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OPEN BURN/OPEN DETONATION DISPERSION MODEL (OBODM) USER'S GUIDE

Volume II. Technical Description

by

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The Open Burn/Open Detonation Dispersion Model (OBODM) is intended for use in evaluating the potential air quality impacts of the open-air burning and detonation (OB/OD) of obsolete munitions and solid propellants. OBODM uses cloud/plume rise, dispersion, and deposition algorithms taken from existing models for instantaneous and quasi-continuous sources to predict the downwind transport and dispersion of pollutants released by OB/OD operations. The model can be used to calculate peak concentration, time-mean concentration, dosage (time-integrated concentration), and particulate gravitational deposition for emissions from multiple OB/OD sources for either a single event or up to a year of sequential hourly source and meteorological inputs. The program is designed for use on IBM-compatible PCs using the MS-DOS (Version 2.1 or higher) operating system with keyboard and optional mouse control. It will also run under most WINDOWS environments. The OBODM computer program requires 505 kilobytes of conventional memory, a math coprocessor, and a minimum of 3 megabytes of hard disk storage. Volume I of this user's guide contains instructions for installing and running the model and example problems. Volume II discusses the model's mathematical algorithms and default meteorological inputs.

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SECTION 1. INTRODUCTION

The Open Burn/Open Detonation Dispersion Model (OBODM) is intended for use in evaluating the potential air quality impacts of the open-air burning or detonation of obsolete munitions, solid rocket propellants, and manufacturing wastes at Department of Defense and Department of Energy installations. OBODM predicts the downwind transport and dispersion of pollutants using cloud rise and dispersion model algorithms taken from existing dispersion models. OBODM is strictly a transport and dispersion model; it does not contain a source preprocessor to predict the total quantities of pollutants released by an open burn or detonation. Rather, it is designed to use either empirical emissions factors such as those derived from measurements in the Dugway Proving Ground Bang Box^{TM} or the emissions predicted by a products of combustion model (for example, Baroody, 1994). (OBODM contains a data base of empirical BangBox emissions factors.) OBODM calculates peak concentration, time-mean concentration, and dosage (time-integrated concentration) for quasi-continuous (open burn) and instantaneous (open detonation) releases. It can also consider the effects on concentration and dosage of the gravitational settling and deposition of particulates such as soil particles entrained into the cloud from an open detonation.

OBODM can consider two types of quasi-continuous or instantaneous sources: volume and line. (The model automatically represents a line source by a series of volume sources.) The vast majority of open burn/open detonation (OB/OD) releases can be modeled using volume sources. Line sources are available to model relatively unusual OB/OD source configurations or other types of releases such as dust released from the detonations used in surface mining operations.

Volume I of this two-volume OBODM User's Guide provides user's instructions, including installation procedures, a tutorial on model use, examples of all menus, and example problems. This volume provides a detailed technical description of OBODM, including the mathematical models and the procedures used to parameterize meteorological conditions in the surface mixing layer.

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SECTION 2. MATHEMATICAL MODELS

2.1 PLUME AND CLOUD RISE

2.1.1 Plume Rise (Open Burn)

OBODM uses the Briggs (1971) plume rise equations to predict the buoyant rise of the plume from an open burn. Following the derivation given by Dumbauld et al. (1973), these equations have been modified to account for the horizontal dimensions of a very large burn (diameter greater than about 5 m). With a stable thermal stratification, the buoyant rise $\Delta h_{cs}(x)$ at downwind distance x from a burn of greater than 15 s duration is given by

$$\Delta h_{cs}(x) = \left\{ \begin{array}{ll} \left[\dfrac{3F}{u\gamma_c^2\, S} \left[1 - \cos\left(S^{1/2}\, x / u\right)\right] + \left(\dfrac{r_R}{\gamma_c}\right)^3 \right]^{1/3} - \left(\dfrac{r_R}{\gamma_c}\right) & ;\ x \le \pi u S^{-1/2} \\ \left[\dfrac{6F}{u\gamma_c^2\, S} + \left(\dfrac{r_R}{\gamma_c}\right)^3 \right]^{1/3} - \left(\dfrac{r_R}{\gamma_c}\right) & ;\ x > \pi u S^{-1/2} \end{array} \right\} \qquad \textbf{(2-1)}$$

$$F = \frac{g H_c R}{\pi \rho_a c_p T_a} \qquad \textbf{(2-2)}$$

$$S = \frac{g}{T_a} \frac{\partial \theta}{\partial z} \qquad \textbf{(2-3)}$$

where

u = mean wind speed (m s^{-1}) at release height h or 2 m, whichever is greater

γ_c = continuous source entrainment coefficient (default value is 0.6)

r_R = radius of the burning material (m)

g = acceleration due to gravity (9.8 m s^{-2})

H_c = material effective heat content (cal g^{-1})

R = material burn rate ($g\ s^{-1}$)

c_p = specific heat of air at constant pressure ($0.24\ cal\ g^{-1}\ K^{-1}$)

ρ_a = air density ($g\ m^{-3}$)

T_a = air temperature (K)

$\frac{\partial\theta}{\partial z}$ = vertical potential temperature gradient in layer through which cloud rises ($K\ m^{-1}$)

With an unstable or neutral thermal stratification ($\partial\theta/\partial z \leq 0$), buoyant rise at downwind distance x from a burn of greater than 15 s duration is given by

$$\Delta h_{cn}(x) = \left[\frac{3Fx'^2}{2\gamma_c^2\ u^3} + \left(\frac{r_R}{\gamma_c}\right)^3 \right]^{1/3} - \left(\frac{r_R}{\gamma_c}\right) \qquad \textbf{(2-4)}$$

$$x' = \begin{cases} x & ;\ x \leq 3.5x^* \\ 3.5x^* & ;\ x > 3.5x^* \end{cases} \qquad \textbf{(2-5)}$$

$$x^* = \begin{cases} 14\,F^{5/8} & ;\ F \leq 55\ m^4\ s^{-3} \\ 34\,F^{5/8} & ;\ F > 55\ m^4\ s^{-3} \end{cases} \qquad \textbf{(2-6)}$$

Inspection of Equations (2-1) through (2-3) shows that the predicted stable rise approaches infinity in the limit as the vertical potential temperature gradient $\partial\theta/\partial z$ approaches zero. Thus, it is possible for the plume rise predicted by Equation (2-1) to exceed that predicted for adiabatic or unstable conditions by Equation (2-4). Consequently, OBODM uses the smaller of the plume rises predicted by Equations (2-1) and (2-4) under stable conditions.

2.1.2 Cloud Rise (Open Detonation)

OBODM calculates the buoyant rise of the cloud from a detonation or burn of duration less than 15 s using equations from the Rocket Exhaust Effluent Diffusion Model (REEDM) (Bjorklund et al., 1982). These equations were derived by Dumbauld et al. (1973) following the same reasoning as used by Briggs (1971) in the derivation of his rise equations for a continuous source. The buoyant cloud rise $\Delta h_{ls}(x)$ at downwind distance x with a stable stratification is given by

$$\Delta h_{Is}(x) = \left\{ \begin{array}{ll} \left[\left[\frac{4F_I}{\gamma_I^3 S}\,[1 - \cos\,(S^{1/2}\,x\,/\,u] + \left(\frac{r_R}{\gamma_I}\right)^{1/4}\right] - \left(\frac{r_R}{\gamma_I}\right) & ;\, x \le \pi\, u S^{-1/2} \\ \left[\frac{8F_I}{\gamma_I^3 S} + \left(\frac{r_R}{\gamma_I}\right)^4\right]^{1/4} - \left(\frac{r_R}{\gamma_I}\right) & ;\, x > \pi\, u S^{-1/2} \end{array} \right\} \tag{2-7}$$

$$F_I = \frac{3g\ H_c\ W_D}{4\pi\,\rho_a\ c_p\ T_a} \tag{2-8}$$

where W_D is the quantity of material detonated in grams, γ_I is the instantaneous source entrainment coefficient, and the other terms are as defined above. Based on the recommendations of Bjorklund et al. (1982), the default value for γ_I is 0.64. Although Dumbauld et al. (1973) derived an equation analogous to Equation (2-4) for an instantaneous source, Bjorklund et al. (1982) use the stable rise equation of Equation (2-7) to approximate instantaneous source cloud rise with adiabatic or unstable conditions by setting the potential temperature gradient equal to 3.344×10^{-4} K m^{-1}. This potential temperature gradient was empirically determined using observations of the buoyant rise of the exhaust clouds from large solid rocket motors such as those used by the Space Shuttle and Titan 34D. Thus, it is likely that this empirical value implicitly includes the buoyancy flux F_I of these large sources.

As an alternative to the use of Equation (2-7) when there is an adiabatic or unstable lapse rate, OBODM allows the user to select the adiabatic cloud rise equation derived by Dumbauld et al. (1973). If the adiabatic rise equation is used, the downwind distance to final cloud rise is defined in a manner similar to the distance to final plume rise for a continuous source [see Equations (2-5) and (2-6)]. The resulting equations are

$$\Delta h_{In} = \left[\frac{2\,F_I\,x'^2}{\gamma_I^3\ u^2}\right]^{1/4} \tag{2-9}$$

$$x' = \left\{ \begin{array}{ll} x & ; x \le x_{\max} \\ x_{\max} & ; x > x_{\max} \end{array} \right\} \tag{2-10}$$

$$x_{\max} = \left\{ \begin{array}{l} 12\ F_I^{1/2}\ u^{1/3}\ ;\ F_I \le 300\ u^{2/3} \\ 50\ F_I^{1/4}\ u^{1/2}\ ;\ F_I > 300\ u^{2/3} \end{array} \right\} \tag{2-11}$$

Note that the x_{max} given by Equation (2-11) is analogous to the 3.5 x* given by Equations (2-5) and (2-6). The derivation of Equation (2-11) is given in Appendix A.

It should be noted that the cloud from an open burn does not always behave as a quasi-continuous source. Specifically, if the burn time is very short, the resulting cloud rises and disperses in the same manner as an instantaneous source. The burn time t_B is given by

$$t_B = \frac{W_B}{R} \tag{2-12}$$

where W_B is the quantity burned in grams. If t_B is less than or equal to 15 s, OBODM treats the source as an instantaneous release with W_B substituted for W_D in Equation (2-8).

2.1.3 Inversion Penetration

OBODM accounts for the fact that a plume or cloud may partially or completely penetrate the elevated layer above the top of the surface mixing layer using a technique similar to that used by the PPSP model (Weil and Brower, 1984). Although this technique was specifically developed to address plume penetration into the elevated stable layer above a convective or adiabatic surface mixing layer, it is also applied by OBODM to the case of the layer capping a stable surface mixing layer.

Plume or cloud height H(x) at downwind distance x is given by

$$H(x) = h + \Delta h(x) \tag{2-13}$$

where h is the release height above ground level (normally zero) and Δh(x) is the plume rise obtained from Equation (2-1), (2-4), (2-7), or (2-9), depending on the source type and stability. If Δh exceeds $0.67(H_m\text{-}h)$, where H_m is the mixing depth, a second plume rise Δh'(x) is calculated using Equation (2-1) or (2-7), depending on source type, and a vertical potential temperature gradient $\partial\theta/\partial z$ of 0.01 K m^{-1}. (If the potential temperature gradient used in the original rise calculation exceeds 0.01 K m^{-1}, Δh'(x) is set equal to the original Δh(x).) The fraction P of the plume or cloud in the elevated layer is then given by

$$P = \left\{ \begin{array}{ll} 1 & ; \frac{(H_m - h}{\Delta h'(x)} \le 0.5 \\ 1.5 - \frac{(H_m - h}{\Delta h'(x)} & ; 0.5 \le \frac{(H_m - h}{\Delta h'(x)} < 1.5 \\ 0 & ; 1.5 \le \frac{(H_m - h)}{\Delta h'(x)} \end{array} \right\} \tag{2-14}$$

OBODM assumes that the portion of a cloud or plume that stabilizes above the top of the surface mixing layer does not contribute to concentrations within the mixing layer. The effective source strength $Q_e(x)$ for the plume or cloud material within the mixing layer is defined by

$$Q_e(x) = Q_o\ (1 - P) \tag{2-15}$$

where Q_o is the original source strength (quantity of pollutant released by the burn or detonation). The effective plume or cloud rise for the material within the mixing layer, which is substituted for $\Delta h(x)$ in Equation (2-13), is defined as

$$\Delta h_e(x) = (0.62 + 0.38\,P)\ (H_m - h) \tag{2-16}$$

2.1.4 Plume/Cloud Rise for Line Sources

OBODM is not specifically designed to calculate buoyant plume or cloud rise for a line source. The model can be directed to use the volume source rise equations described above to estimate buoyant rise for a line source by entering a nonzero heat content H_c, but the user should recognize that the resulting rise predictions may not be realistic.

2.2 PARTICLE DISTRIBUTION, SETTLING VELOCITY, AND REFLECTION COEFFICIENT

OBODM requires the particle size distribution in order to consider the effects of gravitational settling on concentration, dosage, and dry deposition. The size distribution is divided into N size categories. For each category, the model requires the diameter, settling velocity, fraction of total mass contained in the category, and surface reflection coefficient. The user may enter all of this information or direct OBODM to compute it from the mass median particle diameter, geometric standard deviation of the particle size distribution, and density of the particulates.

2.2.1 Particle Size Distribution

The particle size distribution automatically generated by OBODM is a log-normal distribution that extends 2.3 standard deviations to each side of the median. The particle diameter at the lower boundary of the nth size category is given by

$$d_n = \frac{d_m\ \exp\left[4.6(n-1)\ \dfrac{\ln\ \sigma_d}{N}\right]}{\sigma_d^{2.3}} \tag{2-17}$$

where

d_m = mass-median diameter (m)

σ_d = geometric standard deviation ($\sigma_d > 1$)

N = number of particle size categories (maximum of 20)

If σ_d is entered as less than or equal to unity, OBODM assumes monodisperse particles of diameter d_m.

The mass fraction of particles in the n^th size category is given by

$$\phi_n = \begin{cases} 0.01 + \frac{1}{2} A_n & ; \; n = 1 \; or \; N \\ \frac{1}{2} A_n & ; \; 1 < n < N \end{cases} \qquad \textbf{(2-18)}$$

where

$$A_n = \left[erf\left(\frac{\ln d_{n+1} - \ln d_m}{\sqrt{2}\,\sigma_d} \right) - erf\left(\frac{\ln d_n - \ln d_m}{\sqrt{2}\,\sigma_d} \right) \right] \qquad \textbf{(2-19)}$$

Whether the particle size distribution is automatically generated from a log-normal distribution or entered by the user, OBODM represents each particle size category by its mass-mean diameter, which is given by

$$\overline{d_n} = \left[\frac{d_{n+1}^3 + d_n^2 d_{n+1} + d_n d_{n+1}^2 + d_n^3}{4} \right]^{1/3} \qquad \textbf{(2-20)}$$

2.2.2 Gravitational Settling Velocity

OBODM uses the method of McDonald (1960) to compute the terminal settling velocity for the mass-mean diameter of each particle size category. The terminal fall velocity of the nth size category is given by

$$V_{sn} = \left\{ \begin{array}{l} \dfrac{\rho g (\overline{d_n})^2}{18 \mu_a} \quad ; Q'' < 24 \ (Stokes\ law) \\ \\ \dfrac{\mu_a}{\rho'_a} \left[\ Ri \left(\dfrac{Q''}{Q'_i} \right)^q \right] ; 24 < Q'' \ ; Q'_i \ < Q'' \leq Q'_{i+1} \end{array} \right\} \tag{2-21}$$

$$Q'' = \frac{400 g \rho \rho'_a (\overline{d}_n)^3}{3 \mu_a^2} \tag{2-22}$$

$$q = \frac{\ln \left(\dfrac{R_{i+1}}{R_i} \right)}{\ln \left(\dfrac{Q'_{i+1}}{Q'_i} \right)} \tag{2-23}$$

where the mass-mean particle $\overline{d}_n$ is in centimeters, ρ_a' is the air density in grams per cubic centimeter (ρ_a is used in Section 2.1 to indicate air density in grams per cubic meter), and

ρ = particle density (g cm^{-3})
g = acceleration due to gravity (m s^{-2})
R_i, Q_i' = coefficients listed in Table 1
μ_a = absolute viscosity of air (g cm^{-1} s^{-1})

$$= \frac{7.6342 \ X \ 10^{-2}}{(T_a \ + \ 120)} \left(\frac{T_a}{296.16} \right)^{3/2} 24 \tag{2-24}$$

T_a = air temperature (K)

The logarithmic interpolation shown in Equation (2-21) for Q" greater than 24 depends on an empirical relationship between Q" and the Reynolds number R_e. After Q" has been calculated, the values of Q'_i and Q'_{i+1} bounding Q" and the corresponding values of R_i and R_{i+1} are selected from Table 1.

Table 1. Values of R_i and Q'_i for Settling Velocity Computations.

i	R_i	Q'_i
1	1	24
2	2	64
3	4	140
4	6	230
5	10	420
6	20	1.16×10^3
7	40	2.88×10^3
8	60	5.40×10^3
9	100	1.20×10^4
10	200	3.20×10^4
11	400	9.76×10^4
12	600	1.94×10^5
13	1×10^3	4.60×10^5
14	2×10^3	1.64×10^6
15	4×10^3	6.40×10^6
16	6×10^3	1.44×10^7
17	1×10^4	4.10×10^7
18	2×10^4	1.76×10^8
19	4×10^4	7.33×10^8
20	6×10^4	1.65×10^9
21	1×10^5	4.40×10^9
22	2×10^5	1.64×10^{10}

2.2.3 Reflection Coefficient

The reflection coefficient is the fraction of material reaching the surface through the combined processes of gravitational settling and atmospheric turbulence that is assumed to be reflected from the surface. It ranges from unity for complete reflection to zero for complete deposition. Thus, an upper bound on dosage or concentration can be obtained by setting the reflection coefficient equal to unity, while the effects of depletion by dry deposition can be maximized by setting the reflection coefficient to zero. If the user does not enter reflection coefficients, OBODM automatically estimates them using a semi-empirical relationship (Dumbauld et al., 1976) between the reflection coefficient and settling velocity. Rather than require the user to estimate the reflection coefficient from the Dumbauld et al. (1976) nomogram, OBODM uses the Bjorklund et al. (1982) fit to the nomogram

$$\delta_n = \left\{ \begin{array}{ll} O & ;\, V_{sn} > 0.3\, m\, s^{-1} \\ 2.5(0.3 - V_{sn}) & ;\, 0.3 \leq V_{sn} < 0.05\, m\, s^{-1} \\ 1.0 - 1.0179\, V_{sn}^{1/3} & ;\, V_{sn} \leq 0.05\, m\, s^{-1} \end{array} \right\} \qquad \textbf{(2-25)}$$

Note that OBODM requires a surface reflection coefficient that does not vary with downwind distance. The Overcamp (1976) reflection coefficient, which is a function of deposition velocity and downwind distance, is not suitable for use in OBODM.

2.3 CONCENTRATION

OBODM uses the concentration algorithms from Dugway Proving Ground's RTVSM model (Bjorklund, 1990). These algorithms are based on the same steady-state Gaussian dispersion model concepts used by many other models. OBODM has two basic source types, the Gaussian puff and a square-wave quasi-continuous source. The square-wave quasi-continuous source model can be derived by integrating the Gaussian puff equation with respect to time over the limits 0 to τ, where τ is the release duration. Thus, the quasi-continuous source model is the analytic equivalent of representing a quasi-continuous release by an overlapping series of Gaussian puffs.

The concentration produced by an instantaneous or quasi-continuous volume source at downwind distance x, crosswind distance y, height z above the surface, and time t after source function is given by

$$\chi(x,y,z,t) = \chi_p(x) \bullet VT(x,z) \bullet LT(x,y) \bullet AT(x,t) \bullet DC(x) \qquad \textbf{(2-26)}$$

where χ_p, VT, LT, AT, and DC are the peak concentration, vertical, lateral, alongwind, and decay terms, respectively.

The peak concentration term is defined as

$$\chi_p(X) = \left\{ \begin{array}{ll} \dfrac{K\, Q_e(X)}{(2\pi)^{3/2}\ \sigma_x \sigma_y \sigma_z} & ;\ \text{instantaneous source} \\ \dfrac{K\, Q_e\ (X)}{(2\pi)\ \ \sigma_y \sigma_z\ \bar{u}\ \tau} & ;\ \text{quasi - continuous source} \end{array} \right\} \qquad \textbf{(2-27)}$$

where

K = units conversion factor

$Q_e(x)$ = effective source strength [see Equation (2-15)]

σ_x = alongwind (longitudinal) dispersion coefficient (standard deviation of alongwind concentration distribution) (m)

σ_y = lateral dispersion coefficient (standard deviation of crosswind concentration distribution) (m)

σ_z = vertical dispersion coefficient (standard deviation of vertical concentration distribution) (m)

$\bar{u}$ = mean transport wind speed (m s^{-1})

τ = dissemination duration (burn time t_B) (s)

The transport wind speed and dispersion coefficients are discussed in Section 2.6.

The vertical term for gases and aerosols with negligible settling velocities is given by

$$\begin{aligned} \mathrm{VT}(x,z) = \Bigg\{ & \sum_{i=0}^{\infty} \left[\exp\left[-\frac{1}{2} \left(\frac{2iH_m - H + z}{\sigma_z} \right)^2 \right] + \exp\left[-\frac{1}{2} \left(\frac{2iH_m + H + z}{\sigma_z} \right)^2 \right] \right] \\ & + \sum_{i=1}^{\infty} \left[\exp\left[-\frac{1}{2} \left(\frac{2iH_m + H - z}{\sigma_z} \right)^2 \right] + \exp\left[-\frac{1}{2} \left(\frac{2iH_m - H - z}{\sigma_z} \right)^2 \right] \right] \Bigg\} \end{aligned} \qquad \textbf{(2-28)}$$

where H_m is the mixing depth and H is the effective release height [see Equations (2-13) and (2-16)]. At the downwind distance where the exponential terms for i equals 3 exceed exp(-10), the cloud or plume is approximately uniformly mixed within the surface mixing layer. Equation (2-28) is then replaced by

$$VT(x,z) \;=\; \frac{\sqrt{2\pi}\;\sigma_z}{H_m} \tag{2-29}$$

which results in a box model with uniform vertical mixing.

OBODM can also consider the effects on concentration and dosage of the gravitational settling and dry deposition of particulates with appreciable gravitational settling velocities by using a different and more generalized vertical term. The derivations of this algorithm and the associated surface deposition algorithms are discussed by Cramer and Bowers (1980). Similar algorithms are also used in other models such as the original ISC (Bowers et al., 1979), a regulatory model designed for application to industrial particulate emissions, and FSCBG (Teske et al., 1993), an aerial spray dispersion and deposition model.

As discussed in Section 2.2, OBODM allows the user to divide the source strength for particulates with appreciable gravitational settling velocities into as many as 20 settling-velocity categories, or the model can be directed to generate a log-normal distribution from the mass-median diameter and geometric standard deviation. For particulates in the nth settling-velocity category, the vertical term is

$$\begin{aligned}
\mathrm{VT}\;(x,z) = \phi_n \Bigg\{ &\sum_{i=0}^{\infty} \Bigg[\delta_n^{i}\,\exp\Bigg[-\frac{1}{2}\left(\frac{2i\;H_m - H + z + V_{sn}\;x/\bar{u}}{\sigma_z} \right)^2 \Bigg] \\
&+ \delta_n^{+1i}\,\exp\Bigg[-\frac{1}{2}\left(\frac{2i\;H_m + H + z - V_{sn}\;x/\bar{u}}{\sigma_z} \right)^2 \Bigg] \Bigg] \\
&+ \sum_{i=1}^{\infty} \Bigg[\delta_n^{i}\,\exp\Bigg[-\frac{1}{2}\left(\frac{2i\;H_m + H - z - V_{sn}\;x/\bar{u}}{\sigma_z} \right)^2 \Bigg] \\
&+ \delta_n^{i-1}\,\exp\Bigg[-\frac{1}{2}\left(\frac{2i\;H_m - H - z + V_{sn}\;x/\bar{u}}{\sigma_z} \right)^2 \Bigg] \Bigg] \Bigg\}
\end{aligned} \tag{2-30}$$

where

ϕ_n = mass fraction of source strength in nth settling-velocity category

V_{sn} = settling velocity of particulates in the nth settling-velocity category ($m\ s^{-1}$) (see Section 2.2.2)

δ_n = surface reflection coefficient for particulates in the nth settling-velocity category (see Section 2.2.3)

For convenience, 0^0 is defined to be unity in Equation (2-30). The total concentration is obtained by summing over the N settling-velocity categories.

OBODM is a surface depletion deposition model that selectively depletes material at the ground rather than through the entire vertical extent of the cloud. Because of the selective depletion at the surface, uniform vertical mixing is never achieved and Equation (2-30) cannot be replaced with the box model of Equation (2-29).

The OBODM lateral term LT and decay term DC are respectively given by

$$LT(x,y) = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad \textbf{(2-31)}$$

and

$$DC(x) = \exp\left[-k\,x/\bar{u}\right] \quad \textbf{(2-32)}$$

where k is the decay coefficient (fraction of the material lost per unit time). For example, if $T_{1/2}$ is the pollutant half life in seconds, k can be obtained from

$$k = \frac{0.693}{T_{1/2}} \quad \textbf{(2-33)}$$

The alongwind term is given by

$$AT(x,t) = \begin{cases} \exp\left[-\frac{1}{2}\left(\frac{x-\bar{u}t}{\sigma_x}\right)^2\right] & ;\ \text{instantaneous source} \\ \frac{1}{2}\left[erf\left(\frac{x-\bar{u}(t-\tau)}{\sqrt{2}\,\sigma_x}\right)-erf\left(\frac{x-\bar{u}t}{\sqrt{2}\,\sigma_x}\right)\right] & ;\ \text{quasi-continuous source} \end{cases} \quad \textbf{(2-34)}$$

where erf is the Gaussian error function. If OBODM is used to calculate concentration time histories at selected (discrete) receptors, concentrations are calculated at each receptor at equal time steps between times t_1 and t_2, which are defined as

$$t_1 = \frac{x - 2.45\,\sigma_x}{\bar{u}} \tag{2-35}$$

$$t_2 = \left\{ \begin{array}{ll} \dfrac{x + 2.45\,\sigma_x}{\bar{u}} & ;\ \text{instantaneous source} \\[2ex] \tau + \dfrac{x + 2.45\,\sigma_x}{\bar{u}} & ;\ \text{quasi-continuous source} \end{array} \right\} \tag{2-36}$$

In addition to calculating the concentration time histories at discrete receptors, OBODM can be directed to calculate peak or maximum time-mean concentrations at all receptors. If peak concentrations are selected, the alongwind term of Equation (2-34) is evaluated at time t_p, defined as

$$t_p = \left\{ \begin{array}{ll} \dfrac{x}{\bar{u}} & ;\ \text{instantaneous source} \\[2ex] \dfrac{x}{\bar{u}} + \dfrac{\tau}{2} & ;\ \text{quasi-continuous source} \end{array} \right\} \tag{2-37}$$

If time-mean concentration is specified, the alongwind term for an instantaneous source is given by

$$\overline{AT(x)} = \left(\frac{\sqrt{2\pi}\ \sigma_x}{\bar{u}\ \tau_A} \right) erf\left(\frac{\bar{u}\ \tau_A}{2\sqrt{2}\ \sigma_x} \right) \tag{2-38}$$

where τ_A is the concentration averaging time. The equation corresponding to Equation (2-38) for a quasi-continuous source is

$$
\begin{aligned}
\overline{\mathrm{AT}(x)} \;=\; & \left(\frac{\sigma_x}{\sqrt{2}\;\bar{u}\;\tau_A} \right) \Bigg\{ - \left[\frac{\bar{u}(\tau - \tau_A)}{\sqrt{2}\;\sigma_x} \operatorname{erf}\left(\frac{\bar{u}\;(\tau - \tau_A)}{2\sqrt{2}\;\sigma_x} \right) \right. \\
& \left. - \frac{\bar{u}(\tau + \tau_A)}{\sqrt{2}\;\sigma_x} \operatorname{erf}\left(\frac{\bar{u}(\tau + \tau_A)}{2\sqrt{2}\;\sigma_x} \right) \right] \Bigg\rangle \\
& - \frac{2}{\sqrt{\pi}} \left[\exp\left(- \left(\frac{\bar{u}(\tau - \tau_A)}{2\sqrt{2}\;\sigma_x} \right)^2 \right) \right. \\
& \left. - \exp\left(- \left(\frac{\bar{u}(\tau + \tau_A)}{2\sqrt{2}\;\sigma_x} \right)^2 \right) \right] \Bigg\}
\end{aligned}
\qquad \textbf{(2-39)}
$$

Note that the use of Equation (2-38) or (2-39) results in a concentration at each receptor that is the mean concentration over an interval of length τ_A centered on the time of the peak concentration at that receptor. These equations can be derived by integrating the generalized concentration equation with respect to time over the limits of $t_p - \tau_A/2$ to $t_p + \tau_A/2$ and dividing by τ_A.

2.4 DOSAGE

2.4.1 Instantaneous Source (Open Detonation)

The OBODM dosage algorithms are also based on conventional steady-state Gaussian dispersion model concepts. The dosage (time-integrated concentration) produced by an instantaneous volume source at downwind distance x, crosswind distance y, and height z above the surface is given by

$$D(x,y,z) \;=\; D_p(x) \bullet VT(x,z) \bullet LT(x,z) \bullet DC(x) \qquad \textbf{(2-40)}$$

where D_p, VT, LT, and DC are the peak dosage, vertical, lateral, and decay terms, respectively. The equations for the vertical, lateral, and decay terms are identical to the equations previously given in Section 2.3. The peak dosage term is

$$D_p(x) \;=\; \frac{K\;Q_e(x)}{2\pi\;\sigma_y\;\;\sigma_z\;\bar{u}} \qquad \textbf{(2-41)}$$

where the terms are also as defined in Section 2.3.

2.4.2 Quasi-Continuous Source (Open Burn)

OBODM computes the dosage produced by a quasi-continuous source by numerical integration of

$$D(x,y,z) = \int_{t_1}^{t_2} \chi(x,y,z,t')dt' \qquad \textbf{(2-42)}$$

where the concentration χ is given by Equation (2-26) and the limits of integration t_1 and t_2 are given by Equations (2-35) and (2-36), respectively.

2.5 DEPOSITION

2.5.1 Gravitational Deposition

Particulates in OB/OD emissions can consist of those contained in the products of combustion (for example, aluminum oxide particulates for some types of solid rocket propellants), soil dust entrained by detonations, and fragments of munition casings. OBODM predicts the gravitational settling and deposition (i.e., fallout) of particulates with appreciable settling velocities using an algorithm of the same type as used by several models including REEDM, RTVSM, and the original ISC. The vertical term of Equation (2-30) accounts for the effects on ambient particulate concentrations of gravitational settling and deposition by: (1) depleting the airborne mass to account for the losses at the surface, and (2) changing the shape of the vertical concentration distribution. If the settling velocities of the particulates are sufficiently small that a fraction of the total mass is initially mixed upward to the top of the surface mixing layer where it is reflected downward, OBODM predicts a secondary maximum in the concentration profile as this fraction reaches the surface. This phenomena can be observed in field experiments with sufficiently small particulates if the measurements extend far enough downwind (see Dumbauld et al., 1976).

The OBODM gravitational deposition algorithm can be derived from Equation (2-26) with the vertical term of Equation (2-30) (see Cramer and Bowers, 1980). For both instantaneous and quasi-continuous sources, deposition at downwind distance x and crosswind distance y for particulates in the nth settling velocity category is given by

$$DEP_n(x,y) = DEP_{np}(x) \bullet VT_{nD} \bullet LT(x) \bullet DC(x) \qquad \textbf{(2-43)}$$

where DEP_{np}, VT_{nD}, LT, and DC are the peak deposition, vertical (deposition), lateral, and decay terms, respectively. The lateral and decay terms are as defined in Section 2.3. The peak deposition term for the nth settling-velocity category is given by

$$DEP_{np}(x) = \frac{K\ Q_e(x)(1 - \delta_n)}{2\pi\ \sigma_y\ \ \sigma_z\ x''} \tag{2-44}$$

$$x'' = x + x_z - x_{rz}(1 - \beta) \tag{2-45}$$

where x_z is the vertical virtual distance, x_{rz} is the rectilinear vertical expansion distance, and β is the vertical expansion coefficient. These three parameters, which are used to calculate the vertical dispersion coefficient σ_z, are discussed in Section 2.6. Note that, except for a source with a very large initial vertical dimension, the x" given by Equation (2-45) is approximately equal to the downwind distance x.

The deposition vertical term for particulates in the nth settling- velocity category is given by

$$VT_{nD}(x) = \phi_n\ \{M + N\} \tag{2-46}$$

where

$$\begin{aligned} M = & \left[\beta H + \left(1 - \frac{\beta x}{x''}\right)\left(\frac{V_{sn}\,x''}{\bar{u}}\right)\right] \\ & \bullet\ \exp\left[-\frac{1}{2}\left(\frac{H - V_{sn}\ x/\bar{u}}{\sigma_z}\right)^2\right] \end{aligned} \tag{2-47}$$

$$\begin{aligned} N = \sum_{i=1}^{\infty} \Bigg\{ & \delta_n^{i-1}\left[\beta(2iH_m - H) - \left(1 - \frac{\beta x}{x''}\right)\left(\frac{v_{sn}\ x''}{\bar{u}}\right)\right] \\ & \bullet\ \exp\left(-\frac{1}{2}\left(\frac{2i\ H_m - H + V_{sn}\ x/\bar{u}}{\sigma_z}\right)^2\right) \\ & + \delta_n^i\left[\beta(2i\,H_m + H) + \left(1 - \frac{\beta x}{x''}\right)\left(\frac{V_{sn}\ x''}{\bar{u}}\right)\right] \\ & \bullet\ \exp\left(-\frac{1}{2}\left(\frac{2i\,H_m + H - V_{sn}\ x/\bar{u}}{\sigma_z}\right)^2\right) \Bigg\} \end{aligned} \tag{2-48}$$

As in the case of Equation (2-30), 0^0 is defined as unity in Equation (2-48). OBODM obtains the total gravitational deposition by summing over the N settling-velocity categories.

2.5.2 Dry Deposition

Gravitational deposition is not the only mechanism by which material from an OB/OD cloud or plume can be transferred to the surface. Small quantities of gases and aerosols that come in contact with the surface can be retained as a result of processes such as absorption, vegetative uptake, and impaction on surface roughness elements. This overall process is usually described as dry deposition. For a short-term release, the total dry deposition at downwind distance x and crosswind distance y is typically estimated from

$$\mathrm{DRY}(x,y) = v_d \bullet D(x,y,0) \qquad \textbf{(2-49)}$$

where D(x,y,0) is the total ground-level dosage at that point and v_d is an empirical or theoretical dry deposition velocity. A summary of empirical deposition velocities for gases and small particles is given by McMahon and Denison (1982).

Gaussian dispersion models that use the deposition velocity parameterization normally use an effective source strength that decreases with downwind distance to account for the losses due to dry deposition. This approach, which reduces concentrations throughout the entire vertical extent of the cloud or plume, is known as source depletion. In contrast, OBODM is a surface depletion model because it removes material just at the surface and not throughout the entire vertical extent of the cloud.

OBODM is not specifically designed to calculate dry deposition, but can nevertheless be used as a screening tool to place an upper bound on dry deposition. The worst-case assumption that can be made for dry deposition is that 100 percent of the pollutant of concern that is mixed to the surface is deposited. The resulting deposition can be obtained from OBODM's gravitational deposition option by assuming a zero settling velocity and zero surface reflection coefficient. (For a gas, the OBODM user must assume monodisperse particulates with a negligible settling velocity and zero reflection coefficient.) A more realistic estimate of maximum possible dry deposition can be obtained from Equation (2-49). That is, the OBODM ground-level dosage predictions can be multiplied by an appropriate deposition velocity to estimate the dry deposition at each receptor. Because this approach effectively assumes that there are no dry deposition losses between the source and each receptor of interest, it provides the dry deposition that would occur if deposition did not begin until each receptor

2.6 DISPERSION COEFFICIENTS, TRANSPORT WIND SPEED, AND INITIAL SOURCE DIMENSIONS

2.6.1 Dispersion Coefficients

OBODM uses semi-empirical Dugway Proving Ground dispersion coefficients which directly relate plume and puff growth to atmospheric turbulence and vertical wind shear. These coefficients are also used in other models such as REEDM, the FSCBG aerial spray model (Teske et al., 1993), and the SHORTZ/LONGZ complex terrain dispersion models (Bjorklund and Bowers, 1982). The lateral (crosswind) dispersion coefficient σ_y and longitudinal (alongwind) dispersion coefficient σ_x are each comprised of atmospheric turbulence and wind shear terms, whereas the vertical dispersion coefficient σ_z is a function of turbulence only.

The OBODM equation for the lateral dispersion coefficient is (Cramer et al., 1972)

$$\sigma_y = \left[\sigma_{yt}^2 + \left(\frac{\Delta\theta' x}{4.3} \right)^2 \right]^{1/2} \qquad \textbf{(2-50)}$$

where σ_{yt} is the turbulence contribution to lateral dispersion and $\Delta\theta'$ is the wind-direction difference in radians between the top and bottom of the plume or cloud. This difference is normally set to zero in hazard analyses to obtain maximum possible predicted downwind impacts. The coefficient 4.3 in Equation (2-50) is the normalized distance between the points on a Gaussian plume at which the concentration is 10 percent of the centerline concentration.

Cramer et al. (1972) derive a generalized equation for σ_{yt} under the assumption that σ_{yt} is directly proportional to the lateral intensity of turbulence and varies linearly with downwind distance x (i.e., $\sigma_{yt} \propto x$) from the origin of an ideal point source to downwind distance x_{ry}, beyond which σ_{yt} varies as x^{α}. After provision for an initial source dimension (i.e., a volume source) by means of a lateral virtual distance, the resulting σ_{yt} equation is

$$\sigma_{yt} = \sigma_A' \; x_{ry} \left[\frac{x + x_y - x_{ry}\,(1-\alpha)}{\alpha\, x_{ry}} \right]^{\alpha} \qquad \textbf{(2-51)}$$

$$x_y = \left\{ \begin{array}{ll} \dfrac{\sigma_{yR}}{\sigma_A{}'} - x_{Ry} & ; \sigma_{yR} \le \sigma_A{}' \; x_{ry} \\ \\ \alpha \, x_{ry} \left(\dfrac{\sigma_{yR}}{\sigma_A{}' \; x_{ry}} \right)^{1/\alpha} - x_{Ry} + x_{ry} \; (1-\alpha) & ; \sigma_{yR} > \sigma_A{}' \; x_{ry} \end{array} \right\} \quad \textbf{(2-52)}$$

where

σ_A' = standard deviation of wind direction angle in radians [depends on source type; see Equation (2-55) below]

x_{ry} = downwind distance from an ideal point source over which rectilinear crosswind expansion occurs (normally assumed to be 50 m)

α = lateral expansion coefficient (normally assumed to be 0.9 for continuous or quasi-continuous sources and 1.0 for instantaneous sources)

x_{Ry} = reference downwind distance at which σ_{yR} is measured (equals zero if σ_{yR} is measured at the origin)

Note that the lateral virtual distance x_y given by Equation (2-52) is not allowed to be less than zero.

The generalized σ_{yt} algorithm given by Equations (2-51) and (2-52) is used for both puff (instantaneous source) and plume (quasi-continuous source) dispersion, but the turbulence inputs and empirical coefficients differ for the two source types. For quasi-continuous sources, the OBODM defaults for the lateral rectilinear expansion distance x_{ry} and lateral expansion coefficient α are 50 m and 0.9, respectively. If these default values are used with the SHORTZ default rural turbulence intensities, the σ_{yt} values predicted by Equations (2-51) and (2-52) for a point source closely match the Pasquill-Gifford σ_y curves (Turner, 1970). For instantaneous sources, the OBODM defaults for x_{ry} and α are 50 m and 1.0, respectively. However, the exact value of x_{ry} is unimportant because Equations (2-51) and (2-52) reduce to

$$\sigma_{yt} = \sigma_{A'}(x + x_y) \quad \textbf{(2-53)}$$

$$x_y = \frac{\sigma_{yR}}{\sigma_{A'}} - x_{Ry} \quad \textbf{(2-54)}$$

Thus, lateral puff expansion (neglecting any shear effects) is normally assumed by OBODM to be rectilinear at all downwind distances. Using the $x = \overline{u}t$ relationship, this model assumption provides a good overall fit to the available lateral puff dispersion data (Gifford, 1995).

As noted above, the magnitude of the σ_A' used to calculate σ_{yt} depends on the source type. OBODM adjusts σ_A' from the measurement time τ_o to averaging time T using the relationship

$$\sigma_{A'}(T) = \sigma_{A'}(\tau_o)\left(\frac{T}{\tau_o}\right)^{0.2} \qquad \textbf{(2-55)}$$

where

$$T = \left\{ \begin{array}{ll} t_S & ;\ \text{instantaneous source} \\ t_S & ;\ \text{quasi - continuous source, } t_S \geq t_B \\ MIN\,(t_B, \tau_A) & ;\ \text{quasi - continuous source, } t_S < t_B \end{array} \right\} \qquad \textbf{(2-56)}$$

and t_S is the cloud stabilization time, t_B is the burn time, and τ_A is the concentration averaging time. The stabilization time t_S is obtained by dividing the distance to final rise x_R (see Section 2.6.3) by the mean wind speed u. Note that T is not allowed to be less than 2.5 s. The $t^{0.2}$ time dependence of Equation (2-55) has been suggested by numerous authors (for example, see Slade, 1968; Osipov, 1972; and Wilson and Du, 1995) to account for the averaging time variation of σ_y. See Barr and Clements (1984) for a further discussion of the rationale for the use of Equation (2-55).

The OBODM algorithm for the vertical dispersion coefficient σ_z is given by Equations (2-51) and (2-52) with σ_E' (the standard deviation of the wind elevation angle in radians) substituted for σ_A', z substituted for y in the subscripts, and β substituted for α. For both instantaneous and quasi-continuous sources, the model defaults for the vertical rectilinear expansion distance x_{rz} and vertical expansion coefficient β are 50 m and 1.0, respectively. Thus, the OBODM default values assume rectilinear expansion analogous to that of Equations (2-53) and (2-54) at all downwind distances for all stabilities. Analyses of Army field test data (for example, Cramer et al., 1972) suggest that β can be approximated as unity for all stabilities for elevated releases, but depends on stability for near-surface releases. Also, it should be recognized that the restriction on mixing at the top of the surface mixing layer [accounted for by the multiple reflection terms of Equation (2-28) or (2-30)] causes the effective rate of vertical expansion to decrease with distance as the cloud or plume begins to fill the mixing layer. OBODM does not make any averaging time adjustments to σ_E'. However, when Equation (2-55) is used to adjust σ_A' to short averaging times, the model does not allow σ_A'(T) to be less than σ_E'.

The OBODM algorithms for the dispersion and deposition of particles with appreciable gravitational settling velocities assume that the particles follow ballistic trajectories that are modified by atmospheric turbulence. As the settling velocities of particles increase, the perturbations of their trajectories by atmospheric turbulence are decreased. OBODM accounts for this effect by reducing σ_A' and σ_E' using a method based on the suggestions of Csanady (1963, 1967). The effective turbulence inputs used in the σ_{yt} and σ_z algorithms for the nth settling-velocity category are

$$\sigma'_{An}\,(eff) = \left\{ \begin{array}{ll} \sigma'_A\,(T) & ; \quad \dfrac{V_{sn}}{\sigma'_E\,\bar{u}} \leq 0.24 \\[2ex] \dfrac{\sigma'_A\,(T)}{\left[1 + 4\left(\dfrac{\beta_1\, v_{sn}}{\sigma'_E\,\bar{u}}\right)^2\right]^{1/4}} & ; \quad \dfrac{v_{sn}}{\sigma'_e\,\bar{u}} > 0.24 \end{array} \right\} \tag{2-57}$$

$$\sigma'_{En}\,(eff) = \left\{ \begin{array}{ll} \sigma'_E & ; \quad \dfrac{V_{sn}}{\sigma'_E\,\bar{u}} \leq 0.24 \\[2ex] \dfrac{\sigma'_E}{\left[1 + 4\left(\dfrac{\beta_1\, v_{sn}}{\sigma'_E\,\bar{u}}\right)^2\right]^{1/4}} & ; \quad \dfrac{v_{sn}}{\sigma'_e\,\bar{u}} > 0.24 \end{array} \right\} \tag{2-58}$$

where β_1 is the ratio of the Lagrangian and Eulerian time scales. Analyses of Dugway Proving Ground field tests in which large drops were disseminated (Dumbauld and Rafferty, 1979) have found that the Dugway gravitational depo-sition algorithm when used with Equations (2-57) and (2-58) closely reproduces the observed deposition patterns if β_1 is assumed to be unity. Although the OBODM default for β_1 is unity, other values may be entered. If β_1 is entered as zero, OBODM does not use the crossing-trajectories correction.

OBODM computes the longitudinal dispersion coefficient σ_x using the generalized equation (Dumbauld and Bowers, 1983)

$$\sigma_x = \left[\sigma_{xt}^2 + \sigma_{xs}^2 \right]^{1/2} \qquad \textbf{(2-59)}$$

$$\sigma_{xt} = aI_x(x + x_x) \qquad \textbf{(2-60)}$$

$$x_x = \left(\frac{\sigma_{xR}}{aI_x} \right)^{1/b} - x_{Rx} \qquad \textbf{(2-61)}$$

$$\sigma_{xs} = E_s \left(\frac{\Delta u}{\bar{u}} \right) x \qquad \textbf{(2-62)}$$

where

I_x = longitudinal intensity of turbulence, adjusted to time T using Equation (2-55)

a,b, and E_s = empirical constants

σ_{xR} = standard deviation of the alongwind concentration distribution at downwind distance x_{Rx} (m)

Δu = wind-speed difference through the layer containing the cloud (m s^{-1}); see Section 2.6.2 for the Δu equation

and the other terms are as defined above. (Note that the longitudinal virtual distance x_x is not allowed to be less than zero.)

In the absence of user-specified I_x values, OBODM uses the Dumbauld and Bowers (1983) suggestion that

$$I_x \approx 1.33 I_y \approx 1.33 \sigma_{A'} \qquad \textbf{(2-63)}$$

where I_y is the lateral turbulence intensity. The averaging time adjustment of Equation (2-55) is applied to I_x with T equal to the stabilization time for a buoyant source and 2.5 s for a nonbuoyant source. The crossing-trajectories correction of Equation (2-57) is also applied to I_x. Under the assumption that the coefficients a and b are both unity, Dumbauld and Bowers (1983) used the Nickola (1971) data to estimate that E_s is approximately 0.06.

2.6.2 Wind-Speed Profile and Transport Wind Speed

OBODM assumes that the height variation of wind speed within the surface mixing layer can be described by the power-law profile

$$u(z) \ = \ u(z_R) \left(\frac{z}{z_R} \right)^p \qquad \textbf{(2-64)}$$

where

$u(z)$ = wind speed at height z above the surface

$u(z_R)$ = wind speed at height z_R above the surface

p = wind-profile exponent

The typical (and default) wind measurement height z_R is 10 m.

It follows from Equation (2-64) that the wind-speed difference Δu required by Equation (2-62) is

$$\Delta u \ = \ \frac{u(z_R)}{(z_R)^p} \ [z_2^p \ - \ z_1^p] \qquad \textbf{(2-65)}$$

where z_1 and z_2 are the heights of the cloud bottom and top, respectively. The bottom of the cloud z_1 is defined as

$$z_1 \ = \left\{ \begin{array}{ll} H(x) - 2.15\ \sigma_z\,(x) & ;\ H - 2.15\ \sigma_z > 2\ m \\ \ 2 & ;\ H - 2.15\ \sigma_z \leq 2\ m \end{array} \right\} \qquad \textbf{(2-66)}$$

Similarly, the top of the cloud z_2 is defined as

$$z_2 \ = \left\{ \begin{array}{ll} H(x) + 2.15\ \sigma_z\,(x) & ;\ H + 2.15\ \sigma_z < H_m \\ H_m & ;\ H + 2.15\ \sigma_z \geq H_m \end{array} \right\} \qquad \textbf{(2-67)}$$

OBODM assumes that the mean transport wind speed is given by

$$\bar{u} \ = \ \left(\frac{1}{z_2 \ - \ z_2} \right) \int_{z_1}^{z_2} u(z)dz \qquad \textbf{(2-68)}$$

If Equation (2-64) is entered in Equation (2-68), the resulting expression for the transport wind speed is

$$\bar{u} = \frac{u(z_R)\,[z_2^{(1+p)} - z_1^{(1+p)}]}{(z_2 - z_1)\, z_R^p\, (1+p)} \tag{2-69}$$

2.6.3 Buoyant Source Dimensions

Observations of the buoyant rise of stack plumes (for example, Briggs, 1971) show that the visible radius of the rising plume can be approximated by

$$r(x) = \gamma_c \Delta h_c(x) \tag{2-70}$$

where Δh_c is the stable or adiabatic plume rise for a continuous source, depending on the thermal stratification. If this result is generalized to the case of a source with a large initial horizontal radius r_R, Equation (2-70) becomes

$$r(x) = \gamma_c \Delta h_c(x) + r_R \tag{2-71}$$

OBODM sets r_R equal to the radius of a circle with the same horizontal area as the material to be burned. Under the assumption of a bivariate Gaussian distribution, the lateral and vertical concentration (and dosage) standard deviations at the downwind distance x_R of plume stabilization are

$$\sigma_{yR} = \sigma_{zR} = \frac{\gamma_c \Delta h_c(x_R) + r_R}{2.15} \tag{2-72}$$

As indicated by Equation (2-1) and Equations (2-4) through (2-6), the downwind distance to plume stabilization is given by

$$x_R = \begin{Bmatrix} \pi\, u\, S^{-1/2} & ; \ \partial\theta / \partial z > 0 \\ 3.5\, x^* & ; \ \partial\theta / \partial z \le 0 \end{Bmatrix} \tag{2-73}$$

For consistency with the plume rise calculations, x_R is never allowed to exceed 3.5x*. At downwind distances less than x_R, σ_{yR} and σ_{zR} are given by Equation (2-72) with Δh_c evaluated at x rather than x_R.

Source dimensions are defined for an instantaneous source in the same manner as for a continuous source except that there is a third degree of freedom, the alongwind dimension. Thus, cloud dimensions at the downwind distance of stabilization are defined by

$$\sigma_{xR} = \sigma_{yR} = \sigma_{zR} = \frac{\gamma_I \Delta h_I (x_R) + r_R}{2.15} \tag{2-74}$$

where x_R is given by Equation (2-73) with x_{max} [from Equation (2-11)] substituted for 3.5x* in the second line. [If Equation (2-7) is used to calculate final cloud rise with an adiabatic or unstable thermal stratification, x_R is given by the top line of Equation (2-73) with the stability parameter S obtained using a potential temperature gradient of 3.344 x 10^{-4} K m^{-1}.] At downwind distances less than x_R, σ_{xR} is set equal to the value given by Equation (2-74) with Δh_I evaluated at x rather than x_R. Using the approximation that the average temperature of the initial buoyant cloud produced by a detonation is $1.44T_a$ (Hoock et al., 1987), OBODM computes r_R from

$$r_R = 0.89 \left(\frac{3 \; H_c \; W_D}{4\pi \; c_p \; \rho_a \; T_a} \right)^{1/3} \tag{2-75}$$

where

H_c = material effective heat content (cal g^{-1})

W_D = quantity of material detonated (g)

c_p = specific heat of air at constant pressure (0.24 cal g^{-1} K^{-1})

ρ_a = air density (g m^{-3})

T_a = air temperature (K)

If the release height h is entered as zero for a detonation, OBODM sets it equal to r_R.

2.6.4 Nonbuoyant Source Dimensions

In the case of a single nonbuoyant volume source, the initial standard deviations of the horizontal concentration distributions are given by

$$\sigma_{xo} = \frac{[W \sin b + L \cos b]}{4.3} \tag{2-76}$$

$$\sigma_{yo} = \frac{[W \cos b + L \sin b]}{4.3} \qquad \textbf{(2-77)}$$

where W is the width of the short side, L is the length of the long side, and b is the minimum angle between the wind vector and the long side. The initial standard deviation of the vertical concentration distribution σ_{zo} is given by the source's actual depth or vertical dimension divided by 2.15 for a surface-based (h=0) source and by 4.3 for an elevated (h>0) source.

As noted in Section 1, OBODM represents a line source by a series of overlapping volume sources. The number of volume sources used to represent a line source is given by the line's length L divided by its width W, rounded up to the nearest integer. For each volume source used to represent a line source, σ_{xo} is given by Equation (2-76) with L replaced by W, while σ_{yo} is given by Equation (2-77) with L replaced by W and 4.3 replaced by 2.3548. The initial standard deviation of the vertical concentration distribution is defined in the same manner as for a volume source.

2.7 COMPLEX TERRAIN SCREENING PROCEDURES

OBODM uses complex terrain screening procedures that are based on the procedures used by the SHORTZ/LONGZ complex terrain dispersion models (Bjorklund and Bowers, 1982). Although these procedures have been used with some success in modeling industrial stack emissions in complex terrain (for example, Cramer et al., 1975), they are likely to overestimate the ground-level impacts of OB/OD releases in many situations. The OBODM complex terrain procedures also do not address the buildup of OB/OD emissions that may become trapped within deep valleys during air stagnation episodes.

When OBODM is applied in complex terrain, the receptor height z above ground level must be zero, and the model cannot be used to calculate concentration, dosage, or deposition for particulates with appreciable settling velocities because the assumptions upon which Equations (2-30), (2-43), (2-44), and (2-46) through (2-48) are based are violated. The OBODM complex terrain procedures modify the flat terrain model methodologies described in the preceding sections by defining effective cloud or plume heights and mixing depths. The following assumptions are made in complex terrain:

a. The actual top of the surface mixing layer extends over the calculation grid at a constant height above mean sea level. The **actual** top of the surface mixing layer should not be confused with the **effective** top of the surface mixing layer, which is a mathematical device used to preclude violations of the Second Law of Thermodynamics when clouds or plumes pass over elevated terrain.

b. The centroid of a cloud or axis of a plume contained within the surface mixing layer remains at the stabilization height above mean sea level, and the cloud or plume may impact elevated terrain under stable, neutral, or unstable conditions.

c. Clouds or plumes that stabilize above the top of the surface mixing layer do not contribute to significant ground-level concentrations at any receptor, including receptors that are above the top of the surface mixing layer.

The OBODM transitional (distance-dependent) plume/cloud rise algorithms are not used in complex terrain. That is, the final plume/cloud rise is assumed to apply at all downwind distances, including distances less than the distance to plume/cloud stabilization. The height H_o above mean sea level of the axis of a stabilized plume or centroid of a stabilized cloud is given by the sum of the height H above ground level of the stabilized plume or cloud and the elevation z_s above mean sea level of the OB/OD source.

In order to determine the fraction of the plume or cloud that is contained within the surface mixing layer, the mixing depth H_{ms} at the source is substituted for H_m in Equation (2-14). The mixing depth at the source is given by

$$H_{ms} = H_{ma} + z_a - z_s \qquad \textbf{(2-78)}$$

where H_{ma} is the mixing depth measured at a point with elevation z_a above mean sea level. Note that H_{ms} is also used in Equation (2-16) to determine the effective plume or cloud rise for the material in the surface mixing layer.

The effective height of the cloud centroid or plume axis above a receptor with elevation z_r above mean sea level is defined as

$$H'(z_r) = \begin{Bmatrix} H_o - z_r & ; & H_o - z_r \geq 0 \\ 0 & ; & H_o - z_r < 0 \end{Bmatrix} \qquad \textbf{(2-79)}$$

The effective height $H'(z_r)$ is substituted for H in the vertical term of Equation (2-30). The effective mixing depth above the same receptor is given by

$$H'_m(z_r) = \begin{Bmatrix} H_{ma} & ; \; z_r \geq z_a \\ H_{ma} + z_a - z_r & ; \; z_r < z_a \end{Bmatrix} \qquad \textbf{(2-80)}$$

The SHORTZ/LONGZ models allow the user to assume that the wind speed is a function of height above the ground surface or height above mean sea level. Rather than allow this user choice, OBODM always assumes that the wind speed is a function of the height above the local ground level. The wind profile and transport wind speed equations in Section 2.6.2 are used without modification except that H_{ma} is substituted for H_m in the definition of z_2 in Equation (2-67).

SECTION 3. DEFAULT METEOROLOGICAL INPUTS

The minimum OBODM meteorological inputs consist of the wind speed and wind direction at 10 m above the surface, the air temperature, and either the Pasquill stability category or the Net Radiation Index (NRI). With this minimum information, the program will provide default values for all other meteorological inputs. However, the user is encouraged to use measured or site-specific climatological values whenever available.

Table 2 summarizes the meteorological conditions represented by the Pasquill stability categories. As shown by Table 3, Turner (1964) defines each Pasquill stability category by the combination of the 10-m wind speed and NRI. Table 4 lists the steps used to estimate the NRI from the solar altitude angle and standard surface observations of cloud cover and ceiling height. The OBODM default meteorological inputs are assigned based on the combination of the 10-m wind speed and NRI. If the Pasquill stability category rather than the NRI (or the information needed to compute the NRI) is entered, OBODM uses Table 5 to estimate the NRI.

Table 2. Meteorological Conditions Represented by the Pasquill Stability Categories.

Pasquill Stability Category	Meteorological Conditions
A	Very Unstable
B	Unstable
C	Slightly Unstable
D	Neutral
E	Stable
F	Very Stable

Table 3. Pasquill Stability Categories as a Function of Wind Speed and Net Radiation Index (Turner, 1964).

Wind Speed	Net Radiation Index						
at 10 m [a] (kt)	4	3	2	1	0	-1	-2
0,1	A	A	B	C	D	E	F
2,3	A	B	B	C	D	F	F
4,5	A	B	C	D	D	E	F
6	B	B	C	D	D	E	F
7	B	B	C	D	D	D	E
8,9	B	C	C	D	D	D	E
10	C	C	D	D	D	D	E
11	C	C	D	D	D	D	D
ł12	C	D	D	D	D	D	D

[a] The Turner (1964) scheme uses wind speeds in knots (1 kt = 0.514 m/s).

Table 4. Procedures Used to Calculate Net Radiation Indices from Cloud Cover and Ceiling Observations and the Solar Altitude.

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1. If the total cloud cover is 10/10 (overcast) and the cloud ceiling is less than 2134 m (7000 ft), the net radiation index (NRI) is 0 (whether day or night).

2. For night (between sunset and sunrise):

   (a) If the total cloud cover is less than or equal to 4/10, use NRI equal to -2.

   (b) If the total cloud cover is greater than 4/10, use NRI equal to -1.

3. For daytime:

   (a) Determine the insolation class number from the solar altitude (a) as follows:

SOLAR ALTITUDE (deg)	INSOLATION CLASS NUMBER
$a > 60$	4
$60 \geq a > 35$	3
$35 \geq a > 15$	2
$15 \geq a$	1

   (b) If the total cloud cover is less than or equal to 5/10, the NRI is equal to the insolation class number.

   (c) If the total cloud cover is greater than 5/10, the NRI is equal to the insolation class number modified using the following five steps:

      (i) If the ceiling is less than 2134 m (7000 ft), subtract 2.

      (ii) If the ceiling is greater than or equal to 2134 m (7000 ft) but less than 4877 m (16,000 ft), subtract 1.

      (iii) If the total cloud cover equals 10/10, subtract 1. (This will only apply to ceilings greater than 2134 m (7000 ft) since cases with 10/10 coverage below 2134 m are considered in item 1 above.)

      (iv) If the insolation class number has not been modified by steps (I), (ii), or (iii) above, assume the NRI is equal to the insolation class number.

      (v) If the modified insolation class number is less than 1, let the NRI equal 1.

Table 5. Net Radiation Index as a Function of Pasquill Stability Category and Wind Speed.

Pasquill Stability Category	10-m wind Speed (kt)								
	0-1	>1-3	>3-5	>5-6	>6-7	>7-9	>9-10	>10-11	>11
A	4	4	4	4	4	4	4	4	4
B	2	3	3	3	3	4	4	4	4
C	1	1	2	2	2	3	4	4	4
D	0	0	1	1	0	0	0	0	0
E	-2	-2	-1	-1	0	0	0	0	0
F	-2	-2	-2	-2	-1	-1	-1	0	0

Table 6. Default Standard Deviations of the Wind Direction Angle in Degrees Measured Over 600 s at a Height of 10 m Above Open Terrain (Dumbauld and Bowers 1983).

Wind Speed (m/s)	Net Radiation Index					
	4	3	2	1	0	-1, -2
0 – 1	26.0	22.0	21.0	15.0	11.0	4.0
>1 – 3	22.0	20.0	16.0	11.0	10.0	4.0
>3 – 5	19.0	16.0	13.0	11.0	9.0	7.0
>5 – 7	15.0	13.0	12.0	9.0	8.0	6.7
>7	13.0	12.0	10.0	8.0	7.0	6.7

Table 7. Default Standard Deviations of the Wind Elevation Angle in Degrees at 10 m Above Open Terrain (Dumbauld and Bowers, 1983).

10-m Wind Speed (m/s)	Net Radiation Index					
	4	3	2	1	0	-1,-2
0 - 1	8.7	8.7	7.0	5.0	4.0	3.0
>1 - 3	7.0	7.0	6.0	4.0	3.5	3.0
>3 - 5	7.0	6.0	5.5	5.3	5.0	5.0
>5 - 7	6.0	5.3	5.0	4.8	4.8	4.7

>7	5.3	5.0	4.5	4.5	4.5	4.5

The OBODM turbulence inputs consist of the standard deviations of the wind direction and elevation angles and the longitudinal turbulence intensity. (The standard deviations of the wind direction and elevation angles in radians are respectively equivalent to the lateral and vertical turbulence intensities.) The default values for the standard deviations of the wind direction and elevation angles are listed in Tables 6 and 7, respectively. These values, which are intended to be representative of measurements made at 10 m above a surface with a roughness length z_o of about 10 cm, were adapted by Dumbauld and Bowers (1983) from the values suggested by Dumbauld (1982). The Dumbauld (1982) turbulence intensities, which are for a measurement height of 5 m above open terrain, were based on analyses of turbulence measurements at White Sands Missile Range, New Mexico (Swanson and Cramer, 1965); Round Hill, Massachusetts (Cramer et al., 1966); and Dugway Proving Ground, Utah (Cramer et al., 1972). Dumbauld (1982) also considered the turbulence profiles shown by Lumley and Panofsky (1964) in arriving at his recommended values. The OBODM default longitudinal turbulence intensities are 1.33 times the wind direction standard deviations in Table 6 (Counihan, 1975). If the user enters the standard deviation of the wind direction, but not the longitudinal turbulence intensity, OBODM sets the longitudinal turbulence intensity equal to 1.33 times the user-specified wind direction standard deviation.

OBODM does not make any height adjustments to the default turbulence inputs in Tables 6 and 7. However, the program makes surface roughness adjustments if the user enters a nonzero roughness length z_o. The roughness adjustment is

$$\sigma_A(z_o) = \sigma_A \ (Table\ 6) \left(\frac{z_o}{10}\right)^{0.2} \qquad \textbf{(3-1)}$$

$$\sigma_E(z_o) = \sigma_E \ (Table\ 7) \left(\frac{z_o}{10}\right)^{0.2} \qquad \textbf{(3-2)}$$

where z_o is in centimeters and σ_A and σ_E are the standard deviations of the wind direction (azimuth) and elevation angles, respectively. Equations (3-1) and (3-2) are taken from Hanna et al. (1977).

Table 8 gives the OBODM default wind-profile (power law) exponents. These exponents were adapted by Dumbauld and Bowers (1983) from the coefficients suggested by Dumbauld (1982), which were based on analyses of wind speed profiles at White Sands Missile Range and Dugway Proving Ground.

Table 8. Default Wind Speed Power Law Exponents Over Open Terrain (Dumbauld and Bowers, 1983).

10-m Wind Speed (m/s)	Net Radiation Index					
	4	3	2	1	0	-1,-2
0 - 1	0.10	0.10	0.20	0.20	0.25	0.40
>1 - 3	0.10	0.10	0.20	0.20	0.25	0.30
>3 - 5	0.10	0.10	0.15	0.15	0.20	0.25
>5 - 7	0.10	0.10	0.10	0.10	0.10	0.20
>7	0.10	0.10	0.10	0.10	0.10	0.10

Table 9. Default Vertical Potential Temperature Gradients in Degrees Kelvin Per Meter (Bjorklund and Bowers, 1982).

10-m Wind Speed (m/s)	Pasquill Stability Category					
	A	B	C	D	E	F
			Relative Humidity >70%			
0 - 1	0.000	0.000	0.000	0.015	0.030	0.035
>1 - 3	0.000	0.000	0.000	0.010	0.020	0.025
>3 - 5	0.000	0.000	0.000	0.005	0.015	0.015
>5 - 7	0.000	0.000	0.000	0.003	0.010	0.010
>7	0.000	0.000	0.000	0.003	0.003	0.003
			Relative Humidity ≤ 70%			
0 - 1	0.000	0.000	0.000	0.020	0.030	0.040
>1 - 3	0.000	0.000	0.000	0.010	0.020	0.030
>3 - 5	0.000	0.000	0.000	0.005	0.010	0.020
>5 - 7	0.000	0.000	0.000	0.000	0.005	0.010
>7	0.000	0.000	0.000	0.000	0.000	0.005

Table 10. Default Surface Mixing Layer Depths in Meters for Open Terrain (Dumbauld and Bowers, 1983).

10-m Wind Speed (m/s)	Net Radiation Index 4	3	2	1	0	-1,-2
0 - 1	2500	2000	1000	500	100	30
>1 - 3	2200	1800	1200	600	200	100
>3 - 5	1800	1500	1200	600	300	200
>5 - 7	1500	1200	1000	600	300	200
>7	1200	1000	700	500	300	200

The OBODM default vertical potential temperature gradients and mixing layer depth are listed in Tables 9 and 10, respectively. The potential temperature gradients in Table 9 are the default inputs used by the SHORTZ and LONGZ diffusion models (Bjorklund and Bowers, 1982). The potential temperature gradients for high relative humidities are principally taken from a modeling study of sulfur dioxide (SO_2) air quality in Allegheny County, Pennsylvania (Cramer et al., 1975). The potential temperature gradients for the lower relative humidities are principally based on measurements made at Dugway Proving Ground. The mixing depths in Table 10, which are taken from Dumbauld and Bowers (1983), are generally representative of noncoastal regions in the western United States (for example, see Holzworth, 1972).

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SECTION 4. EMISSIONS FACTOR DATABASE

The OBODFUEL.OBD file contains a database of source information required by OBODM for 36 propellant, explosive, and pyrotechnic energetic fuels/ materials. For each fuel/material, the file contains a list of gases, volatile organic compounds, semivolatile organic compounds, and metals produced by open burning or open detonation. For each gas, compound, or metal, the file provides the molecular weight, density at 1 atmosphere and 20 °C, and emissions factor. As discussed below, the emissions factors were derived from OBOD experiments conducted at U.S. Army Dugway Proving Ground. The OBODM user can modify the OBODFUEL.OBD database file by entering updated emissions data or emissions data for new fuels or materials.

The emissions factors in the OBODFUEL.OBD file were developed from the emissions data in the 1997 OBOD Database Lite V1.2 program. The majority of the information in the 1997 Database Lite V1.2 comes from experiments in Dugway's BangBox™ facility in which small amounts of the fuel or material were burned or detonated, and the resulting gases, compounds, and metals were sampled and assayed to quantify the emissions. Limited data were also obtained from aircraft sampling of open air OBOD events during earlier OBOD programs at Dugway. Depending on the fuel/material and combustion product, the 1997 OBOD Database Lite V1.2 contains emissions factors for one to three trials. If emissions factors are available for only one trial, those emissions factors are provided in the OBODFUEL.OBD file. If emissions factors are available for two trials, OBODFUEL. OBD contains the highest emissions factor for each gas, compound, or metallic element as a safe-sided, "worst-case" estimate. If emissions factors are available for three trials, OBODFUEL.OBD contains the average emission factor for each combustion product. In some cases, two different sampling techniques were used for the same constituent. In these cases, OBODFUEL.OBD provides the highest of the average emissions factors obtained for that constituent using the two sampling methods. If a gas, compound, or metal was below the detection limit for all trials, that constituent is not included in the model database file.

The format of the OBODFUEL.OBD file is the MS-DOS text mode. The first line for each of the 36 propellant, explosive, and pyrotechnic energetic fuels and materials contains the name of the fuel/material, the estimated heat content and burn rate, and the number (N) of combustion products for which emissions data are provided. This line is followed by N lines, each listing the molecular weight, density, and emissions factors for one of the N products of combustion. Thus, OBODFUEL.OBD contains N+1 lines per propellant, explosive, or pyrotechnic energetic fuel or material. The effective heat contents and burn rates are not known for many materials. For those fuel/materials with unknown heat contents, OBODFUEL.OBD assigns a value of 1000 cal/g. This value should underestimate the actual heat release and buoyant rise for most fuels/materials, resulting in a tendency toward overestimation of maximum ground-level impacts. No burn rates are provided if the burn rate is not known. Also, in some cases the molecular weight and/or density could not be found and are not provided.

SECTION 5. APPENDICES

APPENDIX A. DERIVATION OF EQUATION (2-11)

Briggs (1970) assumes that only eddies with sizes on the same order as the plume radius are effective in mixing ambient air into the plume. These eddies are in the inertial subrange, which can be characterized by the eddy dissipation rate ε. For eddies on the order of the plume radius r, Briggs assumes that

$$\frac{dr}{dt} = \beta\, \varepsilon^{1/3}\ r^{1/3} \qquad \textbf{(A-1)}$$

where β is a dimensionless constant.

The closure assumption used by Briggs is

$$r = \gamma z \qquad \textbf{(A-2)}$$

where γ is the entrainment coefficient and z is the plume height, which is given by Briggs' equation for the rise of a buoyant plume in an adiabatic atmospheric. It follows from Equation (A-2) that

$$\frac{dr}{dt} = \gamma \frac{dz}{dt} = \gamma w \qquad \textbf{(A-3)}$$

where w is the plume's vertical velocity. Briggs combines Equations (A-1) and (A-3) and solves for the distance x* at which

$$\frac{dr}{dt} = \gamma w = \beta \varepsilon^{1/3}\ r^{1/3} \qquad \textbf{(A-4)}$$

This distance is given by

$$x^* = \left(\frac{2}{3}\right)^{7/5} (F\gamma)^{2/5}\ u^{3/5}\ (\beta \varepsilon^{1/3})^{-9/5} \qquad \textbf{(A-5)}$$

where F is the plume's buoyancy flux. Briggs then reasons that maximum or final plume rise is attained at 3.5 x*.

Equation (A-4) also forms the basis for estimating the distance to final rise for a buoyant cloud in an adiabatic or unstable atmosphere. Neglecting the initial radius r_R, Dumbauld et al. (1973) give the cloud height at downwind distance x in an adiabatic atmosphere as

$$Z_i = \left[\frac{2\ F_I\ x^2}{\gamma_I^3\ u^2} \right]^{1/4} \qquad \textbf{(A-6)}$$

where F_I is the cloud's buoyancy flux and u is the mean wind speed. The closure assumption of Equation (A-2) then gives

$$r = \gamma_I\ z_I = \left[\frac{2F_I\ \gamma_I\ x^2}{u^2} \right]^{1/4} \qquad \textbf{(A-7)}$$

The vertical velocity w and wind speed u are related by

$$\mathrm{w} = \frac{dx}{dt}\ \frac{dz_I}{dx} = u\ \frac{dz_I}{dx} \qquad \textbf{(A-8)}$$

Combination of Equations (A-6) and (A-8) yields

$$\mathrm{w} = \left[\frac{F_I\ u^2}{(2\gamma_I)^3} \right]^{1/4} x^{-1/2} \qquad \textbf{(A-9)}$$

Consequently,

$$\gamma_I \mathrm{w} = \left[\frac{F_I\ \gamma_I\ u^2}{8\mathrm{x}^2} \right]^{1/4} \qquad \textbf{(A-10)}$$

If Equations (A-7) and (A-10) are substituted into Equation (A-4), the resulting distance is

$$\mathrm{x}_* = \left[\beta \varepsilon^{1/3} \right]^{-3/2} \left(\frac{1}{2} \right)^{5/4} \left(F_I\ \gamma_I \right)^{1/4} u \qquad \textbf{(A-11)}$$

Use of Equation (A-11) to determine the downwind distance of final cloud rise 3.5x* requires estimates of β and γ. Following Briggs (1970), β is conservatively estimated as unity and ε is assumed to be given by

$$\varepsilon = \begin{cases} 0.068\ u / z & ; \ z \leq 100\ m \\ 0.00068\ u & ; \ z > 100\ m \end{cases} \qquad \textbf{(A-12)}$$

where z is height above the ground. For γ_I equal to 0.64 and z equal to z_I and less than or equal to 100 m, substitution of Equation (A-12) into Equation (A-11) gives the distance to final cloud rise as

$$3.5\ \mathrm{x}{*} = 5\ z_I^{1/2}\ F_I^{1/4}\ u^{1/2} \qquad \textbf{(A-13)}$$

If Equations (A-6) and (A-13) are combined and solved for z_I, the predicted final rise is

$$z_I\ (3.5x{*}) = \left[\frac{50\ F_I^{3/2}}{\gamma_I^3\ u}\right]^{1/3} \qquad \textbf{(A-14)}$$

Comparison of Equations (A-6) and (A-14) shows that Equations (A-14) can be rewritten as

$$z_I\ (\mathrm{x}_{\max}) = \left[\frac{2\ F_I\ x_{\max}^2}{\gamma_I^3\ u^2}\right]^{1/4} \qquad \textbf{(A-15)}$$

where

$$\mathrm{x}_{\max} = 12\ F^{1/2}\ u^{1/3} \qquad \textbf{(A-16)}$$

As indicated by Equation (A-12), Equations (A-15) and (A-16) are not valid for cloud rises above 100 m. If the left-hand side of Equation (A-14) is set equal to 100 m and γ_I is set equal to 0.64, the resulting range of applicability of Equations (A-15) and (A-16) is

$$F_I\ \leq\ 300\ u^{2/3} \qquad \textbf{(A-17)}$$

For larger values of F_I, the second line of Equation (A-12) should be used in Equation (A-11). The resulting distance to final cloud rise is

$$3.5\ \mathrm{x}{*}\ =\ 50\ F_I^{1/4}\ u^{1/2} \qquad \textbf{(A-18)}$$

The generalized cloud rise equations under adiabatic or unstable conditions then become

$$\Delta h\ =\ \left[\frac{2\ F_I\ x^{2'}}{\gamma_I^3\ u^2}\right]^{1/4} \qquad \textbf{(A-19)}$$

$$x' = \begin{Bmatrix} x & ; \ x \le x_{\max} \\ x_{\max} & ; \ x > x_{\max} \end{Bmatrix} \tag{A-20}$$

$$x_{\max} = \begin{Bmatrix} 12\ F_I^{1/2}\ u^{1/3} & ; \ F_I \le 300\ u^{2/3} \\ 50\ F_I^{1/4}\ u^{1/2} & ; \ F_I > 300\ u^{2/3} \end{Bmatrix} \tag{A-21}$$

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