Chapter 8

Environmental Safety Analysis

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8-1 INTRODUCTION

One facet of the complete environmental-safety examination of a nuclear plant is the analysis of the behavior of airborne effluents both from normal operations and from possible accidents and the estimation of the resulting exposure to radiations or noxious substances. Other facets include examination of the fate of liquid effluents and of the radiation dose that may result from direct gamma radiation from any source within the facility either during normal operation or following accidental release from primary shielding.

In general, such safety analyses are performed for one or more of the following purposes:

1. To provide operating limits for normal release of effluents.
2. To predict potential exposures from abnormal releases and to indicate the adequacy of design safeguards.
3. To provide a basis for planning action in case of abnormal release.
4. In unusual cases, to provide a basis for meteorological control of operations.

In estimations of average concentrations over the period of cloud passage at downwind locations, three main release-time-dependent mechanisms influence the effluent behavior:

1. A near-instantaneous release in which dilution occurs by the classical concepts of turbulent diffusion, i.e., the dilution rate is

characterized by the turbulence within the volume as it travels downwind.

2. A short-term release period ranging from several minutes to, perhaps, several tens of hours in which the average concentration downwind is affected by both the turbulent dilution and the dispersive effect of large eddies that are too big to affect the turbulent mixing within the plume, i.e., wind meander.

3. A generally longer release period in which discrete changes in wind direction and speed occur so that the effective concentration at any point is a function of the first two mechanisms, as well as the fraction of the release time that the point is within the plume pattern.

The safety analysis and specific meteorological inputs vary widely, depending upon the purpose or purposes of the analysis and the individual plant characteristics. Even within a given category of nuclear installations, the types and quantities of material released and the rates and location of emission vary widely, particularly when possible accidents are being considered. These variations result from differences in containment or confinement design, materials, ventilation, and locations. For this reason it is difficult, if not impossible, to provide a detailed plan of computation that is applicable to all, or even to a majority, of the cases. The approach in this chapter has therefore been one of illustrating some types of computational procedures that can be used and considering the specific input data needed for the safety analysis. Calculations are made for each of the diffusion-time regimes that are of importance with different source characteristics.

In the practical case, particularly when the effects of accidents are being assessed, the

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source may consist of a mixture of materials. In this case one can obviously obtain the answer by calculation for each material involved according to its individual emission characteristics and reaction in the environs. In most problems it is adequate to group materials according to their chemical and physical characteristics and their behavior after release to the atmosphere. Thus, in analyzing reactor accidents, the groups considered are frequently (1) the noble gases, which do not deposit on surfaces, (2) the very small particulates, which deposit only slightly, and (3) the iodines, which deposit strongly on nearly all surfaces if they are in vapor form or deposit only slightly if they are in organic compounds or attached to very small particles.

In establishing such groups, one must take care to see that the behavior of individual materials within the group is consistent. For example, if there is evidence that one isotope has a considerably different particle size distribution from another (perhaps because of a different method of formation), the evidence indicates that the rate of deposition from the airstream is different. Thus the distribution in the environment will differ.

The methods for estimating the types of atmospheric statistics used in dosage calculations vary widely among the various installations (see Chap. 4). Most of these methods are comparable, however, because of common initial assumptions, e.g., a multivariate normal material distribution. Final results using various of these models and methods are generally similar.

The analyses presented in this chapter are based on experience at Hanford (now Battelle-Northwest; see Sec. 4-4.2.2). This approach has been adopted because of the broad experience at this installation with a variety of different sources and because of the consistent treatment of a wide variety of problems on the basis of a large number of turbulence and diffusion investigations. Other techniques, e.g., for estimating cloud-spread rates, are equally applicable but have not generally been applied to so wide a range of operational problems.

Note that the calculations in this chapter have been carried out for distances considerably greater than those for which data are available. This was done intentionally to illustrate the magnitude of the computed quantities

at great distances. Actual patterns would be considerably more irregular since the long-distance travel of a cloud becomes increasingly affected by large-scale fluctuations in the meteorological patterns and by changes in topography, circumstances not accounted for in the models used here.

Symbols used frequently in Chap. 8 are included in the List of Symbols given in Chap. 7.

8-2 INSTANTANEOUS RELEASE

For a demonstration of calculational methods, consider a puff release of $Q_0 = 10^6$ curies of each of three radioisotopes, ^{41}Ar , ^{137}Cs , and ^{131}I , from a 70-m stack during moderately stable conditions with a wind speed of 5 m/sec.

8-2.1 Ground-level Concentrations

For calculations of ground-level concentrations, a bivariate normal distribution was used as expressed in Eq. 8.1, which is identical to Eq. 3.158,

$$\psi_{(x,y,0)} = \frac{Q_x}{\pi \bar{u} \sigma_{y1} \sigma_{z1}} \exp - \left(\frac{y^2}{2\sigma_{y1}^2} + \frac{h^2}{2\sigma_{z1}^2} \right) \quad (8.1)$$

where ψ is the integral of the concentration over a specified time interval in curie sec/m³, Q_x is equal to $Q_0(Q_x/Q_0)_d \exp(-\lambda_R x/\bar{u})$ curies (the amount of radioactive material in the cloud at the downwind distance x meters), and $(Q_x/Q_0)_d$ is the correction for depletion of source from ground deposition.

First, calculations were made for the concentration time integral under the cloud center line at ground level, i.e., $y = 0$ and $z = 0$. With data from zinc sulfide tracer experiments performed at Hanford, Wash., empirical equations for σ_{y1} and σ_{z1} have been determined for moderately stable conditions. These equations, discussed in Sec. 4-4.2.2, are

$$\sigma_{y1}^2 = At - \frac{A^2}{2(\sigma_0 \bar{u})^2} \left\{ 1 - \exp \left[\frac{-2(\sigma_0 \bar{u})^2 t}{A} \right] \right\} \quad (8.2)$$

where A is a constant related to the scale of turbulence and has a value of $13.0 + 232 \sigma_0 \bar{u}$, $\sigma_0 \bar{u}$ equals 0.05, and t equals $x/\bar{u}$.

$$\sigma_{z1}^2 = a [1 - \exp(-k^2 t^2)] + bt \quad (8.3)$$

where a , k^2 , and b are functions of the degree of stability ($a = 97 \text{ m}^2$, $k^2 = 2.5 \times 10^{-4} \text{ sec}^{-2}$, and $b = 0.33 \text{ m}^2/\text{sec}$).

The values of the standard deviation of cloud concentration as determined from Eqs. 8.2 and 8.3 for the horizontal direction, σ_{y1} , and the vertical direction, σ_{z1} , for various downwind distances are shown in Fig. 8.1. As the cloud proceeds downwind, the amount of radioactive

Fig. 8.1—Standard deviations of cloud concentration distribution in the crosswind and vertical directions (instantaneous release).

material in the cloud will decrease owing to radioactive decay and, in the case of ^{137}Cs and ^{131}I , owing to ground deposition. The correction for radioactive decay was made for each isotope using Eq. 7.23, $(Q_x/Q_0)_R = \exp(-\lambda_R x/\bar{u})$, and the following decay constants:

Isotope	λ , sec^{-1}
^{41}Ar	1.05×10^{-4}
^{137}Cs	8.27×10^{-10}
^{131}I	9.96×10^{-7}

The correction for depletion from ground deposition was determined by the deposition integral as discussed in Sec. 5-3.2.2:

$$\left(\frac{Q_x}{Q_0}\right)_d = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2} \left(\frac{v_d}{\bar{u}}\right) \int_0^x \frac{\exp(-h^2/2\sigma_{z1}^2)}{\sigma_{z1}} dx\right] \quad (8.4)$$

where $(Q_x/Q_0)_d$ is the fraction of the original material released which remains in the cloud after traveling x meters.

This equation can also be written in the Sutton form:

$$\left(\frac{Q_x}{Q_0}\right)_d = \exp\left[-\left(\frac{2}{\pi}\right)^{1/2} \left(\frac{v_d}{\bar{u} C_z}\right) \int_0^x (x)^{\frac{n-2}{2}} \times \exp\left(-\frac{h^2}{C_z^2 x^{2-n}}\right) dx\right] \quad (8.4a)$$

For this particular demonstration $(v_d/\bar{u})$ values of 2.2×10^{-4} and 3.4×10^{-3} were assumed for ^{137}Cs and ^{131}I , respectively. Values of $(v_d/\bar{u})$ depend on the physical and chemical characteristics of the source and the meteorological conditions prevailing. Therefore caution is required in selecting such values for a specific application. The values used here were somewhat arbitrarily selected. Equation 8.1 may be written for the ground-level concentration time integral at various distances directly under the path of the center of the cloud, i.e., $y = 0$, $z = 0$, as

$$\psi_{(x,0,0)} = \frac{Q_0}{\pi \bar{u} \sigma_{y1} \sigma_{z1}} \exp\left(-\lambda_R \frac{x}{\bar{u}}\right) \left(\frac{Q_x}{Q_0}\right)_d \times \exp\left(-\frac{h^2}{2\sigma_{z1}^2}\right) \quad (8.1a)$$

This equation was evaluated, and the results for the three radioisotopes are shown in Fig. 8.2.

Fig. 8.2—Cloud concentration time integral at ground level under the cloud center line (instantaneous release).

For the crosswind concentration time integral distribution, the following equation was evaluated at various downwind distances of $x = \bar{u}t$:

$$\psi_{(x,y,0)} = \psi_{(x,0,0)} \exp\left(-\frac{y^2}{2\sigma_{yI}^2}\right) \quad (8.5)$$

Isopleths of ψ (location of points of equal concentration time integral) were determined by solving for y for specific x values with the following equation:

$$y = (2)^{1/2} \left\{ -\ln \left[\frac{\psi_{(x,y,0)}}{\psi_{(x,0,0)}} \right]^{1/2} \right\} \sigma_{yI} \quad (8.6)$$

Isopleths of ψ (curie sec/m³) for the three radioisotopes are presented in Fig. 8.3.

8-2.2 Ground Deposition

The deposition of a specific isotope from the cloud on the ground along the path beneath the center of the cloud can be determined from

$$\omega_{(x,0,0,t_1)} = \psi_{(x,0,0)} v_d \exp(-\lambda_R t_1) \quad (8.7)$$

where ω is the quantity of deposited radioactive material in units of curies per square meter and the subscript $(x, 0, 0, t_1)$ indicates that the value is time dependent owing to radioactive decay.

For a puff release of a single isotope, the value of t_1 in the exponential in the decay correction factor represents the time interval after cloud passage. A correction factor has already been included in the formulation of ψ to correct for isotope decay en route to the receptor. In the following examples for determining ω and the associated gamma dose, the calculations were made for $t = (x/\bar{u})$ and $t_1 = 0$, and the subscripts for time dependence have been discarded.

With the values of $\psi_{(x,0,0)}$ and $v_d/\bar{u}$ given in Sec. 8-2.1, values of $\omega_{(x,0,0)}$ in curies per square meter were determined as presented in Fig. 8.4 for ¹³⁷Cs and ¹³¹I. Argon-41 will not deposit because it is a stable gas.

In a manner similar to that used to determine $\psi_{(x,y,0)}$, the crosswind distribution of deposition, $\omega_{(x,y,0)}$, in curies per square meter, can be determined.

$$\omega_{(x,y,0)} = \omega_{(x,0,0)} \exp\left[-\frac{y^2}{2\sigma_{yI}^2}\right] \quad (8.8)$$

$$y = (2)^{1/2} \left\{ -\ln \left[\frac{\omega_{(x,y,0)}}{\omega_{(x,0,0)}} \right]^{1/2} \right\} \sigma_{yI} \quad (8.9)$$

Isopleths of the ground deposition, $\omega_{(x,y,0)}$, obtained from this evaluation are presented in Fig. 8.5 for ¹³⁷Cs and ¹³¹I.

8-2.3 External Gamma Dose from Cloud Passage

The equation for the gamma dose to a receptor from the passage of a cloud of finite size was developed in Sec. 7-5.2.2. Equation 7.42 as applied to a puff release was used to calculate the gamma dose in rads from the released 10⁶ curies of each of the three radioisotopes ⁴¹Ar, ¹³⁷Cs, and ¹³¹I.

$$\gamma D_{(x,y,0)} = \frac{0.1616 \mu \mu_a \bar{E}_\gamma Q_x (I_1 + kI_2)}{\bar{u}} \quad (8.10)$$

where Q_x is the source term corrected for depletion prior to arrival x meters downwind.

Spectral diagrams for each of the radioisotopes are shown in Fig. 8.6. These diagrams indicate schematically the decay mode, energies involved, and probable energy per emission. Average gamma energies have also been included. From the graph of μ and μ_a for various gamma energies shown in Fig. 7.8 and the spectral diagrams, the following values of $\bar{E}_\gamma$, μ , and μ_a were obtained for the three radioisotopes:

Isotope	$\bar{E}_\gamma$, Mev/dis	μ , 1/m	μ_a , 1/m
⁴¹ Ar	1.29	7.0×10^{-3}	3.4×10^{-3}
¹³⁷ Cs	0.61	1.03×10^{-2}	3.9×10^{-3}
¹³¹ I	0.39	1.25×10^{-2}	3.85×10^{-3}

Corrections for cloud depletion due to ground deposition and radioactive decay were made and applied to Eq. 8.10. The values of I_1 and I_2 were obtained by using Figs. 7.10 and 7.11. For this demonstration a value of σ_I , needed to ascertain the values of I_1 and I_2 , was determined by the following relations as explained in Sec. 7-5.2.2:

$$\sigma_I = (\sigma_d \sigma_{yI})^{1/2}$$

$$\mu s = \mu(y^2 + h^2)^{1/2}$$

Fig. 8.3—Isopleths of cloud concentration time integral at ground level (instantaneous release).

Fig. 8.4—Ground deposition directly under a cloud center line and immediately after cloud passage (instantaneous release).

The calculations of the gamma dose at various distances downwind under the path of the center of the cloud were made for $y = 0$ and $s = h$, and the appropriate values of μs and k are

Isotope	μs	k
^{41}Ar	0.50	1.2
^{137}Cs	0.70	1.6
^{131}I	0.875	2.3

With these values the gamma dose $\gamma D_{(x,0,0)}$, presented in Fig. 8.7, was determined for each of the isotopes. Values of the dose to receptors at locations not directly under the cloud, i.e., $\gamma D_{(x,y,0)}$, can be determined by substituting the appropriate y values into the equation $\mu s = \mu(y^2 + h^2)^{1/2}$ and evaluating Eq. 8.10.

8-2.4 External Gamma Dose Rate from Ground Deposition

Equations for the dose rate, $\gamma D'_{(x,0,0)}$, from material deposited on the ground directly under a cloud center line were developed in Sec. 7-5.3.2. These equations dealt with the radiation from ground patterns of finite size at the time $x/\bar{u}$, i.e., immediately after cloud passage. The form of Eq. 7.72 used here is

$$\gamma D'_{(x,0,b)} = 0.36 \omega_{(x,0,0)} \sigma_y \mu \mu_a \bar{E}_\gamma \times \left(G_1 + \frac{k}{2} G_2 \right) \quad (8.11)$$

The calculations of $\omega_{(x,0,0)}$ are explained in Sec. 8-2.2, and the results are presented in Fig. 8.4. From values of G_1 and G_2 given in Figs. 7.26 and 7.27, specific values of the gamma dose rate were obtained by using, in this case, the relation $\sigma_I = (\sigma_{yI} \sigma_{zI})^{1/2}$ and assuming the receptor height, b , to be 1 m above the ground. Results of these calculations are presented in Fig. 8.8 for ^{137}Cs and ^{131}I .

Isopleths of the gamma dose rate obtained with relations similar to those in Secs. 8-2.2 and 8-2.3 are shown in Fig. 8.9.

The gamma dose rate to a receptor at locations other than those directly under the path of the cloud center line (i.e., $\gamma D'_{(x,y,b)}$) can be obtained by using the following equation:

$$\gamma D'_{(x,y,b)} = \gamma D'_{(x,0,b)} \exp\left(-\frac{y^2}{2\sigma_{yI}^2}\right) \quad (8.12)$$

8-3 INTERMEDIATE-LENGTH RELEASES

The release intervals defined here as intermediate in length range from 10 minutes or so to a few hours. Much of the diffusion experiment work over the last 10 years has been concentrated on this time scale, and a considerable body of data has accumulated.

For a demonstration of the calculational methods for intermediate-length releases, consider a continuous source of radioactive material with a uniform emission rate of $Q_0' = 1$ curie/sec for a discharge period of 1 hr ($t_d = 3600$ sec) from a 70-m stack into a moderately stable atmosphere with an average wind speed of $\bar{u} = 5$ m/sec. Again, the three radioisotopes ^{41}Ar , ^{137}Cs , and ^{131}I will be considered.

8-3.1 Ground-level Concentrations

When the release occurs over an intermediate time interval, the same equations for exposure, dosage, etc. used in Sec. 8-2.1 are applicable if proper values of σ_y and σ_z are used. The plume released over a 1-hr period can be expected to spread horizontally more than the cloud formed by a puff release. For the Hanford site the value of $\sigma_0 \bar{u} = 0.2$ was selected as representative for a 1-hr release under moderately stable conditions. Equations 8.2 and 8.3 were again used to determine σ_y and σ_z , respectively.

Fig. 8.5—Isopleths of ground deposition (instantaneous release).

Fig. 8.6—Spectral diagrams for ^{41}Ar , ^{137}Cs , and ^{131}I .

Fig. 8.7—Direct gamma dose from passing cloud to receptor under cloud center line (instantaneous release).

Fig. 8.8—Gamma dose rate from ground deposition under cloud center line immediately after cloud passage (instantaneous release).

Fig. 8.9—Isopleths of gamma dose rate from ground deposition immediately after cloud passage (instantaneous release).

The bivariate normal distribution as given in Eq. 8.1 can be applied to continuous-release conditions. In this case Eq. 8.1 will yield the concentration time integral of the plume if the product of Q'_x (curie/sec) times t_d (sec) is substituted for Q_x (curies) of the puff release (both terms corrected for depletion en route to the point of reference). If the release rate Q'_x (curies/sec) is substituted for Q_x (curies), Eq. 8.1 will yield the concentration $\bar{\chi}$ (curies/m³) of the established plume. These modifications of Eq. 8.1 are indicated as Eqs. 8.1a and 8.1b, respectively:

$$\psi_{(x,y,0)} = \frac{Q'_x t_d}{\pi \bar{u} \sigma_y \sigma_z} \exp \left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right) \right] \text{ curie sec/m}^3 \quad (8.1a)$$

$$\bar{\chi}_{(x,y,0)} = \frac{Q'_x}{\pi \bar{u} \sigma_y \sigma_z} \exp \left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right) \right] \text{ curies/m}^3 \quad (8.1b)$$

The source term Q_x in Eq. 8.1, or Q'_x as applied to the plume, is the amount of source material in the cloud or plume at the receptor downwind at distance x or at time $x/\bar{u}$ (sec). The source terms as measured at the time of release must be corrected for both ground deposition and radioactive decay in Eqs. 8.1a and 8.1b. The correction factors for depletion by ground deposition and radioactive decay are identical for both the puff release and the plume.

The values of $\bar{\chi}_{(x,0,0)}$ for the established plume determined with Eq. 8.1b are given in Fig. 8.10 for various downwind distances for the three isotopes.

The isopleths of the plume equilibrium concentration were determined from Eq. 8.6 with $\bar{\chi}$ substituted for ψ . These isopleths are shown in Fig. 8.11 for the three isotopes.

8-3.2 Ground Deposition

The rate of deposition from the established plume to the ground can be determined by using Eq. 7.30 for $t_d \rightarrow 0$ and including appropriate depletion factors en route. The total deposition for the 1-hr release was determined for points directly under the plume center line

Fig. 8.10 — Equilibrium plume concentration at ground level under a cloud center line (intermediate release).

by using $\psi_{(x,0,0)}$ for the plume as discussed in Sec. 8-3.1. In the case of the plume, Eq. 7.30 was used.

For the special case of $t = 0$, the ground deposition $\omega_{(x,y,0,t)}$ is a maximum. Figure 8.12 shows the values of $\omega_{(x,0,0)}$ for ^{137}Cs and ^{131}I obtained with Eq. 7.30. Isopleths of ω can be determined for the short-term release in a manner similar to that used for the puff release.

8-3.3 External Gamma Dose Rate and Dose from Cloud Passage

Equation 7.43 yields the gamma dose rate from an established plume. This equation was used to calculate the gamma dose rate of the established plume directly under the plume center line, $\gamma D'_{(x,0,0)}$, i.e., $y = 0$ and s (the distance from the receptor to the plume center line) = h . In evaluating Eq. 7.43 for the plume, values of I_1 and I_2 are functions of $\sigma = (\sigma_y \sigma_z)^{1/2}$, and the σ values for the plume were used. The dose rates from the plume are shown in Fig. 8.13 for the three isotopes. Dose rates for receptor points other than those directly under the plume center line can be obtained by evaluating I_1 and I_2 in Eq. 7.43 for $s = (h^2 + y^2)^{1/2}$.

The gamma dose received at a point during the plume passage can be obtained by multiplying the dose rate $\gamma D'_{(x,y,0)}$ by the time interval of release t_d (sec). In this case $t_d = 3600$ sec.

Fig. 8.11—Isopleths of plume concentration at ground level under the cloud (intermediate release).

Fig. 8.12—Ground deposition directly under the plume center line immediately after cloud passage (intermediate release).

Fig. 8.13—Direct gamma dose rate from a plume to a receptor under the center line (intermediate release).

8.3.4 External Gamma Dose Rate from Ground Deposition

The gamma dose rate from ground deposition from the plume can be determined for any time if the appropriate modifications are made to the equations for the dose rate from ground deposition patterns of finite size (Sec. 7-5.3.2). For dose rates at points directly under the plume center line, Eq. 7.69 may be used.

With the appropriate σ value for the plume, Eq. 7.69 was evaluated for the release of ^{137}Cs and ^{131}I at the rate of 1 curie/sec and the deposition dose rates at $t = 0$ when the end of

the plume had just passed the receptor points. These dose rates are shown in Fig. 8.14.

Isopleths for the gamma dose rate from the deposition described in the preceding paragraph can be determined using Eq. 8.12 in Sec. 8-2.4 with σ values appropriate to the intermediate-length release.

Fig. 8.14—Gamma dose rate from ground deposition under the plume center line during plume passage (intermediate release).

8.4 LONG-PERIOD RELEASE

Equations for evaluating doses from continuous releases at uniform rates over long periods of time (i.e., from days to years) were developed in Sec. 7-5.2.5. In addition to the information required for dispersion calculations, data on the joint frequency of occurrence of wind speed, wind direction, and stability are required.

Table 8.1 presents the percentage frequency distribution of wind speed and direction as determined from measurements taken at the 200-ft level of the Hanford meteorology tower for various stability classes in the 200-ft layer for 16 compass sectors.

The many individual calculations required to evaluate long-term release effects generally make the use of a computer mandatory. From the Hanford data shown in Table 8.1, the average air concentrations, deposition rate, direct dose rate from cloud passage, and dose rate from material deposited on the ground were determined with the assumption that ^{41}Ar , ^{137}Cs ,

Table 8.1—ANNUAL PERCENTAGE FREQUENCY DISTRIBUTION OF WIND SPEED AND DIRECTION AS A FUNCTION OF ATMOSPHERIC STABILITY AT HANFORD*

Wind speed, miles/hr	Atmospheric stability	Wind direction																	Calm	Total
		NNE.	NE.	ENE.	E.	ESE.	SE.	SSE.	S.	SSW.	SW.	WSW.	W.	WNW.	NW.	NNW.	N.	Variable		
0 to 3	Very stable	0.16	0.20	0.14	0.22	0.24	0.41	0.21	0.24	0.20	0.25	0.24	0.46	0.38	0.53	0.41	0.37	0.15	0.56	5.37
	Moderately stable	0.19	0.25	0.19	0.22	0.44	0.48	0.22	0.22	0.13	0.17	0.16	0.23	0.29	0.40	0.37	0.41	0.12	0.67	5.17
	Neutral	0.27	0.38	0.28	0.36	0.40	0.47	0.22	0.18	0.13	0.14	0.12	0.23	0.22	0.44	0.50	0.50	0.15	0.50	5.47
	Unstable	0.38	0.65	0.40	0.45	0.36	0.26	0.11	0.22	0.12	0.18	0.10	0.14	0.16	0.30	0.40	0.64	0.49	0.02	5.38
4 to 7	Very stable	0.18	0.19	0.11	0.15	0.16	0.31	0.22	0.22	0.21	0.35	0.44	0.93	1.03	1.04	0.65	0.35	0.02	0.00	6.57
	Moderately stable	0.16	0.12	0.12	0.16	0.22	0.40	0.22	0.18	0.18	0.22	0.26	0.46	0.58	0.81	0.49	0.33	0.01	0.00	4.92
	Neutral	0.10	0.13	0.10	0.10	0.15	0.25	0.13	0.11	0.07	0.10	0.12	0.18	0.30	0.66	0.31	0.16	0.02	0.00	2.98
	Unstable	0.70	0.77	0.43	0.50	0.43	0.56	0.35	0.47	0.46	0.49	0.38	0.39	0.42	1.09	0.97	1.20	0.28	0.00	9.88
8 to 12	Very stable	0.12	0.10	0.08	0.09	0.05	0.14	0.20	0.10	0.11	0.23	0.55	1.07	1.80	1.88	0.55	0.20	0.00	0.00	7.28
	Moderately stable	0.11	0.09	0.02	0.07	0.07	0.19	0.19	0.15	0.21	0.33	0.48	0.90	1.62	1.89	0.35	0.16	0.00	0.00	6.84
	Neutral	0.06	0.05	0.03	0.03	0.03	0.06	0.06	0.05	0.06	0.08	0.12	0.12	0.36	0.87	0.17	0.09	0.00	0.00	2.26
	Unstable	0.47	0.35	0.11	0.06	0.07	0.09	0.10	0.12	0.28	0.59	0.54	0.33	0.49	1.33	0.47	0.49	0.00	0.00	5.91
13 to 18	Very stable	0.04	0.03	0.02	0.02	0.00	0.05	0.08	0.02	0.03	0.11	0.25	0.41	1.05	1.64	0.22	0.07	0.00	0.00	4.04
	Moderately stable	0.08	0.03	0.02	0.01	0.02	0.09	0.13	0.14	0.26	0.60	0.84	1.07	2.81	2.71	0.18	0.12	0.00	0.00	9.10
	Neutral	0.06	0.01	0.01	0.01	0.00	0.03	0.03	0.05	0.07	0.15	0.20	0.14	0.28	0.51	0.07	0.04	0.00	0.00	1.66
	Unstable	0.25	0.15	0.04	0.00	0.00	0.03	0.03	0.04	0.19	0.53	0.64	0.26	0.59	1.00	0.10	0.12	0.00	0.00	3.97
19 to 24	Very stable	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.01	0.02	0.03	0.03	0.04	0.20	0.00	0.00	0.00	0.00	0.37
	Moderately stable	0.03	0.03	0.01	0.00	0.00	0.02	0.07	0.09	0.23	0.56	0.50	0.35	1.37	1.69	0.04	0.01	0.00	0.00	5.00
	Neutral	0.01	0.02	0.00	0.00	0.00	0.01	0.01	0.02	0.07	0.12	0.14	0.05	0.18	0.30	0.01	0.01	0.00	0.00	0.96
	Unstable	0.06	0.05	0.01	0.00	0.00	0.00	0.01	0.01	0.10	0.30	0.44	0.11	0.26	0.60	0.01	0.03	0.00	0.00	2.00
Over 24	Very stable	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
	Moderately stable	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.08	0.33	0.60	0.24	0.08	0.48	0.84	0.01	0.00	0.00	0.00	2.70
	Neutral	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.15	0.07	0.02	0.10	0.27	0.00	0.01	0.00	0.00	0.71
	Unstable	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.37	0.27	0.08	0.11	0.48	0.01	0.00	0.00	0.00	1.41
Total	Very stable	0.50	0.52	0.35	0.48	0.45	0.91	0.73	0.59	0.58	0.97	1.52	2.90	4.30	5.29	1.83	0.99	0.17	0.56	23.67
	Moderately stable	0.57	0.52	0.36	0.46	0.75	1.19	0.85	0.87	1.35	2.48	2.49	3.09	7.15	8.34	1.45	1.03	0.14	0.67	33.74
	Neutral	0.50	0.59	0.41	0.49	0.59	0.82	0.46	0.43	0.46	0.73	0.77	0.75	1.45	3.06	1.07	0.81	0.17	0.50	14.04
	Unstable	1.85	1.97	0.99	1.02	0.86	0.95	0.61	0.87	1.22	2.47	2.37	1.32	2.02	4.80	1.96	2.48	0.77	0.02	28.55

*Measured on Hanford tower at 200 ft during the period January 1955 through July 1961.

and ^{131}I were each released from a 70-m stack at a constant rate of 1.0 curie/sec for a period of 1 year.

8-4.1 Average Ground-level Concentration

The average ground-level air concentration is given by Eq. 7.60. For stable atmospheric stratifications, σ_z was calculated with Eq. 8.3 evaluated from the data in Table 8.2.

Table 8.2—VALUES OF DIFFUSION PARAMETERS FOR STABLE CONDITIONS AT HANFORD

Parameter	Degree of stability	
	Very stable	Moderately stable
a	34 m ²	97 m ²
b	2.5×10^{-2} m ² /sec	0.33 m ² /sec
k ²	8.8×10^{-4} sec ⁻²	2.5×10^{-4} sec ⁻²

The values for σ_z in meters during neutral and unstable conditions were determined by the Sutton form

$$\sigma_z = \frac{C_z x^{(1-n/2)}}{(2)^{1/2}}$$

where values of C_z are given in Table 8.3, $n = 0.25$ for neutral conditions, and $n = 0.20$ for unstable conditions.

Table 8.3—VERTICAL DIFFUSION PARAMETER VALUES (C_z) FOR NEUTRAL AND UNSTABLE ATMOSPHERES AS USED AT HANFORD

Wind speed, m/sec	Degree of stability	
	Neutral	Unstable
1.0	0.15	0.30
2.5	0.14	0.28
5.0	0.12	0.26
7.5	0.115	0.25
10.0	0.11	0.24
15.0	0.10	0.23

The value of Q'_R in Eq. 7.60 is the rate at which the source in the cloud passes the vertical plane perpendicular to the cloud path at the receptor point in the sector (that is, corrected for depletion en route per Eq. 5.48). Values of v_d used in evaluating the deposition integral depend upon the atmospheric stability during the dispersion and the characteristics of the

source material. For this particular demonstration the values of $v_d/\bar{u}$ given in Table 8.4 were assumed. These values are somewhat arbitrary and may not be applicable to other situations.

Table 8.4—VALUES OF $v_d/\bar{u}$ USED IN DEPOSITION CALCULATIONS AT HANFORD

Atmospheric conditions	Particulates (^{137}Cs)	Halogens (^{131}I)
Strong inversion	1.5×10^{-4}	2.4×10^{-3}
Moderate inversion	2.2×10^{-4}	3.4×10^{-3}
Neutral	3.0×10^{-4}	4.6×10^{-3}
Unstable	6.0×10^{-4}	8.0×10^{-3}

Calculations of the average ground-level concentration, $\bar{\chi}_{(R,\theta,0)}$ (curie/m³), were made for each of the 16 compass sectors by using the values of percentage frequency in Table 8.1. The concentrations were then added for each of the joint frequencies for a given isotope at several downwind distances in each sector. The isopleths of $\bar{\chi}$ about the release point are shown in Figs. 8.15, 8.16, and 8.17. The calculated values have been located on the center line of the individual sectors, and smooth curves have been drawn to connect common $\bar{\chi}_{(R,\theta,0)}$ values.

8-4.2 External Gamma Dose

The external doses for individuals at various locations in the vicinity of the release point were calculated with Eq. 7.63 and the data in Table 8.1.

Isopleths of the dose contributed by each of the radionuclides are shown in Figs. 8.18, 8.19, and 8.20 for the 1-year exposure period. The total dose from cloud passage would, of course, be the sum of the contributions by each radionuclide.

8-4.3 External Gamma Dose Rate from Ground Deposition

The dose rate from ground deposition will increase continuously during the period of release because the ^{137}Cs does not attain equilibrium in 1 year. The isopleths of dose rate from ^{137}Cs and ^{131}I sources computed for the end of the year are shown in Fig. 8.21. The time-integrated dose can be determined by integrating the activity on the ground over the period of concern and using this value as a source in Eq. 7.63.