

$$= \exp\left[-\left(\frac{V_d}{\bar{\mu}_h}\right)\sqrt{\frac{2}{\pi}}\left(\frac{\mu_0}{\bar{\mu}_h}\right)\int_0^t \bar{\mu}_h \frac{\exp\left(-\frac{z}{2\sigma_z^2}\right)}{\sigma_z}\,dt\right];$$

V_d = Deposition "velocity" (m/sec) (see Table C-1) for values of this parameter);

$\overline{\mu}_0$ = Average wind speed at ground level (m/sec); and

exp [ ] = Function which is a power of "e"; and

y,z = Horizontal and vertical distance from cloud centerline; y = 0 and z = 0 gives cloud centerline concentration and z = h (height of release) gives ground level concentration. The cloud centerline is assumed transported downwind at the same height as the release height.

Equation (D-1) does not take into account the depletion of the radioactive content of the cloud by radioactive decay of the isotope of concern. With this taken into account, the equation becomes:

$$(X) = \left(\frac{Q_0}{2\pi\sigma_y\sigma_z\overline{\mu}_h}\right)\exp\left[-\frac{z^2}{2\sigma_z^2}-\frac{y^2}{2\sigma_y^2}\right]\left[\frac{Q}{Q_0}\right]\exp\left[-\lambda t\right] \quad \text{(D-2)}$$

where:

exp [-λt] = Radioactive decay function.

Equation (D-2) describes air concentration in a cloud which is not restrained in its expansion and dilution. This is the case for an elevated cloud which has not expanded enough to reach ground level. For cases where the cloud has reached ground level some modification of Equation (D-2) is needed. In the case of a ground-level release, Equation (D-2) is generally multiplied by two.

It can be seen from Equation (D-2) that the important parameters to be calculated are σ_y and σ_z. As indicated previously, the scale of horizontal wind variation changes considerably with time so that two methods of calculating σ_y are used, one for the puff release period and the other for the prolonged period. In the case of σ_z only one method of calculation is employed since the vertical wind fluctuations are not as strongly time dependent.

For the puff release case the standard deviation of cloud width in the horizontal and vertical directions has been described[4] by Equations (D-3) and (D-4):

$$\sigma_y^2 = \frac{C_y^2 X^{2-n}}{2} \text{ , and} \quad \text{(D-3)}$$

$$\sigma_z^2 = a\left[1-\exp\left(-k^2t^2\right)\right]+bt \quad , \quad \text{(D-4)}$$

where:

a, k^2, b, n, C_y = Diffusion coefficients dependent on wind speed and atmospheric stability (see Table D-1 for recommended values).

TABLE D-1
VALUES FOR VARIABLES

Atmospheric Stability[a]

Variable	Height of Release (meters)	Wind Speed (m/sec)	Very Stable	Moderately Stable	Neutral	Unstable
$(V_d/\overline{U}_0)$ Noble Gases	--	--	0	0	0	0
$(V_d/\overline{U}_0)$ Halogens	--	--	0.0024	0.0034	0.0046	0.0080
$(V_d/\overline{U}_0)$ Particulates	--	--	0.00015	0.00022	0.00030	0.00060
R	all	--	6.37	8.146	10.6	17.66
a	all	--	34	97	--	--
b	all	--	0.025	0.33	--	--
K^2	all	--	0.0088	0.00025	--	--
n	=0.0	--	0.3	0.3	0.25	0.20
n	>0.0	--	0.4	0.4	0.25	0.20
C_y	=0.0	1 - 3	0.18	0.18	0.21	0.35
C_y	=0.0	4 - 7	0.18	0.18	0.15	0.30
C_y	=0.0	> 7	0.18	0.18	0.14	0.28
C_y	>0.0	1 - 3	0.18	0.18	0.15	0.30
C_y	>0.0	4 - 7	0.18	0.18	0.12	0.26
C_y	>0.0	> 7	0.18	0.18	0.11	0.24
C_z	=0.0	1 - 3	--	--	0.17	0.35
C_z	=0.0	4 - 7	--	--	0.14	0.30
C_z	=0.0	> 7	--	--	0.13	0.28
C_z	>0.0	1 - 3	--	--	0.15	0.30
C_z	>0.0	4 - 7	--	--	0.12	0.26
C_z	>0.0	> 7	--	--	0.11	0.24

[a] The degree of atmospheric stability is defined here in terms of the standard dry adiabatic vertical temperature lapse rate of -1 °C per 100 meter increase in elevation (-5.4 °F per 1000 feet). This is taken as a convenient reference point for defining the four classes of stability:

very stable	≥ +1.5 °C
moderately stable	≥ -0.5 °C but < +1.5 °C
neutral	≥ -1.5 °C but < -0.5 °C
unstable	< -1.5 °C

In the case of the prolonged release the vertical standard deviation is described by Equation (D-4) but the horizontal deviation is described[5] by Equation (D-5):

$$\sigma_y^2 = At - A\alpha\left[1 - \exp\left(-\frac{t}{\alpha}\right)\right], \tag{D-5}$$

where:

A,α = Diffusion coefficients;

and

A = 13 + 232.5 ($\sigma\theta\overline{\mu}_h$);

α = $\dfrac{A}{2\left(\sigma\theta\overline{\mu}_h\right)^2}$; and

σθ = Standard deviation of horizontal wind direction variation during release.

The distinction between what is a puff release and what is a prolonged release is arbitrarily set at 30 minutes. That is, releases of less than 30 minute duration are considered puff releases and above that are prolonged releases.

3.0 RADIATION DOSE MODEL

Three different varieties of ground-level radiation exposure are consequential to a release of radioactive materials. These are:

1. External radiation to persons on the ground from the cloud as it passes by. (This may be gamma-only dose for an elevated cloud, or beta and gamma dose from a ground-level cloud.)

2. Internal radiation exposure to persons in the cloud as a consequence of inhalation.

3. External radiation to persons on the ground from fallout on the ground after passage of the cloud.

Each type of exposure is considered separately below.

3.1 External Passing Cloud Dose (Gamma)

The ground-level gamma dose rate from a cloud of radioactive materials having a distribution as given in Equation (D-2) may be considered as the sum of the dose rates from all the points in the cloud. The source strength of each point is (X)dV and the total source is

$$S = \int_{-\infty}^{\infty} (X) dV \quad , \qquad \text{(D-6)}$$

where:

dV = dx dy dz, and is an incremental volume of the cloud which may be considered as a point source. The integration is theoretically carried out to infinity to include the entire cloud.

The flux from a point source, considering buildup in the air is given by Glasstone[6]:

$$\phi = \frac{BS \exp(-\mu T)}{4\pi T^2} \qquad \text{(photons/m}^2\text{/sec)} \qquad \text{(D-7)}$$

where:

B = Buildup factor = 1 + KμT;

K = $\frac{\mu - \mu_a}{\mu_a}$ where μ is total absorption coefficient and μa is energy absorption coefficient (see Figure D-1)

T = Distance from source and is equal to $\sqrt{x_1^2 + y_1^2 + z_1^2}$ in the coordinate system used; and x_1, y_1, z_1, are coordinates of point at ground-level relative to incremental volume of cloud.

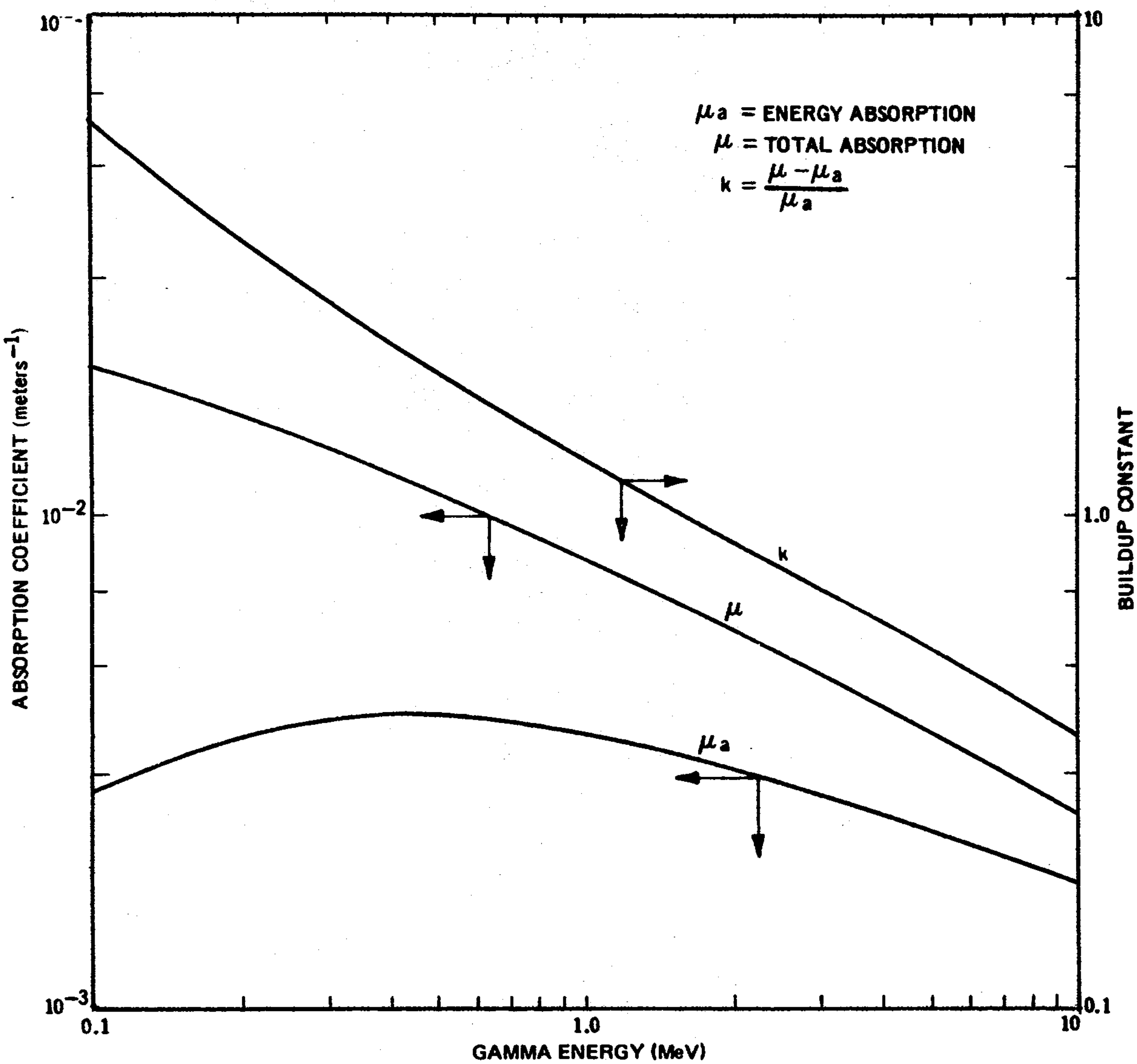

Figure D-1. Gamma Radiation Absorption Coefficients and Buildup Constants for Air (STP)

The gamma dose rate from a flux of a given energy (E) from Glasstone[6] is

$$(D.R.)_\gamma = 1.4 \times 10^{-11}\ \theta E \mu_a \text{ (rad/sec)}, \qquad \text{(D-8)}$$

so that the total dose from the cloud at any point is found by combining Equations (D-2), (D-7), and (D-8).

$$(D)\gamma = \frac{1.4x10^{-11} E\mu_a}{4\pi} \int_{-\infty}^{\infty} \frac{B(X)\exp(-\mu T)dV}{T^2} \quad \text{(rad)} \qquad \text{(D-9)}$$

Solution of Equation (D-9) requires use of numerical techniques. As the equation is written it assumes a monoenergetic source. For a mixture of isotopes, it is proper to perform the calculation for each gamma energy present considering its abundance. Since μ and μ_a are energy dependent and appear in an exponential term, care must be exercised if an average energy is to be used. See Table D-2 for the typical noble gases of interest in reactor accident analyses.

TABLE D-2
RADIOBIOLOGICAL FACTORS -- NOBLE GASES

Isotope		Disintegration Gammas Emitted	
Name	**Half-Life**	**Number**	**Energy**
Noble Gases			
Kr-83m	1.86 h	1	0.032
		2	0.009
Kr-85m	4.4 h	1	0.15
		2	0.305
Kr-85	10.76 y	1	0.522
Kr-87	76 m	1	2.05
		2	2.57
		3	0.847
		4	0.347
Kr-88	2.8 h	1	2.4
		2	2.21
		3	0.19
		4	1.55
		5	0.85
		6	0.17
		7	0.02
Xe-131m	12 d	1	0.164
Xe-133m	2.3 m	1	0.233
Xe-133	5.27 d	1	0.081
Xe-135m	16 m	1	0.53
Xe-135	9.2 h	1	0.604
		2	0.36
		3	0.244
Xe-138	14 m	1	0.42
Particulate Daughters[a]			
Rb-88	18 m	1	0.91
		2	1.28
		3	1.85
		4	2.18

		5	4.2
Cs-138	32.2 m	1	0.14
		2	0.19
		3	0.23
		4	0.41
		5	0.46
		6	0.55
		7	0.87
		8	1.01
		9	1.43
		10	2.21
		11	2.62
		12	3.34

[a] Significant particulate daughters only

3.2 External Dose (Beta β)

The range of β particles in air is only a few meters. Hence, for β calculations, a cloud of material which expands to fairly large dimensions (say >20 meters or 60 feet) at downwind distances is frequently considered an "infinite" cloud. In such a cloud, the air dose rate is calculated assuming that the rate of energy release per unit volume in the cloud is equal to the rate of absorption in that volume (no buildup). The body is considered a small volume within the flux in the cloud, and therefore, causes no perturbation in the flux.

β flux incident on the human body comes from one direction only, so that the air dose rate at the surface of the body is only one half of that in the air. In addition, the cloud is not infinite since the ground represents a boundary to the cloud, such that at the ground the cloud is a hemisphere of "infinite" radius but approaches the "infinite" cloud at some height above ground equal to the range of the β in air. Thus, the dose rate varies across the body (vertically) and so an average value of 0.64 for the actual dose rate compared to the "infinite" cloud calculation is used from Taylor[7]. Thus the β dose is given by:

$$(D)_\beta = 0.15(X)\overline{E} \qquad \text{(rad)} \qquad \text{(D-10)}$$

3.3 Internal Dose from Inhalation

Internal dose from inhalation may be related directly to ground-level air concentration. The air concentration at ground level is as given in Equation (D-2) for any specific meteorological condition. The dose due to inhalation of the cloud is calculated by first determining the quantity inhaled and then multiplying by the conversion factor of dose per unit amount inhaled. The Quantity inhaled (Q_i) is calculated from

$$Q_i = 230(X) \qquad (\mu\text{Ci}), \qquad \text{(D-11)}$$

where 230 is taken as the standard average breathing rate from ICRP[8] in cc/sec.

The dose conversion factor (k) for a unit amount inhaled is calculated from ICRP[8]. In ICRP the permissible body burden (q) which is equivalent to a permissible dose rate (weekly, quarterly, yearly dose rate) for each isotope is given. Considering the effective half-life of the isotope in the critical organ (or other organ) permits calculation of the lifetime dose to the organ. Since the permissible body burden (q) refers to total quantity in the body, some factor to account for the fraction of total burden which is in an organ or interest must be applied. This factor is given as (f_2) by ICRP. Additionally, to convert quantity breathed to quantity deposited in the organ of interest, an additional factor (f_a) from ICRP is used. Thus the dose from inhalation (D_i) is calculated from

$$D_i = 230(X) q f_2 f_a \frac{t_{1/2}}{0.693} \quad \text{(Rem)}, \qquad \text{(D-12)}$$

where:

q = Quantity (µCi) in total body equivalent to a dose rate of Y Rem/week (from ICRP);

$\frac{t_{1/2}}{0.693}$ = Mean life of isotope in organ; and

$q f_2 f_a \frac{t_{1/2}}{0.693}$ = k Rem/µCi inhaled.

Values for the factor k are given in Tables D-3, D-4, and D-5 for the halogen, volatile solid, and nonvolatile solid mixtures. In the case of the halogens and nonvolatile solids, if they are assumed to be soluble, the thyroid and bone are the critical organs, respectively. If the volatile solids are assumed insoluble then the lung is the critical organ.

3.4 Fallout Dose (Gamma Dose)

The fallout dose (D_f) is almost entirely due to the halogens because of their larger assumed release fraction and the larger deposition velocity assigned to them. Fallout dose is calculated by determining the deposition (Ci/m^2) and multiplying by the dose rate conversion factor (R rad/h per Ci/m^2) and integrating over the decay during the time of dose received:

$$D_f = (X) V_d R \left(\frac{1 - e^{-\lambda t'}}{\lambda} \right) \quad \text{(rad)}. \qquad \text{(D-13)}$$

where:

$(X)V_d$	=	The deposition (curies/m^2);
R	=	Dose rate conversion factor;
λ	=	Decay constant of the isotope; and
t'	=	Dose period.

Values of the dose rate conversion factor (R) are given[9] in Figure D-2 for the various gamma energies. Since these values are for an infinite plane source and the cloud size and deposition pattern is not always infinite, a correction factor must be applied in some cases. The correction factor[9] is given in Figure D-3.

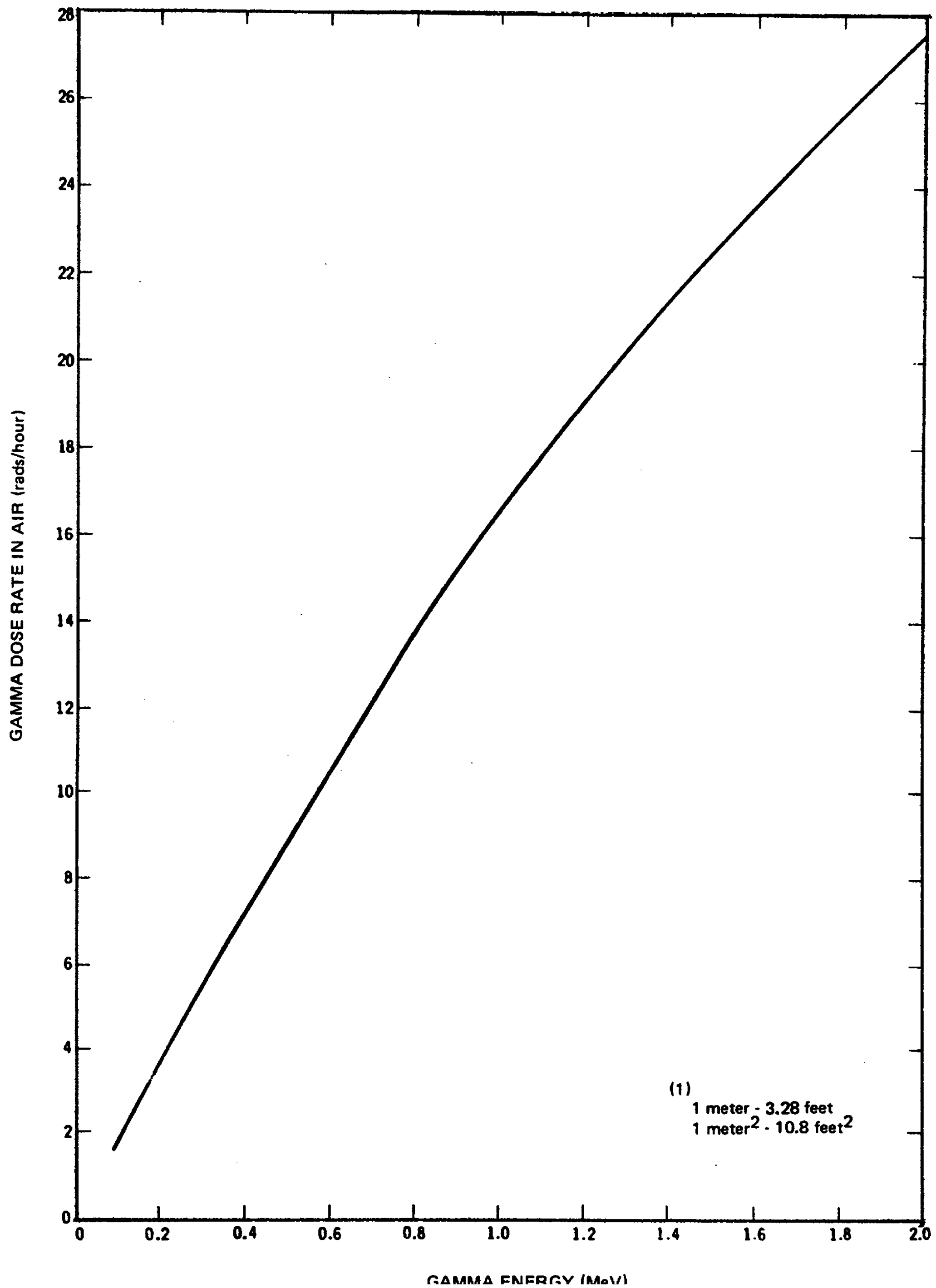

Figure D-2. Gamma Dose Rate at One Meter Height Above Smooth Infinite Plane Source of One Curie Per Square Meter.

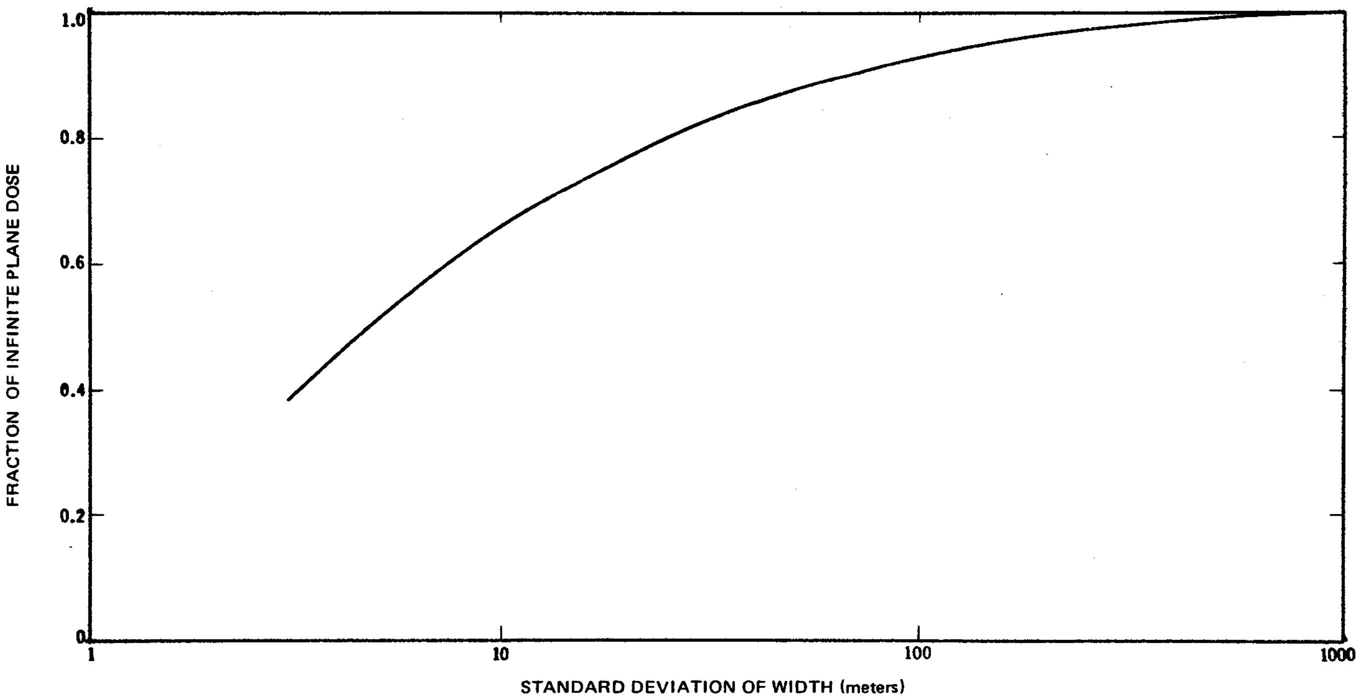

Figure D-3. Ratio of Gamma Dose from Finite Pattern to Infinite Plane Dose.

TABLE D-3
RADIOBIOLOGICAL FACTORS -- HALOGEN RADIOISOTOPES

Isotope Name	Half-Life[a]	Eff Half-Life[b]	$\overline{E}_\gamma$ (MeV)	$\overline{E}_\beta$ (MeV)	$\overline{E}_{Eff}$ (MeV)[c]	k (Rem/μCi)[d]
*I-131	8.05 d	7.0 d	0.39	0.191	0.23	1.6
*I-132	2.3 h	2.3 h	1.992	0.434	0.65	4.5×10^{-2}
*I-133	21 h	21 h	0.444	0.45	0.14	4.0×10^{-1}
*I-134	53 m	53 m	1.27	0.6	--	2.6×10^{-2}
*I-135	6.7 h	6.7 h	1.54	0.308	0.066	1.3×10^{-1}

a Radioactive half-life
b Effective half-life in the thyroid from ICRP
c Effective energy in the thyroid from ICRP
*d Dose per μCi inhaled based on IAEA recommended values in IAEA Safety Series No. 7.

TABLE D-4
RADIOBIOLOGICAL FACTORS -- VOLATILE SOLID RADIOISOTOPES

Isotope Name	Half-Life[a]	Eff Half-Life[b]	$\overline{E}_\gamma$ (MeV)	$\overline{E}_\beta$ (MeV)	$\overline{E}_{Eff}$ (MeV)[c]	k (Rem/μCi)[d]

*Mo-99	66 h	66 h	0.24	0.376	0.45	$2.6x10^{-2}$
*Te-127m	105 d	105 d	0.0885	0	0.083	$1.7x10^{-1}$
*Te-127	9.3 h	9.3 h	--	0.23	0.24	$4.6x10^{-3}$
*Te-131	25 m	25 m	0.475	0.577	0.73	--
*Te-132	78 h	78 h	0.231	0.073	0.13	$6.4x10^{-2}$
*Cs-134	2.1 y	120 d	1.41	0.52	0.074	$5.6x10^{-1}$
*Cs-137	30 y	138 d	0	0.192	0.192	$4.6x10^{-1}$

[a] Radioactive half-life
[b] Effective half-life in the lung from ICRP
[c] Effective energy in the lung from ICRP
*[d] Dose per μCi inhaled based on IAEA recommended values in IAEA Safety Series No. 7.

TABLE D-5
RADIOBIOLOGICAL FACTORS -- NONVOLATILE SOLID RADIOISOTOPES

Isotope Name	Half-Life[a]	Eff Half-Life[b]	$\overline{E}_{\gamma}$ (MeV)	$\overline{E}_{\beta}$ (MeV)	$\overline{E}_{Eff}$ (MeV)[c]	k (Rem/μCi)[d]
*Sr-89	50.4 d	50.4 d	0	0.487	0.49	$4x10^{-1}$
*Sr-90	28 y	17.53 y	0	0.2	1.1	36
*Sr-91	9.7 h	9.7 h	0.845	0.523	3.3	$5.0x10^{-3}$
*Y-90	64.2 h	64.2 h	--	0.73	4.4	$2.6x10^{-2}$
*Y-91	59 d	59 d	0.551	0	2.9	$3.3x10^{-1}$
*Zr-95	65 d	59.5 d	0.733	0.127	0.57	$5.5x10^{-2}$
*Nb-95m	90 h	59.5 d	0.235	0	3.8	--
*Nb-95	35 d	33.8 d	0.745	0.053	0.36	$1.2x10^{-2}$
*Ru-103	40 d	2.4 d	0.473	0.08	0.43	--
*Ru-106	1.0 y	15 d	--	0.013	0.013	--
*Rh-105	36 h	1.39 d	0.032	0.183	0.86	--
*Ba-140	12.8 d	10.7 d	0.237	0.268	1.5	$8x10^{-2}$
*La-140	40.2 m	1.68 d	2.11	0.495	2.7	$5.0x10^{-3}$
*Ce-141	32.5 d	31 d	0.097	0.163	0.17	$2.2x10^{-2}$
*Ce-143	33 h	1.33 d	0.344	0.355	2.2	$3.8x10^{-3}$
*Ce-144	285 d	243 d	0.043	0.087	1.3	1.1
*Pr-143	13.7 d	13.7 d	0	0.311	1.6	$2.0x10^{-2}$
*Nd-147	11.1 d	11.1 d	0.286	0.228	1.2	$1.8x10^{-2}$
*Pm-147	2.7 y	570 d	--	0.074	0.22	$2x10^{-1}$
*Pm-149	53 h	2.2 d	0.285	0.35	1.9	$3.3x10^{-1}$
*Pu-240	$6.7x10^{3}$ y	$1.95x10^{3}$ y	0.011	0	0.88	$7x10^{+3}$

[a] Radioactive half-life
[b] Effective half-life in the thyroid from ICRP
[c] Effective energy in the thyroid from ICRP
*[d] Dose per μCi inhaled based on IAEA recommended values in IAEA Safety Series No. 7.

4.0 APPLICATION OF METHODS

In utilizing the methods of calculation described here, several factors are of significance. These are discussed in the following paragraphs.

4.1 Height of Release

From Equation (D-2) it is evident that the dose is significantly affected by the height of the cloud above ground level. In case of stack releases this height is made up of the physical stack height plus cloud rise due to exit velocity and buoyancy. Many formulae are available to calculate the cloud rise. The method used here is the Holland formula[7] as modified by Moses[10].

$$\Delta H = c\frac{\left(1.5V_s d + 4x10^{-5}Q_h\right)}{\overline{\mu}_h}, \qquad \text{(D-14)}$$

where:

ΔH	=	Cloud rise (m);
V_s	=	Exit velocity (m/sec);
Q_h	=	Heat emission of effluent (cal/sec);
$\overline{\mu}_h$	=	Wind speed at stack exit (m/sec);
c	=	Correction factor from Moses; and
d	=	Stack diameter (m);

In proposing the correction factor "c" in the plume rise formula, Moses used data from an experimental stack at Argonne with a diameter of about 1.5 feet and from a stack at Duisburg, Germany which has a diameter of 3.5 meters. His conclusions are that a value of 3 for the correction factor is proper for large stacks with appreciable buoyancy, whereas a factor of 2 is recommended for small stacks with modest buoyancy. In applying the Moses correction to individual situations a linear interpolation is made from the actual stack diameter compared to those from which data were obtained (see Figure D.4).

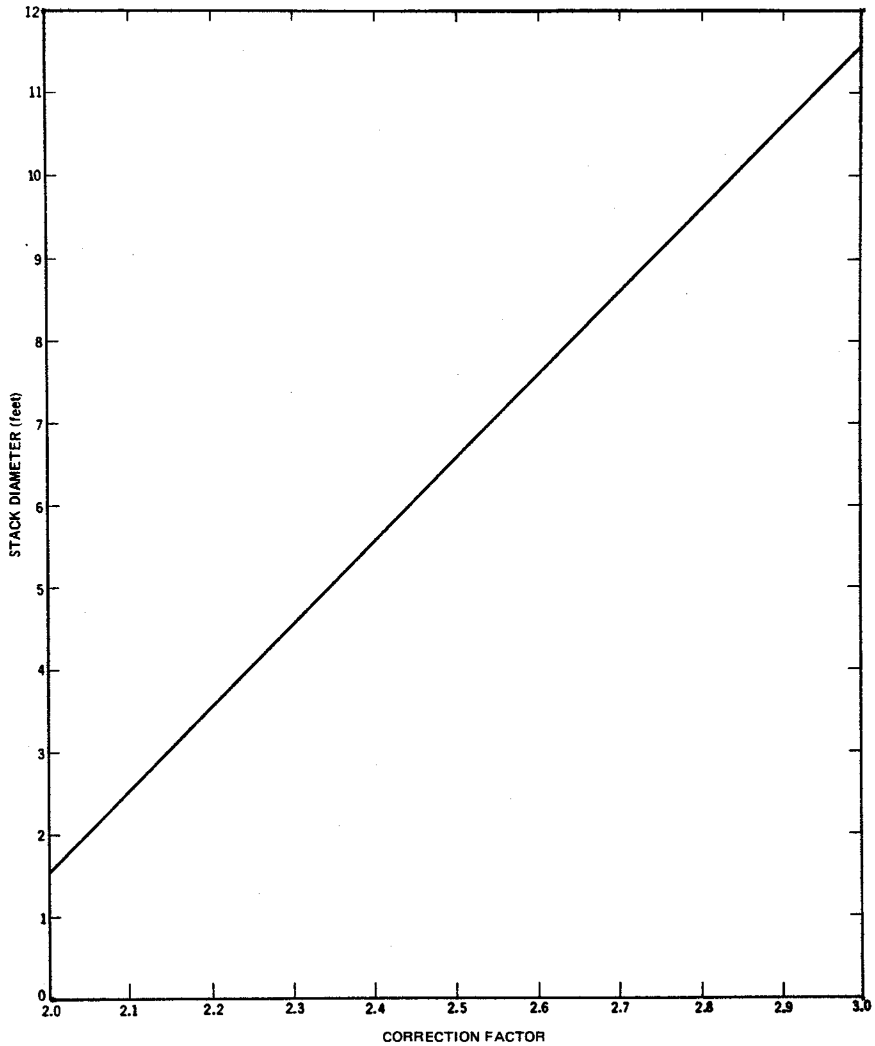

Figure D-4. Holland Plume Rise Formula Correction Factor

4.2 Prolonged Release

For calculations of air concentration in the prolonged-release case the application of two parameters is significant. These parameters are the duration of persistent wind direction during which transport in the same direction is likely, and the second is the wind fluctuation as measured by σ_θ during the persistent direction. This latter parameter is of particular interest since it is not generally available in standard meteorological data. It is suggested that since, theoretically, any duration of persistence is possible as is any value of $\sigma_\theta \overline{\mu}_h$, that a probabilistic approach be used in the choice of these parameters.

Wind direction persistence data have been summarized by the Weather Bureau for several locations. The data are partially shown in Table D-6 for ten locations including valley, desert, coastal, and lake-shore locations. These data do not differentiate between stability conditions or wind speed (see Table D-7 for typical wind speed frequencies). However, the distribution of various periods of persistent wind direction is indicated. From these data the amount of persistence applicable to an analysis can be chosen on the basis of the probability level deemed appropriate.

Subsequent to choosing a period of persistent wind direction, a representative value of $\sigma_\theta \bar{\mu}_h$ must be selected. A sample of the distribution of this parameter for three time periods is given in Figure D-5. These data are solely for daily periods of inversion observed during an entire year. Additionally, these data are the minimum values observed in each 24-hour day during the time increment indicated. It is considered that a similar analysis for non-inversion conditions (neutral or unstable) would not be markedly different from the one described. Therefore, use of these data would seem to give a reasonable indication of the over-all distribution of the parameter desired.

4.3 Cloud Depletion

In Equation (D-2) it will be observed that there is a term accounting for depletion of the cloud contents due to prior deposition on the ground. Within this equation is inclusion of the effect of vertical wind speed variations (wind shear). This is used primarily in calculations for elevated release of a cloud where a significant vertical shear may exist. The ratio of wind speed at any height compared to the ground level speed is calculated using a logarithmic profile as in Equation (D-15).

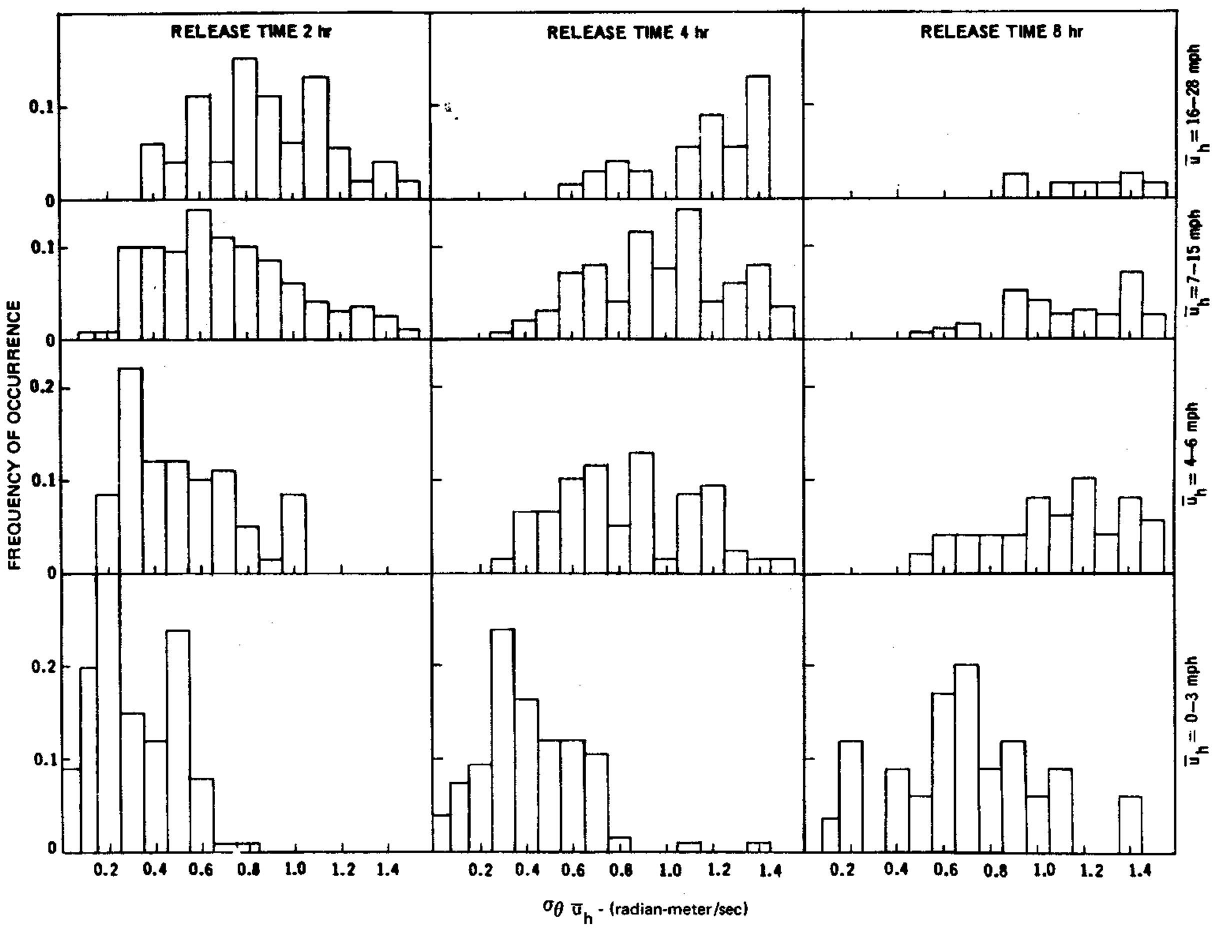

Figure D-5.

$$\overline{U}_0 = \overline{U}_h \frac{(1 - \ln h)}{R} , \qquad \text{(D-15)}$$

where:

h	=	Height of cloud centerline (release height); and
R	=	Constant dependent on stability (see Table D-1).

4.4 Sample Calculation

A sample calculation is described for purposes of completing the discussion of the methods presented here.

Assumptions:

1. Quantities of materials released are:

   A. Noble gases - 1 curie $E\gamma$ = 0.65 MeV,

$\lambda = 1 \times 10^{-4}\ sec^{-1}$, and

B. Halogens - 1 curie I-131.

2. Release period of 2 hrs.

3. Release height is 100 m (stack height).

4. Meteorological conditions are:

A. Inversion (moderately stable);

B. Wind speed at release height - 1 m/sec or 2 mph (about 12% chance of this for <u>any one</u> hour, from Table D-7);

C. Wind direction is persistent during release (50% chance of this from Table D-6); and

D. $\sigma_\theta \bar{\mu}_h$ = 0.1 radian-meters/sec (30% chance of this value or lower during 0-2 mph wind speed).

5. Radiation effects to be calculated:

A. Dose point 1600 m (1 mile) downwind; and

B. Passing cloud, lifetime thyroid and fallout doses to be estimated for a person standing at ground level under the cloud centerline during total time of cloud passage (2 hrs).

Calculations:

1. Using Equation (D-2) for the noble gases:

$(X) = 1.5 \times 10^{-8}$ μCi-sec/cc at 1600 m,
$\sigma_y = 140$ m, and
$\sigma_z = 25$ m.

2. Integration of Equation (D-9)[11] gives a passing cloud dose of 1.0×10^{-6} rad.

3. Using Equation (D-2) for the halogens at 1600 m:

$(X) = 1.5 \times 10^{-8}$ μCi-sec/cc,
$\sigma_y = 140$ m, and
$\sigma_z = 25$ m.

From Equation (D-11):

Q_i = 230 x 1.5 x 10^{-8} = 3.45 x 10^{-6} μCi inhaled.

From Table D-3:

(k) for I-131 = 1.48 Rem/μCi inhaled

Therefore, the lifetime thyroid dose is:

D_i = 3.45 x 10^{-6} x 1.48 = 5.1 x 10^{6} Rem.

From Equation (D-13):

$$D_f = (X)V_d R \frac{\left(1 - e^{-\lambda t}\right)}{\lambda},$$

where:

(X) = 1.5 x 10^{-8} μCi-sec/cc (or Ci-sec/m^3);

V_d = 3.4 x 10^{-3} m/sec (Table D-1);

R = 7.0 rad/h per Ci/m^2 (Figure D-2; and

$\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{8.05 \times 86{,}400} = 9.9 \times 10^{-7}\ \mathrm{sec}^{-1}$ (Table D-3).

Therefore;

$$D_f = 1.5 \times 10^{-8} \times 3.4 \times 10^{-3} \times \frac{7}{3600} \times \frac{\left(1 - e^{-7200 \times 9.9 \times 10^{-7}}\right)}{9.9 \times 10^{-7}}$$

= 7.1 x 10^{-7} rad.

TABLE D-6
WIND DIRECTION PERSISTENCE
(One Sector = 22 1/2 degrees)

Frequency of Duration in Hours[a]

Station	Direction[b]	50%	10%	1%	0.1%	Longest # Hours	Longest # Hours[c] In Any Direction	
Augusta, Georgia	W	2	3	8	13	18	W	18
Birmingham, Alabama	S	2	4	9	16	16	SSE	20
Chicago, Illinois	SSW	2	5	12	21	22	NNE	25
Little Rock, Arkansas	SSW	2	4	9	17	28	SSE	28
Phoenix, Arizona	E	2	3	6	9	12	E	12
Rochester, New York	WSW	2	6	13	23	28	WSW	28
Salt Lake City, Utah	SSE	2	4	7	13	15	S	17
San Diego, California	NW	2	6	12	16	17	WNW	33
Tampa, Florida	ENE	2	3	7	13	14	SSW	18
Yakima, Washington	W	2	5	8	14	17	WNW	19
Average	--	2	4	9	15	--	--	--

[a] The numbers should be read as follows: Augusta, Georgia (1) 50% of the hours are the beginning of a wind direction persistence period of at least 2 hours duration; 50% of less than 2 hours duration; (2) 10% of the hours are the beginning of a wind persistence period of at least 3 hours duration; 90% of less than 3 hours; (3) 1% of the hours are the beginning of a wind direction persistence period of at least 8 hours duration; 99% of less than 8 hours, etc. The data are standard Weather Bureau hourly observations (one observation per hour) so no time periods less than one hour are distinguishable, i.e., 100% of the hours are beginning of a wind direction persistence period of at least 1 hour. Persistence of direction is defined as within a sector of 22 1/2 degrees are centered on direction indicated.

[b] Direction examined is the one showing greatest frequency of persistent winds.

[c] Longest number of hours observed may not be same direction as direction showing most frequency of persistent winds.

TABLE D-7
WIND SPEED FREQUENCY[a]
(From U.S. Weather Bureau Data)

Site	Wind Speed (mph) 0-3[b]	4-7	8-12	13-18	19-24	25
Albany, New York	23	24	27	21	4	1
Chicago, Illinois	7	26	36	25	5	1
Jacksonville, Florida	10	33	35	18	3	1
Kansas City, Missouri	7	25	37	25	6	1
Los Angeles, California	28	33	27	11	1	1
Miami, Florida	14	30	34	20	2	1
New York, New York	6	15	30	31	12	5
Philadelphia, Pennsylvania	11	27	35	21	5	1
Springfield, Missouri	4	13	34	32	13	4

Tulsa, Oklahoma	9	24	34	26	7	1
Average	12	25	33	23	6	1

[a] Frequency of total time is represented, e.g., Albany, New York, 24% of the time the wind speed is 4 - 7 mph, etc.

[b] The data used are referred to as ground-level wind measurements with actual height of measurement varied from about 20 feet to 95 feet.

5.0 CONCLUSION

A method of estimating ground-level doses from a cloud of airborne radioactive materials has been described and a sample calculation is included for completeness. It has been assumed that the standard Gaussian diffusion equations describe the cloud dispersion. Situations where topographic or nearby manmade structures could have significant effects on the cloud were not considered. Special calculations should be used for such situations.

At locations where contemplated construction or operation of a facility includes a need to estimate environmental effects, the method described here may be used. Generally, the method lends itself to simple hand calculations. The exception is the passing-cloud dose calculation which requires numerical integration. A digital computer program can perform such integrations and is recommended.

6.0 REFERENCES

[1] Originally Appendix D, NEDO-10178, Safety Analysis Report, Midwest Recovery Plant, Morris, Illinois (Docket 50-268). Figure numbers, table numbers, and other identification within this appendix are those of the original document.

[2] For radiation dose calculations, the time integrated $\frac{\mu Ci-\sec}{cc}$ air Concentration air concentration is of interest since dose rather than dose rate is calculated.

[3] Simpson, C. L. Fuquay, J. J., and Hinds, W. T., "Forecasting Dispersion From a Source Near the Ground, "HW-SA-3192 (January 29, 1964).

[4] Watson, E. C., and Gamertsfelder, C. C., "Environmental Radioactive Contamination as a Factor in Nuclear Plant Siting Criteria, "HW-SA-2809 (February 1963).

[5] Fuquay, J. J., Simpson, C. L., and Hinds, W. T., "Prediction of Environmental Exposures from Sources Near the Ground Based on Hanford Experimental Data," Journal of Applied Meteorology, Volume 3, No. 6 (December 1964).

[6] Glasstone, S., and Sesonski, A., "Nuclear Reactor Engineering, "D. Van Nostrand Co. (1963).

[7] "Meteorology and Atomic Energy," AECU-3066.

[8] "Report of Committee II (ICRP) on Permissable Dose for Internal Radiation" (1959).

[9] "Meteorology and Atomic Energy," revised, to be published.

[10] Moses, H., Strom, G. J., and Carson, J. E., "Effects of Meteorological and Engineering Factors on Stack Plume Rise," Nuclear Safety, Vol. 6, No. 1 (Fall, 1964).

[11] A digital computer program was used for this calculation.