Atmospheric Dispersion

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  – Fundamental concepts
  – Classification of models

• Gaussian plume model
  – Derivation and limitations

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• Examples

• Exposure pathways and radiological impact assessment
What is an atmospheric dispersion model?

An atmospheric dispersion model is a:

- mathematical simulation of the physics and chemistry governing the transport, dispersion and transformation of pollutants in the atmosphere.

- means of estimating downwind air pollution concentrations, given information about the pollutant emissions and nature of the atmosphere.
Industrial facilities are required to obtain permits to emit into the atmosphere and to demonstrate their compliance with regulations.

In the process of applying for permits, dispersion models are generally used to assess the impact of point source emission.
Dispersion Model

- Emission Source Information
- Topography
- Meteorology
- Receptors

Atmospheric Concentration at Receptors
Meteorological Model

Emission Model

Chemical Model

Source Dispersion Model

Receptor Model
Emission Model

- Estimates temporal and spatial emission rates based on activity level, emission rate per unit of activity and meteorology

Meteorological Model

- Describes transport, dispersion, vertical mixing and moisture in time and space

Chemical Model

- Describes transformation of directly emitted particles and gases to secondary particles and gases; also estimates the equilibrium between gas and particles for volatile species
Source Dispersion Model

- Uses the outputs from the previous models to estimate concentrations measured at receptors; includes mathematical simulations of transport, dispersion, vertical mixing, deposition and chemical models to represent transformation.

Receptor Model

- Infers contributions from different primary source emissions or precursors from multivariate measurements taken at one or more receptor sites.
Classifications of Models

• Developed for a number of pollutant types and time periods

  ◦ **Short-term** models – for a few hours to a few days; worst case episode conditions
  ◦ **Long-term** models – to predict seasonal or annual average concentrations; health effects due to exposure

• Classified by

  ◦ **Non-reactive** models – pollutants such as SO$_2$ and CO, FPNG, Ar-41 etc
  ◦ **Reactive** models – pollutants such as O$_3$, NO$_2$, etc.
Classifications of Models

• Classified by coordinate system used
  ◦ Grid-based
    • Region divided into an array of cells
    • Used to determine compliance with NAAQS
  ◦ Trajectory
    • Follow plume as it moves downwind

• Classified by level of sophistication
  ◦ Screening: simple estimation use preset, worst-case meteorological conditions to provide conservative estimates.
  ◦ Refined: more detailed treatment of physical and chemical atmospheric processes; require more detailed and precise input data.
Data Inputs: Emission Sources

• Source types

• Emissions of each pollutant

• Location and Height of emission sources

• Stack Characteristics
Source Types

- **Point sources** (stacks)
- **Line sources** (roads)
- **Area sources** (treatment ponds)
- **Volume sources** (buildings)
Atmospheric dispersion modeling procedure

- Background concentrations of pollutant
- Meteorological conditions
- Source data:
  - site description
  - emission rate
- Model options:
  - receptor grid
  - dispersion parameters
- Local topographical features

Atmospheric dispersion model

Stage 1
Data input

Stage 2
Data processing

Stage 3
Data output

Stage 4
Data analysis

Prediction of ground level concentrations of pollutants

Assessment of potential environmental and health effects
• Dispersion models
  – Box model
  – Gaussian plume model
  – Gaussian puff model
  – Complex numerical models
    • ‘now-casting’ (diagnostic)
    • 'forecasting' (prognostic)
The modeling procedures can be categorized into four generic classes:

- Gaussian
- Numerical
- Statistical or empirical
- Physical

The emphasis is on Gaussian-plume type models for continuous releases, which are at the core of most regulatory models.

Gaussian models are the most widely used techniques for estimating the impact of nonreactive pollutants.
Gaussian Dispersion Models

- Most widely used
- Based on the assumption
  - plume spread results primarily by **molecular diffusion**
  - horizontal and vertical pollutant concentrations in the plume are normally distributed (double Gaussian distribution)
- Plume spread and shape vary in response to meteorological conditions
Atmospheric Modelling

**Gaussian Plume Model (GPM):**

The three-dimensional diffusion equation for atmospheric diffusion is:

\[
\frac{\partial \chi}{\partial t} = \frac{\partial}{\partial x} \left[ K_x \left( \frac{\partial \chi}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ K_y \left( \frac{\partial \chi}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ K_z \left( \frac{\partial \chi}{\partial z} \right) \right]
\]

Where,

- \( x, y \) and \( z \) = the downwind, cross-wind and vertical directions, respectively
- \( K_x, K_y, K_z \) = Diffusivity in x-, y- and z- directions
Atmospheric Modelling

Assuming continuity of mass, solution to the diffusion equation with varying initial and boundary conditions, yields Gaussian Distribution of concentration, $\chi$.

and, the standard deviation of the Gaussian distribution is given by:

$$\sigma^2 = 2Kt$$
The mass rate of diffusion $N_x$ of a gaseous species in the $x$-direction at some cross-sectional area $A$ is given by the expression:

$$N_x = -A \left( \frac{\partial (D_x C)}{\partial x} \right)$$

Where;
- $N_x$ is the mass transfer per unit time
- $D_x$ is the mass diffusivity, area/time, in the $x$ direction
- $C$ is the concentration in mass per unit volume
- $A$ is the cross-sectional area in the $x$-direction
Schematic for the Development of Gaussian Plume Model

\[ N_x = -dydz \frac{\partial(DxC)}{\partial x} \]

(bulk motion in) = \( CU \ dy \ dz \)

Bulk Motion Out
\[ N_x = -dy \, dz \, \frac{\partial (Dx \cdot C)}{\partial x} \]

\[ N_{x+dx} = -dy \, dz \, \frac{\partial (Dx \cdot C)}{\partial x} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial (Dx \cdot C)}{\partial x} \right) dy \, dz \right] \, dx \]

\[ N_{x+dx} - N_x = \frac{\partial}{\partial x} \left[ \left( \frac{\partial (Dx \cdot C)}{\partial x} \right) dy \, dz \right] \, dx \, dy \, dz \]

**rate in (bulk motion)** = \( CU \, dy \, dz \)

**rate out (bulk motion)** = \( CU \, dy \, dz + \frac{\partial}{\partial x} (CU \, dy \, dz) \, dx \)

**net rate (bulk motion)** = \(- \frac{\partial}{\partial x} CU \, dx \, dy \, dz \)

**rate of change within** \( dx \, dy \, dz \) = \( \frac{\partial C}{\partial t} \, dx \, dy \, dz \)
\[
\frac{\partial C}{\partial t} = -\frac{\partial}{\partial x}(CU) + \frac{\partial}{\partial x}\left(\frac{\partial(DxC)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial(DyC)}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial(DzC)}{\partial z}\right)
\]

Where;

- \(x\) = along-wind coordinate measured in wind direction from the source
- \(y\) = cross-wind coordinate direction
- \(z\) = vertical coordinate measured from the ground
- \(C(x,y,z)\) = mean concentration of diffusing substance at a point \((x,y,z)\) [kg/m\(^3\)]
- \(D_y, D_z\) = mass diffusivity in the direction of the y- and z- axes [m\(^2\)/s]
- \(U\) = mean wind velocity along the x-axis [m/s]

\[
\frac{\partial C}{\partial t} + \frac{\partial(CU)}{\partial x}
\]

Time rate of change and advection of the cloud by the mean wind

\[
\frac{\partial}{\partial x}\left(\frac{\partial(DxC)}{\partial x}\right), \text{etc.}
\]

Turbulent diffusion of material relative to the center of the pollutant cloud. (the cloud will expand over time due to these terms.)
Assumptions

✓ Mass transfer due to bulk motion in x-direction far out shadows the contribution due to mass diffusion. That is the second term on the right side of Equation is far smaller than the first term and may be dropped from the equation

✓ We are primarily interested in the steady-state solution to the dispersion of the pollutants in the atmosphere. Hence the $\frac{\partial C}{\partial t}$ quantity is zero

✓ Even though the wind speed does vary in the three coordinate directions, the variation is relatively small. Therefore it is appropriate to assume that the wind speed $U$ is constant

✓ The major transport direction due to the wind is chosen to lie along the x-axis

✓ $D_x$, $D_y$ and $D_z$ are constant
The general solution to this second-order partial differential equation is

\[ C = Kx^{-1} \exp\left\{-\left(\frac{y^2}{Dy} + \frac{z^2}{Dz} \right)\frac{U}{4x}\right\} \]

Where K is an arbitrary constant whose value is determined by the boundary conditions.

The rate of transfer of pollutant through any vertical plane downwind from the source is a constant in steady state, and this constant must equal the emission rate of the source, Q.

\[ Q = \int \int UC \ dy \ dz \]

Generally the limits of integration on dy are minus to plus infinity and for a point source at Elevation H above the ground level the limits of integration on z are taken from

\[ Q = \int \int \int KUx^{-1} \exp\left[-\left(\frac{y^2}{Dy} + \frac{z^2}{Dz}\right)\frac{U}{4x}\right] dy \ dz \]
After integrating

\[
K = \frac{Q}{4\pi (Dy Dz)^{1/2}}
\]

Where \( Q \) is the strength of the emission source, mass emitted per unit time

\[
C(x, y, z) = \frac{Q}{4\pi x (Dy Dz)^{1/2}} \exp \left[ -\left( \frac{y^2}{Dy} + \frac{z^2}{Dz} \right) \frac{U}{4x} \right]
\]

Gaussian parameters

\[
\sigma_y = \sqrt{2Dy \frac{x}{U}} \quad \text{and} \quad \sigma_z = \sqrt{2Dz \frac{x}{U}}
\]
The general equation to calculate the steady state concentration of an air contaminant in the ambient air resulting from a point source is given by:

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

Where;
\[
c(x, y, z) = \text{mean concentration of diffusing substance at a point (x, y, z) [kg/m}^3\text{]}
\]
\[
x = \text{downwind distance [m]},
\]
\[
y = \text{crosswind distance [m]},
\]
\[
z = \text{vertical distance above ground [m]},
\]
\[
Q = \text{contaminant emission rate [mass/s]},
\]
\[
\sigma_y = \text{lateral dispersion coefficient function [m]},
\]
\[
\sigma_z = \text{vertical dispersion coefficient function [m]},
\]
\[
U = \text{mean wind velocity in downwind direction [m/s]},
\]
\[
H = \text{effective stack height [m]}.\]
Plume Boundary
Plume Dispersion by Gaussian Distribution and Coordinate System
Effect of atmospheric stability on plumes:
The lateral dispersion coefficient function and, the vertical dispersion coefficient functions depend on the downwind distance and the atmospheric stability class. These coefficients in meters can be obtained using Pasquill-Gifford-Turner estimates shown in the equations below:

\[
\sigma_{PGT_y}(s, x) = (k_{s,1} x) \left[ 1 + \left( \frac{x}{k_{s,2}} \right) \right]^{-k_{s,3}}
\]

\[
\sigma_{PGT_z}(s, x) = (k_{s,4} x) \left[ 1 + \left( \frac{x}{k_{s,2}} \right) \right]^{-k_{s,5}}
\]

where,

- \( s \) = an integer [1-6] representing the atmospheric stability shown in Table 1
- \( k_x, x \) = empirical constants, values for each of the stability class can be obtained from Green et al. (1960)
## Atmospheric Stability Classes

<table>
<thead>
<tr>
<th>Wind Speed, 10 m (m/sec)</th>
<th>Day</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt;2</td>
<td>A</td>
<td>A–B</td>
</tr>
<tr>
<td>2–3</td>
<td>A–B</td>
<td>B</td>
</tr>
<tr>
<td>3–5</td>
<td>B</td>
<td>B–C</td>
</tr>
<tr>
<td>&gt;6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

Pasquill Stability categories (1995)
Dispersion Coefficients: Horizontal

Graph showing the relationship between the horizontal dispersion coefficient (m) and the distance from the source (m). The graph includes lines labeled A through F, each representing different stability conditions:

- A: Extremely unstable
- B: Moderately unstable
- C: Slightly unstable
- D: Neutral
- E: Slightly stable
- F: Moderately stable

Axes:
- Y-axis: Horizontal dispersion coefficient (m)
- X-axis: Distance from source (m)
Dispersion Coefficients: Vertical

- A - Extremely unstable
- B - Moderately unstable
- C - Slightly unstable
- D - Neutral
- E - Slightly stable
- F - Moderately stable

Graph showing the relationship between vertical dispersion coefficient ($\sigma_z$) and distance from source (m).
Gaussian Dispersion Equation

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

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

Plume Rise

- \( H \) is the sum of the physical stack height and plume rise. \( H = \Delta h_{\text{plume rise}} + h_{\text{actual stack}} \)
Plume Rise

**Buoyant plume:** Initial buoyancy >> initial momentum

**Forced plume:** Initial buoyancy ~ initial momentum

**Jet:** Initial buoyancy << initial momentum

- For neutral and unstable atmospheric conditions, **buoyant rise** can be calculated by

\[
\Delta h_{\text{plume rise}} = \frac{21.425 F^{0.75}}{u} \quad (F < 55 \, m^4 / s^3)
\]

\[
\Delta h_{\text{plume rise}} = \frac{38.71 F^{0.6}}{u} \quad (F > 55 \, m^4 / s^3)
\]

where **buoyancy flux** is

\[
F = g V_s d^2 (T_s - T_a) / 4 T_s
\]

- \(V_s\): Stack exit velocity, m/s
- \(d\): top inside stack diameter, m
- \(T_s\): stack gas temperature, K
- \(T_a\): ambient temperature, K
- \(g\): gravity, 9.8 m/s²
\[ C(x, y, z) = \frac{Q}{2\pi\sigma_x \sigma_y \bar{u}} \exp \left[ -\frac{y^2}{2\sigma_y^2} \right] \left\{ \exp \left[ -\frac{(z-H)^2}{2\sigma_z^2} \right] + \exp \left[ -\frac{(z+H)^2}{2\sigma_z^2} \right] \right\} \]
Effect of ground reflection on pollutant concentration downwind.

Ground level concentration

\[
C = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp \left[ -\frac{y^2}{2\sigma_y^2} \right] \exp \left[ -\frac{H^2}{2\sigma_z^2} \right]
\]
Under moderately stable to near neutral conditions, 
\[ \sigma_y = k_1 \sigma_z \]

The ground level concentration at the center line is
\[
C(x,0,0) = \frac{Q}{\pi k_1 \sigma_z^2 u} \exp \left[ - \frac{H^2}{2 \sigma_z^2} \right]
\]

The maximum occurs at
\[
dC / d\sigma_z = 0 \quad \Rightarrow \quad \sigma_z = \frac{H}{\sqrt{2}}
\]

Once \( \sigma_z \) is determined, \( x \) can be known and subsequently \( C \).
\[
C(x,0,0) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp[-1] = 0.1171 \frac{Q}{\sigma_y \sigma_z u}
\]
• Restrictions for GPM
  – In practical terms, Gaussian Plume Model should not be applied under conditions of:

1. Low wind speed
2. Complex terrain
3. Spatial and temporal changes in meteorological parameters
4. deposition and transformation (e.g. radiological decay) within the plume during travel
Limitations of simplified models
## Atmospheric Modelling

**Limitations of GPM:**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Conditions</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>1. Ideal Conditions:</strong></td>
<td>10% to 20%</td>
</tr>
<tr>
<td></td>
<td>Near field (&lt;1.0 km) short averaging times (min to hour), flat terrain, steady meteorology, surface source</td>
<td></td>
</tr>
<tr>
<td></td>
<td>same as above for elevated source</td>
<td>20% to 40%</td>
</tr>
<tr>
<td>2</td>
<td><strong>2. Real World Applications:</strong></td>
<td>Factor of two</td>
</tr>
<tr>
<td></td>
<td>Meteorological parameters reasonably well known and steady with no exceptional circumstances</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td><strong>3. Exceptional Circumstances:</strong></td>
<td>Poorer than a factor of two; may be as poor as factor of ten.</td>
</tr>
<tr>
<td></td>
<td>Building wakes, buoyant plumes, varied surfaces such as forests, cities, shorelines, rough terrain, extreme stable and unstable conditions, distances greater than 10-20 km</td>
<td></td>
</tr>
</tbody>
</table>

*Site-specific field studies or physical modelling, or numerical modelling using complex models may be required to understand the airflow and the resultant diffusion in practical situations.*
Theoretically, the Gaussian Plume Model (GPM) is only valid when certain basic assumptions are completely met.

In reality, some of these basic assumptions are never met.
Three of the most common scenarios, where modification of the basic GPM would be necessary, are:

1. Complex terrain
2. Building wake effect
3. Sea breeze fumigation
Complex Terrain

- Complex terrain, such as hills, valleys etc, influences the path and diffusion of a pollutant plume.

- Depending upon meteorological condition, the same terrain can affect a plume in different ways.
Atmospheric Modelling

Building Wake Effect

Complex airflow condition around buildings in the plume pathway
Sea Breeze Fumigation

-Cold marine air advects over land during daytime.

-The lower layer of the air mass gets progressively heated up.

-In consequence, boundary layer develops over land region (highly turbulent) known as 'Thermal Internal Boundary Layer' (TIBL).
Empirically based adjustments to the basic Gaussian plume formation, allow it to be applied in many situations, where theoretically it should not be applied.
### Atmospheric Modelling

**Comparative evaluation of dispersion models and their application**

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Input data needed</th>
<th>Application</th>
<th>Accuracy</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box Model</td>
<td>Meteorological model</td>
<td>Vertical average wind speed, volume of model domain, Mixing height</td>
<td>Area sources, distributed sources, long range plume trajectory modeling</td>
<td>Gives uniform concentration in domain, hence poor for point source near field application</td>
<td>Generally used as screening model</td>
</tr>
<tr>
<td>Gaussian Plume Model</td>
<td>Combined meteorology and diffusion model</td>
<td>Surface wind speed, direction, insolation, cloud cover</td>
<td>Point, area, volume source</td>
<td>Gives concentration estimates within an order of magnitude for continuous releases over homogeneous terrain</td>
<td>Widely used</td>
</tr>
<tr>
<td>Gaussian puff model</td>
<td>Dispersion model</td>
<td>Surface wind speed, direction, insolation, cloud cover</td>
<td>Dispersion under time varying meteorological Conditions, continuous short term releases under emergency situations.</td>
<td>Better than Gaussian plume model for time varying meteorology. Not satisfactory under strong wind shear</td>
<td>Used also in mesoscale models</td>
</tr>
<tr>
<td>Particle trajectory model</td>
<td>Dispersion model</td>
<td>Atmospheric stability, wind and turbulence data from prognostic model</td>
<td>Dispersion over complex terrain</td>
<td>Good for complex terrain</td>
<td>Used also in mesoscale models</td>
</tr>
</tbody>
</table>
Other Models

• Numerical Modelling
  – Diagnostic modeling
  – Prognostic modeling
    • Meteorological model to obtain space-time evolution of meteorological parameters
    • Particle trajectory model-to obtain concentration estimates using the meteorological model values as inputs
Example-1: Routine release scenario of NPP

Suppose Argon-41 is routinely released at a rate of 1Bq/sec from a stack of height 100m from a reactor. Find out the centreline Ground Level concentration at 1km from the stack, maximum GLC and downwind distance of its occurrence, given wind speed at 10m is 4m/sec and stability class is B-C. (note: \( \sigma_z = H/\sqrt{2} \) )
• \( U_{100} = u_{10} \left(\frac{100}{10}\right)^{0.11} = 5.15 \text{ m/sec} \)

• \( \sigma_z \) and \( \sigma_y \) from graphs for B and C category are
  • \( \sigma_z = 100 \text{ m (B cat)} \) and \( 60 \text{ m (C cat)} \)
  • \( \sigma_y = 140 \text{ m (B cat)} \) and \( 100 \text{ m (C cat)} \)

• Using \( Q = 1 \text{ Bq/sec, } h = 100 \text{m, } u = 5.15 \text{ m/s} \) in
  \[
  C = \frac{Q}{\pi \sigma_y \sigma_z u} \exp\left[-\frac{H^2}{2\sigma_z^2}\right]
  \]
• GLC (1000, 0, 0) = 2.654 E-6 Bq/m³ for B category
• and 2.568 E-6 Bq/m³ for C category

• GLC (B-C class) = average of the two values = 2.611 E-6 Bq/m³

• Now, \( \sigma_z = \frac{H}{\sqrt{2}} = \frac{100}{1.14} = 71 \) m

• From the graph, the corresponding X max = 820 m

• \( \text{GLC(max)} = \left(\frac{2Q}{\rho u H_{\text{eff}}^2}\right) \left(\frac{\sigma_z}{\sigma_y}\right) \)

• \( \sigma_y \) for B-C category for 820m estimated from graph is 105m

• Therefore, GLC (max) = 3.08 E-6 Bq/m³ which will occur at 820m downwind
Example-2: Accidental release scenario of NPP

Suppose 1 Bq/sec of I-131 is released at ground level from a reactor building whose cross sectional area is 1600 m². Find out downwind, centreline GLC at 1 km downwind and deposited activity for the worst meteorological conditions (i.e. F category with surface level speed of 2m/sec).

Assume deposition velocity of 0.1m/s

Formulae used:
GLC = Q/\left[u(\nu \sigma_y \sigma_z + C_w A)\right] where C_w = 0.5
• From the graph,
• \( \sigma_y \) and \( \sigma_y \) for F category at 1000m is 38m and 15m respectively
• \( u = 2 \text{m/s} \)
• \( Q = 1 \text{ Bq/sec} \)
• \( A = 1600 \text{ m}^2 \)

• \( \text{GLC} = 1.93 \times 10^{-4} \text{ Bq/m}^3 \)

Deposited Activity = GLC x deposition velocity
• = \( 1.93 \times 10^{-4} \text{ Bq/m}^3 \times 0.1 \text{ m/sec} = 1.93 \times 10^{-5} \text{ Bq/m}^2. \)

• In actual practice, GLC should be corrected for plume decay and then used for estimation of deposited activity.
Typical components of Radiological Impact Assessment

- Atmospheric Transport
- Surface Water Transport
- Groundwater Transport
- Terrestrial Pathway
- Reference Man - Exposure
- Internal & External Dosimetry
- Health Effects
- Impact Assessment
- Regulatory Standards
Radiation exposure from an atmospheric releases could result in:

• **External exposure**
  – Direct radiation from plume (immersion)
  – Deposited radio nuclides on surfaces (ground shine)

• **Internal Exposure**
  – Inhalation of radionuclides in air
  – Ingestion of foods, contaminated by radio nuclides
Accumulation of contaminants in human and other biological tissues plays a key role in contributing to overall dose and risk resulting from environmental releases of radionuclides.
Evaluation of *physical and biological transport processes* is essential for environmental dose and risk assessment.

**Processes related to Terrestrial food chain pathways:**
- Direct deposition on to plant surfaces
  - Reduction of radionuclide concentration from surfaces of vegetation
- Deposition on soil
  - Reduction of radionuclide concentration in the soil surface
- Uptake from soil by edible portions of vegetation and the implicit assumption of inadvertent soil ingestion
- Intake of radionuclides by animals and transfer to milk and meat
- Ingestion of milk / meat by human

Radionuclides discharged into the *aquatic environment* are also passed along the aquatic food chain and may eventually reach humans.
During normal operating conditions, Radionuclides are released through high Stack after treatment.
The radionuclides may get deposited on soil and vegetation surfaces by wet and dry deposition.
Radionuclides may directly get deposited on grass surfaces by dry deposition.
Foliar Dry Deposition

Or get deposited on the leaves of plants or trees
Assimilation

And then get incorporated in leaf and other edible parts of the plant.
Radionuclides enter to grazing animals through grass and finally appear in their milk and meat.
Ingestion by Human

Enters to human body through intake of plant and animal products
Once the concentrations in various environmental media are estimated, dose to human can be computed.

- Safety Report Series no. 19 of IAEA describes the procedure to be followed for individual dose calculation.

- Basic equations for calculation of following doses from airborne radionuclides are presented in following slides:
  - Immersion dose
  - Inhalation dose
  - Ingestion dose
  - Dose from ground deposition
The annual effective dose from **immersion in the atmospheric discharge plume** $E_{im}$ $(Sv/a)$ is given by

$$E_{im} = C_A \ Df_{im} \ O_f$$

Where,

- $C_A$ = annual average concentration of nuclide ‘$i$’ in air ($Bq/m^3$)
- $DF_{im}$ = effective dose coefficient for immersion (Sv/a per Bq/m),
- $O_f$ = fraction of the year for which the hypothetical critical group member is exposed to this particular pathway.

The annual effective dose from **inhalation** $E_{inh}$ $(Sv/a)$ is:

$$E_{inh} = C_A \ R_{inh} \ DF_{inh}$$

Where,

- $R_{inh}$ = inhalation rate ($m^3/a$),
- $DF_{inh}$ = inhalation dose coefficient (Sv/Bq)
Exposure pathways and dose assessment

The ingestion doses for infants and adults are calculated using the following general equation:

\[ E_{\text{ing},p} = C_{p,i} \ H_p \ DF_{\text{ing}} \]

where

- \( E_{\text{ing},p} \) = annual effective dose from consumption of nuclide ‘\( i \)’ in foodstuff ‘\( p \)’ (Sv/a),
- \( C_{p,i} \) = concentration of radionuclide ‘\( i \)’ in foodstuff ‘\( p \)’ at the time of consumption (Bq/kg),
- \( H_p \) = consumption rate for foodstuff ‘\( p \)’ (kg/a),
- \( DF_{\text{ing}} \) = dose coefficient for ingestion of radionuclide ‘\( i \)’ (Sv/Bq).

The annual effective dose from ground deposition \( E_{\text{gr}} \) (Sv/a) is given by

\[ E_{\text{gr}} = C_{\text{gr}} \ DF_{\text{gr}} \ O_f \]

- \( DF_{\text{gr}} \) = dose coefficient for exposure to ground deposits (Sv/a per Bq/m²),
- \( C_{\text{gr}} \) = deposition density of radionuclide ‘\( i \)’ (Bq/m²).

\( C_{\text{gr}} \) is obtained from the ground deposition rate.
Exposure pathways and dose assessment

• Recommended values of different dose coefficients are given in the Safety Report Series no. 19 of IAEA.

• Subsequent to the dose assessment, epidemiologic analyses are to be carried out to evaluate potential health effects of human exposure to radioactive materials.
Thank you