# Transport and Dispersion of Air Pollution

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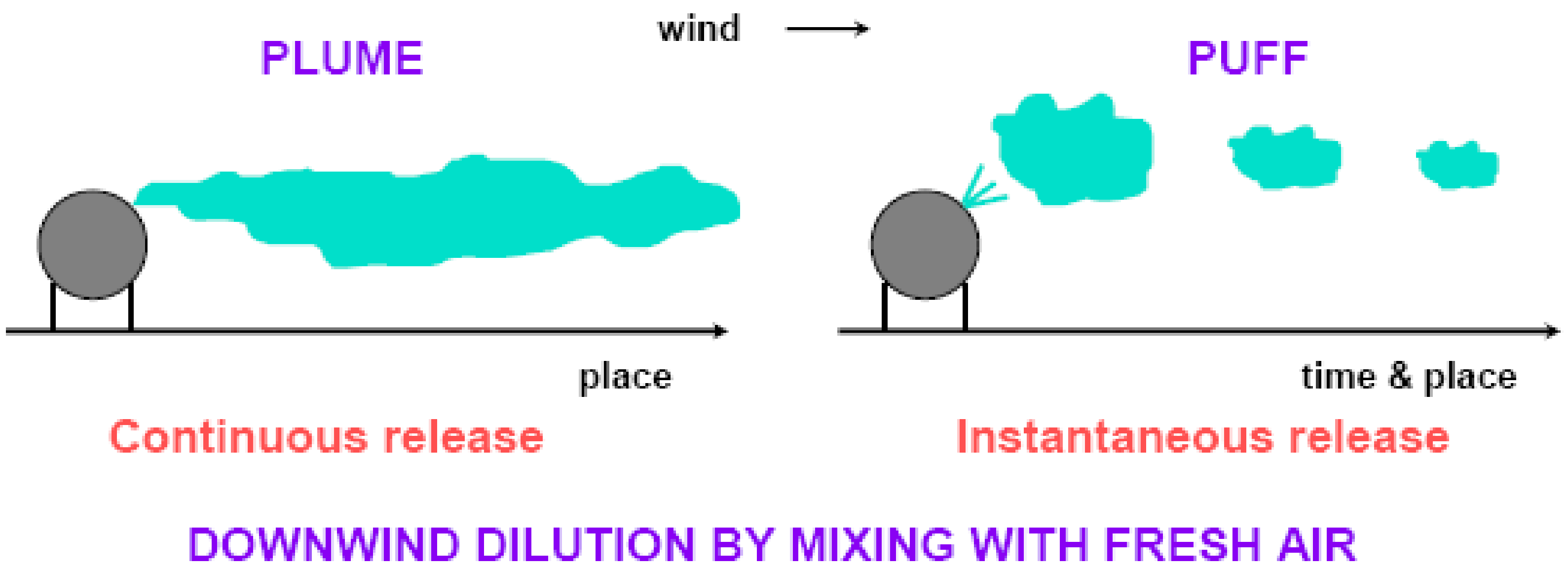
# Air Quality Dispersion Models

- Air quality dispersion models consist of a set of mathematical equations that interpret and predict pollutant concentrations due to plume dispersal and impaction.

- **There are four generic types of models:**

- **The Gaussian models** use the Gaussian distribution equation and are widely used to estimate the impact of nonreactive pollutants.
- **Numerical models** are more appropriate than Gaussian models for area sources in urban locations that involve reactive pollutants, but numerical models require extremely detailed source and pollutant information and are not widely used
- **Statistical models** are used when scientific information about the chemical and physical processes of a source are incomplete or vague and therefore make the use of either Gaussian or numerical models impractical.
- **Physical models** require fluid modeling studies or wind tunneling. This approach involves the construction of scaled models and observing fluid flow around these models.

- Selection of an air quality model for a particular air quality analysis is dependent on *the type of pollutants being emitted*, *the complexity of the source*, and *the type of topography surrounding the facility*.



# Gaussian Distribution

- The Gaussian distribution equation uses relatively simple calculations requiring only two dispersion parameters (i.e. σy and σz) to identify the variation of pollutant concentrations away from the center of the plume.

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z u} e^{\frac{-1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left\{ e^{\frac{-1}{2}\left(\frac{z-H}{\sigma_z}\right)^2} + e^{\frac{-1}{2}\left(\frac{z+H}{\sigma_z}\right)^2} \right\}$$

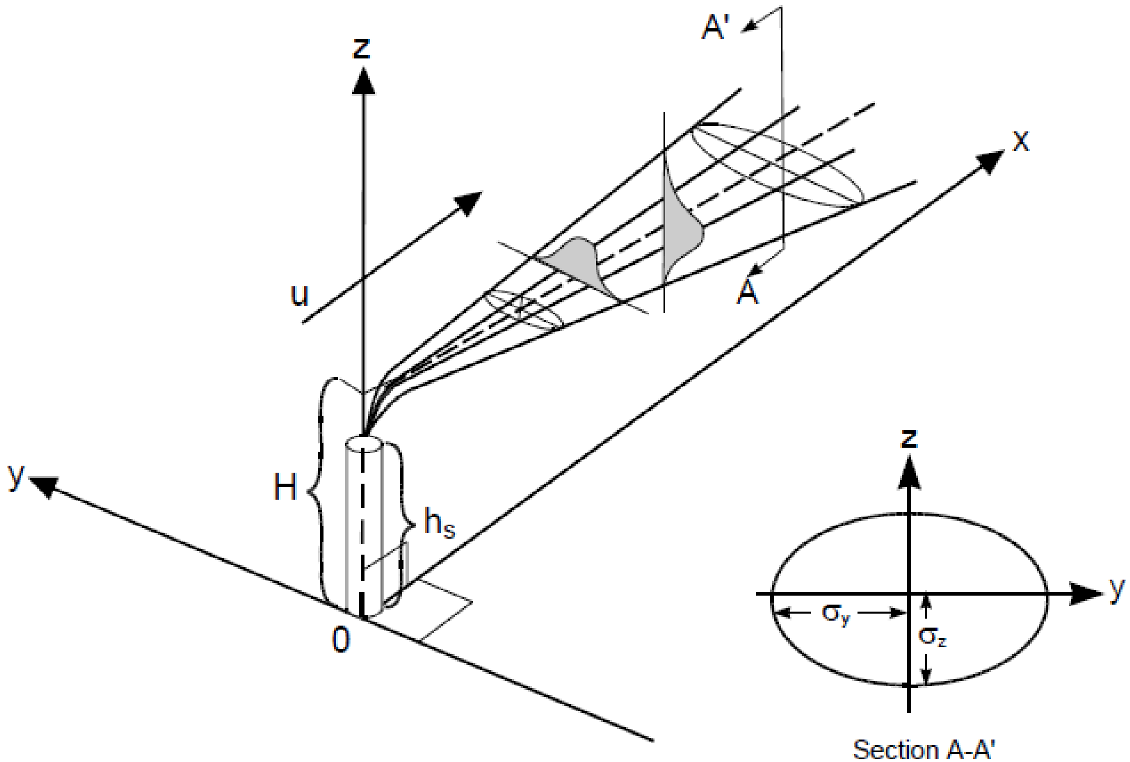
Where:

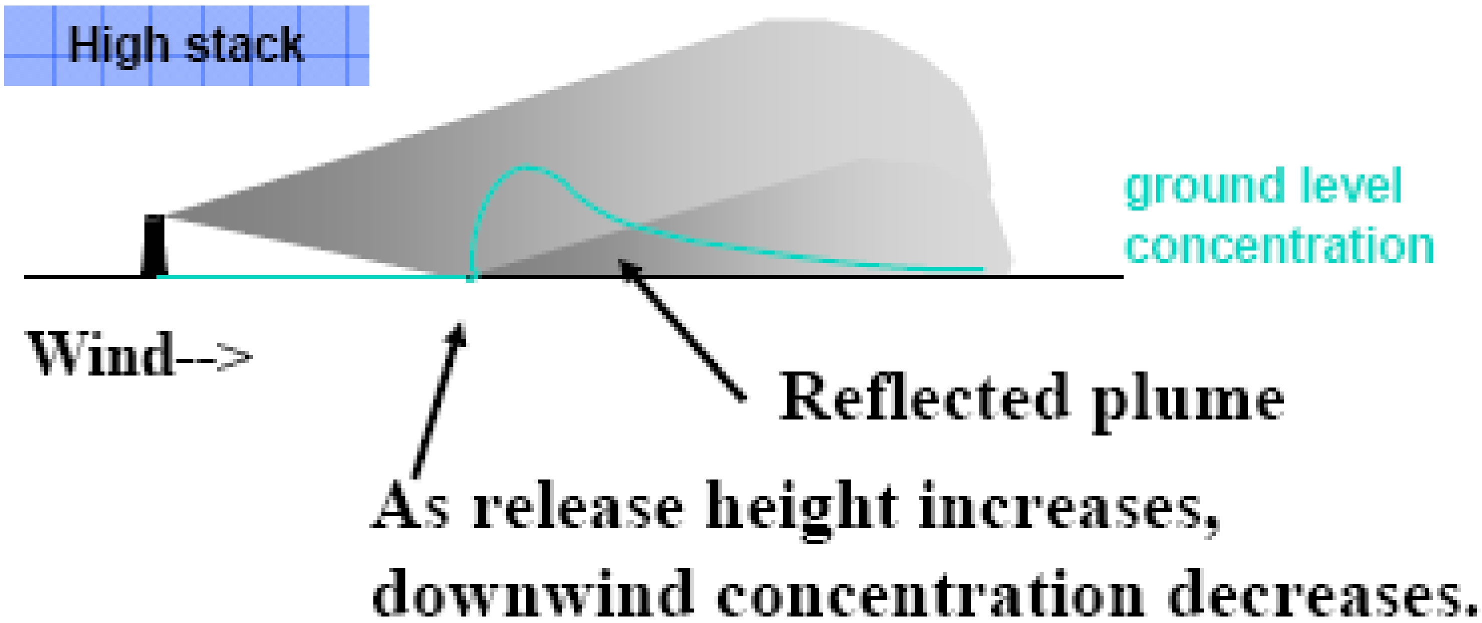
$\chi$ = ground level pollutant concentration ($g/m^3$)
Q = mass emitted per unit time
$\sigma_y$ = standard deviation of pollutant concentration in y (horizontal) direction
$\sigma_z$ = standard deviation of pollutant concentration in z (vertical) direction
u = wind speed
y = distance in horizontal direction
z = distance in vertical direction
H = effective stack height

- ✓ This distribution equation determines ground level pollutant concentrations based on time-averaged atmospheric variables (e.g. temperature, wind speed).

In order for a plume to be modeled using the Gaussian distribution the following assumption must be made:

- The plume spread has a normal distribution
- The emission rate (Q) is constant and continuous
- Wind speed and direction is uniform




High stack
ground level
concentration
Wind-->
Reflected plume
As release height increases,
downwind concentration decreases.

# Stability Classifications

- For the dispersion estimation and modeling purposes, the levels of stability are classified into six stability classes based on five surface wind speed categories, three types of daytime insolation, and two types of nighttime cloudiness.

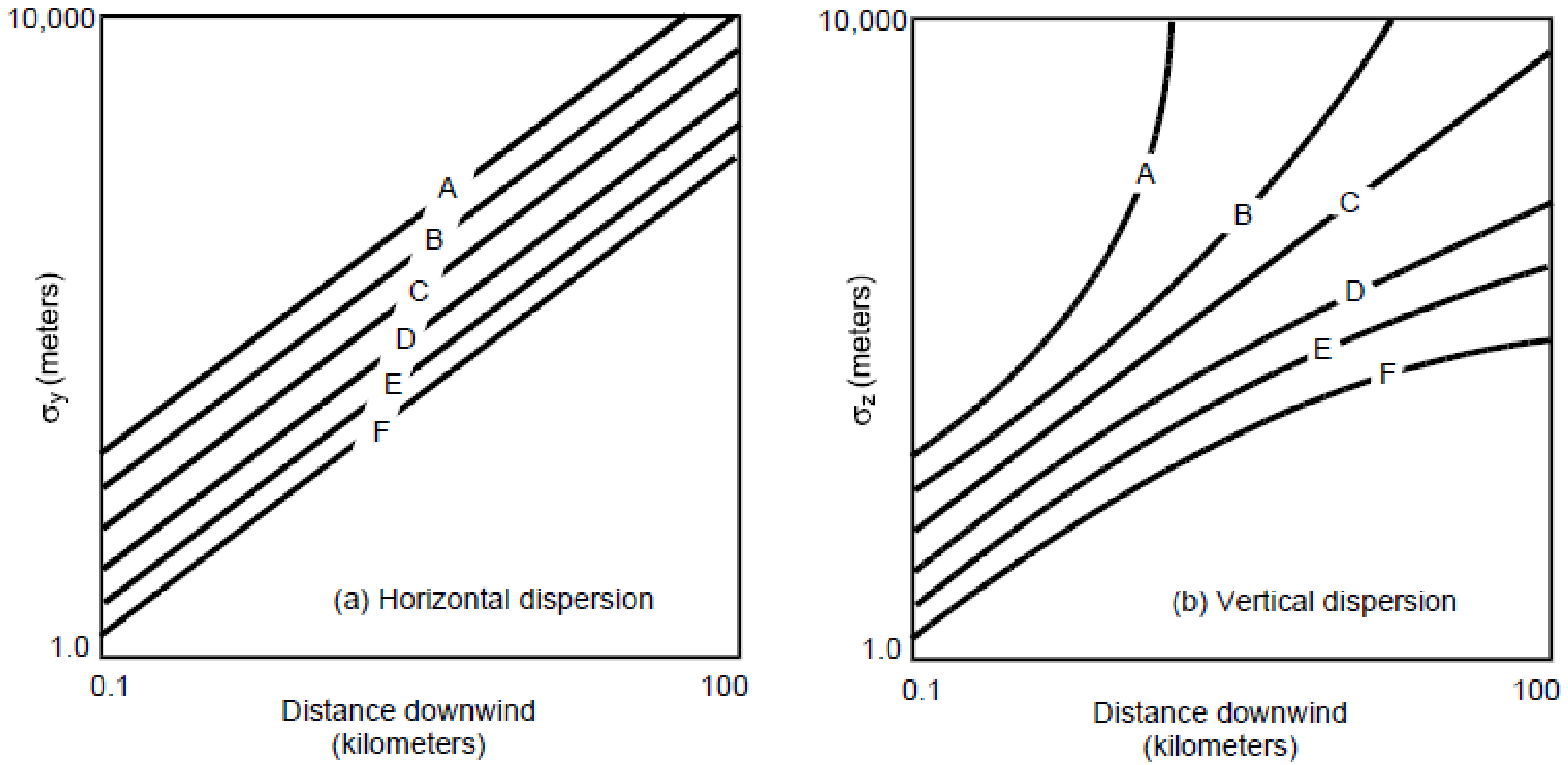
- These stability classes are referred to as Pasquill-Gifford stability classes:

| Surface wind | Insolation | | | Night | |
|---|---|---|---|---|---|
| Speed (at 10 m) (m/s) | Strong | Moderate | Slight | ≥ 4/8 low cloud cover* | ≤ 3/8 cloud cover |
| < 2 | A | A-B | B | - | - |
| 2-3 | A-B | B | C | E | F |
| 3-5 | B | B-C | C | D | E |
| 5-6 | C | C-D | D | D | D |
| > 6 | C | D | D | D | D |

* Thinly overcast

Note: Neutral Class D should be assumed for overcast conditions during day or night.

| | |
|---|---|
| A: extremely unstable | D: Neutral condition |
| B: Moderately unstable | E: Slightly stable |
| C: Slightly unstable | F: Moderately stable |



# Gaussian form of plume equation

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

**Top View of plume**

**--> Wind**

$\langle C\rangle(x,y,z)=$ Ave. conc. (20-30 min ave)

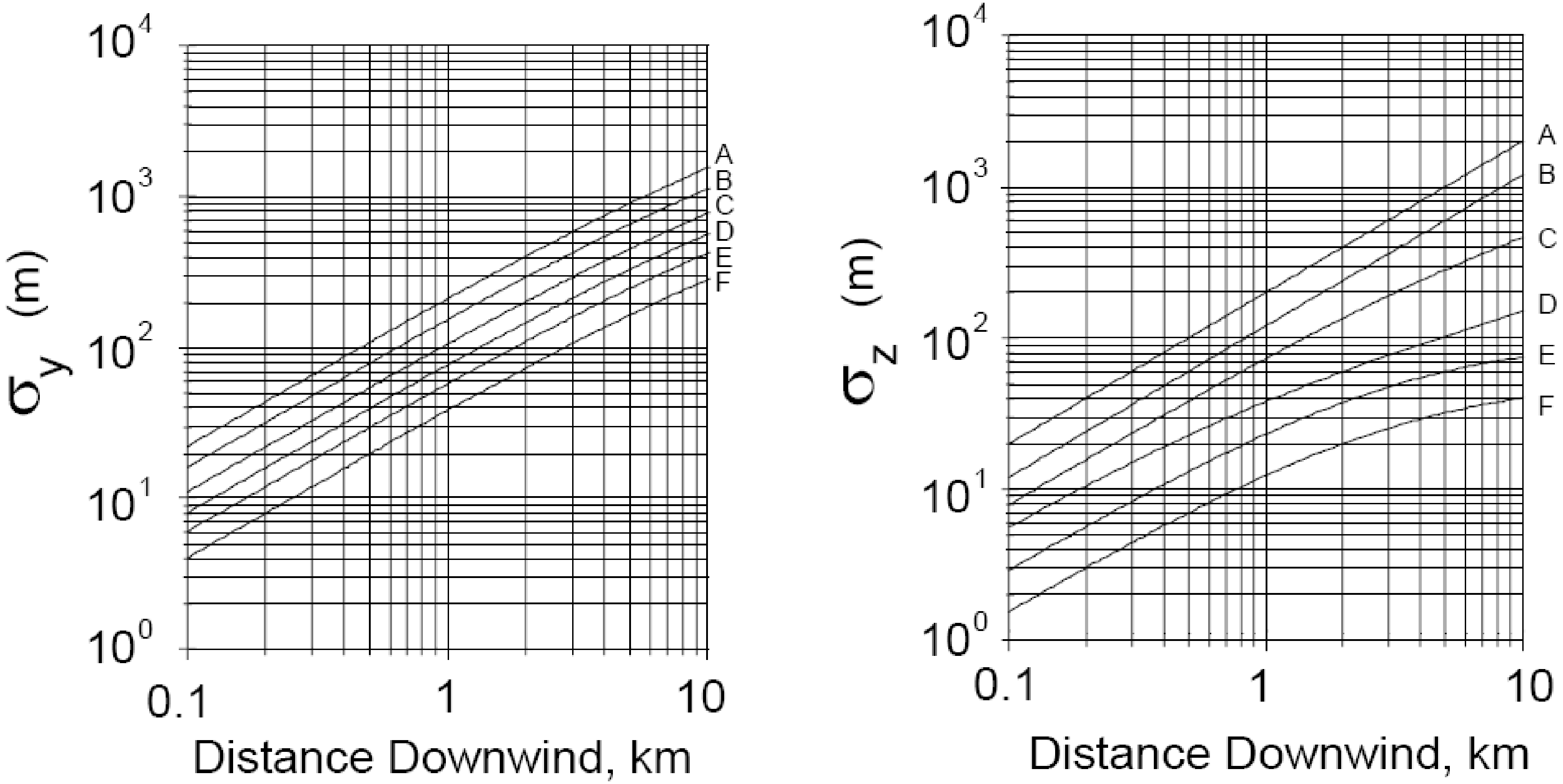
$Q_m=$ Release rate (mass/time)

$\sigma_y,\sigma_z=$ Dispersion coefficients = f(stability class, downwind distance)

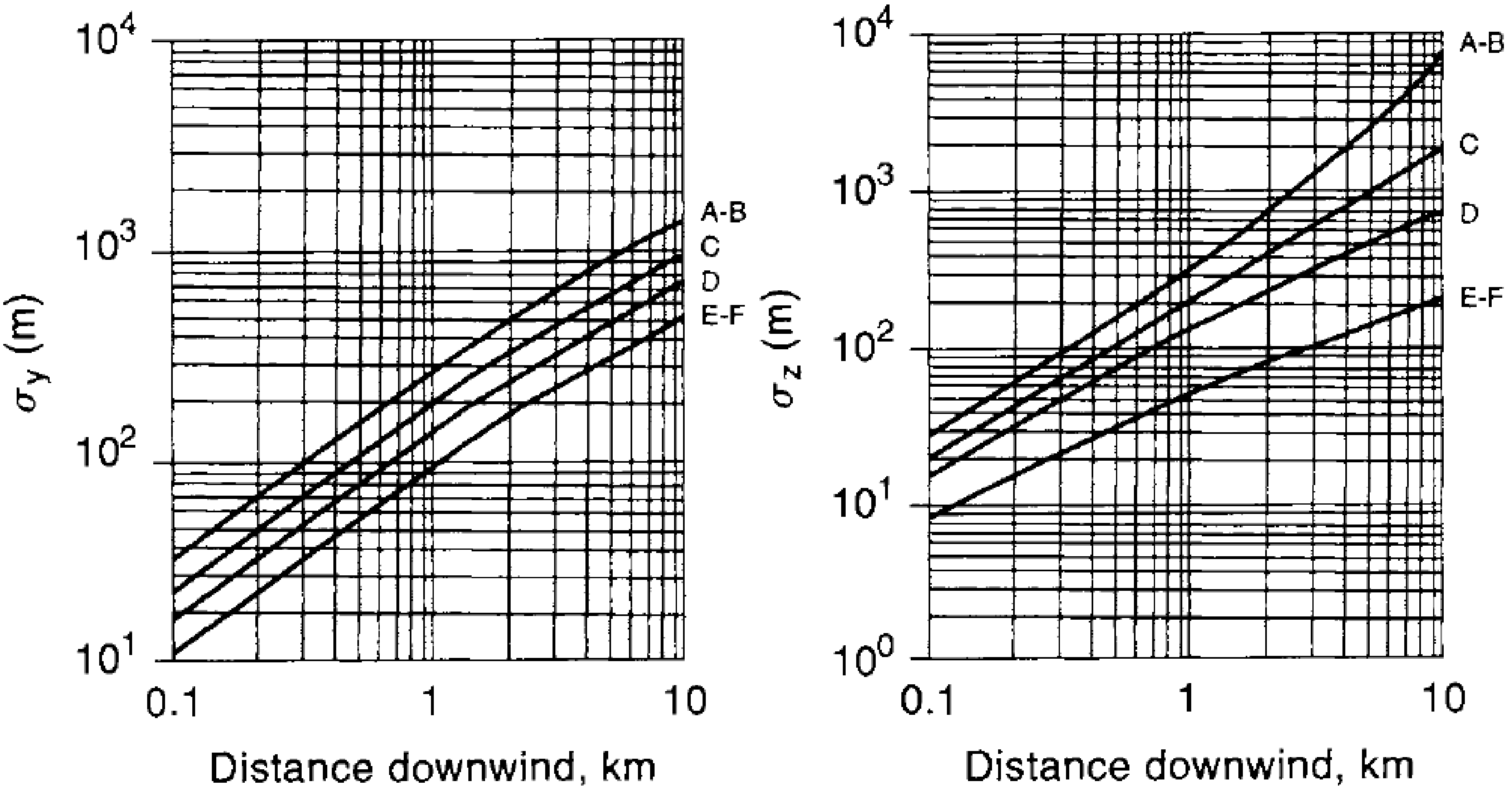
$u=$ Wind speed (length/time)

$y,z=$ Coordinates (length)

$H_r=$ Release height (length)




**Dispersion coefficients for plume model for rural releases.**




**Dispersion coefficients for plume model for urban releases.**

**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 | $\sigma_y$ (m) | $\sigma_z$ (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 | $0.11x(1 + 0.0004x)^{-1/2}$ | $0.08x(1 + 0.0015x)^{-1/2}$ |

A–F are defined in Table 5-1.

**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] |

Stability classes:

- A, extremely unstable
- B, moderately unstable
- C, slightly stable
- D, neutrally stable
- E, slightly stable
- F, moderately stable

[3]Strong insolation corresponds to a sunny midday in midsummer in England. Slight insolation to similar conditions in midwinter.

[4]Night refers to the period 1 hour before sunset and 1 hour after dawn.

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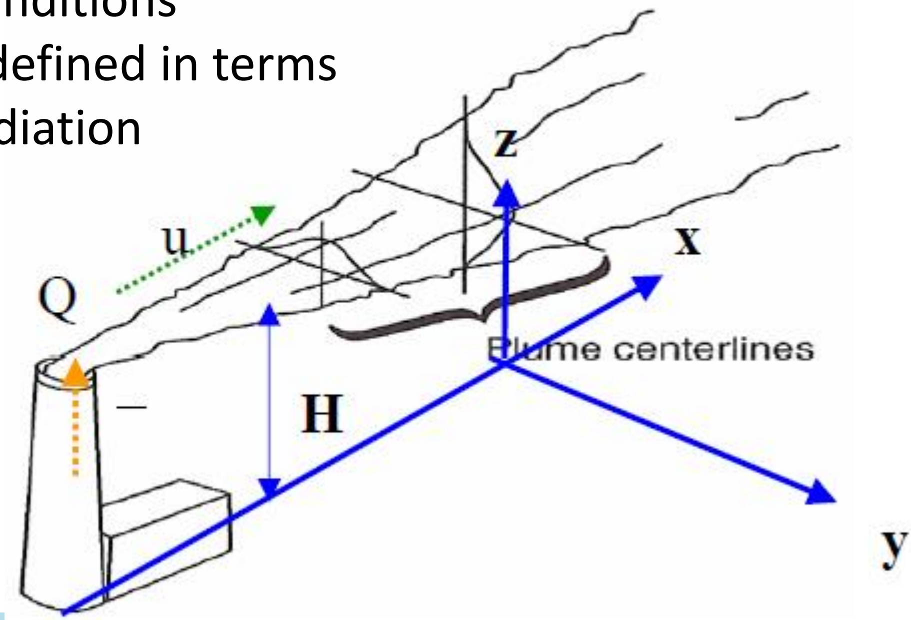
A–F are defined in Table 5-1.

# Gaussian Model Assumptions

Gaussian dispersion modeling based on a number of assumptions including

- Source pollutant emission rate = constant (Steady-state)
- Constant Wind speed, wind direction, and atmospheric stability class
- Pollutant Mass transfer primarily due to bulk air motion in the x-direction
- No pollutant chemical transformations occur
- Wind speeds are >1 m/sec.
- Limited to predicting concentrations > 50 m downwind
- σy and σz depend on the atmospheric conditions
- Atmospheric stability classifications are defined in terms of surface wind speed, incoming solar radiation and cloud cover



# Plume Dispersion Equations

- **Ground-level concentration due to an elevated source (z=0 , H)**

$$C(x, y, 0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp - \left[ \frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2} \right]$$

- **Ground-level concentration due to an elevated source, directly downwind of the source at ground level (Center Line), (y=z=0 , H)**

$$C(x, 0, 0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp \left[ \frac{-H^2}{2\sigma_z^2} \right]$$

- **If the emission source is at ground level with no effective plume rise then**

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

- **Ground Level Center Line –Ground Point Source (y = 0, H = 0)**

$$C(x,0,0;0) = \frac{Q}{\pi u \sigma_y \sigma_z}$$

- **Maximum Ground Level Concentration**

The ground level concentration at the center line is

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

where, ***e*** **= 2.71**

The maximum occurs at

$$dC / d\sigma_z = 0 \quad \Rightarrow \sigma_z = \frac{H}{\sqrt{2}}$$

at the distance $x_{max}$ for which $\sigma_z = \frac{H}{\sqrt{2}}$

## Example 5-1

On an overcast day a stack with an effective height of 60 m is releasing sulfur dioxide at the rate of 80 g/s. The wind speed is 6 m/s. The stack is located in a rural area. Determine

a. The mean concentration of $SO_2$ on the ground 500 m downwind.
b. The mean concentration on the ground 500 m downwind and 50 m crosswind.
c. The location and value of the maximum mean concentration on ground level directly downwind.

### Solution

a. This is a continuous release. The ground concentration directly downwind is given by Equation 5-51:

$$\langle C \rangle (x, 0, 0) = \frac{Q_m}{\pi \sigma_y \sigma_z u} \exp\left[ -\frac{1}{2} \left( \frac{H_r}{\sigma_z} \right)^2 \right]. \qquad (5\text{-}51)$$

From Table 5-1 the stability class is D.

The dispersion coefficients are obtained from either Figure 5-11 or Table 5-2. Using Table 5-2:

$$\sigma_y = 0.08x(1 + 0.0001x)^{-1/2}$$
$$= (0.08)(500 \text{ m})[1 + (0.0001)(500 \text{ m})]^{-1/2} = 39.0 \text{ m},$$
$$\sigma_z = 0.06x(1 + 0.0015x)^{-1/2}$$
$$= (0.06)(500 \text{ m})[1 + (0.0015)(500 \text{ m})]^{-1/2} = 22.7 \text{ m}.$$

Substituting into Equation 5-51, we obtain

$$\langle C \rangle (500 \text{ m}, 0, 0) = \frac{80 \text{ g/s}}{(3.14)(39.0 \text{ m})(22.7 \text{ m})(6 \text{ m/s})} \exp\left[ -\frac{1}{2} \left( \frac{60 \text{ m}}{22.7 \text{ m}} \right)^2 \right]$$
$$= 1.45 \times 10^{-4} \text{ g/m}^3.$$

**b.** The mean concentration 50 m crosswind is found by using Equation 5-50 and by setting $y$ = 50. The results from part a are applied directly:

$$\langle C\rangle(500\text{ m}, 50\text{ m}, 0) = \langle C\rangle(500\text{ m}, 0, 0)\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$

$$= (1.45 \times 10^{-4}\text{ g/m}^3)\exp\left[-\frac{1}{2}\left(\frac{50\text{ m}}{39\text{ m}}\right)^2\right]$$

$$= 6.37 \times 10^{-5}\text{ g/m}^3.$$

**c.** The location of the maximum concentration is found from Equation 5-53:

$$\sigma_z = \frac{H_r}{\sqrt{2}} = \frac{60\text{ m}}{\sqrt{2}} = 42.4\text{ m}.$$

From Figure 5-10 for D stability, $\sigma_z$ has this value at about 1200 m downwind. From Figure 5-10 or Table 5-2, $\sigma_y = 88$ m. The maximum concentration is determined using Equation 5-52:

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

$$= \frac{(2)(80\text{ g/s})}{(2.72)(3.14)(6\text{ m/s})(60\text{ m})^2}\left(\frac{42.4\text{ m}}{88\text{ m}}\right)$$

$$= 4.18 \times 10^{-4}\text{ g/m}^3. \qquad (5\text{-}52)$$

# Example (Process Safety Book, Page 208)

Chlorine is used in a particular chemical process. A source model study indicates that for a particular accident scenario 1.0 kg of chlorine will be released instantaneously. The release will occur at ground level. A residential area is 500 m away from the chlorine source. Determine

a. The time required for the center of the cloud to reach the residential area. Assume a wind speed of 2 m/s.

**b.** The maximum concentration of chlorine in the residential area. What stability conditions and wind speed produces the maximum concentration?

c. Determine the distance the cloud must travel to disperse the cloud to a maximum concentration