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ATMOSPHERIC DISPERSION MODELS FOR POTENTIAL ACCIDENT CONSEQUENCE ASSESSMENTS AT NUCLEAR POWER PLANTS

A. INTRODUCTION

Section 100.10 of 10 CFR Part 100, "Reactor Site Criteria," states that meteorological conditions at the site and surrounding area should be considered in determining the acceptability of a site for a power reactor. Section 50.34 of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," requires that each applicant for a construction permit or operating license provide an analysis and evaluation of the design and performance of structures, systems, and components of the facility with the objective of assessing the risk to public health and safety resulting from the operation of the facility. Section 50.34 of 10 CFR Part 50 also states that special attention should be directed to the site evaluation factors identified in 10 CFR Part 100 in the assessment of the site.

The regulatory positions presented in this guide represent a substantial change from procedures previously used to determine relative concentrations for assessing the potential offsite radiological consequences for a range of postulated accidental releases of radioactive material to the atmosphere. These procedures now include consideration of plume meander, directional dependence of dispersion conditions, and wind frequencies for various locations around actual exclusion area and low population zone (LPZ) boundaries.

The direction-dependent approach was developed to provide an improved basis for the Part 100-related review of proposed reactor and site considerations. Accordingly, this guide provides an acceptable methodology for determining site-specific relative concentrations (χ/Q) and should be used in determining χ/Q values for the evaluations discussed in Regulatory Guide 1.3, "Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors," and Regulatory Guide 1.4, "Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors." A number of other regulatory guides also include recommendations for or references to radiological analyses of potential accidents. The applicability of the specific criteria discussed herein to these other analyses will be considered on a case-by-case basis. Until such time as generic guidelines are developed for such analyses, the methodology provided in this guide is acceptable to the NRC staff.

B. DISCUSSION

The atmospheric diffusion[1] models described in this guide reflect review of recent experimental data on diffusion from releases at ground level without buildings present and from releases at various locations on reactor facility buildings during stable atmospheric conditions with low windspeeds (Refs. 1 through 6). These tests verify the existence of effluent plume "meander" under light windspeed conditions and neutral (D) and stable (E, F, and G) atmospheric stability conditions (as defined by the ΔT criteria in Regulatory Guide 1.23, "Onsite Meteorological Programs"). Effluent concentrations measured over a period of 1 hour under such conditions have been shown to be substantially lower than would be predicted using the traditional curves (Ref. 7)

[1] In discussions throughout this regulatory guide, atmospheric dispersion will be considered as consisting of two components: atmospheric transport due to organized or mean airflow within the atmosphere and atmospheric diffusion due to disorganized or random air motions.

of lateral and vertical plume spread, which are functions of atmospheric stability and downwind distance.

The procedures in this guide also recognize that atmospheric dispersion conditions and wind frequencies are usually directionally dependent; that is, certain airflow directions can exhibit substantially more or less favorable diffusion conditions than others, and the wind can transport effluents in certain directions more frequently than in others. The procedures also allow evaluations of atmospheric dispersion for directionally variable distances such as a noncircular exclusion area boundary.

C. REGULATORY POSITION

This section identifies acceptable methods for (1) calculating atmospheric relative concentration (χ/Q) values, (2) determining χ/Q values on a directional basis, (3) determining χ/Q values on an overall site basis, and (4) choosing χ/Q values to be used in evaluations of the types of events described in Regulatory Guides 1.3 and 1.4.

Selection of conservative, less detailed site parameters for the evaluation may be sufficient to establish compliance with regulatory guidelines.

1. CALCULATION OF ATMOSPHERIC RELATIVE CONCENTRATION (χ/Q) VALUES

Equations and parameters presented in this section should be used unless unusual siting, meteorological, or terrain conditions dictate the use of other models or considerations. High-quality site-specific atmospheric diffusion tests may be used as a basis for modifying the equations and parameters.

1.1 Meteorological Data Input

The meteorological data needed for χ/Q calculations include windspeed, wind direction, and atmospheric stability. These data should represent hourly averages as defined in regulatory position 6.a of Regulatory Guide 1.23.

Wind direction should be classed into 16 compass directions (22.5-degree sectors centered on true north, north-northeast, etc.).

Atmospheric stability should be determined by vertical temperature difference (ΔT) between the release height and the 10-meter level or by other well-documented parameters that have been substantiated by diffusion data. Acceptable stability classes are given in Table 2 of Regulatory Guide 1.23.

Calms should be defined as hourly average windspeeds below the vane or anemometer starting speed, whichever is higher (to reflect limitations in instrumentation). If the instrumentation program conforms to the regulatory position in Regulatory Guide 1.23, calms should be assigned a windspeed equal to the vane or anemometer starting speed, whichever is higher. Otherwise, consideration of a conservative evaluation of calms, as indicated by the system, will be necessary. Wind directions during calm conditions should be assigned in proportion to the directional distribution of noncalm winds with speeds less than 1.5 meters per second.[2]

1.2 Determination of Distances for χ/Q Calculations

For each wind direction sector, χ/Q values for each significant release point should be calculated at an appropriate exclusion area boundary distance and outer low population zone (LPZ) boundary distance. The following procedure should be used to determine these distances. The procedure takes into consideration the possibility of curved airflow trajectories, plume segmentation (particularly in light wind, stable conditions), and the potential for windspeed and direction frequency shifts from year to year.

For each of the 16 sectors, the distance for exclusion area boundary or outer LPZ boundary χ/Q calculation should be the minimum distance from the stack or, in the case of releases through vents or building penetrations, the nearest point on the building to the exclusion area boundary or outer LPZ boundary within a 45-degree sector centered on the compass direction of interest.

For stack releases, the maximum ground-level concentration in a sector may occur beyond the exclusion area boundary distance or outer LPZ boundary distance. Therefore, for stack releases, χ/Q calculations should be made in each sector at each boundary distance and at various distances beyond the exclusion area boundary distance to determine the maximum relative concentration for consideration in subsequent calculations.

1.3 Calculation of χ/Q Values at Exclusion Area Boundary Distances

Relative concentrations that can be assumed to apply at the exclusion area boundary for 2 hours immediately following an accident should be determined.[3] Calculations based on meteorological data averaged over a 1-hour period should be assumed to apply for the entire 2-hour period. This assumption is reasonably conservative considering the small variation of χ/Q values with averaging time (Ref. 8). If releases associated with a postulated event are estimated to occur in a period

[2] Staff experience has shown that noncalm windspeeds below 1.5 meters per second provide a reasonable range for defining the distribution of wind direction during light winds.

[3] See §100.11 of 10 CFR Part 100.

of less than 20 minutes, the applicability of the models should be evaluated on a case-by-case basis.

Procedures for calculating "2-hour" χ/Q values depend on the mode of release. The procedures are described below.

1.3.1 Releases Through Vents or Other Building Fenetrations

This class of release modes includes all release points or areas that are effectively lower than two and one-half times the height of adjacent solid structures (Ref. 9). Within this class, two sets of meteorological conditions are treated differently, as follows:

a. During neutral (D) or stable (E, F, or G) atmospheric stability conditions when the windspeed at the 10-meter level is less than 6 meters per second, horizontal plume meander can be considered. χ/Q values may be determined through selective use of the following set of equations for ground-level relative concentrations at the plume centerline:

$$\chi/Q = \frac{1}{\bar{U}_{10}(\pi\sigma_y\sigma_z + A/2)} \quad (1)$$

$$\chi/Q = \frac{1}{\bar{U}_{10}(3\pi\sigma_y\sigma_z)} \quad (2)$$

$$\chi/Q = \frac{1}{\bar{U}_{10}\pi\Sigma_y\sigma_z} \quad (3)$$

where

χ/Q is relative concentration, in sec/m^3,

π is 3.14159,

$\bar{U}_{10}$ is windspeed at 10 meters above plant grade,[4] in m/sec,

σ_y is lateral plume spread, in m, a function of atmospheric stability and distance (see Fig. 1),

σ_z is vertical plume spread, in m, a function of atmospheric stability and distance (see Fig. 2),

Σ_y is lateral plume spread with meander and building wake effects, in m, a function of atmospheric stability, windspeed $\bar{U}_{10}$, and distance [for distances of 800 meters or less, $\Sigma_y = M\sigma_y$, where M is determined from Fig. 3; for distances greater than 800 meters, $\Sigma_y = (M - 1)\sigma_{y800m} + \sigma_y$], and

A is the smallest vertical-plane cross-sectional area of the reactor building, in m^2. (Other structures and/or a directional consideration may be justified when appropriate.)

χ/Q values should be calculated using Equations 1, 2, and 3. The values from Equations 1 and 2 should be compared and the higher value selected. This value should be compared with the value from Equation 3, and the lower value of these two should be selected as the appropriate χ/Q value. Examples and a detailed explanation of the rationale for determining the controlling conditions are given in Appendix A to this guide.

b. During all other meteorological conditions [unstable (A, B, or C) atmospheric stability and/or 10-meter level windspeeds of 6 meters per second or more], plume meander should not be considered. The appropriate χ/Q value is the higher value calculated from Equation 1 or 2.

1.3.2 Stack Releases

This class of release modes includes all release points at levels that are two and one-half times the height of adjacent solid structures or higher (Ref. 9). Nonfumigation and fumigation conditions are treated separately.

a. For nonfumigation conditions, the equation for ground-level relative concentration at the plume centerline for stack releases is:

$$\chi/Q = \frac{1}{\pi\bar{U}_h\sigma_y\sigma_z}\exp\left[\frac{-h_e^2}{2\sigma_z^2}\right] \quad (4)$$

where

$\bar{U}_h$ is windspeed representing conditions at the release height, in m/sec,

h_e is effective stack height, in m: $h_e = h_s - h_t$,

h_s is the initial height of the plume (usually the stack height) above plant grade, in m, and

h_t is the maximum terrain height above plant grade between the release point and the point for which the calculation is made, in m; h_t cannot exceed h_s.

b. For fumigation conditions, a "fumigation χ/Q" should be calculated for each sector as follows. The equation for ground-level relative concentration at the plume centerline for stack releases during fumigation conditions is:

[4] The 10-meter level is representative of the depth through which the plume is mixed with building wake effects.

$$\chi/Q = \frac{1}{(2\pi)^{1/2}\,\bar{U}_{h_e}\,\sigma_y h_e}, \quad h_e > 0 \qquad (5)$$

where

$\bar{U}_{h_e}$ is windspeed representative of the layer of depth h_e, in m/sec; in lieu of information to the contrary, the NRC staff considers a value of 2 meters per second as a reasonably conservative assumption for h_e of about 100 meters, and

σ_y is the lateral plume spread, in m, that is representative of the layer at a given distance; a moderately stable (F) atmospheric stability condition is usually assumed.

Equation 5 cannot be applied indiscriminately because the χ/Q values calculated, using this equation, become unrealistically large as h_e becomes small (on the order of 10 meters). The χ/Q values calculated using Equation 5 must therefore be limited by certain physical restrictions. The highest ground-level χ/Q values from elevated releases are expected to occur during stable conditions with low windspeeds when the effluent plume impacts on a terrain obstruction (i.e., $h_e = 0$). However, elevated plumes diffuse upward through the stable layer aloft as well as downward through the fumigation layer. Thus ground-level relative concentrations for elevated releases under fumigation conditions cannot be higher than those produced by nonfumigation, stable atmospheric conditions with $h_e = 0$. For the fumigation case that assumes F stability and a windspeed of 2 meters per second, Equation 4 should be used instead of Equation 5 at distances greater than the distance at which the χ/Q values, determined using Equation 4 with $h_e = 0$, and Equation 5 are equal.

1.4 Calculation of χ/Q Values at Outer LPZ Boundary Distances

Two-hour χ/Q values should also be calculated at outer LPZ boundary distances. The procedures described above for exclusion area boundary distances (see regulatory position 1.3) should be used.

An annual average (8760-hour) χ/Q should be calculated for each sector at the outer LPZ boundary distance for that sector, using the method described in regulatory position 1.c of Regulatory Guide 1.111, "Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors." (For stack releases, h_e should be determined as described in regulatory position 1.3.2.)

These calculated 2-hour and annual average values are used in regulatory position 2.2 to determine sector χ/Q values at outer LPZ boundary distances for various longer time periods.[5]

2. DETERMINATION OF MAXIMUM SECTOR χ/Q VALUES

The χ/Q values calculated in regulatory position 1 are used to determine "sector χ/Q values" and "maximum sector χ/Q values" for the exclusion area boundary and the outer LPZ boundary.

2.1 Exclusion Area Boundary

2.1.1 General Method

Using the χ/Q values calculated for each hour of data according to regulatory position 1.3, a cumulative probability distribution of χ/Q values should be constructed for each of the 16 sectors. Each distribution should be described in terms of probabilities of given χ/Q values being exceeded in that sector during the total time. A plot of χ/Q versus probability of being exceeded should be made for each sector, and a curve should be drawn to form an upper bound of the data points. From each of the 16 curves, the χ/Q value that is exceeded 0.5% of the total time should be selected (Ref. 10). These are the sector χ/Q values. The highest of the 16 sector values is defined as the maximum sector χ/Q value.

2.1.2 Fumigation Conditions for Stack Releases

Regulatory position 1.3.2 gave procedures for calculating a fumigation χ/Q for each sector. These sector fumigation values, along with the general (nonfumigation) sector values obtained in regulatory position 2.1.1, are used to determine appropriate sector χ/Qs for fumigation conditions, based on conservative assumptions concerning the duration of fumigation. These assumptions differ for inland and coastal sites, and certain modifications may be appropriate for specific sites.

a. Inland Sites: For stack releases at sites located 3200 meters or more from large bodies of water (e.g., oceans or Great Lakes), a fumigation condition should be assumed to exist at the time of the accident and continue for 1/2 hour (Ref. 11). For each sector, if the sector fumigation χ/Q exceeds the sector nonfumigation χ/Q, use the fumigation value for the 0 to 1/2-hour time period and the nonfumigation value for the 1/2-hour to 2-hour time period. Otherwise, use the nonfumigation sector value for the entire 0 to 2-hour time period. The 16 (sets of) values thus determined will be used in dose assessments requiring time-integrated concentration considerations.

[5]See §100.11 of 10 CFR Part 100.

b. Coastal Sites: For stack releases at sites located less than 3200 meters from large bodies of water, a fumigation condition should be assumed to exist at the exclusion area boundary at the time of the accident and continue for the entire 2-hour period. For each sector, if the sector fumigation χ/Q exceeds the sector nonfumigation χ/Q, use the fumigation value for the 2-hour period. Otherwise, use the nonfumigation value for the 2-hour period. Of the 16 sector values thus determined, the highest is the maximum sector χ/Q value.

c. Modifications: These conservative assumptions do not consider frequency and duration of fumigation conditions as a function of airflow direction. If information can be presented to substantiate the likely directional occurrence and duration of fumigation conditions at a site, the assumptions of fumigation in all appropriate directions and of duration of 1/2 hour and 2 hours for the exclusion area boundary may be modified. Then fumigation need only be considered for airflow directions in which fumigation has been determined to occur and of a duration determined from the study of site conditions.[6]

2.2 Outer LPZ Boundary

2.2.1 General Method

Sector χ/Q values for the outer LPZ boundary should be determined for various time periods throughout the course of the postulated accident.[7] The time periods should represent appropriate meteorological regimes, e.g., 8 and 16 hours and 3 and 26 days as presented in Section 2.3.4 of Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants--LWR Edition," or other time periods appropriate to release durations.

For a given sector, the average χ/Q values for the various time periods should be approximated by a logarithmic interpolation between the 2-hour[8] sector χ/Q and the annual average (8760-hour) χ/Q for the same sector. The 2-hour sector χ/Q for the outer LPZ boundary is determined using the general method given for the exclusion area boundary in regulatory position 2.1. The annual average χ/Q for a given sector is determined as described in regulatory position 1.4.

The logarithmic interpolation procedure produces results that are consistent with studies of variations of average concentrations with time periods up to 100 hours (Ref. 8). Alternative methods should also be consistent with these studies.

For each time period, the highest of the 16 sector χ/Q values should be identified. In most cases, these highest values will occur in the same sector for all time periods. These are then the maximum sector χ/Q values. However, if the highest sector χ/Qs do not all occur in the same sector, the 16 (sets of) values will be used in dose assessments requiring time-integrated concentration considerations. The χ/Q values for the various time periods within that sector should be considered the maximum sector χ/Q values.

2.2.2 Fumigation Conditions for Stack Releases

Determination of sector χ/Q values for fumigation conditions at the outer LPZ boundary involves the following assumptions concerning the duration of fumigation for inland and coastal sites:

a. Inland Sites: For stack releases at sites located 3200 meters or more from large bodies of water, a fumigation condition should be assumed to exist at the outer LPZ boundary at the time of the accident and continue for 1/2 hour. Sector χ/Q values for fumigation should be determined as for the exclusion area boundary in regulatory position 2.1.2.

b. Coastal Sites: For stack releases at sites located less than 3200 meters from large bodies of water, a fumigation condition should be assumed to exist at the outer LPZ boundary following the arrival of the plume and continue for a 4-hour period. Sector χ/Q values for fumigation should be determined as for the exclusion area boundary in regulatory position 2.1.2.

c. The modifications discussed in regulatory position 2.1.2 may also be considered for the outer LPZ boundary.

3. DETERMINATION OF 5% OVERALL SITE χ/Q VALUE

The χ/Q values that are exceeded no more than 5% of the total time around the exclusion area boundary and around the outer LPZ boundary should be determined as follows (Ref. 10):

Using the χ/Q values calculated according to regulatory position 1, an overall cumulative probability distribution for all directions combined should be constructed. A plot of χ/Q versus probability of being exceeded should be

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[6]For example, examination of site-specific information at a location in a pronounced river valley may indicate that fumigation conditions occur only during the downvalley "drainage flow" regime and persist for durations of about 1/2 hour. Therefore, in this case airflow directions other than the downvalley directions can be excluded from consideration of fumigation conditions, and the duration of fumigation would still be considered as 1/2 hour. On the other hand, data from sites in open terrain (noncoastal) may indicate no directional preference for fumigation conditions but may indicate durations much less than 1/2 hour. In this case, fumigation should be considered for all directions, but with durations of less than 1/2 hour.

[7]See §100.11 of 10 CFR Part 100.

[8]The χ/Qs are based on 1-hour averaged data but are assumed to apply for 2 hours.

made, and an upper bound curve should be drawn. The 2-hour χ/Q value that is exceeded 5% of the time should be selected from this curve as the dispersion condition indicative of the type of release being considered. In addition, for the outer LPZ boundary the maximum of the 16 annual average χ/Q values should be used along with the 5% 2-hour χ/Q value to determine χ/Q values for the appropriate time periods by logarithmic interpolation.

4. SELECTION OF χ/Q VALUES TO BE USED IN EVALUATIONS

The χ/Q value for exclusion area boundary or outer LPZ boundary evaluations should be the maximum sector χ/Q (regulatory position 2) or the 5% overall site χ/Q (regulatory position 3), whichever is higher. All direction-dependent sector values should be presented for consideration of the appropriateness of the exclusion area and outer LPZ boundaries and the efficacy of evacuation routes and emergency plans. Where the basic meteorological data necessary for the analyses described herein substantially deviate from the regulatory position stated in Regulatory Guide 1.23, consideration should be given to the resulting uncertainties in dispersion estimates.

D. IMPLEMENTATION

This proposed guide has been released to encourage public participation in its development and is not intended to foreclose other options in safety evaluations. Except in those cases in which an applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method to be described in the active guide reflecting public comments will be used in the evaluation of applications tendered on or after the implementation date to be specified in the active guide (in no case will this date be earlier than November 1, 1979) as follows:

1. For early site review applications.

2. For construction permit applications (including those incorporating or referencing a duplicate plant design and those submitted under the replicate plant option of the Commission's standardization program).

For the following cases, either the proposed guide or the procedures described in Standard Review Plan Section 2.3.4 (1975) may be used:

1. Construction permit applications tendered before the implementation date.

2. Operating license applications whose construction permits precede the implementation date.

3. Operating reactors.

This proposed guide does not apply to the following options specified in the Commission's standardization policy under the reference system concept:

1. Preliminary design approval applications.

2. Final design approval, Type 1, applications.

3. Final design approval, Type 2, applications.

4. Manufacturing license applications.

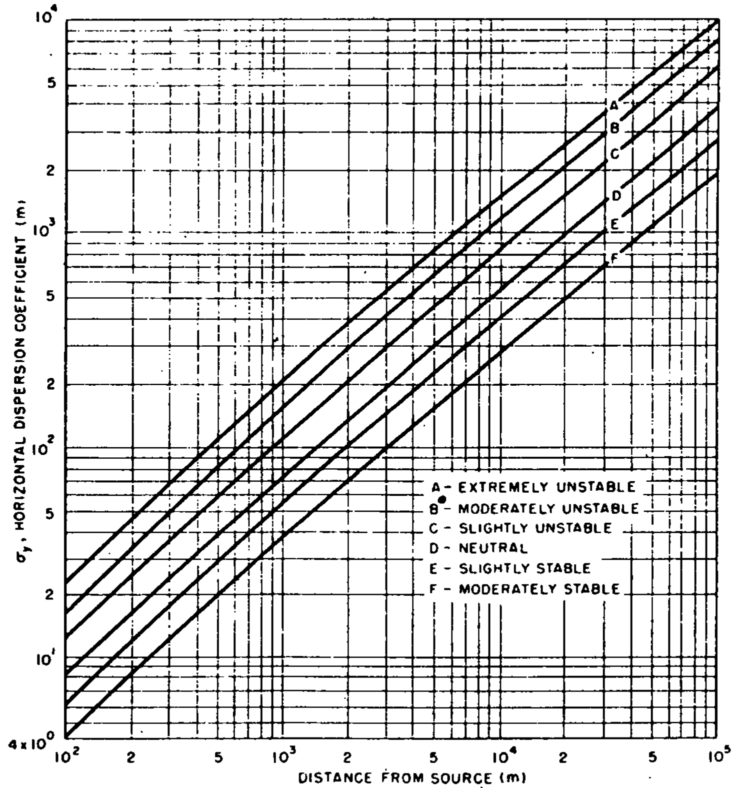

Figure 1. Lateral diffusion without meander and building wake effects, σ_y, vs. downwind distance from source for Pasquill's turbulence types (atmospheric stability) (Ref. 7).

For purposes of estimating σ_y during extremely stable (G) atmospheric stability conditions, without plume meander or other lateral enhancement, the following approximation is appropriate:

$$\sigma_y(G) = \frac{2}{3}\sigma_y(F)$$

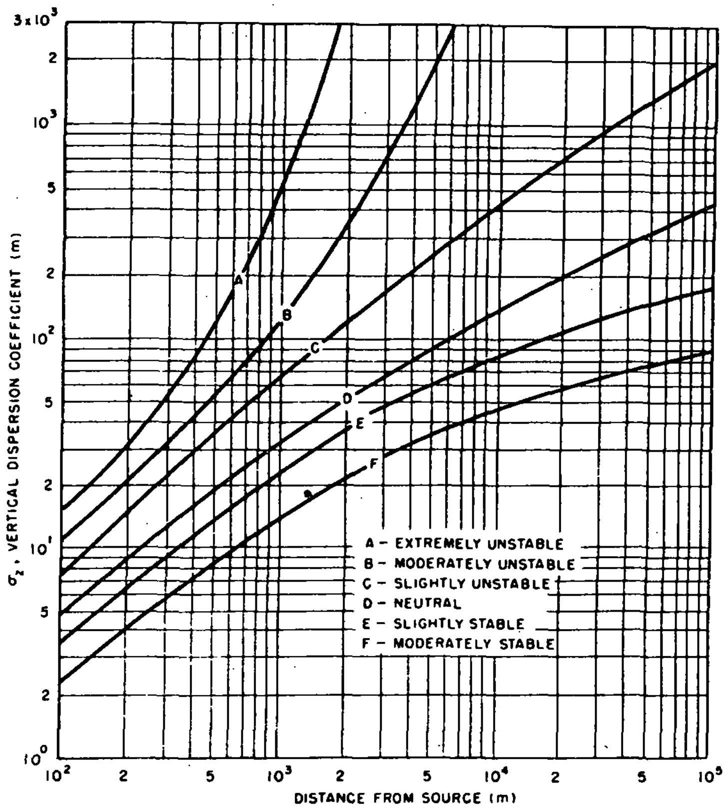

Figure 2. Vertical diffusion without meander and building wake effects, σ_z, vs. downwind distance from source for Pasquill's turbulence types (atmospheric stability) (Ref. 7).

For purposes of estimating σ_z during extremely stable (G) atmospheric stability conditions, the following approximation is appropriate:

$$\sigma_z(G) = \frac{3}{5}\sigma_z(F)$$

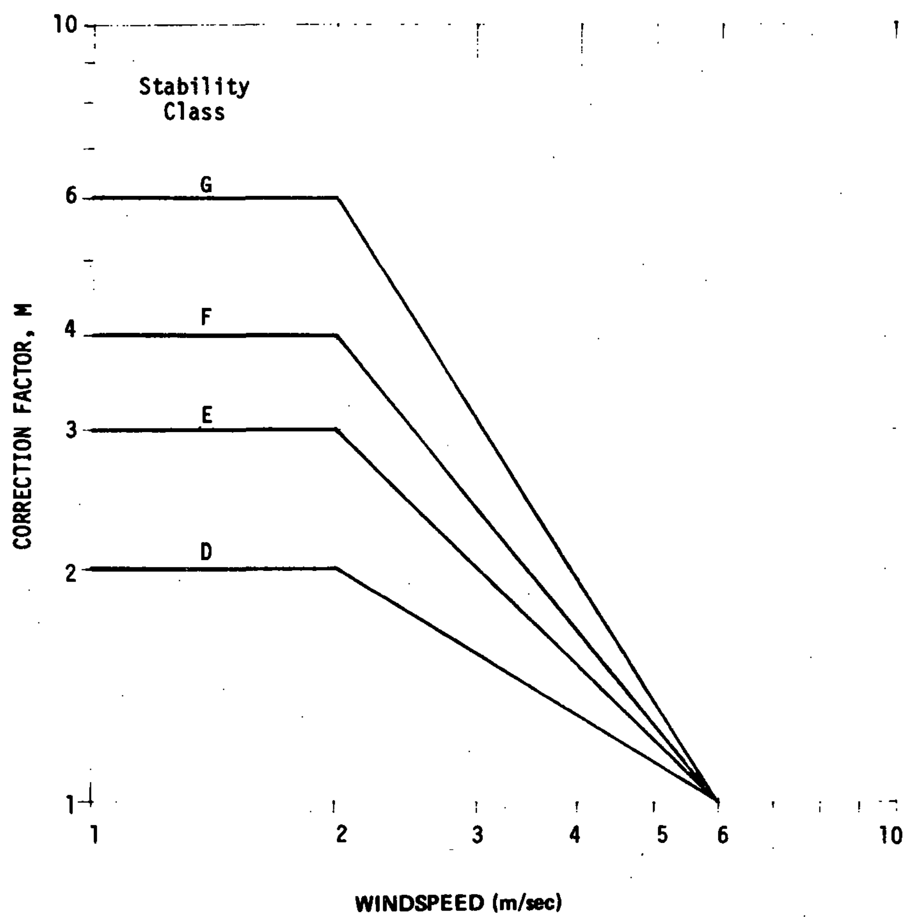

Figure 3. Correction factors for Pasquill-Gifford σ_y values by atmospheric stability class (see Appendix A to this guide)

APPENDIX A

ATMOSPHERIC DIFFUSION MODEL FOR RELEASES THROUGH VENTS AND BUILDING PENETRATIONS

Rationale

The effects of building wake mixing and ambient plume meander on atmospheric dispersion are expressed in this guide in terms of conditional use of Equations 1, 2, and 3.

Equations 1 and 2 are formulations that have been acceptable for evaluating nuclear power plant sites over a period of many years (Ref. 7 and Regulatory Guides 1.3 and 1.4) but have recently been found to provide estimates of ground-level concentrations that are consistently too high during light wind and stable or neutral atmospheric conditions for 1-hour release durations (Refs. 1 through 6).

Equation 3 is an empirical formulation based on NRC staff analysis of atmospheric diffusion experiment results (Ref. 2). The NRC staff examined values of lateral plume spread with meander and building wake effects (Σ_y) by atmospheric stability class (based on ΔT), calculated from measured ground-level concentrations from the experimental results. Plots of the computed Σ_y values by atmospheric stability class and downwind distance were analyzed conservatively but within the scatter of the data points by virtually enveloping most test data. The resultant analysis is the basis for the correction factors applied to the Pasquill-Gifford σ_y values (see Fig. 3 of this guide). Thus, Equation 3 identifies conservatively the combined effects of increased plume meander and building wake on diffusion in the horizontal crosswind direction under light wind and stable or neutral atmospheric conditions, as quantified in Figure 3. These experiments also indicate that vertical building wake mixing is not as complete during light wind, stable conditions as during moderate wind, unstable conditions although the results could not be quantified in a generic manner.

The conditional use of Equations 1, 2, and 3 is considered appropriate because (1) horizontal plume meander tends to dominate dispersion during light wind and stable or neutral conditions and (2) building wake mixing becomes more effective in dispersing effluents than meander effects as the windspeed increases and the atmosphere becomes less stable.

Examples of Conditional Use of Diffusion Equations

Figures A-1, A-2, and A-3 show plots of $\chi\overline{U}_{10}/Q$ (χ/Q multiplied by the windspeed $\overline{U}_{10}$) versus downwind distance based on the conditional use (as described in regulatory position 1.3.1) of Equations 1, 2, and 3 during atmospheric stability class G. The variable M for Equation 3 equals 6, 3, and 2 respectively in Figures A-1, A-2, and A-3 (M is as defined in regulatory position 1.3.1). The windspeed conditions are those appropriate for G stability and M = 6, 3, and 2.

In Figure A-1, the $\chi\overline{U}_{10}/Q$ from Equation 3 (M = 6) is less than the higher value from Equation 1 or 2 at all distances. Therefore, for M = 6, Equation 3 is used for all distances.

In Figure A-2, the $\chi\overline{U}_{10}/Q$ from Equation 3 (M = 3) is less than the higher value from Equation 1 or 2 beyond 0.8 km. Therefore, for M = 3, Equation 3 is used beyond 0.8 km. For distances less than 0.8 km, the value from Equation 3 equals that from Equation 2. Equation 2 is therefore used for distances less than 0.8 km.

In Figure A-3, the $\chi\overline{U}_{10}/Q$ from Equation 3 (M = 2) is never less than the higher value from Equation 1 or 2. Therefore, for M = 2, Equation 3 is not used at all. Instead, Equation 2 is used up to 0.8 km, and Equation 1 is used beyond 0.8 km.

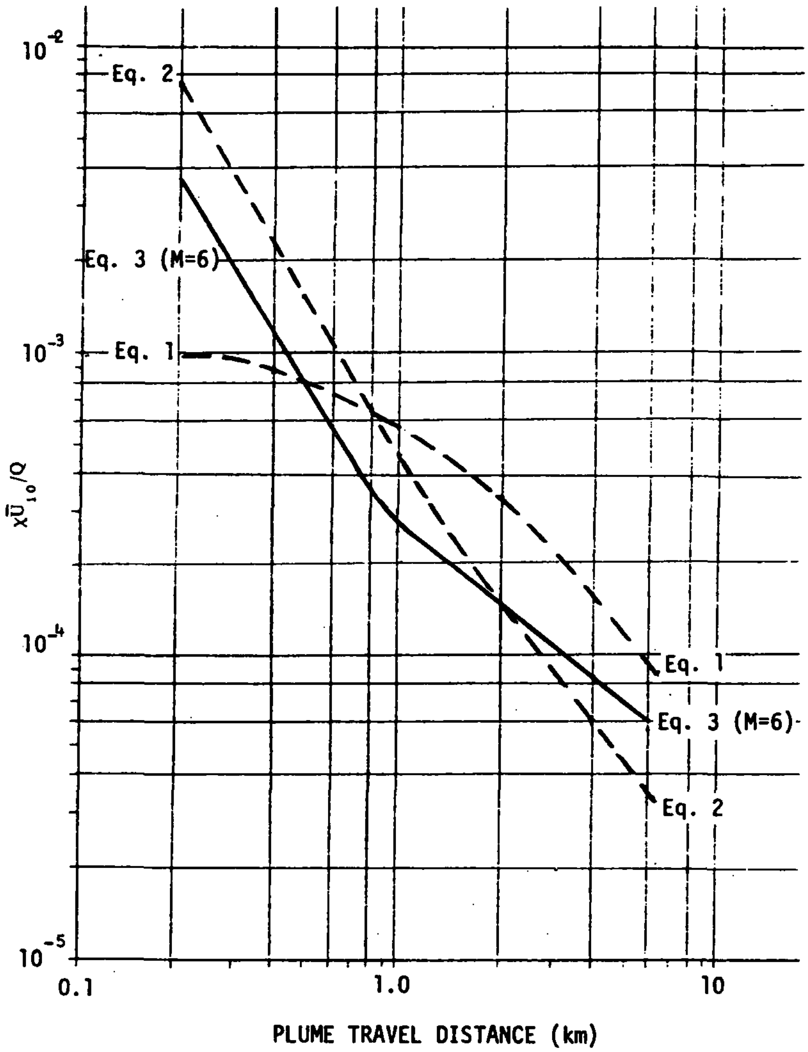

Figure A-1. $\chi\bar{U}_{10}/Q$ as a function of plume travel distance for G stability condition using Equations 1, 2, and 3 (M = 6).

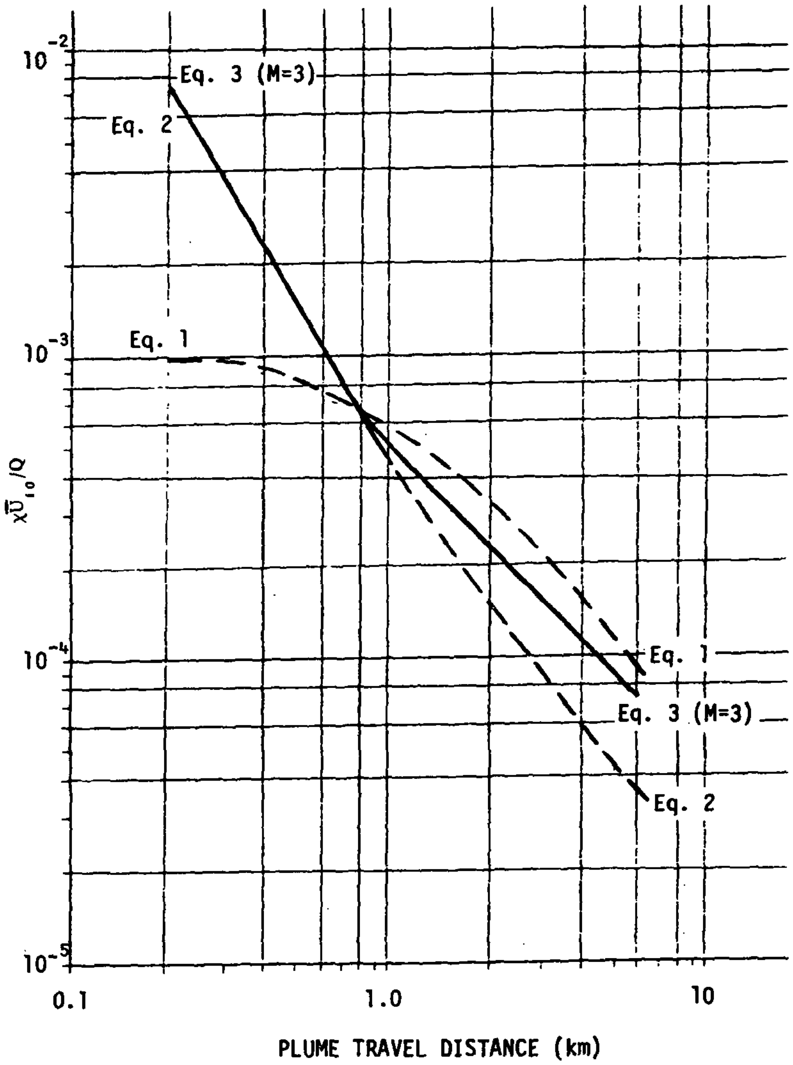

Figure A-2. $\chi\bar{U}_{10}/Q$ as a function of plume travel distance for G stability using Equations 1, 2, and 3 (M = 3).

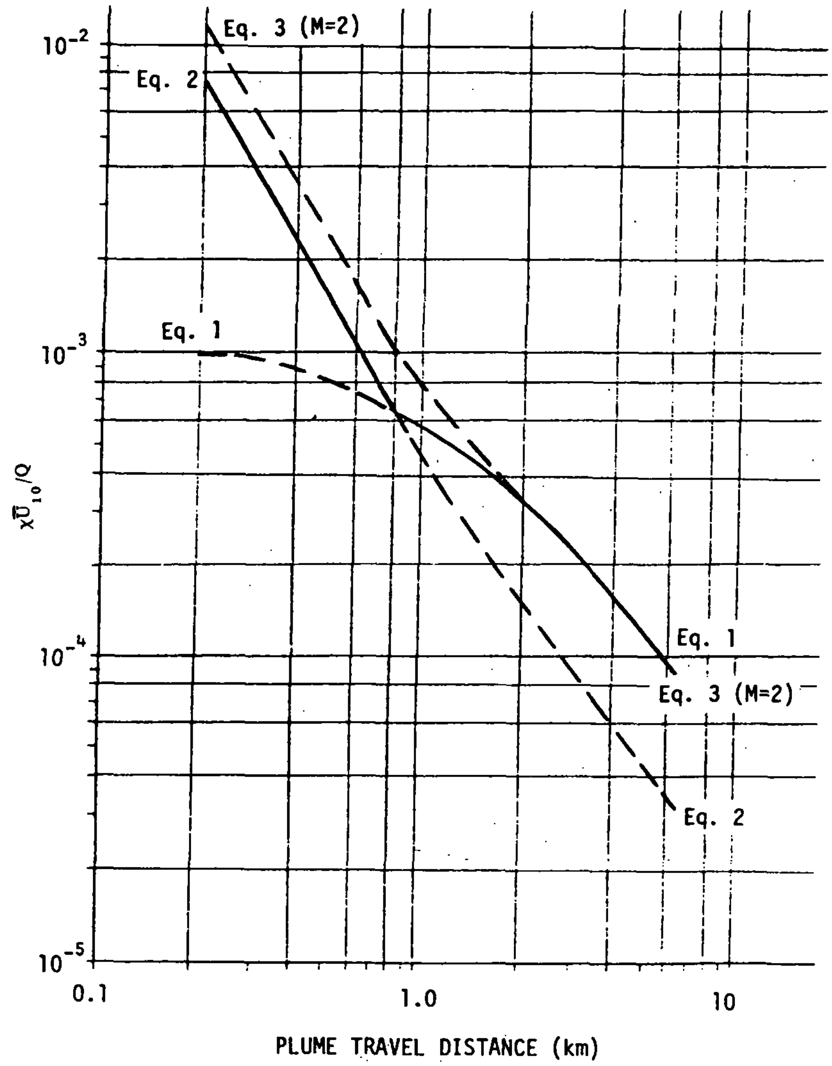

Figure A-3. $\chi\bar{U}_{10}/Q$ as a function of plume travel distance for G stability condition using Equations 1, 2, and 3 (M = 2).

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