11 SPECIAL APPLICATIONS OF AIR POLLUTION MODELS

This chapter presents some discussion of special applications of air pollution models:

- complex (rough) terrain problems
- coastal diffusion
- diffusion around buildings
- gravitational settling
- heavy gas dispersion
- cooling tower plumes
- source emission modeling of accidental spills
- indoor air pollution
- regulatory modeling

11.1 COMPLEX (ROUGH) TERRAIN

Dispersion in complex terrain is still poorly understood, even though recent dispersion experiments and studies, such as the U.S. EPA Complex Terrain Model Development Project, have allowed important parameterizations of simplified cases (e.g., dispersion near an isolated small hill and possible plume impact on it). The three major problems in complex terrain applications are

1. The correct evaluation of the trajectory of plume centerline and, in particular, its possible impact upon the elevated terrain.
2. The computation of the enhancement of plume dispersion (both in the horizontal and the vertical) caused by the extra turbulence induced by the complexity of the terrain features.
3. The determination of possible effects caused by streamlines dividing around the terrain obstacles.

An overview of complex terrain modeling is given by Egan (1984), Egan and Schiermeier (1986), and Venkatram (Venkatram and Wyngaard, 1988).

Many studies (Sacre, 1979; Mason and Sykes, 1979; Hunt et al., 1979; Britter et al., 1981; Taylor and Walmsley, 1981; Jenkins et al., 1981; Ryan and Lamb, 1984) have focused on the "small hill" case. Snyder (1985) has reviewed pollutant transport and diffusion in stable, stratified flow. A report on air flow and dispersion in rough terrain has also been provided by Hunt et al. (1984).

In the simplified case of plume dispersion near a small hill, Hunt et al. (1979) demonstrated experimentally the existence of a critical height H_c

$$H_c = H_h\,(1 - Fr) \tag{11-1}$$

where H_h is the hill height and Fr is the Froude number. Equation 11-1 is derived under the simplifying assumptions of strongly stable atmosphere, constant density gradient and uniform velocity profile, and gives an estimate of H_c, which is the height that separates the streamlines that can pass over the crest of the hill and those that cannot. The Froude number is defined as

$$Fr = \frac{u}{N H_h} \tag{11-2}$$

where u is the characteristic wind speed, N is the Brunt–Vaisala frequency

$$N = \left(-\frac{g}{\varrho}\frac{\partial \varrho}{\partial z}\right)^{1/2} \tag{11-3}$$

ϱ is the density of the air and g is the gravity acceleration. Strongly stable conditions occur for $0 < Fr < 1$, which is the case when Equation 11-1 applies.

Egan (1984) describes how the Gaussian plume model in Equation 7-1 can be used to treat the two extremes of flow behaviors defined by whether streamlines are above or below H_c. For dispersion below H_c (i.e., the "wrap" component), the flow is restricted to travel in horizontal planes toward or around the sides of the hill, as shown in Figure 11-1 and in Region I of Figure 11-2. Concentrations on the "impact" side of the hill, i.e., its upwind face, are given by

$$c(d, z_r) = \frac{P(\theta_d)}{d}\, c_0(d, z_r) = \frac{Q\, P(\theta_d)}{\sqrt{2\pi}\,\sigma_z(d)\, u\, d} \cdot \left(\exp\left[-0.5\left(\frac{z_r - h_e}{\sigma_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z_r + h_e}{\sigma_z}\right)^2\right]\right) \tag{11-4}$$

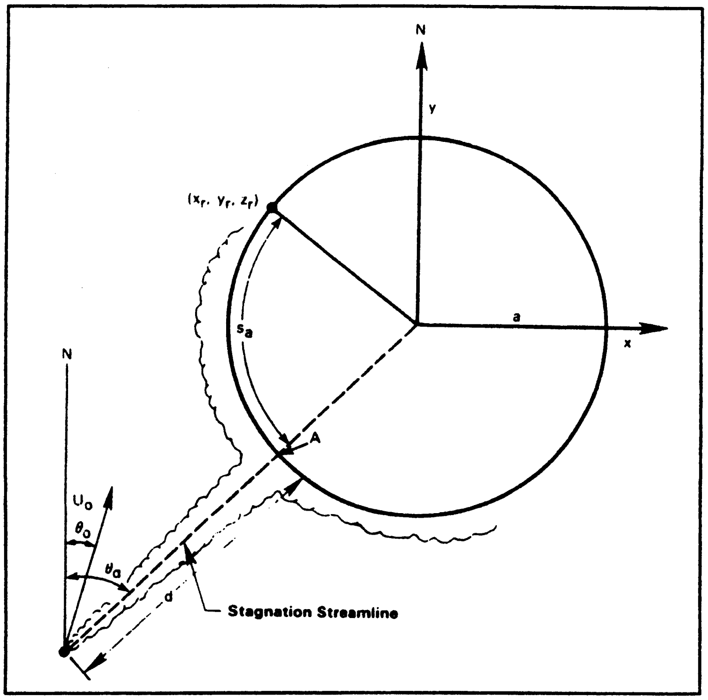

Figure 11-1. Plume dispersion in the region of horizontal flow (from Egan, 1984). [Reprinted with permission from D. Reidel.]

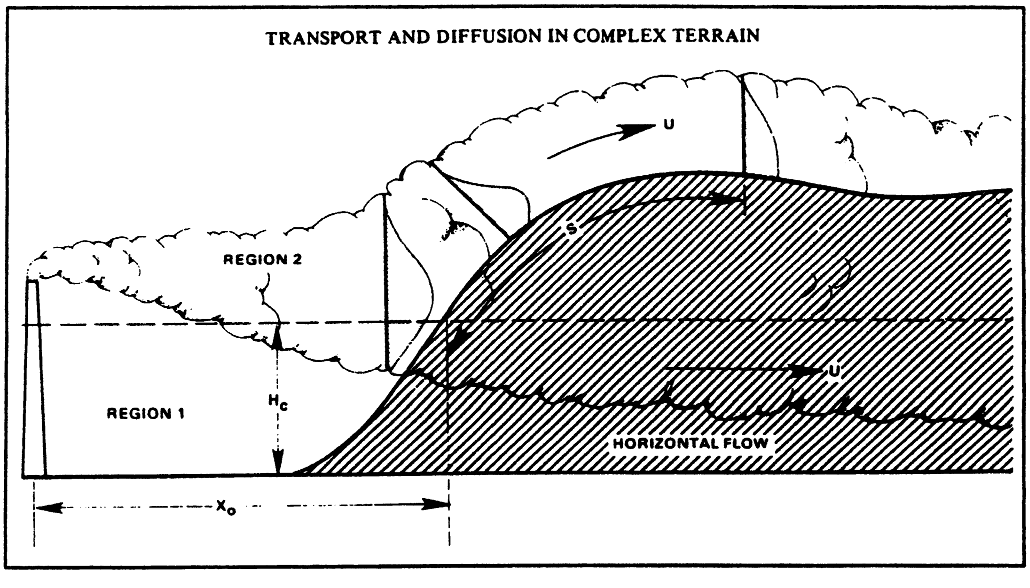

Figure 11-2. Dispersion and flow regions for stratified flow around hills (from Egan, 1984). [Reprinted with permission from D. Reidel.]

where Q is the emission rate, d is the distance from the source to the hillside receptor, z_r is the receptor elevation (above the base of the hill), u is the wind speed, σ_z is the vertical standard deviation of the plume concentration distribution at distance d, h_e is the effective plume height (above the base of the hill), and $P(\theta_d)$ is the probability density function of wind direction θ over an hour averaging time. If $P(\theta_d)$ is Gaussian, we have

$$P(\theta) = \frac{1}{\sqrt{2\pi}} \exp\left[-0.5\left(\frac{\theta-\overline{\theta}}{\sigma_\theta}\right)^2\right] \tag{11-5}$$

where $\overline{\theta}$ is the mean wind direction and σ_θ is the standard deviation of θ in the hour. In Equation 11-4, ground reflection is relative to the base of the hill (i.e, $z = 0$) and not to the hill surface.

For receptors around the side of the hill, the horizontal distance s of the source to a receptor is

$$s = d + s_a \tag{11-6}$$

as illustrated in Figure 11-1. In this case, the plume is reflected by the hill and the concentration at the receptor is computed by treating the vertical distribution of plume material below H_c as a source distribution and integrating the response function (or Green's function) from the hill base to H_c. This integration gives

$$c(s, z_r) = \frac{P(\theta_d)}{s} \int_0^{H_c} \frac{c_o(d, z)}{\sqrt{2\pi}\, \sigma_z'} \cdot \left(\exp\left[-0.5\left(\frac{z_r - z}{\sigma_z'}\right)^2\right] + \exp\left[-0.5\left(\frac{z_r + z}{\sigma_z'}\right)^2\right]\right) dz \tag{11-7}$$

where $c_o(d, z)$ is given by Equation 11-4, and

$$(\sigma_z')^2 = \sigma_z^2(s) - \sigma_z^2(d) \tag{11-8}$$

The portion of the plume above H_c is treated by the "lift" algorithm, in which plume material, as shown in Region 2 of Figure 11-2, is assumed to travel up and over the hill, the horizontal dispersion is enhanced, and the material is fully reflected from the hill surface. In this region, concentrations are computed by integrating the response function from H_c to infinity, i.e.,

$$c(s, \theta_d, z_p) = \frac{2\,P(\theta_d)}{s} \int_{H_c}^{\infty} \frac{c_o(s, z)}{\sqrt{2\pi}\;\sigma_z'} \cdot \exp\left[-0.5\left(\frac{z - H_c}{\sigma_z'}\right)^2\right] dz \qquad (11\text{-}9)$$

where z_p denotes the elevation of the ground surface (above the base of the hill), and c_o, σ_z' and s were previously defined.

In this case, instead of Equation 11-8, σ_z' can be defined in a way to enhance vertical dispersion through a terrain factor τ, i.e.,

$$(\sigma_z')^2 = \frac{\sigma_z^2(s)}{\tau^2} - \sigma_z^2(d) \qquad (11\text{-}10)$$

where

$$\tau = PPC \qquad (11\text{-}11)$$

for $z_p \geq h_e$, and

$$\tau = 1 - (1 - PPC)\,\frac{z_p - H_c}{h_e - H_c} \qquad (11\text{-}12)$$

for $z_p \leq h_e$, where PPC is the plume path coefficient, which is about 0.4–0.5 (Hanna et al., 1984).

The U.S. EPA has presently only five models that can be used where the height of the terrain exceeds the height of the emission stack: VALLEY, COMPLEX I, COMPLEX II, RTDM, and CTDM. Only the latter, however, incorporates the equations presented above. Much R&D activity is in progress to improve both theoretical and actual performance of dispersion models in complex terrain. In particular, the U.S. EPA has sponsored model development efforts for stable plume impaction on high terrain (Lavery et al., 1982), and the U.S. DOE has sponsored the Atmospheric Sciences in Complex Terrain program (ASCOT), in which tracer experiments in very rugged terrain have been performed with the objective of understanding the wind transport pattern near the surface (Dickerson and Gudiksen, 1980). Moreover, important results are expected in future from the third experiment in the EPRI Plume Model Validation and Development (PMV&D) program that took place in 1985.

11.2 COASTAL DIFFUSION

The literature contains reports of many studies in which the air pollution dispersion near the shoreline of a large body of water is simulated with advanced numerical techniques in order to take into account the hydrodynamics of the breeze effect and the consequent dispersion (Bornstein and Runca, 1977; Dieterle and Tingle, 1979; Dobosy, 1977; Pielke et al., 1983; Pielke et al., 1988; Lyons et al., 1987; and Segal et al., 1988). Unfortunately, application of such methodologies requires depth of technical expertise in the selection of modeling parameters and the interpretation of results, and extensive computer time and storage (even though prototypes of real-time mesoscale modeling systems can run today on the new generation of minisupercomputers integrated with graphics workstations). Therefore, these methods cannot currently be considered practical for routine applications. However, they do provide realistic numerical simulations that should be considered in the development of simpler techniques. Summary articles on mesoscale transport in coastal zones are provided in Lyons (1975), Lyons et al. (1983), Kaleel et al. (1983), and Moran et al. (1986).

A simple Gaussian model application in these circumstances has often given interesting results in spite of the complexity of the problem (e.g., Runca et al., 1976). Therefore, many studies have been developed for extending and improving the Gaussian formula to simulate coastal dispersion conditions. The work of Lyons and Cole (1973; further developed by van Dop et al., 1979), postulates a stable Gaussian plume advected over an unstable mainland surface, as depicted in Figure 11-3. This can be simulated by a fumigation formula in which concentration is vertically homogeneous and varies only with the distance from the shoreline (see Section 7.5.6). Because of recirculating flows, however, straight-line Gaussian models may fail catastrophically. Also, the coastal environment has very high levels of shear that are difficult to describe with plume models and require high-resolution methods (e.g., a combination of a mesoscale numerical model and a Lagrangian particle model; Lyons et al., 1988).

As discussed by Stunder and SethuRaman (1986), plume dispersion modules in coastal regions need to include calculations of the following parameters:

1. the Thermal Internal Boundary Layer (TIBL) height, i.e., the variation of *h* with the distance inland from the shoreline
2. the dispersion rates inside the convective, unstable TIBL and in the stable air above the TIBL
3. partial penetration of the TIBL by the plume
4. overwater dispersion rates (if the plume is emitted offshore)

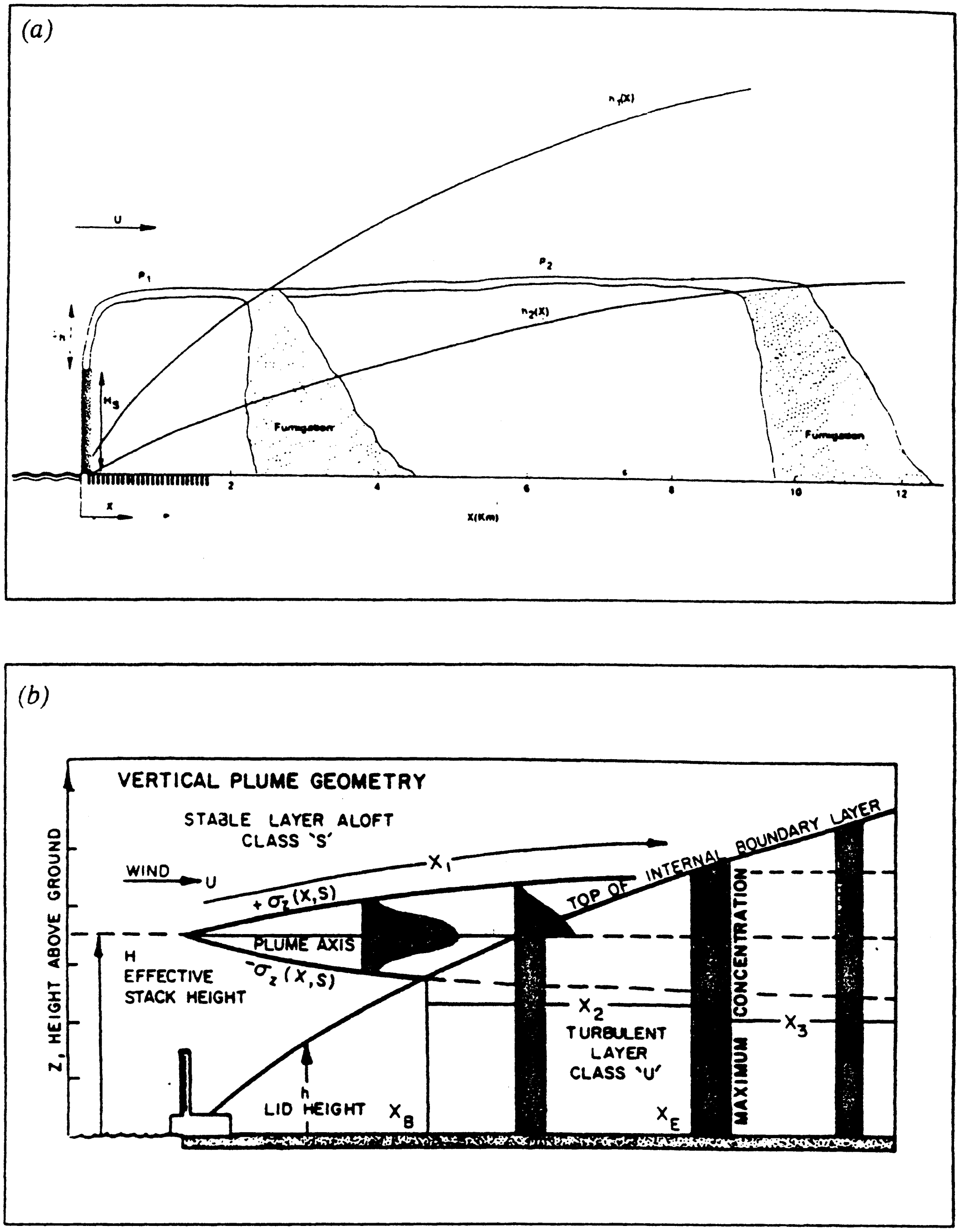

Figure 11-3. *(a) Typical dispersion pattern in coastal areas. (b) Plume geometry of Lyons and Cole (1973 model).* $\sigma_z(x,s)$*represents vertical dispersion coefficients.* X_B, X_E *represents the beginning and end points of fumigation. (From Stunder and SethuRaman, 1986.) [Reprinted with permission from Pergamon Press.]*

11.2.1 The TIBL Height

Weisman (1976) proposed the following equation for the TIBL height $h(x)$

$$h(x) = \left(\frac{2\, H_o\, x}{\varrho\, c_p\, \frac{\partial \theta}{\partial z}\, u(10)} \right)^{1/2} \tag{11-13}$$

where x is the downwind distance from the shoreline (m), H_o is the overland heat flux ($w\,\mathrm{m}^{-2}$), ϱ is the density of the air ($1.2\ 10^3\ \mathrm{g}\, m^{-3}$), c_p is the specific heat at constant pressure ($0.24\ cal\ g^{-1}\ K^{-1}$), $\partial\theta/\partial z$ is the overwater potential temperature gradient and $u(10)$ is the wind speed at 10 m above the ground.

Equation 11–13 was successfully tested against field studies by Stunder and SethuRaman (1986). More extended calculations of $h(x)$ are provided by Lyons et al. (1981) and Stunder and SethuRaman (1985).

11.2.2 Dispersion Rates (Plume Sigmas) Inside and Above the TIBL

Inside the TIBL, the dispersion of a plume can be described by the σ_y, σ_z formulas discussed in Chapter 7 for unstable conditions. Above the TIBL, plume sigmas for stable atmospheric conditions are often suggested. It must be noted, however, that little or no turbulence can be found above h and that, therefore, even the most stable σ_y, σ_z formulas can overestimate the plume spread above the TIBL. On the other side, however, if wind shear is strong above the TIBL, horizontal diffusion will be larger than suggested by the stable σ_y formulae.

11.2.3 Plume Partial Penetration

Since $h(x)$, defined by Equation 11–13, increases with the distance x from the shoreline, an elevated plume will progressively penetrate the TIBL, as illustrated in Figure 11–3. If the vertical concentration distribution of the plume is Gaussian with standard deviation $\sigma_z(x)$, the fraction of the plume that has penetrated the TIBL at x is (Stunder and SethuRaman, 1986)

$$\int_{-\infty}^{P} (2\pi)^{-1/2} \exp\left(-\frac{P^2}{2} \right) dP \tag{11-14}$$

where

$$P = \frac{h(x) - h_e}{\sigma_z(x)} \tag{11-15}$$

11.2.4 Overwater Dispersion Rates

Several dispersion experiments have recently provided new information on plume dispersion rates over water. This has allowed new, more realistic parameterizations of the phenomenon.

Hanna et al. (1985) developed the Offshore and Coastal Dispersion (OCD) model, in which the overwater plume is described by the Gaussian equation, whose σ_y and σ_z are computed as follows. The total σ_y is calculated by adding the contributions from turbulence, σ_{yt}, buoyant plume enhancement, σ_{yb}, wind direction shear, σ_{ys}, and structural downwash, σ_{yo}, i.e.,

$$\sigma_y^2 = \sigma_{yt}^2 + \sigma_{yb}^2 + \sigma_{ys}^2 + \sigma_{yo}^2 \qquad (11\text{–}16)$$

Similarly, the total σ_z is computed by

$$\sigma_z^2 = \sigma_{zt}^2 + \sigma_{zb}^2 + \sigma_{zo}^2 \qquad (11\text{–}17)$$

since wind direction shear does not affect σ_z.

According to Pasquill (1976)

$$\sigma_{yb}^2 = \sigma_{zb}^2 = (\Delta h)^2/10 \qquad (11\text{–}18)$$

and

$$\sigma_{ys}^2 = 0.03\,(\Delta WD)^2\,x^2 \qquad (11\text{–}19)$$

where ΔWD is the wind direction shear in radians.

The turbulence contributions are

$$\sigma_{yt} = i_y\ x\ S_y(x) \qquad (11\text{–}20)$$

$$\sigma_{zt} = i_z\ x\ S_z(x) \qquad (11\text{–}21)$$

where

$$i_y = \sigma_v/u\ (\simeq\ \sigma_\theta \text{ for small angles}) \qquad (11\text{–}22)$$

$$i_z = \sigma_w/u\ (\simeq\ \sigma_\phi \text{ for small angles}) \qquad (11\text{–}23)$$

are the turbulence intensities.

For overwater dispersion, Hanna et al. (1985) propose the following interpretation of the Briggs' (1973) formulation:

$$S_y(x) = (1 + 0.0001\,x)^{-1/2} \tag{11-24}$$

for $x \leq 10^4$ m (S_y is kept constant for $x > 10^4$ m) and

$S_z(x)$	Overwater Stability	
1	A and B	(11–25a)
$(1 + 0.0002\,x)^{-1/2}$	C	(11–25b)
$(1 + 0.0015\,x)^{-1/2}$	D	(11–25c)
$(1 + 0.0003\,x)^{-1}$	E and F	(11–25d)

Overwater stability is computed from the Monin–Obukov length L (defined using the virtual temperature) and the roughness length z_o, using the method of Golder (1972) illustrated in Figure 3–10. An additional stability class is added (Class G) when $\partial\theta/\partial z \geq 5°\mathrm{C}\ 10^{-2}\ \mathrm{m}^{-1}$, a value found only when warm air is advected over cold water.

If σ_θ is not measured, an approximate formula (Hanna, 1983), which agrees with boundary layer theory and recent field observations, gives

$$i_y \simeq 0.5/u \tag{11-26}$$

for $u < 10\ \mathrm{m}\,s^{-1}$.

The above parameterization is the most applicable, at the present time, since it has been fully implemented into a common-domain computer package — the OCD model. Other studies, however, have provided similar parameterizations, e.g., Dabberdt (1986), who analyzed ten atmospheric tracer experiments, which provided 62 hours of dispersion data. He used these data to evaluate four dispersion parameterization schemes:

1. the Pasquill–Gifford–Turner method (Turner, 1970)
2. the Pasquill (1976) method
3. the Draxler (1976)–Irwin (1979) method
4. the Briggs (1976) method

He found the second and third scheme to provide a good estimate of σ_y, while all methods give a poor estimate of σ_z.

An additional parameterization of plume dispersion over water is also provided by Skupniewicz and Schacher (1986).

11.3 DIFFUSION AROUND BUILDINGS

Several studies have tried to evaluate the dispersion behavior around buildings (see Figure 7-5) and a few of them have proposed empirical algorithms to simulate these peculiar effects. One of the commonest techniques is based on the studies of Huber and Snyder (1976) and Huber (1977) and has been incorporated into the U.S. EPA Industrial Source Complex model (ISC; Bowers et al., 1979). This technique is based on the results of tunnel experiments with a building crosswind dimension double that of the building height, and with atmospheric stability from C (slightly unstable) to D (neutral).

The first step in this wake-effect evaluation method (Bowers et al., 1979) is to calculate the plume rise due to momentum alone. If the plume height, given by the sum of the stack height and the momentum rise at a downwind distance of two building heights, is greater than either 2.5 building heights ($2.5\ h_b$) or the sum of the building height and 1.5 times the building width ($h_b + 1.5\ h_w$), the plume is assumed to be unaffected by the building wake. Otherwise, the plume is assumed to be affected by the building wake.

The effects of building wakes are accounted for by modifying only σ_z, for plumes from stacks with plume height to building height ratios greater than 1.2 (but less than 2.5), and by modifying both σ_y and σ_z, for plume height to building height ratios less than or equal to 1.2. The plume height used for computing the plume height to stack height ratio is the same plume height used to determine whether the plume is affected by the building wake. The procedure defines buildings as squat ($h_w \geq h_b$) or tall ($h_w < h_b$). The building width h_w is approximated by the diameter of a circle with an area equal to the horizontal area of the building. Then, a general procedure is defined below for modifying σ_z and σ_y at distances greater than $3\ h_b$, for squat buildings, or $3\ h_w$, for tall buildings.

The modified σ_z equation for a squat building is given by

$$\sigma_z' = 0.7\, h_b + 0.067\,(x - 3\, h_b) \qquad (11\text{-}27)$$

for $3\ h_b < x < 10\ h_b$, and

$$\sigma_z' = \sigma_z(x + x_z) \qquad (11\text{–}28)$$

for $x \geq 10\, h_b$, where h_b is the building height, x is the downwind distance, σ_z is the value of a selected sigma function, and x_z is defined below. For a tall building, Huber (1977) suggests that the width scale h_w replace h_b in Equations 11–27 and 11–28. The modified σ_z equation for a tall building is then given by

$$\sigma_z' = 0.7\, h_w + 0.067\,(x - 3\, h_w) \qquad (11\text{–}29)$$

for $3\, h_w < x < 10\, h_w$ or

$$\sigma_z' = \sigma_z(x + x_z) \qquad (11\text{–}30)$$

for $x \geq 10\, h_w$.

The vertical virtual distance x_z is added to the actual downwind distance x at downwind distances beyond 10 h_b (squat buildings) or 10 h_w (tall buildings), in order to account for the enhanced initial plume growth caused by the building wake. Thus, x_z for a squat building is

$$x_z = \left(\frac{1.2\, h_b}{a}\right)^{1/b} - 0.01\, h_b \qquad (11\text{–}31)$$

where the constants a and b are dependent upon atmospheric stability. Similarly, the vertical virtual distance for tall buildings is given by

$$x_z = \left(\frac{1.2\, h_w}{a}\right)^{1/b} - 0.01\, h_w \qquad (11\text{–}32)$$

Similar equations are also provided by Bowers et al. (1979) for the computation of the modified (i.e., enhanced) σ_y' for both squat and tall buildings.

The air flow in the building cavity (see Figure 7–5) is highly variable and generally recirculating, and the procedure defined in this section is not appropriate for estimating concentrations within such cavities. In this case, the downwash procedure found in Budney (1977) may be used to obtain a worst-case estimate.

Other schemes, in addition to those presented above, are available for computing atmospheric downwash. A comparative study of four different schemes has been performed by Starheim and Knudson (1981). Modifications of the downwash algorithms presented in this section have also been proposed by Shulman and Hanna (1986).

11.4 GRAVITATIONAL SETTLING

Gravitational settling is the major factor affecting the dry deposition of large particles (say, with diameter greater than 10 μm), such as wind-raised dust. The settling velocity is a function of shape, density and size of the particle and, for small particles, is negligible when compared with turbulent vertical velocities. However, small particles may form larger particles by aggregation and then be effectively removed by gravitational settling. Figure 11–4 presents typical values of the settling velocity V_G as a function of particle diameter and density. These values were computed using Stokes' law for particles with diameters up to 60 μm, i.e.,

$$V_G = \frac{d^2 g \varrho_P}{18\mu} \qquad (11\text{–}33)$$

where d is the diameter of the particle, g is the gravity acceleration, ϱ_p is the particle density and μ is the dynamic viscosity of the air (= 1.8 10^{-4} g s^{-1} cm^{-1}). For larger particles, Stokes' law is modified according to Van der Hoven (1968).

The behavior of a "titled" plume, i.e., a plume of particles affected by gravitational settling V_G, is presented in Figure 7–6.

11.5 HEAVY GAS DISPERSION

The production, transportation and storage of large quantities of heavy gases represent a serious danger to the public. Heavy gas clouds constitute a severe environmental hazard. A cloud of methane, propane or butane may be flammable if its mean volume concentration is higher than about 1 percent (Eidsvik, 1980); a cloud of chlorine may be poisonous at concentrations of about 10^{-5} percent! A typical scenario is given by the spill of liquified natural gas (LNG) (Zeman, 1982). After the liquid spills, heat is transferred to the liquid layer from the underlying surface (soil or water) and the liquid boils off. The released vapor has a temperature of 113°K and a specific gravity of about 1.65. After building up to a certain depth, it starts to spread under the forces of gravity. As the cold vapor comes into contact with a warm surface, strong turbulent convection is triggered. After the gravity current exhausts its excess potential

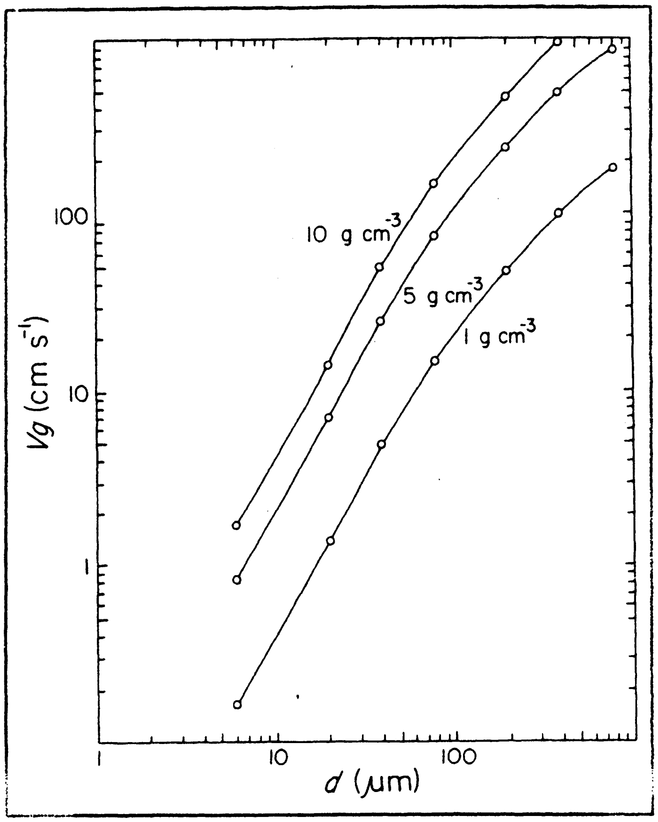

Figure 11-4. *Fall velocity of spherical particles as a function of particle diameter and density. Source: Adapted from Hanna et al. (1982) as presented by Stern et al. (1984). [Reprinted with permission from Academic Press.]*

energy through mixing, heating and spreading, the diluted vapor cloud will behave like a passive contaminant subject to atmospheric dispersion.

Some modeling techniques have been proposed and tested for the simulation of heavy gas dispersion. In the simple model proposed by Eidsvik (1980), the horizontal dimension of the cloud is assumed to increase due to the gravity fall of the cloud, and the cold cloud is heated from below and from air entrainment. The model predicts accurately some experimental data on heavy gas dispersion.

Zeman (1982) investigated gravity currents and developed a simple one-layer model that simulates the formation of the gravity flow by boiling the spilled liquified gas, the three-dimensional gravity flow in the presence of wind, and the convective heating and its contribution to the entrainment of ambient air. He also identified the scaling laws of the above phenomena, which are shown to agree with the model predictions.

An interesting comparison of the performance of three dense gas dispersion models is presented by Ermak et al. (1981). In this study, the predictions from three vapor dispersion models for cold dense gas releases are compared with the results from several 40 m^3 LNG spill experiments conducted at China Lake, California, in 1980. The models vary considerably in the degree to which they approximate important physical phenomena and include restricting assumptions. The simplest model (GD), a modified Gaussian plume model, predicted a vapor cloud that was always too high and too narrow by a factor of 1.5 to 3. The second model (SLAB), a layer-averaged conservation equation model with one independent spatial variable (downwind distance), generally predicted the maximum distance to the lower flammability limit (LFL) and cloud width quite well. SLAB assumes the vertical concentration distribution is nearly uniform, so that the vertical concentration gradient $\partial c/\partial z$ is essentially zero from the ground up through most of the cloud and then very steep at the top of the cloud. This was generally not the case in these experiments, especially in the high wind speed tests, where the vertical concentration gradient was found to be more gradual throughout the cloud. The last model (FEM3) is a fully three-dimensional conservation equation model, which predicted the concentration distribution in time and space rather well. A particular achievement of this model was the prediction of a bifurcated cloud structure observed in one experiment conducted with a low ambient wind speed. Both the SLAB and FEM3 models accurately predicted the length of time required for the cloud to disperse to a level below the LFL, even in the low wind speed test, where the vapor cloud lingered over the source region for a considerable length of time after the LNG spill was terminated.

Modeling reviews of heavy gas dispersion in the atmosphere are provided by McNaughton and Berkowitz (in Hartwig, 1980), Havens (1985), and Krogstad and Jacobsen (1989). Fay and Zemba (1985) propose an algorithm for treating initially compact dense gas clouds, i.e., clouds whose initial shapes have nearly equal vertical and horizontal dimensions. In particular, they model the initial spreading motion of the cloud with a constant global entrainment rate obtained from experimental values. Turbulence is then added to this initial entrainment. Fay and Zemba (1986) also propose a quasi-one-dimensional flow model of an isothermal dense gas plume (integral model). The interactions of a heavier-than-air gas near a two-dimensional obstacle have been studied and modeled by Sutton et al. (1986), who added streamline curvature and buoyancy corrections to the basic turbulence formulation. A review of recent field tests and mathematical modeling of atmospheric dispersion of large spills of denser-than-air gases is provided by Koopman et al. (1989).

11.6 COOLING TOWER PLUMES

Cooling towers conserve water and prevent the discharge of heated water to streams, lakes and estuaries. A brief review of cooling tower plumes and drift deposition phenomena can be found in the handbook by Hanna et al. (1982).

In a cooling tower, hot water from the industrial process drips over wooden or plastic barriers and evaporates into the air that passes through the tower. As a result, about 540 calories of heat are lost for each gram of water evaporated. Cooling towers can be tall (e.g., 150 m tall and 30 m in radius) natural-draft towers, in which vertical motions are induced by density differences, or short (e.g., 20 m tall and 5 m in radius) mechanical-draft towers, in which vertical motions are forced by large fans. Vertical velocities of about 5 m s^{-1} are observed in natural draft towers and about 10 m s^{-1} in mechanical draft towers. Temperature and moisture differences between the plume and the environment are about the same in both types of towers, about 20°C and 0.03 g/g, respectively. The plume is saturated when it leaves the tower, and liquid water concentrations are about 0.001 g/g.

Heat and moisture fluxes from cooling towers at large power plants can cause fog or cloud formation and can, at times, induce additional precipitation. Another potential problem is drift deposition, in which circulating cooling water with drop sizes ranging from 50 to 1,000 μm is carried out of the tower and may be deposited on nearby structures and vegetation. These drops generally contain salts, fungicides, and pesticides, which may harm the surfaces they strike. A comprehensive review of atmospheric effects of cooling tower plumes is given by Hanna (1981).

A schematic illustration of a cooling tower plume is presented in Figure 11-5, while the outlines of a cooling tower vapor plume and a drift drop plume are illustrated in Figure 11-6.

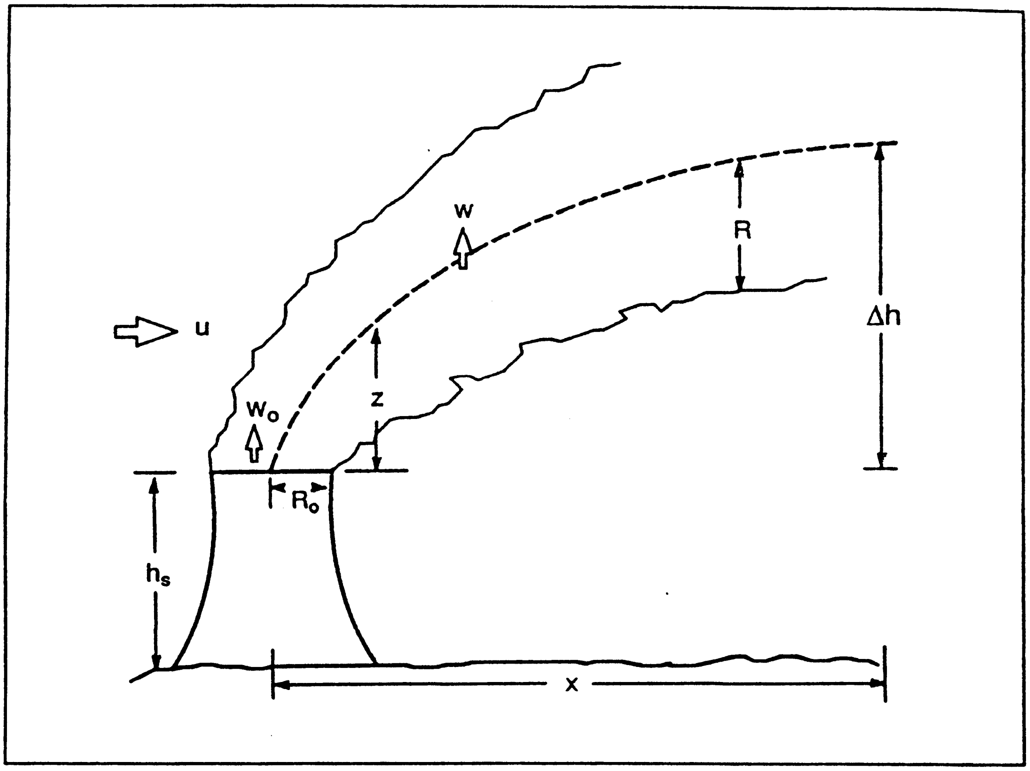

Figure 11-5. Cooling tower plume (adapted from Hanna et al., 1982).

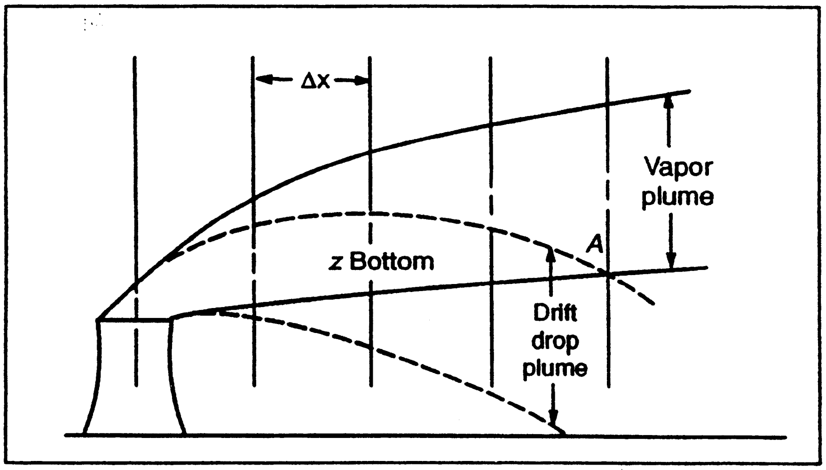

Figure 11-6. Outline of a cooling tower vapor plume and a drift drop plume (for drops in a narrow size range). By point A, all drift drops in this size range have dropped out of the plume (adapted from Hanna et al., 1982).

Several mathematical models are available to simulate the peculiar characteristics of cooling-tower plume dispersion. The fundamental nondimensional parameters that govern the dispersion of natural-draft cooling tower (NDCT) plumes are (Carhart et al., 1982)

- the initial densimetric Froude number F_o, where

$$F_o = W_o \left(g \, \frac{\varrho_o - \varrho_a}{\varrho_a} \right)^{-1/2} \tag{11-34}$$

- the velocity ratio

$$U_o / W_o \tag{11-35}$$

- the local ambient stability s', where

$$s' = \left(\frac{d}{4 \, U_o} \right)^2 \frac{g}{T_a} \, \frac{d\theta_a}{dz} \tag{11-36}$$

- and the ambient moisture deficit

$$V^* = q_o - q_a \tag{11-37}$$

where W_o is the top exit velocity, U_o is the wind speed at the tower top, d is the tower exit diameter, θ_a is the ambient potential temperature, ϱ_o and ϱ_a are, respectively, the tower exit density and ambient density at the tower top (including moisture effects), and q_o, q_a are the exit plume and ambient specific humidities, respectively.

Carhart et al. (1982) provide an evaluation of the theory and actual performance of 16 models commonly used for the prediction of plume rise from natural draft cooling towers. The best models can predict visible plume rise within a factor of two and visible plume length within a factor of 2.5, but only for 50 percent of the cases tested.

Finally, a new, calibrated, advanced integral model for plume rise from single natural draft cooling towers has been proposed by Schatzmann and Policastro (1984). This model is based on the integration of three-dimensional conservation equations and includes a treatment of plume thermodynamics and tower downwash effects.

11.7 SOURCE EMISSION MODELING OF ACCIDENTAL SPILLS

The most important parameter in the simulation of accidental spills of hazardous materials is the "source term," i.e., the quantitative evaluation of the dimension, rate and duration of the spill. Source emission models are summarized in Chapter 4 of Hanna and Drivas (1987), who describe the physical and chemical principles that are appropriate for the various types of spill scenarios and provide formulae for the simulation of

- gas jet releases, generated from a small puncture in a pressurized pure gas pipeline or in the vapor space of a pressurized gas storage tank (as illustrated in Figure 11-7)
- liquid jet releases
- two-phase jet releases
- flashing processes
- liquid pool evaporation (single and multicomponent)

Table 11-1 lists some available source emission models (see Table 14-1 for additional information on these models).

11.8 INDOOR AIR POLLUTION

It is evident that the air people breathe inside buildings (at home or at work) and while traveling (by car, bus, subway, airplane, etc.) is quite different from the air outdoors. Traditional pollutants, such as SO_2 and CO, can infiltrate into buildings from outside. The real problem with indoor air quality, however, is the indoor emission of pollutants and their accumulation due to poor ventilation and air exchange.

The major indoor air pollution problems are (U.S. EPA, 1988):

- Radon, a naturally occurring gas resulting from the radioactive decay of radium, found in many types of rocks and soils. Radon enters buildings through cracks in the foundations.
- Environmental tobacco smoke, i.e., smoke that nonsmokers are exposed to from smokers. It contains inorganic gases, heavy metals, particulates, VOCs, and products of incomplete burning. Major progress has been made in North America in reducing or eliminating tobacco smoke in many indoor environments. Unfortunately,

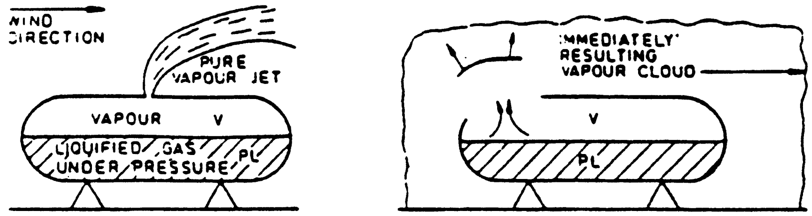

FIG 6A SMALL HOLE IN VAPOUR SPACE-PRESSURIZED TANK

FIG 6B CATASTROPHIC FAILURE OF PRESSURIZED TANK

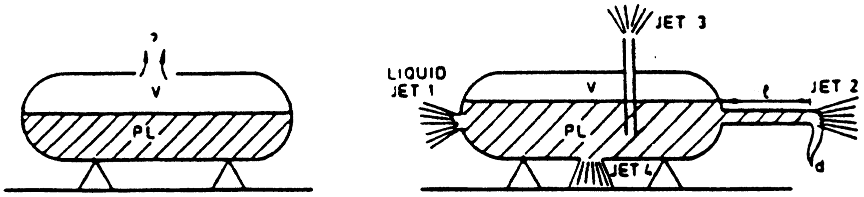

FIG 6C INTERMEDIATE HOLE IN VAPOUR SPACE-PRESSURIZED TANK

FIG. 6D ESCAPE OF LIQUIFIED GAS FROM A PRESSURIZED TANK

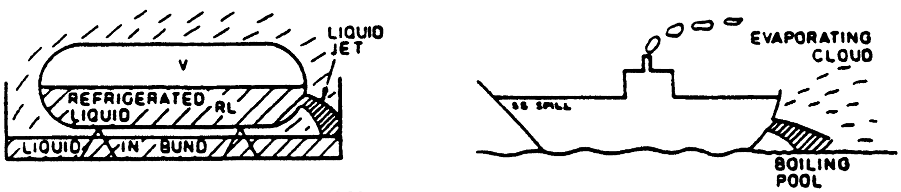

FIG 6E SPILLAGE OF REFRIGERATED LIQUID INTO BUND

FIG. 6F SPILLAGE OF REFRIGERATED LIQUID ONTO WATER

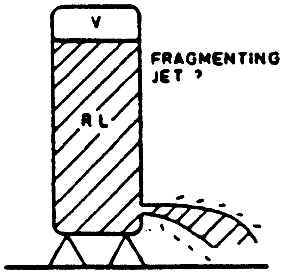

FIG 6G HIGH VELOCITY FRAGMENTING JET FROM REFRIGERATED CONTAINMENT

Figure 11–7. *Illustration of some conceivable release mechanisms, from Fryer and Kaiser (1979), as presented by Hanna and Drivas (1987). In most cases, the jet could be two phase (vapor plus entrained liquid aerosol). [Reprinted with permission from the American Institute of Chemical Engineers.]*

Table 11–1. List of some available source emission models. More details are given in Table 14–1 (from Hanna and Drivas, 1987; see this publication for the references listed below). [Reprinted with permission from the American Institute of Chemical Engineers.]

- Evaporation Models:
    - Ille and Springer (1978)
    - Army (Whitacre et al., 1986)
    - Shell SPILLS (Fleischer, 1980)
    - USAF ESL (Clewell, 1983)
    - Air Weather Service (AWS, 1978)
    - Illinois EPA (Kelty, 1984)
    - Stiver and Mackay (1982)
    - Monsanto (Wu and Schroy, 1979)
    - Shaw and Briscoe (1978)
- Jet Models:
    - Wilson (1979)
- Jet and Evaporation Models:
    - CHARM (Eltgroth et al., 1983)
    - Ontario MOE (MOE, 1983)
    - AIRTOX (Paine et al., 1986)
    - Kunkel (1983, 1985)
    - DENZ (Fryer and Kaiser, 1979)
    - COBRA (Alp, 1985)

the rest of the world lags behind in the progress toward a civilized respect for nonsmokers' rights.

- Asbestos fibers, used in a variety of building materials for insulation, fireproofing, wallboard, ceiling tiles, floor tiles, etc.
- Formaldehyde, used in furniture, foam insulation, and pressed wood products.
- Other VOCs, such as perchlorethylene emitted by dry-cleaned clothes, and paints and cleaning compounds.
- Biological pollutants, originating from heating, ventilation, air conditioning systems and humidifiers, when improperly cleaned and maintained.

- Pesticides, such as termiticides and wood preservatives.

Clearly, since most people spend a large majority of their time indoors (at least in the industrialized countries), indoor air quality may affect human health more than outdoor air quality. Therefore, the common practice of relating measurements of outdoor pollutants to human exposure can be fundamentally wrong in most circumstances.

Direct measurements of indoor air quality are, naturally, the best way to evaluate the existence and the gravity of indoor air pollution. In some cases, however, indoor air quality modeling may provide useful complementary information. A general mathematical model of indoor dynamics of gases and aerosols was presented by Nazaroff and Cass (1986, 1989) and is summarized below.

The building is represented by a set of interconnected chambers, where, in each chamber, pollutants are well mixed. Within each chamber i, the rate of change of concentration C_{ijk}, for each component k and (for aerosols) each section j, is given by the equation

$$\frac{dC_{ijk}}{dt} = S_{ijk} - L_{ijk}C_{ijk} \tag{11-38}$$

where S_{ijk} is the source term, which includes direct emission, avective transport from other chambers and outside, and (for aerosols) coagulation of mass from smaller particles into the section j; L_{ijk} is the sum of all sinks, including loss to the surfaces, removal by ventilation and filtration, and (for aerosols) loss to a larger size due to coagulation.

Equation 11-38 provides a solution of $C_{ijk}(t)$ if the input parameters, S_{ijk} and L_{ijk}, and the initial conditions $C_{ijk}(0)$ are provided. The input parameters, of course, vary with time.

11.9 REGULATORY MODELING

In the U.S., laws and regulations have been formalized into a series of procedures dealing with air quality permitting requirements that affect the operations of existing industrial facilities and the design of new ones. As a consequence of the Clean Air Act and its amendments, the use of selected air pollution models has been formalized in order to achieve the goal of definite answers (yes or no) for the permitting process.

This regulatory application of air pollution models has the main advantage of being performed under the same set of procedures for all applicants, aiming at the objective evaluation of the air quality impact generated by their proposed pollutant-emitting modifications or new facilities. Clear, objective rules are a prerequisite of fairness, which is accomplished through a set of procedures developed by the U.S. Environmental Protection Agency (EPA) (each state, however, may have its own set of additional local regulations to comply with). Generalized rules may, sometimes, however, be in contrast with best scientific judgment, which, in a complex field such as atmospheric dispersion, would require flexibility and subjective interpretation. As a consequence, regulatory application of dispersion models may, sometimes, use bad science or, often, push scientific methodologies beyond the limits of their applicability.

Historical reviews of U.S. air quality laws are presented by Stern (1977; 1982). A useful summary of practical requirements is contained in the handbook prepared by ERT (1985).

The most important regulatory process is the process of evaluating an application for a federal "permit to construct," i.e., a New Source Review (NSR). This review is required for new plants that could emit 100 tons per year of any pollutant or for modifications to major existing plants that will cause increases greater than defined minimum values. These "De Minimis" amounts are presented in Table 11–2.

An NSR process varies depending on the location of the new source. Areas where the National Ambient Air Quality Standards (NAAQS) for all criteria(*) pollutants are met are designated "attainment" and are subject to the Prevention of Significant Deterioration (PSD) doctrine. If one or more pollutants do not meet the NAAQS standards, the area is designated as "nonattainment" (NA) for those pollutants.

For PSD areas, maximum "increments" of SO_2 and Total Suspended Particles (TSP) have been established. Therefore, a PSD review will use appropriate techniques (i.e., dispersion models) to evaluate whether the proposed emission will consume a "tolerable" part of the allowable increment. The size of these increments depends on the classification of the area. In Class I areas, i.e., regions that require the highest degree of protection, such as national parks and wilderness areas, the increments are small, while Class II and Class III areas have larger increments to allow some industrial development. No Class III areas have been designated yet, however.

(*) A criteria pollutant is a pollutant for which an NAAQS exists.

Table 11–2. De Minimis emission rates (from ERT, 1985). [Reprinted with permission from ENSR.]

Pollutant	Emission Rates (tons per year)
Carbon monoxide	100
Nitrogen oxides	40
Sulfur dioxide	40
Particulate matter	25
Ozone	40 tpy of volatile organic compounds
Lead	0.6
Asbestos	0.007
Beryllium	0.0004
Mercury	0.1
Vinyl chloride	1
Fluorides	3
Sulfuric acid mist	7
Hydrogen sulfide (H_2S)	10
Total reduced sulfur (including H_2S)	10
Reduced sulfur compounds (including H_2S)	10

For NA areas, no further air quality deterioration is allowed. Consequently, "offsets" need to be found. In other words, other existing emissions in the area need to be eliminated or reduced by control technology, in order to obtain a permit for the new source.

The entire NSR process is outlined in Figure 11–8. Mathematical modeling plays an important role in both PSD and NA areas. In the former, modeling simulations verify that the new source impacts are below the allowable fraction of the increment level for that pollutant in that region. In the latter, modeling simulations confirm the net improvement in air quality achieved by adding the new source and subtracting the offsets in the region. Models can also be used to clarify monitoring needs and select both meteorological and air quality monitoring sites. Modeling guidelines are available (U.S. EPA, 1984) to help in the proper regulatory use of these numerical techniques. Specific regulatory models are discussed in Chapter 14.

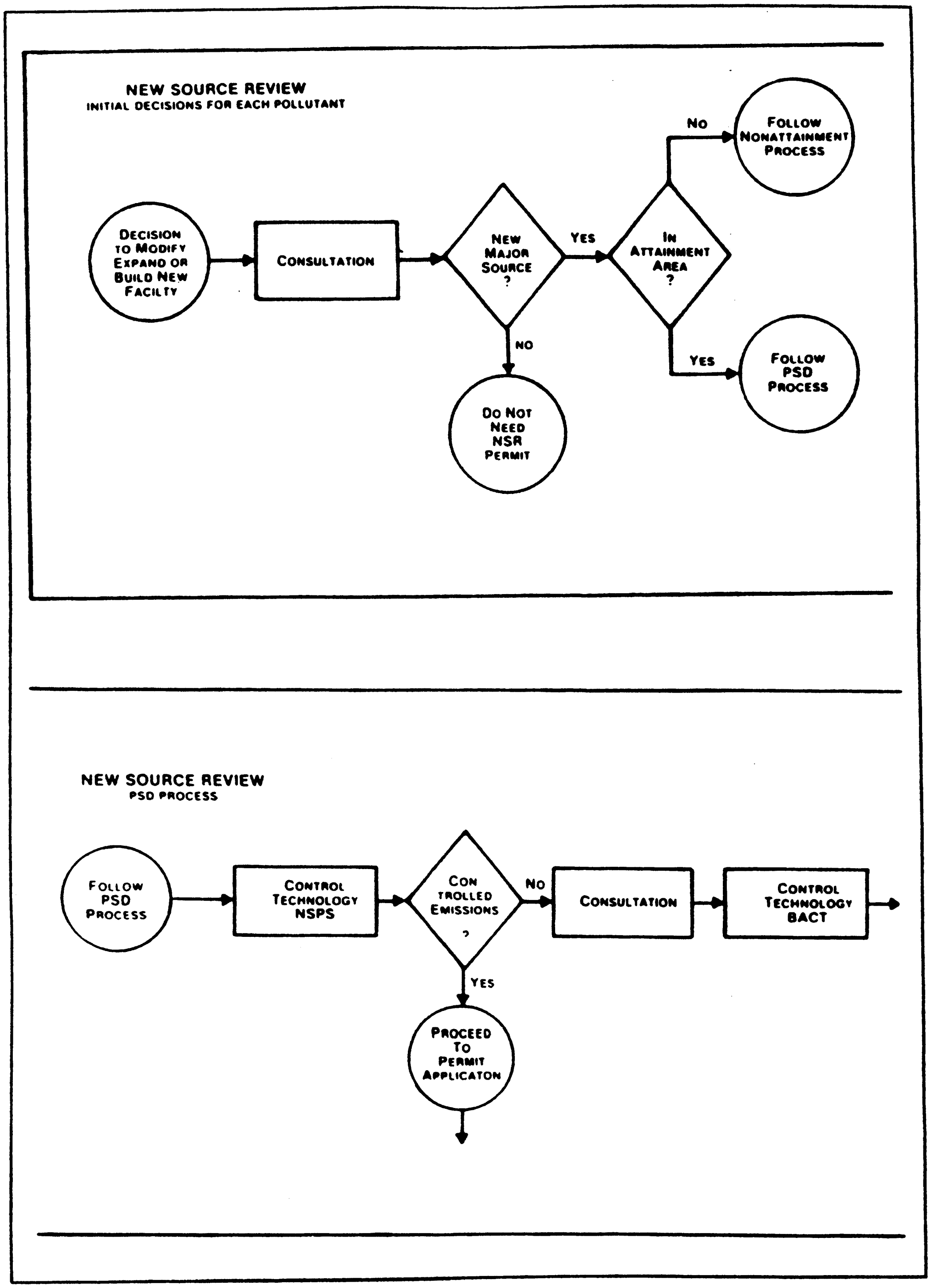

Figure 11–8. *New source review (from ERT, 1985). [Reprinted with permission from ENSR.]*

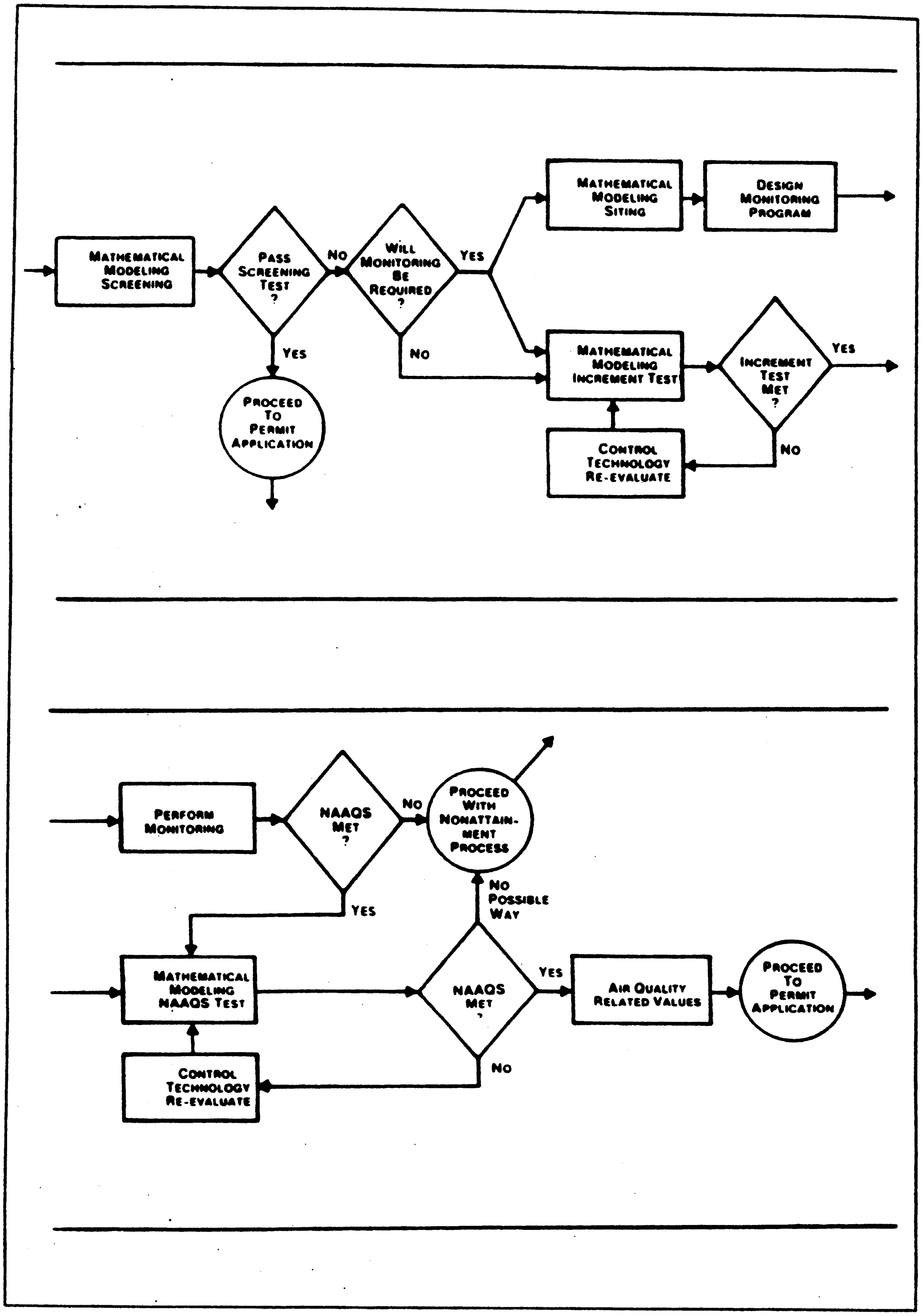

Figure 11–8. New source review (continued)

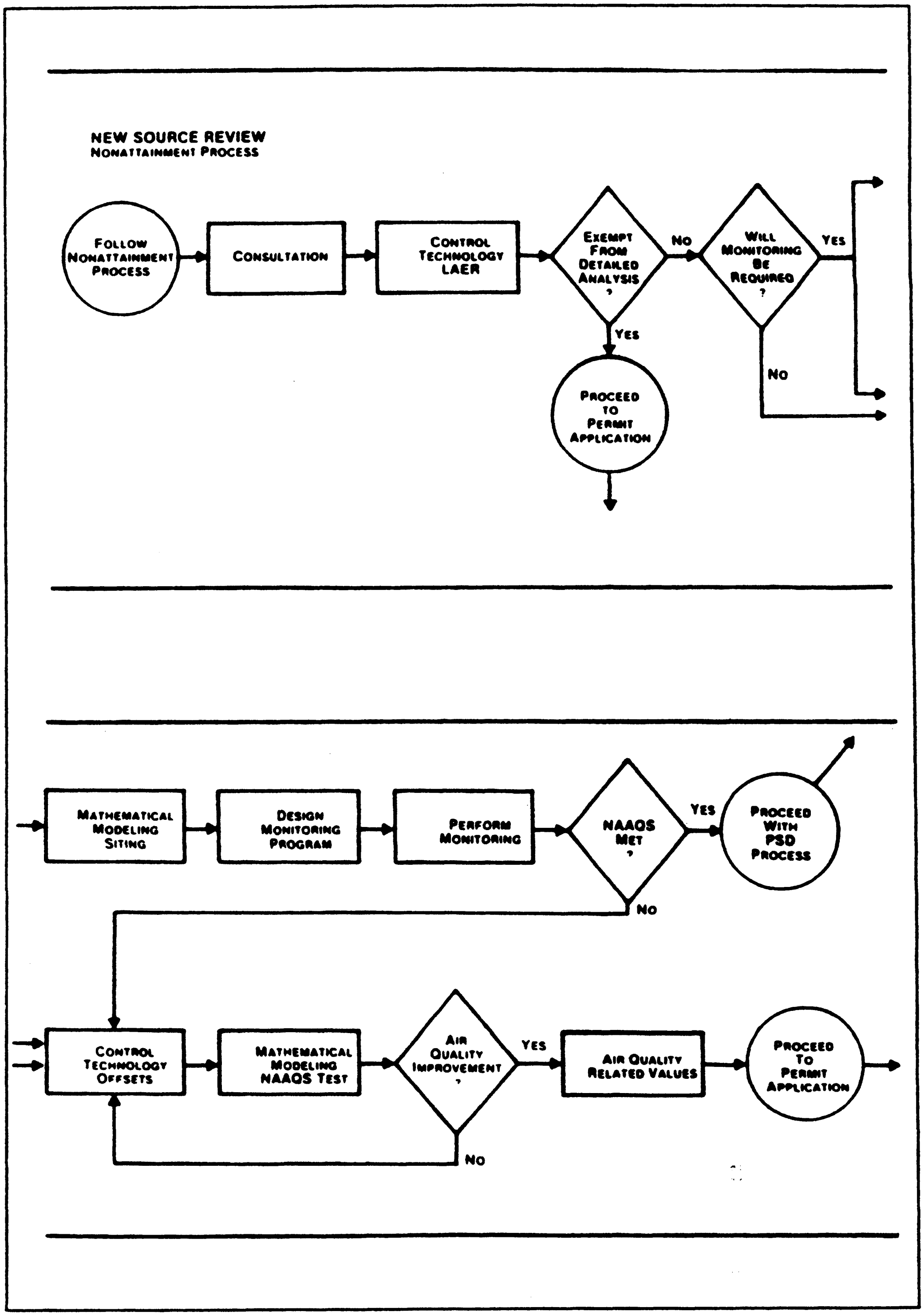

Figure 11–8. New source review (continued)

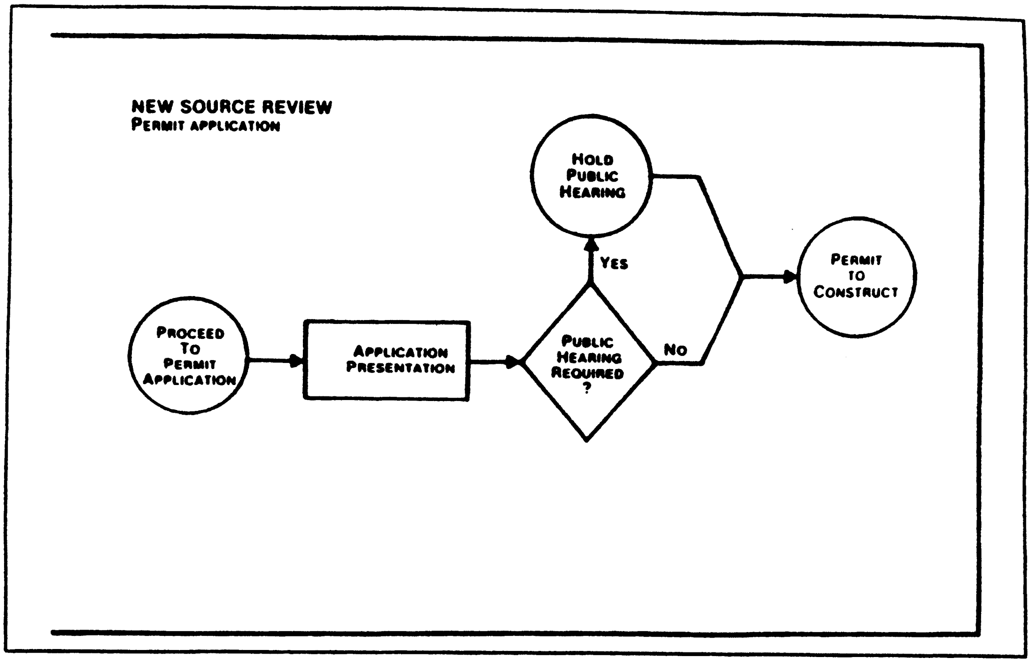

Figure 11–8. New source review (continued)

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