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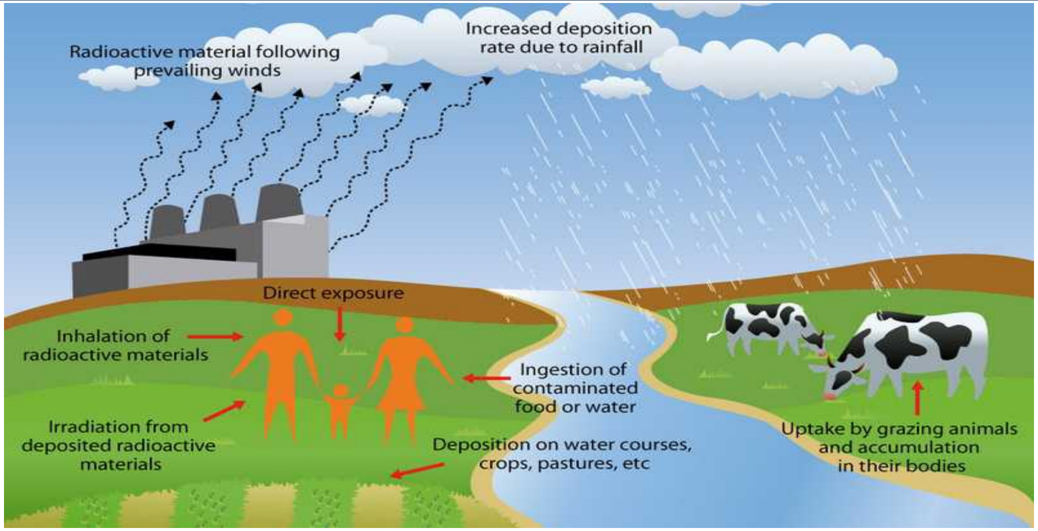

Level-3 Consequence Analysis Part 1
Atmospheric Transport and Dispersion

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Sandia National Laboratories

27 April – 1 May, 2015

Haiyang, China

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Objectives

- Learn the mechanisms that describe
  - Atmospheric transport and dispersion
  - Wet and dry deposition

Processes That Affect a Released Contaminant

Plume transport mechanisms

- Buoyant plume rise
- Dilution and transport
- Dispersion
- Chemical reactions (not usually treated in a PSA)

Plume depletion mechanisms

- Radioactive decay
- Wet deposition - rainout by interaction with cloud droplets and washout by falling precipitation
- Dry deposition – gradual loss of reactive vapors and aerosols by deposition onto the surface cover

Atmospheric Transport Inputs and Outputs

- Basic weather inputs
  - Wind speed
  - Wind direction
  - Atmospheric stability
  - Precipitation rate
- Basic outputs
  - Air concentrations
  - Surface deposition

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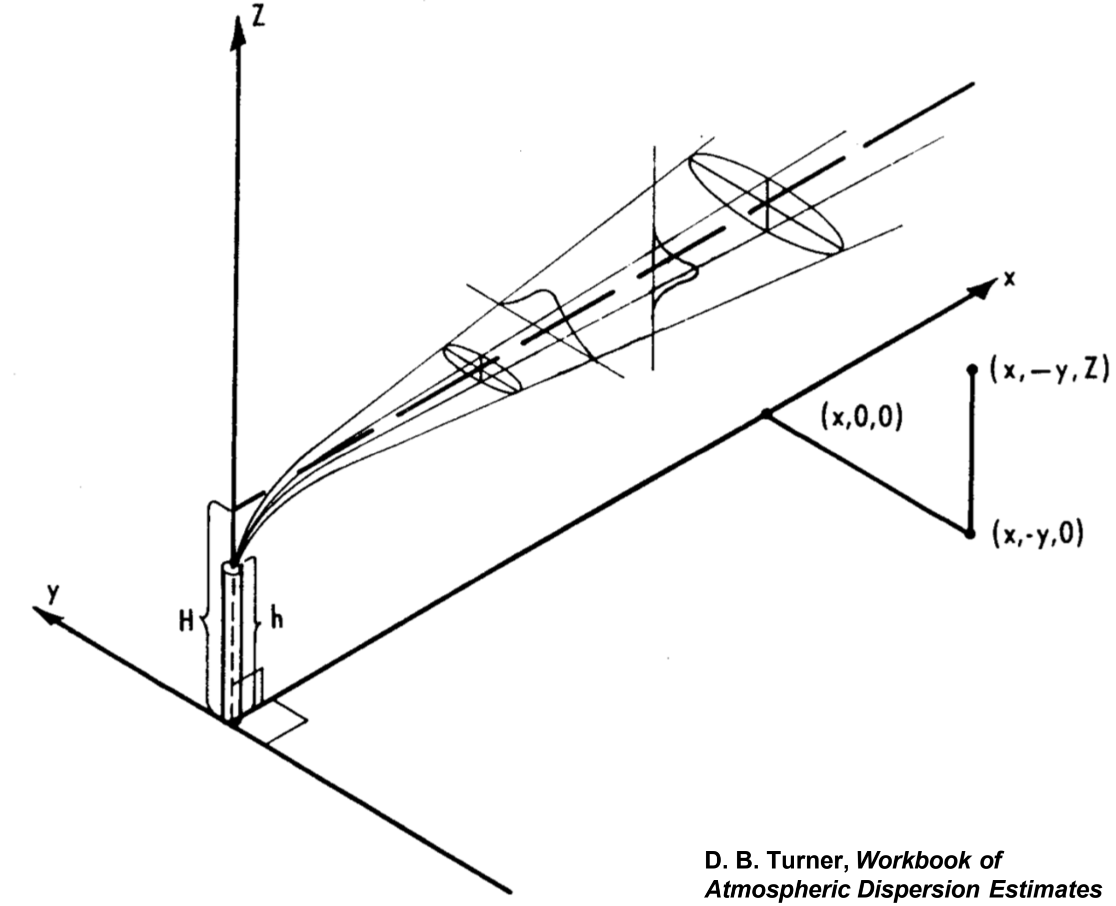
Coordinate System for Atmospheric Transport and Dispersion



D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*

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Basic Concentration Equation

- **Continuous release**
- **Point source**
- **No boundaries**

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\exp\left\{-\frac{1}{2}\left[\left(\frac{y}{\sigma_y}\right)^2+\left(\frac{z}{\sigma_z}\right)^2\right]\right\}$$

C = Plume concentration (Bq/m^3)
$\dot{Q}$ = Release rate of contaminant (Bq/s)
y = Cross-wind (lateral) distance from plume centerline (m)
z = Vertical distance from plume centerline (m)
σ_y = Standard deviation of plume in the y direction as a function of x (m)
σ_z = Standard deviation of plume in the z direction as a function of x (m)
u = Average wind speed along plume centerline

$$\frac{\int C dt}{\int \dot{Q} dt} = \frac{\chi}{Q}$$

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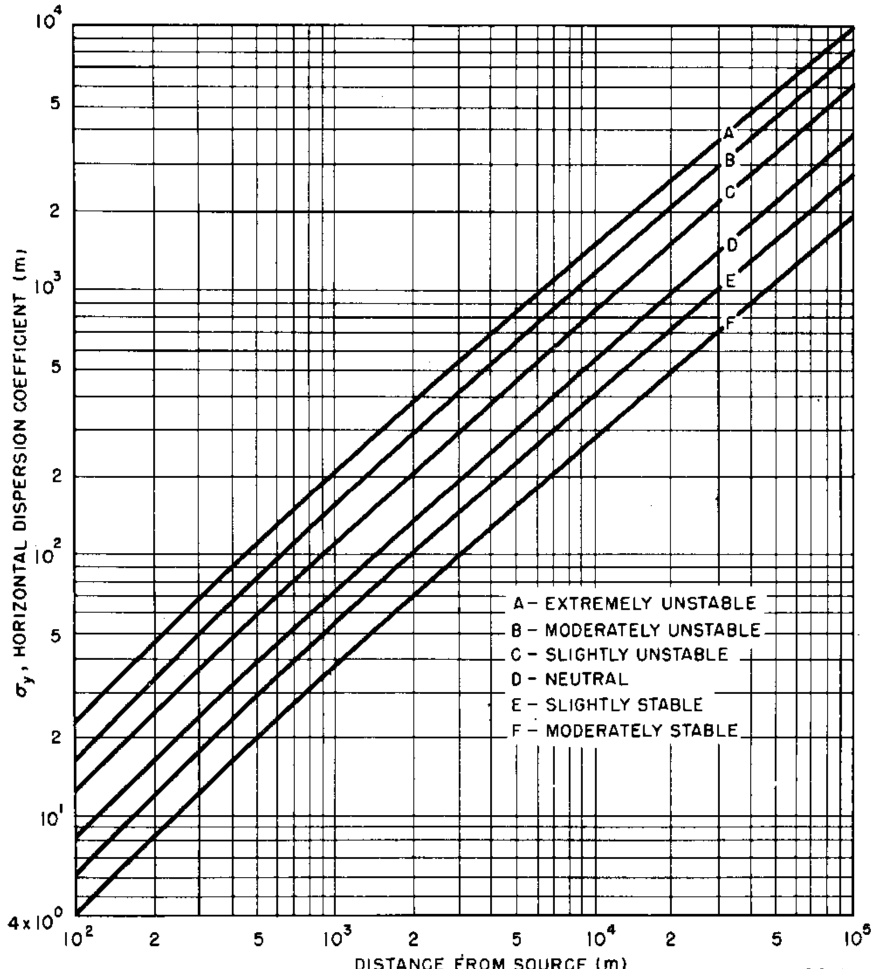
Lateral Dispersion, σ_y, vs. Downwind Distance From Source



Meteorology and Atomic Energy, 1968

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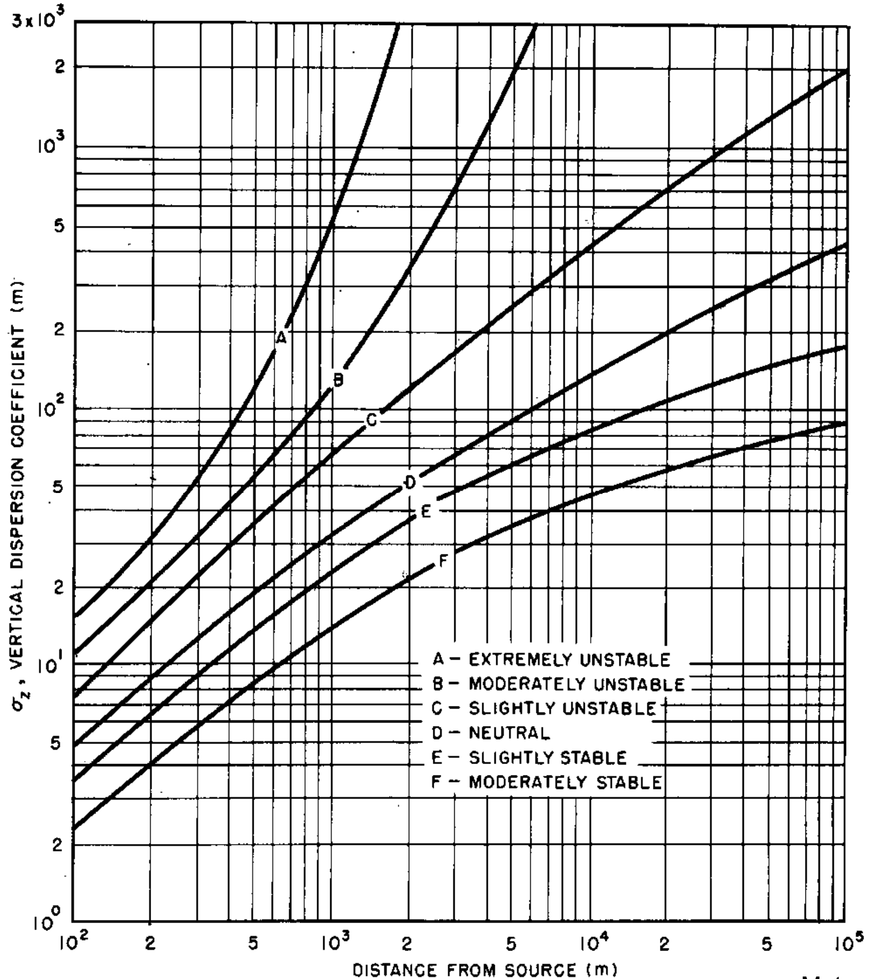
Vertical Dispersion, σ_z, vs. Downwind Distance From Source (Pasquill-Gifford)



Meteorology and Atomic Energy, 1968

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Power-Law Representation of Dispersion

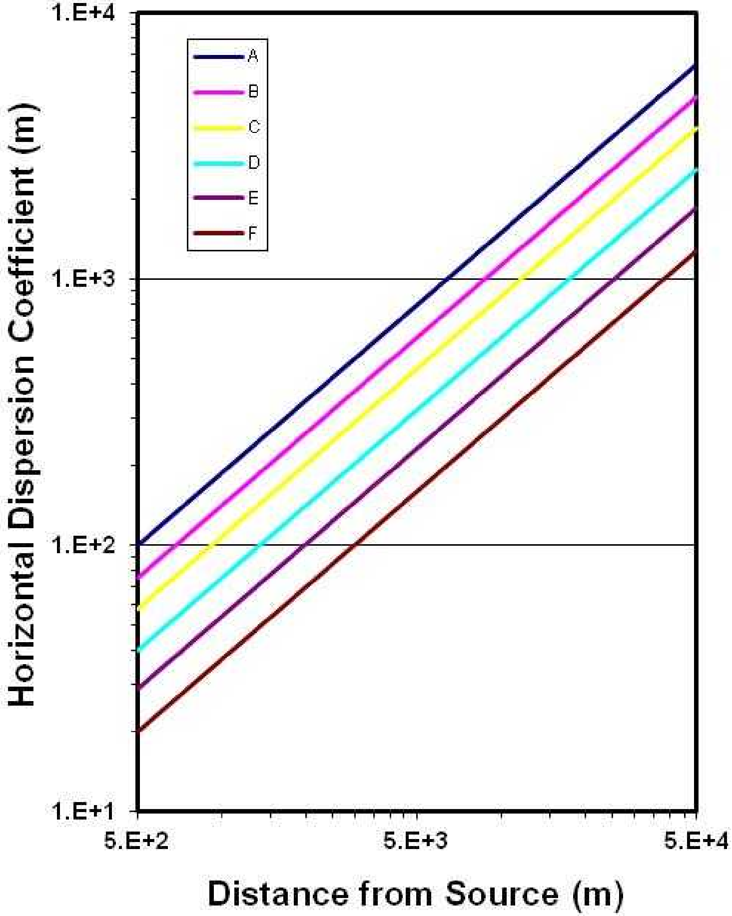
- Power-law representation

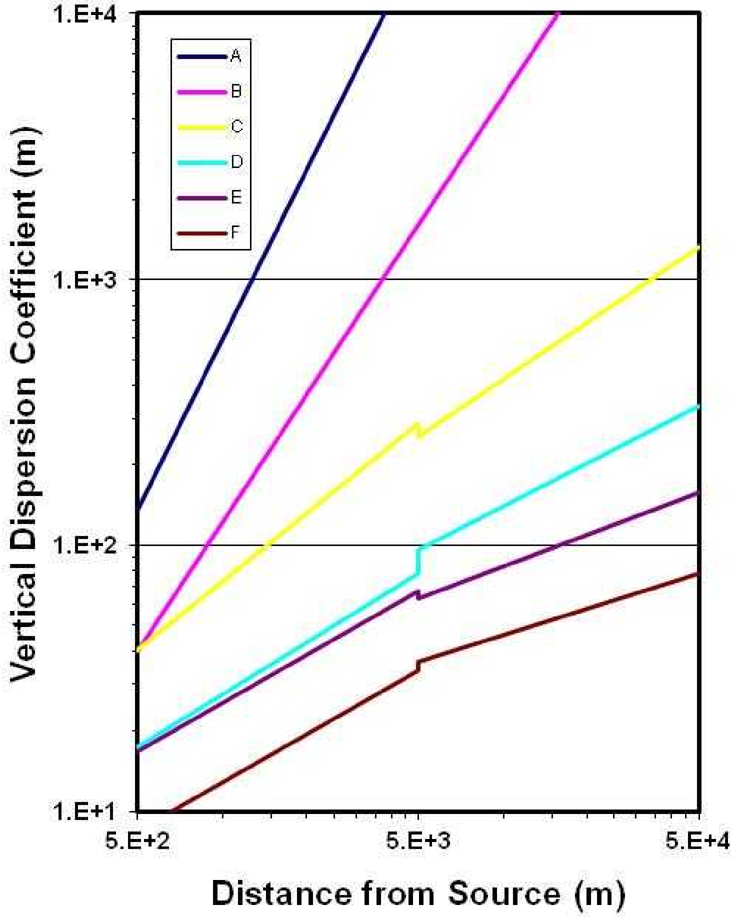
$$\sigma_y = a \cdot x^b \qquad \sigma_z = c \cdot x^d$$

- Excellent representation for σ_y
- Two-piece, less accurate, representation for σ_z

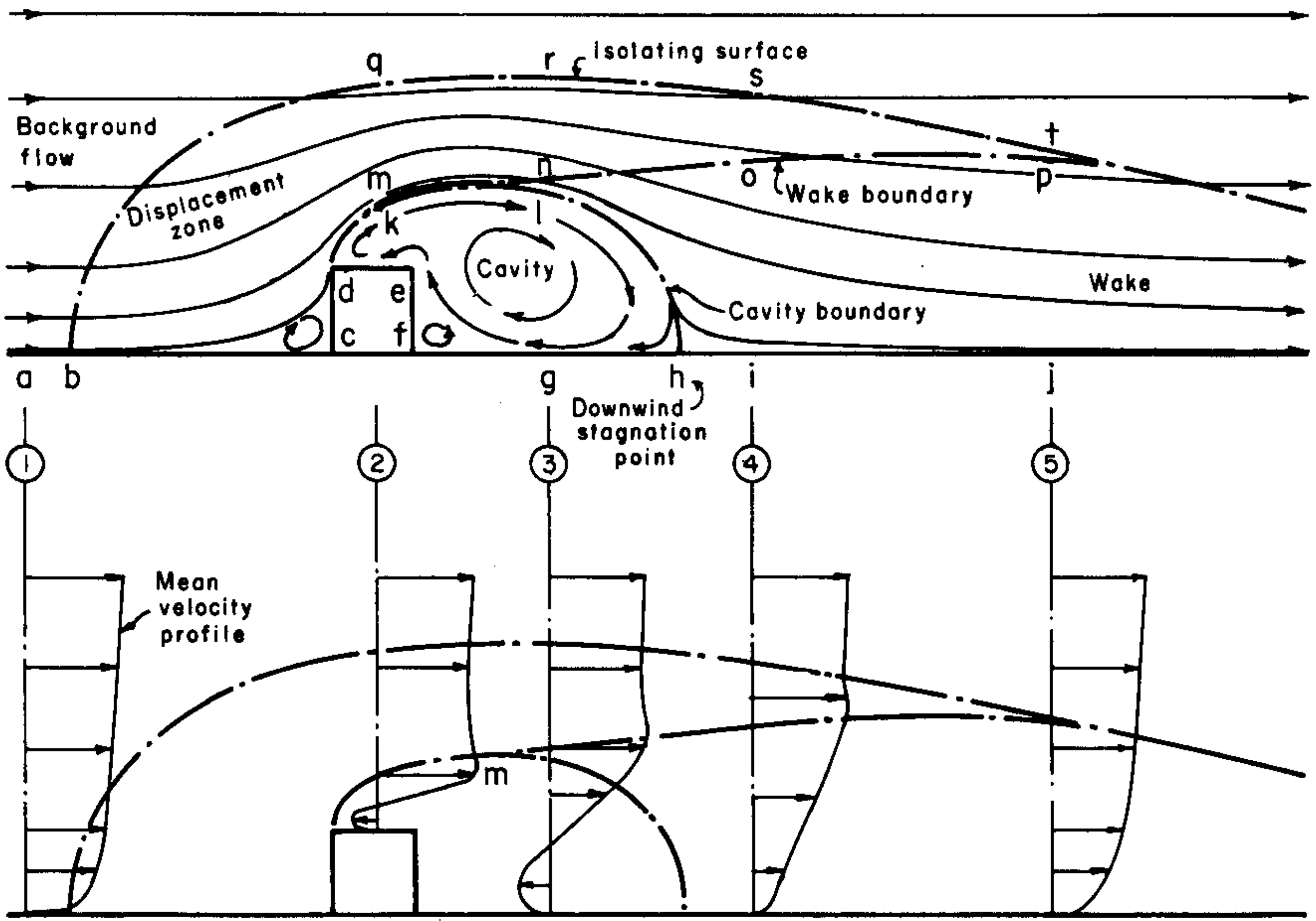
Parameter	Distance Range (km)	Stability Class A	B	C	D	E	F
a	0.5 - 50	0.36580	0.2751	0.2089	0.1474	0.1046	0.0722
b	0.5 - 50	0.90310	0.9031	0.9031	0.9031	0.9031	0.9031
c	0.5 - 5	0.00025	0.0019	0.2000	0.3000	0.4000	0.2000
	5 - 50			0.5742	0.9605	2.1250	2.1820
d	0.5 - 5	2.12500	1.6021	0.8543	0.6532	0.6021	0.6020
	5 - 50			0.7160	0.5409	0.3979	0.3310

Plots of Power-Law Functions for Tadmor and Gur Parameters



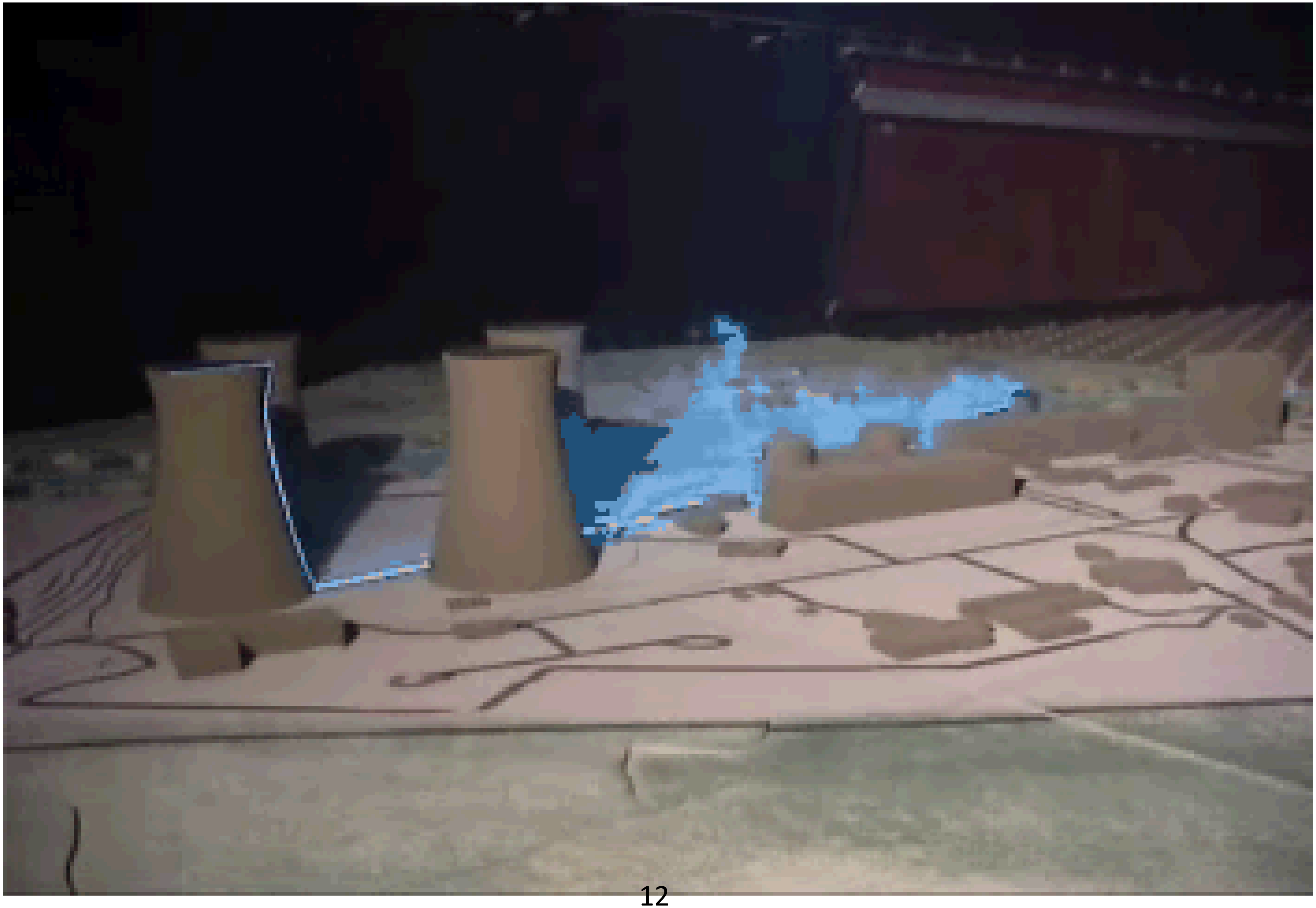


General Arrangement of Flow Zones Near a Sharp-edged Building



Meteorology and Atomic Energy, 1968

Wind-Tunnel Test of Scaled Plant

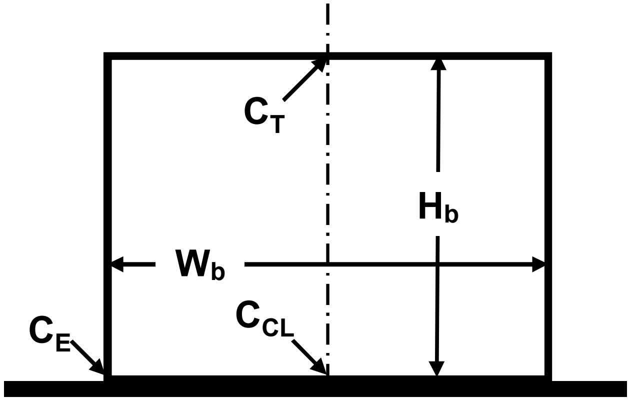


Building Wake - Area Source

- Assume fraction, f, of centerline concentration at building edge and top

$$f = \frac{C_E}{C_{CL}} = \exp\left(\frac{-(W_b/2)^2}{2\sigma_{y_0}^2}\right)$$

$$f = \frac{C_T}{C_{CL}} = \exp\left(\frac{-H_b^2}{2\sigma_{z_0}^2}\right)$$

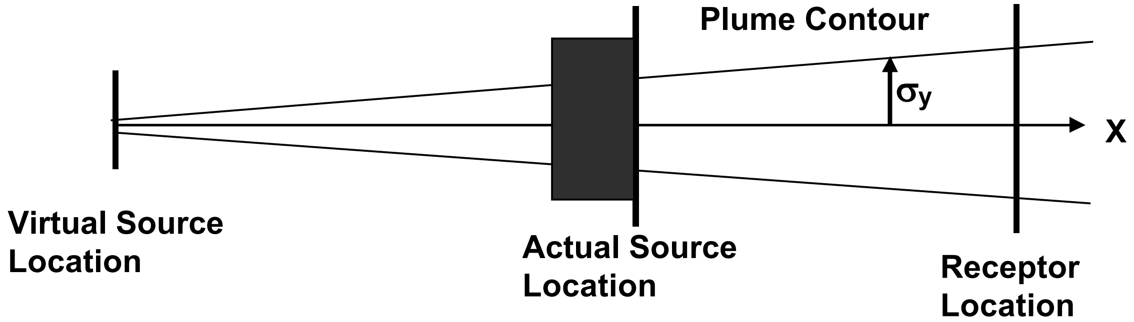


For f = 0.1, $\sigma_{y_0} = 0.23\ W_b$ and $\sigma_{z_0} = 0.47\ H_b$

Where W_b and H_b are the width and height of the building, respectively

Virtual Sources

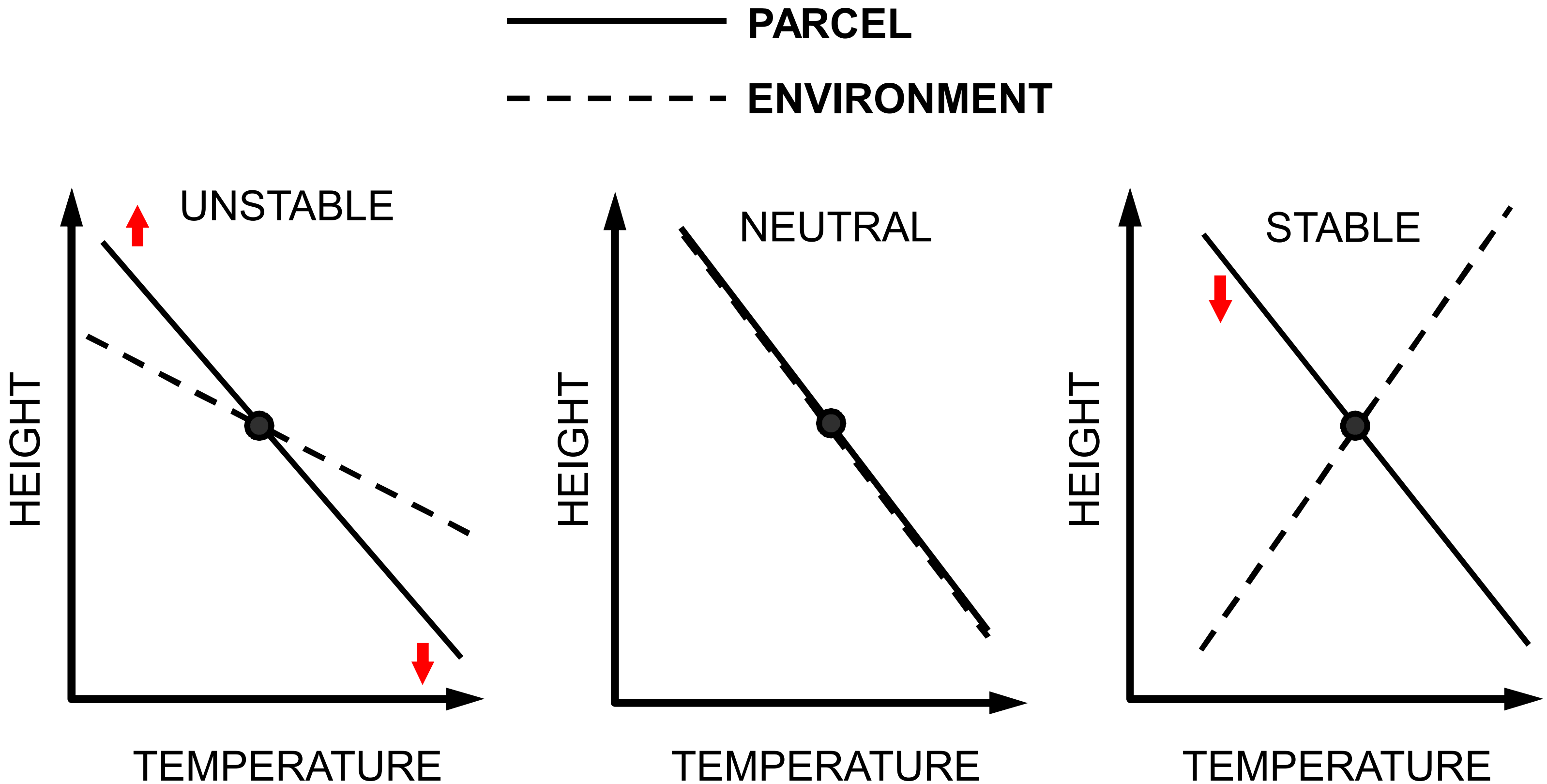
- Virtual source is the location of a “point” source that produces an equivalent plume size
- Actual source location corresponds to a finite distance downwind from the virtual source
  - X_{y0} for crosswind dispersion
  - X_{z0} for vertical dispersion
- Receptor locations are relative to actual source location



Planetary Boundary Layer

- Region of atmosphere between earth's surface and an upper region of nonturbulent, geostrophic flow
- Ranges in height from 50 m – height of troposphere (10 to 18 km)
- Consists of three parts
  - Surface layer (first 10%, turbulence is created)
  - Core (up to 70% of PBL, turbulence is dissipated)
  - Top (remainder)
- Principal types are convective and stably stratified
- Wind speed and direction tend to vary with height in surface layer
- Stability of atmosphere within PBL determines turbulence intensity (dispersion effects)
- Radioactive materials are assumed to be trapped in this layer
- Here we assume it is the same as the mixing layer

Illustrations of PBL Stability Conditions



ORNL-DWG 83-10939

Atmospheric Stability Classifications by Vertical Temperature Gradient (Lapse Rate)

Stability classification	Pasquill categories	Temperature change with height (°C/100 m)
Extremely unstable	*A*	$\Delta T/\Delta z \leq -1.9$
Moderately unstable	*B*	$-1.9 < \Delta T/\Delta z \leq -1.7$
Slightly unstable	*C*	$-1.7 < \Delta T/\Delta z \leq -1.5$
Neutral	*D*	$-1.5 < \Delta T/\Delta z \leq -0.5$
Slightly stable	*E*	$-0.5 < \Delta T/\Delta z \leq 1.5$
Moderately stable	*F*	$1.5 < \Delta T/\Delta z \leq 4.0$
Extremely stable	*G*	$4.0 < \Delta T/\Delta z$

Mixing Height

- Mixing height is usually determined by
  - Thermal mixing (convection) during daytime
  - Mechanical mixing during nighttime
- Varies continuously (hour to hour, day to day, season to season)
- Usually lowest at night and early morning
- Usually highest in afternoon
- Inhibits plume rise (we assume that it is an absolute barrier)

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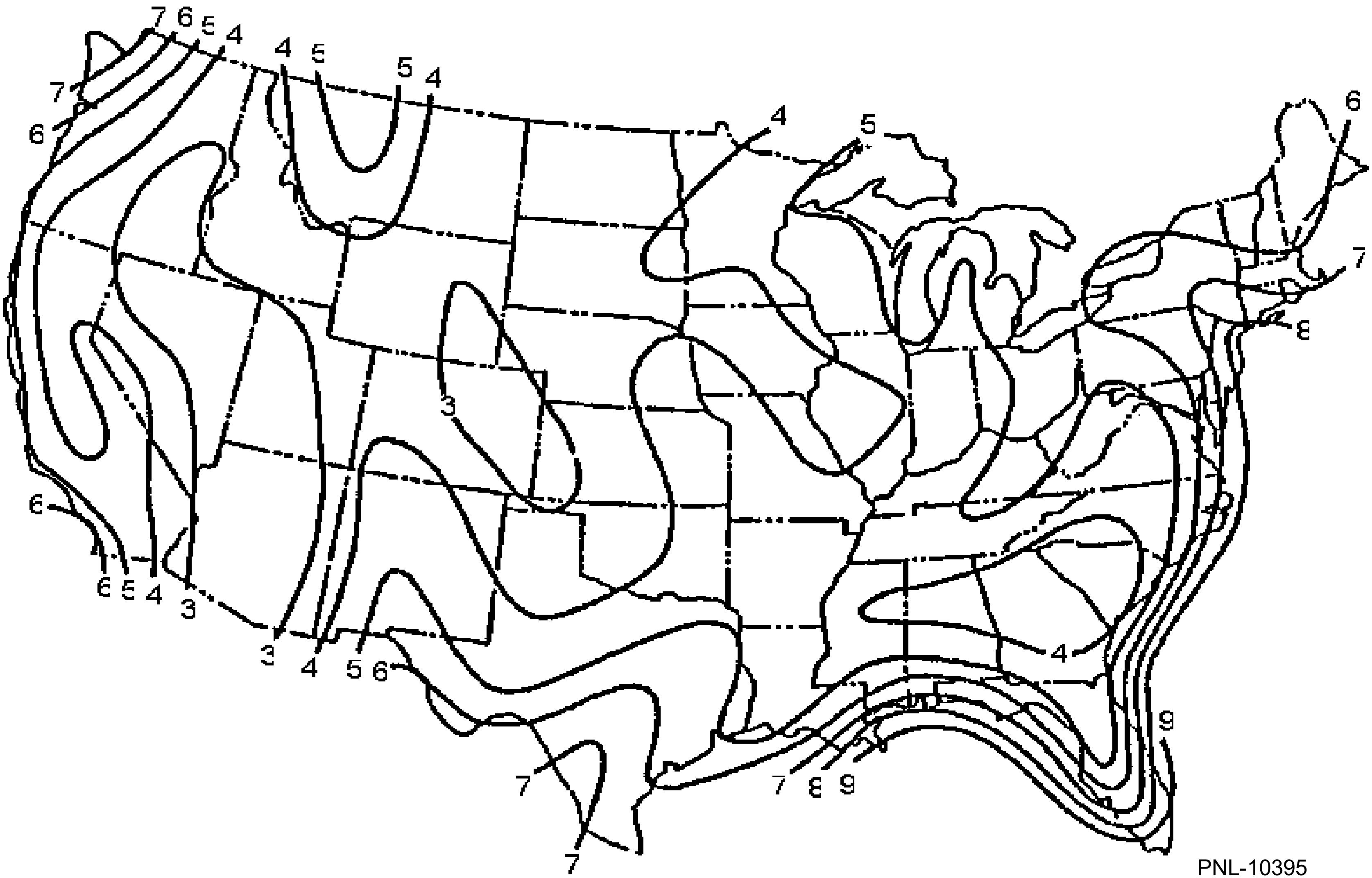
Mean Annual Morning Mixing Heights (m x 10^2)



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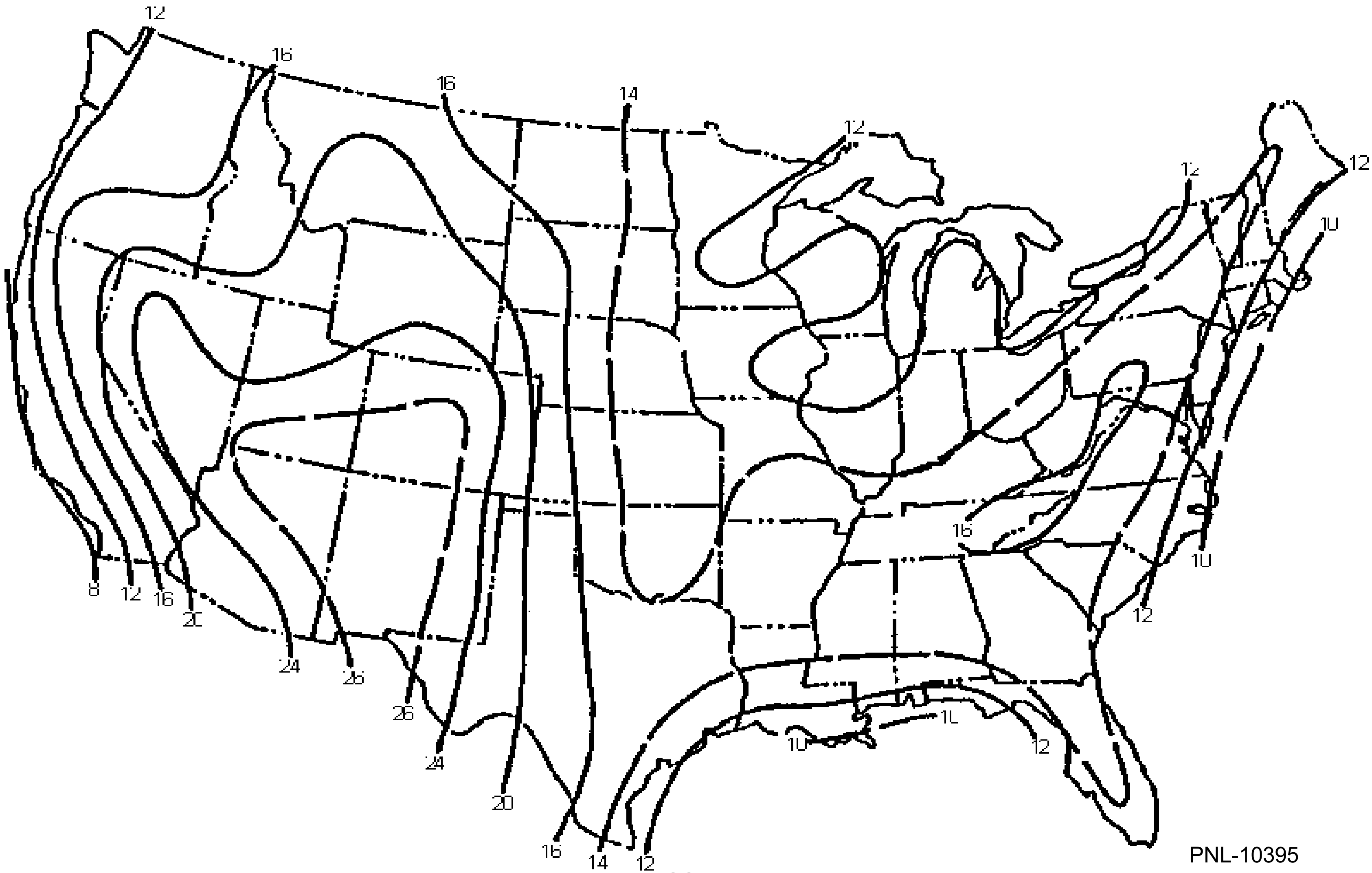
Mean Annual Afternoon Mixing Heights (m x 10^2)



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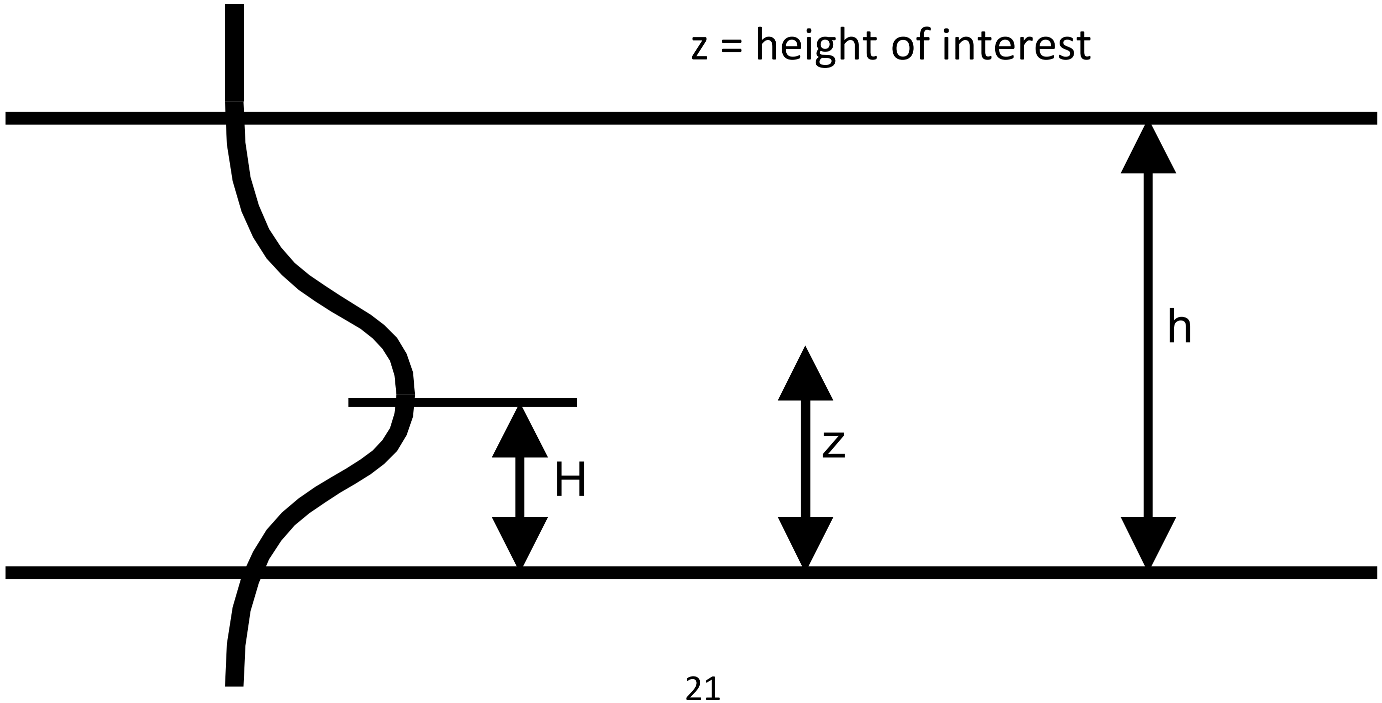
Vertical Boundaries Ground and Mixing Layer

H = release height (or lofting height) above ground

h = height of mixing layer

z = height of interest



General Gaussian Plume Equation With Reflective Boundaries

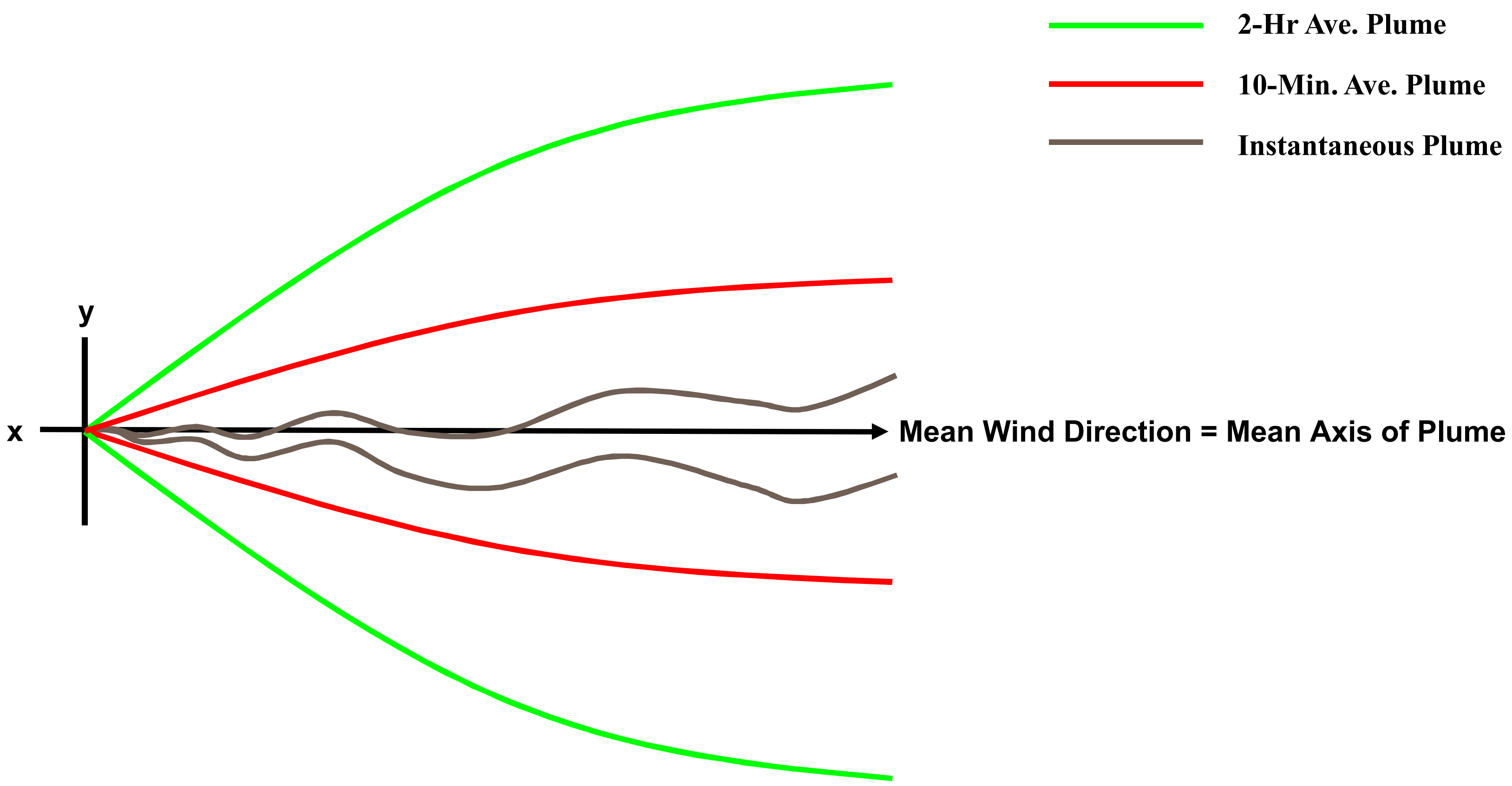
- Account for material that would have been lost through boundaries

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\sum_{n=-\infty}^{\infty}\left\{\exp\left[-\frac{1}{2}\left(\frac{2nh - H - z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{2nh + H - z}{\sigma_z}\right)^2\right]\right\}$$

- Simplified equation when release is at ground level and observation point is on plume centerline (H = y = z = 0)

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\sum_{n=-\infty}^{\infty} 2\exp\left[-2\left(\frac{nh}{\sigma_z}\right)^2\right]$$

Effect of Diffusion Times – Plume Meander



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Original MACCS2 Plume Meander

- Increases effective plume spread in y direction
- Effect of plume meander continues downwind indefinitely

$$\sigma_{y,\,m} = \sigma_y \left(\frac{\Delta t}{\Delta t_{ref}} \right)^m$$

Δt = Release duration (s)

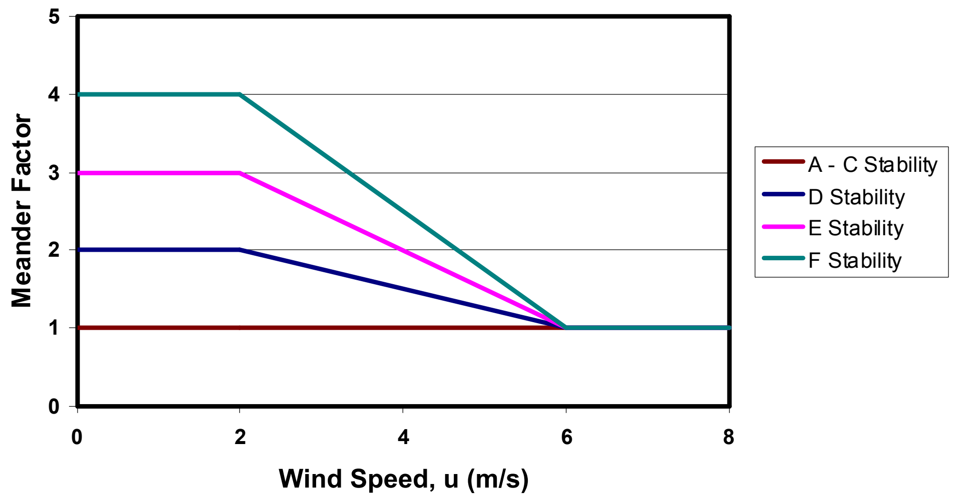
Δt_{ref} = 600, the experimental duration of the Prairie Grass tests (s)

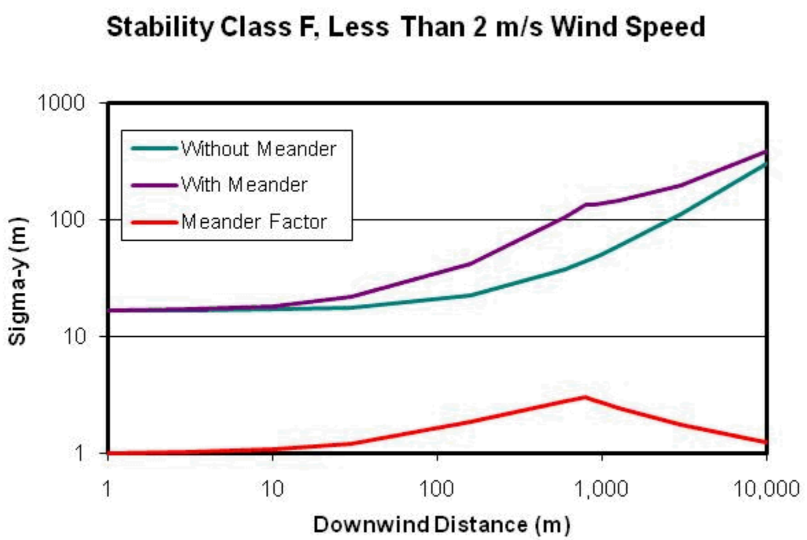
m = an empirical exponent

= 0.2 when Δt < 1 hr

= 0.25 when Δt > 1 hr

Regulatory Guide 1.145 Plume Meander Model





- Meander factor depends on stability class and wind speed
- Model is based on a 1-hr plume duration
- Effect of plume meander diminishes beyond 800 m from source
- Plot shows
  - Dispersion not accounting for plume meander
  - Dispersion accounting for plume meander (<2 m/s and F stability)
  - Effective meander factor

Plume Rise

- Earlier Briggs' model is used to estimate plume rise
  - Near-field trajectory (used for stability classes A – D)

$$\Delta H(x) = \frac{1.6(Fx^2)^{1/3}}{\bar{u}}$$

  - Final rise for stability classes A – D

$$\Delta H_f = 38.7\frac{F^{0.60}}{\bar{u}} \quad \text{when} \quad F \geq 55$$

$$\Delta H_f = 21.4\frac{F^{0.75}}{\bar{u}} \quad \text{when} \quad F < 55$$

  - Final rise for stability classes E – F

$$\Delta H_f = 2.4\left(\frac{F}{\bar{u}s}\right)^{1/3}$$

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Plume Trapping in Building Wake

- Plume is trapped in building wake when

$$u > \left(\frac{9.09F}{H_b}\right)^{1/3}$$

Where H_b is the building height (m)

F is the buoyancy flux defined previously (m^4/s^3)

u is wind speed (m/s)

- A trapped plume is
  - Released at the level of the initial release point

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Roughness Length, z_0

- Function of size and spacing of roughness elements
- Dependent on the frontal area of the average element (facing the wind) divided by the ground width it occupies
- A lower roughness length implies less momentum exchange between the surface and the atmosphere
- σ_z measured over flat terrain during Prairie Grass tests (z_0 = 3 cm)

$$\sigma_z = \sigma_{z,\,PG}\left(\frac{z_0}{3}\right)^{0.2}$$

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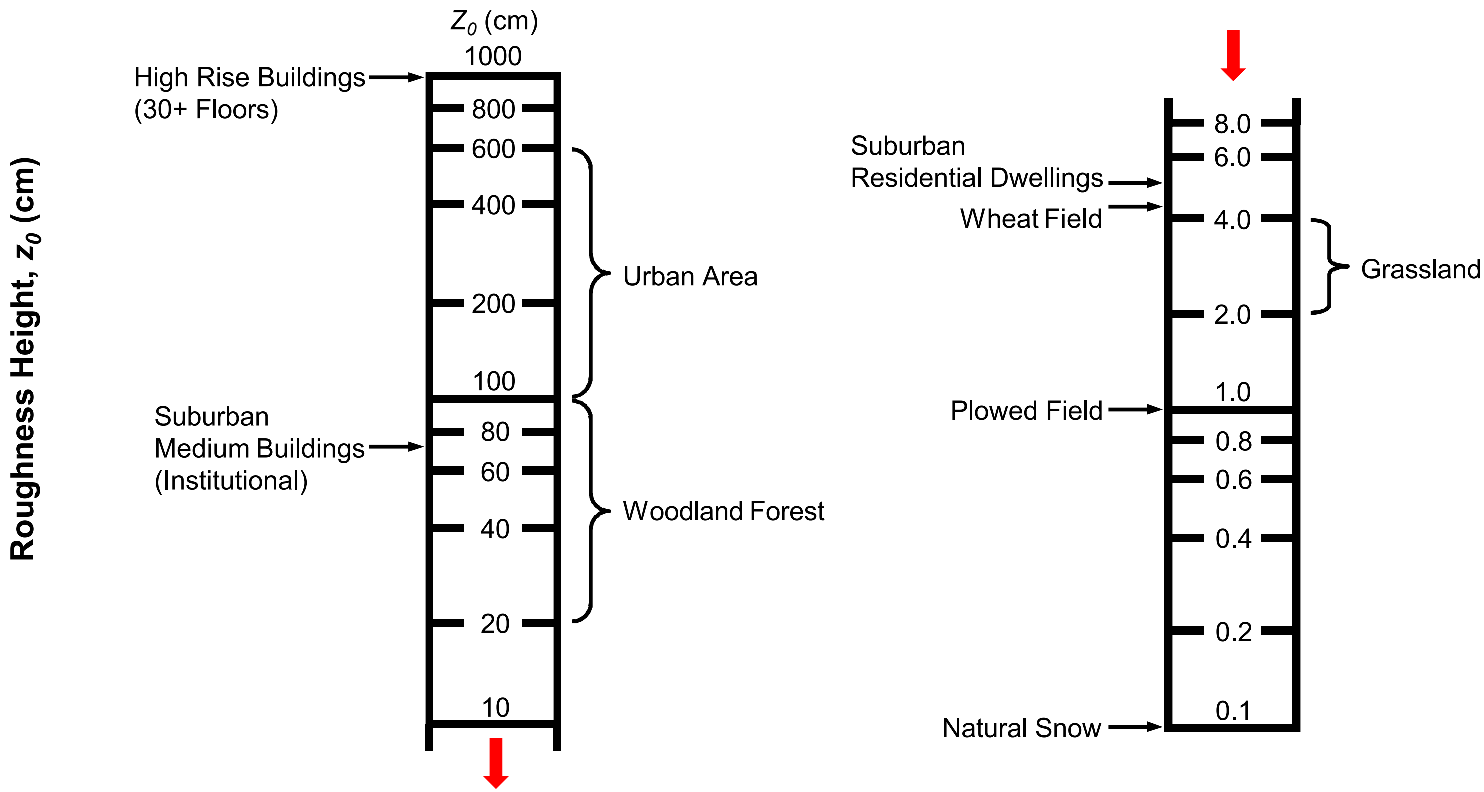
Roughness Lengths for Various Surfaces



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Workshop Example 1 – Pasquill-Gifford Chart

For a 30 minute release from this building (assume dimensions of 200 ft. high by 120 ft. wide) of 1 Ci of ^{137}Cs, what is the maximum ground concentration 1/2 mile downwind and at the mall (8 miles downwind). Assume worst case conditions.

Assumptions:

Worst Case - Wind blowing directly towards mall

Concentration at plume centerline (y = z = H = 0)

Low wind speed (u = 1 m/s; may not be worst case for short half lives)

Minimize atmospheric dispersion; stability = F

Heat low enough so that no plume rise

Other - Converting dimensions of interest:

1/2 mi ~ <u>800m</u>

8 mi ~ <u>13000m</u>

Building height = 200ft ~ <u>60m</u>

Building width = 120ft ~ <u>37m</u>

Roughness length (z_0) = 100cm (suburban/urban)

WORKSHOP EXAMPLE 1 (cont.)

Meander (5-26): $\sigma_{y,m} = \sigma_y \left(\frac{30}{10}\right)^{0.2} = 1.25\sigma_y$

Roughness (5-32): $\sigma_{z,z_0} = \sigma_z \left(\frac{100}{3}\right)^{0.2} = 2.0\sigma_z$

Building Wake (5-15):

$$\sigma_{y_0} = .23(37) = 8.6m$$

$$\sigma_{z_0} = .47(60) = 28m$$

Mixing Height: Morning = 550m (worst case meteorologically)
(5- 21, 5-22) Afternoon = 1500m (worst case because most people at mall)

WORKSHOP EXAMPLE 1 (cont.)

from (5-9) and (5-10)

Receptor Distance (m)	σ_y (m)	σ_z (m)
	$8.6/1.25 = 6.9 \Rightarrow X_{y_0} = 180$	$28/2.0 = 14 \Rightarrow X_{z_0} = 1100$
800	39 (@ X = 800 + 180) * 1.25 = 49	21 (@ X = 800 + 1100) * 2 = 42
13000	390 (@ X = 13000 + 180) * 1.25 = 490	53 (@ X = 13000 + 1100) * 2 = 106

Series Terms (5-24):

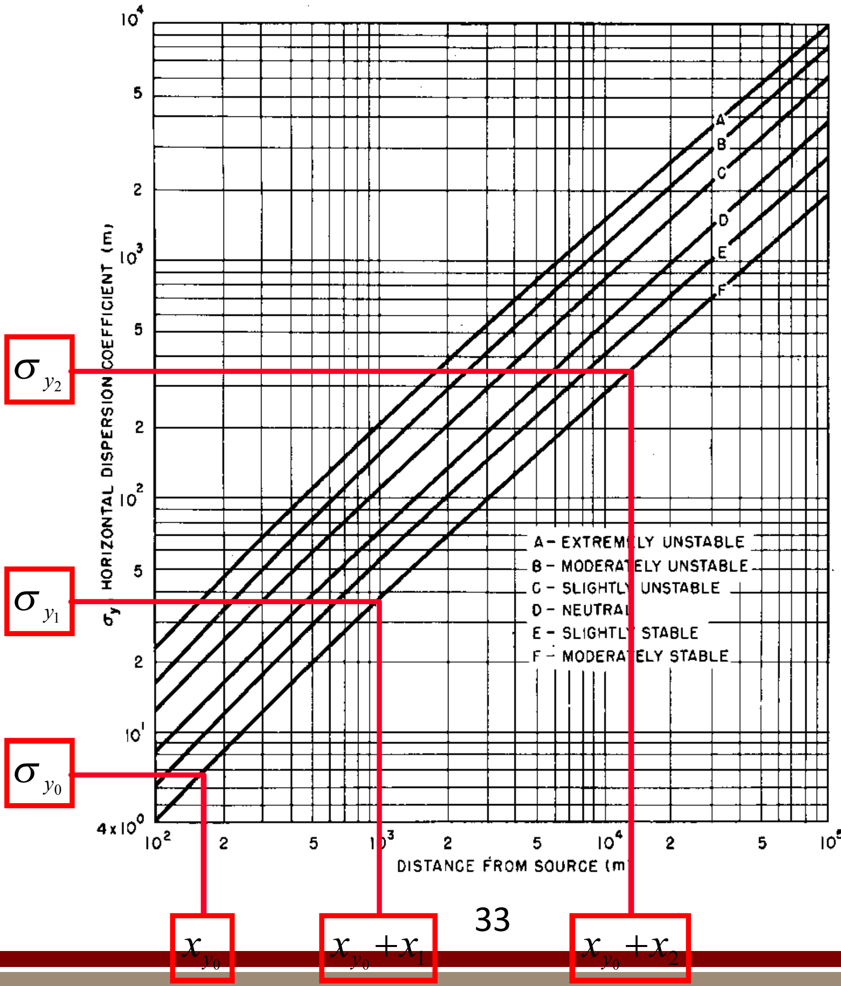
$$\sum_{n=-\infty}^{\infty} 2e^{\left[-2\left(\frac{n1500}{\sigma_z}\right)^2\right]}$$

Z=0
H=0

σ_z \ n	0	-1	+1
42	2	0	0
106	2	0	0

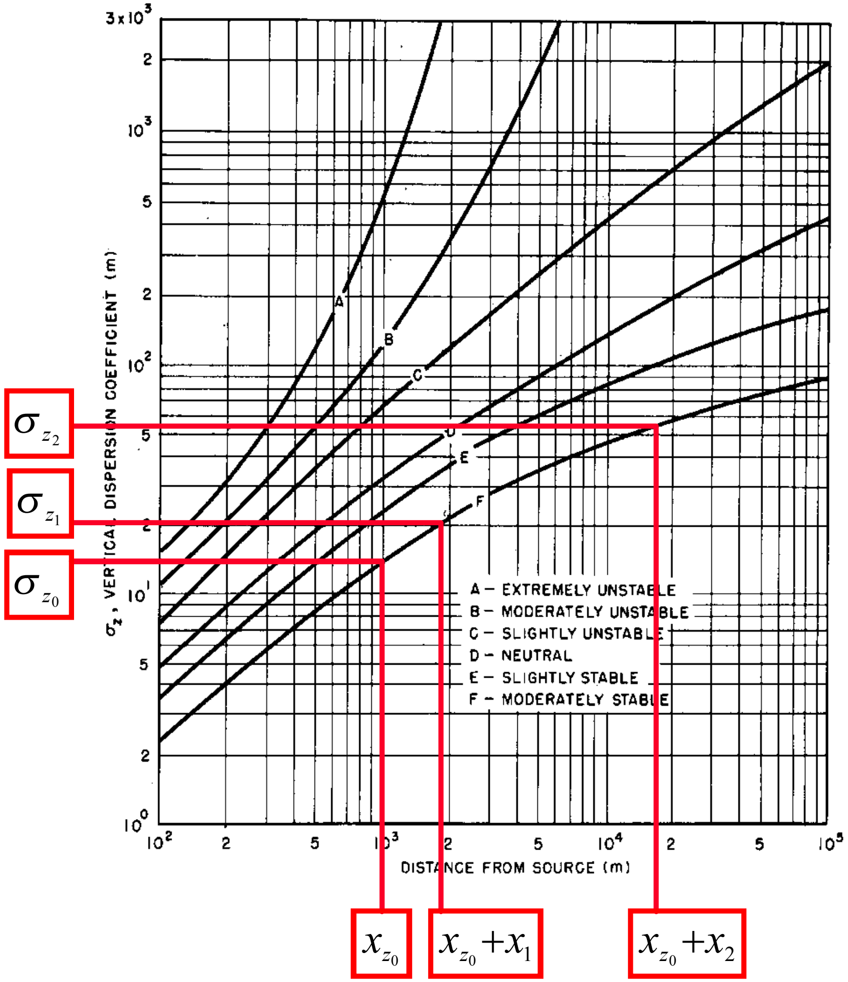
WORKSHOP EXAMPLE 1 (cont.)

Lateral Dispersion (5-9), σ_y, vs. Downwind Distance From Source for Pasquill's Stability Classes



WORKSHOP EXAMPLE 1 (cont.)

Vertical Dispersion (5-10), σ_z, vs. Downwind Distance From Source for Pasquill's Stability Classes



WORKSHOP EXAMPLE 1 (cont.)

(5-24)

1/2 mile

$$\frac{C}{\dot{Q}} = \frac{1}{2\pi(49)(42)(1)}(2) = 1.6x10^{-4}\frac{\text{sec}}{m^3}$$

$$C = 1.6x10^{-4}\frac{\text{sec}}{m^3}\,x\,\frac{1\ \ curie}{1800\ \text{sec}} = 8.9x10^{-8}\frac{curie}{m^3}$$

8 miles

$$= \frac{1}{2\pi(490)(106)(1)}(2) = 6.1x10^{-6}\frac{\text{sec}}{m^3}$$

$$= 6.1x10^{-6}\frac{\text{sec}}{m^3} \times \frac{1\ \ curie}{1800\ \text{sec}} = 3.4x10^{-9}\frac{curie}{m^3}$$

C = Inversely proportional to $\sigma_y \cdot \sigma_z$ (plume centerline, no reflections, no decay)

dist	**$\sigma_y \cdot \sigma_z$**	**$C/C_{0.5\ mi}$**
0.5 mi	**(39) (21)**	**1**
8 mi	**(390) (53)**	**1/25**
50 mi	**(1700) (87)**	**1/180**

Workshop Example 1 – Tadmor and Gur Parameters

For a 30 minute release from this building (assume dimensions of 200 ft. high by 120 ft. wide) of 1 Ci of ^{137}Cs, what is the maximum ground concentration 1/2 mile downwind and at the mall (8 miles downwind). Assume worst case conditions.

Assumptions:

Worst Case - Wind blowing directly towards mall

Concentration at plume centerline (y = z = H = 0)

Low wind speed (u = 1m/s; may not be worst case for short half lives)

Minimize atmospheric dispersion; stability = F

Heat low enough so that no plume rise

Other - Converting dimensions of interest:

1/2 mi ~ 800m

8 mi ~ 13000m

Building height = 200ft ~ 60m

Building width = 120ft ~ 37m

Roughness length (z_0) = 100cm (suburban/urban)

WORKSHOP EXAMPLE 1 – T&G (cont.)

Meander: $$\sigma_{y,m} = \sigma_y \left(\frac{30}{10}\right)^{0.2} = 1.25\sigma_y$$

Roughness: $$\sigma_{z,z_0} = \sigma_z \left(\frac{100}{3}\right)^{0.2} = 2.0\sigma_z$$

Building Wake:
$$\sigma_{y_0} = .23(37) = 8.6m$$
$$\sigma_{z_0} = .47(60) = 28m$$

Mixing Height: Morning = 550m (worst case meteorologically)
Afternoon = 1500m (worst case because most people at mall)

WORKSHOP EXAMPLE 1 – T&G (cont.)

from (5-11)

Parameter	Distance Range (km)	A	B	C	D	E	F
		Stability Class					
a	0.5 - 50	0.36580	0.2751	0.2089	0.1474	0.1046	0.0722
b	0.5 - 50	0.90310	0.9031	0.9031	0.9031	0.9031	0.9031
c	0.5 - 5	0.00025	0.0019	0.2000	0.3000	0.4000	0.2000
	5 - 50			0.5742	0.9605	2.1250	2.1820
d	0.5 - 5	2.12500	1.6021	0.8543	0.6532	0.6021	0.6020
	5 - 50			0.7160	0.5409	0.3979	0.3310

Receptor Distance (m)	σ_y(m)	σ_z(m)
Initial Virtual Source Distance	$8.6 = 1.25 \cdot 0.0722 \cdot x^{0.9031}$ $x = 155$	$28 = 2.0 \cdot 0.2000 \cdot x^{0.6020}$ $x = 1160$
800 m	$1.25 \cdot 0.0722 \cdot (155 + 800)^{0.9031}$ $= 44$	$2.0 \cdot 0.2000 \cdot (1160 + 800)^{0.6020}$ $= 38$
5000 m	$1.25 \cdot 0.0722 \cdot (155 + 5000)^{0.9031}$ $= 203$	$2.0 \cdot 0.2000 \cdot (1160 + 5000)^{0.6020}$ $= 76$

WORKSHOP EXAMPLE 1 – T&G (cont.)

Distance (m)	σ_y (m)	σ_z (m)
Virtual Source Distance @ 5000 m	$203 = 1.25 \cdot 0.0722 \cdot x^{0.9031}$ $x = 5155 - 5000 = 155$	$76 = 2.0 \cdot 2.1820 \cdot x^{0.3310}$ $x = 5712 - 5000 = 712$
13,000	$1.25 \cdot 0.0722 \cdot (155 + 13000)^{0.9031}$ $= 474$	$2.0 \cdot 2.1820 \cdot (712 + 13000)^{0.3310}$ $= 102$

Reflections: $$\sum_{n=-\infty}^{\infty} 2e^{\left[-2\left(\frac{n\times 1500}{\sigma_z}\right)^2\right]}$$

Z=0
H=0

	n		
σ_z	0	-1	+1
38	2	0	0
124	2	0	0

WORKSHOP EXAMPLE 1 – T&G (cont.)

1/2 mile

$$C/\dot{Q} = \frac{2}{2\pi(44\ m)(38\ m)(1\ \frac{m}{s})} = 1.8\text{x}10^{-4}\ \text{s}/m^3$$

8 miles

$$C/\dot{Q} = \frac{2}{2\pi(474\ m)(102\ m)(1\ \frac{m}{s})} = 6.6\text{x}10^{-6}\ \text{s}/m^3$$

$$C = 1.8\text{x}10^{-4}\ \frac{s}{m^3} \times \frac{1\ Ci}{1800\ s} = 1.0\ \text{x}10^{-7}\ \frac{Ci}{m^3}$$

$$C = 6.6\text{x}10^{-6}\ \frac{s}{m^3} \times \frac{1\ Ci}{1800\ s} = 3.7\ \text{x}10^{-9}\ \frac{Ci}{m^3}$$

Workshop Exercise 1

- For a two hour ground level release in the morning of 10 curies of ^{132}I (half-life = 2.3 hours) containing one-half million Btu (147 KW-hr) heat content from a building which is 38.3 meters high and 56.5 meters wide located in a rural area of central Kentucky, what is the concentration of iodine that would be inhaled by a farmer standing in his plowed field 5.67 miles (9100 meters) downwind? Measurements on a met tower near the release indicate a typical day of 4 m/sec wind speed; the temperature at the 10-meter (height) sensor is 0.6 deg F (0.33 deg C) higher than that at the 30-meter sensor.

- Part 2: What concentration would the farmer see if the PBL were moderately stable?
- Part 3: Moderately stable with a wind speed of 1 m/sec?

Deposition Processes

- Dry Deposition
  - Impaction
  - Diffusion (Brownian motion)
  - Gravitational settling
- Wet Deposition
  - Scavenging by precipitation (washout)
  - Scavenging by cloud droplets (rainout)

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Dry Deposition

- **Continuous and slow**

$$D = CV_d\Delta t$$

$D =$ **dry deposition (ground concentration) (Bq/m²)**

$C =$ **near-surface air concentration (Bq/m³)**

$V_d =$ **deposition velocity (m/s)**

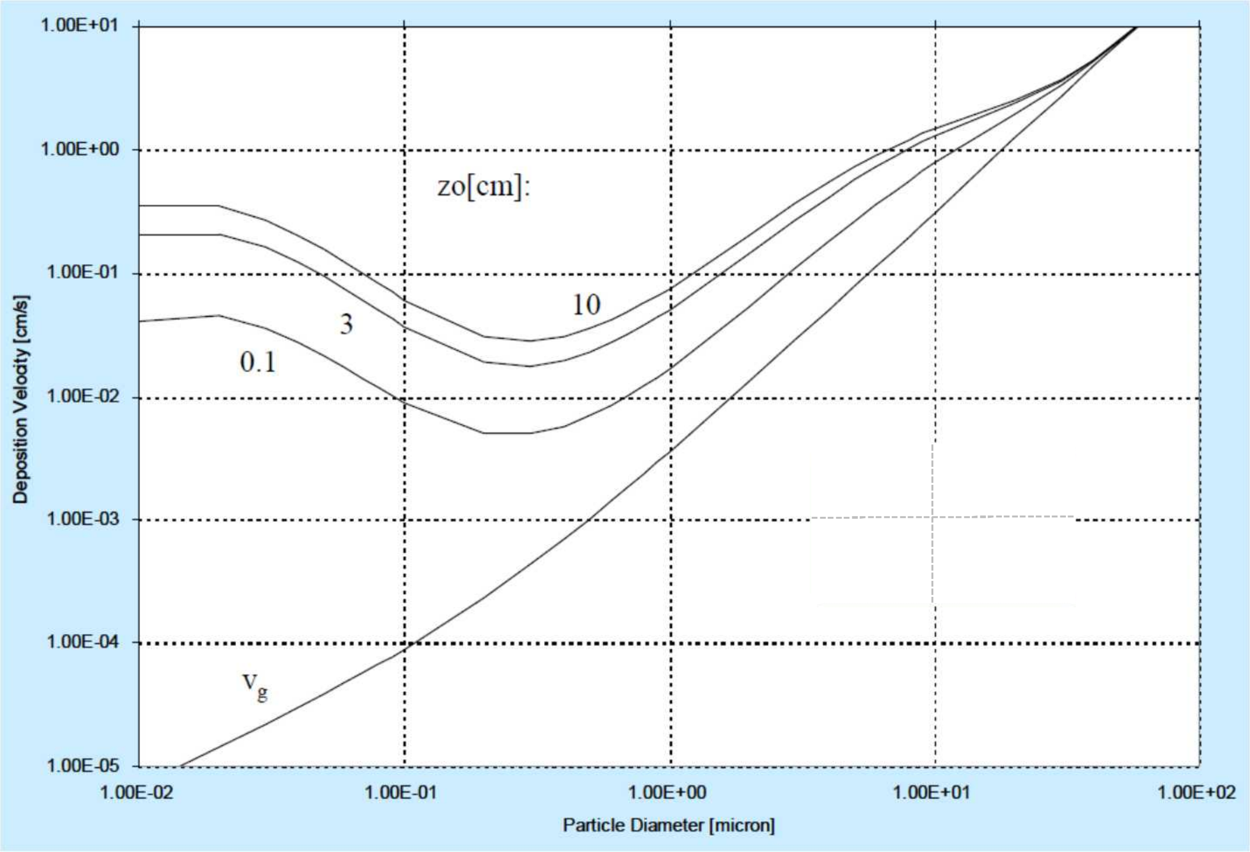
$\Delta t =$ **plume residence time (s)**

- **Approximate formula for deposition losses**

$$\frac{Q}{Q_0} = exp\left(-\frac{V_d\Delta t}{\bar{z}}\right) \qquad \bar{z} = \sqrt{\frac{\pi}{2}}\left(\frac{\sigma_z}{\Sigma}\right)$$

Where Q is the material suspended in the plume (Bq) and Σ represents the summation term in the expression for σ_z (p. 5-24).

Average Deposition Velocities (cm/s)



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Wet Deposition

- Discontinuous (precipitation events)
- Rapid (relative to dry)
  - Λ = scavenging or washout rate (1/s)
  - Λ = function of precipitation type and rate, saturation conditions, contaminant characteristics

$$\frac{dQ}{dt} = -\Lambda\, Q \quad ; \quad \frac{Q}{Q_0} = e^{-\Lambda \cdot \Delta t}$$

Δt = duration of precipitation (s)

$\Lambda = aI^b$

Λ = scavenging rate (1/s)

I = precipitation rate (mm/hr)

a = 9.5×10^{-5}

b = 0.8

Workshop Exercise 2 (Deposition)

- For the release of ^{137}Cs analyzed in the workshop example, what is the deposition (Ci/m^2) one-half mile downwind and at the mall?
- Assumptions (same as workshop example):
  - No rain
  - V_d = 1 cm/sec
- How much of the plume would have deposited prior to the mall if it had been raining steadily throughout the plume's path at a rate of 1 inch/hour?

References

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