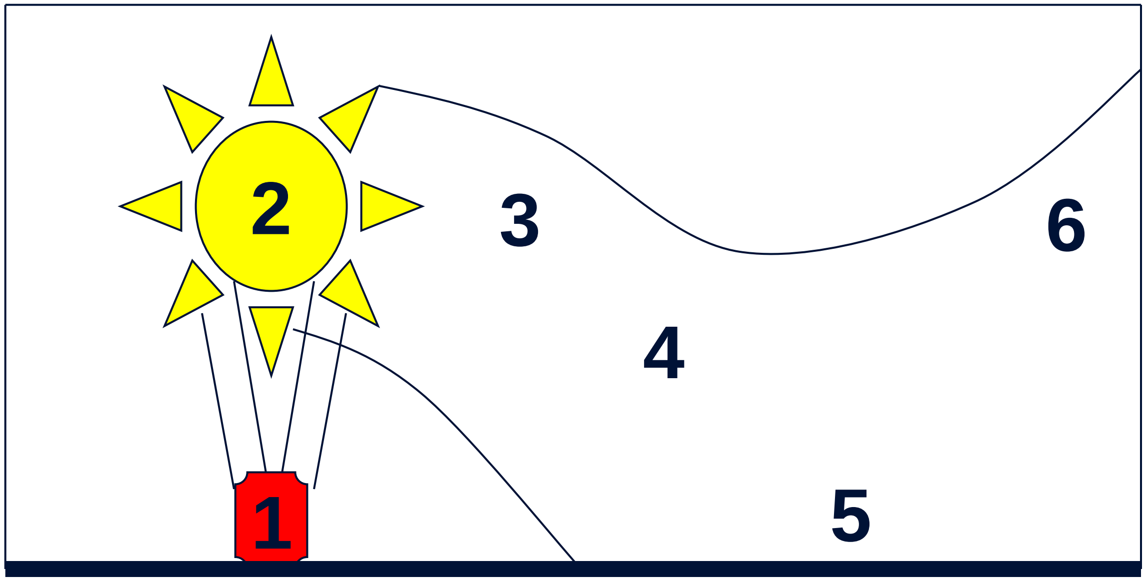
Dispersion Models

Exposure to Release

Predict effects of exposure near the surface.



Stages

1. Source
2. Acceleration, Diffusion
3. Gravity
4. Transition
5. Surface
6. Turbulence

Predict % affected by the exposure.

Fluids Beyond the Sources

- Effluent properties dominate near a leak
- Material then migrates and mixes with air
- Ambient conditions eventually dominate
  - Pressure, temperature, wind velocity, humidity, sun light
- Transport and mixing with air at a vapor cloud boundary
- *Isopleth*: constant concentration boundary of a vapor cloud

Accidental Flow

Safety Levels

Prevention
- Mechanical integrity
- Predictive/preventive maintenances, inspection, testing
- Operator training
- Human factors
- Impact barriers

Control
- Automatic process control systems
- Manual control
- On-line spares
- Backup Systems

Protection
- Alarms
- Operator intervention
- Interlocks, traps
- Emergency shutdown
- Last-resort controls
- Emergency relief
- Ignition source control

Mitigation
- Emergency response
- Sprinkler, deluge
- Dike, trench
- Blast wall, barricade
- Water curtain
- Personal protective equipment

Hazard: Material/energy Contained and controlled during normal operation
- Toxicity
- Flammability
- Reactivity
- Elevated pressure etc.

Cause: Initiating event of process upset; Start of accident event sequence
- Mechanical failure
- Procedural error
- External force
- Fouling etc.

Deviation: Excursion Beyond design/ Operating limits
- No flow
- High temperature
- Low level
- Impurities
- Wrong material
- Step omitted etc.

Accidental Event: Loss of contain-ment of process material/energy
- Fire
- Explosion
- Hazardous material release etc.
- Other energy releases

Impact: Loss of contain-ment of process material/energy
- Illnesses/injuries/ Death
- Property damage
- Business interruption
- Environmental damage etc.

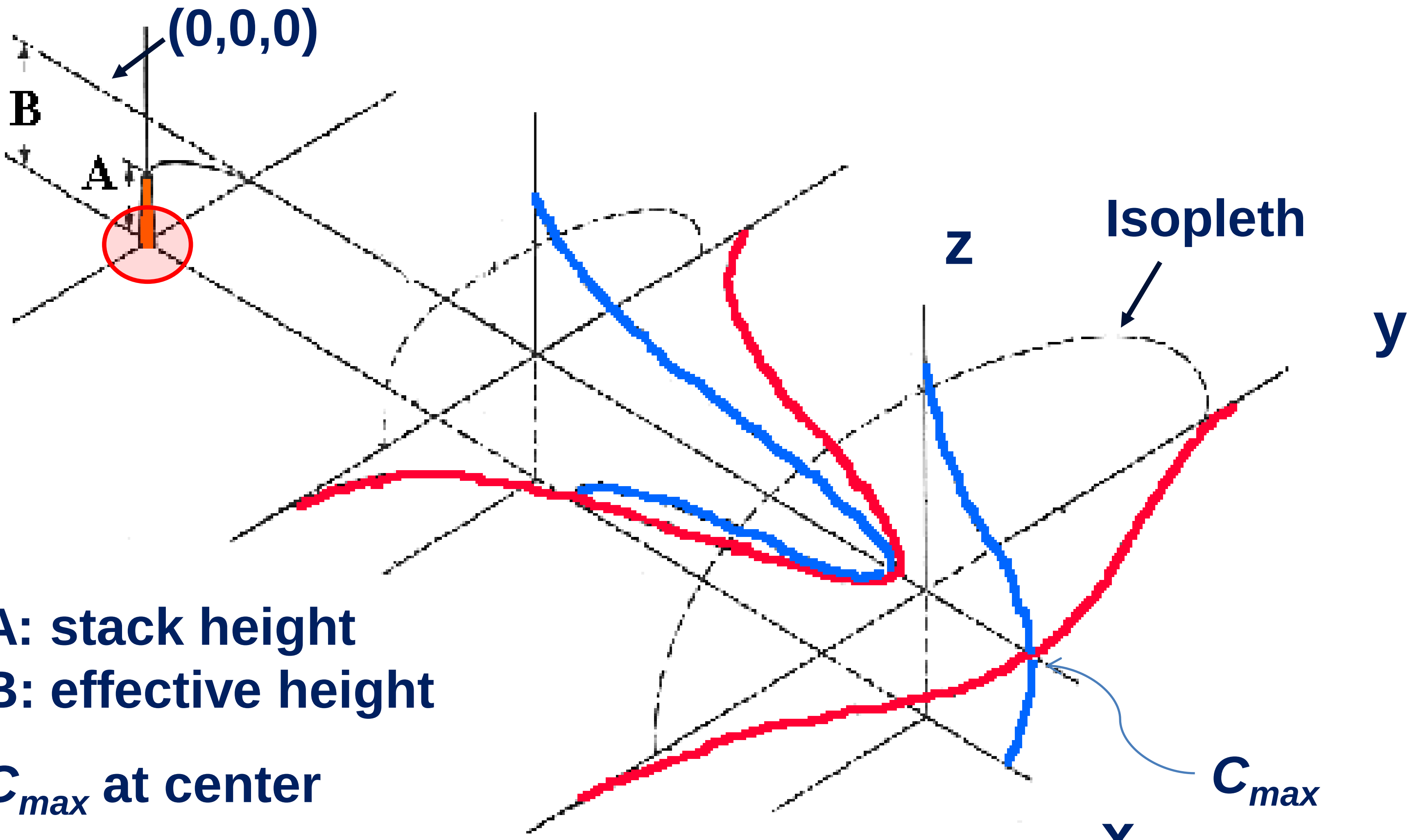
Dispersion Modeling Needed

- Goals: prevent releases; mitigation
- Prevent
  - Inherent safety practices: reduction, substitution, attenuation
  - Process design and integrity
  - PSM management; PHA
- Mitigation measures
  - Emergency response planning

Hazard Levels

- **Concentration**
- **Air velocity and turbulence**
- **Time period of release; *C*(*time*) following release**
- **Position of cloud relative to ground**

Gaussian Dispersion Pattern



A: stack height

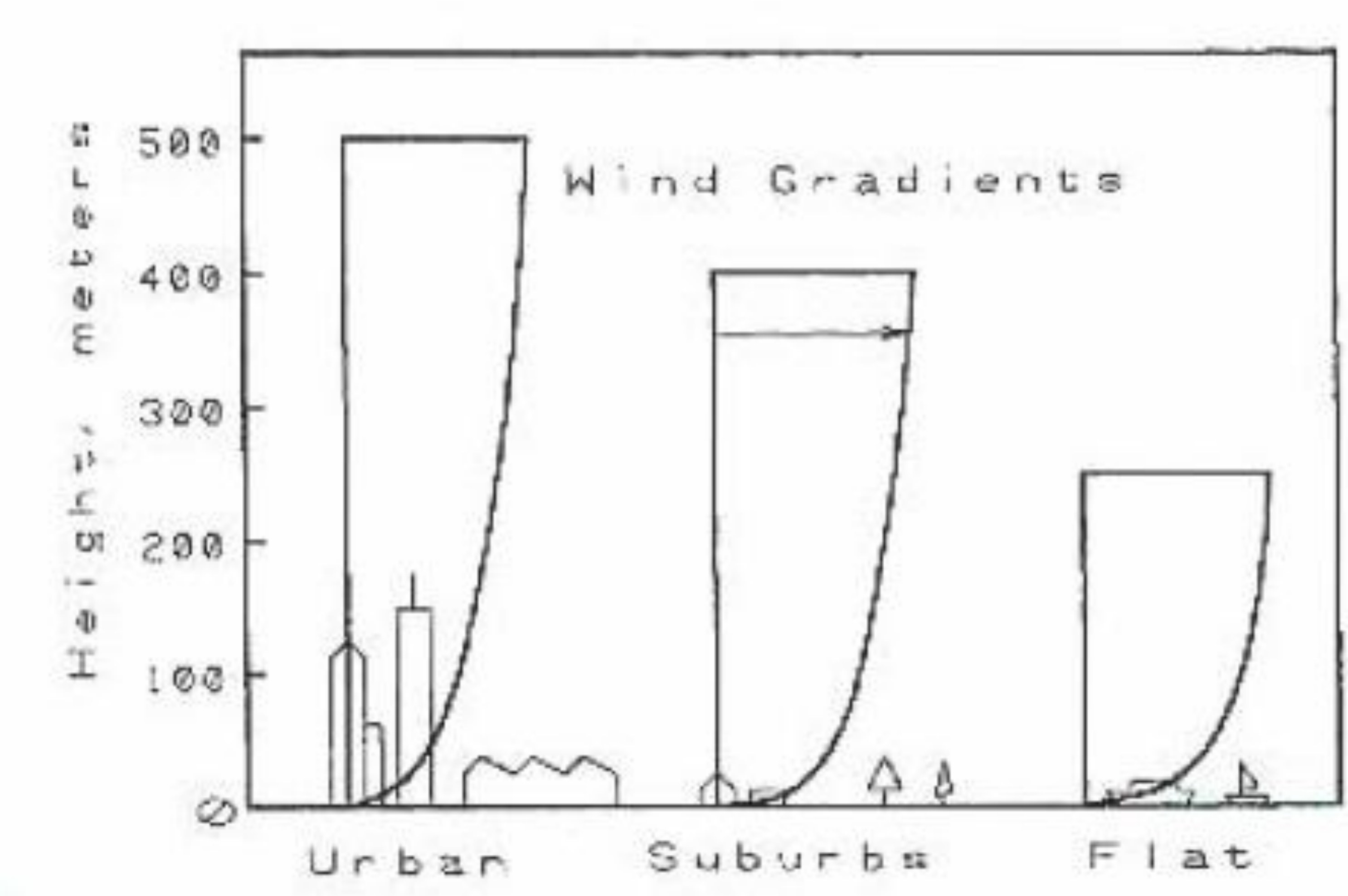
B: effective height

C_{max} at center

Along X $\bar{u}$

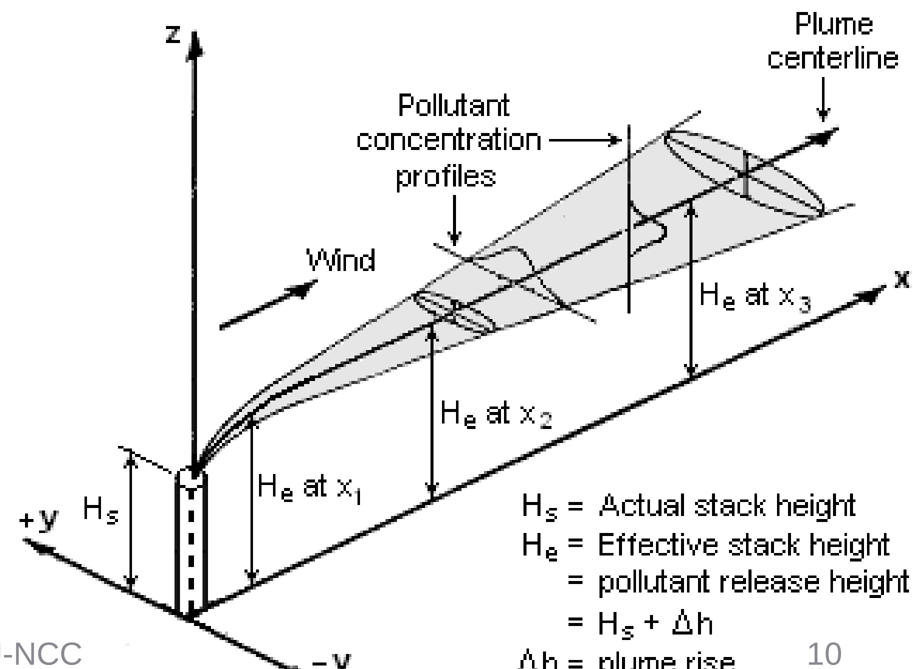
Dispersion Parameters

- **Cloud of effluents expands, mixes with air**
- **Mixing dilutes the effluent: *C* decreases**
- **Lower downwind *C* ⇒ *greater area* affected**
- **Dominant dispersion mechanism: turbulent dispersion ⇒ horizontal and vertical movement**
- **Mixing rate depends on *u*, atmosphere stability, buoyancy**
- **Light winds, strong sun ⇒ most unstable: rapid diffusion**


Wind Gradients
Height, meters
500
400
300
200
100
Ø
Urban
Suburbs
Flat

Plume & Puff


l o s c i l
p l u m e


z
Plume centerline
Pollutant concentration profiles
Wind
x
H_e at x_3
H_e at x_2
H_e at x_1
H_s
+y
−y
H_s = Actual stack height
H_e = Effective stack height
= pollutant release height
= $H_s + \Delta h$
Δh = plume rise

Plume Model

- Steady state concentration from a continuous source, e.g. smokestack
- Initially increases in size, additions from source
- Steady state: same amount of effluent added to plume as is mixed with air; constant volume
- Source stopped: plume size decreases as mixing with air is dominant, plume returns to source origin, finally disappears.

Puff Model

- **Cloud formed from a fixed amount of effluent, e.g., from a ruptured vessel**
- **Release over a short period of time that source is active**
- **Movement from source: dependent on air velocity**
- **Material mixes with air, boundary diminished in size, finally disappears**

$$\frac{\partial\langle C\rangle}{\partial t}+\langle u_j\rangle\frac{\partial\langle C\rangle}{\partial x_j}=\frac{\partial}{\partial x_j}\left(K_j\frac{\partial\langle C\rangle}{\partial x_j}\right)$$

P. 179, 5-9

Plumes ← *Plume* — **Plume Of Puff** — *Puff* → **Puffs**

$1.\ SS, <u_j>=0, K_j=K^*$

$$\langle C\rangle(r)=\frac{Q_m}{4\pi K^* r}$$

$3.\ NSS, <u_j>=0, K_j=K^*$

$$\langle C(r,t)\rangle=\frac{Q_m}{4\pi K^* r}\,erfc\left(\frac{r}{2\sqrt{K^* t}}\right)$$

$4.\ SS, <u_j>=<u_x>=u, K_j=K^*$

$$\langle C(r)\rangle=\frac{Q_m}{4\pi K^* r}\exp\left(-\frac{u(r-x)}{2K^*}\right)$$

$6.\ SS, <u_j>=<u_x>=u, K_x, K_y, K_z$

$9.\ SS, <u_j>=<u_x>=u, K_x, K_y, K_z\ Source$

$9.\ SS, <u_j>=<u_x>=u, K_x, K_y, K_z\ H\ Source$

$$\frac{\partial \langle C \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle C \rangle}{\partial x_j} = \frac{\partial}{\partial x_j}\left(K_j \frac{\partial \langle C \rangle}{\partial x_j} \right)$$

P. 179, 5-9

Plumes ← *Plume* — **Plume Of Puff** — *Puff* → Puffs

$$\langle C(r,t) \rangle = \frac{Q_m}{8(\pi K^* t)^{3/2}} \exp\left(-\frac{r^2}{4K^* t} \right)$$

$$2.\ <u_j> = 0, K_j = K^*$$

$$5.\ <u_j> = 0, K_x, K_y, K_z$$

$$7.\ <u_j> = <u_x> = u, K_x, K_y, K_z$$

$$8.\ <u_j> = 0, K_x, K_y, K_z\ \ Source$$

Neutrally Buoyant Dispersion

- **No reactions; small effect of molecular diffusion**
- **Mixing mechanism: air turbulence**
- **Turbulence $\Rightarrow$ fluctuations in *C*, *u***

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x_j}(u_j C)=0$$

***u_j*, air velocity**

C, concentration

$$u_j=\langle u_j\rangle+u_j' \quad \rightarrow \quad C=\langle C\rangle+C'$$

u_j', C' **, fluctuation components**

Eddy Diffusivity, K_j

Represent *C* fluctuation due to turbulence

$$\langle u'_j \rangle = 0; \ \langle C'_j \rangle = 0$$

$$\langle u'_j C' \rangle = -K_j \frac{\partial \langle C \rangle}{\partial x_j}$$

Governing equation:

$$\frac{\partial \langle C \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle C \rangle}{\partial x_j} = \frac{\partial}{\partial x_j}\left(K_j \frac{\partial \langle C \rangle}{\partial x_j} \right)$$

1. Steady State, Point Release, No Wind

- **Q_m constant; C independant of t, wind, u ~ 0**
- **Constant $K_j = K^*$ in all directions**

$$\frac{\partial^2 \langle C \rangle}{\partial x^2} + \frac{\partial^2 \langle C \rangle}{\partial y^2} + \frac{\partial^2 \langle C \rangle}{\partial z^2} = 0$$

Polar coordinates, integrate over r :

$$\langle C \rangle(r) = \frac{Q_m}{4\pi K^* r}$$

Q_m, source term

$$r = \sqrt{x^2 + y^2 + z^2}$$

2. Puff Release, No Wind

- **Wind velocity, *u* ~ 0**
- **Constant $K_j = K^*$ in all directions**

$$\frac{1}{K^*}\frac{\partial\langle C\rangle}{\partial t} = \frac{\partial^2\langle C\rangle}{\partial x^2} + \frac{\partial^2\langle C\rangle}{\partial y^2} + \frac{\partial^2\langle C\rangle}{\partial z^2}$$

Instantaneous concentration:

$$\langle C(r,t)\rangle = \frac{Q_m}{8(\pi K^* t)^{3/2}} \exp\left(-\frac{r^2}{4K^* t}\right)$$

3. Non SS Point Release, No Wind

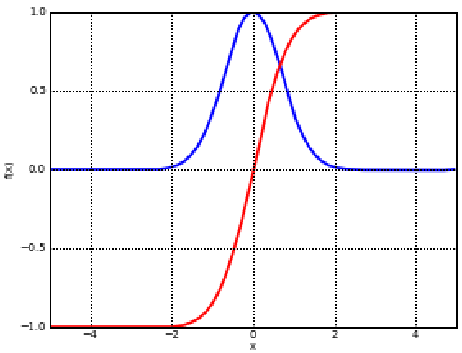
- Q_m constant; wind, $u \sim 0$
- Constant $K_j = K^*$ in all directions

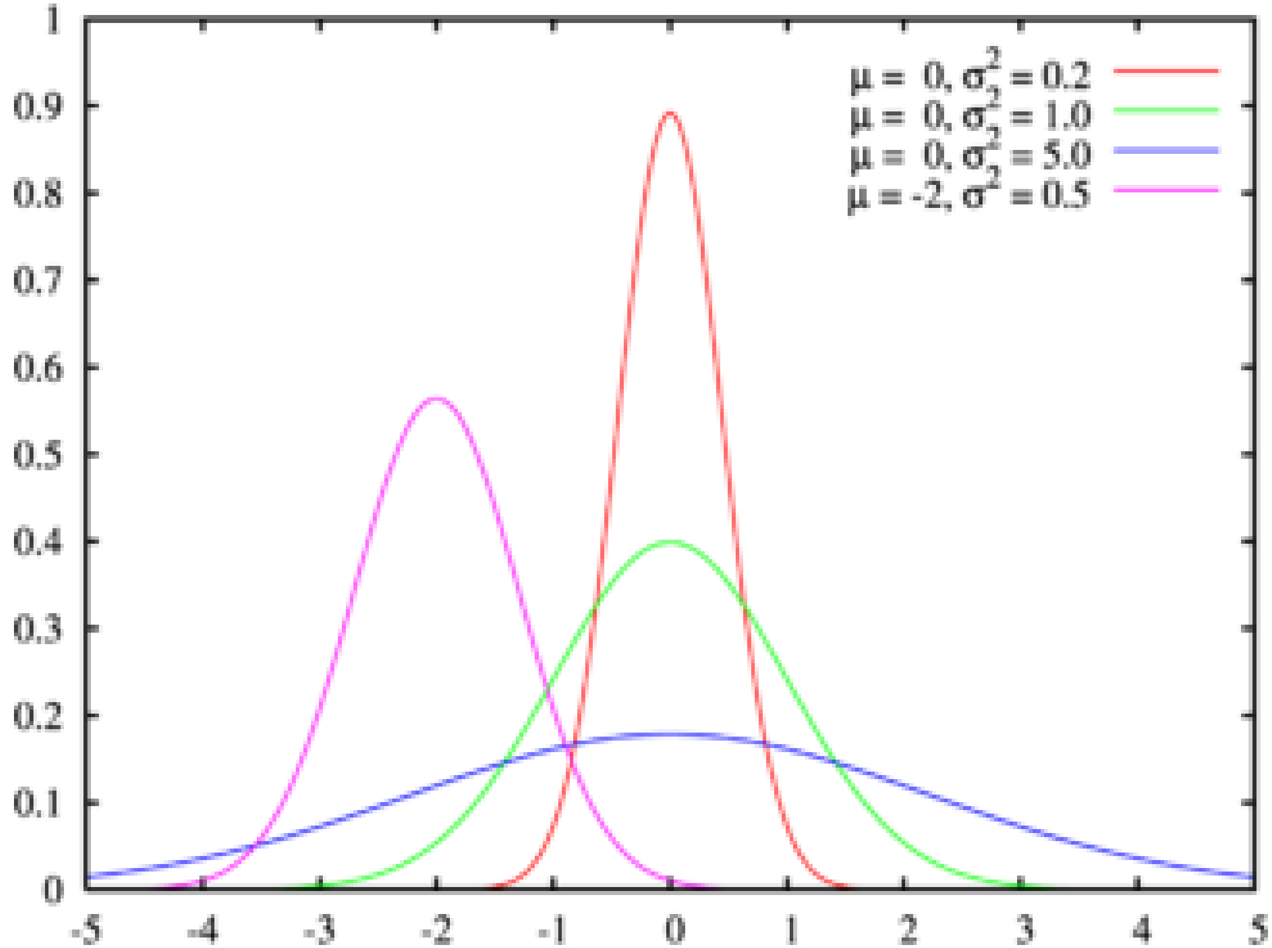
$$\frac{1}{K^*}\frac{\partial\langle C\rangle}{\partial t} = \frac{\partial^2\langle C\rangle}{\partial x^2} + \frac{\partial^2\langle C\rangle}{\partial y^2} + \frac{\partial^2\langle C\rangle}{\partial z^2}$$

Integrate instantaneous concentration:

$$\langle C(r,t)\rangle = \frac{Q_m}{4\pi K^* r}\, erfc\left(\frac{r}{2\sqrt{K^* t}}\right)$$

Error function & its Integration





4. SS Point Source with Wind

- Q_m constant; *C* independent of *t*
- Wind in *x* direction, u_x constant
- Constant $K_j = K^*$ in all directions

$$\frac{u}{K^*}\frac{\partial\langle C\rangle}{\partial x} = \frac{\partial^2\langle C\rangle}{\partial x^2} + \frac{\partial^2\langle C\rangle}{\partial y^2} + \frac{\partial^2\langle C\rangle}{\partial z^2}$$

$$\langle C(r)\rangle = \frac{Q_m}{4\pi K^* r}\exp\left(-\frac{u(r-x)}{2K^*}\right)$$

Centerline for $y^2 + z^2 << x^2$: $\langle C(x)\rangle = \dfrac{Q_m}{4\pi K^* x}$

5. Puff with No Wind, K_j Varies

- **Q^*_m constant; Puff release**
- **No wind($\langle u_j \rangle = 0$)**
- **$K_j \neq K^*$, but constant in all directions**

$$\frac{\partial \langle C \rangle}{\partial t} = K_x \frac{\partial^2 \langle C \rangle}{\partial x^2} + K_y \frac{\partial^2 \langle C \rangle}{\partial y^2} + K_z \frac{\partial^2 \langle C \rangle}{\partial z^2}$$

$$\langle C \rangle (x,y,z,t) = \frac{Q_m^*}{8(\pi t)^{3/2}\sqrt{K_x K_y K_z}} \exp\left[-\frac{1}{4t}\left(\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z} \right) \right]$$

6. SS Point Source with Wind, K_j Varies

- Q_m constant; *C* independent of *t*
- Wind in *x* direction, u_x constant
- $K_j \neq K^*$, but constant in all directions

$$u\frac{\partial\langle C\rangle}{\partial x} = K_x\frac{\partial^2\langle C\rangle}{\partial x^2} + K_y\frac{\partial^2\langle C\rangle}{\partial y^2} + K_z\frac{\partial^2\langle C\rangle}{\partial z^2}$$

$$\langle C\rangle(x,y,z) = \frac{Q_m^*}{4\pi x\sqrt{K_x K_y}}\exp\left[-\frac{u}{4x}\left(\frac{y^2}{K_y}+\frac{z^2}{K_z}\right)\right]$$

Centerline for y = z = 0 :

$$\langle C(x)\rangle = \frac{Q_m}{4\pi x\sqrt{K_y K_z}}$$

7. Puff with Wind

- ***Q^*_m* constant; Puff release**
- **Wind in x direction only($\langle u_j \rangle = \langle u_x \rangle = u = \text{constant}$)**
- ***$K_j \neq K^*$*, but constant in all directions**

$$\frac{\partial \langle C \rangle}{\partial t} = K_x \frac{\partial^2 \langle C \rangle}{\partial (x - ut)^2} + K_y \frac{\partial^2 \langle C \rangle}{\partial y^2} + K_z \frac{\partial^2 \langle C \rangle}{\partial z^2}$$

$$\langle C \rangle (x, y, z, t) = \frac{Q_m^*}{8(\pi t)^{3/2} \sqrt{K_x K_y K_z}} \exp\left[-\frac{1}{4t} \left(\frac{(x - ut)^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z} \right) \right]$$

8. Puff with No Wind, Source on Ground

- **Q^*_m constant; Puff release**
- **No wind(<u_j> =0)**
- **$K_j \neq K^*$, but constant in all directions**

$$\frac{\partial \langle C \rangle}{\partial t} = K_x \frac{\partial^2 \langle C \rangle}{\partial x^2} + K_y \frac{\partial^2 \langle C \rangle}{\partial y^2} + K_z \frac{\partial^2 \langle C \rangle}{\partial z^2}$$

$$\langle C \rangle (x,y,z,t) = \frac{Q_m^*}{4(\pi t)^{3/2}\sqrt{K_x K_y K_z}} \exp\left[-\frac{1}{4t}\left(\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z} \right) \right]$$

Impervious boundary (the factor 4)

9. SS Point Source with Source on Ground

- Q_m constant; C independent of t
- Wind in x direction, u_x constant
- $K_j \neq K^*$, but constant in all directions

$$u\frac{\partial\langle C\rangle}{\partial x} = K_x\frac{\partial^2\langle C\rangle}{\partial x^2} + K_y\frac{\partial^2\langle C\rangle}{\partial y^2} + K_z\frac{\partial^2\langle C\rangle}{\partial z^2}$$

$$\langle C\rangle(x,y,z) = \frac{Q_m^*}{2\pi x\sqrt{K_x K_y}}\exp\left[-\frac{u}{4x}\left(\frac{y^2}{K_y}+\frac{z^2}{K_z}\right)\right]$$

Impervious boundary

10. SS Point Source with Source at Height H_r above the Ground

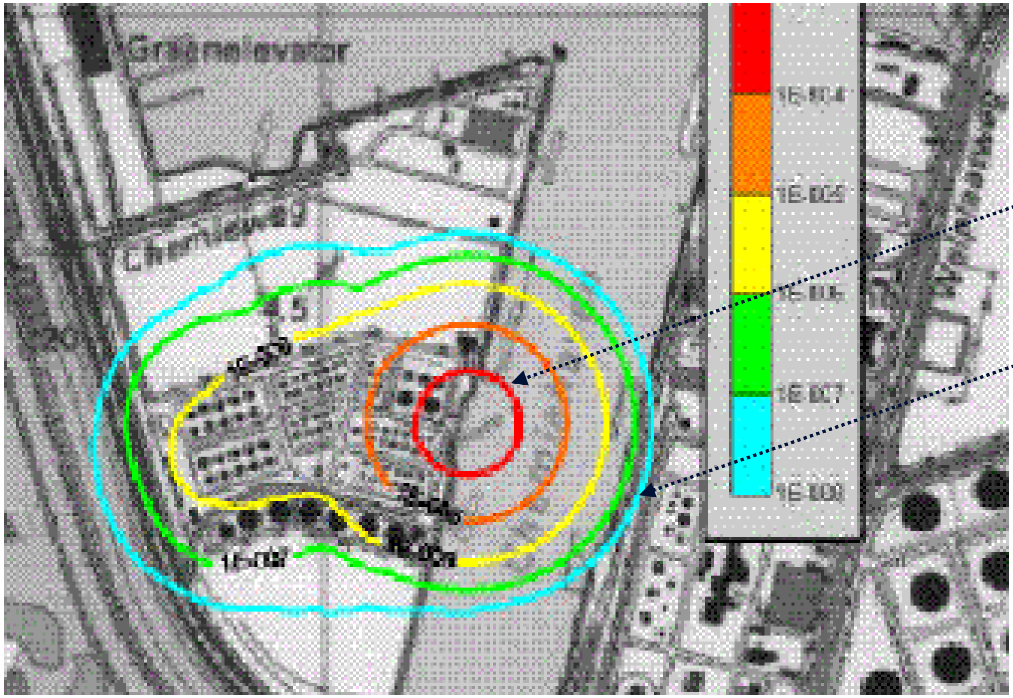
- Q_m constant; *C* independent of *t*
- Wind in *x* direction, u_x constant
- $K_j \neq K^*$, but constant in all directions

$$u\frac{\partial\langle C\rangle}{\partial x} = K_x\frac{\partial^2\langle C\rangle}{\partial x^2} + K_y\frac{\partial^2\langle C\rangle}{\partial y^2} + K_z\frac{\partial^2\langle C\rangle}{\partial z^2}$$

$$\langle C\rangle(x,y,z) = \frac{Q_m^*}{4\pi x\sqrt{K_x K_y}}\exp\left(-\frac{uy^2}{4K_y x}\right)$$

$$\times\left\{\exp\left[-\frac{u}{4K_z x}(z-H_r)^2\right] + \exp\left[-\frac{u}{4K_z x}(z+H_r)^2\right]\right\}$$

Consequence Analysis (Ex)

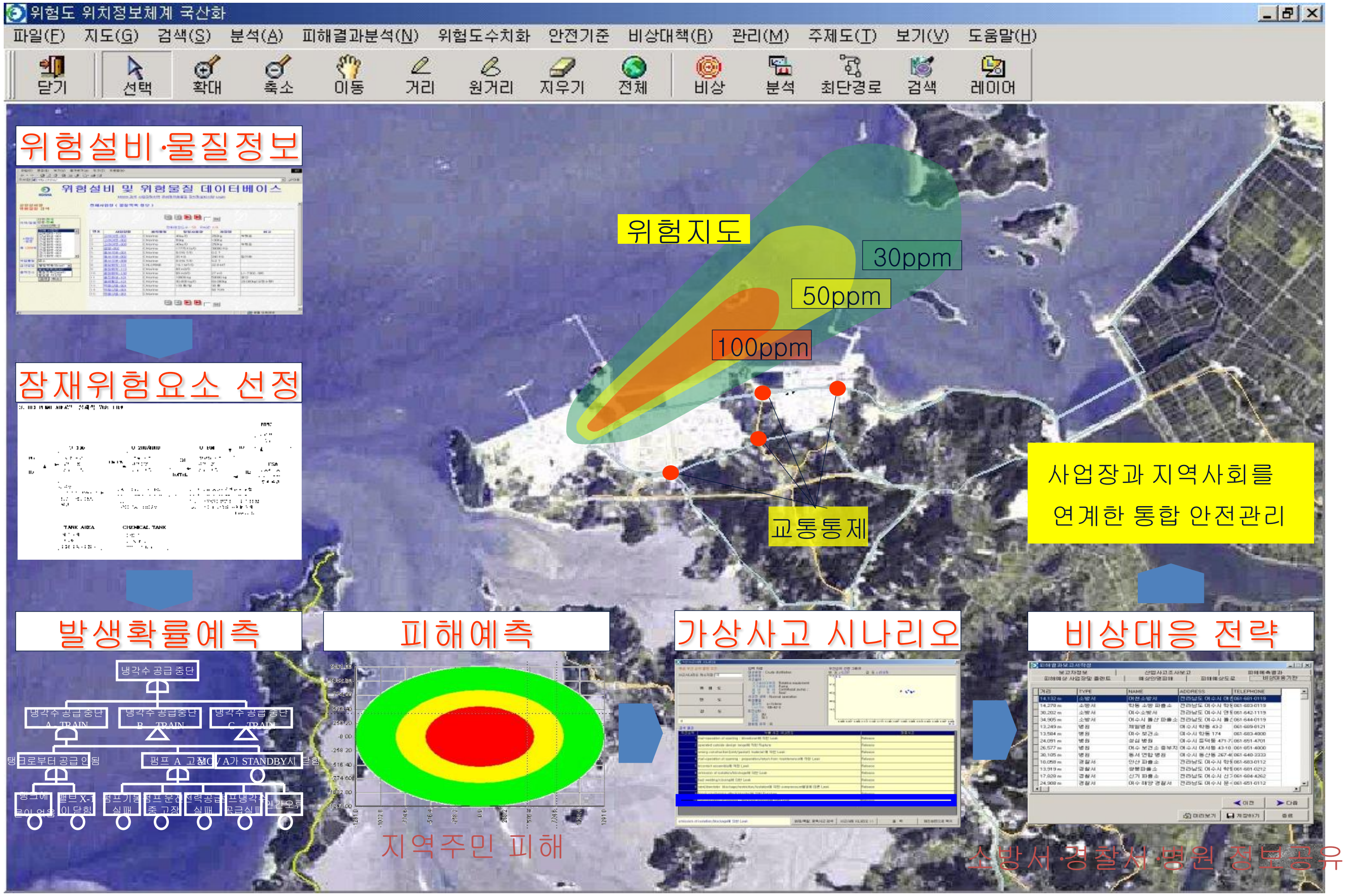


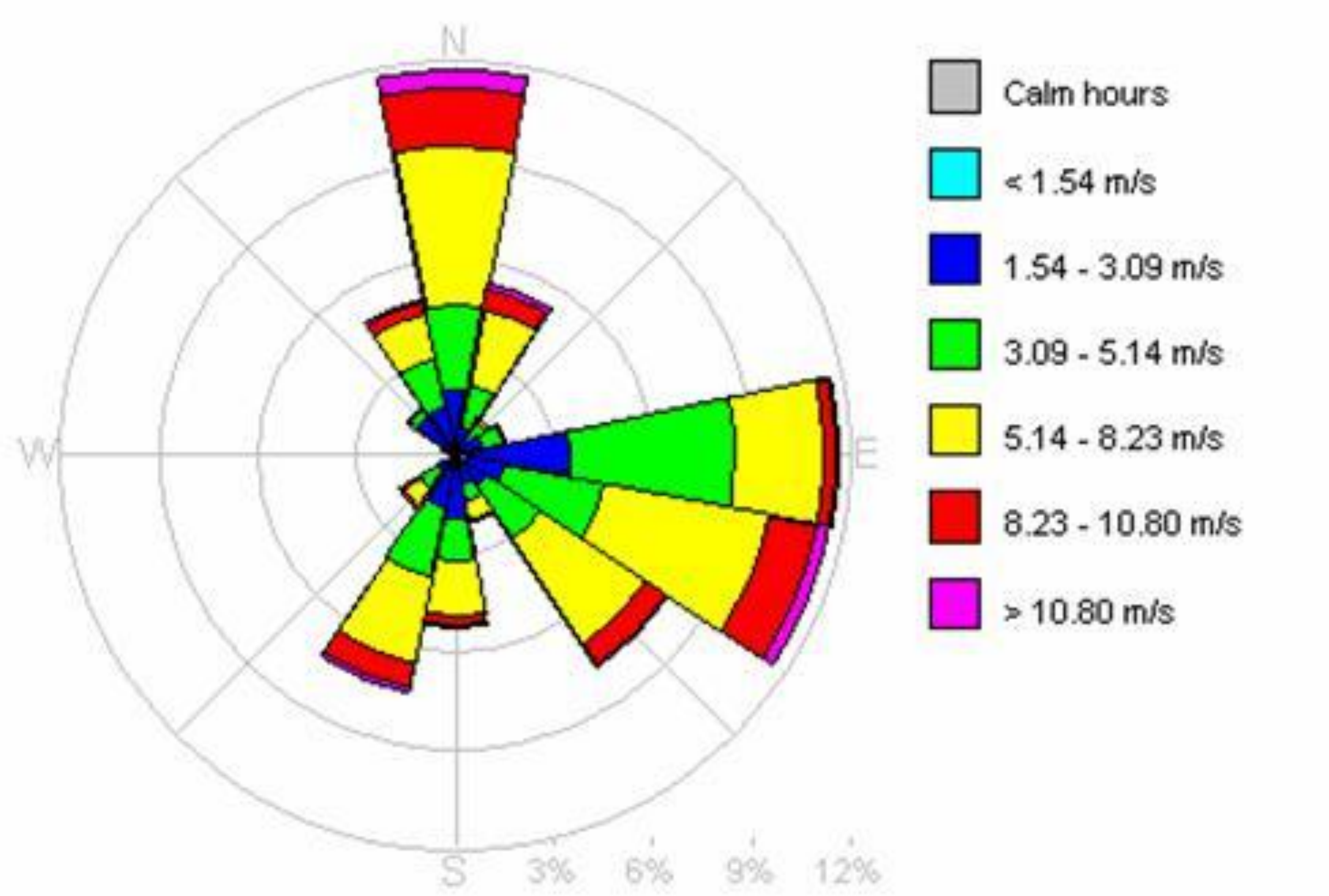
1×10^{-4}/yr

1×10^{-8}/yr

Risk contour

Consequence Analysis (Ex)




N
W
E
S
3%
6%
9%
12%
Calm hours
< 1.54 m/s
1.54 - 3.09 m/s
3.09 - 5.14 m/s
5.14 - 8.23 m/s
8.23 - 10.80 m/s
> 10.80 m/s

Pasquill-Gifford Model

- K_j values difficult to measure
- Define: *dispersion coefficient* ~ st dev for *C*

$$\sigma_i^2 = \frac{1}{2}\langle C\rangle^2 (ut)^{2-n}$$ ***i* = *x*, *y*, *z*; *n*, parameter**

σ_j: functions of downwind distance, *x*, and atmospheric conditions in stability classes, *A - F*, based on sunlight and wind speed. Tab 5-1, p. 187

σ_j values for rural or urban plumes, or puffs from Figs 5-10 - 5-12 or Tabs 5-1 - 5-3, pp., 187-189

Table 5-1 Atmospheric Stability Classes for Use with the Pasquill-Gifford Dispersion Model[1,2]

Surface wind speed (m/s)	Daytime insolation[3]			Nighttime conditions[4]	
	Strong	Moderate	Slight	Thin overcast or >4/8 low cloud	≤3/8 cloudiness
<2	A	A–B	B	F[5]	F[5]
2–3	A–B	B	C	E	F
3–4	B	B–C	C	D[6]	E
4–6	C	C–D	D[6]	D[6]	D[6]
>6	C	D[6]	D[6]	D[6]	D[6]

A: Extremely unstable
B: Moderately unstable
C: Slightly unstable

D: Neutrally stable
E: Slightly stable
C: Moderately stable

Table 5-2 Recommended Equations for Pasquill-Gifford Dispersion Coefficients for Plume Dispersion[1,2] (the downwind distance *x* has units of meters)

Pasquill-Gifford stability class	σ_y (m)	σ_z (m)
Rural conditions		
A	$0.22x(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-1/2}$	$0.08x(1 + 0.0002x)^{-1/2}$
D	$0.08x(1 + 0.0001x)^{-1/2}$	$0.06x(1 + 0.0015x)^{-1/2}$
E	$0.06x(1 + 0.0001x)^{-1/2}$	$0.03x(1 + 0.0003x)^{1}$
F	$0.04x(1 + 0.0001x)^{-1/2}$	$0.016x(1 + 0.0003x)^{-1}$
Urban conditions		
A–B	$0.32x(1 + 0.0004x)^{-1/2}$	$0.24x(1 + 0.0001x)^{+1/2}$
D	$0.22x(1 + 0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1 + 0.0004x)^{-1/2}$	$0.14x(1 + 0.0003x)^{-1/2}$
E–F	$0.11x(1 + 0.0004x)^{-1/2}$	$0.08x(1 + 0.0015x)^{-1/2}$

Table 5-3 Recommended Equations for Pasquill-Gifford Dispersion Coefficients for Puff Dispersion[1,2] (the downwind distance x has units of meters)

Pasquill-Gifford stability class	σ_y (m) or σ_x (m)	σ_z (m)
A	$0.18x^{0.92}$	$0.60x^{0.75}$
B	$0.14x^{0.92}$	$0.53x^{0.73}$
C	$0.10x^{0.92}$	$0.34x^{0.71}$
D	$0.06x^{0.92}$	$0.15x^{0.70}$
E	$0.04x^{0.92}$	$0.10x^{0.65}$
F	$0.02x^{0.89}$	$0.05x^{0.61}$

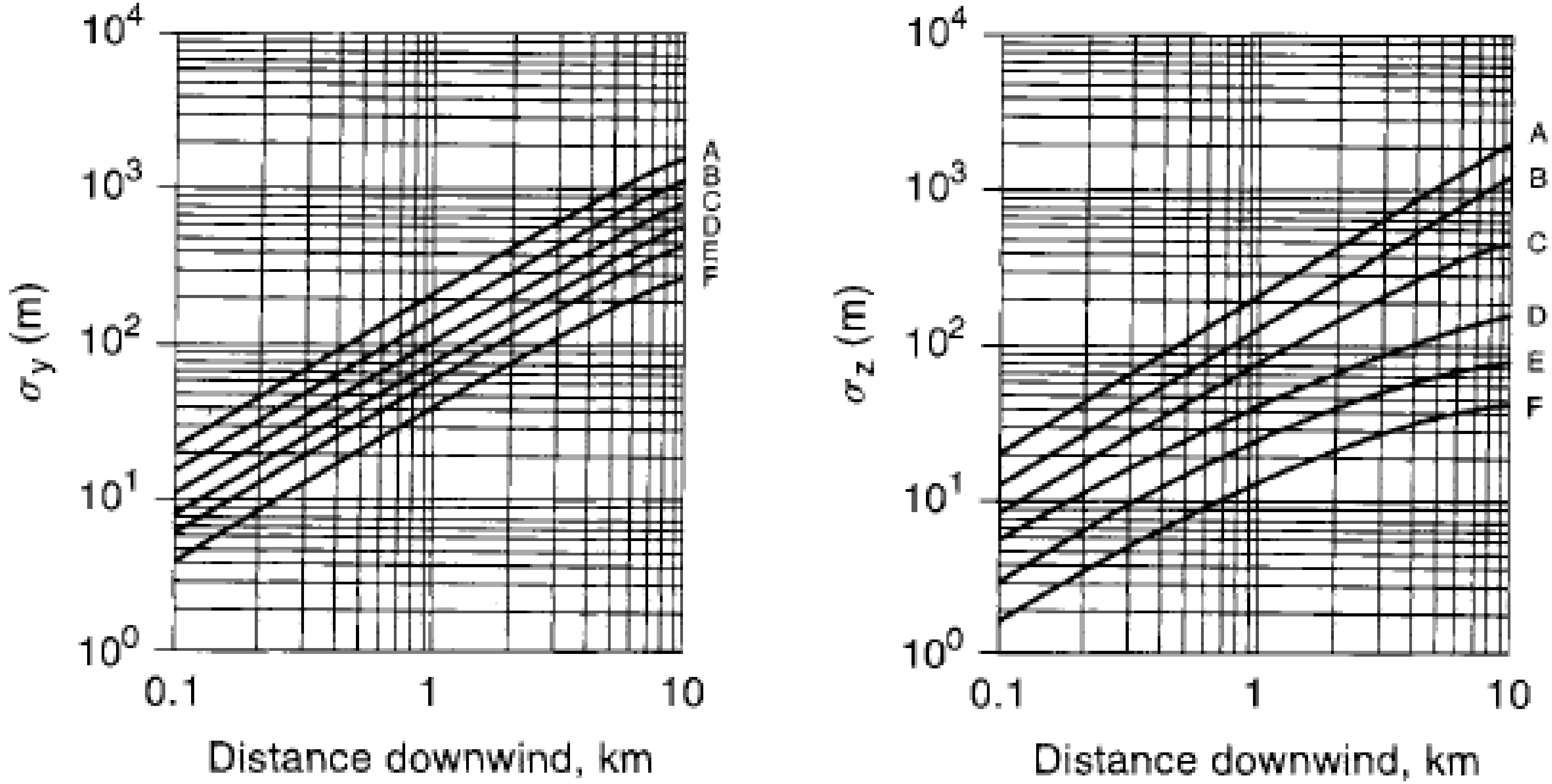


Figure 5-10 Dispersion coefficients for Pasquill-Gifford plume model for rural releases.

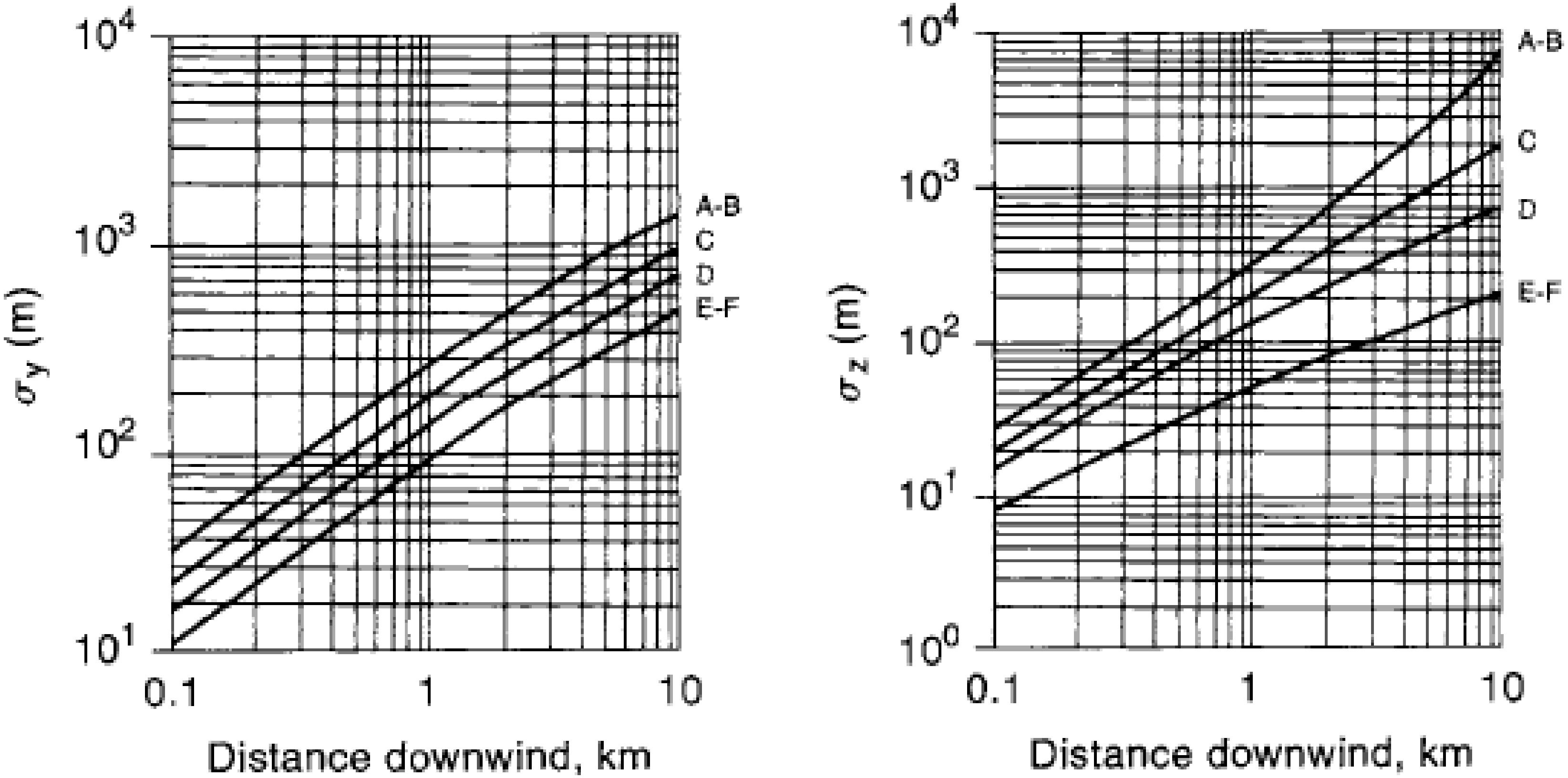


Figure 5-11 Dispersion coefficients for Pasquill-Gifford plume model for urban releases.

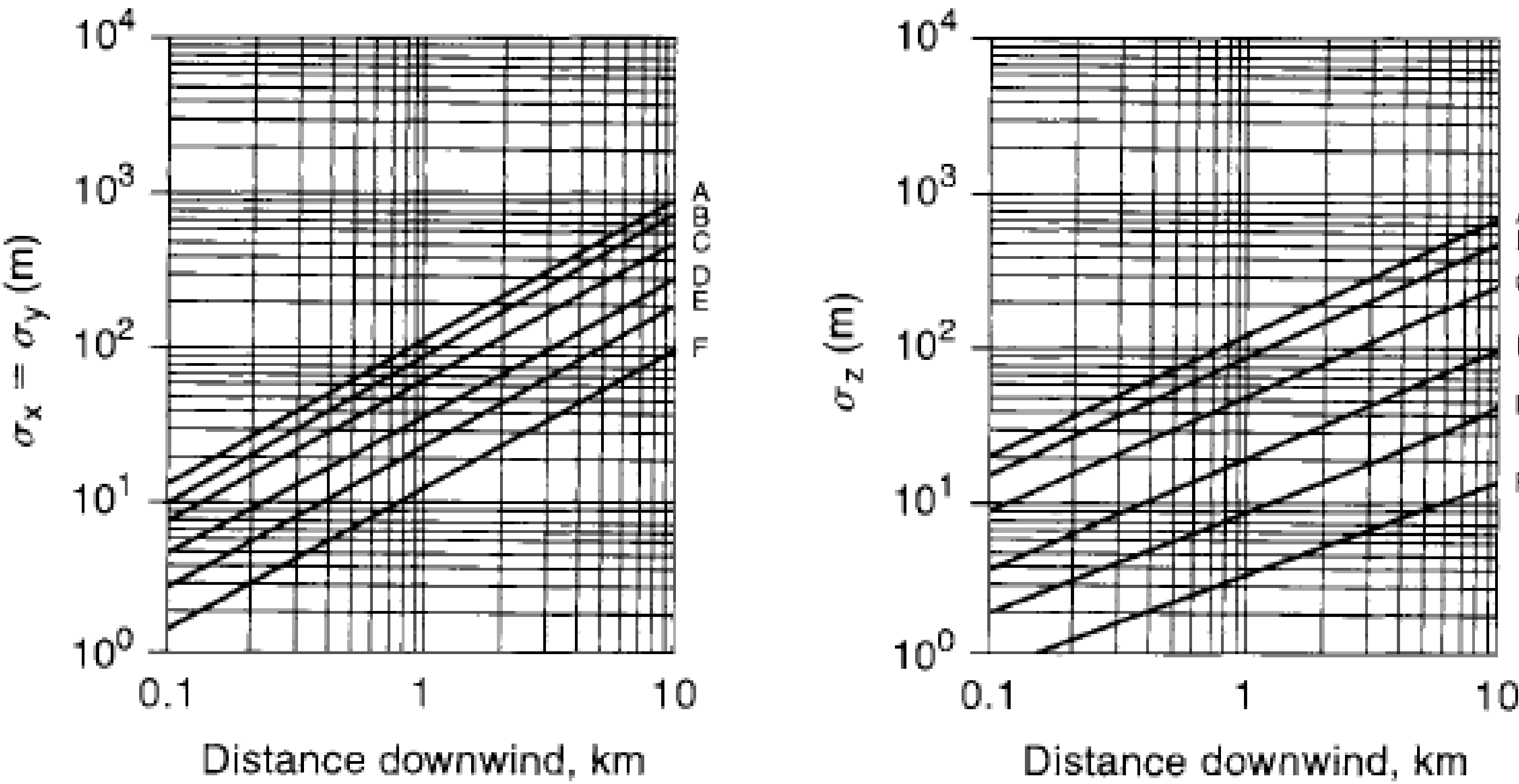
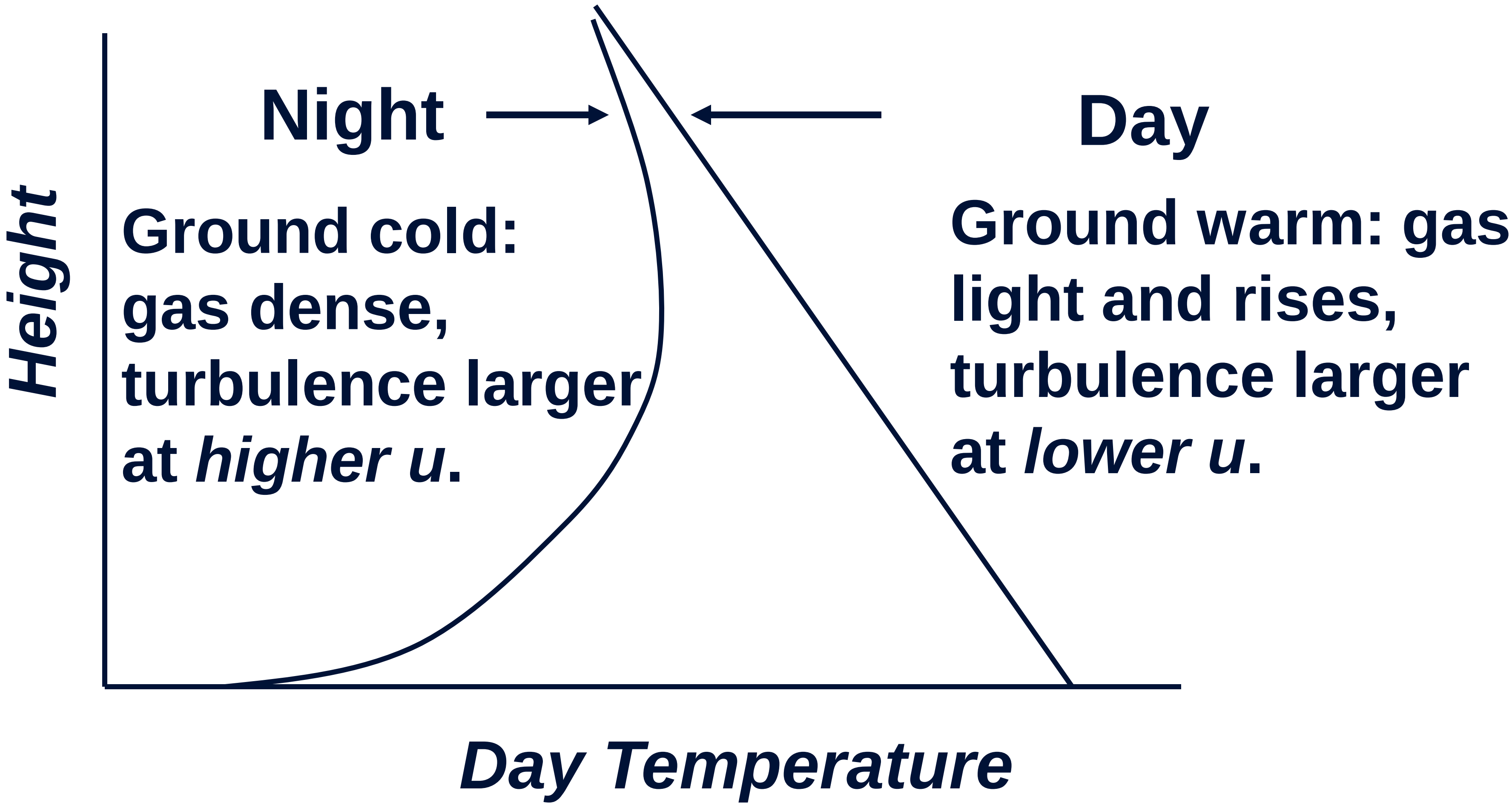


Figure 5-12 Dispersion coefficients for Pasquill-Gifford puff model.

Atmospheric Stability Classes



Stability classes classify level of turbulance:
A, least stable; F, most stable (Tab. 5-1, p. 187)

11. Puff, Ground Source, *u* Constant

$$\langle C(x,y,z,t)\rangle = \frac{Q_m^*}{\sqrt{2}\pi^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left[\left(\frac{x-ut}{\sigma_x}\right)+\frac{y^2}{\sigma_y}+\frac{z^2}{\sigma_z}\right]\right\}$$

Ground concentration: *z* = 0

Ground concentration along *x: y* = *z* = 0

Center of moving puff, *x* = *ut*:

$$\langle C(ut,0,0,t)\rangle = \frac{Q_m^*}{\sqrt{2}\pi^{3/2}\sigma_x\sigma_y\sigma_z}$$

Total Dose

$$D_{tid}(x,y,z)=\int_0^{\infty}\langle C\rangle(x,y,z,t)dt$$

Puff, ground source, constant *u*:

Ground level: $$D_{tid}(x,y,0)=\frac{Q_m^*}{\pi\sigma_y\sigma_z u}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)$$

Along *x* : $$D_{tid}(x,0,0)=\frac{Q_m^*}{\pi\sigma_y\sigma_z u}$$

12. Plume, Ground Source, *u* Constant

$$\langle C(x,y,z)\rangle = \frac{Q_m}{\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y}+\frac{z^2}{\sigma_z}\right)\right]$$

Ground C(x,y,0) : *z* = 0

Ground, C(x,0,0) along *x: y* = *z* = 0

Isopleth concentration, *C :**

$$y = \pm\sigma_y\sqrt{2\ln\left(\frac{\langle C(x,0,0,t)\rangle}{\langle C(x,y,0,t)\rangle}\right)} = \pm\sigma_y\sqrt{2\ln\left(\frac{\langle C(x,0,0,t)\rangle}{\langle C^*\rangle}\right)}$$

13. Plume, Source at H_r, *u* Constant

Ground concentration:

$$\langle C(x,y,0)\rangle = \frac{Q_m}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 - \frac{1}{2}\left(\frac{H_r}{\sigma_z}\right)^2\right]$$

Centerline:

$$\langle C(x,0,0)\rangle = \frac{Q_m}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{H_r}{\sigma_z}\right)^2\right]$$

Max ground *C* along x:

$$\langle C(x,0,0)\rangle_{\max} = \frac{2Q_m}{e\pi u H_r^2}\left(\frac{\sigma_z}{\sigma_y}\right)$$

Distance downwind for C_{max} : $\sigma_z = \frac{H_r}{\sqrt{2}}$ ⟶ **Find x**

Model Implementation

- **Plume C_{max}: release position**
- **Puff C_{max}: center of cloud**
- **If atmosphere conditions not known, assume worst case for highest *C*.**
- **If wind speed not known, assume 2 m/s**
- **Consider P-G model assumptions: neutral buoyancy, turbulent mixing, time concentrations (10 min), 0.1 - 10 km distances**

Britter-McQuaid Dense Gas Model

- **Ground level releases; rural, flat terrain**
- **Atmospheric stability effects not included**
- **Mixing from drop by gravity of effluent into air**
- **Main parameters: initial buoyancy, g_o, initial volume flux, q_o, or total initial volume, V_o, wind speed at 10 m elevation, u**

$$g_o = g(\rho_o - \rho_a) / \rho_a$$

ρ_a **= density of ambient air**

Applicability of B-M Model

Plume	Puff	Information
$\left(\dfrac{g_o q_o}{u^3 D_c}\right)^{1/3} \geq 0.15$	$\dfrac{\sqrt{g_o V_o}}{u D_i} \geq 0.20$	**buoyancy*amnt/*u***
$D_c = \left(\dfrac{q_o}{u}\right)^{1/2}$	$D_i = V_o^{1/3}$	**source dimension**
$\dfrac{u R_d}{x} \geq 2.5$	$\dfrac{u R_d}{x} \leq 0.6$	**R_d, release duration**

If model criteria satisfied, use Figs 5-13, 5-14 or Tabs 5-4, 5-5 to est. *C* or downwind distance, *x*

Implementation of B-M Model

- C_o = 1 for pure material initially released
- C_m / C_o : ratio of material conc in air to pure

$$q_o = q_L \frac{\rho_L}{\rho_V}$$

q_L : liquid volumetric discharge rate

$V_o = q_o R_d$: initial volume, Puff

Adjust conc for density at T_a :

$$C_e = \frac{C^*}{C^* + (1 - C^*)(T_a / T_o)}$$

C_e : effective conc
C^* : unadjusted conc
T_o : T at release, K
T_a : T ambient, K

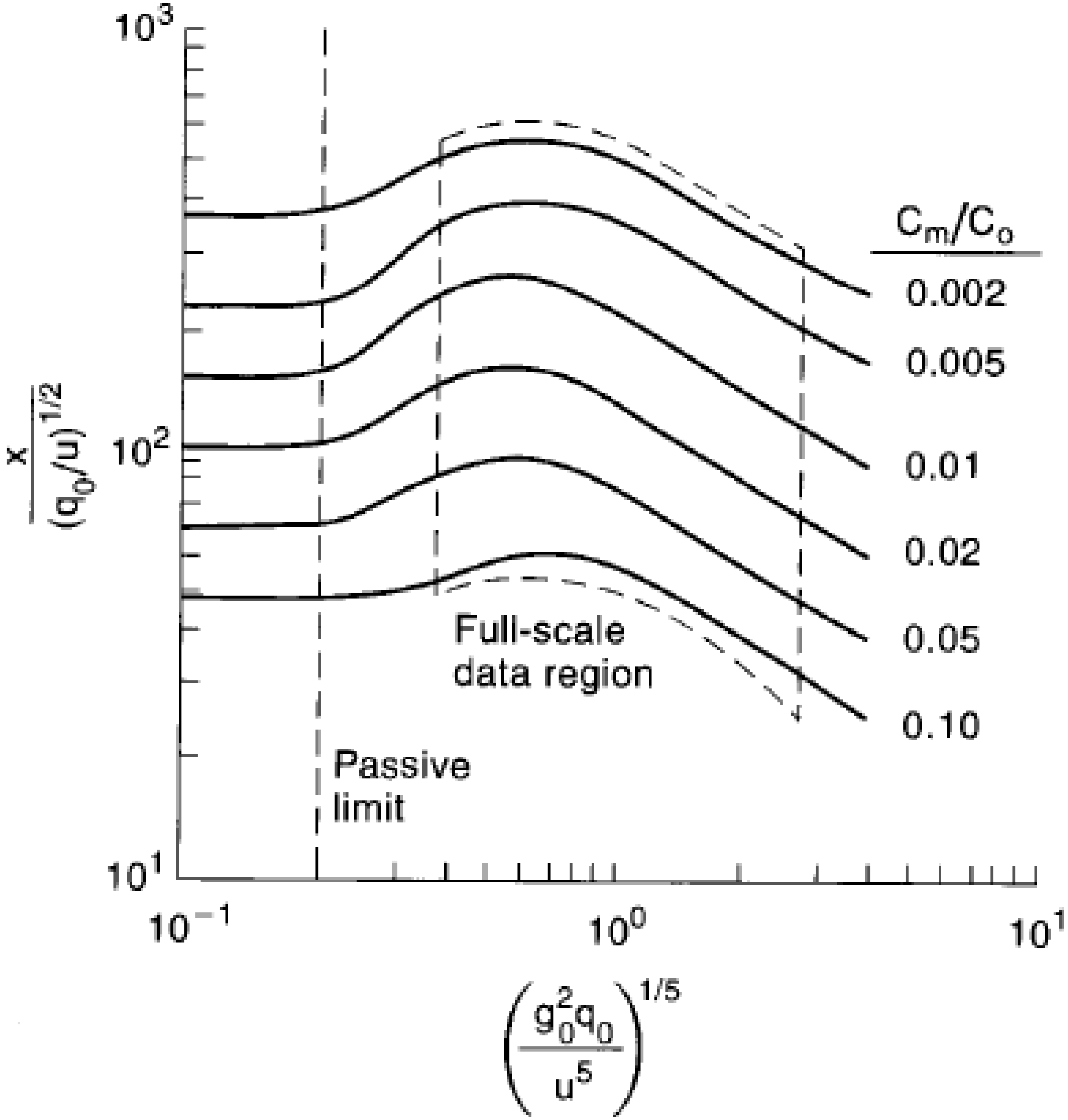


Figure 5-13 Britter-McQuaid dimensional correlation for dispersion of dense gas plumes.

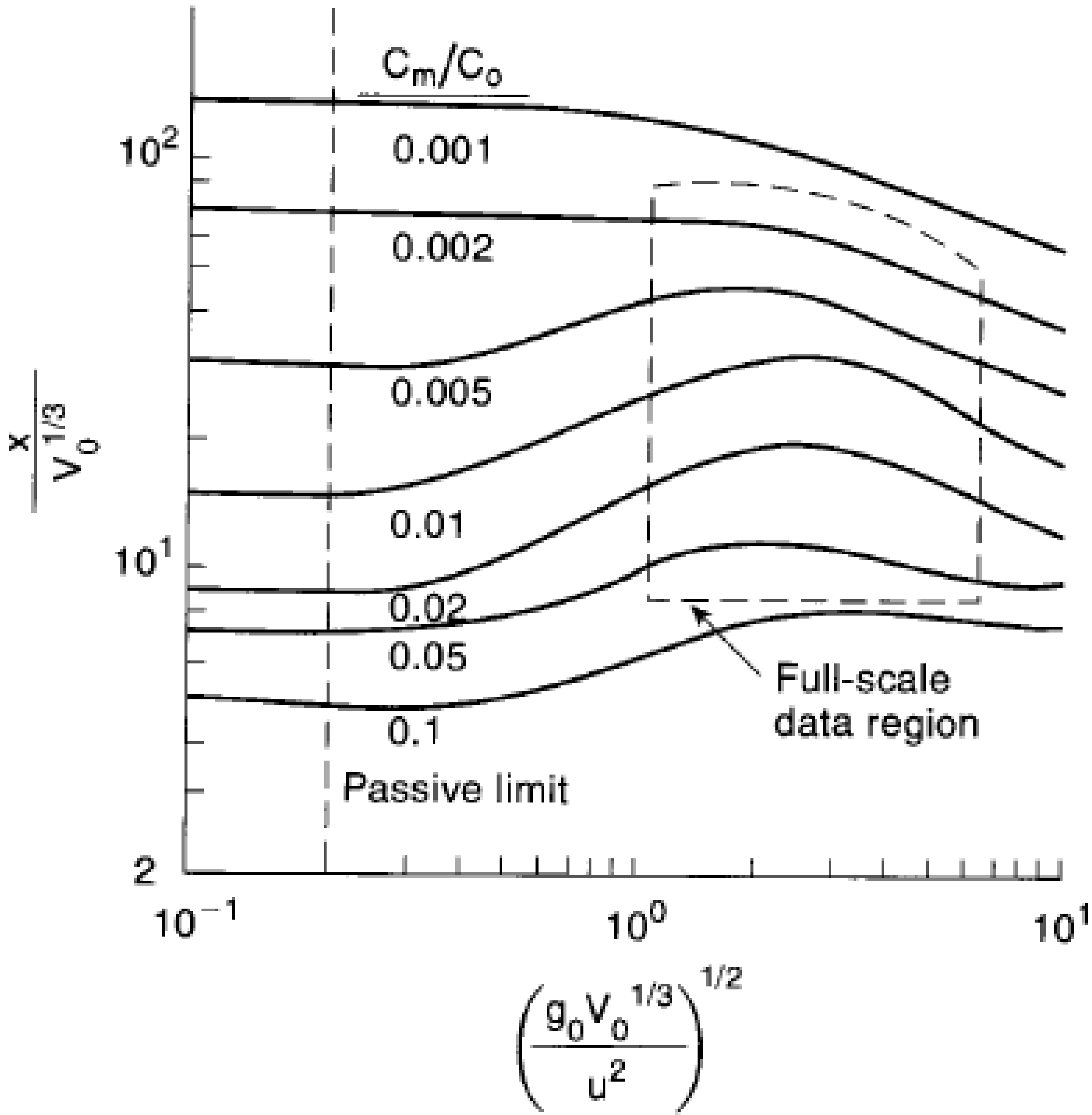


Figure 5-14 Britter-McQuaid dimensional correlation for dispersion of dense gas puffs.

Table 5-4 Equations Used to Approximate the Curves in the Britter-McQuaid Correlations Provided in Figure 5-13 for Plumes

Concentration ratio (C_m/C_o)	Valid range for $\alpha = \log\left(\frac{g_o^2 q_o}{u^5}\right)^{1/5}$	$\beta = \log\left[\frac{x}{(q_o/u)^{1/2}}\right]$
0.1	$\alpha \le -0.55$	1.75
	$-0.55 < \alpha \le -0.14$	$0.24\alpha + 1.88$
	$-0.14 < \alpha \le 1$	$0.50\alpha + 1.78$
0.05	$\alpha \le -0.68$	1.92
	$-0.68 < \alpha \le -0.29$	$0.36\alpha + 2.16$
	$-0.29 < \alpha \le -0.18$	2.06
	$-0.18 < \alpha \le 1$	$-0.56\alpha + 1.96$
0.02	$\alpha \le -0.69$	2.08
	$-0.69 < \alpha \le -0.31$	$0.45\alpha + 2.39$
	$-0.31 < \alpha \le -0.16$	2.25
	$-0.16 < \alpha \le 1$	$-0.54\alpha + 2.16$

Table 5-4 Equations Used to Approximate the Curves in the Britter-McQuaid Correlations Provided in Figure 5-13 for Plumes

Concentration ratio (C_m/C_o)	Valid range for $\alpha = \log\left(\frac{g_o^2 q_o}{u^5}\right)^{1/5}$	$\beta = \log\left[\frac{x}{(q_o/u)^{1/2}}\right]$
0.01	$\alpha \leq -0.70$	2.25
	$-0.70 < \alpha \leq -0.29$	$0.49\alpha + 2.59$
	$-0.29 < \alpha \leq -0.20$	2.45
	$-0.20 < \alpha \leq 1$	$-0.52\alpha + 2.35$
0.005	$\alpha \leq -0.67$	2.40
	$-0.67 < \alpha \leq -0.28$	$0.59\alpha + 2.80$
	$-0.28 < \alpha \leq -0.15$	2.63
	$-0.15 < \alpha \leq 1$	$-0.49\alpha + 2.56$
0.002	$\alpha \leq -0.69$	2.6
0.002	$-0.69 < \alpha \leq -0.25$	$0.39\alpha + 2.87$
0.002	$-0.25 < \alpha \leq -0.13$	2.77
0.002	$-0.13 < \alpha \leq 1$	$-0.50\alpha + 2.71$

Table 5-5 Equations Used to Approximate the Curves in the Britter-McQuaid Correlations Provided in Figure 5-14 for Puffs

Concentration ratio (C_m/C_o)	Valid range for $\alpha = \log\left(\frac{g_o V_o^{1/3}}{u^2}\right)^{1/2}$	$\beta = \log\left(\frac{x}{V_o^{1/3}}\right)$
0.1	$\alpha \le -0.44$	0.70
	$-0.44 < \alpha \le 0.43$	$0.26\alpha + 0.81$
	$0.43 < \alpha \le 1$	0.93
0.05	$\alpha \le -0.56$	0.85
	$-0.56 < \alpha \le 0.31$	$0.26\alpha + 1.0$
	$0.31 < \alpha \le 1.0$	$-0.12\alpha + 1.12$
0.02	$\alpha \le -0.66$	0.95
	$-0.66 < \alpha \le 0.32$	$0.36\alpha + 1.19$
	$0.32 < \alpha \le 1$	$-0.26\alpha + 1.38$
0.01	$\alpha \le -0.71$	1.15
	$-0.71 < \alpha \le 0.37$	$0.34\alpha + 1.39$
	$0.37 < \alpha \le 1$	$-0.38\alpha + 1.66$
0.005	$\alpha \le -0.52$	1.48
	$-0.52 < \alpha \le 0.24$	$0.26\alpha + 1.62$
	$0.24 < \alpha \le 1$	$0.30\alpha + 1.75$
0.002	$\alpha \le 0.27$	1.83
	$0.27 < \alpha \le 1$	$-0.32\alpha + 1.92$
0.001	$\alpha \le -0.10$	2.075
	$-0.10 < \alpha \le 1$	$-0.27\alpha + 2.05$

Toxic Effect Criteria

- Normal work hours criteria: TLV-TWA (ACGIH), PEL (OSHA)
- Probit correlations for wide ranges of concentrations and exposure times
- Criteria for short term exposures at higher than TLV-TWA values: available from many sources
- IDLH (NIOSH), 30 min exposures: SCBA required for higher levels

ERPG Toxic Effect Criteria

- American Industrial Hygiene Association (AIHA): Emergency response planning guidelines (ERPG) for exposures up to 1 hour
- ERPG-1: mild transient effects
- ERPG-2: reversible health effects
- ERPG-3: without life-threatening effects
- Tab 5-6, pp. 201, 202
- Alternative guidelines in lieu of ERPG data: Tab 5-9, p 206
- EPA Toxic Endpoints based on ERPG-2

Table 5-6 *(continued)*

Chemical	ERPG-1	ERPG-2	ERPG-3
Methyl isocyanate	0.025	0.5	5
Methyl mercaptan	0.005	25	100
Methyltrichlorosilane	0.5	3	15
Monomethylamine	10	100	500
Perfluoroisobutylene	NA	0.1	0.3
Phenol	10	50	200
Phosgene	NA	0.2	1
Phosphorus pentoxide	5 mg/m^3	25 mg/m^3	100 mg/m^3
Propylene oxide	50	250	750
Styrene	50	250	1,000
Sulfonic acid (oleum, sulfur trioxide, and sulfuric acid)	2 mg/m^3	10 mg/m^3	30 mg/m^3
Sulfur dioxide	0.3	3	15
Tetrafluoroethylene	200	1000	10,000
Titanium tetrachloride	5 mg/m^3	20 mg/m^3	100 mg/m^3
Toluene	50	300	1000
Trimethylamine	0.1	100	500
Uranium hexafluoride	5 mg/m^3	15 mg/m^3	30 mg/m^3
Vinyl acetate	5	75	500

Table 5-9 Recommended Hierarchy of Alternative Concentration Guidelines[1]

Primary guideline	Hierarchy of alternative guidelines	Source
ERPG-3		AIHA
	EEGL (30-minute)	NRC
	IDLH	NIOSH
ERPG-2		AIHA
	EEGL (60 minute)	NRC
	LOC	EPA/FEMA/DOT
	PEL-C	OSHA
	TLV-C	ACGIH
	5 × TLV-TWA	ACGIH
ERPG-3		AIHA
	PEL-STEL	OSHA
	TLV-STEL	ACGIH
	3 × TLV-TWA	ACGIH

EEGL Toxic Effect Criteria

- **National Research Council (NRC): Emergency exposure guidance levels (EEGL)**
- **Acceptable exposure levels for emergency condition tasks up to 1 or up to 24 hours**
- **Includes reversible effects that do not impair work performance**
- **Tab 5-7, p 204**

Table 5-7 Emergency Exposure Guidance Levels (EEGLs) from the National Research Council (NRC) (all values are in ppm unless otherwise noted)

Compound	1-hr EEGL	24-hr EEGL	Source
Acetone	8500	1000	NRC I
Acrolein	0.05	0.01	NRC I
Aluminum oxide	15 mg/m^3	100	NRC IV
Ammonia	100		NRC VII
Arsine	1	0.1	NRC I
Benzene	50	2	NRC VI
Bromotrifluoromethane	25,000		NRC III
Carbon disulfide	50		NRC I
Carbon monoxide	400	50	NRC IV
Chlorine	3	0.5	NRC II
Chlorine trifluoride	1		NRC II
Chloroform	100	30	NRC I
Dichlorodifluoromethane	10,000	1000	NRC II
Dichlorofluoromethane	100	3	NRC II
Dichlorotetrafluoroethane	10,000	1000	NRC II
1,1-Dimethylhydrazine	0.24[1]	0.01[1]	NRC V

Release Mitigation

- **Part of consequence modeling, Fig 4-1, p 110. Mitigation methods, Tab 5-10, p 214**
- **Mitigation measures depend on likelihood of a release**
- **Preventive: Inherent safety, process and mechanical integrity, training, maintenance, sensors, software**
- **Protective, reduce effect of incidents: curtains, foams, emergency response program**

Table 5-10 Release Mitigation Approaches[1]

Major area	Examples
Inherent safety	Inventory reduction: Less chemicals inventoried or less in process vessels Chemical substitution: Substitute a less hazardous chemical for one more hazardous Process attentuation: Use lower temperatures and pressures
Engineering design	Plant physical integrity: Use better seals or materials of construction Process integrity: Ensure proper operating conditions and material purity Process design features for emergency control: Emergency relief systems Spill containment: Dikes and spill vessels
Management	Operating policies and procedures Training for vapor release prevention and control Audits and inspections Equipment testing Maintenance program Management of modifications and changes to prevent new hazards Security

Table 5-10 Release Mitigation Approaches[1]

Major area	Examples
Early vapor detection and warning	Detection by sensors Detection by personnel
Countermeasures	Water sprays Water curtains Steam curtains Air curtains Deliberate ignition of explosive cloud Dilution Foams
Emergency response	On-site communications Emergency shutdown equipment and procedures Site evacuation Safe havens Personal protective equipment Medical treatment On-site emergency plans, procedures, training, and drills

[1] Richard W. Prugh and Robert W. Johnson, *Guidelines for Vapor Release Mitigation* (New York: American Institute of Chemical Engineers, 1988).