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of air quality:
impacts on the
lake powell region

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LAKE POWELL RESEARCH PROJECT BULLETIN

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IN THE LAKE POWELL REGION

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THEORETICAL ANALYSIS OF AIR QUALITY:
IMPACTS ON THE LAKE POWELL REGION

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May 1975

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework

for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user Groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

A major area of possible conflict has arisen between recreational use of Lake Powell and new industrial developments which potentially can change the quality of the air in the region. Presently there is exceptionally high air quality in the Lake Powell area.

This Bulletin presents theoretical calculations of contaminant emissions from elevated point sources. Models have been developed and applied to predict deposi-

tion rates of various atmospheric contaminants near Lake Powell. The calculations suggest that the Navajo Generating Station may have significant effects on visibility in the Lake Powell region, although uncertainties in certain parameters remain. Models differ dramatically in their predictions. There is an urgent need for comprehensive monitoring of air quality and for improvement of theoretical methods for treating high-terrain situations such as the Lake Powell region.



THEORETICAL ANALYSIS OF AIR QUALITY: IMPACTS ON THE LAKE POWELL REGION

INTRODUCTION

One of the goals of the Lake Powell Research Project (LPRP) is the assessment of the impact of conflicting uses of the Lake Powell region. A major arena of possible conflict has arisen between the recreational use of the area and new industrial developments changing the quality of air in the region. Presently, the region is blessed with exceptionally high air quality; however, large industrial emissions of particulates, sulfur oxides, and nitrogen oxides conceivably could alter the picture. For this reason, the Air Quality Subproject of the LPRP has been designed to assess the nature and extent of air quality changes in the Lake Powell region.

In a region as vast and as varied as the Lake Powell area, the assessment of air quality changes requires a two-pronged attack. The first method of attack is the monitoring of changes at various points in the region, and the second is the development of theoretical models. The theoretical approach is an essential part of the total program for a number of reasons. First, any monitoring program must be limited in space and time, and therefore a theoretical approach is required to extend the results to the remainder of a region and to other periods of time. Furthermore, the theoretical work may be used to define the ranges of various parameters (thus facilitating the selection of equip-

ment) and to identify sites where monitoring can provide the most relevant information. In addition, the theoretical work makes possible an assessment of the significance of the results from a limited monitoring program. For example, theoretical considerations can show how much information about air quality impacts for the entire region can be gleaned from 2 months of monitoring at a single location 6 kilometers distant from a large point source of pollution. Such functions of the theoretical work are essential to an assessment of the impact of air quality changes.

There are three main mechanisms by which air contaminants may produce relevant impacts within a region. The first mechanism is the modification of the atmosphere's ability to transmit light. For example, particles and light-absorbing gases may obscure distant features of the terrain or may reduce the amount of sunlight reaching the earth's surface. The second mechanism is the direct effect of ground level concentrations of contaminants on materials, plants, animals, and humans. The third mechanism is the deposition of materials on surfaces which may produce direct changes in the medium beneath the surfaces. The deposition mechanism can be subdivided into three deposition paths. The first path is the gravitational settling of large particles to the surface. A second path is the turbulent impaction of very small particles against surfaces. The third deposition path is the washout of particles by rain or snowfall. Of these three paths, only the second is treated here. The first is probably insignificant for the new air pollution sources in the Lake Powell region, which mainly emit very fine particulates with negligible settling velocities. The third path has not been

sufficiently well described to allow its consideration in this Bulletin.

It is also possible to classify impacts by the nature of the sources. There are principally two types of sources which are undergoing change. The first type consists of low-level area sources associated primarily with auto emissions, boat emissions, and unpaved roads. These sources are changing relatively slowly. The second source class is that of elevated point sources. This class is rapidly growing in the Lake Powell region, and hence it is the main subject of this Bulletin. Elevated point sources have been the target of a major multi-agency interdisciplinary study by the federal government.^{1,2} Concern has been expressed about their effects on scenic values, plant and animal life, and water quality.

GENERAL THEORY OF GAUSSIAN PLUME DISPERSION

The effect of ground level concentrations of air contaminants on plants depends upon the specific contaminants present, the length of exposure, and the environmental conditions of exposure (sunlight, humidity, soil moisture, and temperature).³ Plants can be damaged by high concentrations of gases for short periods of time or by lower concentrations during longer periods of time.

Effects on animals may be caused by either short-term or long-term exposures. For materials, effects are usually caused by long-term exposures. Thus it is important to be able to determine both the highest short-term exposure and the average long-term exposure.

The basic technique for calculating pollution concentration is the Gaussian

dispersion model. This formula describes the average contaminant concentration downwind from the source in terms of distance from the source and from the plume centerline. In general, the formula is given by equation (1). This mathematical expression is based on the assumption of a statistically normal pollutant concentration distribution in both the transverse and vertical directions. The assumption is that at any given instant of time the concentrations will not necessarily satisfy equation (1), but that over periods of time longer than a few minutes the average concentration will be described by the equation.

Equation (1) applies only to contaminants which are chemically non-reactive in the atmosphere, to periods of time when the atmospheric stability is uniform in space, and to the case of perfect reflection of contaminants from the ground. The dispersion coefficients σ_y and σ_z are usually based on field experiments and are dependent upon the distance x and the atmospheric stability. Various dispersion models are differentiated by the relations used for σ_y and σ_z and the modifications of the Gaussian relation which are used in more complex circumstances.

More complex situations arise because of differences in plume behavior related to differing conditions of atmospheric stability. For example, under unstable conditions the atmosphere has more vertical motion. The reason for this motion can be understood by considering the fate of a small parcel of air which is displaced upward. As the air undergoes displacement, it expands because the pressure decreases, and it cools. In an unstable atmosphere, the parcel cools less quickly than does the surrounding atmosphere, and it will tend to rise still more because it

$$(1) \quad \chi(x, y, z; H) = \frac{Q}{2\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] \right\}$$

- χ = concentration at the point x, y, z
 x = distance downwind from the source
 y = horizontal distance transverse from the plume centerline
 z = height above the ground
 H = height of the emission above ground
 Q = emission rate of the source
 u = mean wind speed
 σ_y = dispersion coefficient of the plume in a horizontal plane transverse to the direction of plume travel
 σ_z = dispersion coefficient of the plume in the vertical direction

will be warmer and less dense than the surrounding air. Had the initial displacement been downward, the parcel would have warmed more slowly than the surrounding atmosphere and would have continued to sink.

In a neutral atmosphere, a displaced parcel would find itself at the same temperature as its surroundings and therefore it would stop moving. In a stable atmosphere a parcel displaced either upward or downward tends to return toward its original position. Thus, vertical motion is suppressed.

The atmosphere tends to have neutral stability during high winds or cloudy conditions when the ground is neither heated nor cooled with respect to the air. During the daytime, when the sun heats the ground, the atmosphere becomes unstable. During the nighttime, when the ground ra-

diates heat away from the earth, the atmosphere stabilizes.

More complex situations arise from transitions in space or time from one atmospheric stability to another. For example, consider a case in which there is a stable layer adjacent to an unstable one. The stable layer will tend to inhibit vertical motion while the unstable layer will enhance it. Thus, a parcel near the boundary of the two layers will tend to move into the main body of the unstable layer. In the same way, a smoke plume will be reflected from a stable layer. With a stable layer aloft and an unstable layer below, the plume may be reflected back and forth between the ground and the stable layer. Through consideration of the various paths by which a given plume parcel might reach the point (x, y, z) , Bierly and Hewson⁴ developed the relationship given by equation (2), where J is

$$(2) \chi(x, y, z; H) = \frac{Q \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right]}{2\pi \sigma_y \sigma_z u} \left\{ \exp \left[-\frac{1}{2} \left(\frac{z-H}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z+H}{\sigma_z} \right)^2 \right] \right. \\ \left. + \sum_{N=1}^{N=J} \left\{ \exp \left[-\frac{1}{2} \left(\frac{z-H-2NL}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z+H-2NL}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z-H+2NL}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{z+H+2NL}{\sigma_z} \right)^2 \right] \right\} \right\}$$

the maximum number of reflections considered and L is the depth of the mixed layer. In this expression the first term within the outer brackets represents the contribution associated with contaminants which travel directly to the point (x, y, z) with no layer or surface reflections. The second term gives the contribution from contaminants which have been reflected by the surface only. Within the summation, the first term represents one surface and one mixing layer reflection, the second term represents one mixing layer reflection, and the last term represents reflections from the surface, the mixing layer, and the surface again. Each increment in the index adds one surface and one layer reflection.

The role of the multiple reflections is to mix the plume uniformly between the surface and the mixing layer. Accordingly, an approximation which has been developed to treat this situation is

$$(3) \chi(x, y, z; H) = \frac{Q \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right]}{\sqrt{2\pi} \sigma_{yt} L u}$$

This relationship⁵ is used for distances beyond $2x_m$ where x_m satisfies the equation

$$(4) 2.15 \sigma_z (x_m) = L.$$

For distances out to x_m , equation (1) is used, and for distances between x_m and $2x_m$ the concentrations are determined by connecting the concentrations at x_m and $2x_m$ by a straight line on a log-log plot.

The other case of concern is that of the transition from a stable layer to an unstable layer under the influence of solar heating of the ground. This particular condition is called inversion breakup or fumigation. In this case, a plume is emitted into a stable atmosphere and drifts downwind until the stable layer between the stack top and the bottom of the plume is eliminated. Normally there is some plume rise due to buoyancy or momentum so that the bottom of the plume and the stack top are somewhat different. Thus the breakup occurs at some distance x_f (the breakup distance) downwind. From this point the concentration is given by⁶

$$(5) \chi(x, y, z; H) = \frac{Q \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right]}{\sqrt{2\pi} \sigma_{yf} L_{\text{eff}} u}$$

where L_{eff} in this case is the height of the layer that is mixed to the ground during breakup. The notation σ_{yf} is used to indicate that an additional term is added to σ_y to account for the additional spread of the plume as it descends. The added term is different for various models and will be discussed in the context of these models.

In the three models, the parameters σ_y and σ_z are calculated from the following equations:

$$(6) \sigma_z = 1000 A x^b$$

$$(7) \sigma_y = 1000 C x^d$$

where the parameters A, b, C, and d are functions of the atmospheric stability and, perhaps, the wind speed.

For a source with significant buoyancy or momentum, the stack height H_s will be less than the plume height because the plume will continue to rise beyond the stack top. The plume rise ΔH , in models used by the Tennessee Valley Authority^{7,8} and Briggs⁹ for unstable conditions, is

$$(8) \Delta H = \frac{(x_{FR})^{2/3} C_p F^{1/3}}{u} \quad x > x_{FR}$$

$$= \left(\frac{x}{x_{FR}} \right)^{2/3} \frac{(x_{FR})^{2/3} C_p F^{1/3}}{u} \quad x < x_{FR}$$

where

$$F = g V_s R_s^2 \left(1 - \frac{\rho_s}{\rho_a} \right)$$

x_{FR} = distance to the point of full plume rise
 K = a constant for each model
 g = acceleration due to gravity
 V_s = exit velocity
 R_s = stack radius
 ρ_s = density of stack gases
 ρ_a = density of ambient air at stack top

The Briggs' plume rise formula for stable conditions is

$$(9) \Delta H = \frac{2.9 F^{1/3}}{(us)^{1/3}} \quad x > \frac{2.4 u}{s^{1/2}}$$

where

$$(10) s = \frac{g}{T_a} \frac{d\phi}{dz}$$

where T_a is the ambient temperature, and $\frac{d\phi}{dz}$ is the potential temperature gradient, related to the temperature gradient by

$$(11) \frac{d\phi}{dz} = 0.01 + \frac{dT_a}{dz}$$

The other differences between the two plume rise models as applied to power-plant plumes are summarized in Table 1.

The limitation to idealized point sources can be relaxed through a procedure suggested by Turner¹² which replaces an actual source with an equivalent source positioned further upwind. For example, a source which initially has a crosswind extent of S, that is, the effluent is uniformly distributed over a length S transverse to the wind, can be considered to have an effective horizontal dispersion coefficient σ_{y0} . Usually, one presumes that the plume is defined by portions which are at least 10 percent of the maximum. The value of y_a , the transverse distance, where the concentration is equal to 10 percent of the maximum, is found from the expressions

Table 1: Parameters in Plume Rise Models

Model	Applicable Conditions	x_{FR} (meters)	C_p	ρ_s/ρ_a
NOAA ¹⁰ -Briggs	Neutral - Unstable	10 H_s	1.6	T_a/T_s
TVA ¹¹	Neutral - Stable	1219	1.58 - 41.4 $\frac{d\phi}{dz}$	1.02 T_a/T_s

$$(12) \exp \left[-\frac{1}{2} \left(\frac{y_a}{\sigma_{y0}} \right)^2 \right] = 0.10$$

$$(13) y_a = 2.15 \sigma_{y0}$$

Thus, the initial plume half-width is $2.15 \sigma_{y0}$ and the plume width is $4.3 \sigma_{y0}$. Since the initial plume width is S , the equivalent horizontal plume dispersion parameter is

$$(14) \sigma_{y0} = \frac{S}{4.3}$$

The virtual source is located at a distance x_0 such that

$$(15) \sigma_y(x_0) = \frac{S}{4.3}$$

and the actual σ_y used for distances further downwind is

$$(16) \sigma_y = \sigma_y(x+x_0)$$

The estimate for the maximum concentration along the plume centerline can be extended to longer periods of time, if conditions remain relatively steady. The method suggested by Turner¹³ gives

$$(17) \chi_T = (T)^{-0.17} \chi_{1hr}$$

where the notation χ_T refers to the average concentration over T hours and χ_{1hr} refers to the 1-hour average concen-

tration. If the particular condition lasted only T hours out of T_L hours, where T_L is the time period of interest, and there was no contribution during the remaining $T-T_L$ hours, the average over the T_L hours would be

$$(18) \chi_{T_L} = \frac{T}{T_L} \chi_T$$

More generally, where there are N separate conditions, each lasting a period T_i with an average concentration χ_{T_i} over the period T_i , the average over T_L would be

$$(19) \chi_{T_L} = \sum_{i=1}^N \frac{T_i}{T_L} \chi_{T_i}$$

In those instances where the wind conditions shift from one condition to the next, the appropriate value of y_i , the off-centerline distance, must be found for each condition. Then the average concentration is found by

$$(20) \chi_{T_L} = \sum_{i=1}^N \frac{T_i}{T_L} \chi_{T_i} \exp \left[-\frac{1}{2} \left(\frac{y_i}{\sigma_{y_{T_i}}} \right)^2 \right]$$

where χ_{T_i} refers to the centerline concentration and the value $\sigma_{y_{T_i}}$ is related to the 1-hour value by

$$(21) \sigma_{y_{T_i}} = (T)^{0.17} \sigma_{y_{1hr}}$$

with σ_{y1hr} the horizontal dispersion parameter for a 1-hour period.

For relatively long averaging times, as long as a year, the assumption is made that the wind direction is uniformly distributed over a sector. This assumption leads to the conclusion that the concentrations vary with distance only. For NS wind sectors (NS is the number of sectors), the average concentration \bar{x}_i , over the sector will be

$$(22) \quad \bar{x}_i = \sqrt{2\pi} \frac{\sigma_y \chi(x, 0, z; H)}{\left(\frac{2\pi x}{NS}\right)}$$

For the entire year considering all wind directions, speeds, and atmospheric stabilities, the average is:

$$(23) \quad \bar{\chi}(x, \theta) = \sum_u \sum_N \sqrt{2\pi} \frac{\sigma_{yuN} \chi_{uN}(x, 0, z; H) f(\theta, u, N)}{\left(\frac{2\pi x}{NS}\right)}$$

where $f(\theta, u, N)$ is the frequency of winds in sector θ , with speed u and atmospheric stability N .

SPECIAL CHARACTERISTICS OF THE SOURCES IN THE LAKE POWELL REGION

The principal new source in the Lake Powell region is the coal-fired Navajo Generating Station, including its three stacks and its multiple cooling towers. This large plant burns low-sulfur, low-ash coal. The principal emissions are sulfur dioxide, particulates, and nitrogen oxides. In addition, releases of fluorides and a number of trace elements are also of concern. The principal emissions from cooling towers are particulates contained in the drift losses. Of concern are the

deposition and possible effects of these salts in the vicinity of the powerplant.

The region itself has some specific characteristics which modify the traditional air pollution considerations. The most important of these factors are the presence of high terrain, the exceptional scenic qualities of the area, and the extensive recreational use of the region. Until our research began, most of the dispersion work done by others dealt only with ground level concentration of contaminants.

GROUND LEVEL CONCENTRATIONS

Knowledge of ground level concentrations is important for the consideration of the direct action of contaminants. Three models have been used to deal with the specific characteristics of the Lake Powell region. The first was the Tennessee Valley Authority (TVA) model¹⁴ modified to consider high terrain; the second was the so-called NOAA model¹⁵ (developed by investigators within the National Oceanic and Atmospheric Administration as part of the Southwest Energy Study); and the third was the AeroVironment (AV) model¹⁶ developed by Dr. Paul McCready on behalf of the utilities in the Navajo Power Project.

In the modified TVA model, high terrain is taken into account in the case of limited mixing (or trapping). In this formulation, the mixing depth was reduced by the height of the terrain above the plant site as long as the terrain height was less than half of the mixing depth. It was assumed that the plume would not drift toward terrain which was higher than half of the mixing depth.

The NOAA model follows the recommendations of Turner¹⁷ and permits subtraction of terrain height from the plume height under stable conditions or inversion breakup. This assumption permits the plume to be at ground level for terrain height at or above the calculated plume height.

The AeroVironment model makes the same assumption about the role of terrain height, but the dispersion is treated differently. In this model, much greater dispersion is assumed to exist near rough terrain. Furthermore, an initial dilution is added during the plume rise. Both the NOAA and AeroVironment models use the Briggs' plume rise.⁹

The initial dilution is treated in the following fashion. First, a mixing ratio is defined as the mass of air entrained by the rising plume divided by the mass of the stack gases. The principal assumption is that the net change of potential temperature $\Delta\phi$ is zero, implying that

$$(24) \quad m\Delta\phi_s + M \Delta \frac{\phi_a}{2} = 0.$$

The subscript s refers to the stack, the subscript a refers to ambient conditions, and m is the mass of the effluent gases. The entrained mass M is assumed to have a temperature midway between the

ambient temperature at stack height and the ambient temperature at plume height. From the definition of potential temperature the following relationships are valid:

$$(25) \quad \Delta\phi_s = T_a - T_s + \frac{d\phi}{dz} \Delta H$$

and

$$(26) \quad \Delta\phi_a = \frac{d\phi}{dz} \Delta H$$

so that

$$(27) \quad \frac{M}{m} = \frac{2(T_s - T_a - \frac{d\phi}{dz}\Delta H)}{\frac{d\phi}{dz}\Delta H}$$

The initial σ_y and σ_z can be found by equating the contaminants at plume height to those at the stack top. Since a Gaussian plume has a mathematically infinite width, some definition of the plume must be used. For this purpose, we define the plume as that portion of the atmosphere containing 90 percent of the plume. At plume height,

$$(28) \quad 90 \text{ percent of the contaminants} \\ = 15.2 \sigma_y \sigma_z \frac{m}{M} \rho_a u.$$

At stack height

$$(29) \quad 90 \text{ percent of the contaminants} \\ = 0.90 \pi R_s^2 \rho_s V_s.$$

Equating the above two expressions, we find:

$$(30) \quad \sigma_{y0} \sigma_{z0} = \frac{0.90}{15.2} \frac{M}{m} \pi \frac{V_s R_s^2}{u} \frac{T_a}{T_s}.$$

This relationship is used to define the virtual distance x_0 as in equation (16).

The remaining differences among the models are summarized in Table 2. There are additional differences between the two models which deal with trapping and inversion breakup. These differences are summarized in Table 3.

There is one additional difference which was suggested by investigators with Dames & Moore.²¹ The mixing layer height may be less than the calculated plume height and still confine the plume. The minimum mixing height permitted by such modeling is given by

$$(31) \quad L = H_s + \frac{2}{3}\Delta H.$$

The NOAA investigators did not describe any such adjustment.

With the use of the explicit forms for σ_y and σ_z , the maximum ground level concentration for a given stability and wind speed can be calculated. The maximum x_{\max} , is

$$(32) \quad x_{\max} = \frac{Q(1000A)^{d/b} \exp\left[-\frac{1}{2}\left(1+\frac{d}{b}\right)\right]}{\pi u(1000C) \left(\frac{H}{\sqrt{1+\frac{d}{b}}}\right)^{1+d/b}}$$

which occurs at a distance

$$(33) \quad x_{\max} = \left(\frac{H}{\sqrt{1+\frac{d}{b}} 1000A}\right)^{1/b}.$$

These formulae are valid for the cases where the terrain can be considered flat

and where the stability is uniform in the region of interest. For fumigation or trapping conditions the maximum concentration will generally occur at the minimum distance for which the breakup or trapping equations are valid. The presence of high terrain can significantly modify these considerations.

The principal concern with respect to ground level concentrations has been focused on sulfur dioxide and to a lesser extent on nitrogen oxides and particulates. The predicted emission rates for the Navajo plant²² and the relevant stack parameters are presented in Table 4. There is a regulation currently in existence which, if not modified, will change these values. However, the tabulated values are correct until at least 1977, and the regulation itself is still being questioned.

Predictions based upon these parameters have been made for maximum ground level concentrations in three cases. In the first case, terrain height has been ignored, giving the conventional estimate. In the second case, intermediate terrain height, a maximum of approximately $[(\Delta H + H_s)/2]$, has been considered. The terrain profile is shown in Figure 1. In the third case, full plume height terrain has been considered. In all cases, the estimates were made both for the actual terrain near Navajo and for "worst case terrain." These predictions are presented in Tables 5 through 7.

In Table 6, the 10-kilometer values for the high terrain of Leche-e Rock at the Navajo site have been reduced by a factor of two because the rock is a topologically slender feature which would not give the factor of two associated with total reflection at ground level.

Table 2: Characteristics of Various Models

Model	Condition	A	b	C	d	Effective Height	Terrain Height
NOAA ¹⁸	Unstable-A	0.45	2.1	0.20	0.88	$H_S + \Delta H$	All Heights
	Unstable-B	0.11	1.1	0.16	0.88	$H_S + \Delta H$	All Heights
	Unstable-C	0.061	0.92	0.10	0.88	$H_S + \Delta H$	All Heights
	Neutral-D	0.033	0.60	0.070	0.88	$H_S + \Delta H$	All Heights
	Stable-E	0.023	0.51	0.052	0.88	$\begin{cases} \circ \\ H_S + \Delta H - H_T \end{cases}$	$H_T > H_S + \Delta H$ $H_T < H_S + \Delta H$
	Very Stable-F	0.015	0.45	0.035	0.88	$\begin{cases} \circ \\ H_S + \Delta H - H_T \end{cases}$	$H_T > H_S + \Delta H$ $H_T < H_S + \Delta H$
TVA ¹⁹	Neutral	0.0694	0.75	0.0747	0.75	$H_S + \Delta H$	
	Very Stable	0.02862	0.21	0.05896	0.55	$H_S + \Delta H$	
	Trapping	0.02862	0.21	0.05896	0.55	$L - H_T$	$H_T < L/2$
AV ²⁰	Very Stable	$\frac{0.081}{\sqrt{u}}$	0.50	$\frac{0.2569}{\sqrt{.00461u + .01188}}$	0.50	$\begin{cases} \circ \\ H_S + \Delta H - H_T \end{cases}$	$H_T > H_S + \Delta H$ $H_T < H_S + \Delta H$

Table 3: Model Differences for Inversion Breakup and Trapping

Model	Condition	Minimum Distance At Which Model Applied	σ_y	σ_z
NOAA	Trapping	$2x_m$ with $2.15\sigma_z(x_m) = 0.75L$	σ_y Unstable or Neutral	σ_z Unstable or Neutral
TVA	Trapping	3 km	$\sigma_{yt} = \sigma_y + [L/1.1 - 2.15\sigma_z](0.47)$ σ_y Stable	σ_z Stable
NOAA	Inversion Breakup	$\frac{1}{2}x_F = \frac{0.13u}{2} \left(\frac{\rho}{1200g/m^3} \right) \left(\frac{d\phi/dz}{0.03C/m} \right) \left[\frac{\Delta H - H_T}{2} \left(\frac{\Delta H - H_T}{2} + H_S \right) \right]$	$\sigma_{yf} = \sigma_y + \frac{1}{8}(H_S + \Delta H - H_T)$ σ_y Stable	σ_z Stable
TVA	Inversion Breakup	$x_F = \frac{0.24\rho_a}{4K_d} (H_f^2 - H_s^2)$ with $H_f = 2.15\sigma_z + H$ $K_d = 24,000 \exp[-98.08 \frac{d\phi}{dz}]$ $\rho_a = \frac{352,330}{T} a$	$\sigma_{yf} = \sigma_y + 0.47H$ σ_y Stable	σ_z Stable

Table 4: Stack Parameters and Emission Rates for Navajo Generating Station

Units	Height	Radius	100% Load Velocity	Temperature	Emission Rates		
					SO ₂ (g/sec)	NO _x (g/sec)	Particulates (g/sec)
1,2,3	236m	3.8m	30.2 m/s	350° K	604	612	43.7



Figure 1: Terrain Height as a Function of Distance South of the Navajo Generating Station.

Table 5: Navajo Generating Station Maximum Predicted
1-Hour SO₂ Concentrations--Flat Terrain

Model	Condition Stability	Wind Speed (m/s)	Distance (km)	Concentration (µg/m ³)
TVA	Neutral	4	12.2	197
TVA	Neutral	6.9	8.1	206
TVA	Neutral	8	7.4	205
TVA	Trapping	3	3	496
TVA	Trapping	3.5	3	499
TVA	Trapping	4	3	496
TVA	Fumigation	2	23.6	688
TVA	Fumigation	3	33.3	416
NOAA	A	2	1.7	356
NOAA	B	3	6.2	120
NOAA	C	5	10.7	51
NOAA	D	10	43	28
NOAA	Trapping-A	2	2.2	601
NOAA	B	3	6.2	276
NOAA	C	5	9.8	261
NOAA	D	8	39	92
NOAA	Fumigation-F	1	16	5206
AV	F	1	18.7	1086
AV	F	2	25	596

It is evident that the various models give somewhat different predictions. The TVA model predicts the highest concentrations during the trapping conditions, which last for 1 to 6 hours and can occur over a significant area surrounding the plant. The TVA model gives a slightly higher fumigation value with a wind speed of 1 meter per second, but such a wind speed is below the range for which the plume rise model is considered valid.

Under the NOAA model, very high concentrations are produced during inversion breakup or during stable plume interaction

with high terrain. The inversion breakup occurs some distance downwind and usually lasts for less than 1 hour; it would normally occur in the mid-morning hours. The stable plume interaction would occur only in a few specific locations where high terrain is present; it would normally occur during nighttime or early morning hours.

The highest concentrations under the AeroVironment (AV) model occur during stable plume passage over terrain of intermediate height. These concentrations could persist for several hours during

Table 6: Navajo Generating Station Maximum Predicted 1-Hour SO₂ Concentrations--Intermediate Terrain

Model	Condition	Wind Speed (m/s)	Distance (km)	Concentration (µg/m ³)
TVA	Trapping	4	10	1,035
TVA	Trapping	3.5	11	1,050
NOAA	Fumigation	1	10	9,913
AV	F	1	10	3,478
AV	F	2	10	2,774
TVA	Trapping	3.5	3 (Worst Case) ^a	1,620
NOAA	Fumigation	1	3 (Worst Case) ^b	23,713

^aHypothetical worst case where distance is that of maximum concentration

^bDifferent hypothetical worst case in which distance is to high terrain rather than to the maximum concentration.

Table 7: Navajo Generating Station Worst Case SO₂ Plume Concentrations--High Terrain

Distance (km)	AV Hypothetical (µg/m ³)	AV Prediction Navajo Site (µg/m ³)	NOAA Hypothetical (µg/m ³)	NOAA Prediction Navajo Site (µg/m ³)
5	11,000		111,000	
10	5,500	2,752	46,100	23,000
15	3,670		27,500	
20	2,750		19,200	
25	2,200		14,400	
30	1,830	1,830	11,800	11,800
50	1,100	1,100	6,700	6,700

nighttime or early morning hours. They are not restricted to a few locations.

The problem of the frequency of high concentrations has two components: (1) frequency of the condition which gives rise to the high concentrations, and (2) the probability that any given location will receive high concentrations during the condition. This latter feature is dependent primarily upon the width of the plume and the distance to the maximum concentration under the condition of interest.

According to the AV model, there is only one point which will receive exactly the peak concentrations. For any specified fraction of the peak value, a band can be determined that is exposed to equal or greater concentrations. For example, the distance on either side of the plume centerline that will contain concentrations equal to 80 percent or more of the maximum is found from

$$(34) \quad \exp \left[-\frac{1}{2} \left(\frac{y_{0.8}}{\sigma_y} \right)^2 \right] = 0.8,$$

thus

$$(35) \quad y_{0.8} = 0.668 \sigma_y.$$

Thus, a total band width $2y_{0.8} = 1.34\sigma_y$ would be exposed to concentrations equal to 80 percent or more of the peak value. If the wind were in the appropriate sector among NS sectors, the probability that any given station, at the appropriate distance, would receive 80 percent of the maximum is

$$(36) \quad P = \frac{1.34\sigma_y}{\frac{2\pi x}{NS}}$$

Table 8 gives values for some of the more important conditions.

Next we consider what concentrations might be expected at Page, Arizona, 6 kilometers west of the Navajo plant. Since existing monitoring includes only the impact of the plant Unit 1, all total predictions for the total plant must be divided by 3. Table 5 indicates that the most likely condition to produce significant concentrations would be B stability with an expected maximum of $40\mu\text{g}/\text{m}^3$. The relative frequency for 80 percent of this value would be

$$P = \frac{3.41}{6} (0.774) = 0.44 .$$

The frequency of winds for the east, during B stability, is only 0.004; thus the probability is about 0.0018. During 60 days (1,440 hours), about 2.6 hours with readings above $32\mu\text{g}/\text{m}^3$ (0.012 ppm) would be expected according to the NOAA model. If the particular instance of B stability were accompanied by the presence of a mixing layer near expected plume height, higher concentrations could occur. However, such a combination of wind direction, stability, and mixing height would be even less frequent than the situation described above.

The foregoing discussion is primarily an application of models developed by other investigators in the manner they have applied them. We have used a more unified format, the development of formulas for maximum concentration, and some slight extensions of parameter ranges. The AV model was originally applied only to high terrain. The TVA model was applied with higher stabilities ($dT/dz = 0.025^\circ\text{C}/\text{meter}$) than are normally assumed. Aside from these differences, we have used the models in the same way as have other workers in the Southwest. However, there are additional problems which are not addressed in these models.

Table 8: Relative Frequencies of Worst Cases Associated with Navajo Generating Station Emissions

Model	Terrain	Conditions ^a	80 Percent Concentration ($\mu\text{g}/\text{m}^3$)	Relative Frequency
AV	Flat	F; u = 1m/sec	869	0.10
AV	Intermediate	F; u = 1m/sec	2,782	0.14
TVA	Flat	Trapping	400	0.34
TVA	Intermediate	Trapping	840	0.094
NOAA	Flat	Fumigation u = 1m/sec	4,165	0.10
NOAA	Intermediate	Fumigation u = 1m/sec	7,930	0.10

^aConditions refer to those described in Tables 5 and 6; F is Pasquill stability classification

One problem is related to the attachment of gases and fine particles to surfaces. This has been suggested as a mechanism which will reduce the ground level concentrations. In order to deal with this question, equation (1) must be modified to relax the assumption of perfect reflection from the ground. The second term in the bracketed expression represents the portion of the plume which is reflected at ground level. If we consider that SRF (surface reflection factor) is the fraction of the plume which is reflected by the ground after a surface interaction, we obtain (37):

Where there is no mixing layer, the ground level concentrations could be reduced to one-half the expected level if all of the plume interacting with the ground were absorbed. This treatment would not apply to a sampler which is screened by vegetation above the sampler height.

In the same fashion, surface absorption may be incorporated in the mixing layer formulation. Each surface reflection term in equation (2) must be multiplied by SRF. Thus, if a particular term represents K ground reflections, it would have a coefficient of SRF^K . Equation (38) is thus obtained from (37):

$$(37) \quad \chi(x, y, z; H) = \frac{Q \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]}{2\pi \sigma_y \sigma_z u} \left\{ \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right] + \text{SRF} \exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] \right\}.$$

$$\begin{aligned}
 (38) \quad \chi(x, y, z; H) = & \frac{Q \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]}{2\pi \sigma_y \sigma_z u} \left\{ \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right] + \text{SRF} \exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] \right. \\
 & + \sum_{N=1}^{N=J} \left\{ \text{SRF}^N \exp\left[-\frac{1}{2}\left(\frac{H+2NL-z}{\sigma_z}\right)^2\right] + \text{SRF}^{N-1} \exp\left[-\frac{1}{2}\left(\frac{z+H-2NL}{\sigma_z}\right)^2\right] \right. \\
 & \left. \left. + \text{SRF}^N \exp\left[-\frac{1}{2}\left(\frac{H-2NL-z}{\sigma_z}\right)^2\right] + \text{SRF}^{N+1} \exp\left[-\frac{1}{2}\left(\frac{z+H+2NL}{\sigma_z}\right)^2\right] \right\} \right\} .
 \end{aligned}$$

In this case, the role of the surface reflection factor is twofold: (1) values of SRF less than unity reduce the peak concentrations by a factor of $(1+\text{SRF})/2$, and (2) low values of SRF cause the concentrations to drop off much more rapidly with distance. In Figure 2 the estimated sulfur oxide concentrations for low wind speed and A stability are shown. Figure 3 is an analogous plot for the case of D stability. In both instances the mixing height is set at stack height plus two-thirds of the predicted plume rise.

There are a number of uncertainties in these models. The first uncertainty relates to the actual behavior near high terrain. It seems clear that stable plumes do interact with high terrain on some occasions. However, the appropriate dispersion parameters for such interaction remain unknown. The second problem is that inversion breakup is difficult to monitor because the breakup usually occurs at a considerable distance (e.g., 15 to 45 kilometers) and affects a relatively small area. This latter feature results from the very narrow plume which is characteristic of inversion breakup. The discrepancy between the NOAA and TVA predictions illustrates the degree of uncertainty. Experience in Pennsylvania²³ indicates that values considerably higher than the

TVA prediction, but significantly less than the NOAA prediction, can occur. Another major concern is limited mixing and choice of the appropriate minimum layer height and stability to be used. Again, the Pennsylvania experience²⁴ would indicate that A or B stability with mixing heights considerably less than predicted plume height can be expected. In one instance in the Pennsylvania study²⁵ the stability as determined by the temperature gradient was A stability only near the surface; however, the plume behaved as though it were in an A-stability limited mixing situation. Another variable is the role of contaminant conversion. This will be discussed later in another section.

IMPACTS OF PLUMES ON LIGHT TRANSMISSION

Visual range is the distance at which the average observer can just distinguish a high contrast object. It is very long in the Lake Powell region.²⁶ In addition, the region includes a great deal of terrain relief which is considered to enhance the recreational value of the area. Significant aesthetic value of the region might be lost if the visual range were to be appreciably decreased through some activity.

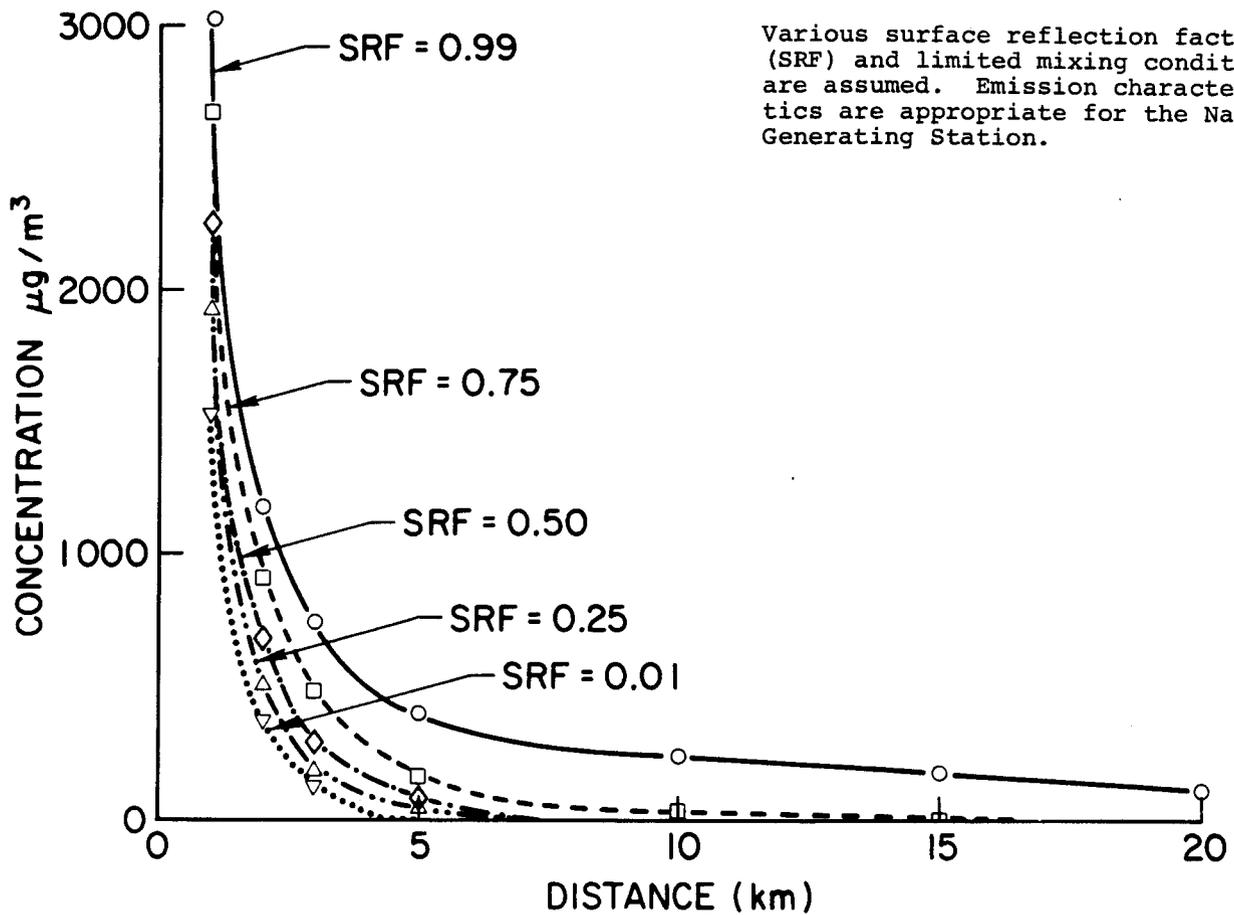


Figure 2: Calculated Ground Level Sulfur Oxide Concentrations During Class A Stability.

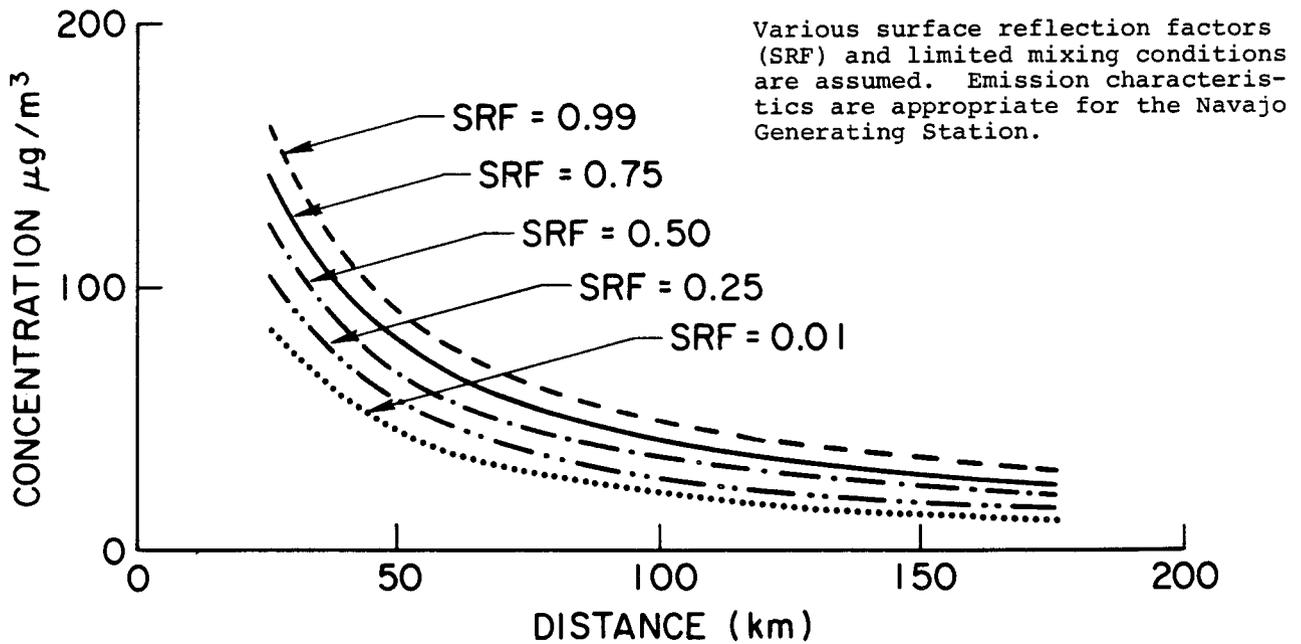


Figure 3: Calculated Ground Level Sulfur Oxide Concentrations During Class D Stability.

Some plumes from powerplants have been implicated in visibility reductions in other areas. For example, the plume from a natural-gas-fired facility in California has produced considerable public concern²⁷ and has been tracked for a distance of 55 miles.²⁸ A coal-fired powerplant in New Mexico has produced degradation of visibility over 100 miles downwind.²⁹

Reduced light transmission through powerplant plumes is related to the concentrations of particulates and nitrogen dioxide. The particulates are from three sources: (1) fly ash emitted from the stacks; (2) sulfates from the conversion of sulfur oxides; and (3) nitrates from the conversion of nitrogen oxides. The nitrogen dioxide either is directly emitted from the stacks or is produced from the oxidation of nitric oxide which is emitted from the stacks. The latter is probably the dominant process. In either case, conversion of one contaminant to another must be included in dispersion modeling.

The conversion of one contaminant to another can be treated through a modification of the source strength Q . For an exponential decay the source strength for the primary contaminant is:

$$(39) \quad Q_p = Q_o \exp\left[-\frac{0.693(x/u)}{\tau}\right].$$

Q_o is the release rate at the stack, x is the distance downwind, u is the wind speed, and τ is the half-life. For a secondary contaminant which is produced from a primary contaminant through chemical conversion we have:

$$(40) \quad Q_s = Q_o \text{MCF} \left[1 - \exp\left(-\frac{0.693x}{u\tau}\right)\right].$$

MCF denotes the ratio of the mass of a molecule of secondary contaminant to the mass of a molecule of primary contaminant.

The choice of an exponential decay law has not been well tested. There are theoretical reasons why the rate of reaction should be proportional to the square of the concentration of the primary contaminant. Exponential decay would imply that the rate of reaction is proportional to the concentration itself. However, since the question is not resolved, the assumption of exponential decay appears appropriate at this time.

Under the assumption that the plume is completely confined between the observer and the object he is viewing, the mass of the contaminant per unit area perpendicular to the viewing direction is:

$$(41) \quad C_m = \int_{-\infty}^{+\infty} \chi(x, y, z; H) dy \\ = \sqrt{2\pi} \chi(x, 0, z; H) \sigma_y$$

From equation (1) this is merely:

$$(42) \quad C_m = \frac{Q_{\text{eff}}}{\sqrt{2\pi} \sigma_z u} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\}.$$

Q_{eff} is the adjusted source strength given by equation (39) or (40).

The integrated mass can be multiplied by the extinction coefficient per unit mass, denoted SRM (scattering area to mass ratio), to obtain the total light

extinction along the optical path. The visual range for an observer looking through the plume is:

$$(43) \quad V_r = V_{rb} - \frac{V_{rb}}{3} \sum_i \text{SRM}_i C_{mi}.$$

The term V_{rb} denotes the background visual range and the subscript i refers to the particular contaminant, e.g., sulfate, nitrate, or fly ash. The factor of 3.0 is based on an assumed contrast threshold of 0.05 for the average observer.

A major problem is the choice of the appropriate value for the half-life of sulfur dioxide or nitrogen dioxide. A number of experiments have been conducted for sulfur dioxide under a variety of circumstances. The experiments indicate that its half-life is very long in laboratory experiments with clean air and low humidities. However, the half-life becomes rather short (less than 1 hour) for atmospheres contaminated with other compounds. A number of studies^{30,31,32,33,34} have been conducted on powerplant effluents or simulated powerplant effluents; the half-life ranged from less than 1 hour to a few days. A typical value would probably be about 3 hours.

Much less work has been done on nitrates produced from nitrogen oxides. Particulate nitrate samples collected in cities indicate that such conversions occur with somewhat longer half-lives than those for sulfates. The conversion of nitric oxide to nitrogen dioxide is much more rapid. Measurements near a large Southwestern powerplant³⁵ indicated that approximately 40 percent of the total nitrogen oxides was in the form of nitrogen dioxide within a short distance of the plant.

The calculation of visual range also requires knowledge of the values of SRM for the fly ash, sulfate, and nitrate. These values are influenced by the composition of the material and the size distribution of the particulates. For nitrates and sulfates, the values used here were obtained from an approximation for Mie scattering,³⁶ applied to size distribution measured in the Los Angeles Basin.³⁷ The SRM values for fly ash were obtained using the same approximation, but with an estimated size distribution. The estimates were based on characteristics of the collectors³⁸ and on size distributions measured for coal-fired powerplants.³⁹ There are significant uncertainties in these calculations. The values of SRM for nitrates and sulfates are near the average for undistinguished particulates,⁴⁰ while the fly ash values are higher but still within the range measured in the atmosphere. The values of half-life, mass conversion factor, and extinction per unit mass are presented in Table 9. These values were used with the models described above to estimate visual ranges across the Navajo plume (Table 10). The values denoted by < indicate that the plume would be opaque. The number listed gives the approximate plume width. A value of 140 kilometers was used for the background visual range.⁴¹

The various models all suggest that significant impairment of visibility is to be expected for stable conditions, or for low wind speed and neutral stability. For unstable conditions or neutral conditions with high speeds, little effect is expected.

DEPOSITION OF CONTAMINANTS

Recently, there has been increased attention devoted to problems which may

Table 9: Assumptions Used in Visibility Calculations

Material	Conversion Half-Life (hours)	Mass Conversion Factor	Extinction Per Unit Mass ($m^2/\mu g$)
Fly Ash	-	-	7×10^{-6}
Particulate Sulfate	3	1.5	3.56×10^{-6}
Particulate Nitrate	9	1.35	4.55×10^{-6}

arise from the deposition of materials from the air onto surfaces. Examples of deposition include heavy metal buildups around a powerplant near Lake Michigan,⁴² acid rain in Sweden,⁴³ and heavy metal poisoning of livestock.⁴⁴ Mercury from powerplants has been suggested as a contributor to high mercury levels in a Southwestern lake.⁴⁵

In the Lake Powell region, an additional consideration is the possible impairment of water quality through deposition of nitrates or phosphates on the lake's watershed. Significant additions of such materials might produce algal blooms. The deposition could occur through transport in rainwater (wet deposition) or through impaction of fine particulates on surfaces (dry deposition).

A theoretical framework for approaching this problem may be developed by considering the flux of contaminants leaving the source. The total outward flux is:

$$(44) \quad F^+ = \int_0^L \int_{-\infty}^{\infty} u \chi(x, y, z; H) dy dz.$$

The L in the outer integration is the mixing layer height. In cases where the atmosphere is uniform L approaches infinity ($L \rightarrow \infty$). In this case, we are considering a contaminant (for example, fly ash) which does not decay; thus the only loss mechanism is that of surface deposition. The amount of material lost between x and $x + dx$ is:

$$(45) \quad F^+(x) - F^+(x+dx) = - \frac{dF^+}{dx} dx.$$

All of this material must be deposited in an area given by

$$(46) \quad Ar = 2\pi x dx.$$

Thus, the deposition rate is

$$(47) \quad D(x) = - \frac{1}{2\pi x} \frac{dF^+}{dx}.$$

Using equations (44) and (38), the flux is found in equation (48):

Table 10: Predicted Visual Range (V_R) Across the Navajo Generating Station^r Plume

Model	Stability	Wind Speed (m/sec)	Distance Downwind (km)	V_R (km)
NOAA	A		25	140
NOAA	B		25	140
NOAA	C		25	119
NOAA	D		25	69
NOAA	E		25	<4.
NOAA	F		25	<2.6
NOAA	C		50	114
NOAA	D		50	53
NOAA	E		50	<6.8
NOAA	F		50	<4.4
NOAA	C		100	118
NOAA	D		100	43
NOAA	E		100	<12
NOAA	F		100	<8
TVA	Neutral	2.5	25	66
TVA	Neutral	5	25	117
TVA	Neutral	8	25	130
TVA	Neutral	2.5	50	73
TVA	Neutral	5	50	118
TVA	Neutral	8	50	130
TVA	Neutral	2.5	100	85
TVA	Neutral	5	100	120
TVA	Neutral	8	100	130
TVA	Stable	3	25	<1.4
TVA	Stable	--	50	<2.0
TVA	Stable	--	100	<3
TVA	Stable	2	25	<2.1
TVA	Stable	2	50	<2.9
TVA	Stable	2	100	<4.1

$$\begin{aligned}
(48) \quad F = \frac{Q}{2} & \left\{ \operatorname{erf}\left(\frac{L-H}{\sqrt{2} \sigma_z}\right) + \operatorname{erf}\left(\frac{H}{\sqrt{2} \sigma_z}\right) + \left[\operatorname{SRF} \operatorname{erf}\left(\frac{L+H}{\sqrt{2} \sigma_z}\right) - \operatorname{erf}\left(\frac{H}{\sqrt{2} \sigma_z}\right) \right] \right. \\
& + \sum_{N=1}^{N=J} \left\{ \operatorname{SRF}^N \left[\operatorname{erf}\left(\frac{H+2NL}{\sqrt{2} \sigma_z}\right) - \operatorname{erf}\left(\frac{H+2NL-L}{\sqrt{2} \sigma_z}\right) \right] + \operatorname{SRF}^{N-1} \left[\operatorname{erf}\left(\frac{2NL-H}{\sqrt{2} \sigma_z}\right) - \operatorname{erf}\left(\frac{2NL-H-L}{\sqrt{2} \sigma_z}\right) \right] \right. \\
& \left. \left. + \operatorname{SRF}^N \left[\operatorname{erf}\left(\frac{L+2NL-H}{\sqrt{2} \sigma_z}\right) - \operatorname{erf}\left(\frac{2NL-H}{\sqrt{2} \sigma_z}\right) \right] + \operatorname{SRF}^{N+1} \left[\operatorname{erf}\left(\frac{L+H+2NL}{\sqrt{2} \sigma_z}\right) - \operatorname{erf}\left(\frac{H+2NL}{\sqrt{2} \sigma_z}\right) \right] \right\} \right\}.
\end{aligned}$$

where

$$(49) \quad \operatorname{erf}(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-w^2} dw.$$

The total amount deposited prior to distance x is simply $Q \cdot F$. With the use of equations (47) and (48) we can find the deposition as shown in equation (50).

$$\begin{aligned}
(50) \quad D(x) = \frac{Qb}{(2\pi)^{3/2} x^2 \sigma_z} & \left\{ (L-H) \exp\left[-\frac{1}{2}\left(\frac{L-H}{\sigma_z}\right)^2\right] + H \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] + \operatorname{SRF} \right. \\
& \left\{ (L+H) \exp\left[-\frac{1}{2}\left(\frac{L+H}{\sigma_z}\right)^2\right] - H \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \right\} + \sum_{N=1}^{N=J} \left\{ \operatorname{SRF}^N \left\{ (L-H-2NL) \right. \right. \\
& \left. \exp\left[-\frac{1}{2}\left(\frac{L-H-2NL}{\sigma_z}\right)^2\right] + (H+2NL) \exp\left[-\frac{1}{2}\left(\frac{H+2NL}{\sigma_z}\right)^2\right] \right\} + \operatorname{SRF}^{N-1} \\
& \left\{ (L+H-2NL) \exp\left[-\frac{1}{2}\left(\frac{L+H-2NL}{\sigma_z}\right)^2\right] + (2NL-H) \exp\left[-\frac{1}{2}\left(\frac{2NL-H}{\sigma_z}\right)^2\right] \right\} + \operatorname{SRF}^N \\
& \left\{ (L-H+2NL) \exp\left[-\frac{1}{2}\left(\frac{L-H+2NL}{\sigma_z}\right)^2\right] + (H-2NL) \exp\left[-\frac{1}{2}\left(\frac{H-2NL}{\sigma_z}\right)^2\right] \right\} \\
& \left. \left. + \operatorname{SRF}^{N+1} \left\{ (L+H+2NL) \exp\left[-\frac{1}{2}\left(\frac{L+H+2NL}{\sigma_z}\right)^2\right] - (H+2NL) \exp\left[-\frac{1}{2}\left(\frac{H+2NL}{\sigma_z}\right)^2\right] \right\} \right\} \right\}.
\end{aligned}$$

Much simpler expressions are obtained if there is no mixing layer present.

$$(51) \quad F = \frac{Q}{2} \left[1 + \text{SRF} + (1 - \text{SRF}) \operatorname{erf} \left(\frac{H}{\sqrt{2} \sigma_z} \right) \right]$$

and

$$(52) \quad D(x) = \frac{Qb(1 - \text{SRF})}{(2\pi)^{3/2} x^2 \sigma_z} H \exp \left[-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2 \right]$$

These expressions give the average deposition at distance x if the specified stability persists throughout the period of interest. For the total annual deposition in the wind sector θ_i we have

$$(53) \quad D_t = \sum_s \frac{f(\theta_i, s) D(x, s)}{\frac{2\pi}{NS}},$$

where $f(\theta_i, s)$ is the frequency of wind direction θ_i and stability s .

Equation (51) implies that only half of the plume may interact with the ground in the absence of a mixing layer. In order for 90 percent of the lower half of the plume to interact, the distance must be such that

$$(54) \quad \operatorname{erf} \left(\frac{H}{\sqrt{2} \sigma_z} \right) \leq 0.1$$

which implies that

$$(55) \quad \sigma_z = 2.8 H.$$

For an interaction of half of the downward portion of the plume we find

$$(56) \quad \sigma_z = 0.96 H.$$

With a mixing layer present, the situation is much more complex but a similar result can be obtained for the upper half of the

plume if

$$(57) \quad \sigma_z = 2.8 (2L - H)$$

for 90 percent interaction or

$$(58) \quad \sigma_z = 0.96 (2L - H)$$

for 50 percent interaction.

For the stack emissions of a large powerplant, such as the Navajo plant at Lake Powell, Table 11 summarizes the distances for 50 percent and 90 percent interaction of the downwind diffusing portion of the plume.

The plume interacts rapidly for stabilities A through C, very slightly for stability D, and virtually not at all for stabilities E and F. Values beyond 100 kilometers are probably meaningless because the dispersion relations have not been tested at those distances. Furthermore, there is a significant likelihood that the stability conditions will change before the plume has traveled distances of over 100 kilometers. During transition from stable to unstable conditions, deposition is probably rather rapid.

The formulae developed earlier are directly applicable for the stack emissions, although some slight modifications are required for the cooling tower emissions. The first question relates to the plume rise. Hanna⁴⁶ suggests that the Briggs plume rise can be used if allowance is made for multiple sources. Others⁴⁷ indicate that the Briggs plume rise should be increased by about 10 percent for each additional tower if the spacing factor is less than 0.1. The spacing factor is defined as:

$$\text{SF} = \frac{\text{crosswind component of tower spacing}}{\text{plume rise for a single tower}}$$

For $SF > 0.25$, no correction is required.

The second modification is for finite sources as described earlier. In this case, the initial dispersion parameters are calculated from the dimensions as:

$$\sigma_{y0} = W_s/4.28$$

$$\sigma_{z0} = L_s/4.29$$

where the width W_s is the crosswind dimension and the length L_s is along the wind.

The materials which are most apt to be environmentally important are those which can escape particulate collectors and which are significant in the sense

that they may produce ecosystem changes at very low concentrations. Nitrate, phosphorus, selenium, mercury, fluoride, and arsenic are potentially the most important with respect to effects on the environment. All of these substances have relatively high vapor pressures at the collector temperatures of approximately 700°F. Mass balance calculations based on data from the Southwest Energy Study⁴⁸ were used to estimate the release rates in Table 12. The mercury data are based on detailed studies at the Four Corners Power Plant. Complete release is expected for nitrate converted from nitrogen oxides.

Figure 4 depicts the variation of fractional deposition with distance for each stability category except F , which

Table 11: Plume Interaction Parameters for Stack Emissions of Large Powerplants

Stability Class ^a	Plume Height (m)	σ_z (50 percent) (m)	σ_z (90 percent) (m)	x (50 percent) (km)	x (90 percent) (km)
A	1,291	1,235	3,620	1.6	2.7
B	954	911	2,670	7	18.5
C	782	746	2,190	15.3	51
D	611	534	1,710	120	720
E	401	383	1,120	250	2,000
F	415	396	1,160	1,100	15,000

^aPasquill stability classes are defined in the Glossary.

Table 12: Estimated Release Rates of Trace Elements for the Navajo Generating Station Units 1, 2, and 3

Material	Assumed Fractional Release ^a	Total Estimated Release Rate (g/sec)
Phosphorus	0.5	80.
Selenium	0.25	.077
Mercury	0.96	.0049
Fluoride	0.50	9.0
Arsenic	0.25	0.15

^afraction in fuel which actually escapes from stacks

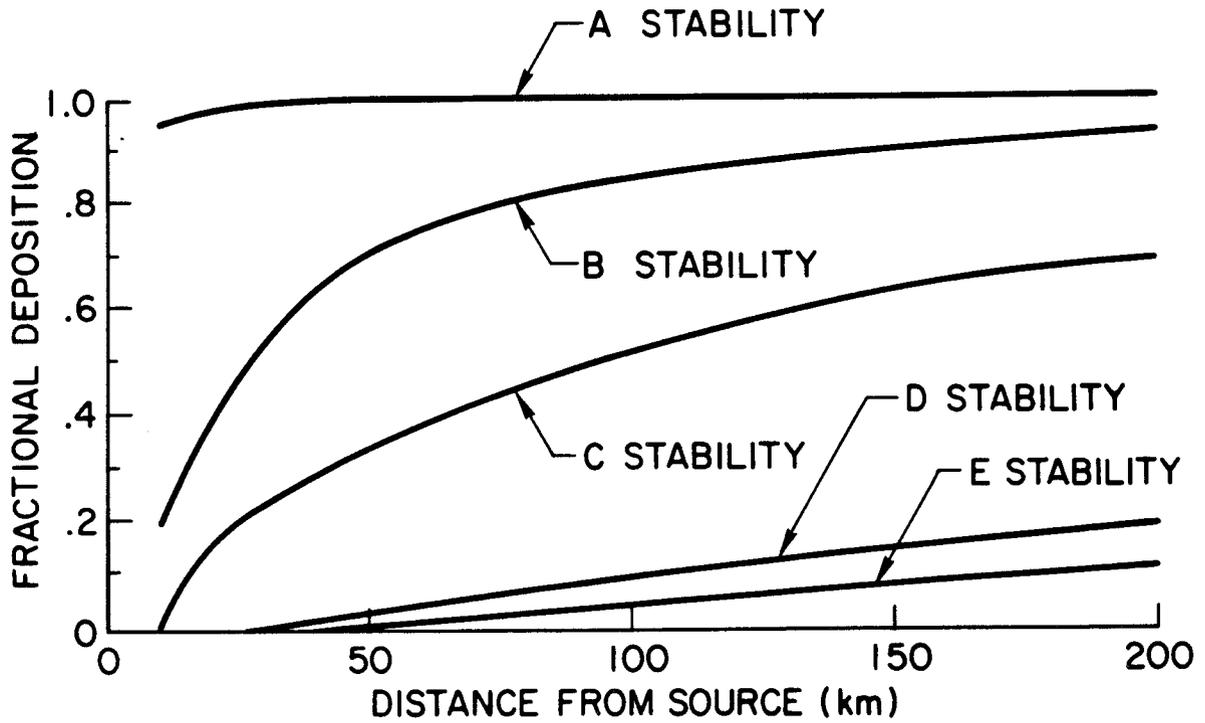


Figure 4: Fractional Deposition of Contaminants Calculated for the Navajo Generating Station. A mixing depth of 2,600 meters is assumed.

produces negligible deposition for distances less than 200 kilometers.

Figure 5 depicts the influence of stack height on deposition for stability and wind directions north of the Navajo plant. The mixing layer height is the mean afternoon mixing layer height for the closest upper air station. These late afternoon values probably are somewhat greater than those that occur earlier in the day. The deposition may be underestimated for this reason.

The two other models produce somewhat different deposition rates, as is evident in Table 13.

In general the AV model would be used to replace the NOAA or TVA predictions for stable flow only. The predictions of TVA or NOAA for unstable or neutral conditions and AV for stable conditions could be obtained by adding the AV values to those of either of the other models. Neither of the other models predicts any significant deposition during stable flow.

The significance of deposition of trace elements is difficult to assess. There are approximately four cases which might have some significance. The first is the direct deposition of materials on a body of water, such as Lake Powell, rapidly enough to change the water chemistry.

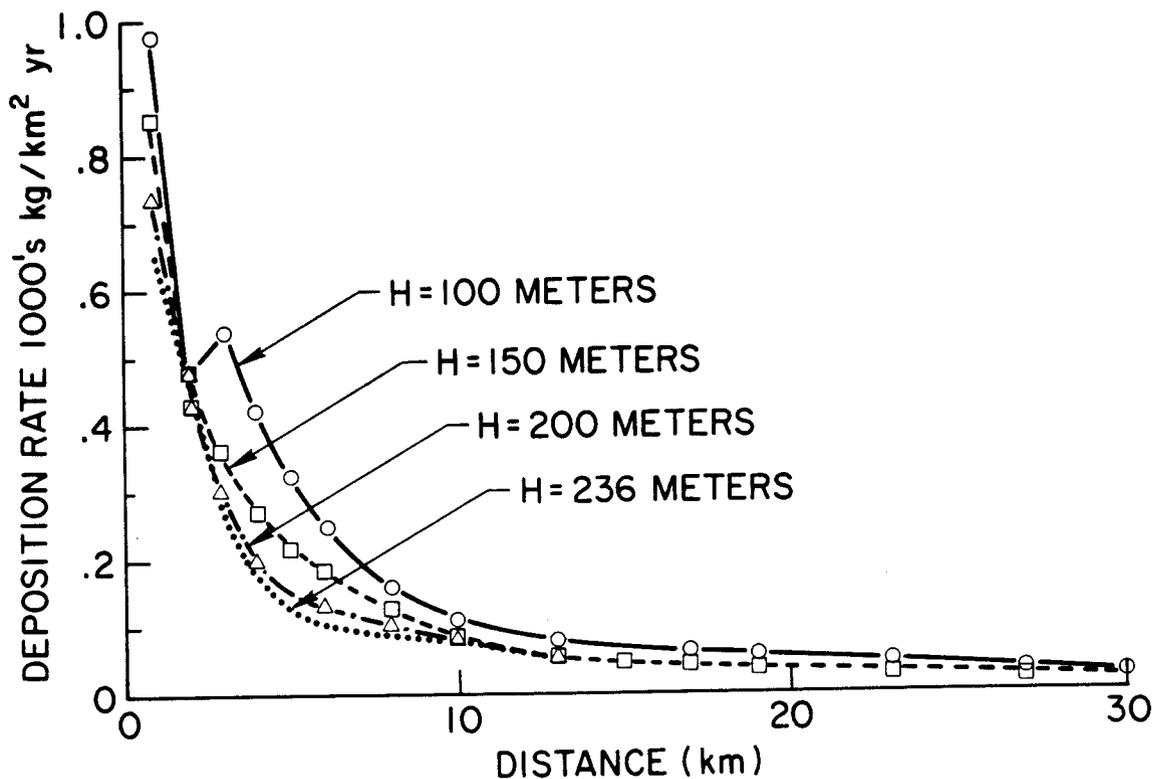


Figure 5: Calculated Phosphorus Deposition Rates for Terrain North of the Navajo Generating Station. Various stack heights and a surface reflection factor of 0.10 are assumed.

Table 13: Comparison of Predicted Phosphorus Deposition Rates North of the Navajo Plant (kg/km²/yr)

Distance (km)	TVA	NOAA	AeroVironment
1	-	650	-
2	-	470	-
3	90	280	-
4	206	170	-
5	273	125	6
6	283	100	10
8	235	90	17
10	180	70	20
12.5	126	50	21
15	88	45	20

Table 14 shows what additions might be expected for the Navajo Creek arm of Lake Powell, where the deposition rate should be relatively high. There is potentially a problem here associated with high phosphorus levels.

A second potentially significant class is the deposition of materials which could locally damage the productive capacity of soils. Table 15 gives the amounts of various contaminants which might be added to the upper 10 centimeters of soil over the theoretical 35-year life of the Navajo Generating Station, if there were no leaching of these contaminants from the soils. If this assumption is valid, there may be a problem relating to secondary poisoning from selenium because soils with 1 ppm of selenium have been known to produce grains toxic to mammals.

The third case includes small shallow bodies of water which might be affected by deposition. Table 16 indicates that mea-

surable additions may be expected but their significance cannot be assessed because critical values are not known in this context.

The fourth potential problem is that material deposited in the watershed might be carried into the reservoir at a rate sufficient to cause significant ecosystem changes either in the lake as a whole or in some isolated area of the lake. This problem has not been analyzed in detail. However, if 15 percent of the phosphorus were deposited in the watershed, critical levels for algal blooms (as measured in other lakes) would be reached.

In addition to deposition from the stack emissions, there will also be a contribution from the cooling towers. Each of the cooling towers will circulate water containing 135,500 ppm of salts with an expected average drift loss of 0.05 percent and a maximum loss of 0.1 percent. Salt concentrations and emissions

Table 14: Expected Average Concentrations in the Navajo Creek Arm of Lake Powell

Material	Expected Concentrations (ppb)	Critical Levels (ppb)	Existing Levels (ppb)
Phosphorus	5.	15 ⁴⁹	-
Nitrate	6.2	1300 ⁴⁹	-
Sulfate	25.	-	300,000
Arsenic	9.4x10 ⁻³	-	-
Selenium	4.8x10 ⁻³	-	-
Fluorine	0.056	>2000	-
Mercury	3.1x10 ⁻⁴	-	-

Table 15: Expected Addition to Upper 10 Centimeters of Soil

Material	Expected Concentrations (ppm/year)	Critical Levels (ppm)	Average Levels (ppm)
Phosphorus	10.5	-	-
Fluorine	1.2	-	-
Mercury	0.0006	-	-
Selenium	0.01	≈1	0.08
Arsenic	0.02	-	<10
Nitrate	3.2	-	-
Sulfate	12.6	-	-

Table 16: Expected Maximum Addition to Shallow Ponds (1 meter depth)

Material	Expected Concentrations (ppb)
Phosphorus	2630
Fluorine	300
Mercury	0.162
Selenium	2.52
Arsenic	4.96
Nitrate	820
Sulfate	3200

using the expected drift loss are given in Table 17. It is interesting to note that the total estimated particulate emissions from the cooling towers (252 g/sec) exceed those from the stacks (131 g/sec).

Table 18 reports the peak deposition rates of some of the salts at the point for which the highest rates were calculated (1.3 kilometers to the east-southeast of the Navajo Generating Station).

Table 17: Calculated Emission Rates for a Single Cooling Tower at the Navajo Generating Station

Material	Concentration (ppm)	Emission Rate (g/sec)
Calcium (as CaCO ₃)	1,000	4.1
Magnesium (as CaCO ₃)	1,580	6.5
Sodium	2,409	9.9
Bicarbonate (as CaCO ₃)	35	0.145
Sulfate	5,821	23.8
Chloride	1,221	5.0
TDS (Total Dissolved Solids)	10,280	42.0

Table 18: Peak Deposition Rates from the Navajo Cooling Towers

Constituent	Peak Deposition Rate (1000 kg/km ² /yr)
Sulfate	9.72
Sodium	4.03
Chloride	2.03
Magnesium (as CaCO ₃)	2.65
Calcium (as CaCO ₃)	1.74
Total Dissolved Salts	17.0

SUMMARY AND CONCLUSIONS

Validated theoretical models can be very helpful in the determination of environmental impact. Unfortunately, existing models for prediction of toxic concentrations produced by powerplants differ dramatically in their predictions. However, the models do indicate the need for a comprehensive monitoring program. Also, once the models have been validated and improved for high-terrain situations, their usefulness will be greatly enhanced.

During the course of this work, models have been developed for the prediction of effects of contaminant emissions on visibility. These models suggest that the Navajo Generating Station may have significant effects on visibility in the Lake Powell region, although uncertainties in important parameters remain.

Models for the prediction of contaminants have also been developed and applied to predict deposition rates of various atmospheric contaminants near Lake Powell. The significance of the rates awaits further study, while the accuracy of the predictions will have to be defined experimentally.

ACKNOWLEDGMENT

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GLOSSARY

AeroVironment (AV)	a California-based firm with expertise in meteorology and turbulence theory	fly ash	the light-attenuating constituent mineral solids emitted to the atmosphere during coal combustion
ambient air	the air surrounding plants and animals	fumigation	see inversion breakup
collector	a device which removes contaminants from flue gas	fractional deposition	the fraction of a contaminant deposited between the source and the distance x
dispersion modeling	a technique used to predict the concentrations of contaminants which are emitted from sources as a function of time, space, and meteorological conditions	Gaussian plume dispersion	dispersion in which the concentrations are normally distributed with respect to the vertical and horizontal distances from the plume centerline
extinction coefficient	<p>a measure of the ability of light to pass through gases which permits the calculation of the light attenuation; the intensity of light, I, passing through a thickness τ of air is given by</p> $I = I_0 e^{-\alpha\tau}$ <p>where α is the extinction coefficient and I_0 is the incident light intensity</p>	inversion	a layer of air in which the temperature increases with height
		inversion breakup	a situation in which an inversion layer is destroyed by heating of the ground, resulting in elevated ground level concentrations of pollutants which were previously trapped in the inversion
		limited mixing	a situation in which an inversion layer aloft traps contaminants in a mixed layer below
extinction coefficient per unit mass concentration	the extinction coefficient divided by the mass concentration of	mass balance calculation	a calculation in which the material released is found by subtracting

	the material collected from that entering the plant	plume height	the height of the plume centerline sometimes referred to as an effective stack height
mass conversion factor	the ratio of the mass of a molecule of a derived contaminant to that of its precursor	plume interaction	a situation in which significant portions of an elevated plume reach ground level
mixing layer	the layer of air which reflects the plume during a limited mixing situation	ppb	parts per billion
		ppm	parts per million
NOAA	National Oceanic and Atmospheric Administration	secondary contaminant	produced from a primary contaminant through chemical conversion
normal distribution	a statistical distribution in which the frequency is proportional to the negative exponential of a factor multiplied by the square of the variable	stable flow	the flow of air within which vertical fluctuations are inhibited
		stack height	the actual physical height of a stack
particulates	solid or liquid particles drifting in air	TVA	Tennessee Valley Authority
Pasquill stability categories	see table on page 37	visual range	the distance at which an average observer can just distinguish a high contrast object
plume	a region in the atmosphere with elevated concentrations of contaminants associated with one or more sources		

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Pasquill Stability Categories^a

Stability Category	Wind Speed (meters/second)	Condition	Temperature Gradient Range °C/100m
A Extremely Unstable	<2	Daytime--strong to moderate insolation	<-1.9
	2	Daytime--strong insolation	
B Moderately Unstable	2	Daytime--slight to moderate insolation	-1.9 to -1.5
	4	Daytime--moderate to strong insolation	
C Slightly Unstable	4	Daytime--slight to moderate insolation	-1.7 to -1.5
	6	Daytime--moderate to strong insolation	
	>6	Daytime--strong insolation	
	2	Daytime--slight insolation	
D Neutral	6	Daytime--slight to moderate insolation	-1.5 to -0.5
	>6	Daytime--slight to moderate insolation	
	4	Nighttime-->4/8 cloudiness	
	6	Nighttime-->4/8 cloudiness	
	>6	Nighttime	
E Slightly Stable	2	Nighttime-->4/8 cloudiness	-0.5 to 1.5
	4	Nighttime-->3/8 cloudiness	
F Moderately Stable		Nighttime-->3/8 cloudiness	

^aNormally the Pasquill categorization scheme is used to deduce the atmospheric stability through the surface wind speed, cloudiness, and sun angle. However, temperature gradients may also be used.

NOTATION

		g	acceleration due to gravity
		H	height of emission above ground after plume rise
		ΔH	plume rise
A	the constant multiplying distance in the relationship for σ_z	H_s	stack height
Ar	deposition area	i	the particular contaminant
b	the exponent of distance in the relationship for σ_z	J	the maximum number of ground reflection considered
C	the constant multiplying distance in the relationship for σ_y	K	the number of ground reflections for particulates
C_m	mass of contaminant per unit area perpendicular to viewing direction	K_d	a parameter used in the TVA plume rise formulation
C_p	a model-dependent constant in plume-rise relationships	L	mixing layer height, also called depth of the mixed layer
d	the exponent of distance in the relationship for σ_y	L_{eff}	the height of the layer mixed to the ground during inversion breakup
D_t	total annual deposition of contaminant	L_s	length of the source along the wind
$D(x)$	deposition rate as a function of distance x	m	mass of effluent gases
e	base of the natural logarithm	M	the entrained mass
erf	error function	MCF	ratio of mass of secondary contaminant to its predecessor, the primary contaminant
exp	exponential	N	atmospheric stability
F	flux	NS	number of wind sectors
F^+	total outward flux of contaminants leaving source	P	probability
$f(\theta_i, s)$	frequency of wind direction θ_i and stability s	Q	emission rate of the source, also called the source strength

Q_{eff}	adjusted source strength	x	distance downwind from source
Q_o	release rate at the stack	x_f	inversion-breakup distance
Q_p	source strength for primary contaminant	x_{FR}	the distance to full plume rise
Q_s	secondary contaminant	x_m	limited mixing distance
R_s	stack radius	x_{mx}	the distance to the maximum ground level concentration
s	stability	y	horizontal distance from plume centerline transverse to the direction of flow
S	initial plume width		
SF	spacing factor	z	height above ground
SRF	surface reflection factor	θ, θ_i	wind-direction sector
SRM	ratio of scattering area to mass, or, the extinction coefficient per unit mass	ρ_a	the density of the ambient air
		ρ_b	the density of the stack gases
t	travel time of a pollutant	σ_y	the horizontal dispersion coefficient
T	time period of interest		
T_a	ambient temperature	σ_{yf}	the equivalent horizontal dispersion coefficient for fumigation situations
dT/dz	atmospheric temperature gradient	σ_{yt}	the equivalent horizontal dispersion coefficient for trapping situations
u	mean wind speed		
V_r	visual range for observer looking through plume	σ_z	the vertical dispersion coefficient
V_{rb}	background visual range	ϕ	potential temperature
V_s	exit velocity	χ	concentration at point x, y, z
w	dummy variable in the definition of error function	$\bar{\chi}_i$	average concentration
W_s	width of the source in the crosswind direction	χ_T	average concentration over T hours

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