Theory and Practice of Consequence Analysis using MACCS

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Outline

- Code Overview
- Atmospheric Dispersion and Deposition
- Dosimetry
- Protective Actions
- Social and Economic Impacts
- Radiogenic Health Effects

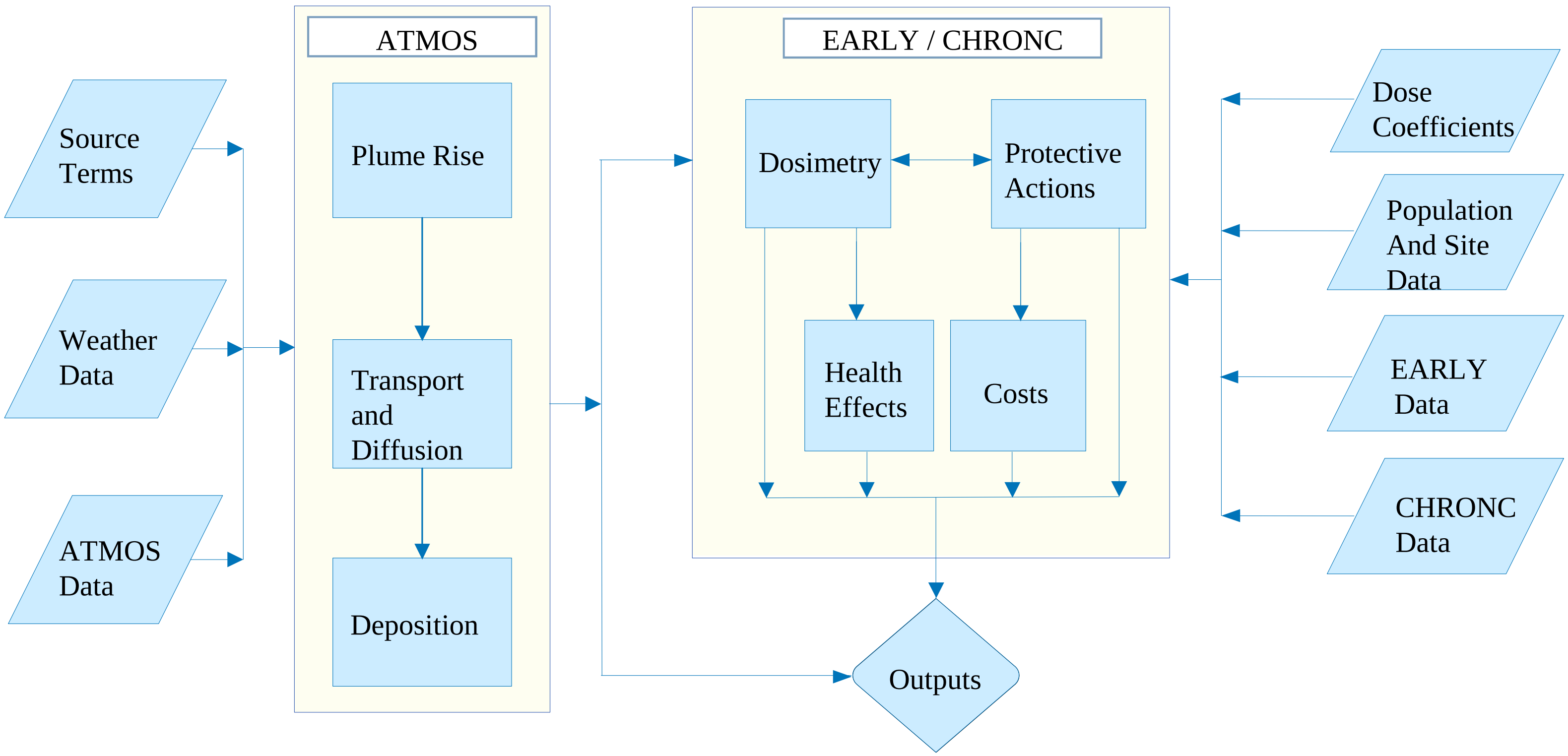
CODE OVERVIEW

Outline

- Computational framework
- Spatial grid
- Population cohorts
- MACCS outputs

CODE OVERVIEW

Computational Framework



U.S.NRC
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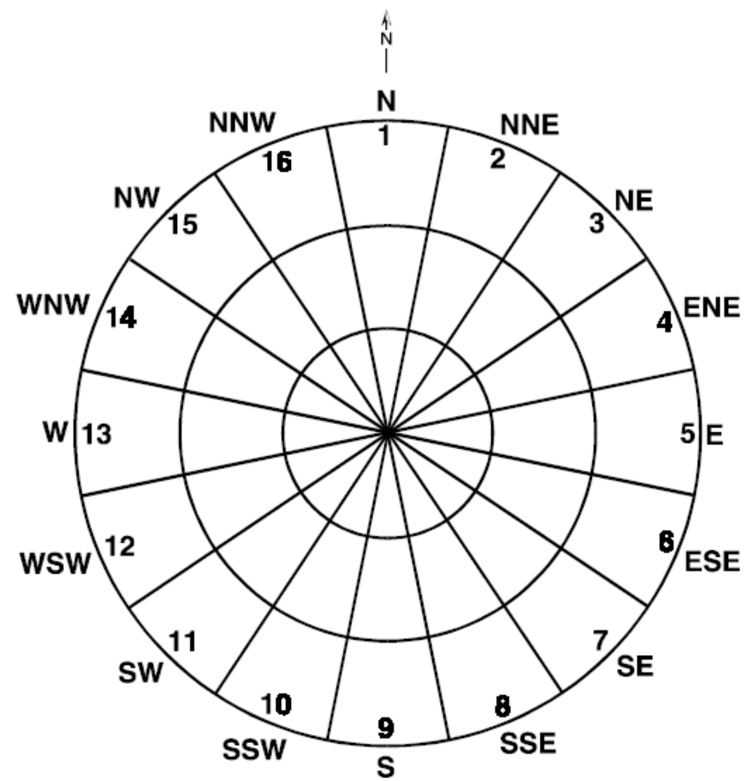
Protecting People and the Environment

CODE OVERVIEW

Spatial Grid

- Calculations are performed on a radial polar grid
- The user specifies the number of compass sectors and radial intervals, and the outer distance of each radial interval
- MACCS calculates results for each spatial element



Example of MACCS polar coordinate grid with 16 sectors and 3 radial divisions.
(reproduced from Fig. 2-1 of NUREG/CR-6613 Vol. 1

CODE OVERVIEW

Population Cohorts

- User can divide the regional population into population cohorts that have similar characteristics during an emergency response
  - Cohorts can have different protection factors, breathing rates, evacuation timelines, evacuation regions, and other factors.
  - In the intermediate and long-term phases, MACCS treats all survivors as a single population cohort.
- For each cohort, MACCS runs a separate simulation
- Many outputs report both summary results from all cohorts and cohort-specific results

CODE OVERVIEW

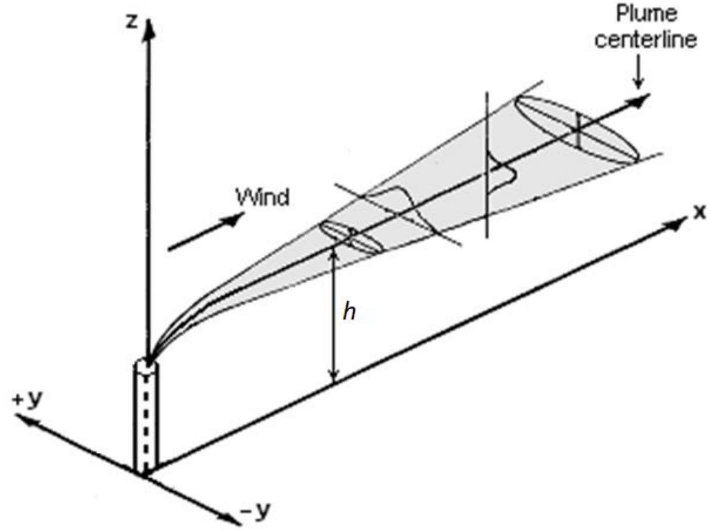
MACCS outputs

Output Name	ATMOS	EARLY	CHRONC
Type 0: Atmospheric Results for Specified Downwind Distances	X		
Type 1: Health Effect Cases		X	X
Type 2: Early Fatality Distance		X	
Type 3: Population Exceeding Early Dose Threshold		X	
Type 4: Average Individual Risk		X	X
Type 5: Population Dose		X	X
Type 6: Centerline Dose		X	X
Type 7: Centerline Risk		X	X
Type 8: Population-Weighted Individual Risk		X	X
Type A: Peak Dose for Specified Distances		X	X
Type B: Peak Dose for Specified Spatial Elements		X	X
Type C: Land Area Exceeding Dose		X	
Type D: Land Area Exceeding Concentration		X	
Type E: Population Movement Across Radius		X	
Type 9: Breakdown of Long-term Population Dose			X
Type 10: Economic Cost Measures			X
Type 11: Maximum Distance for Protective Actions			X
Type 12: Impacted Area / Population			X
Type 13: Maximum Annual Food Ingestion Dose			X
Type 14: Evacuated and Relocated Population			X

ATMOSPHERIC DISPERSION AND DEPOSITION

Outline

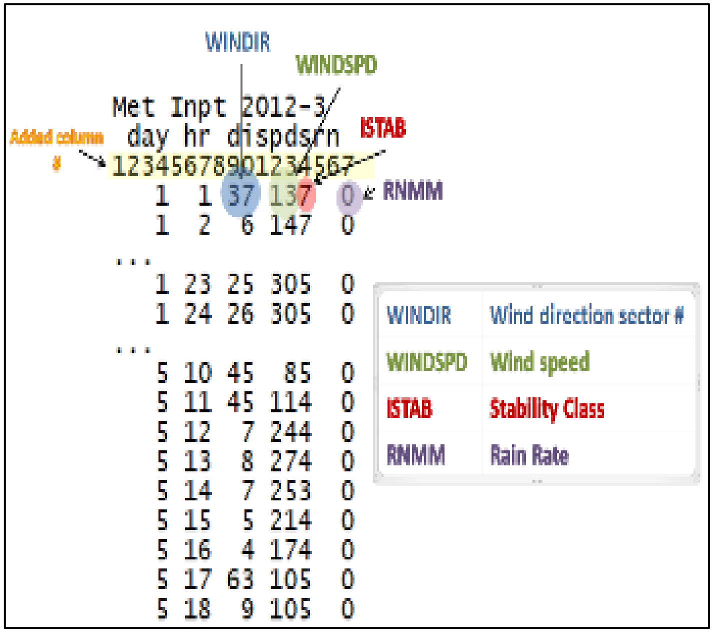
- Meteorological data
- Gaussian plume equations
- Virtual source calculation
- Diffusion parameters
- Plume rise
- Wet and dry deposition
- Off-centerline correction factors
- Atmospheric source term
- Weather sampling
- Plume meander
- Various other models (wind rotation, mixing height model, boundary weather, radioactive decay and ingrowth, weather and source term alignment)



ATMOSPHERIC DISPERSION

Meteorological Data

- User supplies one year's worth of hourly meteorological data in an external file
- Windspeeds generally based on 10 m observations
- Wind directions are defined by the compass sectors of the spatial grid and is given as the direction towards which the wind is blowing
- The plume segment direction is based on observed wind direction at time of release.
- After release, plume segments do not change direction.
- After release, plume segment dispersion changes with observed changes in weather
  - Plume speed changes with windspeed
  - Plume diffusion rate changes with stability class
  - Wet deposition rate changes with rain rate



ATMOSPHERIC DISPERSION

Gaussian Plume Equations

$$\chi(x, y, z) = \frac{Q}{u} \cdot f_G(y) \cdot \psi(z) \quad for \quad z \in [0, H]$$

where

- $\chi(x, y, z)$ is the time-integrated air concentration (*Bq·s/m^3*) at downwind location (x, y, z),
- Q_0 is the released activity (*Bq*),
- *u* is the windspeed (*m/s*), as given by the weather data,
- $f_G(y)$ is the Gaussian distribution (*m*$^{-1}$) representing lateral dispersion,
- $\psi(z)$ is the vertical distribution (*m*$^{-1}$)
- *H* is the height (*m*) of the capping inversion layer, i.e., the height of the mixing layer

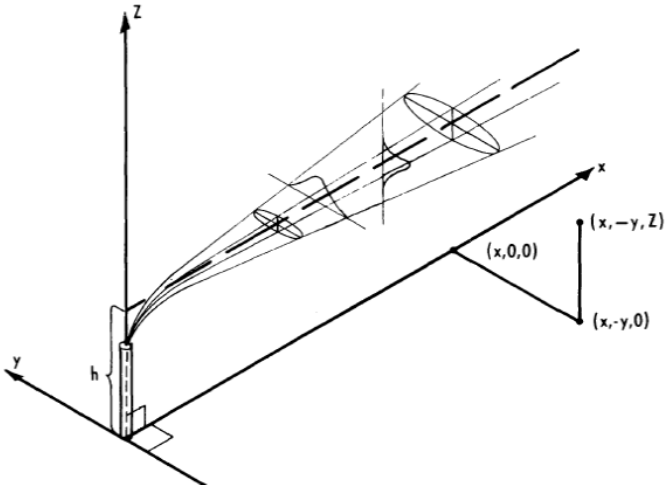


Figure adapted from Figure 3-1 of Turner (1970)

ATMOSPHERIC DISPERSION

Lateral and Vertical Distribution

Lateral distribution function

$$\boldsymbol{f_G(y)}$$

All distances:

$$\frac{1}{\sqrt{2\pi}\sigma_y} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

Where

- $\sigma_y(x)$ is the lateral dispersion parameter representing one standard deviation of the Gaussian distribution (*m*)

Vertical distribution function

$$\boldsymbol{\psi(z)}$$

Incomplete vertical mixing, i.e., shorter distances:

$$\frac{1}{\sqrt{2\pi}\sigma_z}\sum_{n=-100}^{100}\left\{exp\left[-\frac{1}{2}\left(\frac{z-h+2nH}{\sigma_z}\right)^2\right]+exp\left[-\frac{1}{2}\left(\frac{z+h+2nH}{\sigma_z}\right)^2\right]\right\}$$

Complete vertical mixing, e.g., longer distances

$$\psi(z) = \frac{1}{H}$$

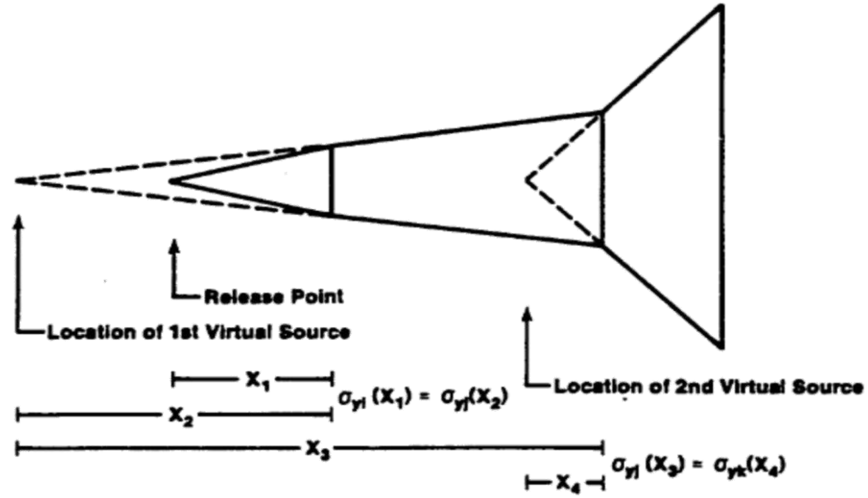
Where

- $\sigma_z(x)$ is the vertical dispersion parameter representing one standard deviation of the Gaussian distribution (*m*).
- *h* is the height of the plume centerline (*m*)
- *H* is the height (*m*) of the capping inversion layer, i.e., the height of the mixing layer

ATMOSPHERIC DISPERSION

Virtual Sources

- Basic Gaussian equations assume a point source
- To represent an area source (e.g., to account for initial dispersion due to turbulent wake effects), MACCS computes a “virtual source” distance as shown below:



(reproduced from Fig. 2.2 of NUREG/CR-4691 Vol. 2)

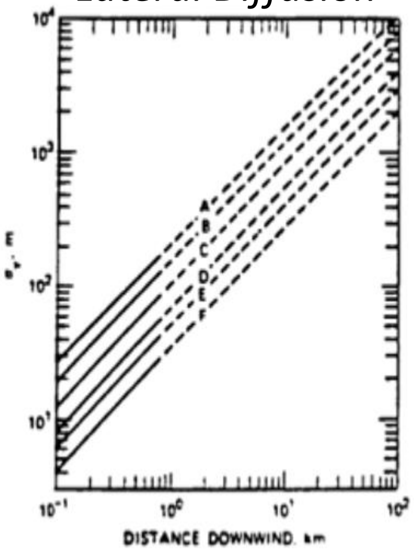
- Also used to ensure continuity of the plume during changes in meteorological conditions, i.e., stability class.

ATMOSPHERIC DISPERSION

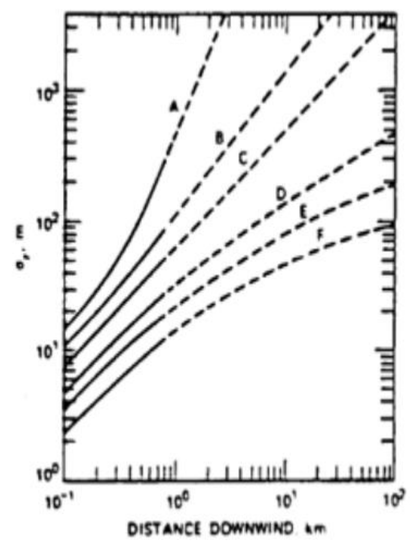
Diffusion Parameters

- Diffusion is represented as a function of downwind distance rather than plume travel time
- Diffusion curves may be represented in MACCS by a either power law or by a lookup table.

Lateral Diffusion



Vertical Diffusion



- Values based on Pasquill-Gifford diffusion curves are commonly used, but user may enter any desired set of diffusion parameter data

ATMOSPHERIC DISPERSION

Surface Roughness Effects on Vertical Scaling

- Users can specify scaling factors, YSCALE and ZSCALE, that act as multipliers on diffusion parameters, σ_y and σ_z, respectively.
- Scaling factors can reflect increased or decreased plume expansion.
- Users commonly use ZSCALE to model increased vertical dispersion σ_z due to surface roughness of terrain:

$$ZSCALE = \left(\frac{z_0}{z_{0,ref}}\right)^q = \left(\frac{z_0}{3\ cm}\right)^{0.2}$$

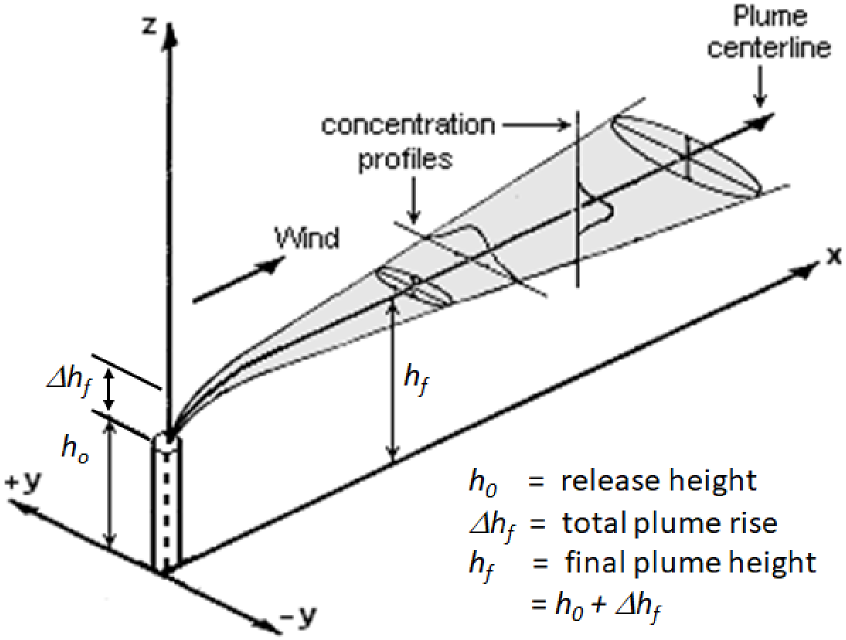
ATMOSPHERIC DISPERSION

Plume Rise

- Liftoff criterion

- Plume rise equations calculate:
  - Plume trajectory, $\Delta h(x)$
  - Total plume rise, Δh_f

- Calculated factors that affect plume rise:
  - Buoyancy flux, F
  - Average windspeed, $\overline{u}$
  - Stability parameter, S
  - Downwind distance where the plume reaches its final rise height, x_f



ATMOSPHERIC DISPERSION

Buoyant Plume Trapping/Liftoff

- Based on model proposed by Briggs (1973b)
- Plume rise occurs only when the wind speed upon release of the segment is less than a critical wind speed u_c, which is calculated using the following formula:

$$u_c = \left(\frac{9.09F}{H_b}\right)^{\frac{1}{3}}$$

where

- H_b is the height (m) of the building from which the plume escapes (BUILDH), and
- F is the buoyancy flux (m^4/s^3) of the plume segment

ATMOSPHERIC DISPERSION

Plume Trajectory $\Delta h(x)$

For bent-over plume trajectory $\Delta h(x)$, MACCS uses the Briggs "two-thirds law" (Hanna, Briggs, & Hosker, 1982):

$$\Delta h(x) = \frac{1.6F^{\frac{1}{3}}x^{\frac{2}{3}}}{\overline{u}}$$

Where

- $\Delta h(x)$ is the plume rise (*m*), as measured from the initial release height (PLHITE),
- *x* is downwind distance (*m*),
- *F* is the buoyancy flux (m^4/s^3) of the plume segment, and
- $\overline{u}$ is the wind speed (*m/s*) averaged between the initial release height and the final plume height (h_f)

ATMOSPHERIC DISPERSION

Final Plume Rise Δh_f

Unstable or neutral conditions
(stability classes A through D)

Final plume rise Δh_f based on the work of Briggs (1970):

$$\Delta h_f = \begin{cases} \dfrac{38.7 \cdot F^{0.6}}{\overline{u}} & if \quad F \geq 55\, m^4/s^3 \\ \dfrac{21.4 \cdot F^{0.75}}{\overline{u}} & if \quad F < 55\, m^4/s^3 \end{cases}$$

Stable conditions
(stability classes E or F)

Final plume rise Δh_f depends on the downwind distance x_f where the plume reaches its final rise height. If $x_f \leq 1.84 \frac{\bar{u}}{\sqrt{S}}$, Δh_f is identical to the formulae used for unstable conditions (stability class A through D)

If $x_f > 1.84 \frac{\bar{u}}{\sqrt{S}}$, then:

$$\Delta h_f = 2.4 \left(\frac{F}{\overline{u} S} \right)^{\frac{1}{3}}$$

Stability parameters S for classes E and F are 5.04×10^{-4} s^{-2} and 1.27×10^{-3} s^{-2}, respectively.

ATMOSPHERIC DEPOSITION

- Radioactivity is removed from plume segments by decay and by deposition of radioactive materials onto the ground. MACCS considers decay and ingrowth in a separate step.
- The amount of material ΔQ_j of a given radionuclide that is deposited onto the ground during transport of a plume segment across radial interval *j* is given by the following:

$$\Delta Q_j = Q_j\left(1 - f_{dj} \cdot f_{wj}\right)$$

Where

- Q_j is the amount of radioactive material (*Bq*) that is transported into radial interval *j* by the plume segment,
- f_{dj} is the fraction of material (dimensionless) that would remain in the plume after transport across radial interval *j* if only dry deposition occurred, and
- f_{wj} is the fraction of material (dimensionless) that would remain in the plume after transport across radial interval *j* if only wet deposition occurred.

ATMOSPHERIC DEPOSITION

Dry Deposition

The fraction f_d of material not removed by dry deposition from transport across a radial interval is a weighted average of each particle size bin *i* (i.e., $f_d = \sum_i p_i \cdot f_{di}$), where f_{di} is the following:

$$f_{di} = exp\left[-v_{di} \cdot \psi_0 \cdot \Delta t_{ref}\right]$$

where

- p_i is the fraction of all aerosol materials in particle size bin *i* (PSDIST)
- v_{di} is the dry deposition velocity (*m/s;* VDEPOS)
- ψ_0 is the ground-level value of the plume distribution in the vertical direction (m^{-1}), and
- Δt_{ref} is the time (*s*) required for the reference location (REFTIM) of a plume segment to transverse the radial interval.

The material removed by dry deposition is uniformly deposited along the length of the radial interval.

ATMOSPHERIC DEPOSITION

Wet Deposition

Wet deposition depends on both precipitation duration and intensity (Brenk and Vogt 1981).

The total fraction f_w of material not removed by wet deposition from transport across a radial interval is the product of the fractions not removed during period $\Delta t_1, \Delta t_2, \Delta t_3, \ldots$ (i.e., $f_w = \prod_i f_{wi}$), where f_{wi} is the following:

$$f_{wi} = 1 - f_{av,i} \cdot \left(1 - exp\left[-C_1 \left(\frac{I_i}{I_0}\right)^{C_2} \Delta t_i\right]\right)$$

where

- $f_{av,i}$ is the average fraction (dimensionless) of the plume segment within the radial interval during Δt_i,
- Δt_i is a period (s) during which the plume segment is crossing the radial interval (where $\sum_i \Delta t_i$ is the duration for the full plume segment to cross both ends of the radial interval),
- C_1 is the linear wet deposition coefficient (*1/s*), as given by the parameter CWASH1
- C_2 is the exponential wet deposition coefficient (dimensionless), as given by the parameter CWASH2,
- I_i is the intensity of precipitation (*mm/hr*), as specified by the weather data, and
- I_0 is the unit rain intensity, 1 mm/hr

The material removed by wet deposition is uniformly deposited along the length of the radial interval

ATMOSPHERIC DISPERSION

Standard *Off-Centerline Corrections*

- ATMOS calculates air and ground concentrations directly along and / or directly under the plume centerline
- Off-centerline correction factors are adjustments to calculate the concentrations in the spatial elements
- EARLY calculations for stationary individuals use fine spatial elements
- CHRONC calculations use coarse spatial elements
- Correction factors are computed for all fine or coarse grid sectors within 2.15 standard deviations of the plume centerline
- MACCS uses special correction factors for evacuees and for cloudshine

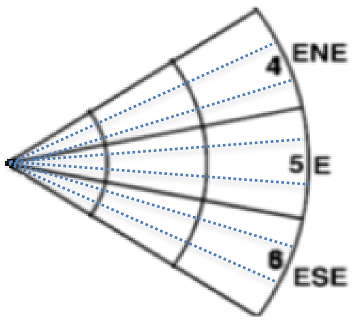
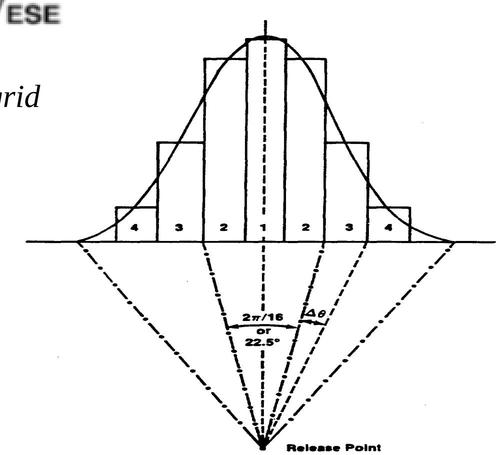


Illustration of fine grid subdivisions



Approximation of a Gaussian Distribution by fine grid histogram. (reproduced from Fig. 3.2 of NUREG/CR-4691 Vol. 2)

ATMOSPHERIC DISPERSION AND DEPOSITION

QUESTIONS?