

Atmospheric Transport and Dispersion Technical Manual

Version 2.0

A SIERRA Module

September 2026



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Atmospheric Transport and Dispersion Technical Manual

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Revision History

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Atmospheric Transport and Dispersion Technical Manual Introduction

1.0 Introduction

This document provides detailed descriptions of the methods and models implemented within the Atmospheric Transport and Dispersion (ATD) module which is part of the Software Integration for Environmental Radiological Release Assessments (SIERRA) software package. For instructions on software usage of the models and various modeling options available, the user is referred to the SIERRA ATD User Manual [11.1]. SIERRA ATD consists of submodules to perform assessments for three scenarios:

- Routine Release (RR) - For the meteorological evaluation of continuous or anticipated intermittent routine effluent releases, using a Gaussian dispersion model with hourly meteorological data to compute X/Q and D/Q values at multiple distances and directions, in accordance with Regulatory Guide (RG) 1.111. This submodule is described in Section 4.0.
- Design Basis Accidents (DBA) - For evaluating onsite releases to offsite boundaries following a design-basis accident, using a Gaussian plume model to estimate accident-related downwind relative concentrations (χ/Q) at the exclusion area boundary (EAB) and the outer boundary of the low-population zone (LPZ) in accordance with RG 1.145 [11.3]. This submodule is described in Section 5.0. Offsite χ/Q assessments per RG 1.249 [11.5] use the ARCON methodology implemented in the Control Room module; see Sections 5.0 and 6.0.
- Control Room (CR) - For evaluating control-room radiological habitability based on intakes of released radioactive material by control room normal and emergency air handling systems applying a building-wake-sensitive dispersion model that computes accident-related χ/Q values using hourly meteorological data, consistent with RG 1.194. This submodule is described in Section 6.0.

As many of the methods and models are shared amongst the above submodules, those models and methods are collected and discussed in Section 7.0, Shared Input Models. In addition, the processing of the meteorological data is described in Section 8.0 and is shared amongst all modules. Any variations in meteorological data processing for a specific submodule is described in the section describing that submodule.

Statistical methods used to describe the results are found in Section 9.0. Supplemental derivations are provided in Section 10.0.

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A summary review of the key models and methods for each submodule is summarized in Table 1-1.

Table 1-1. ATD module differences summary.

Topic	ATD Module		
	Routine Release (RR)	Design Basis Accident (DBA)	Control Room (CR)
Primary regulatory basis	RG 1.111	RG 1.145	RG 1.194 RG 1.249
Problem focus / domain	Long-term routine effluent compliance.	Offsite EAB and LPZ accident χ/Q .	Onsite near field χ/Q at control room intake(s) per RG 1.194 and Offsite EAB and LPZ accident χ/Q for shorter transport distances ($\leq \sim 1200$ m) per RG 1.249.
Plume geometry (≤ 8 h)	N/A	Centerline used for short averaging; includes special fumigation treatment for elevated releases.	Centerline Gaussian with composite wake coefficients (Σ_y, Σ_z).
Plume geometry (> 8 h)	Sector-averaged χ/Q with 16 sectors; factor $2.0318/x$; apply RF·DEPL·DEC.	Sector-averaged used as applicable for DBA summaries.	Sector-averaged after 8 h with modified sector width $w' = \max(2\pi x/16, 4.3 \cdot \Sigma_y)$.
Diffusion options (σ_y, σ_z)	NRC PG; EPA/ISC; Briggs rural; Briggs urban; Desert.	NRC PG; Desert.	NRC PG.

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Topic	ATD Module		
	Routine Release (RR)	Design Basis Accident (DBA)	Control Room (CR)
Building wakes (ground release)	RG 1.111 C.2.c wake-enhanced Σ_z with $C=0.5$ and D_z (building height).	RG 1.145 wake terms; meander correction, M , for neutral/stable and $u < 6$ m/s; area term A and coefficient C .	Composite near-field wake diffusion (Σ_y , Σ_z) per NUREG/CR-6331; low-wind & building area A corrections.
Elevated releases	Allowed; uses effective release height, h_e , and sector-averaged formula; plume rise as applicable.	Allowed; centerline with fumigation logic (inland/coastal).	Allowed; elevated cases omit near-field wake corrections; includes stack flow limiter for χ/Q .
Ground releases	Allowed; Σ_z modified by wake.	Allowed; explicit wake/meander formulations.	Allowed; primary focus with Σ_y/Σ_z composites.
Mixed/Vent releases	Yes – weighted mix via $\phi = w_0/u$ with piecewise fractions; Section 4.2.8.	Not used.	Not used.
Calm wind speed treatment	Ground: use half calm threshold; Elevated: use calm threshold.	Sector-average: one-half threshold (ground and elevated); centerline: full threshold.	Set equal to user threshold.
Calm directional distribution	Evenly distributed to 16 sectors by stability class.	Evenly distributed to 16 sectors by stability class.	All calms set in the direction of the receptor.

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Topic	ATD Module		
	Routine Release (RR)	Design Basis Accident (DBA)	Control Room (CR)
Elevation to adjust wind speed for ground release	10 m	10 m	10 m
Wind speed adjustment to height	Power-law to release height.	Power-law to release height.	MO–Ramsdell wind profile with stability corrections; height limits applied.
Effective release height h_e	$h_e = h_s + \Delta h_{pr} - \Delta h_{tr} + EL_{ref}$ for elevated release; Section 7.2	Same as RR.	h_e uses h_s , Δh_{dw} , Δh_{tr} , Δh_{in} for elevated option and Δh_{in} for ground release; Section 7.2
Plume Rise (buoyancy and momentum)	Section 7.4 (always applied for elevated releases and the elevated portion of vent releases)	Section 7.4 (user option; default off)	Not used.
Stack downwash	Not used.	Not used.	Section 7.5
Depletion/deposition	DEPL (fraction remaining) and D (relative deposition rate) via piecewise log fits; D/Q computed with RF.	Not used.	Not used.
Open terrain recirculation factor (RF)	Empirical piecewise exponential fit (user option); Section 4.2.1	Empirical piecewise fit (user option; applied to sector annual averages); Section 4.2.1	Not used.

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Topic	ATD Module		
	Routine Release (RR)	Design Basis Accident (DBA)	Control Room (CR)
Distance(s) evaluated	22 fixed distances (0.25–50 mi) + 10 radial segments; Section 4.2.6.	Fixed grids of 20 logarithmically spaced points from the EAB and from the LPZ out to 90 km to capture the maximum χ/Q ; Section 5.1.1.	User specified distance for onsite receptors (e.g., control room and/or TSC) up to ~1200 m for near-field receptors (e.g., EAB or LPZ); slant-range logic for distance.
Special receptors of interest allowed	Yes	No	No
Averaging periods / outputs	Averages by distance and sector; three configurations (no decay, 2.26-day decay, and 8-day decay + deposition).	Running averages: 0–2 h (max of 1h and 2h), 0–8 h, 8–24 h, 1–4 d, 4–30 d, and annual.	Running means for 1, 2, 4, 8, 12, 24, 96, 168, 360, and 720 h.
Percentiles Reported	N/A	50 th , 95 th , and 99.5 th percentiles	95th percentile (standard); optional additional user-specified percentile (e.g., 99.5 th)
Sector width / angular treatment	16 sectors (22.5°); coefficient 2.0318 from sector width integration.	16 sectors (22.5°) when sector-averaging is used.	Modified sector width: $w' = \max(2\pi x/16, 4.3 \cdot \Sigma y)$; Section 6.1 and 6.2.2.

Atmospheric Transport and Dispersion Technical Manual
Definitions and Acronyms

2.0 Definitions and Acronyms

Term / Acronym	Definition
$\Delta T/\Delta z$	Vertical temperature gradient used to determine atmospheric stability class.
χ/Q	Relative atmospheric concentration normalized by emission rate.
ϕ (Phi)	Ratio of vertical vent velocity to adjusted wind speed for determining vent/mixed-mode release fractions.
σ_y	Lateral plume spread coefficient.
σ_z	Vertical plume spread coefficient.
Σ_y	Modified lateral plume spread including building wake effects, etc.
Σ_z	Modified vertical plume spread including building wake effects, etc.
ATD	Atmospheric Transport and Dispersion module within the SIERRA software package.
Briggs Models	Empirical rural/urban dispersion parameterizations used in Gaussian plume models.
Calm Wind	Condition where wind speed falls below the user-specified calm threshold, triggering special treatment for that hour of data.
CL (Centerline)	Dispersion along the plume's centerline ($y = 0$), typically used for short averaging times.
CR (Control Room)	ATD submodule for control-room radiological habitability assessments using near-field, wake-sensitive dispersion methods per RG 1.194.
D/Q	Relative deposition per unit area normalized by release rate.
DBA (Design Basis Accident)	ATD submodule for evaluating accident-related χ/Q at the EAB and LPZ per RG 1.145 [11.3].
DEC	Radioactive decay correction factor applied to plume concentration.
DEPL	Fraction of plume remaining after dry deposition depletion during transport.

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Definitions and Acronyms

Term / Acronym	Definition
EAB (Exclusion Area Boundary)	Minimum distance around a reactor where an individual must not exceed regulatory dose limits during the first 2 hours of a DBA.
Gaussian Plume Model	A dispersion model assuming pollutant concentration spreads with a Gaussian distribution horizontally (σ_y) and vertically (σ_z).
h_e	Effective release height of the plume; accounts for physical stack height, plume rise, terrain correction, and downwash adjustments.
JFD (Joint Frequency Distribution)	Distribution of meteorological data by stability class, wind speed, and wind direction. See Section 10.1 for summary description.
LPZ (Low Population Zone)	Region surrounding the EAB where an individual must not exceed regulatory dose limits during the entire plume passage.
P-G (Pasquill–Gifford) Curves	Empirical dispersion curves for σ_y and σ_z versus distance and stability class.
Pasquill Stability Class (A–G)	Atmospheric stability categories describing turbulence/mixing levels as defined by NRC RG 1.23 (A = extremely unstable, G = extremely stable).
RF (Recirculation Factor)	Correction factor accounting for open-terrain recirculation effects.
RG	Regulatory Guide.
RR (Routine Release)	ATD submodule used to evaluate long-term, continuous, or intermittent routine effluent releases using Gaussian dispersion per RG 1.111 using hourly meteorological data.
SA (Sector-Averaged)	Averaged dispersion result across a 22.5° directional sector (one of 16 sectors).
SIERRA	Software Integration for Environmental Radiological Release Assessments; software suite containing ATD.
Slant Range	Line-of-sight (three-dimensional straight-line) distance between the release point and the receptor,

Atmospheric Transport and Dispersion Technical Manual
Definitions and Acronyms

Term / Acronym	Definition
	accounting for their elevation difference; see Section 6.2.6.
TSC	Technical Support Center
w_0	Stack or vent exit velocity used for plume rise and release mode classification.
w'_{sector}	Modified sector width for near-field (Control Room) sector averaging; Equation [6.2].

3.0 Governing Dispersion Models

- centerline plume model (Section 3.1) calculating the peak ground-level concentration directly downwind on the plume axis ($y = 0$) yielding the highest χ/Q a fixed receptor could see. and
- sector average plume model (Section 3.2) that spreads the released material uniformly across one of sixteen 22.5° sectors. This makes it the long-averaging-period form appropriate when the wind meanders over hours or a year, and it gives lower, more representative values than the centerline model.

A 3D schematic diagram illustrating the geometry of a curved beam. The beam is shown in a perspective view, curving upwards and outwards. It is supported by a trapezoidal base. The vertical axis is labeled z , the horizontal axis along the beam's length is labeled x , and the axis perpendicular to the beam's length is labeled y . The beam's cross-section is a semi-circle. The vertical distance from the base to the center of the beam is labeled h_s . The vertical distance from the base to the top of the beam is labeled Δh_{pr} . The vertical distance from the base to the top of the beam is also labeled h_e . The beam's cross-section is labeled σ_y and σ_z . The beam's length is labeled El_{ref} . The beam's cross-section is labeled $y=0$. The beam's cross-section is labeled h_{tr} .

Figure 3-1. Generalized plume representation with terrain elevation change.

Atmospheric Transport and Dispersion Technical Manual Governing Dispersion Models

This model assumes that a constant mean wind transports and diffuses effluents in the direction of airflow at the release point. It is modeled as a Gaussian plume assuming a straight-line trajectory. The wind speed and stability are used to determine the dispersion characteristics in the downwind direction at the appropriate receptor distances. Spatial and temporal variations in airflow cannot be explicitly accounted for in this model as this model uses meteorological data from a single station to represent dispersion conditions for the entire region of interest which can extend to 50 miles beyond the release point. Thus, when using this model, it is important to consider the regional characteristics of the transport and diffusion conditions along with the applicability of single-location measurement data. Processing of hourly meteorological data is used as described in Section 8.0.

The SIERRA atmospheric engine is based on hourly simulations; therefore, the equations implemented here do not use a factor for the joint frequency distribution (JFD) of meteorological data in the sector-averaged model. All hourly values are collected in an array, and long-term averages are computed. See Section 10.1 for summary description of hourly versus JFD data use.

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Governing Dispersion Models

3.1. Centerline Plume Model

The model for ground-level ($z = 0$) lateral centerline ($y = 0$) relative concentrations is as follows:

$$\left. \frac{\chi}{Q} \right|_{CL} = \frac{1}{\pi u \sigma_y \sigma_z} \cdot e^{\left(-0.5 \left(\frac{h_e}{\sigma_z} \right)^2 \right)} \quad [3.1]$$

$\left. \frac{\chi}{Q} \right|_{CL}$ Centerline (CL) effluent relative concentration normalized by emission rate [s/m^3]

x Downwind distance [m]

u Wind speed [m/s]; Section 7.7

h_e Effective release height [m]; Section 7.2

σ_y Lateral plume spread at downwind distance x for a specific atmospheric stability class without building wake effects [m]

σ_z Vertical plume spread at downwind distance x for a specific atmospheric stability class without building wake effects [m]

This equation provides the centerline relative concentrations for an elevated release with the effective stack height. The above expression can be utilized for both elevated and ground release with $h_e = 0$ for ground-level releases.

For instances where either the lateral or vertical spread is less than 10^{-7} , the relative centerline concentration is set to 0, $\left. \frac{\chi}{Q} \right|_{CL} = 0$.

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Governing Dispersion Models

3.2. Sector Average Plume Model

The centerline relative concentrations in the previous section are appropriate for short averaging periods. In some situations, it may be unlikely that the plume position will remain constant in the same direction for long periods; therefore, a sector-averaged model is used to estimate the relative concentrations for longer averaging periods.

The sector-averaged plume model is derived by integrating the concentration across the normal plume model and dividing the result by the sector width.

$$\left. \frac{\chi}{Q} \right|_{SA} = \frac{2}{\sqrt{2\pi} w_{sector} \cdot u \cdot \sigma_z} \cdot e^{\left(-0.5\left(\frac{h_e}{\sigma_z}\right)^2\right)} \quad [3.2]$$

$\left. \frac{\chi}{Q} \right|_{SA}$ Sector-averaged (SA) effluent relative concentration normalized by emission rate [s/m³]

w_{sector} Sector width [m] at a distance, x , with $w_{sector} = 2\pi x/n_{sector}$

x Downwind distance from source [m]

n_{sector} Number of directional sectors, $n_{sector} = 16$

u wind speed [m/s]; Section 7.7

h_e Effective release height [m]; Section 7.2

σ_z Vertical plume spread at downwind distance x for a specific atmospheric stability class without building wake effects [m]

This can be reduced to a more convenient form that is dependent on the distance from a source. The final expression for sector-averaged relative concentration for an elevated source at a given distance with 16 equal sectors is then given by Equation [3.3].

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Governing Dispersion Models

$$\left. \frac{\chi}{Q} \right|_{SA} = \frac{2.0318}{x \cdot u \cdot \sigma_z} \cdot e^{\left(-0.5 \left(\frac{h_e}{\sigma_z}\right)^2\right)} \quad [3.3]^a$$

Equation [3.3] is based on 16 sectors noted in RG 1.111, and the 2.0318 numerical factor related to the sector width arises from the implementation of sixteen 22.5-degree sectors. The above expression can be utilized for both elevated and ground release, it is utilized for ground releases by setting $h_e = 0$.

The constant 2.032 arises in the sector-averaged Gaussian plume dispersion model. It is produced when averaging a lateral Gaussian distribution over a 22.5° sector (one of 16 sectors in the wind rose). Three mathematical components combine to form this constant (the integrated lateral Gaussian is divided by the sector width):

- Gaussian normalization constant: $1/\sqrt{(2\pi)}$,
- reciprocal of the sector width in radians: $16/(2\pi) = 2.546$ (16 sectors each 22.5°), and
- symmetry of the plume: integration over $\pm\theta$ gives a factor of 2.

Multiplying these yields: $2 \times (1/\sqrt{(2\pi)}) \times (16/2\pi) = 2.0318$

In the Routine Release and DBA sector-average paths, X/Q is evaluated for the 16 compass sectors; each 22.5-degree-wide sector is centered on its principal direction (N, NNE, ...), i.e., ± 11.25 degrees about the centerline (a 22.5-degree arc). The Control Room module treats direction differently: it uses the user-specified direction-to-source and a wind-direction acceptance window, rather than tiling the 16 fixed sectors.

^a The Routine Release sector-average function (XOQ.f90, FUNC_PTSECONC) uses $\pi = 3.14$, so the implemented coefficient is effectively 2.0333 rather than 2.0318 (~0.07% high). The Control Room path (FUNC_PTSECONC2) uses $\pi = 3.14159$ and matches 2.0318. This is submitted as an issue: https://gitlab.com/RCD-1/SIERRA/ATD/-/work_items/114.

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Routine Release Module

4.0 Routine Release Module

This section describes the models and parameters coded into the SIERRA ATD module for Routine Releases during normal plant operation. ATD modeling for routine releases is largely based on RG 1.111 [11.2].

Of primary importance in routine-release evaluations are the long-term average relative concentrations for specified receptor locations, discrete distances, and radial segments extending outward to large distances (typically up to 50 miles). Unlike accident analyses, which assess shorter-duration and higher-consequence events, routine-release models address continuous or intermittent low-level emissions, incorporating meteorological datasets, sector-averaged plume geometry, and terrain-appropriate diffusion parameters. These calculations support compliance with Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20 public dose limits and Appendix I to 10 CFR Part 50, which establishes design objectives for routine effluent releases.

Atmospheric Transport and Dispersion Technical Manual
Routine Release Module

4.1. Dispersion Models

In calculating sector-averaged effluent relative concentrations, ATD implements Constant Mean Wind Direction modeling from Section C.1.c of RG 1.111. This model is described in Section 3.2 and applied for both elevated and ground releases.

The calculation of long-term average (e.g., annual) values of χ/Q and D/Q assumes a continuous release and that resulting effluent relative concentrations will be distributed evenly across a 22.5° direction sector for 22 downwind discrete distances between 0.25 and 50 miles and 10 downwind radial segments between 0.5 and 50 miles (Section 4.2.6), and at any special receptors of interest (Section 4.3.3).

Correction factors additionally applied include:

- open terrain recirculation (Section 4.2.1),
- depletion due to dry deposition during transport (Section 4.2.2),
- radioactive decay (Section 4.2.3), and
- building wake effects for ground releases (Section 4.2.5).

RG 1.111 Section C.3.c notes that, for long-term average assessments, excluding wet deposition typically does not result in significant changes to calculated concentrations. Nonetheless, the guidance recommends considering wet deposition for facilities with predominantly elevated releases and for sites where a pronounced rainy season coincides with the grazing season. ATD does not model wet deposition processes, which means its predictions of downstream ground concentrations may over- or under-estimate impacts in situations where wet deposition effects are expected to be significant.

Utilizing hourly meteorological data, the general expression for sector-averaged effluent relative concentrations considering the above correction factors for Routine Release implemented are as follows:

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Routine Release Module

$$\left. \frac{\chi}{Q} \right|_{RR} = \left. \frac{\chi}{Q} \right|_{SA} \cdot RF \cdot DEPL \cdot DEC \quad [4.1]$$

$\left. \frac{\chi}{Q} \right _{RR}$	Average effluent relative concentration normalized by emission rate [s/m ³] with correction factors for Routine Release (RR)
$\left. \frac{\chi}{Q} \right _{SA}$	sector-averaged (SA) effluent relative concentration normalized by emission rate [s/m ³] without correction factors; Equation [3.3]
RF	Open terrain recirculation factor [unitless]; Section 4.2.1
$DEPL$	Plume depletion due to dry deposition during transport [unitless]; Section 4.2.2
DEC	Depletion due to radioactive decay calculated individually for each radionuclide in the plume [unitless]; Section 4.2.3

RG 1.111 provides guidance on classifying three types of releases based on the release elevation and release velocity as defined in Section 7.3:

- Elevated Release: Release points higher than twice the height of adjacent solid structures, or release points at or above the height of adjacent solid structures with a vertical release velocity at least five times the horizontal wind speed at the height of release.
- Ground Releases accounting for Building Wakes: Release points that are less than the height of adjacent solid structures or are not classified as elevated and have a ratio of the vertical release velocity to horizontal wind speed less than 1.0 at the release height; or if this ratio is unknown.
- Mixed (Vent) Elevation Release: Release points that are at or above the elevation of adjacent structures that are not evaluated as elevated and the ratio of the vertical release velocity to horizontal wind speed at the release height is between one and five.

The release type determines which variations of the specific input models described throughout Section 7.0 will be applied. The user specifies via input the release type of elevated, ground, or vent (mixed-mode) considering the guidance in RG 1.111.

Atmospheric Transport and Dispersion Technical Manual Routine Release Module

The plume spread coefficient is modified to account for building wake effects as described in Section 4.2.5. Here the coefficient without considering building wake effects (σ_z) is replaced with (Σ_z) in Equation [3.3]. The effective release height is calculated as described by Section 7.2 using Equation [4.2]:

$$h_e = h_s + \Delta h_{pr} + EL_{ref} - \Delta h_{tr} \quad [4.2]$$

h_s Physical height of stack above ground surface [m] (user input)

Δh_{pr} Change in height due to plume rise with downwash correction and heat emission corrections [m]; Section 7.4

Δh_{tr} Change in height due to terrain elevation at receptor location [m]

EL_{ref} Reference elevation of plant [m] (user input)

Routine release analysis specifically calculates sector-averaged effluent relative concentrations normalized by emission rate for three main configurations using representative half-lives specified in RG 1.111 [11.2, Section C.3.a]:

1. Open terrain recirculation without decay and without plume deposition:

$$\left. \frac{\chi}{Q} \right|_{RR,1} = \left. \frac{\chi}{Q} \right|_{SA} \cdot RF \quad [4.3]$$

2. Open terrain recirculation with 2.26-day half-life decay for depletion of short-lived noble gases without plume deposition:

$$\left. \frac{\chi}{Q} \right|_{RR,2} = \left. \frac{\chi}{Q} \right|_{SA} \cdot RF \cdot DEC \quad [4.4]$$

3. Open terrain recirculation with 8-day half-life decay for depletion of radioiodines and with plume deposition:

$$\left. \frac{\chi}{Q} \right|_{RR,3} = \left. \frac{\chi}{Q} \right|_{SA} \cdot RF \cdot DEC \cdot DEPL \quad [4.5]$$

Definition and handling of calm winds is described in Sections 4.2.9 and 4.2.10.

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The average deposition per unit area as defined in Equation [4.6] providing the relative deposition per unit area, $\overline{D/Q}$, for each of the 16-directional sector at 22 downwind specific distances and 10 downwind segments (Section 4.2.6), and for any special receptors of interest (Section 4.3.3).

$$\frac{D}{Q} = \left(\frac{16}{2\pi}\right) \left(\frac{1}{x}\right) \cdot D' \cdot RF \quad [4.6]$$

$\frac{D}{Q}$	Average deposition per unit area at downwind distance x normalized by emission rate [1/m ²]
x	Downwind distance [m]
D'	Relative deposition rate [1/m] – Section 4.2.4
RF	Open terrain recirculation factor [unitless] – Section 4.2.1

The χ/Q and D/Q values are calculated for ground-level and elevated releases based on Equations [4.1] and [4.6]. If the release is a mixed-mode (vent) release, between what would be considered either a ground or elevated release, the resultant relative concentration value is based on a weighting of the ground and elevated release depending on the ratio of the release velocity (Section 7.3) and wind speed at the release height and the percentage of time each type of release would occur; see Section 4.2.8.

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4.2. Input Models

4.2.1. Open Terrain Recirculation Factor (RF)

The open terrain recirculation factor, RF , is an empirical fit based on [11.7, Figure 3.2] as shown below in Figure 4-1. NUREG/CR-2919 [11.7, Section 4.22] recommends this feature should be used for all sites unless specific diffusion test, or other data, indicate other factors are more appropriate.

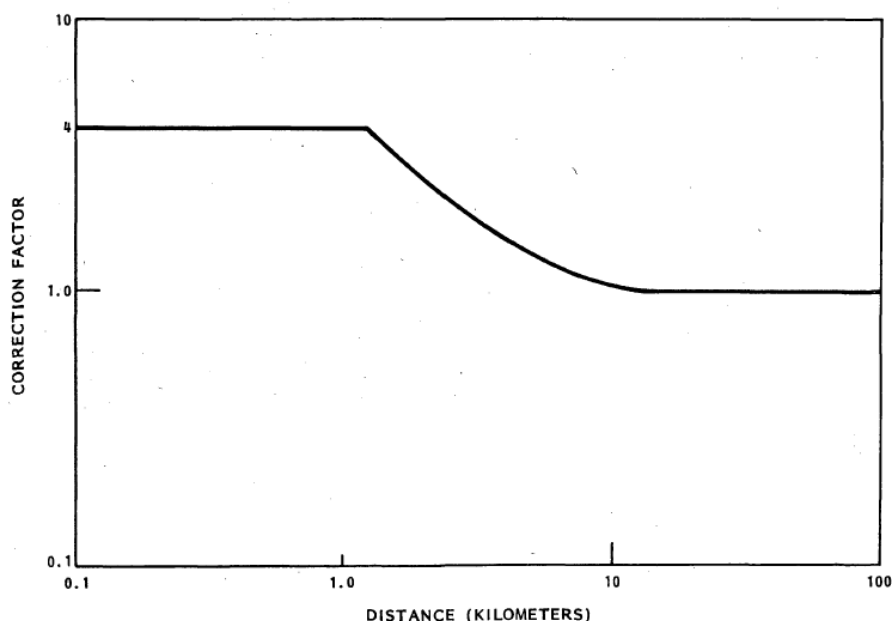


FIGURE 3.2. Open Terrain Correction Factor

Figure 4-1. Open terrain correction factor [11.7, Figure 3.2]

The following piecewise regression with second-order natural logarithmic terms, implemented in the XOQDOQ code (subroutine OPENTR) [11.7, Section 4.22 and Appendix A], yields the open terrain recirculation factor and is limited to no more than 4.0:

$$RF = \begin{cases} \exp[16.125 - 3.18951 \ln(x) + 0.1569306 \ln^2(x)] & \text{for } x < 10,000 \text{ m} \\ \exp[1.1865 - 0.1225 \ln(x)] & \text{for } 10,000 \leq x < 16,090 \text{ m} \\ 1.0 & \text{for } x \geq 16,090 \text{ m} \end{cases} \quad [4.7]$$

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4.2.2. Dry Depletion (*DEPL*)

For routine releases, RG 1.111 [11.2] allows for plume depletion due to deposition during transport represented with a factor for the fraction remaining in the plume. This fraction depends on downwind distance and stability class groupings (unstable, neutral, or stable). The fraction remaining in the plume is plotted for predetermined release heights at 0 (ground level), 30, 60, and 100 m in Figures 3, 4, 5, and 6, respectively from RG 1.111 [11.2]. The fraction remaining in the plume, *DEPL*, is determined from a piecewise nonlinear regression (Equation [4.8]) for a range of downwind distances with a given stability class grouping (i.e., unstable, neutral, stable).

$$DEPL = a + b \ln(x) + c \ln^2(x) \quad [4.8]$$

In Equation [4.8], *a*, *b*, and *c* are regression coefficients determined for joint groupings of release height (*h_e*), stability class (*j*), and downwind distance (*x*). Regression coefficients are identified in Table 4-1 as function of these variables. The calculated *DEPL* value is limited to being no larger than one.

Table 4-1. Dry depletion correction factors

Effective Release Height (<i>h_e</i>) [m]	Stability Class	Distance From Source (<i>x</i>) [m]	<i>a</i>	<i>b</i>	<i>c</i>
<i>h_e</i> < 15	A - G	<i>x</i> < 1,000	0.7793717	0.09578526	−0.01132715
		1,000 ≤ <i>x</i> < 10,000	0.5659763	0.1425852	−0.01363635
		<i>x</i> ≥ 10,000	0.7203016	0.1085504	−0.01172335
15 ≤ <i>h_e</i> ≤ 45	A - C	<i>x</i> ≤ 180	1	0	0
		180 < <i>x</i> < 20,000	0.9535697	0.04267785	−0.0065097
		20,000 ≤ <i>x</i> < 50,000	−4.521979	1.153126	−0.06286699
		<i>x</i> ≥ 50,000	−1.441149	0.6080616	−0.03878529
	D	<i>x</i> ≤ 400	1	0	0
		<i>x</i> > 400	0.8622019	0.07496899	−0.00873217
	E - G	<i>x</i> ≤ 6,000	1	0	0
		6,000 < <i>x</i> < 20,000	−3.524029	1.055262	−0.06153549
		<i>x</i> ≥ 20,000	4.247176	−0.4075444	0.007074166

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Effective Release Height (h_e) [m]	Stability Class	Distance From Source (x) [m]	a	b	c
$45 < h_e \leq 80$	A - C	$x \leq 300$	1	0	0
		$300 < x < 10,000$	0.6938609	0.1123458	-0.01046413
		$10,000 \leq x < 50,000$	2.10853	-0.1364853	0
		$x \geq 50,000$	-3.952915	1.059189	-0.05883216
	D	$x \leq 1,000$	1	0	0
		$1,000 < x < 10,000$	0.6127362	0.1386609	-0.01197688
		$x \geq 10,000$	0.4809772	0.1645758	-0.0132591
	E - G	$x \leq 60,000$	1	0	0
		$x > 60,000$	-8.220195	1.694657	-0.07789403
$h_e > 80$	A - C	$x \leq 600$	1	0	0
		$600 < x < 10,000$	0.864906	0.07226318	-0.007984452
		$10,000 \leq x < 60,000$	-2.2825	0.745051	-0.04395715
		$x \geq 60,000$	-0.7504639	0.5173622	-0.03590246
	D	$x \leq 1,700$	1	0	0
		$1,700 < x < 10,000$	0.1212574	0.2528144	-0.01812868
		$10,000 \leq x < 70,000$	0.3417348	0.2006985	-0.01506006
		$x \geq 70,000$	2.533078	-0.1632279	0
	E - G	any	1	0	0

4.2.3. Radioactive Decay (*DEC*)

Plume depletion due to radioactive decay is determined by Equation [4.9]. The decay relationship corresponds to NUREG/CR-2919 [11.7], Equation 5, with the 2.26-day and 8-day half-lives following the standard XOQDOQ decay groups.

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$$DEC = \exp \left[-0.693 \left(\frac{x}{u T_{1/2}} \right) \right] \quad [4.9]$$

$T_{1/2}$ Radioactive half-life [s]

u Average wind speed [m/s]

x Distance from source to receptor [m]

4.2.4. Relative Dry Deposition Rate (D)

Per RG 1.111, relative deposition rates for dry deposition during transport depends on downwind distance from the source and stability class groupings (unstable, neutral, or stable) and are plotted for predetermined release heights at 0 (ground level), 30, 60, and 100 m in RG 1.111 [11.2] Figures 7, 8, 9, and 10 respectively. The relative deposition rate, D , is evaluated from a piecewise second-order natural logarithmic regression (Equation [4.10]) for a range of downwind distances with a given stability class developed from the figures discussed above.

$$D = \exp[a + b \ln(x) + c \ln^2(x)] \quad [4.10]$$

In Equation [4.10], a , b , and c are regression coefficients determined for joint groupings of release height (h_e), stability class (j), and downwind distance (x) as defined in Table 4-2.

For a ground-level release, the relative deposition rate due to dry deposition during transport, D , is used based on fixed effective release height of 10 m.

For any evaluation of $[a + b \ln(x) + c \ln^2(x)] \geq 0$, the deposition fraction is set to zero, $D = 0$.

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Table 4-2. Deposition rate coefficients.

Effective Release Height (h_e) [m]	Stability Class	Distance From Source (x) [m]	a	b	c
$h_e \leq 15$	A - G	$x < 1,000$	-9.07794	0.4357604	-0.07881594
		$1,000 \leq x < 10,000$	-6.64143	-0.2466506	-0.03098147
		$x \geq 10,000$	-14.06597	1.10343	-0.09031373
$15 < h_e \leq 45$	A - C	$x < 400$	-35.30917	9.57035	-0.8727484
		$400 \leq x < 2,000$	-3.946649	-0.882866	0
		$2,000 \leq x < 5,000$	-3.256392	-1.20884	0.03092014
		$5,000 \leq x < 13,000$	-5.975507	-0.6270642	0
		$13,000 \leq x < 20,000$	12.1268	-4.455138	0.202586
		$20,000 \leq x < 60,000$	-10.79479	0.01276474	-0.01497699
		$x \geq 60,000$	-54.18442	7.877314	-0.3715153
	D	$x < 200$	-42.9116	8.624134	-0.5286823
		$200 \leq x < 400$	-45.08005	9.502915	-0.6178266
		$400 \leq x < 1,500$	-46.40474	10.93155	-0.8182561
		$1,500 \leq x < 7,000$	-12.06068	1.105205	-0.1167178
		$7,000 \leq x < 15,000$	-4.148934	-0.821923	0
		$x \geq 15,000$	-4.640997	-0.7696691	0
	E - G	$x < 5,000$	-156.334	29.93037	-1.5483

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Effective Release Height (h_e) [m]	Stability Class	Distance From Source (x) [m]	a	b	c
		$5,000 \leq x < 8,400$	-140.62	26.18382	-1.324944
		$8,400 \leq x < 42,000$	-87.89882	15.38889	-0.7753119
		$x \geq 42,000$	-12.94973	1.265261	-0.1098207
$45 < h_e \leq 80$	A - C	$x < 400$	-30.45023	5.76941	-0.394098
		$400 \leq x < 900$	-36.23268	8.23023	-0.6448782
		$900 \leq x < 3,000$	-1.56127	-1.725164	0.0694564
		$3,000 \leq x < 13,000$	-5.807573	-0.6388715	0
		$13,000 \leq x < 50,000$	-0.2792892	-1.959056	0.07773757
		$x \geq 50,000$	-58.14337	8.633218	-0.4071184
	D	$x < 300$	-177.431	55.32239	-4.658777
		$300 \leq x < 1,000$	-58.73299	12.91683	-0.8705195
		$1,000 \leq x < 3,000$	-45.04643	9.088059	-0.6027659
		$3,000 \leq x < 20,000$	-13.59167	1.164582	-0.1036683
		$x \geq 20,000$	-4.867893	-0.7430947	0
	E - G	$x < 80,000$	-357.2949	59.55312	-2.583151
		$x \geq 80,000$	-134.0653	20.00078	-0.8306277
$h_e > 80$	A - C	$x < 400$	-57.04822	13.82261	-1.019382
		$400 \leq x < 3,000$	-35.26215	7.297182	-0.5343292

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Effective Release Height (h_e) [m]	Stability Class	Distance From Source (x) [m]	a	b	c
		$3,000 \leq x < 30,000$	-1.488902	-1.694416	0.06353313
		$x \geq 30,000$	-45.70724	6.464447	-0.3122405
	D	$x < 1,500$	-63.81157	11.90979	-0.6561428
		$1,500 \leq x < 10,000$	-44.54416	8.03507	-0.4868832
		$x \geq 10,000$	-9.971805	0.1761891	-0.04063289
	E - G	any	0	0	0

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4.2.5. Plume Spread and Building Wake Effects (Σ_z)

For calculating sector-averaged effluent relative concentrations for elevated releases the plume spread is characterized by the standard vertical spread coefficient depending on selected diffusion model:

$$\Sigma_z = \sigma_z \quad [4.11]$$

For calculating sector-averaged effluent relative concentrations for ground-level releases, the building wake correction outlined in RG 1.111 [11.2, Section C.2.c] is applied to modify the standard diffusion corrections for the case without adjacent buildings and defined as:

$$\Sigma_z = \min \left[\sqrt{\sigma_z^2 + \frac{C D_z^2}{\pi}}, \hat{\sigma}_z \right] \quad [4.12]$$
$$\hat{\sigma}_z = \begin{cases} \sqrt{3} \sigma_z, & D_z > 0 \\ \sigma_z, & D_z = 0 \end{cases}$$

C Building wake mixing coefficient, internally set to 0.5 [unitless]

D_z Maximum adjacent building height either upwind or downwind from the ground-level release [m] (user input)

ATD checks for very small values of vertical plume spread and assigns $\chi/Q = 0$ when $\Sigma_z < 10^{-7}$.

4.2.6. Distances and Intervals Evaluated

The Routine Release analysis submodule considers 22 discrete distances (in units of miles) for evaluation:

0.25, 0.50, 0.75, 1.00, 1.50, 2.00, 2.50, 3.00, 3.50, 4.00, 4.50, 5.00,

7.50, 10.00, 15.00, 20.00, 25.00, 30.00, 35.00, 40.00, 45.00, and 50.00.

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In addition, averages are calculated for ΔR radial interval segments for each of the 16 sectors. Segment groups are defined as follows in units of miles:

0.5 – 1.0	1.0 – 2.0	2.0 – 3.0	3.0 – 4.0	4.0 – 5.0
5.0 – 10.0	10.0 – 20.0	20.0 – 30.0	30.0 – 40.0	40.0 – 50.0

For the radial interval segments, Figure 4-2 provides a representation of the sector averaging (red) that is performed for a specific radial interval.

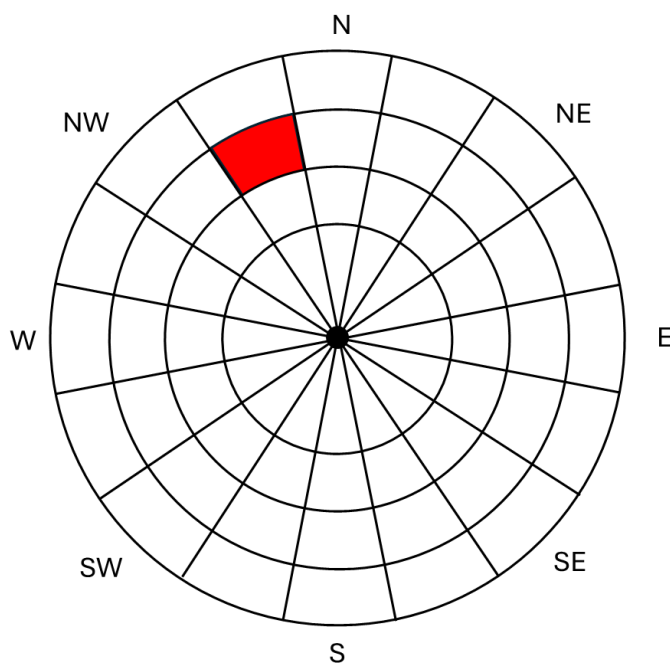


Figure 4-2. Representation of sector radial interval averaging.

4.2.7. Diffusion Models

Routine Release implements the five following diffusion options which are discussed in detail in Section 7.1:

- PG relationships implemented in NRC models (NRC)
- PG relationships implemented in EPA models; Industrial Source Complex Dispersion Model (ISC2)
- Briggs rural models
- Briggs urban models
- Desert models

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4.2.8. Vent (Mixed) Release

Vent releases are modeled as a mixture of elevated and ground-level release behavior. As outlined in RG 1.111 Section C.2.b, these mixtures are determined from comparing the vertical vent velocity to the adjusted horizontal wind speed as defined by Equation [4.13]. The vertical vent (release) velocity is defined in Section 7.3.

$$\phi = \frac{\text{Vertical vent velocity}}{\text{Adjusted wind speed}} \quad [4.13]$$

Table 4-3. Plume fraction mixture treatment for elevated and ground-level release behavior.

ϕ	Ground Release Fraction	Elevated Release Fraction
$\phi \leq 1.0$	1	0
$1 < \phi \leq 1.5$	$2.58 - 1.58 \cdot \phi$	$1.58 \cdot (\phi - 1)$
$1.5 < \phi \leq 5.0$	$0.30 - 0.06 \cdot \phi$	$0.70 + 0.06 \cdot \phi$
$\phi > 5.0$	0	1

4.2.9. Calm Wind Threshold

For ground releases, calm wind calculations are performed with a wind speed equal to half the user-specified calm threshold.

For elevated releases, calm wind calculations are performed with a wind speed equal to the user-specified calm threshold^b.

4.2.10. Distribution of Calm Winds

Because calm winds do not have a prevailing direction, their occurrence is distributed evenly across all 16 sectors during a routine release^c. First, all calm records are tallied by their stability class groups. Next, the calm winds are evenly

^b RG 1.111 C.4 identifies that the wind speed assumed for calms should be one-half of the starting speed of the vane or anemometer (whichever is higher); i.e., one-half the calm threshold with no distinction between ground and elevated releases.

^c RG 1.111 identifies that calms for hourly data should be assigned a direction of the “recorded wind direction averaged over the time interval.” This is not done in ATD as discussed above.

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distributed to each of the 16 sectors with rounding to the nearest integer to ensure an integer value is returned.

$$N_{calm}[j, k] = Round(N_{calm}[j]/16) \quad [4.14]$$

$N_{calm}[j, k]$ Number of calms for stability class (j) and sector (k)

$N_{calm}[j]$ Number of calms for stability class (j) for all sectors

j Stability class

k Sector (16 sectors total)

The rounding in Equation [4.14] defines a per-sector allocation for each stability class. Each calm hour is then assigned a sector within its stability class, filling sectors in order (1 through 16) as the per-sector allocations are met. Because of the rounding, the summed allocation can differ from the actual number of calm hours. If the summed allocation is exhausted before all calm hours are assigned (e.g., 17 calm hours in a class round to one per sector, or 16 total), each remaining calm hour is assigned to sectors 1 (North), 2 (NNE), and so on in order, and its stability class is reassigned to 7 (G, extremely stable). If the summed allocation exceeds the number of actual calm hours, the excess allocation positions are simply unused.

4.2.11. Wind Speed Adjustment

Wind speeds are adjusted to account for the release elevation by applying the power-law method, Section 7.7.1.

For pure elevated releases, measured wind speeds are adjusted for the input source release elevation. For pure ground releases, measured wind speeds are adjusted for a source release elevation of 10 m. For a mixed-mode release (combination of ground and elevated), the wind speed measurements for those portions of time that are determined to be of type ground, an elevation of 10 m is used to evaluate the wind speed.

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4.3. Calculation of Output Results

4.3.1. Average of All Distances and All Sectors

The average for all discrete distances defined in Section 4.2.6 and the sixteen 22.5° sectors is determined through standard numeric averaging as defined by Equation [4.15]. This is evaluated for each of the three explicit formulations defined in Section 4.1 Equations [4.3] through [4.5]:

1. Open terrain recirculation without decay and without plume deposition.
2. Open terrain recirculation with 2.26-day half-life decay without plume deposition.
3. Open terrain recirculation with 8-day half-life decay and with plume deposition.

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$$\begin{aligned}\left.\frac{\bar{\chi}}{Q}\right|_{i,k} &= \frac{1}{N_{sim}} \sum_n \left(\frac{\chi}{Q}\right)_{RR} (x_i, k, n) \\ \left.\frac{\bar{D}}{Q}\right|_{i,k} &= \frac{1}{N_{sim}} \sum_n \left(\frac{D}{Q}\right) (x_i, k, n)\end{aligned}\tag{4.15}$$

$\left.\frac{\bar{\chi}}{Q}\right|_{i,k}$ Average χ/Q for distance i and sector k

$\left.\frac{\bar{D}}{Q}\right|_{i,k}$ Average D/Q for distance i and sector k

n Hour

N_{sim} Number of non-missing (simulated) hourly records in the meteorological data set

k Sector number (1-16)

x_i Distance where i is the distance index (1-22)

4.3.2. Average of 10 Radial Segments for All Sectors

Averages as described in Section 4.3.1 are calculated for 22 fixed radial distances (x_i) and 10 ΔR radial segments for each of the 16 sectors as defined in Section 4.2.6. The average results calculated at the 22 fixed distances are grouped into the 10 radial segment intervals as follows such that for segment k , for segment l , J_l is the set of all distance indices (between 1 and 22) whose distances fall within the segment's lower bound (LB_l) and upper bound (UB_l):

$$J_l = \{i \in \{1,22\} \mid LB_l \leq x_i \leq UB_l\}\tag{4.16}$$

The segment averages for each sector are calculated as weighted averages of the average based on the distances as defined in Equation [4.17]. This equation is applied to each of the 3 decay solutions described in Section 4.3.1.

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$$\begin{aligned}\left. \frac{\bar{X}}{\bar{Q}} \right|_{l,k} &= \frac{\sum_{i \in J_l} \left(\left. \frac{\bar{X}}{\bar{Q}} \right|_{i,k} \cdot x_i \right)}{\sum_{i \in J_l} (x_i)} \\ \left. \frac{\bar{D}}{\bar{Q}} \right|_{l,k} &= \frac{\sum_{i \in J_l} \left(\left. \frac{\bar{D}}{\bar{Q}} \right|_{i,k} \cdot x_i \right)}{\sum_{i \in J_l} (x_i)}\end{aligned}\tag{4.17}$$

- l Radial segment index (1–10)
- J_l Set of distance indices i whose distances x_i fall within segment l ; Equation [4.16]
- k Sector number (1-16)
- x_i Distance where i is the distance index (1-22)

4.3.3. Average at a Receptor of Special Interest

The user can enter arbitrary receptors of special interest at specific distances for specific sectors (e.g., the site boundary, nearest residence, nearest meat and milk animals, nearest vegetable garden typically within 5 km of the facility). With the distance and sector known, the elevation of a receptor is determined as described in Section 7.6 allowing for determination of the plume effective release height at that location (Section 7.2). With this, the averages are determined as described in Section 4.3.1 with the specified sector and distance for each receptor; see below for sample output.



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SPECIFIC POINTS OF INTEREST

LABEL	LOCATION TYPE	SECTOR	DISTANCE (MILE)	DISTANCE (METER)	CHI/Q (SEC/M3)	CHI/Q (SEC/M3)	CHI/Q (SEC/M3)	D/Q (M^-2)
					NO DECAY	2.260 DAY DECAY	8.000 DAY DECAY	
					UNDEPLETED	UNDEPLETED	DEPLETED	
Receptor1	site boundary	S	0.50	805.00	3.76E-06	3.75E-06	3.43E-06	1.13E-08
Receptor2	milk cow	NNW	1.20	1931.00	5.26E-07	5.23E-07	4.54E-07	1.45E-09
Receptor3	residence	SSE	4.00	6437.00	1.84E-07	1.81E-07	1.40E-07	4.68E-10

Atmospheric Transport and Dispersion Technical Manual
Design Basis Accident Module

5.0 Design Basis Accident Module

This section describes the models and parameters coded into the SIERRA ATD module for Design Basis Accidents (DBAs). ATD modeling for the models and methods implemented are largely based on RG 1.145, [11.3].

Of focus is analysis at two key boundaries. The Exclusion Area Boundary (EAB) is the closest boundary around a reactor, sized so that a person at the boundary during the first 2 hours of an accident would not exceed dose requirements. The Low Population Zone (LPZ) surrounds the EAB and must ensure that a person at its outer boundary, exposed to the entire plume passage, also remains below specified dose limits. Using the models described in the following sections, Section 5.3 outlines the provided outputs.

In addition, RG 1.249 [11.5] outlines an alternative use of ARCON for modeling onsite releases to offsite boundaries from a DBA. The SIERRA ATD Control Room module is the analogous code to ARCON. The basis for the use of ARCON of offsite analyses is summarized in RG 1.249 with the ARCON code being updated to an improved building wake dispersion algorithm, addition of assessment of a ground-level, elevated, and diffuse source release modes, hour-by-hour meteorological observations, sector averaging, and directional dependence of dispersion conditions of which the ATD Control Room module implements (Section 6.0). RG 1.249 outlines how to estimate χ/Q_s at the EAB and the outer boundary of the LPZ out to distances of 1,200 m (3,937 ft) from the nearest edge of a building within the nuclear island. As such, the user may assess the use of the Control Module described in Section 6.0 for their application to perform assessment of DBAs considering guidance from RG 1.249.

Atmospheric Transport and Dispersion Technical Manual
Design Basis Accident Module

5.1. Dispersion Models

5.1.1. Centerline Plume Model for Elevated Releases

Plume centerline ($y = 0$) relative concentrations for an elevated release is determined as described in Section 3.1.

For elevated releases, the maximum ground-level concentration in a sector may occur beyond the EAB distance or outer LPZ boundary distance. Therefore, $\overline{\chi/Q}$ calculations are made in each sector at each minimum boundary distance and at various distances beyond to ensure the maximum $\overline{\chi/Q}$ is determined.

As depicted by Figure 5-1, distances are evaluated starting from the EAB out to 90 km (56 miles) over 20 grid points and from the LPZ out to 90 km over 20 grid points. This ensures the maximum relative concentration is determined within a directional sector. The relative concentrations for elevated releases under non-fumigation conditions are calculated at various predetermined distances up to a maximum of 90 km.

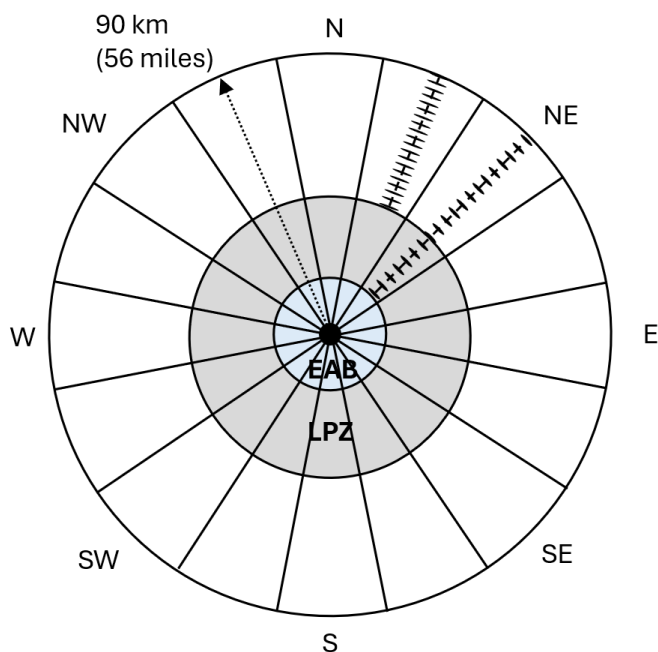


Figure 5-1. Evaluation points beyond EAB and LPZ boundaries.

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For elevated release, centerline plume calculations are performed at each of the grid points described in the previous paragraph to determine the maximum, $\left(\frac{\chi}{Q}\right)_{\max}$.

For an elevated releases, the fumigation flag is set for the current record if the current record has a stability category between (and including) 5 and 7 (i.e., slightly and extremely stable) and the next record has a stability category 3 or less (i.e., slightly unstable to extremely unstable). This hourly fumigation-identification criterion is an ATD-specific extension enabled by the use of hourly meteorological data; RG 1.145 and NUREG/CR-2858 do not identify fumigation hours from the meteorological record but instead assume fumigation exists at the time of the accident (RG 1.145, Regulatory Positions 2.1.2 and 2.2.2). For fumigation conditions during an elevated release, a centerline $\overline{\chi/Q}$ is calculated as the minimum between two calculations to reconcile unrealistically large values for fumigation as described in Regulatory Position 1.3.2.b of RG 1.145. As identified in RG 1.145, ground-level relative concentrations from elevated releases with fumigation conditions cannot be larger than those produced by a ground-level release (i.e., $h_e = 0$), non-fumigation, stable atmospheric conditions; thus, results are limited to being no larger than this. The first term in the fumigation comparison below is based on this fact and uses Section 5.1.2 Equation [5.4] utilizing stability Class F. The second term is relative concentration based on fumigation conditions. These fumigation relationships are consistent with NUREG/CR-2858 [11.8], Equations 10 and 11: the limiting (first) term applies Equation 10 with stability Class F, $u' = 2$ m/s, and an effective height of zero, and the lower of the two values is selected.

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$$\left. \frac{\chi}{Q} \right|_{\text{fumigation}} = \min \left[\frac{1}{\pi u' \sigma_{y,6} \sigma_{z,6}}, \frac{1}{\sqrt{2\pi} u' \sigma_{y,6} h_e} \right] \quad [5.1]$$

h_e Effective release height [m] – Section 7.2

u' Wind speed for fumigation layer at the effective stack height and below $\left[\frac{m}{s} \right]$, ATD applies $u' = 2$ m/s as a reasonably conservative wind speed for effective stack heights ~100 m; RG 1.145

$\sigma_{y,6}$ Lateral plume spread at downwind distance x for atmospheric stability Class F ($j = 6$) without building wake effects [m]; RG 1.145

$\sigma_{z,6}$ Vertical plume spread at downwind distance x for atmospheric stability Class F ($j = 6$) without building wake effects [m]; RG 1.145

How $\left. \frac{\chi}{Q} \right|_{\text{fumigation}}$ is utilized is based on whether the site is coastal or inland as defined in Regulatory Positions 2.1.2 and 2.2.2 in RG 1.145 for the EAB and LPZ, respectively. RG 1.145 distinguishes the cases by proximity to large bodies of water: sites 3.2 km (2 miles) or more from large bodies of water (e.g., oceans or Great Lakes) are treated as inland, and closer sites as coastal. For inland sites, the maximum centerline $\left. \frac{\chi}{Q} \right|_{\text{max,inland}}$ concentration is the average between the fumigation and non-fumigation result.

$$\left. \frac{\chi}{Q} \right|_{\text{max,inland}} = \frac{1}{2} \left(\left. \frac{\chi}{Q} \right|_{\text{max}} + \left. \frac{\chi}{Q} \right|_{\text{fumigation}} \right) \quad [5.2]$$

For coastal, the maximum centerline relative concentration is simply the maximum of the fumigation and non-fumigation result

$$\left. \frac{\chi}{Q} \right|_{\text{max,coastal}} = \max \left[\left. \frac{\chi}{Q} \right|_{\text{max}}; \left. \frac{\chi}{Q} \right|_{\text{fumigation}} \right] \quad [5.3]$$

RG 1.145 Regulatory Position 2.1.2.a prescribes, for inland sites, a half-hour fumigation period within the 2-hour window (a $\frac{1}{4}$ and $\frac{3}{4}$ time weighting), applied only when the sector fumigation χ/Q exceeds the non-fumigation value.

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Regulatory Position 2.2.2.b prescribes a 4-hour fumigation duration at the outer LPZ boundary for coastal sites and then defers to Regulatory Position 2.1.2 for implementation. ATD applies an unconditional arithmetic average to the inland ensuring that at least one half-hour of fumigation occurs for each 1-hour window. It applies the maximum for the coastal between the fumigation and non-fumigation values to each fumigation-flagged hour. This occurs before the frequency distributions are formed.

5.1.2. Centerline Plume Model for Ground Releases

For centerline effluent relative concentrations from releases modeled as ground-level, ATD follows RG 1.145, for modeling building wake effects. This class of release modes should be considered for all release points or areas that are effectively lower than two and one-half times the height of adjacent solid structures, per RG 1.145.

For ground-level releases ($h_e = 0$), the basic centerline $\overline{\chi/Q}$ calculation (Section 3.1 Equation [3.1]) without building wake effects simplifies to:

$$\frac{\chi}{Q} = \frac{1}{\pi u \sigma_y \sigma_z} \quad [5.4]$$

The comparison and selection of building wake terms depend on atmospheric stability class. For ground-level releases during unstable atmospheric conditions or if the wind speed is greater than or equal to 6 m/s, the centerline plume relative concentration with building wake effects is determined from Equation [5.5].

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$$\frac{\chi}{Q} = \max \left[\frac{1}{u (\pi \sigma_y \sigma_z + C \cdot A)}, \frac{1}{3\pi u \sigma_y \sigma_z} \right] \quad [5.5]$$

- u Wind speed [m/s]
- σ_y Lateral plume spread at downwind distance x for atmospheric stability class without building wake effects [m]
- σ_z Vertical plume spread at downwind distance x for atmospheric stability class without building wake effects [m]
- C Building wake mixing coefficient, internally set to 0.5 [unitless]
- A Smallest vertical-plane cross-sectional area of the reactor building or other justified structure [m²] (user input)

For ground-level releases during neutral or stable atmospheric conditions and with wind speeds less than 6 m/s, plume meandering is accounted for only if the NRC PG model is selected; otherwise, Equation [5.5] applies. The centerline plume relative concentration with building wake effects is calculated for two scenarios, one for downwind distances less than or equal to 800 m and another for downwind distances greater than 800 m:

$$\frac{\chi}{Q} = \min \left[\frac{1}{u \pi \Sigma_y \sigma_z}, \max \left[\frac{1}{u (\pi \sigma_y \sigma_z + C \cdot A)}, \frac{1}{3\pi u \sigma_y \sigma_z} \right] \right] \quad [5.6]$$

$$\Sigma_y = \begin{cases} M \cdot \sigma_y(x), & x \leq 800 \\ (M - 1) \cdot \sigma_y(800 \text{ m}) + \sigma_y(x), & x > 800 \end{cases} \quad [5.7]$$

The M correction factor for meandering and building wake effects which depends on wind speed and atmospheric stability class is defined by Equation [5.8]. These logarithmic regression lines are derived from the log-log plot shown in Figure 3 of RG 1.145. The meander correction factor is limited such that it is

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greater than or equal to one; $M = \max(M, 1.0)$. The diffusion coefficients $\sigma_y(800 \text{ m})$ is calculated using the PG model described in Section 7.1.1.

$$M = \begin{cases} 2 & \text{for class D} \\ 3 & \text{for class E} \\ 4 & \text{for class F} \\ 6 & \text{for class G} \end{cases} \quad u \leq 2 \text{ m/s}$$
$$M = \begin{cases} \min(\exp[-0.6309 \ln(u) + 1.1304], 2) & \text{for class D} \\ \min(\exp[-1.0 \ln(u) + 1.7918], 3) & \text{for class E} \\ \min(\exp[-1.2619 \ln(u) + 2.2610], 4) & \text{for class F} \\ \min(\exp[-1.6309 \ln(u) + 2.9222], 6) & \text{for class G} \end{cases} \quad 2 < u < 6 \text{ m/s} \quad [5.8]$$
$$M = 1 \quad u \geq 6 \text{ m/s}$$

5.1.3. Sector Average Plume Model for Ground Releases

For determining sector average relative concentrations for ground releases for DBAs, the same general expression applied to Routine Release is applied (Section 4.1) using:

- an adjusted wind speed (Section 7.7) at an elevation of 10 m,
- an effective release height of $h_e = 0$,
- an open terrain recirculation factor as described in Section 4.2.1 (user option; in the DBA module it is applied to the sector annual-average results only, Section 5.3),
- plume spread and building wake correction factors as described in Section 4.2.5.

5.1.4. Sector Average Plume Model for Elevated Releases

For determining sector average relative concentrations for elevated releases for DBAs, the same models applied to Routine Release are applied (Section 4.1) using:

- an adjusted wind speed (Section 7.7) at the release elevation (minimum height of 10 m),

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- an open terrain recirculation factor as described in Section 4.2.1 (user option; applied to the sector annual-average results only, Section 5.3), and
- an effective release height as described in Section 7.2.

ATD calculations for design basis accidents accept terrain data supplied by the user and consider various user specified directions and distances for the EAB and LPZ boundary.

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5.2. Input Models

5.2.1. Diffusion Models

The DBA submodule implements the following diffusion options which are discussed in detail in Section 7.1:

- PG relationships implemented in NRC models (NRC)
- Desert model

5.2.2. Calm Wind Threshold

For sector-average calculations (ground and elevated releases), calm-wind hours are evaluated with a wind speed equal to one-half the user-specified calm threshold^d.

For centerline calculations (ground and elevated releases), calm-wind hours are evaluated with the full calm-threshold wind speed.

5.2.3. Distribution of Calm Winds

Because calm winds do not have a prevailing direction, their occurrence is evenly distributed as discussed in Section 4.2.10^e.

5.2.4. Wind Speed Adjustment

Measured wind speeds are adjusted for the source release elevation by applying the power-law method, Section 7.7.1. The height used to adjust the wind speed for both elevated and ground releases enforces a minimum height of 10 m.

^d RG 1.145, Regulatory Position 1.1, identifies that calms should be assigned a wind speed equal to the vane or anemometer starting speed (i.e., the full threshold speed), whichever is higher.

^e RG 1.145 C1.1 identifies that calms should be assigned a directional distribution equal to the distribution of the non-calm winds that are less than 1.5 m/s. It is noted that if no non-calm winds below 1.5 m/s exist, PAVAN distributes calms equally in all directions [11.8].

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5.3. Calculation of Output Results

The following averaging time periods (computed as a moving average) are considered: 0–2 h (maximum of 1 h and 2 h), 0–8 h, 8–24 h (16 h), 1–4 days (72 h), 4–30 days (624 h), and annual average^f. Relative concentrations for short periods (≤ 8 h) are calculated using centerline values and those for longer periods (> 8 h) are calculated using both centerline for the first 8 hours and sector-averaged values for the remaining hours. Section 9.1 outlines the moving average procedure implemented in ATD.

Cumulative frequency distributions are then computed for each averaging interval. Exceedance values of 0.5%, 5%, 50% (99.5th, 95th, and 50th percentile) are calculated for both direction-dependent and overall site relative concentrations (described in the following paragraphs). Section 9.2 details the calculation process for determining the percentile χ/Q values. For each averaging period the maximum sector value for each percentile is reported for the EAB and LPZ.

Two values of relative concentration are produced at each boundary distance: the *direction-dependent* (sector) values and the *overall-site* (direction-independent) values. They differ in which hours of the meteorological record are allowed to contribute to the cumulative frequency distribution and, for the annual average, in how the directional results are combined.

The direction-dependent (sector) statistics represent a receptor that remains fixed in one of the 16 compass sectors. For sector m , only the hours during which the wind transports the plume toward that sector contribute a non-zero value; for every other hour the receptor lies outside the plume and its hourly χ/Q is set to zero before the distribution is formed. The corresponding annual-average relative concentration is the frequency-weighted mean of the sector-average values,

$$\left(\frac{\chi}{Q}\right)_m^{ann} = \frac{1}{N_{sim}} \sum_{h \in H_m} \left(\frac{\chi}{Q}\right)_{SA,h} \quad [5.9]$$

where H_m is the set of hours with the wind blowing toward sector m , N_{sim} is the number of non-missing (simulated) hours, and $(\chi/Q)_{SA}$ is the hourly sector-

^f The interpretation of these values and the meanings of the intervals has been submitted as an issue: https://gitlab.com/RCD-1/SIERRA/ATD/-/work_items/109.

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average relative concentration. Because the sum is divided by the total simulated hours N_{sim} rather than by the number of hours the wind actually blows toward the sector, the result is weighted by the directional frequency; physically it is the long-term average χ/Q experienced by a receptor that is only intermittently downwind of the release.

The overall-site statistics are direction-independent. Every non-missing hour contributes its relative concentration at the boundary distance evaluated in whatever direction the wind is blowing that hour:

$$\left(\frac{\bar{\chi}}{Q}\right)_m^{ann} = \frac{1}{N_{sim}} \sum_h \left(\frac{\chi}{Q}\right)_{SA,h} . \quad [5.10]$$

The annual-average overall-site value is defined as the largest of the 16 sector annual averages,

$$\left(\frac{\chi}{Q}\right)_{site}^{ann} = \max_{1 \leq m \leq 16} \left(\frac{\bar{\chi}}{Q}\right)_m^{ann} . \quad [5.11]$$

Physically, the overall-site value characterizes the most-exposed location at the boundary without crediting any particular compass direction, and is the more conservative measure when a receptor's orientation relative to the release is unknown.

For each averaging interval the exceedance (complementary cumulative) χ/Q at the 0.5%, 5%, and 50% levels is read from the respective distribution by the interpolation procedure of Section 9.2. The reported maximum-sector value is the largest of the 16 sector exceedance values.

For a given averaging interval and exceedance level, the overall-site χ/Q is expected to be greater than or equal to the maximum-sector χ/Q ,

$$\left(\frac{\chi}{Q}\right)_{sec}^p \leq \left(\frac{\chi}{Q}\right)_{site}^p \quad [5.12]$$

because the overall-site distribution pools the highest-concentration hours from all 16 directions, whereas each individual sector distribution must locate the same number of exceedances within a single 22.5° sector that receives the wind only a fraction of the time. The two results converge only when a single sector dominates the wind rose. For the annual average defined by Equation [5.11], the maximum-sector and overall-site entries are always equal.

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In the summary output that follows, each line corresponds to one averaging period and one exceedance statistic. The AVG. PERIOD column identifies the averaging interval: the 0-2 Hr entry is the larger of the 1-hour and 2-hour moving averages (Section 9.1), the 0-8 Hr, 8-24 Hr, 1-4 Day, and 4-30 Day entries are the 8-, 16-, 72-, and 624-hour moving averages, and Annual is the annual average of Equation [5.9]. The STATISTIC column is the percentage of time the tabulated χ/Q is equaled or exceeded (0.5%, 5%, or 50%); it is left blank for the annual average, which is a calculated mean rather than an exceedance value. The MAXIMUM SECTOR columns list the direction-dependent χ/Q (the largest value over the 16 sectors) and the OVERALL SITE columns the direction-independent χ/Q , each reported at the EAB and the outer boundary of the LPZ.

An example summary output is provided on the following page.

It is noted that RG 1.145 Section 2.2.1 identifies that for LPZ analysis, an interpolation between the 2-hr and annual sectors values can be used with a logarithmic interpolation to obtain intermediate values. Rather than interpolating, the DBA modules calculate the averages explicitly for the interval of interest. This is consistent with RG 1.145 allowance for alternative methods that produce a monotonic decrease in average χ/Q with time.

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SUMMARY DATA BY AVERAGING INTERVAL

AVG. PERIOD		STATISTIC	MAXIMUM SECTOR		OVERALL SITE	
			EAB	LPZ	EAB	LPZ
			=====	=====	=====	=====
0-2 Hr	Avg. X/Qs	0.5%	4.18E-05	1.82E-05	2.54E-04	1.15E-04
0-2 Hr	Avg. X/Qs	5.0%	8.41E-06	5.31E-06	4.20E-05	1.88E-05
0-2 Hr	Avg. X/Qs	50.0%	1.00E-07	1.00E-07	7.40E-06	4.33E-06
0-8 Hr	Avg. X/Qs	0.5%	2.15E-05	8.93E-06	1.62E-04	7.96E-05
0-8 Hr	Avg. X/Qs	5.0%	5.96E-06	3.26E-06	3.88E-05	1.90E-05
0-8 Hr	Avg. X/Qs	50.0%	2.91E-07	1.00E-07	8.53E-06	4.72E-06
8-24 Hr	Avg. X/Qs	0.5%	1.33E-05	9.58E-06	1.19E-04	5.53E-05
8-24 Hr	Avg. X/Qs	5.0%	3.74E-06	1.84E-06	2.90E-05	1.41E-05
8-24 Hr	Avg. X/Qs	50.0%	4.35E-07	2.71E-07	6.06E-06	3.09E-06
1-4 Day	Avg. X/Qs	0.5%	8.23E-06	6.71E-06	6.08E-05	2.83E-05
1-4 Day	Avg. X/Qs	5.0%	1.68E-06	7.81E-07	2.29E-05	1.08E-05
1-4 Day	Avg. X/Qs	50.0%	4.32E-07	2.34E-07	4.12E-06	1.92E-06
4-30 Day	Avg. X/Qs	0.5%	7.27E-06	3.08E-06	3.86E-05	1.79E-05
4-30 Day	Avg. X/Qs	5.0%	1.31E-06	7.61E-07	1.68E-05	9.21E-06
4-30 Day	Avg. X/Qs	50.0%	3.93E-07	2.10E-07	3.75E-06	1.69E-06
Annual	Avg. X/Qs		5.61E-07	2.77E-07	5.61E-07	2.77E-07

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6.0 Control Room Module

The General Design Criteria (GDC) for Nuclear Power Plants set forth in Appendix A to 10 CFR Part 50, establish minimum requirements for the design criteria for water-cooled nuclear power plants. Specifically, GDC 19, "Control room," requires that a control room be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions. Adequate radiation protection must be provided to permit access to and occupancy of the control room for the duration of accident conditions.

This section describes the models and parameters coded into the SIERRA ATD module for Control Room (CR) analysis. ATD modeling for the models and methods implemented largely follow the guidance of RG 1.194 [11.4].

In addition, RG 1.249 [11.5] outlines an alternative use of ARCON for modeling onsite releases to offsite boundaries from a DBA. The SIERRA ATD Control Room module is the analogous code to ARCON. The basis for the use of ARCON of offsite analyses is summarized in RG 1.249 with the ARCON code being updated to an improved building wake dispersion algorithm, addition of assessment of a ground-level, elevated, and diffuse source release modes, hour-by-hour meteorological observations, sector averaging, and directional dependence of dispersion conditions that the ATD Control Room module implements. RG 1.249 outlines how to estimate χ/Q_s at the EAB and the outer boundary of the LPZ out to distances of 1,200 meters (m) (3,937 feet (ft)) from the nearest edge of a building within the nuclear island. As such, the user may consider using the Control Module described in this section to assess DBAs according to guidance from RG 1.249. The current ARCON implementation and interface are documented in the ARCON 2.0 User's Guide (PNNL-28667, Revision 1; see References).

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6.1. Dispersion Models

6.1.1. Ground Releases

Modeling for control room habitability for ground releases uses the centerline Gaussian plume formulations for time periods up to 8 h based on Section 3.1 Equation [3.1] with an effective release height of zero, $h_e = 0$ and modified lateral and vertical diffusion coefficients to account for wake effects. If $\Sigma_z(x) < 10^{-7}$, then $\chi/Q = 0$.

$$\left. \frac{\chi}{Q} \right|_{CL} = \frac{1}{\pi u \Sigma_y \Sigma_z} \quad [6.1]$$

$\left. \frac{\chi}{Q} \right _{CL}$	Centerline plume model relative atmospheric concentration for evaluating control room habitability for intake distance x normalized by emission rate [s/m ³]
x	Distance between the atmospheric release and control room air intake [m] (user input); See Section 6.2.6 on application of slant range and when applied.
u	Wind speed [m/s]
Σ_y	Composite lateral wake diffusion coefficient for low wind speeds & building wakes at intake distance x for an atmospheric stability class [m]; Equation [6.6]
Σ_z	Composite vertical wake diffusion coefficient for low wind speeds & building wakes at intake distance x for an atmospheric stability class [m]; Equation [6.7]

For time periods after 8 h, ATD performs sector averaging based on Section 3.2 using Equation [3.2] with an effective release height of zero, $h_e = 0$, with modified lateral and vertical diffusion coefficients to account for wake effects, and a modified sector width. If $\Sigma_z < 10^{-7}$, then $\chi/Q = 0$.

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$$\left. \frac{\chi}{Q} \right|_{SA} = \frac{2}{\sqrt{2\pi} w'_{\text{sector}} u \Sigma_z} \quad [6.2]$$

$\left. \frac{\chi}{Q} \right|_{SA}$ Sector-averaged plume model relative atmospheric concentration for evaluating control room habitability for intake distance x normalized by emission rate[s/m³]

w'_{sector} Sector width for near-field relative atmospheric concentration [m];

$$w'_{\text{sector}} = \max \left[\frac{2\pi x}{16}, 4.3 \Sigma_y \right]$$

As shown, for the sector width limit⁹, the ATD Control Room submodule utilizes the value $\alpha = 4.3$ identified as preferred in Table A-2 of RG 1.194 [11.4] (and adopted as the program default in ARCON 2.0), instead of the original ARCON96 default $\alpha = 4$, selected as conservative from a reasonable range between 4 and 6, in Section 3.2.2 of NUREG/CR-6331 [11.9]. NUREG/CR-6331 Section 3.2.2 defines the width as alpha times Sigma-y ("Approximately 95% of the material in a Gaussian plume is within +/-2 Sigma-y of the plume axis").

6.1.2. Mixed/Vent Mode Releases

Control Room assessment submodule does not contain a vent-release mode for design basis assessments of control room habitability. RG 1.194 Section 3.2.3 identifies that the mixed-mode release may not be sufficiently conservative and should not be used in design basis assessments and should be treated as a ground-level or elevated release as appropriate.

6.1.3. Elevated Releases

RG 1.194 identifies that releases should be considered elevated when the stack height is more than 2.5 times the height of nearby structures. The user determines and selects the elevated release mode if needed. For onsite control

⁹ NUREG/CR-6331 Equation 11 additionally limits the sector width to a maximum of $2\pi x$ (the circumference of a circle of radius x), i.e., width = max(min($2\pi x$, $4.3 \cdot \Sigma_y$), $2\pi x/16$). ATD does not implement the $2\pi x$ upper limit; because Σ_y is itself limited to $1.81x$ (Equation [6.6]), the ATD sector width can reach $4.3 \cdot 1.81x = 7.8x$, which exceeds $2\pi x = 6.28x$ and yields sector-average χ/Q values lower than ARCON96 in that regime.

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room assessments, the effective release height is calculated as described in Section 7.2 utilizing Equation [6.3]

$$h_e = h_s + \Delta h_{dw} + EL_{ref} - \Delta h_{in} - \Delta h_{tr} \quad [6.3]$$

h_e Effective release height [m]

h_s Physical height of release point above ground surface [m] (user input)

Δh_{dw} Change in height due to stack downwash [m]

EL_{ref} Reference elevation of plant [m] (user input)

Δh_{in} Change in height due to intake elevation [m]

Δh_{tr} Change in height due to terrain height at stack & control room intake [m]

RG 1.194, Regulatory Position 6, identifies that an applicant may propose adjustments to the effective release height by accounting for plume rise effects, subject to case-by-case justification that the assumed buoyancy or vertical velocity is maintained. A plume rise model is proposed in RG 1.194 but not implemented in the ATD Control Room module.

For elevated releases, the effective stack and intake heights are considered, but the previously described corrections for low wind speed & building wake no longer apply in determining the elevated release relative concentration $\left(\frac{x}{Q}\right)_{Elevated}$.

For onsite control room habitability considerations, the centerline Gaussian plume formulations for time periods up to 8 hours are used based on Section 3.1 Equation [3.1].

For onsite control room assessments with elevated releases greater than 8 h, ATD performs sector averaging based on Section 3.2 using Equation [3.2] with a modified sector width:

$$w_{\text{sector}} = \max \left[\frac{2\pi x}{16}, 4.3 \Sigma_y \right] \quad [6.4]$$

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The release flow rate is used in model calculations whenever entered. Its function is to ensure that effluent relative concentrations in the atmosphere are always less than the relative concentration at the release point. The closer together the release point and receptor are and the larger the flow rate, the more important it is to include the flow rate in the calculations. For both short-term (plume centerline) and long-term (sector-averaged) elevated releases with a specified release flow rate, the relative concentration is limited as follows:

$$\left(\frac{\chi}{Q}\right)'_{Elevated}(x) = \begin{cases} \frac{1}{\left(\left(\frac{\chi}{Q}\right)_{Elevated}\right)^{-1} + \dot{V}}, & \left|\frac{\chi}{Q}\right|_{Elevated} > 10^{-10} \text{ and } \dot{V} > 0 \\ \left|\frac{\chi}{Q}\right|_{Elevated}, & \text{otherwise} \end{cases} \quad [6.5]$$

$\left|\frac{\chi}{Q}\right|_{Elevated}$ Sector-averaged elevated relative atmospheric concentration
[s/m³]

$\left(\frac{\chi}{Q}\right)'_{Elevated}$ Limited sector-averaged elevated relative atmospheric concentration [s/m³]

$\dot{V}$ Volumetric stack flow rate [m³/s] (user input)

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6.2. Input Models

6.2.1. Diffusion Models

The CR submodule implements the following diffusion options which are discussed in detail in Section 7.1:

- PG relationships implemented in NRC models (NRC)

6.2.2. Near-Field Wake Corrections (Ground Releases Only)

ATD implements near-field composite wake diffusion coefficients based on NUREG/CR-6331 Equations 5–8 [11.9] with corrections to account for low wind speeds and building wakes including a restriction on the maximum value for the composite lateral wake diffusion coefficient:

$$\Sigma_y = \min \left[\sqrt{\sigma_y^2(x) + \Delta\sigma_{y1}^2(x) + \Delta\sigma_{y2}^2(x)} ; 1.81 \cdot x \right] \quad [6.6]$$

$$\Sigma_z = \sqrt{\sigma_z^2(x) + \Delta\sigma_{z1}^2(x) + \Delta\sigma_{z2}^2(x)} \quad [6.7]$$

Corrections to account for low wind speed are defined as:

$$\Delta\sigma_{y1}^2 = 9.13 \times 10^5 \left[1 - \left(1 + \frac{\Delta t}{1000} \right) \exp\left(\frac{-\Delta t}{1000}\right) \right] \quad [6.8]$$

$$\Delta\sigma_{z1}^2 = 6.67 \times 10^2 \left[1 - \left(1 + \frac{\Delta t}{100} \right) \exp\left(\frac{-\Delta t}{100}\right) \right] \quad [6.9]$$

Δt Travel time [s]; $\Delta t = x/u$.

x Distance between the atmospheric release point and control room air intake [m] (user input); See Section 6.2.6 on application of slant range and when applied

u Wind speed [m/s]

Corrections to account for building wakes for a building source area greater than zero are defined by Equations [6.10] and [6.11]. If the source cross-sectional

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area

(A) is set to 0.0, then $\Delta\sigma_{y2}^2(x) = \Delta\sigma_{z2}^2(x) = 0$.

$$\Delta\sigma_{y2}^2 = 5.24 \times 10^{-2} u^2 A \left[1 - \left(1 + \frac{x}{10\sqrt{A}} \right) \exp\left(\frac{-x}{10\sqrt{A}}\right) \right] \quad [6.10]$$

$$\Delta\sigma_{z2}^2 = 1.17 \times 10^{-2} u^2 A \left[1 - \left(1 + \frac{x}{10\sqrt{A}} \right) \exp\left(\frac{-x}{10\sqrt{A}}\right) \right] \quad [6.11]$$

- A Source building cross-sectional area [m²] (user input)
- x Distance between the atmospheric release point and control room air intake [m] (user input); See Section 6.2.6 on application of slant range and when applied

6.2.3. Calm Wind Threshold

For ground and elevated releases, calm wind calculations are performed with a wind speed equal to the user-specified calm wind threshold. RG 1.194 [11.4, Table A-2] recommends a default calm threshold of 0.5 m/s.

6.2.4. Distribution of Calm Winds

Calm hours have no defined wind direction, so the Control Room module does not apply the Wind Direction Window test to them. Every calm hour is treated as though the wind carries the plume directly from the release point to the intake. The hour's wind speed is replaced by the Calm Threshold value (not half the threshold as in the other modules), the stack-tip downwash correction is not applied, and x/Q is computed with the same diffusion and building-wake treatment as any other in-window hour. The count of hours handled this way is reported as 'Hours of calm winds' in the output file, separate from the hours excluded because their direction fell outside the window.

6.2.5. Wind Speed Adjustment

Measured wind speeds are adjusted for the source release elevation by applying the MO-Ramsdell method, Section 7.7.2. The height used to adjust the wind speed for both elevated and ground releases enforces a minimum height of 10 m.

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6.2.6. Slant Range

The slant path is used as the distance to the receptor in lieu of the straight-line (ground-level) distance between the receptor (typically the control room) and the source of release. The slant path is computed using the Pythagorean theorem from the difference between the source and receptor elevation (Δz) and lateral distance between the source and receptor (Δx):

$$x_{slant} = \sqrt{\Delta z^2 + \Delta x^2} \quad [6.12]$$

If the slant range (x_{slant}) is 1% greater or more than the lateral distance (Δx), the slant range is used^h. Otherwise, the lateral distance is utilized. Use of the slant-range distance as x follows the ARCON96 technical basis in NUREG/CR-6331 [11.9]. The slant range applies to ground-level releases; elevated releases are evaluated at the horizontal distance, with the source–receptor elevation difference treated through the effective release height. When the slant range is used, the diffusion coefficients are recalculated at the slant distance.

^h RG 1.194 (Definitions; Section 3.4) describes ARCON96 as computing the slant path from the input horizontal distance and the source and receptor elevations, and RG 1.194 Table A-2 and NUREG/CR-6331 apply the slant range to ground-level (and vent) releases only; elevated (stack) releases are evaluated at the horizontal distance with the effective release height treated in the vertical exponential term. ATD follows the ARCON96 implementation, additionally using the horizontal distance whenever the slant range is less than 1 percent longer. This 1 percent threshold could be removed.

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6.3. Calculation of Output Results

For onsite control room DBA analyses, χ/Q is computed for all calm hours and any populated hour when the wind is within the wind direction window, i.e., the direction to the source is within the user-specified wind-direction window. For other hours when the wind direction is outside this window, or not calm, the χ/Q value for that hour is assigned as zero (see Section 6.2.4). The intention is to assess the frequency of χ/Q at the receptor site (typically at the control room but may also be an onsite technical support center (TSC)) during the entire period of meteorological data.

Time-averaged values of relative concentrations are computed as running mean values of the hourly relative concentrations. Time averages are calculated relative to 0 hours for 1, 2, 4, 8, 12, 24, 96, 168, 360, and 720 hours. Section 9.1 outlines the moving average procedure implemented in ATD.

Cumulative frequency distributions are then computed for each averaging interval. The 95th percentile values, which support onsite control room analysis and any other user-provided customized percentile values (e.g., 99.5th), are then calculated from these frequency distributions. In addition to calculating percentile values for each averaging period, the algorithm determines the 95th percentile values for standard averaging intervals: 0–2 h, 2–8 h, 8–24 h, 1–4 days, and 4–30 days. The 0–2 h value is the larger of the 1-hour and 2-hour 95th-percentile values (NUREG/CR-6331, [11.9, Section 3.7]; the remaining standard intervals are obtained by de-averaging as shown in Equation [6.13], with any negative result set to zero. The average 95th percentile relative concentrations for the 2–8 h period, as an example, are calculated as follows:

$$\left. \frac{\bar{\chi}}{Q} \right|_{95, 2-8hr} = \frac{8 \cdot \left. \frac{\bar{\chi}}{Q} \right|_{95, 0-8hr} - 2 \cdot \left. \frac{\bar{\chi}}{Q} \right|_{95, 0-2hr}}{8 - 2} \quad [6.13]$$

The relative concentrations for the other standard time intervals are calculated in a similar manner.

Section 9.2 details the calculation process for determining the percentile χ/Q values.

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A summary output example is shown below.

SUMMARY DATA BY STANDARD TIME INTERVAL		
STANDARD INTERVAL	95% X/Q	99.5% X/Q
0 to 2 hours	1.28E-05	4.39E-05
2 to 8 hours	8.29E-06	1.06E-05
8 to 24 hours	2.08E-06	2.82E-06
1 to 4 days	2.44E-06	3.20E-06
4 to 30 days	2.09E-06	2.32E-06
HOURLY VALUE RANGE		
	MAX X/Q	MIN X/Q
CENTERLINE	7.26E-04	0.00E+00
SECTOR-AVERAGE	4.23E-04	0.00E+00

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7.0 Shared Input Models

This section documents those input models that apply to more than one submodule. Their use is identified and referenced in the specific section describing the submodule.

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7.1. Diffusion Options

The spread of a plume in the horizontal (y) and vertical (z) directions at a prescribed downwind distance is described by diffusion coefficients (σ_y , σ_z). These coefficients are single standard deviations of the Gaussian plume distribution and are related to the atmospheric stability and downwind distance. There are many schemes for estimating these coefficients based on empirical data. The diffusion coefficients have the general form of:

$$\sigma = a \cdot x^b + c \quad [7.1]$$

σ Diffusion coefficient [m]

x Downwind distance [m]

a, b, c Coefficient parameters

The most widely used stability classification approach for atmospheric dispersion modeling purposes is based on the Pasquill–Gifford (PG) diffusion coefficients. It is noted that the PG diffusion coefficients have been established by the U.S. Nuclear Regulatory Commission (NRC) for seven stability categories (A–G), while the U.S. Environmental Protection Agency (EPA) defines them for six stability categories only (A–F). ATD implements the five following diffusion options:

- PG relationships implemented in NRC models (NRC)
- PG relationships implemented in EPA models; Industrial Source Complex Dispersion Model (ISC2)
- Briggs rural models
- Briggs urban models
- Desert models

7.1.1. Pasquill–Gifford Relationships in NRC Atmospheric Dispersion Models

The NRC historically bases its regulatory atmospheric dispersion calculations (e.g., in reactor siting, emergency preparedness evaluations, and radiological accident consequence analysis) on Gaussian plume models that directly implement the Pasquill–Gifford (PG) dispersion relationships for horizontal and vertical spread of airborne material, as implemented in the XOQDOQ and

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PAVAN codes [11.7, 11.8]. These relationships as implemented provide σ_y (crosswind spread) and σ_z (vertical spread) as empirical functions of downwind distance, x , and atmospheric stability class (A–G). The NRC’s implementation closely follows the technical basis presented in Hanna, Briggs & Hosker [11.12]. The PG curves were originally developed from large field experiments, most notably Project Prairie Grass [11.13], conducted over uniform flat terrain, and observational studies summarized by Pasquill [11.14] and later modified by Gifford [11.11]. These datasets produced families of σ_y and σ_z curves as functions of downwind distance and stability class.

In NRC referenced Gaussian plume models, the PG relationships are implemented as power law functions and are limited to a maximum of 1,000 m.

$$\begin{aligned}\sigma_y &= a \cdot x^b \\ \sigma_z &= c \cdot x^d\end{aligned}\tag{7.2}$$

The parameters a , b , c , d depend on the stability class (A–G). These values are drawn from Brookhaven National Laboratory parameterizations and other empirical datasets that formed the original PG curves. A few important notes to mention:

- at short distances, plume spread increases nearly linearly with distance;
- at longer distances, dispersion grows more slowly, approaching asymptotic behavior predicted by turbulence theory; and
- for all PG classes, σ_y grows faster than σ_z , reflecting stronger horizontal than vertical turbulence in typical atmospheric boundary layers.

NRC models that use PG dispersion coefficients include the Gaussian plume implementations underlying early reactor siting models (e.g., PAVAN), radiological accident consequence codes (historical CRAC, MACCS predecessors), and regulatory air dispersion guidance derived from the Handbook on Atmospheric Diffusion [11.12]. The NRC excerpt explicitly notes that PG curves underpin model tables and graphs used in regulatory Gaussian dispersion calculations.

Key considerations include:

- terrain assumptions where the PG relationships assume uniform, relatively flat terrain, and rural surface roughness (Prairie Grass roughness: $z_0 \approx 3$ cm). This means NRC PG based models are most

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accurate for open terrain around nuclear installations, consistent with historical siting practices,

- stability classification where the NRC uses stability classes A–G based on onsite or representative meteorological data. Each class corresponds to a unique set of σ_y and σ_z power law curves, and
- distance applicability where the PG curves (and NRC's use of them) are best supported by field data out to ~1 km and extend empirically out to ~10 km in Briggs' combined formulations. Beyond these distances, the increasing uncertainty arises.

7.1.2. Pasquill–Gifford Relationships in EPA Atmospheric Dispersion Models

EPA atmospheric dispersion models—including SCREEN3, AERMOD, and especially the legacy Industrial Source Complex (ISC) models (ISCST3 and ISCLT3)—use the Pasquill–Gifford (PG) stability class system as the foundation for estimating atmospheric turbulence and pollutant dispersion. The PG system supplies empirical dispersion coefficients (σ_y and σ_z) as functions of downwind distance and atmospheric stability category (A–F). These coefficients originate from classic rural field experiments (e.g., Prairie Grass) and provide the backbone of EPA's Gaussian plume equations.

EPA dispersion models classify atmospheric turbulence into six Pasquill–Gifford stability classes (A–F) based on meteorological factors such as wind speed, solar radiation, and cloud cover. These classes determine the amount of lateral and vertical plume spread used in the Gaussian concentration equation. Class A represents a very unstable atmosphere (i.e., strong vertical mixing) and Class F represents an atmosphere that is very stable (i.e., limited vertical mixing). EPA models rely on these classes to select the appropriate σ_y and σ_z parameters as functions of downwind distance x for the Gaussian plume formula.

The ISCST3 (short-term) and ISCLT3 (long-term) models implement PG dispersion through Gaussian formulations that explicitly reference stability-dependent dispersion parameters [11.17, 11.18]. The ISC3 documentation states that σ_y and σ_z constitute the dispersion parameters used in the horizontal and vertical terms of the Gaussian concentration equation. The ISC model uses pre-tabulated or internally parameterized PG curves to determine plume spread as a function of downwind distance and stability class. In ISC, the lateral (σ_y) and vertical (σ_z) dispersion functions are read directly from the PG relationships for point sources, volume sources, and area sources. Thus, PG stability categories directly govern the shape and width of the modeled plume.

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EPA's regulatory modeling framework air quality modeling guidance (Appendix W) endorses Gaussian plume dispersion for screening and regulatory purposes [11.19]. These Gaussian formulations—including ISC and SCREEN models—are explicitly tied to PG (Pasquill–Gifford) stability definitions and PG dispersion curves for σ_y and σ_z .

The ISC3 model adds several mechanisms to the PG dispersion:

- building downwash and wake effects algorithms that modify the plume's PG spread in the presence of nearby structures;
- buoyancy and plume rise; and
- area and volume source extensions applied within expanded formulas for non-point source types (e.g., area sources, pits, complex terrain modules).

The fundamental PG relationship— σ_y and σ_z depending on stability class and distance—remains unchanged. σ_z is limited to 5,000 m and Stability Class G is evaluated using the class-F coefficients.

7.1.3. The Briggs Rural Models

In the atmospheric dispersion literature, “Briggs models” refer to a set of Gaussian plume dispersion parameterizations developed by G.A. Briggs [11.10]. These models provide empirical formulas for horizontal (σ_y) and vertical (σ_z) plume spread as a function of downwind distance and atmospheric stability class. When applied to rural environments, the term “Briggs rural models” commonly refers to the Briggs dispersion curves and formulas calibrated for rural (low roughness) terrain, as opposed to urban models that account for stronger mechanical turbulence generated by buildings. These rural parameterizations are widely implemented in first generation Gaussian models and are still used for comparisons with more advanced dispersion models.

The Briggs' rural formulations are embedded in the standard Gaussian plume equation, which requires dispersion coefficients σ_y and σ_z as functions of distance, x , and stability category (Pasquill classes A–F). Briggs combined data from Pasquill [11.14], Brookhaven National Laboratory (BNL) studies, and Tennessee Valley Authority (TVA) experiments to produce formulas valid up to ~10 km in flat, rural terrain. Briggs' rural formulas use algebraic interpolation relationships of the general forms:

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$$\sigma_y = \frac{a \cdot x}{(1 + 0.0001 \cdot x)^{1/2}} \quad [7.3]$$
$$\sigma_z = c \cdot x \cdot (1 + d \cdot x)^p$$

The constants depend on stability class and were derived from rural terrain field experiments such as Prairie Grass, which had a roughness length $z_0 \approx 3$ cm; typical of rural plains.

Modern studies often compare “Briggs models” to contemporary dispersion models. When these studies take place in rural environments, the term “Briggs rural model” is used to emphasize that the underlying dispersion coefficients come from rural data sets and model performance is evaluated under rural turbulence and roughness conditions. For example, in tracer-release experiments over a rural plain in France, researchers compared observed SF₆ dispersion to predictions from Briggs (rural) Gaussian models [11.20]. They used the Briggs formulations together with Holland’s plume-rise method to estimate effective stack height. The results showed Briggs models performed reasonably well in neutral conditions, and in unstable conditions, Briggs tended to slightly overestimate horizontal dispersion (σ_y).

7.1.4. The Briggs Urban Models

In dispersion modeling, “Briggs models” refer to a set of empirical Gaussian-plume dispersion parameterizations published by G.A. Briggs [11.10]. When applied to urban environments, the term “Briggs urban models” refers specifically to Briggs’ dispersion curves with σ_y and σ_z formulas tailored to urban conditions, where turbulence is significantly enhanced by buildings and other roughness elements and Neutral stability Briggs σ -curves are intended to be applied for urban areas, providing horizontal (σ_y) and vertical (σ_z) spreading functions based on urban tracer studies and laboratory data. These formulations differ from Briggs’ rural curves, which were based on open-terrain experiments like Prairie Grass.

The scientific literature (via model documentation derived from Briggs’ 1973 work [11.10]) explicitly identifies a set of “Briggs neutral curves for urban areas,” which provide functional relationships $\sigma(x)$ for both σ_y and σ_z under urban neutral stability conditions. These are implemented in several Gaussian-plume modeling frameworks and tools. The curves are used to estimate dispersion in built-up terrain with significant surface roughness, situations where urban

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mechanical turbulence dominates, and scenarios where Pasquill-Gifford rural curves underestimate dispersion.

Urban conditions differ fundamentally from rural terrain due to mechanical turbulence (generated by buildings) and thermal effects (heat released from buildings, vehicles, and industrial sources). Scientific literature notes that in urban areas dispersion coefficients differ substantially from rural Pasquill-Gifford curves, vertical dispersion (σ_z) often resembles Pasquill classes C–D, even under neutral stability, and horizontal dispersion (σ_y) may span a wide range, often between stability categories A and D–E [11.16]. This behavior is consistent with Briggs' justification for separate urban curves—urban roughness produces stronger and more chaotic mixing.

While Briggs' original data compilation emphasized rural and industrial-stack experiments, a synthesization of multiple datasets was also considered—including those from the TVA and BNL programs—to extend applicability to higher roughness environments, including urban settings.

Briggs combined experimental dispersion data and theoretical asymptotic arguments to develop the widely used σ_y and σ_z formulas, which later authors and modelers adapted into urban specific curves. These urban variants preserve the functional structure of Briggs' equations but use empirical coefficients suited for urban turbulence.

7.1.5. Desert Models

Diffusion coefficients representative of desert conditions are available for selection in SIERRA ATD. The horizontal and vertical distribution of the plume is described by the work of Yanskey [11.21] and is based on 15 complete years of meteorological data collection of the Idaho National Laboratory site.

This section describes the calculations of the horizontal (σ_y) and vertical (σ_z) Gaussian plume diffusion coefficients as functions of downwind distance (x) and atmospheric stability class (j); refer to Figure 3-1 for a generalized diagram. The implementation follows empirical desert diffusion curves historically used in the XOQDOQ [11.7] and PAVAN [11.8] atmospheric dispersion models. These continue to be available in ATD within the analogous Routine Release and DBA modules, respectively.

The vertical diffusion coefficient (σ_z) is computed using one of two methods depending on the atmospheric stability class. For unstable conditions (Class A,

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B, or C), σ_z is obtained by polynomial logarithmic interpolation of empirical desert diffusion curves:

$$\log_{10}(\sigma_{z,j}) = \sum_{i=1}^7 \left[s_{i,j} \cdot \prod_{\substack{k=1 \\ k \neq j}}^7 \left[\frac{\log_{10}(x) - a_k}{a_i - a_k} \right] \right] \quad [7.4]$$

$\sigma_{z,j}$ Vertical diffusion coefficient for stability class j [m]

x Downwind distance from source [m]

a_j Coefficient.

$s_{i,j}$ Coefficient.

For neutral and stable conditions (Class D, E, F, or G), σ_z is computed using a power-law function of distance:

$$\sigma_{z,j} = a_j \cdot x^{b_j} \quad [7.5]$$

$\sigma_{z,j}$ Vertical diffusion coefficient for stability class j [m]

x Downwind distance from source [m]

a_j Scalar coefficient for stability class j [m/(m^{-b})].

b_j Power coefficient for stability class j .

The horizontal diffusion coefficient (σ_y) is computed using a power-law formulation for all stability classes:

$$\sigma_{y,j} = a_j \cdot x^{b_j} \quad [7.6]$$

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$\sigma_{y,j}$ Horizontal diffusion coefficient for stability class j [m]

x Downwind distance from source [m]

a_j Scalar coefficient for stability class j [m/(m^{-b})].

b_j Power coefficient for stability class j .

A limit is applied to the vertical and horizontal diffusion coefficients such as defined by Equation [7.7]:

$$\sigma = \min(\sigma, 1000) \quad [7.7]$$

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7.2. Effective Release Height (h_e)

For releases, the general effective release height is calculated as shown with factors applied depending on the analysis type. ATD interpolates the terrain height at the distance of interest from the source point (i.e., receptor location) from user-supplied terrain data.

$$h_e = h_s + \Delta h_{pr} + \Delta h_{dw} + EL_{ref} - \Delta h_{in} - \Delta h_{tr} \quad [7.8]$$

h_e Effective release height [m]

h_s Release height above ground surface [m] (user input)

Δh_{pr} Change in height due to plume rise with downwash correction and heat emission corrections [m]; Section 7.4 (Routine Release and DBA only)

Δh_{dw} Change in height due to downwash correction [m] (Control Room only); Section 7.5

EL_{ref} Reference elevation of plant [m] (user input)

Δh_{in} Change in height due to intake elevation [m] (Control Room only)

Δh_{tr} Change in height due to terrain height at receptor location [m]; Section 7.6

A user selection for ground-level release implies $h_e = 0$. The plume rise, downwash, and terrain effects are applicable for only elevated releases or the portion of mixed-mode releases that are elevated. For elevated releases, ATD interpolates the terrain height at the receptor location from user-supplied terrain data. If the computed effective release height is negative, it is set to zero ($h_e \geq 0$), consistent with NUREG/CR-2919 [11.7, Equation 15].

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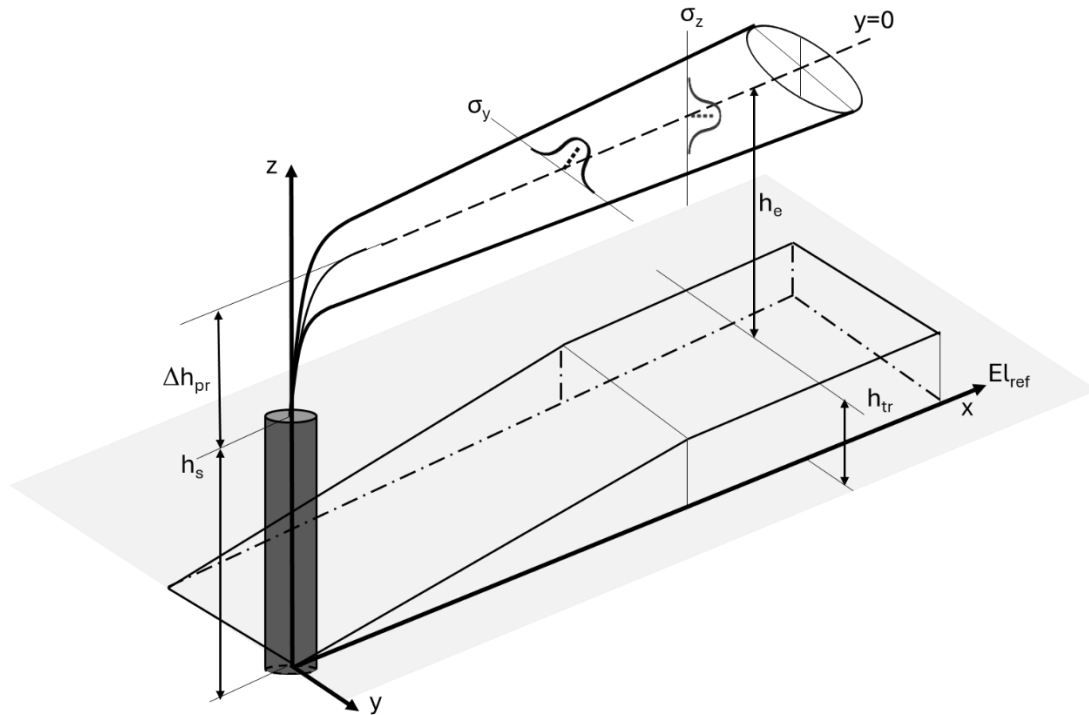


Figure 7-1. Determination of effective release height.

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7.3. Release Velocity (w_0)

Momentum effects on plume rise involve multiple calculations and rely on the utilization of the exit velocity determined from Equation [7.9]. The use of this parameter is intended for release points oriented vertically (directly upwards) and without any obstruction (e.g., a rain cap) and does not apply to horizontal or other non-vertical discharges.

$$w_0 = \frac{\dot{V}}{\pi(D/2)^2} \quad [7.9]$$

w_0	Stack or vent exit velocity [m/s]
$\dot{V}$	Vertical volumetric flow rate [m ³ /s] (user input)
D	Internal stack or vent diameter [m] (user input)

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7.4. Plume Rise

This section describes the determination of plume rise for elevated, or vent releases based on the vertical exit velocity of the source. It is accounted for by adjusting the effective release height as described in Section 7.2. Plume rise can be affected by momentum and thermal buoyancy effects. Thermal buoyancy considerations are unnecessary for effluents released at ambient temperature. They, however, may be important to consider for heated releases in general but especially in extreme and persistent cold environments. The momentum- and buoyancy-driven plume rise relationships implemented derive from NUREG/CR-2919 [11.7].

Plume rise applies only to elevated and vent releases. In the Routine Release module it is always evaluated for those release types; in the DBA module it is evaluated only when specified by the user (default off); it is not available in the Control Room module (Section 6.1.3). When a heat emission rate greater than zero is entered, the buoyant-rise formulation (Equations [7.13] through [7.16]) replaces the momentum formulation (Equations [7.10] through [7.12]) entirely; the downwash correction of Equation [7.12] applies only to unheated (momentum-driven) releases.

For neutral or unstable atmospheric conditions, the momentum calculation for plume rise is selected based on comparing the wind speed at the release height to the stack (or vent) exit velocity.

During neutral or unstable atmospheric classes, plume rise is calculated as a minimum of two expressions:

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$$\Delta h_{pr} = \min \left[\begin{array}{c} 1.44 \left(\frac{w_0}{u} \right)^{2/3} \left(\frac{x}{D} \right)^{1/3} D \\ 3 \left(\frac{w_0}{u} \right) D \end{array} \right] \quad [7.10]$$

Δh_{pr}	Change in height due to plume rise with downwash correction [m]
u	Wind speed adjusted to release height [m/s] – Section 7.7
w_0	Stack or vent exit velocity [m/s] – Section 7.3
D	Internal stack or vent diameter [m] (user input)
x	Downwind distance [m]

For stable atmospheric conditions, plume rise is determined from the minimum of four expressions:

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$$\Delta h'_{pr} = \min \left[\begin{array}{l} 1.44 \left(\frac{w_0}{u} \right)^{2/3} \left(\frac{x}{D} \right)^{1/3} D \\ 3 \left(\frac{w_0}{u} \right) D \\ 4 \left(\frac{F_m}{S} \right)^{1/4} \\ 1.5 \left(\frac{F_m}{u} \right)^{1/3} \left(\frac{1}{S} \right)^{1/6} \end{array} \right] \quad [7.11]$$

S Stability parameter [s^{-2}];

$$S = \begin{cases} 0.000875 & \text{for stability class E} \\ 0.00175 & \text{for stability class F} \\ 0.00245 & \text{for stability class G} \end{cases}$$

F_m Momentum flux parameter [m^4/s^2]; [11.7, Equation 21]

$$F_m = \left(w_0 \cdot \frac{D}{2} \right)^2$$

For unheated releases (no heat emission rate entered), for any stability class when $w_0 < 1.5 u$, a downwash correction factor is applied to the plume rise calculation as follows:

$$\Delta h_{pr} = \Delta h'_{pr} - 3D \left(1.5 - \frac{w_0}{u} \right) \quad [7.12]$$

The narrative of NUREG/CR-2919 [11.7, Section 4.20] applies the downwash correction of Equation [7.12] to only the first expression of Equation [7.10] before taking the minimum, during neutral or unstable classes when $w_0 < 1.5 u$. The XOQDOQ code listing in Appendix A of NUREG/CR-2919 (subroutine RISE), however, subtracts the correction from the two-factor or four-factor minimum for any stability class; ATD implements the same behavior in Equations [7.10] through [7.12].

If the user enters a heat emission rate greater than zero [cal/s] for an elevated or vent release, ATD calculates plume rise due to buoyancy. This is captured through an additional downwind distance, x^* . The following calculations are performed in base English units and then converted back to SI units of [m] once the plume rise height determined for a heated release. For neutral and unstable conditions,

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$$x^* = \begin{cases} 0.52 \left[\frac{s^{\frac{6}{5}}}{ft^{\frac{6}{5}}} \right] \cdot F^{\frac{2}{5}} \cdot h_s^{\frac{3}{5}}, & h_s < 1,000 \text{ ft} \\ 33.0 \left[\frac{s^{\frac{6}{5}}}{ft^{\frac{6}{5}}} \right] \cdot F^{\frac{2}{5}}, & h_s \geq 1,000 \text{ ft} \end{cases} \quad [7.13]$$

x^* Additional downwind distance length [ft]

h_s Physical height of stack above ground surface [ft] (user input)

F Buoyancy flux parameter [ft^4/sec^3]

$$F = 0.0043 \left[\frac{ft^4/sec^3}{cal/sec} \right] \cdot Q_h$$

Q_h Heat emission rate [cal/s] (user input)

For stable conditions:

$$x^* = 2.4 \cdot \frac{u}{\sqrt{S}} \quad [7.14]$$

$$S = \begin{cases} 0.000875 & \text{for stability class E} \\ 0.00175 & \text{for stability class F} \\ 0.00245 & \text{for stability class G} \end{cases} \quad [1/s^2]$$

u Wind speed adjusted to release height [ft/s]

With x^* calculated, the plume rise from a heated release can then be determined. For a buoyant release with $x < x^*$, plume rise is determined as:

$$\Delta h_{pr} = 1.6 \cdot \frac{F^{\frac{1}{3}} \cdot x^{\frac{2}{3}}}{u}, \quad x < x^* \quad [7.15]$$

x Distance from source [ft]

For a buoyant release with $x \geq x^*$, plume rise depending on stability class is then determined as follows, with the evaluation distance limited to $x \leq 5x^*$ in the unstable and neutral expression:

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$$\Delta h_{pr} = \begin{cases} 2.9 \cdot \left(\frac{F}{u \cdot S} \right)^{\frac{1}{3}}, & \text{Stable} \\ \frac{1.6 \cdot F^{\frac{1}{3}} \cdot x^{*\frac{2}{3}} \cdot \left(\frac{2}{5} + \frac{16}{25} \left(\frac{x}{x^*} \right) + \frac{11}{5} \left(\frac{x}{x^*} \right)^2 \right)}{u \cdot \left(1 + \frac{4}{5} \left(\frac{x}{x^*} \right) \right)^2}, & \text{Unstable and Neutral} \end{cases} \quad [7.16]$$

Equation (29) of NUREG/CR-2919 identifies 2.4 instead of 2.9 for stable atmospheric stability classes in the top term of the righthand side of Equation [7.16]; the XOQDOQ code listing in Appendix A of NUREG/CR-2919 (subroutine RISE) implements 2.9, which ATD follows. For unstable and neutral classes, NUREG/CR-2919 assumes the plume reaches its maximum height at, and ATD limits the evaluation distance to, $x = 5x^*$.

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7.5. Stack Downwash Correction Factor

For onsite control room assessments, stack downwash is calculated for non-calm hours per the ARCON96 methodology (11.9, Section 3.2.3, Equations 13 and 14) as:

$$\Delta h_{dw} = \text{Min} \left(0.0, \quad 2D \left(\frac{w_0}{u} - 1.5 \right) \right) \quad [7.17]$$

D	Internal stack or vent diameter [m] (user input)
w_0	Stack or vent exit velocity [m/s] – Section 7.3
u	Wind speed at stack or vent height [m/s]

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7.6. Terrain Elevation at Specific Receptor Location

To determine the effective height of the plume at a distance of interest (i.e., location of special receptor) a linear interpolation is performed with the user supplied distances and elevations to determine the terrain elevation at that point of interest.

Specified via input are pairs of elevation for a distance from the source. Up to 10 distance and elevation pairs can be specified for each of the 16 sectors allowing for a total of 160 pairs.

When evaluating the elevation of a receptor, the sector location of the receptor is determined and linear interpolation of the distances and elevations associated with that given sector is performed to determine the elevation of the terrain in the given sector at a distance from the source. For receptor distances beyond the last user-supplied pair, the last elevation is used; for distances closer than the first pair, an elevation of zero is used.

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7.7. Wind Speed Adjustment to Release Elevation

Elevated releases should use winds measured at a height that is as close as available to the release height. If the winds were not measured at the proper height, or a mixed elevated-ground level release is being evaluated, the program corrects the wind speeds to reflect the proper elevation. ATD selects one of the following relationships to adjust the wind speed to the release height for performing the analysis.

For the height used to adjust the wind speed for both elevated and ground releases, ATD enforces a minimum height of 10 m.

7.7.1. Power Law Model

A simple power-law relationship is described by Equation [7.18] that applies the correction (adjustment) factor previously implemented in XOQDOQ [11.7, Equation 13].

$$\text{Adjusted wind speed} = \text{Measured wind speed} \left(\frac{\text{Release height}}{\text{Measured height}} \right)^P \quad [7.18]$$
$$P = \begin{cases} 0.25 & \text{for unstable and neutral atmospheric conditions} \\ 0.50 & \text{for stable atmospheric conditions} \end{cases}$$

7.7.2. Monin–Obukhov Ramsdell Profile Model

The MO–Ramsdell model is an atmospheric boundary-layer wind-profile formulation that combines Monin–Obukhov similarity theory with empirical stability treatments developed by J.V. Ramsdell. The model provides physically consistent estimates of wind speed, friction velocity, and Monin–Obukhov length for use in near-surface atmospheric transport and dispersion calculations.

At its core, the model applies the Monin–Obukhov (MO) similarity framework, which describes how wind shear and turbulence in the surface layer depend on surface roughness, buoyancy, and mechanical friction. The model evaluates the wind profile using the standard MO relation:

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$$u(z) = \frac{u^*}{\kappa} \left(\ln \left(\frac{z'}{z_o} \right) - \psi_m \right) \quad [7.19]$$

u^*	Friction velocity [m/s]
κ	von-Karman constant [-]; $\kappa = 0.4$
z'	Adjusted release elevation [m]
z_o	Surface roughness length [m] (user input)
ψ_m	Integrated stability correction for momentum [-]

The integrated stability correction factor is determined as a function of stability class as described by Equation [7.20].

$$\psi_m = \begin{cases} \ln \left(\frac{1 + \omega^2}{2} \cdot \left(\frac{1 + \omega}{2} \right)^2 \right) - 2 \cdot \tan^{-1}(\omega) + \frac{\pi}{2}, & \text{stability A - C} \\ 0, & \text{stability D} \\ -5 \cdot z' \cdot \frac{1}{L}, & \text{stability E - G} \end{cases} \quad [7.20]$$

$$\omega = \left(1 - 16 \cdot z' \cdot \frac{1}{L} \right)^{0.25}$$

$\frac{1}{L}$	Inverse Monin–Obukhov length [1/m]
z'	Adjusted release elevation [m]

Limits are applied on the release elevation ($z \rightarrow z'$) such that:

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$$z' = \begin{cases} \min(z, 100), & \text{stability } A - D \\ \min(\min(z, 3 \cdot L), 100), & \text{stability } E - G \end{cases} \quad [7.21]$$

z Elevation [m]

z' Adjusted release elevation [m]

L Monin–Obukhov length [m]

The Inverse Monin–Obukhov length ($1/L$) is a stability-class-based empirical method originally derived from the relationships published by Golder [11.22] and later re-examined for stable conditions by Sharan et al. [11.23], who re-derived the underlying bulk-Richardson-number relationships and identify that their modified curves differ somewhat from those given by Golder, with the modified method performing better relative to stable-condition observations (the CASES-99 experiment). ATD implements the original Golder approach [11.22].

Instead of computing $1/L$ from turbulence or heat-flux measurements, the function uses Turner stability class (A–G) together with the site's surface roughness length (z_o) to select lower and upper bounds of feasible $1/L$ values taken from digitized Golder curves. The digitized bounds are those implemented in the ARCON96 code [11.9, Section 4.6.4, function INVMOL]. The model divides roughness into four regimes:

- very smooth ($z_o \leq 0.01$ m),
- smooth-to-open ($0.01 < z_o \leq 0.1$ m),
- open-to-rough ($0.1 < z_o < 1.0$ m), and
- very rough ($z_o \geq 1.0$ m).

The bullet items above include various surface roughness lengths broader than the 0.1–0.5 m range of reasonable values listed in RG 1.194 [11.4, Table A-2] (default 0.1 m, recommended 0.2 m). Use of values outside the range in Table A-2 should be justified and documented before implementation.

A log-based interpolation between bounding curves is applied with the mid-range value between the lower and upper bounds calculated, providing a representative estimate of atmospheric stability consistent with the input class and roughness.

The friction velocity (u^*) is determined as defined by Equation [7.22]:

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$$u^* = \max \left(\frac{u \cdot \kappa}{\left(\ln \left(\frac{z'}{z_o} \right) - \psi_m \right)}, 0.01 \right) \quad [7.22]$$

u^*	Friction velocity [m/s]
κ	von-Karman constant [-]; $\kappa = 0.4$
u	Measured reference wind speed [m/s]
z_o	Surface roughness length [m] (user input)
z'	Wind speed measurement elevation (the height limits of Equation [7.21] are not applied in the friction-velocity evaluation) ($z = z_{ref}$)
ψ_m	Integrated stability correction for momentum [-] using Equation [7.20]

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Meteorological Data File

8.0 Meteorological Data File

A knowledge of dispersion-related meteorological conditions (i.e., wind speed, wind direction, and an indicator of atmospheric stability) in the vicinity of the reactor site is important to provide the basis for estimating radiation doses resulting from radioactive materials released in airborne effluents. The meteorological data files provide the necessary inputs that the SIERRA ATD program needs to perform such evaluations.

SIERRA ATD processes hourly meteorological input as a continuous time series over the full user-specified Period of Record (POR). The model does not impose calendar-year segmentation or fixed 12-month analysis blocks when computing atmospheric dispersion factors. Instead, all valid hourly records are treated sequentially in the order provided, regardless of year boundaries or the starting month of the dataset.

The following sections summarize the expected format of the meteorological data file (Section 8.1) and what and how SIERRA processes that data (Section 8.2).

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Meteorological Data File

8.1. Meteorological Data File Reading

The section summarizes the processing of validated hourly meteorological data files by SIERRA ATD following the format specified in Appendix A of RG 1.23 [11.6]. The data file read is a fixed format file with the first five lines being header lines of 160 characters for each line. The remaining data lines consist of alpha numeric (A), integer (I), and float/real (F) input values and are of the format:

A4, I4, I3, I4, 25F5.1, F5.2, 3F5.1 (See Table 8-1 for full format listing)

Note: A4 is interpreted as a single set of four characters and 25F5.1 is interpreted as 25 sets of float/real values each containing five digits with one digit reserved for the tenths place.

In the above format, the use of decimal points in the database is not required due to the fixed format. Specific values are used as keys to indicate special treatment of certain inputs; these are as follows:

- 77777 – usage of this in a wind-direction field indicates a calm wind.
- 99999 – usage of this in a record indicates a lost or invalid record.

All data is assumed to be to the tenth of a unit, except solar radiation, which should be provided to a hundredth of a unit. Wind direction is reported in degrees azimuth, measured clockwise from true north and ranging from 0 to 360. The value represents the direction from which the wind is blowing from relative to the measurement location.

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8.2. Meteorological Data File Processing

Table 8-1 summarizes the meteorological file expected data format consistent with RG 1.23 [11.6] including the input description and an identification if the data value is used within ATD. It is noted that ATD only utilizes the upper- and lower-level data within the meteorological data file with the intermediate elevation data not used. Care must be taken to ensure the desired data is assigned to the appropriate elevation within the meteorological data file that is to be used as input to ATD.

Table 8-1. Expected meteorological data file format.

#	Format	Description	Used by ATD
	A4	Identifier, can be any identifier or blank	No
	I4	Year	Yes
	I3	Day of the year (1 – 365, or 366 for a leap year)	Yes
	I4	Hour of the day (24-hour clock)	Yes
	F5.1	Upper-level measurement elevation in meters	Yes
	F5.1	Upper-level wind direction in degrees	Yes
	F5.1	Upper-level wind speed in m/s	Yes
	F5.1	Upper-level σ_θ	No
	F5.1	Upper-level ambient temperature in °C	No
	F5.1	Upper-level atmospheric moisture	No
	F5.1	Upper-level other value, can be used to store any other real/float value	No
	F5.1	Intermediate level measurement elevation in meters	No
	F5.1	Intermediate level wind direction in degrees	No
	F5.1	Intermediate level wind speed in m/s	No
	F5.1	Intermediate level σ_θ	No
	F5.1	Intermediate level ambient temperature in °C	No
	F5.1	Intermediate level atmospheric moisture	No
	F5.1	Intermediate level other value, can be used to store any other real/float value	No

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#	Format	Description	Used by ATD
	F5.1	Lower-level measurement elevation in meters	Yes
	F5.1	Lower-level wind direction in degrees	Yes
	F5.1	Lower-level wind speed in m/s	Yes
	F5.1	Lower level σ_θ	No
	F5.1	Lower-level ambient temperature in °C	No
	F5.1	Lower-level atmospheric moisture	No
	F5.1	Lower-level other value, can be used to store any other real/float value	No
	F5.1	Temperature gradient, upper minus lower level, reported in °C/100 m	Yes
	F5.1	Temperature gradient between upper minus intermediate elevation reported in °C/100 m	No
	F5.1	Temperature gradient between intermediate minus lower elevation reported in °C/100 m	No
	F5.1	Precipitation in millimeters	No
	F5.2	Solar radiation in calories/(cm ² -minute)	No
	F5.1	Visibility in kilometers	No
	F5.1	Other value, can be used to store any other real/float value	No
	F5.1	Other value, can be used to store any other real/float value	No

The midpoint between the lower and upper elevation values are first determined. If the input stack height is greater than this midpoint value then the upper elevation data (i.e., wind speed, wind direction, and elevation of level) is used; otherwise, the lower elevation data are used.

Next the calm and missing data are processed and counted. An entry is considered missing if any of the following are true:

- wind speed ≥ 200 m/s,
- wind direction $\geq 7777.8^\circ$, or
- temperature gradient (upper minus lower level) ≥ 777.8 °C/100 m.

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If any of these conditions are satisfied the wind speed is set to 999.9 and counted as a missing record. If an hour is identified as missing no calculation is performed for that hour. An entry is considered calm if any of the following are true:

- wind direction = 7777.7°,
- wind direction = 777.7°, or
- wind speed < the user specified calm wind speed threshold.

If any of these conditions are satisfied the wind speed is set to the user specified calm threshold and counted as calm record.

The stability based on the vertical temperature gradient (upper minus lower) is determined for each record, as shown by Table 8-2. If a record is determined as missing as described above, the stability flag is internally set to 999.

Table 8-2. Meteorological data file stability categories.

Criterion	Stability Category
$-50.0 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq -1.9$	A / 1 / Extremely Unstable
$-1.9 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq -1.7$	B / 2 / Moderately Unstable
$-1.7 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq -1.5$	C / 3 / Slightly Unstable
$-1.5 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq -0.5$	D / 4 / Neutral
$-0.5 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq 1.5$	E / 5 / Slightly Stable
$1.5 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq 4.0$	F / 6 / Moderately Stable
$4.0 < \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq 50.0$	G / 7 / Extremely Stable
$\frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] \leq -50.0 \text{ or } \frac{\Delta T}{\Delta z} \left[\frac{^{\circ}\text{C}}{100 \text{ m}} \right] > 50$	999 ⁱ

ⁱ Note: The ± 50 °C/100 m outer limits and category 999 (data screened out) are ATD data-validity screens; RG 1.23 Table 1 places no outer bounds on classes A and G.

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9.0 Statistics

This section describes the statistical post-processing that ATD applies to the χ/Q (relative concentration) time series generated by the dispersion modules. Two operations are covered: the calculation of moving (running) averages over user-specified time windows, including the treatment of missing meteorological data (Section 9.1); and the determination of percentile relative concentrations from cumulative distributions of the χ/Q results (Section 9.2).

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9.1. Moving Averages

This section describes the procedure used to compute a moving average of χ/Q time-series data while accounting for missing observations. The method evaluates each integer time window length (w) in hours (e.g., 2, 8, 16, 72-hour, etc.) within the number of meteorological data records of length N , producing a sequence of window-averaged values. Windows exceeding a user-specified threshold for the number of missing data allowed are rejected and excluded from the final output.

The discussion below utilizes Figure 9-1 to depict the moving average scheme implemented in ATD.

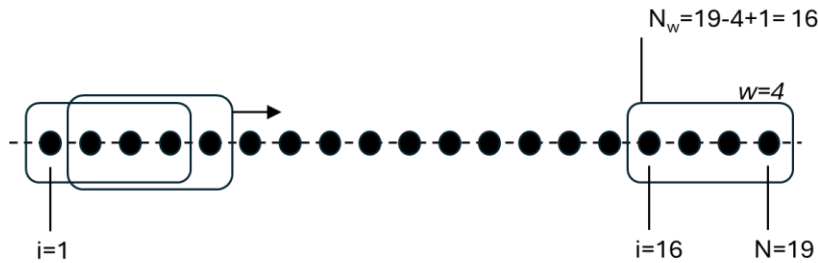


Figure 9-1. Window averaging scheme.

Each window begins at hour i and spans the specified window length (w) inclusive of the beginning and ending meteorological data records.

$$n \in \{i, i + 1, \dots, i + w - 1\} \quad [9.1]$$

i Hour record in meteorological data file [h]

w Interval of which moving average is performed [h]

The total number of windows (N_w) based on the total number of hourly records available (N) is then:

$$N_w = N - w + 1 \quad [9.2]$$

Moving averages are performed as composite averages of the centerline and sector average χ/Q values depending on the time-period of interest. If for example, a 72-hour moving average is specified, the first 8 hours are based on

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the centerline values and the remaining 64 hours are based on the sector-average values.

This is generically described by Equations [9.3] and [9.4] which determines the summation of concentrations based on the time interval for interval i in the set of N_w intervals. If the averaging interval is 8 hours or less, Equation [9.3] is applied, otherwise Equation [9.4] is applied.

$$S_i = \sum_{j=i}^{i+w-1} \left(\frac{\chi}{Q} \right)_{j|_{CL}} , \text{ for } w \leq 8 \text{ hours} \quad [9.3]$$

$$S_i = \sum_{j=i}^{i+8-1} \left(\frac{\chi}{Q} \right)_{j|_{CL}} + \sum_{j=i+8}^{i+w-1} \left(\frac{\chi}{Q} \right)_{j|_{SA}} , \text{ for } w > 8 \text{ hours} \quad [9.4]$$

The above expressions determine the appropriate summations of the values. Next the divisor is determined based on the number of valid records to calculate the average.

If at least one of the meteorological variables (i.e., wind speed, wind direction, $\Delta T/\Delta z$) required for a χ/Q calculation is not defined, the record is considered missing. Missing data are accounted for by deleting those hours with missing data from the calculation of the running average relative concentrations. A missing data tolerance criterion is used to determine when the number of hours with missing data makes a specific average unacceptable. This tolerance criterion is a user input, which by default is 10 percent, consistent with the default for this parameter as given in Table A-2 of RG 1.194. The tolerance applies to every averaging window: if the fraction of missing hours within a window exceeds the criterion, that window average is not calculated. With the default tolerance this permits no missing hours in windows of 8 hours or less (one missing hour in an 8-hour window is 12.5 percent).

As the summations above are calculated for a given averaging interval, the number of missing hours (c) is tallied. If an hour is missing the relative concentration for that record is set to zero. The fraction of missing records within an averaging period is then calculated. If the number of records for that averaging interval is insufficient, the average of that interval is not used. The total valid number of records is then:

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$$n = w - c \quad [9.5]$$

n Number of valid records (hours) within a given averaging interval

w The number of records available within a given averaging interval

c The number of determined missing records

The average χ/Q for the averaging window is then:

$$\left(\frac{\chi}{Q}\right)_i = \frac{S_i}{n} \quad [9.6]$$

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9.2. Percentile Statistics

This section describes the calculation procedure implemented by ATD to determine percentile relative concentration values. The χ/Q percentile values are computed by generating cumulative distributions of χ/Q . The ATD model utilizes the slope between the frequencies where the specified exceedance of (e.g., 0.5%) falls. The statistics performed on the χ/Q dataset for both raw or average values comprise three steps:

1. creation of a set of 100 logarithmically spaced interval boundaries
2. binning of χ/Q based on the bins created in Step 1, and
3. calculation of the percentile value.

First, 100 logarithmically spaced interval boundaries are computed to build a χ/Q frequency distribution and cumulative distribution function (CDF). The complete interval range is derived from the order of magnitude of a specified maximum value (x_{max}) which is the decade of the calculated maximum χ/Q . This upper decade bound of the full distribution interval is determined as defined by Equation [9.7] where the $Int()$ operation is the truncation of a real value (not rounded):

$$UL_{log} = Int\left(\log\left(max\left(\frac{\chi}{Q}\right)\right)\right) \quad [9.7]$$

The lower bound is set four decades below the maximum decade, UL_{log} . The individual boundaries for the 100 bins enforcing 25 intervals for a decade are then described by Equation [9.8]:

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$$x_i = 10^{\left(LL_{log} + \frac{100-i}{25}\right)} \quad [9.8]$$

x_i	Bin boundary for interval i
LL_{log}	Lower decade bounds of full distribution interval; $LL_{log} = UL_{log} - 4$
UL_{log}	Upper decade bounds of full distribution interval, Equation [9.7]

This defines the individual boundaries for binning the χ/Q values. For example, for a maximum χ/Q of $3.7 \cdot 10^{-4}$, the resulting bins are shown in Figure 9-2 with decreasing bin sizes at the lower (left) end of the spectrum.

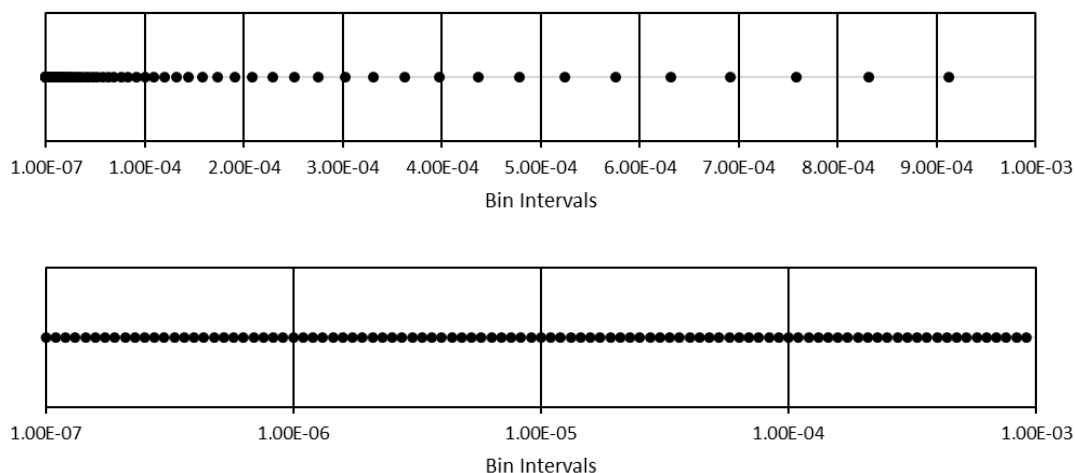


Figure 9-2. Example bin boundaries (represented by dots) for creating a probability distribution; linear scale (top), log-scale (bottom).

Next, the bins are filled to create the frequency distribution by looping through all hourly χ/Q values and a complementary CDF (CCDF) is generated as shown in Figure 9-3.

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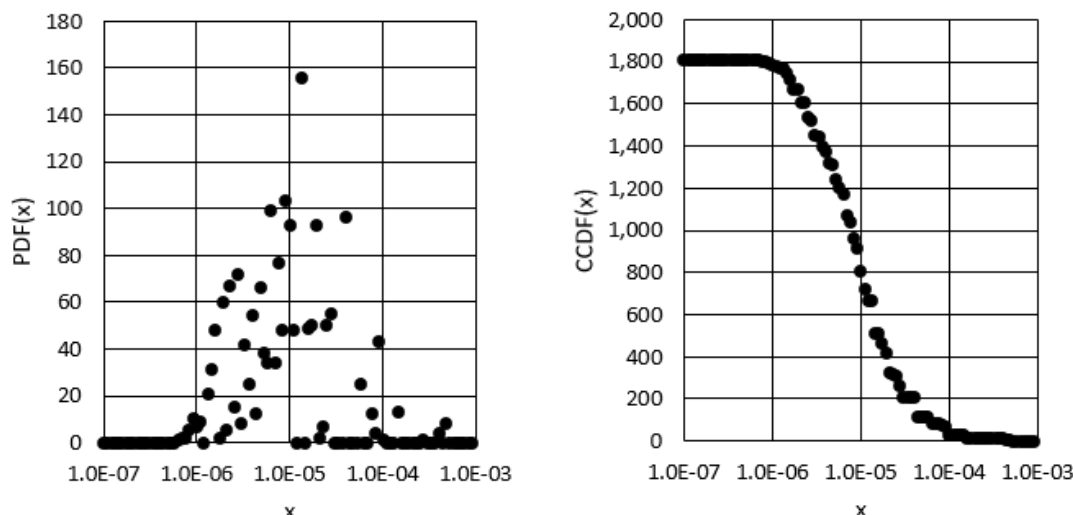


Figure 9-3. PDF (left) and inverse CCDF (right) example.

From the CDF, a cumulative percentage distribution, Figure 9-4, is generated. This is developed by taking the CCDF (right figure of Figure 9-3) and dividing the entire distribution by the total number of hourly records processed. It is noted that this is not necessarily the number of records that make up the PDF (left figure of Figure 9-3). For the example provided here, these plots were generated based on a 5-year data set (43,803 hours), but as observed by the CCDF in Figure 9-3 there are a total of only 1,807 hours included in the dataset window being evaluated. This is due to many of the resulting χ/Q values being less than the lower threshold considered (10^{-7}) and thus they are not binned within the PDF bounds. Figure 9-4 shows that about 4% of the total 43,803 hours are captured by the distribution. This poses no problem since the focus is on the right side of the curve to determine the upper percentile limit described next.

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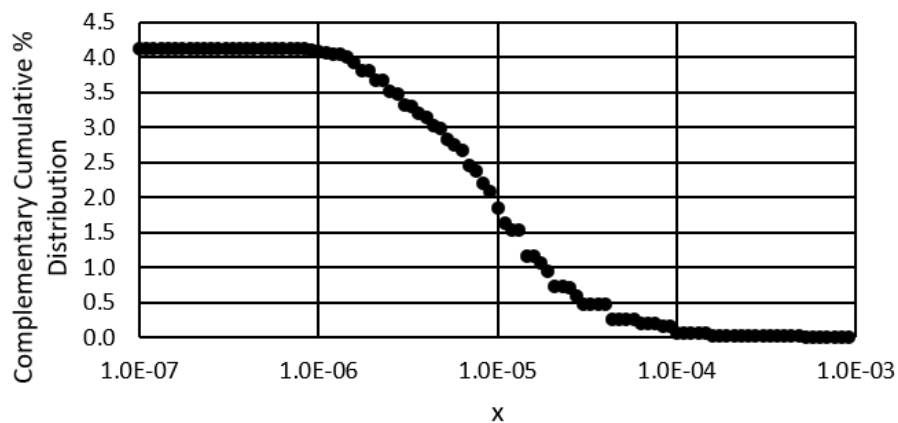


Figure 9-4. Inverse cumulative percentage distribution example.

The last step is to determine the percentile value (P). This is accomplished with the inverse cumulative percentage distribution to determine where the specified exceedance (ϵ) value resides that would produce the desired percentile. For a one-sided evaluation, the exceedance value is: $\epsilon = (1 - P)$. For a desired 95th percentile, the exceedance value would be 0.05 or 5%. ATD loops through the CCDF to find the bin that brackets the exceedance value. Once the bracketing bins are found at position (i), linear interpolation is performed between the boundaries to determine χ/Q at the desired percentile value:

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$$\left. \frac{\chi}{Q} \right|_P = \left. \frac{\chi}{Q} \right|_i + \frac{\left. \frac{\chi}{Q} \right|_i - \left. \frac{\chi}{Q} \right|_{i-1}}{CCDF\%_i - CCDF\%_{i-1}} \cdot (\epsilon - CCDF\%_i) \quad [9.9]$$

$\left. \frac{\chi}{Q} \right|_P$ χ/Q at the desired percentile value (P)

$\left. \frac{\chi}{Q} \right|_i$ χ/Q at bin boundary i

$CCDF\%_i$ Complementary cumulative (exceedance) percentage distribution at bin boundary i

ϵ Exceedance value, $(1 - P)$

P One-sided percentile value

If the desired exceedance value is greater than that available in the cumulative percentage distribution, then the minimum value is selected in the window being evaluated (Figure 9-4). Using Figure 9-4 as an example, if the 95th percentile is requested (5% exceedance) the maximum value exceedance available is at about the 4% level. ATD will report 10^{-7} as the 95th percentile value, although this really represents the 96th percentile value.

As demonstrated, if the desired exceedance value is less than available, the maximum value is reported in the window being evaluated (Figure 9-4). Caution is expressed here that this will be below the desired 95th percentile.

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Supplemental Information

10.0 Supplemental Information

This section provides supplemental material that is not required to describe the core computational methods of the preceding sections but offers useful context for interpreting ATD results and for understanding how the code relates to other established atmospheric dispersion tools. The information here is intended as background rather than as governing methodology.

At present, this section provides a discussion of joint frequency distributions (Section 10.1). It contrasts the two principal ways meteorological data are characterized — time-ordered hourly records versus statistically summarized joint frequency distributions (JFDs) — and explains why SIERRA ATD uses the hourly format for its Routine Release, Control Room, and DBA modules. It further describes how ATD nonetheless generates a JFD summary file for reference.

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Supplemental Information

10.1. Joint Frequency Distribution

This section describes the differences in the treatment of meteorological data within the SIERRA, ARCON, PAVAN, and XOQDOQ atmospheric dispersion codes, with particular emphasis on the use of hourly meteorological records versus joint frequency distributions. These two approaches represent fundamentally different methods for characterizing atmospheric transport and diffusion and reflect the intended application of each code.

Hourly meteorological data preserve temporal variability and correlations among meteorological parameters and are therefore especially important for short-term, time-dependent analyses such as accident consequence evaluations and control room habitability assessments. In contrast, joint frequency distributions (JFDs) provide a statistical summary of large meteorological datasets and are appropriate for models designed to evaluate long-term average atmospheric concentrations resulting over prolonged release periods (e.g., annual). To provide additional background on these two approaches, the following discussion summarizes how each code applies meteorological data, the advantages and limitations of each method, and the resulting impacts on calculated concentrations, doses, and regulatory conservatism.

Meteorological data in the hourly format defined in Appendix A of Regulatory Guide 1.23 [11.6] are used as model input for all three modules within SIERRA ATD (i.e., Routine Release, Control Room, and DBA). The specific processing and application of these data are described in Section 8.0. Hourly meteorological data consist of time-ordered observations of wind speed, wind direction, and atmospheric stability, thereby preserving temporal variability.

Joint frequency distributions summarize long-term climatology by binning combinations of wind direction, wind speed, and atmospheric stability into fractional occurrences. A JFD is created by statistically summarizing a multi-year set of hourly meteorological observations into discrete classes of these parameters. Each hourly record is assigned to predefined bins (e.g., wind direction sectors, wind speed classes, and stability categories), and the number of hours in each combination is normalized by the total number of valid hours to represent the fraction of time each condition occurs. Dispersion is then calculated separately for each bin. This process removes time sequencing while preserving the frequency of occurrence of relevant dispersion conditions, producing a climatological dataset suitable for long-term atmospheric dispersion and dose assessments.

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Although JFDs are derived from hourly meteorological data, they are not equivalent to running a dispersion model on an hour-by-hour basis over multiple years and averaging the results. The hourly meteorological data format preserves time dependency and therefore supports analyses of both short-term and long-term events, which is why it is the implemented meteorological input approach in SIERRA. Table 10-1 maps the code to an applied meteorological data format with a short basis.

In addition to using hourly data directly, ATD generates a joint frequency distribution summary file for each analysis for reference purposes. The JFD tallies non-calm, non-missing hours by the direction from which the wind blows (16 sectors), reference wind speed (ten bins with boundaries at 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, and 10.0 m/s, plus a final bin for speeds above 10 m/s), and stability class (A–G); calm hours are tallied separately by stability class.

Table 10-1. Meteorological data format by code.

Code	Meteorological Data Format	Basis
SIERRA ATD (Routine Release, Control Room, and DBA)	Hourly	Provides broad realistic variability for short and long-term needs.
ARCON	Hourly	Appropriate for short-term exposure windows (e.g., 0–2 hr, 2–8 hr)
PAVAN	JFD	Efficient computation which is statistically representative of long-term behavior. JFD used to construct frequency (probability) distributions of short-term sector χ/Q values [11.8].
XOQDOQ	JFD	

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