Theory of Consequence Analysis using MACCS, Part 1-3

A.J. Nosek, PhD

US Nuclear Regulatory Commission

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Outline

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

CODE OVERVIEW

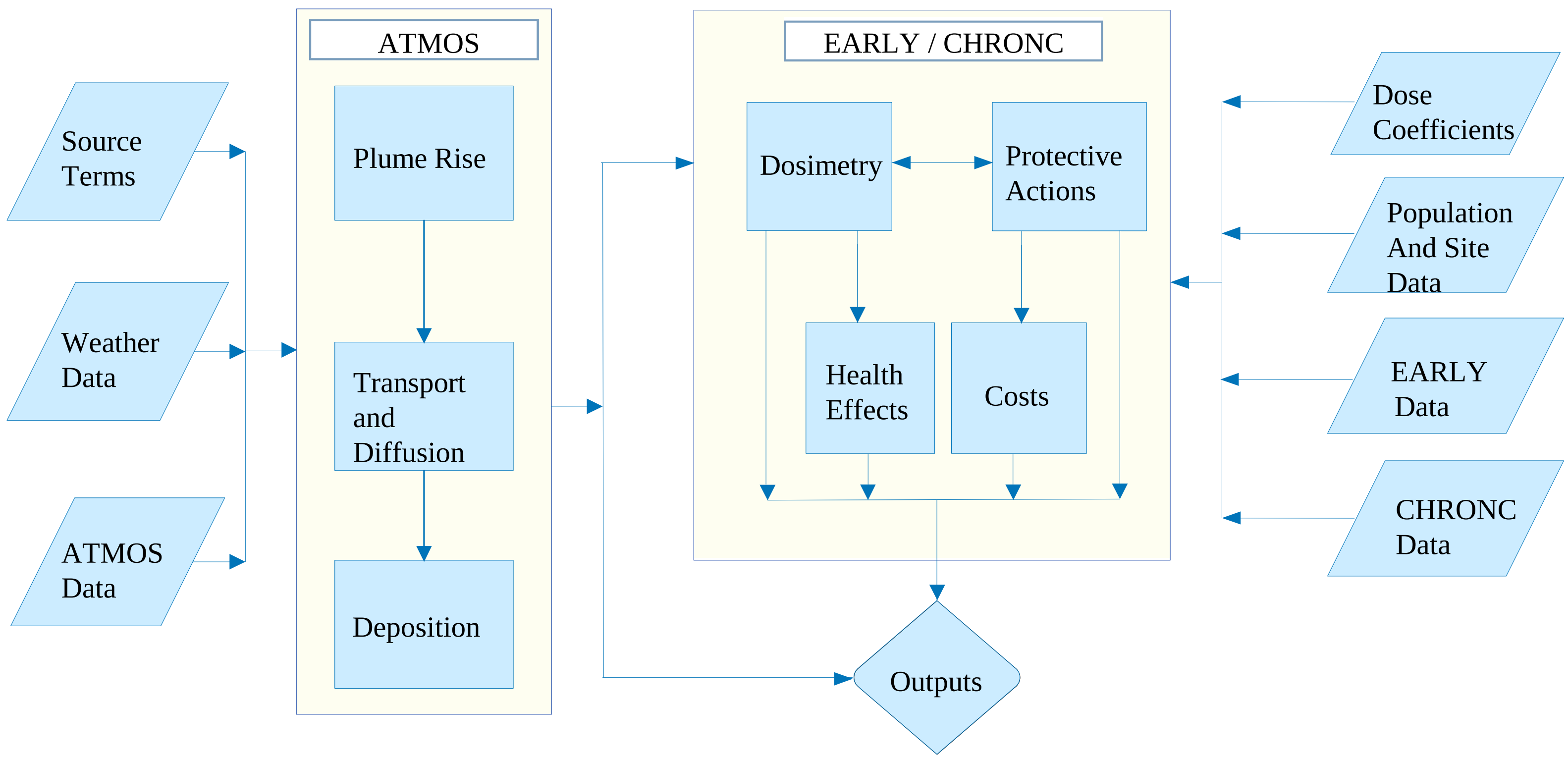
Outline

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

CODE OVERVIEW

Computational Framework

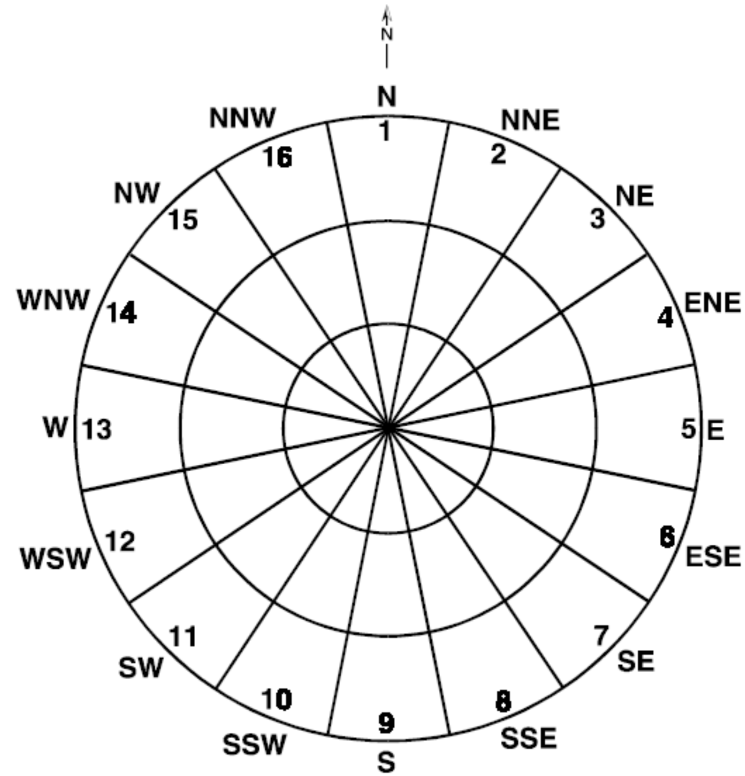


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

CODE OVERVIEW

MACCS outputs

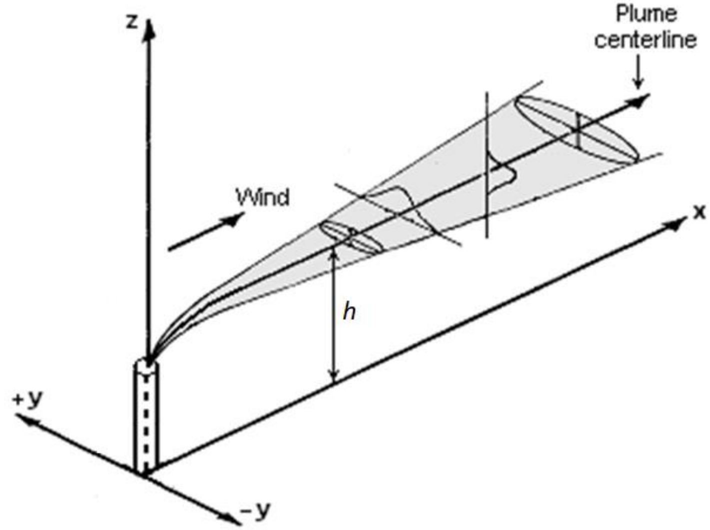
Output Name	ATMOS	EARLY	CHRONC
Type 0: Atmospheric Results for Specified Downwind Distances	X		
Type 1: Health Effect Cases		X	X
Type 2: Early Fatality Distance		X	
Type 3: Population Exceeding Early Dose Threshold		X	
Type 4: Average Individual Risk		X	X
Type 5: Population Dose		X	X
Type 6: Centerline Dose		X	X
Type 7: Centerline Risk		X	X
Type 8: Population-Weighted Individual Risk (i.e., Safety Goal 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 C Flag: Dose by Grid Element		X	X
Type D: Land Area Exceeding Concentration		X	
Type D Flag: Ground Concentration by Grid Element		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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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)

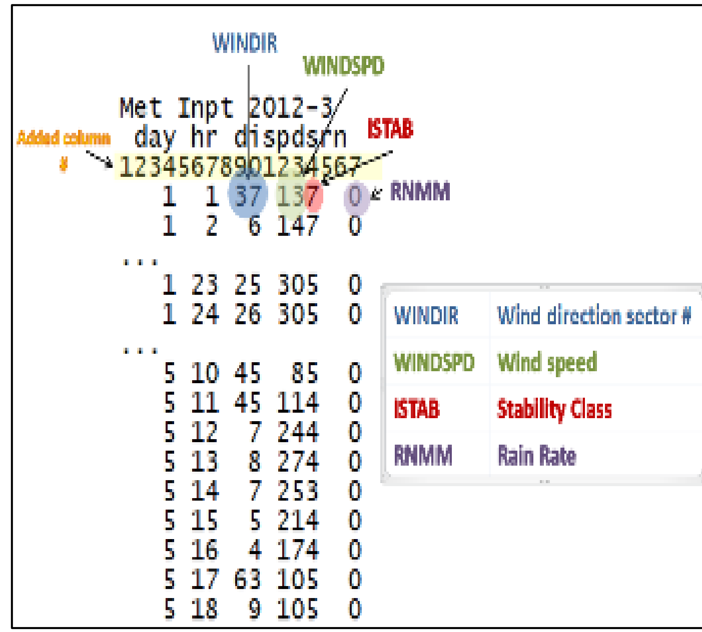


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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/m³*) 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

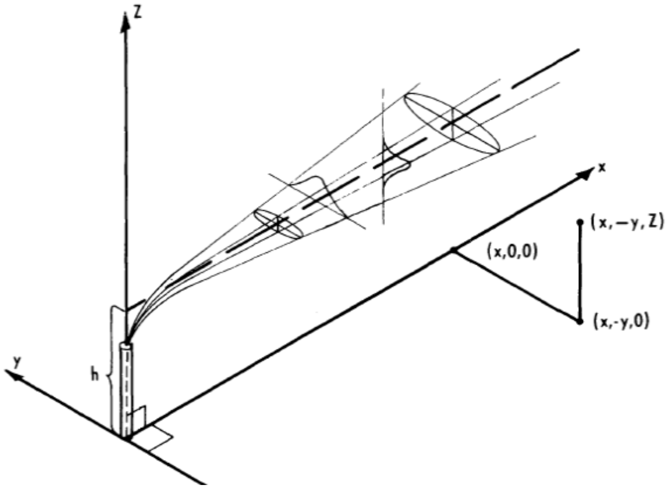


Figure adapted from Figure 3-1 of Turner (1970)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

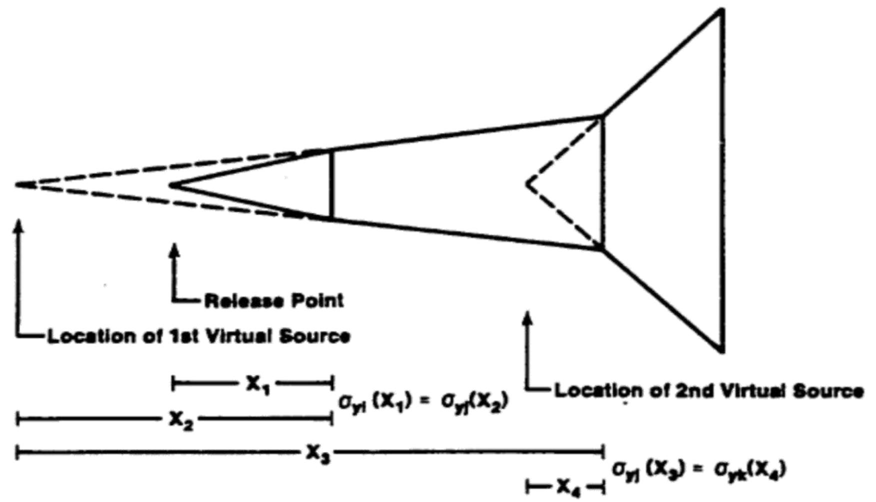
- $\sigma_z(x)$ is the vertical dispersion parameter representing one standard deviation of the Gaussian distribution (*m*).
- *h* is the height of the plume centerline (*m*)
- *H* is the height (*m*) of the capping inversion layer, i.e., the height of the mixing layer

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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)

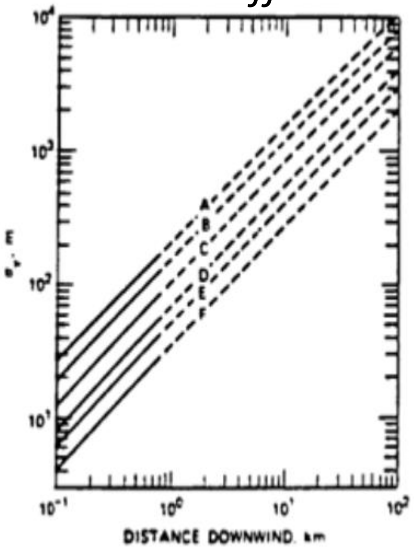
- Also used to ensure continuity of the plume during changes in meteorological conditions, i.e., stability class.

ATMOSPHERIC DISPERSION

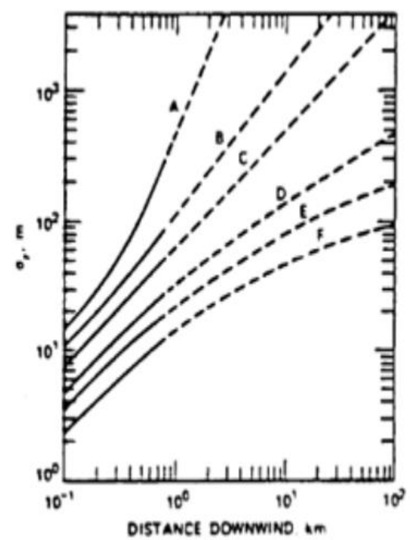
Diffusion Parameters

- 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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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:

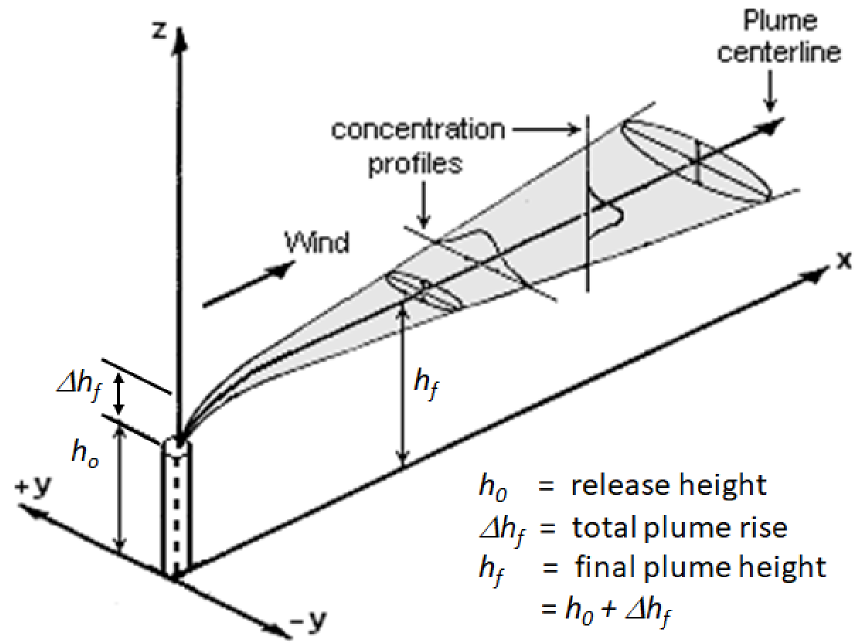
$$ZSCALE = \left(\frac{z_0}{z_{0,ref}}\right)^q = \left(\frac{z_0}{3\ cm}\right)^{0.2}$$

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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):

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

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:

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

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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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 Δt_1, Δt_2, Δt_3, … (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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

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

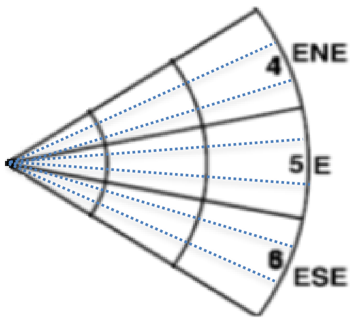
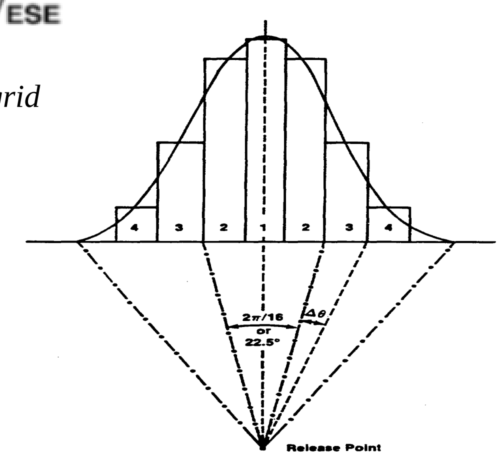


Illustration of fine grid subdivisions



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

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION AND DEPOSITION

QUESTIONS?

DOSIMETRY

Outline

- Exposure pathways
- Dose conversions
- Types of calculated doses
- Example exposure pathways
  - Groundshine
  - Resuspension inhalation
  - Cloudshine
  - Direct inhalation
  - Skin deposition
  - Food ingestion
  - Water ingestion
  - Decontamination worker dose

DOSIMETRY

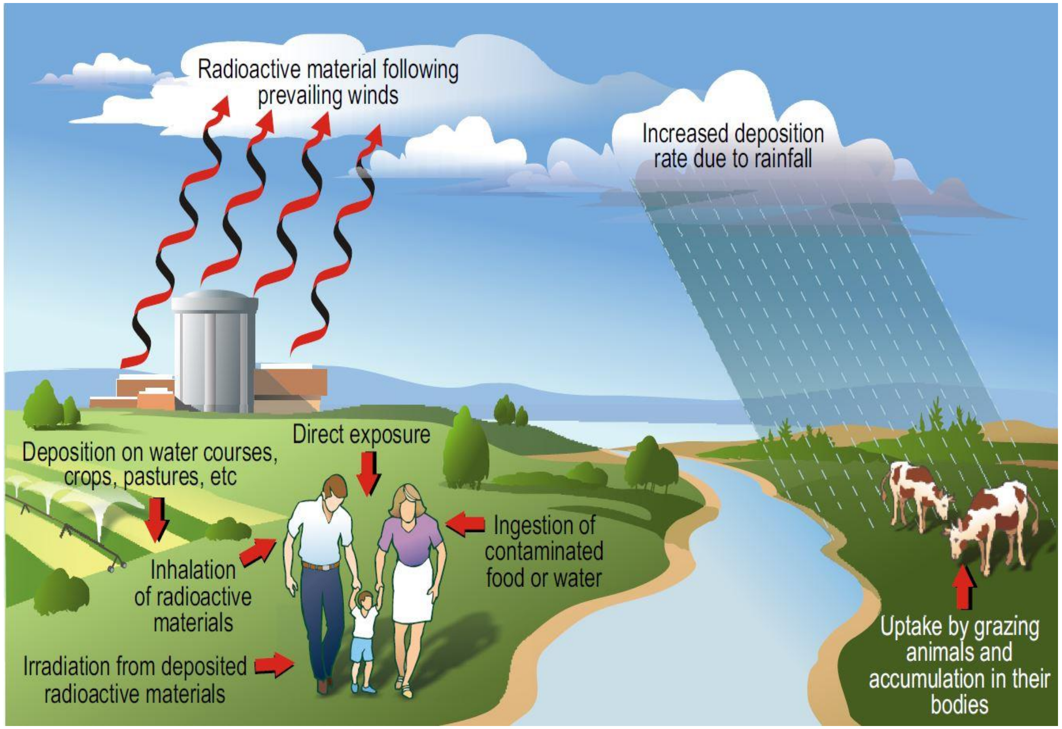
Exposure Pathways

Early Doses

- Cloudshine
- Groundshine
- Direct inhalation
- Resuspension inhalation
- Skin deposition

Late Doses

- Groundshine
- Resuspension inhalation
- Food ingestion
- Water ingestion



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

Dose Coefficients

- The dose models use dose coefficients to convert from time-integrated air concentrations or ground concentrations to dose.
- Dose coefficients:
  - read from a user-supplied DCF file
  - depend on the exposure pathway, organ, and radionuclide
  - treat the effective dose as a pseudo-organ
- External pathways use a dose rate coefficient (e.g., *Sv/s per Bq/*m^2)
- Internal pathways (inhalation and ingestion) use an intake-to-dose coefficient (*Sv/Bq*)
- Separate internal dose coefficients are provided for acute, lifetime, and annual doses

DOSIMETRY

Types of Calculated Doses

- Acute dose
  - The portion of the dose that contributes to early health effects (i.e., accounts for the sparing effect)
  - Includes only early-phase contributions to dose
  - Uses a weighting factor (<1.0) to account for reduced risk associated with protracted internal doses from inhalation
- Lifetime dose
  - The dose that contributes to stochastic health effects (e.g., cancer)
  - Includes both early-phase and late-phase contributions to dose
- Annual dose
  - The same as the lifetime dose, except annual doses are discretized into annual periods
  - Includes both early-phase and late-phase contributions to dose

DOSIMETRY

Groundshine (EARLY and CHRONC)

The groundshine dose DG_k (*Sv*) to organ *k* in a spatial element is calculated using the following equation:

$$DG_k = \left(\sum_i DRCG_{ik} \cdot GC_i \cdot IEF_i \right) \cdot Y \cdot SFG$$

where

- $DRCG_{ik}$ is the groundshine dose rate coefficient (*Sv−m*^{2}*/Bq−s*) to the organ *k* for the radionuclide *i*, supplied in the DCF file,
- GC_i is the ground concentration (*Bq/m*^{2}) of radionuclide *i* under the plume centerline, computed separately for the EARLY and CHRONC phases to account for decay and ingrowth,
- IEF_i is the groundshine integrated exposure factor (*s*) for radionuclide *i* for the time period of interest, computed separately for the EARLY and CHRONC phases
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element (EARLY) or the coarse spatial element (CHRONC),
- SFG is the groundshine protection factor (dimensionless) for the time period of interest

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

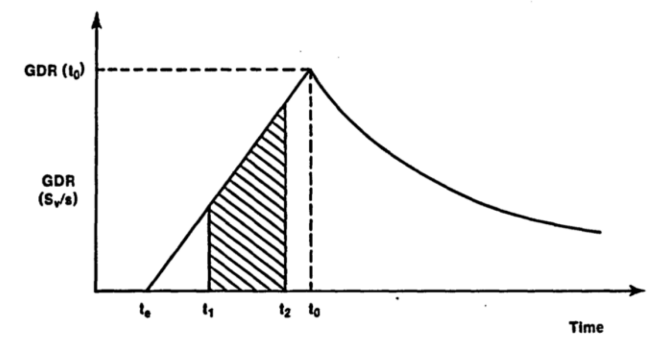
Groundshine (EARLY)

The groundshine integrated exposure factor IEF_i (*s*) for early phase exposures is given by:

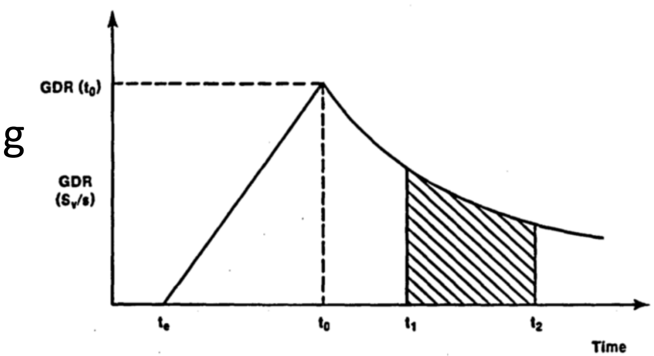
$$IEF_i = \int_{t_1}^{t_2} \frac{(t - t_e)}{(t_0 - t_e)} dt + \int_{t_3}^{t_4} e^{-\lambda_i t} dt$$

where

- t_e and t_0 give the times that the reference location of a plume segment enters and leaves a spatial element
- t_1 and t_2 give the start and end of exposure during plume passage
- t_3 and t_4 give the start and end of exposure after plume passage
- λ_i is the radioactive decay constant of radionuclide *i.*



(a) Exposure During the Plume Passage



(b) Exposure After the Plume Passage

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

Groundshine (CHRONC)

The groundshine integrated exposure factor IEF_i (*s)* for intermediate and long-term phase exposures is given by:

$$IEF_i = \frac{1}{DRF_\ell} \int_{t_1}^{t_2} e^{-\lambda_i t} \cdot \left(WC_1 \cdot e^{-\lambda_1 t} + WC_2 \cdot e^{-\lambda_2 t} \right) dt$$

where

- DRF_ℓ is the dose reduction factor (dimensionless) for decontamination level ℓ, if applicable, as specified by the parameter DSRFCT_ℓ.
- t_1 and t_2 provide the start and end of the exposure period,
- λ_i is the radioactive decay constant (s^{-1}) of radionuclide *i*,
- WC_1 and WC_2 are the groundshine weathering compartment fractions (dimensionless), as specified by GWCOEF, and
- λ_1 and λ_2 are the weathering decay constants (s^{-1}) determined by TGWHLF.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

Resuspension Inhalation (EARLY and CHRONC)

Inhalation dose from resuspended radionuclides DR_k is calculated as follows

$$DR_k = \left(\sum_i DCI_{ik} \cdot GC_i \right) \cdot RF \cdot BR \cdot Y \cdot SFI$$

where

- DCI_{ik} is the inhalation dose coefficient (*Sv/Bq-inhaled*),
- GC_i is the ground concentration (*Bq/m^2^*) of radionuclide *i* in the spatial element, computed separately for the EARLY and CHRONC phases*,*
- *RF* is the time-integrated resuspension factor (*s*/*m*), calculated separately for the EARLY and CHRONC phases
- *BR* is the breathing rate (*m*^3^/*s*),
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element (EARLY) or the coarse spatial element (CHRONC),
- *SFI* is the inhalation protection factor (dimensionless),

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

Resuspension Inhalation (EARLY and CHRONC)

The time-integrated resuspension factor *RF* (*s*/*m*) is given by either:

$$RF_{EARLY} = RC \cdot \int_{t_1}^{t_2} e^{-\lambda_r t} \cdot e^{-\lambda_i t}\, dt$$

$$RF_{CHRONC} = \frac{1}{DRF_{\ell}} \int_{t_1}^{t_2} \left(\sum_{m=1}^{3} \left(RC_m \cdot e^{-\lambda_m t} \right) \right) \cdot e^{-\lambda_i t} \cdot dt$$

where

- RC is the early phase resuspension coefficient (m^{-1}),
- λ_r is the early phase resuspension weathering constant (s^{-1})
- λ_i is the decay constant (s^{-1}) of radionuclide *i*,
- t_1 and t_2 provide the start and end of the exposure period,
- DRF_{ℓ} is the dose reduction factor (dimensionless) for decontamination level ℓ if applicable, as specified by the parameter $DSRFCT_{\ell}$
- RC_m is the long-term resuspension coefficient (m^{-1}) for the m^{th} term, and
- λ_m is the long-term resuspension weathering decay constant (s^{-1}) for the m^{th} term

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

SUPPLEMENTAL SLIDES

ATMOSPHERIC DISPERSION

Plume Meander

- Wind shifts that occur within the time intervals between recorded weather data can lead to dispersion greater than reflected in dispersion data.
- Two optional meander models (MNDMOD = "OLD," "NEW," or "OFF")
  - Both models estimate a meander factor (f_m) that acts as a multiplier on lateral dispersion, $\sigma_{ym} = f_m \cdot \sigma_y$
  - The meander factor is like the lateral dispersion scaling factor, YSCALE, but is not constant.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

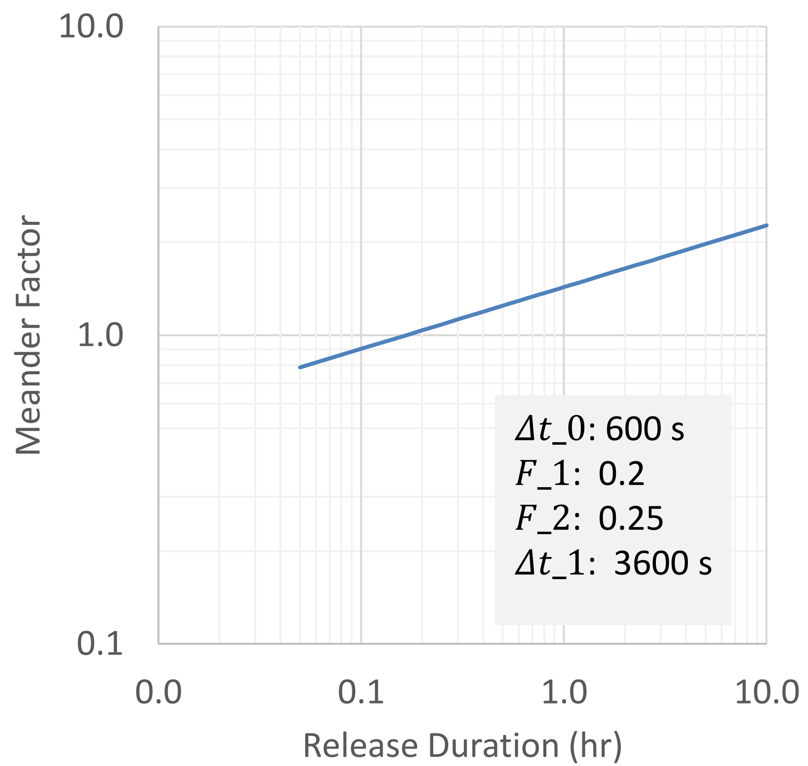
Original Plume Meander Model ("OLD")

The original meander model accounts for release durations that are longer than the sampling duration of the dispersion data.

Meander factor defined as follows:

$$f_m = \begin{cases} 1 & & \Delta t_{release} \leq \Delta t_0 \\ (\Delta t_{release}/\Delta t_0)^{F_1} & if & \Delta t_0 < \Delta t_{release} \leq \Delta t_1 \\ (\Delta t_{release}/\Delta t_0)^{F_2} & & \Delta t_1 < \Delta t_{release} \leq 10 \text{ hr} \end{cases}$$

Values based on recommendations by Gifford (1975)



United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

New Plume Meander Model ("NEW")

The new meander model, based on Equation (3) of Regulatory Guide 1.145, accounts for the effect of windspeed and atmospheric stability on plume meander

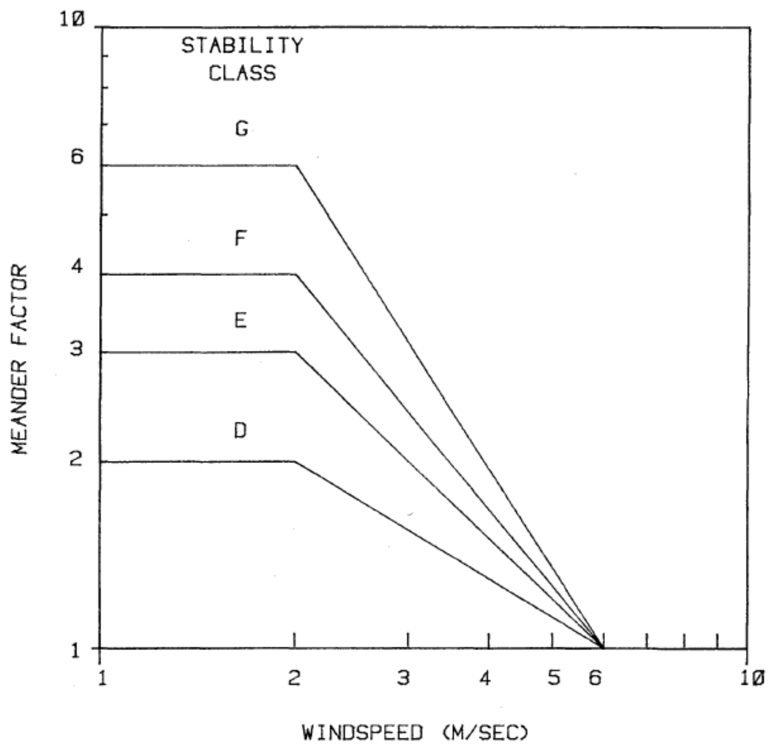
Generalizes the approach given in NUREG/CR-2260 by defining a meander factor as follows:

$$f_m = \begin{cases} m_i \cdot f(u) & x \le D \\ 1 & x > D \end{cases}$$

Where

$$f(u) = \begin{cases} 1 & u \le u_1 \\ \dfrac{1}{m_i} \cdot exp\left[\left(1 - \dfrac{ln(u) - ln(u_1)}{ln(u_2) - ln(u_1)}\right) \cdot ln(m_i)\right] & u_1 < u \le u_2 \\ 1/m_i & u_2 < u \end{cases}$$

- Based on field studies at Rancho Seco and EOCR
- Meander factors are intended for use with one hour plume segments



(reproduced from Fig. II-6 of NUREG/CR-2260)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

Buoyancy Flux

- Buoyancy flux is used to determine whether plume is trapped within building wake and, if not, the amount of plume rise above the initial release elevation
- User may select one of two options: “Power” model or “Density and Flow” model (PLMMOD = “HEAT” or “DENSITY”)

In the power model, the buoyancy flux *F* is related to the sensible heat release rate $\dot{Q}$ (J/s) according to the following formula (Briggs, 1965):

$$F = \frac{g}{\pi C_p \rho_a T_a} \dot{Q}$$

$$= 8.79 \cdot 10^{-6} \cdot \dot{Q}$$

In the density and flow model, buoyancy flux *F* is the computed as follows:

$$F = \frac{g}{\pi} \left[1 - \frac{\rho}{\rho_a} \right] \frac{\dot{m}}{\rho}$$

The “DENSITY” model accounts for release of gases that are lighter than air, such as hydrogen and steam, as well as releases at elevated temperatures.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

Average Windspeed, $\overline{u}$

- For plume rise, $\overline{u}$ is an average of the surface windspeed u_0 and the windspeed u_1 at the final plume height, i.e., $\overline{u} = (u_0 + u_1)/2$
- MACCS calculates the windspeed u_1 at the final plume height using the following iterative technique:

$$u_0 \rightarrow h_1 \rightarrow u_1$$

Where

- h_1 is a first order estimate of the final plume height (using u_0 instead of $\overline{u}$)
- u_1 is windspeed at this height h_1 according to the following formula (Hanna, Briggs, & Hosker, 1982):

$$\mathrm{u} = u_0 \left(\frac{h}{h'}\right)^p$$

Where

- u is the windspeed (*m/s*) at the height h,
- u_0 is the surface windspeed (*m/s*), as provided by the weather data and usually represents a 10-m election above ground level,
- h' is a reference height of 10 m, which is fixed in the code,
- p is a dimensionless parameter that varies with stability class and surface roughness and is fixed in the code

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

Stability parameter, S

- The stability parameters *S* for stability classes E and F are 5.04×10^{-4} s^{-2} and 1.27×10^{-3} s^{-2}, respectively. These values are fixed in the MACCS code.
- The values were manually calculated using the following formula:

$$S = \frac{g}{T_a}\left(\frac{\partial T_a}{\partial z} + \frac{g}{c_p}\right)$$

Where

- g is the acceleration due to gravity (9.8 m/s^2),
- T_a is the ambient temperature (288 K),
- $\partial T_a/\partial z$ is the ambient temperatures lapse rate (K/m) and depends on stability class, which are 0.5 K/100 m for stability class E, and 2.75 K/100 m for stability class F (Regulatory Guide 1.23 [NRC, 2007])
- C_p is the specific heat of air at constant pressure (1.005 kJ/kg-K), and
- g/C_p is the dry adiabatic lapse rate (0.98 K/100 m)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Atmospheric Dispersion: Dispersion Rate Models

- Lateral dispersion $\sigma_y(x)$ and vertical dispersion $\sigma_z(x)$ are inputs to the Gaussian plume equations.
- Two dispersion rate models:
  - A power-law function, or
  - User-supplied lookup tables
- Both options depend on distance and atmospheric stability class.
- Additional time-based model:
  - User can switch lateral dispersion from distance-based dispersion $\sigma_y(x)$ to time-based dispersion $\sigma_y(t)$ at a specified distance downwind.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

Finite duration of plume segments

- Plume Length
- Plume Arrival Time
- Time Overhead
- *(TO BE COMPLETED)*

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

ATMOSPHERIC DISPERSION

Meteorological Sampling

DOSIMETRY

Direct Inhalation (EARLY)

For a given plume segment and spatial element, the direct inhalation dose DI_k to organ *k* during the plume passage is the following equation:

$$DI_k = \left(\sum_i DCI_{ik} \cdot \chi_i^G \right) \cdot BR \cdot Y \cdot F \cdot SFI$$

where

- DCI_{ik} is the inhalation dose coefficient (*Sv/Bq-inhaled*) for either acute or lifetime dose to organ *k* for radionuclide *i*,
- χ_i^G is the time-integrated ground-level air concentration (*Bq-s/m³)* of radionuclide *i* under the plume centerline,
- *BR* is the breathing rate (m^3/s),
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element,
- *F* is the fraction of exposure duration during the plume passage in the fine spatial element, equal to *TE/TO* where *TE* is the exposure time (*s*) of an individual and *TO* is the time duration (*s*) of a plume segment traversing the fine spatial element,
- *SFI* is the inhalation protection factor (dimensionless).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

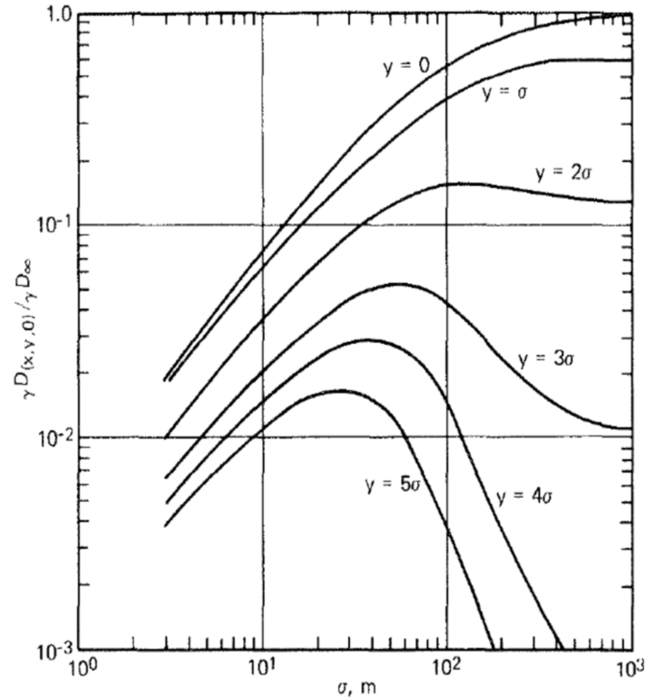
Cloudshine (EARLY)

Cloudshine is based on a "semi-infinite cloud" approximation (Healy, 1984), where the cloudshine dose to organ *k* is given by:

$$DC_k = \left(\sum_i DRCC_{\infty ik} \cdot \chi_i^C\right) \cdot Y \cdot F \cdot SFC$$

where

- $DRCC_{\infty ik}$ is the semi-infinite cloud dose rate coefficient (*Sv-m*^{3}*/Bq-s*) to organ *k* for radionuclide *i*,
- χ_i^C is the time-integrated air concentration (*Bq-s/m*^{3}) of radionuclide *i* at the plume centerline,
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element, which is a special cloudshine correction factor until the plume is fully dispersed vertically,
- *F* is the fraction of exposure duration during the plume passage in the fine spatial element, equal to *TE/TO* where *TE* is the exposure time (*s*) of an individual and *TO* is the time duration (*s*) of a plume segment traversing the fine spatial element,
- *SFC* is the cloudshine protection factor (dimensionless) due to shielding.



Ratio of the gamma dose in a finite cloud to the gamma dose in an infinite cloud for 0.7-MeV gamma rays (reproduced from Figure 16-10 of Healy (1984)

DOSIMETRY

Deposition to Skin (EARLY)

The acute dose (*Sv*) from skin deposition during passage of a plume segment over a fine spatial element (*DS*) is calculated using the following equation:

$$DS = \left(\sum_i DCS_i \cdot \chi_i^G \right) \cdot V_d \cdot Y \cdot F \cdot SFS$$

where

- DCS_i is the acute skin dose coefficient (*Sv-m²/Bq*) from skin deposition for radionuclide *i*, given by $DRCS_i \cdot \int_0^T e^{-\lambda_i t} dt = DRCS_i \cdot \frac{1.0 - e^{-\lambda_i T}}{\lambda_i}$,
- χ_i^G is the time-integrated ground-level air concentration (*Bq-s/m³)* of radionuclide *i* under the plume centerline
- V_d is the deposition velocity to skin (*m/s*), which in MACCS has a fixed value of 0.01 *m/s*,
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element
- *F* is the fraction of exposure duration during the plume passage,
- *SFS* is the skin dose protection factor (dimensionless),
- $DRCS_i$ is the acute skin dose rate coefficient from skin deposition, which in MACCS has a fixed value of 5.4×10^{-14} *Sv-m²/Bq-s*,
- λ_i is the decay constant (s^{-1}) of radionuclide *i*, and
- *T* is the residence time (*s*) of radionuclide material on the skin, which in MACCS has a fixed value of eight hours.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

DOSIMETRY

Indirect Pathways (CHRONC)

Collective exposures are estimated in CHRONC for the following exposure pathways

- Food ingestion
- Water Ingestion
- Doses to decontamination workers

The population dose DF_k (*person-Sv*) from food ingestion to organ *k* resulting from the deposition onto farmland for a spatial element is given by

$$DF_k = \left(\sum_i \left(\sum_{j=n}^{N} DCFI_{ijk} \right) \cdot GC_i \right) \cdot A \cdot FF$$

where

- GC_i is the concentration of radionuclide *i* in a spatial element (*Bq/m*^{2})
- A is the land area of the spatial element,
- FF is the farmland fraction of land area,
- $DCFI_{ijk}$ is the annual population ingestion dose coefficient (*person-Sv-m*$^{-2}$/*Bq-m*$^{-2}$) to organ *k* from exposures in year *j* for radionuclide *i* through all crop pathways and for the specific season at which deposition occur, supplied by the user-specified COMIDA2 file.
- {*n*, ..., *N*} is the set of years *j* that food ingestion occurs, where *n* is the first year after the accident that farming occurs, and *N* is the last year of the ingestion exposure period, as specified by the COMIDA2 parameter LASTACUM.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

PROTECTIVE ACTIONS
Evacuation and Sheltering Region

- Two evacuation options (EVAKEY = "CIRCULAR" or "KEYHOLE")
- Circular evacuation:
  - 360-degree area
  - Evacuation occurs as soon as timeline allows
- Keyhole evacuation:
  - Keyhole-shaped area, with an inner and an outer region
    - Radius of inner region (KEYDIS)
    - Number of sectors in outer region (NSECTR)
  - Evacuation in keyhole area occurs as soon as timeline allows
  - Evacuation expands to remaining area in outer region based on wind-shift weather forecast

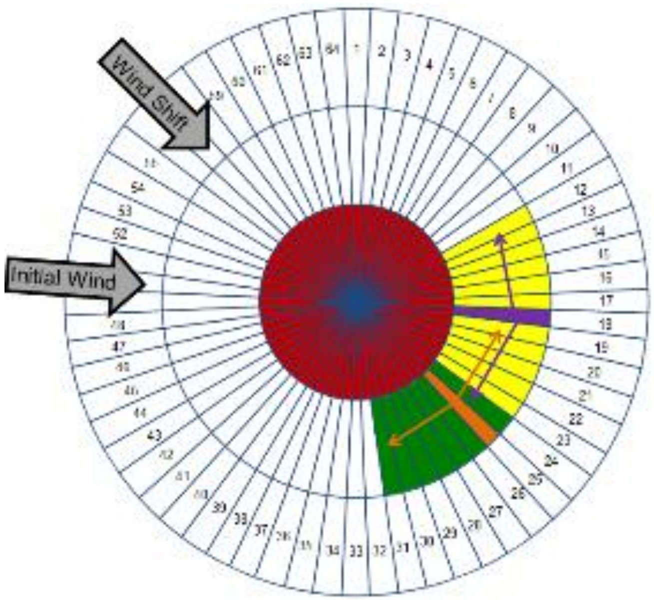


Illustration of a Keyhole Evacuation With a Wind Shift