Diffusion Models

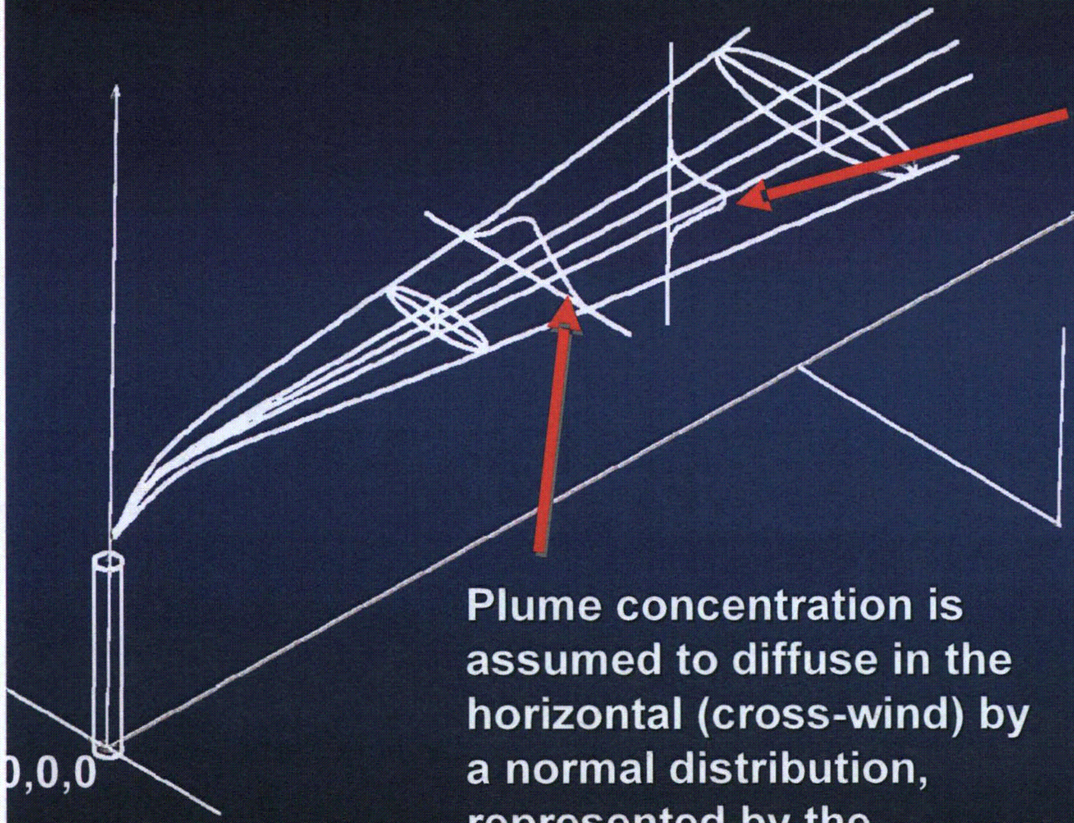
Basic Concept

- Release of a material to environment
  - Certain volume
  - Certain radionuclide concentration
- Release mixes with air due to turbulence
  - Release increases in volume
  - Release decreases in concentration
- Resulting concentration is not uniform
  - Most mixing occurs at the surface of the release volume
  - Concentration greatest at center of release volume, decreases asymptotically

Atmospheric Dispersion Models

- Gaussian plume model most widely used for estimating dispersion in dose projections
  - Generally non-spatial and non-temporal
  - Stylized, straight-line "snapshot"
  - Simple, can be implemented in hand calculations
  - May not be representative for a given site
- Advanced models are available
  - Segmented-plume Gaussian models
  - Modified potential flow numerical models
  - Particle tracking models

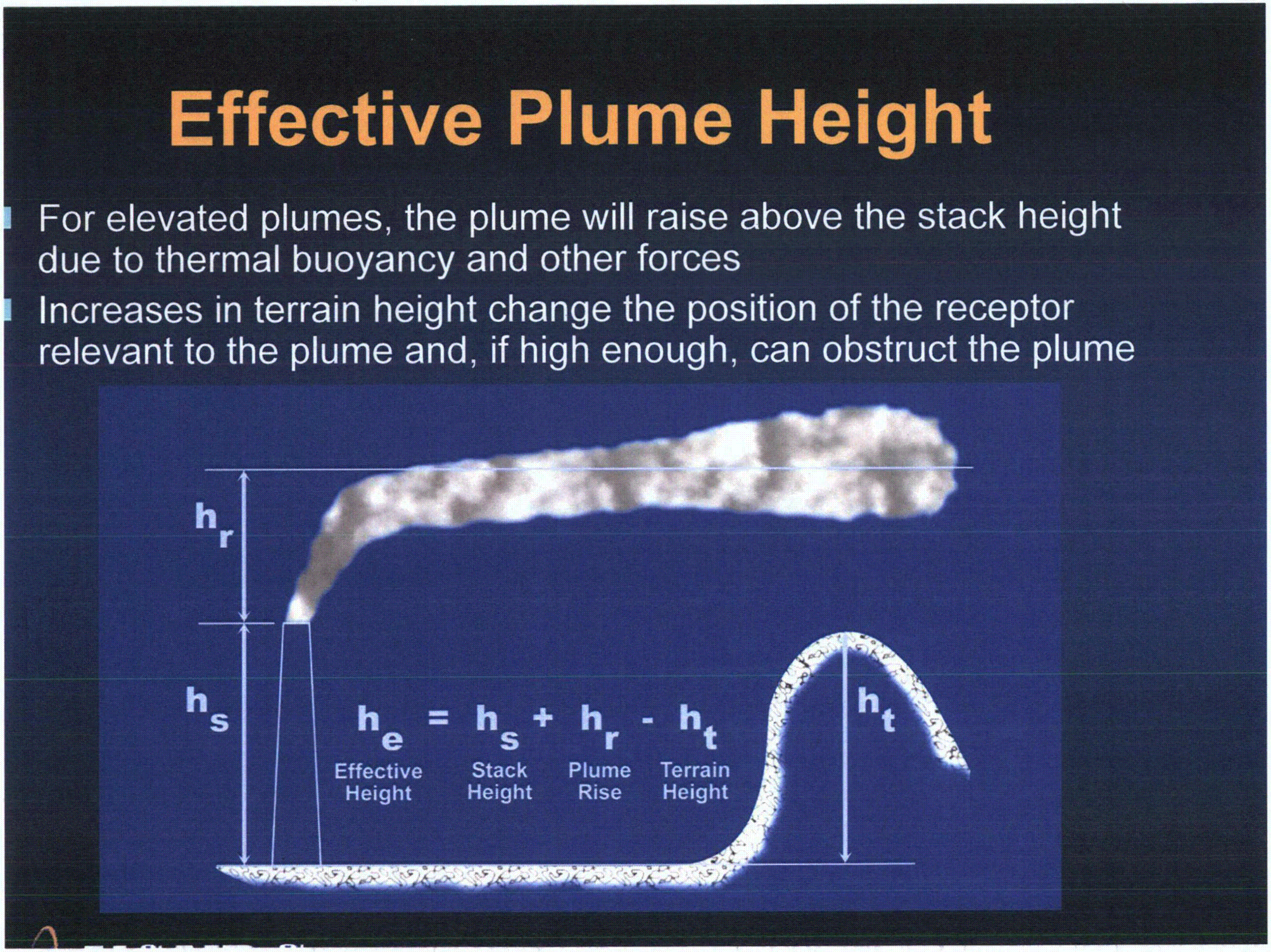
Gaussian Model



Plume concentration is assumed to diffuse in the vertical by a normal distribution, represented by the standard deviation, σ_y

There is also diffusion downwind (σ_x) but this is small compared to the distribution by the wind, represented by the wind speed, U

Plume concentration is assumed to diffuse in the horizontal (cross-wind) by a normal distribution, represented by the standard deviation, σ_z



Effective Plume Height

- For elevated plumes, the plume will raise above the stack height due to thermal buoyancy and other forces
- Increases in terrain height change the position of the receptor relevant to the plume and, if high enough, can obstruct the plume

Gaussian Model

- Essential conditions:
  - Non-zero wind speed
  - Wind direction constant over time and downwind area
  - Release rate constant over time for the duration of the release
  - Atmospheric stability constant over time and downwind area
- Because of these conditions:
  - Gaussian assessment is a straight-line, “snapshot”
  - Gaussian model is not temporal nor spatial

Gaussian Model

$$X_{xyz} = \frac{Q'}{2\pi\,\bar{u}\,\sigma_y\sigma_z}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left[\exp\left[-\frac{(z-h_e)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+h_e)^2}{2\sigma_z^2}\right]\right]$$

X_{xyz} = Downwind concentration at coordinates X,Y,Z (e.g., Ci/M^3)

Q' = Release rate (e.g., CI/sec)

x = Receptor downwind distance (along wind)

y = Receptor horizontal (crosswind) offset from plume centerline

z = Receptor height (ground level =0)

h_e = Plume centerline effective height above terrain

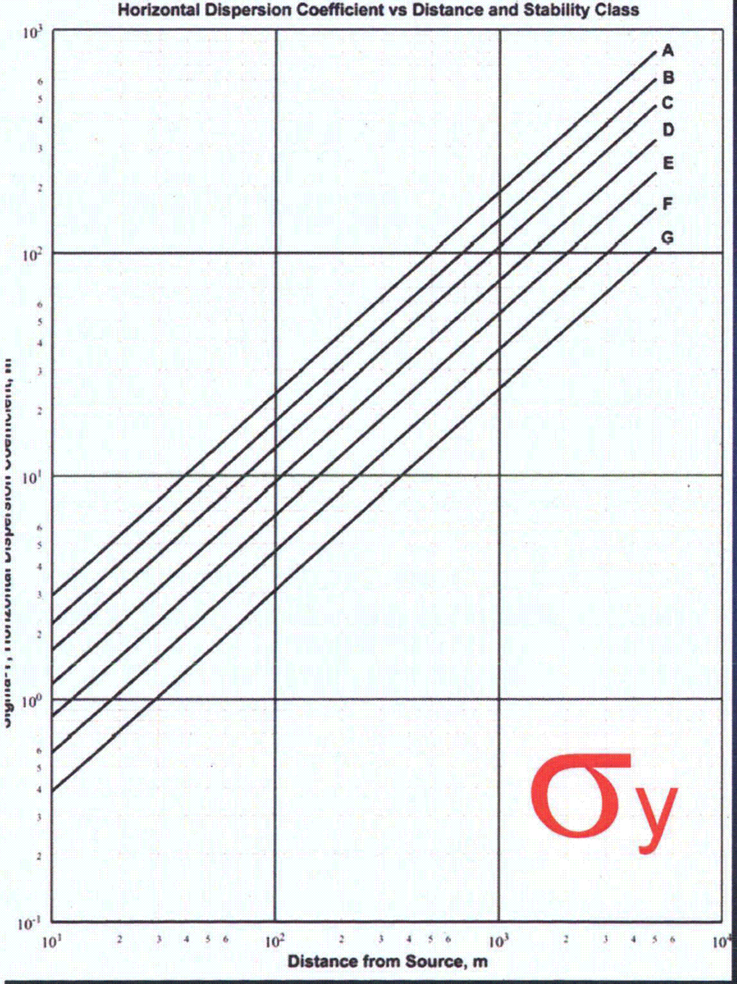
u = Wind speed

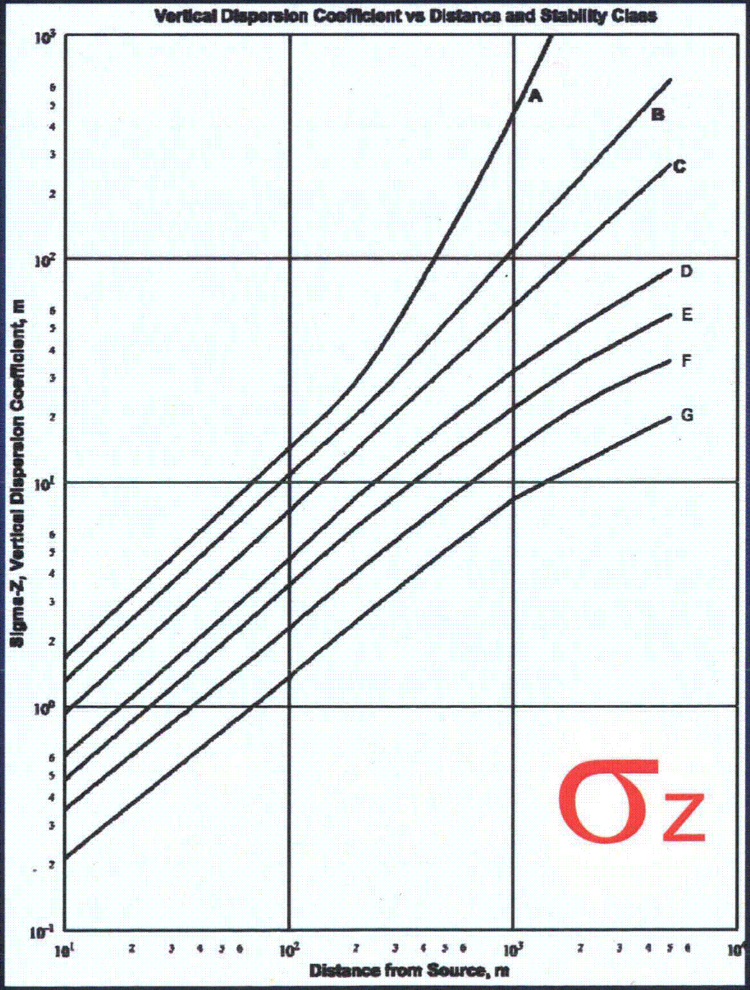
σ_y, σ_z = Dispersion Coefficient on Y-axis and Z-axis

Dispersion Coefficients

- Input parameters can be measured or projected
- σ_y and σ_z vary as functions of the downwind distance and atmospheric stability class
  - Values were determined by correlations to experimental field measurements.
  - Correlations by Pasquill and Gifford typically used
  - There are other datasets

P-G Dispersion Coefficients


Horizontal Dispersion Coefficient vs Distance and Stability Class


Vertical Dispersion Coefficient vs Distance and Stability Class

Gaussian Model

the receptor is at ground level, z = 0, and:

$$\chi_{xyz} = \frac{Q'}{\pi \bar{u} \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2} + \frac{{h_e}^2}{2\sigma_z^2} \right]$$

f the receptor is at ground level under plume centerline, z = 0, y=0, and:

$$\chi_{xyz} = \frac{Q'}{\pi \bar{u} \sigma_y \sigma_z} \exp\left[\frac{{h_e}^2}{2\sigma_z^2} \right]$$

the receptor and plume is at ground level, h_e= 0, and:

$$\chi_{xyz} = \frac{Q'}{\pi \bar{u} \sigma_y \sigma_z}$$

Normalized Air Concentration

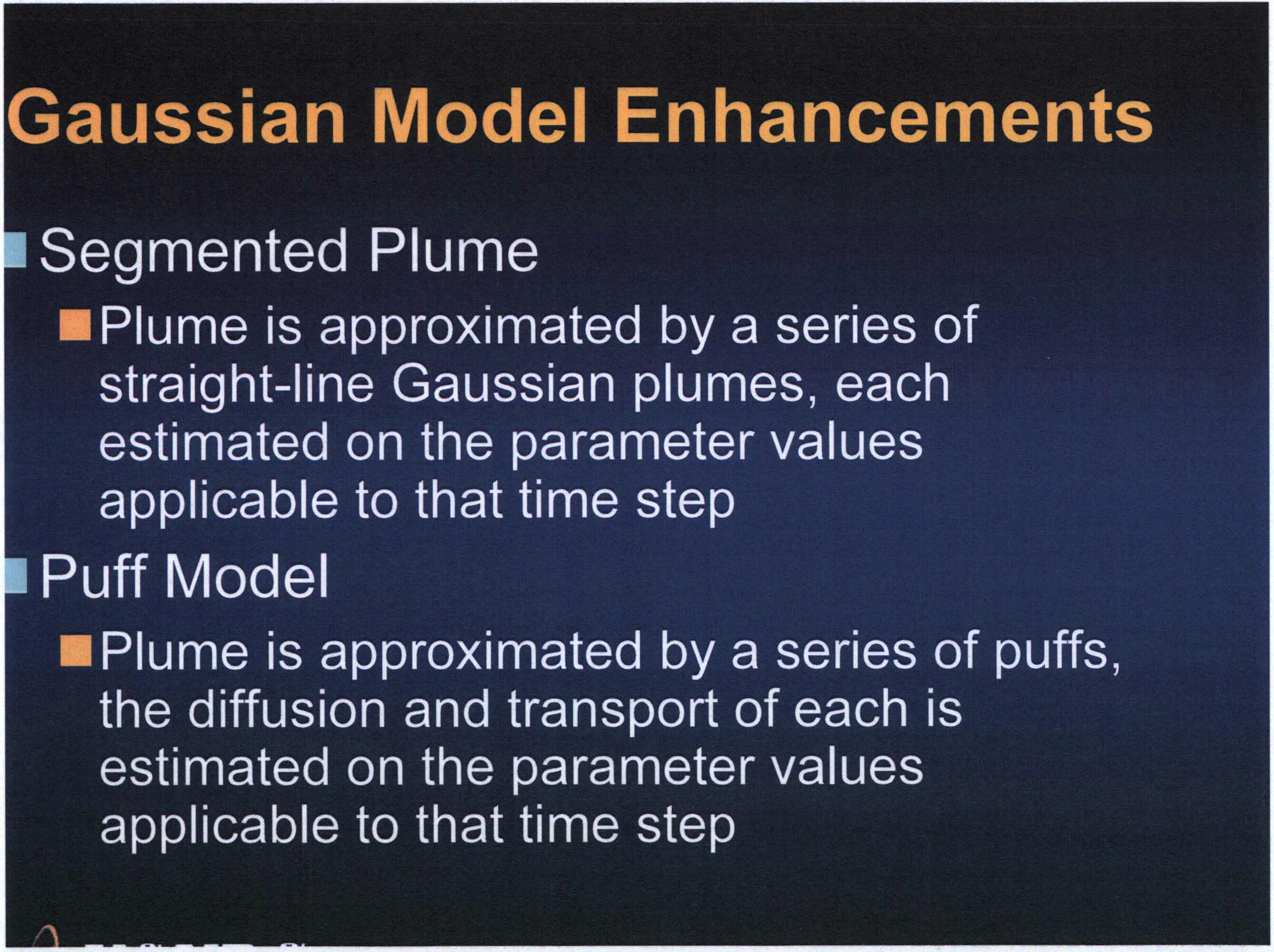
- The preceding equations are often restructured to calculate normalized airborne concentration, or χ /Q
- Normalized concentration = χ divided by Q
  - where χ = airborne radionuclide concentration, e.g., Ci/m3
  - Q = source term, Ci/s and
  - χ /Q = s/m3

Gaussian Model Enhancements

- Most limiting aspect of basic Gaussian model is inability to evaluate spatial and temporal differences in model inputs
- Enhanced Gaussian models can address these inabilities
  - Puff model
  - Segmented plume models
- Enhanced Gaussian models generally address both diffusion and transport

Enhanced Gaussian Model Structure

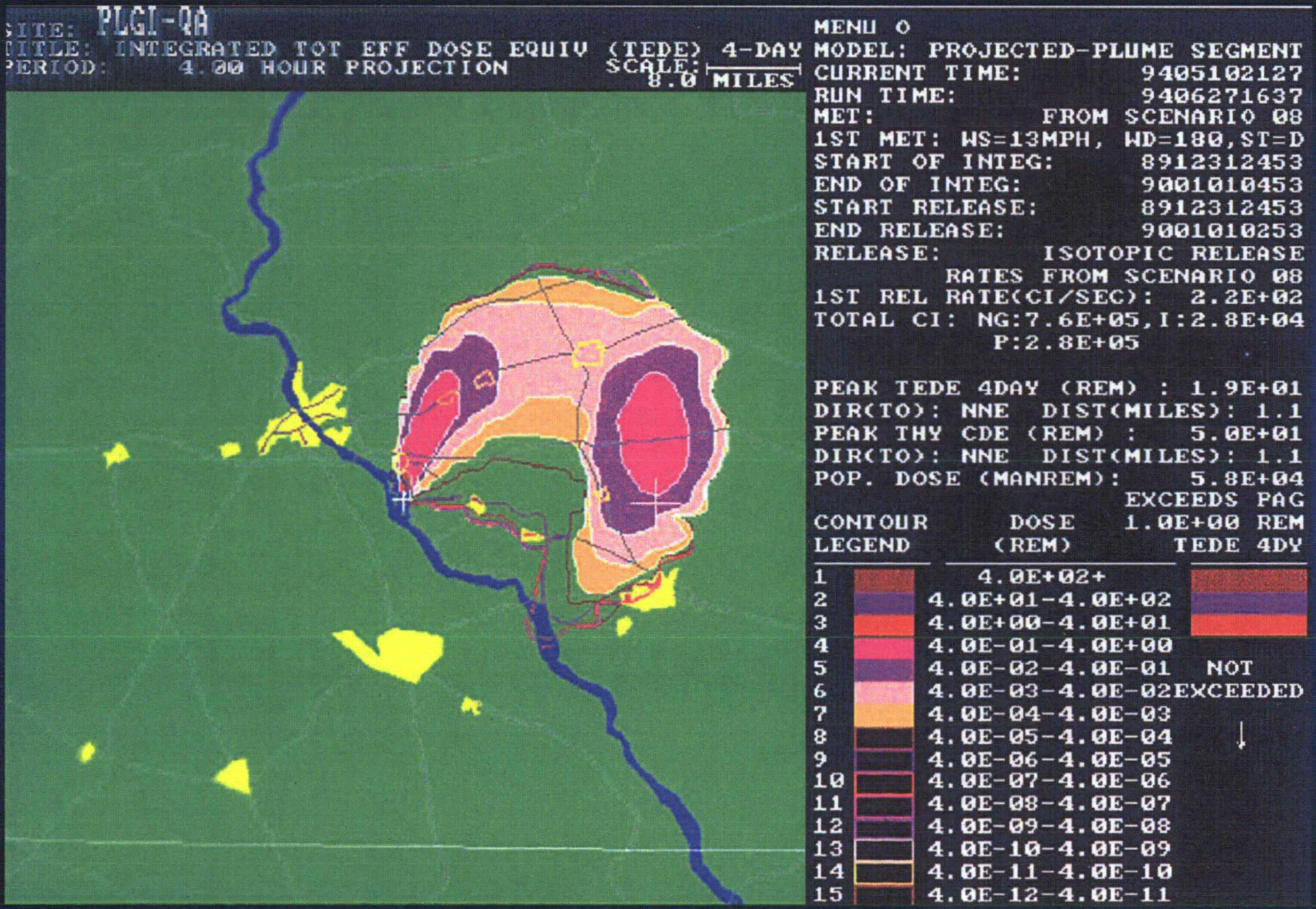
- Processing algorithm that:
  - Divides the calculation domain into equal time steps
  - Assign meteorological and release data to each time step
  - Processes each time step individually, integrating the calculation results
  - Use of time steps allow model to reflect temporal changes
- A rectangular two-dimensional (x,y) wind field
  - Each cell is assigned a wind vector for each time step
  - The wind vector assigns the initial conditions for that time step



Gaussian Model Enhancements

- Segmented Plume
  - Plume is approximated by a series of straight-line Gaussian plumes, each estimated on the parameter values applicable to that time step
- Puff Model
  - Plume is approximated by a series of puffs, the diffusion and transport of each is estimated on the parameter values applicable to that time step

Segmented Plume Model



```
ITE:  PLGI-QA
ITLE:  INTEGRATED TOT EFF DOSE EQUIV (TEDE) 4-DAY
ERIOD:     4.00 HOUR PROJECTION          SCALE:
                                         8.0 MILES
```

```
MENU O
MODEL: PROJECTED-PLUME SEGMENT
CURRENT TIME:             9405102127
RUN TIME:                 9406271637
MET:               FROM SCENARIO 08
1ST MET: WS=13MPH, WD=180,ST=D
START OF INTEG:           8912312453
END OF INTEG:             9001010453
START RELEASE:            8912312453
END RELEASE:              9001010253
RELEASE:           ISOTOPIC RELEASE
        RATES FROM SCENARIO 08
1ST REL RATE(CI/SEC):   2.2E+02
TOTAL CI: NG:7.6E+05,I:2.8E+04
           P:2.8E+05

PEAK TEDE 4DAY (REM) : 1.9E+01
DIR(TO): NNE  DIST(MILES): 1.1
PEAK THY CDE (REM) :   5.0E+01
DIR(TO): NNE  DIST(MILES): 1.1
POP. DOSE (MANREM):     5.8E+04
                     EXCEEDS PAG
CONTOUR      DOSE    1.0E+00 REM
LEGEND      (REM)       TEDE 4DY
1   ■     4.0E+02+         ■
2   ■   4.0E+01-4.0E+02    ■
3   ■   4.0E+00-4.0E+01    ■
4   ■   4.0E-01-4.0E+00
5   ■   4.0E-02-4.0E-01  NOT
6   ■   4.0E-03-4.0E-02EXCEEDED
7   ■   4.0E-04-4.0E-03
8   □   4.0E-05-4.0E-04    ↓
9   □   4.0E-06-4.0E-05
10  □   4.0E-07-4.0E-06
11  □   4.0E-08-4.0E-07
12  □   4.0E-09-4.0E-08
13  □   4.0E-10-4.0E-09
14  □   4.0E-11-4.0E-10
15  □   4.0E-12-4.0E-11
```

Screen capture from MIDAS™ software by PLG, Inc.

Advanced Diffusion Models

Advanced Models

- In many Gaussian models, terrain height is addressed only in determining the effective plume height
- The impact of terrain on plume transport is not addressed
- Straight-line models can not “curve” a plume around mountains or follow a river valley
- Advanced models can address terrain impact on plume transport

Advanced Models

- In a particle-in-cell (PIC) model, the wind field is three-dimensional
  - Wind vectors have x,y,z components
  - Calculated for each time step using modified potential flow algorithms
  - Requires wind speed and direction data for multiple elevations
  - Terrain displaces affected wind field cells; wind vectors for these cells = 0

Dispersion in Advanced Models

- In lieu of Gaussian formulation, PIC models use large numbers of virtual particles, each of which are tagged with:
  - Time step of injection into wind field
  - Radionuclide characterization
  - Three-axis diffusion coefficient
- A group of particles is created for each time step, and injected into the wind field in sequence

Dispersion in Advanced Models

- The particles disperse through the wind field
  - Movement depends on three-axis diffusion coefficients and three-axis wind field vectors
  - On encountering a terrain face, particles follow vectors into adjacent cells, moving around or over the terrain
  - Particle positions are periodically recorded and integrated over time
- When dispersion is complete, the integrated particles in each cell are converted to concentrations and then dose
  - Inhalation dose assigned only for particles in cell layer adjacent to the ground
  - Ground deposition can only occur from the cell layer adjacent to the ground

Particle Tracking Model

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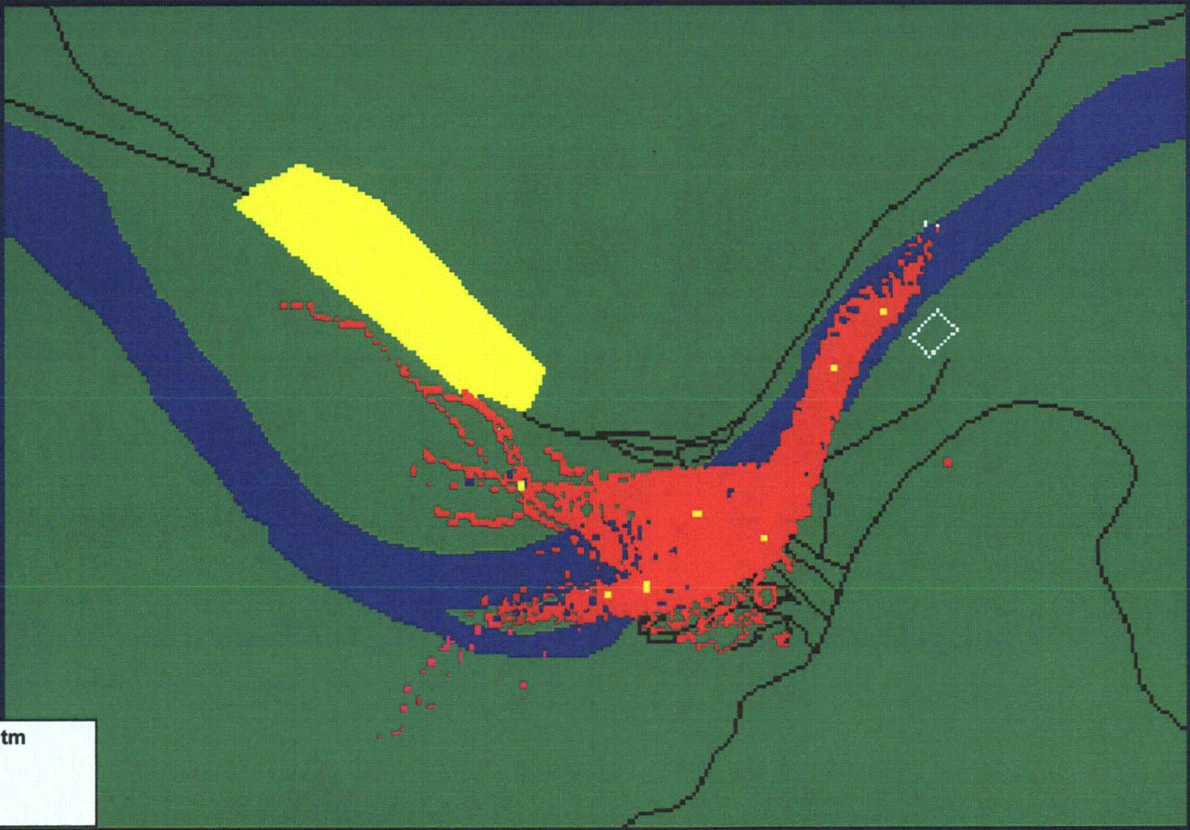
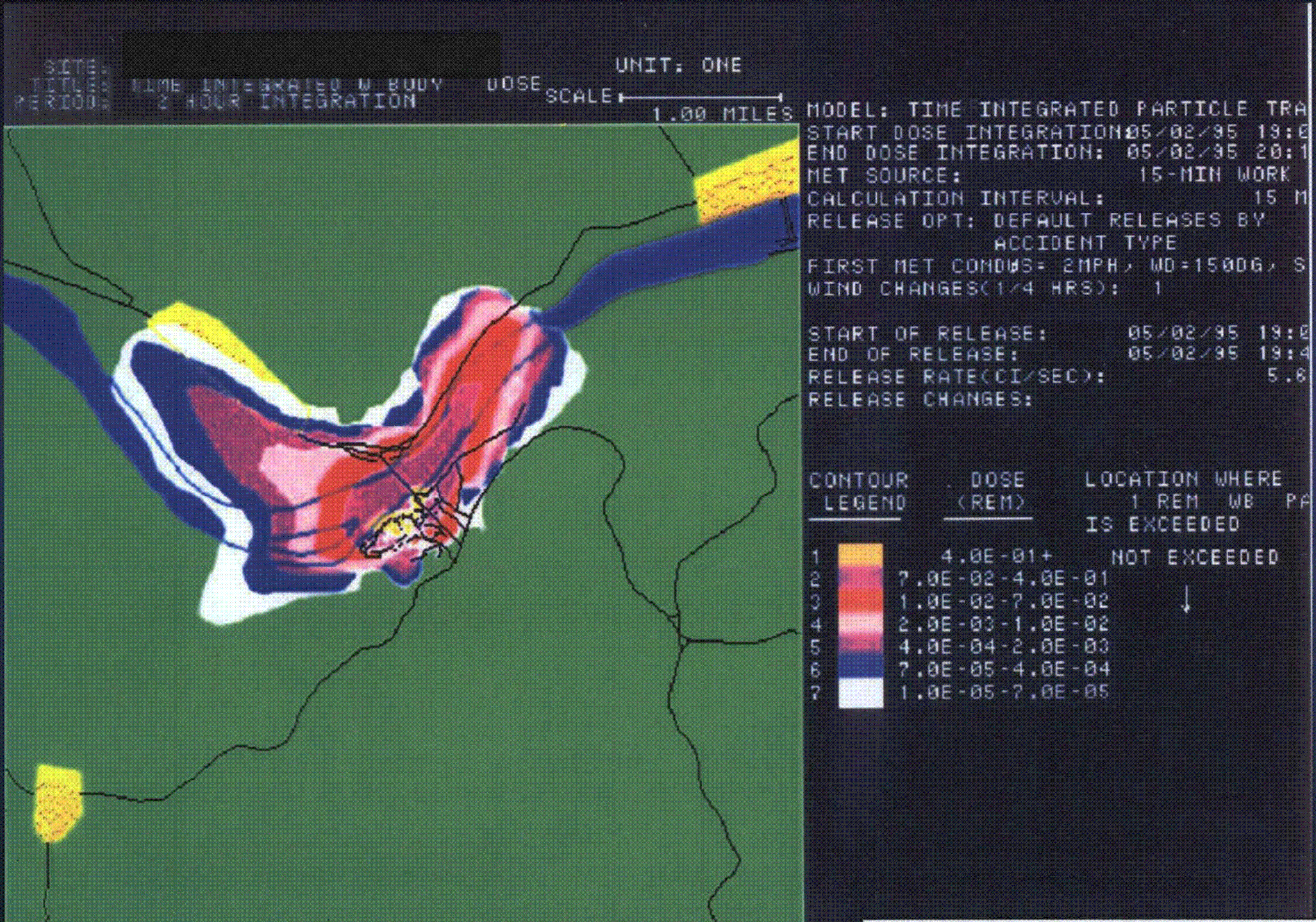


Screen capture from MIDAS^{tm}
oftware by PLG, Inc.

Particle Tracking Model

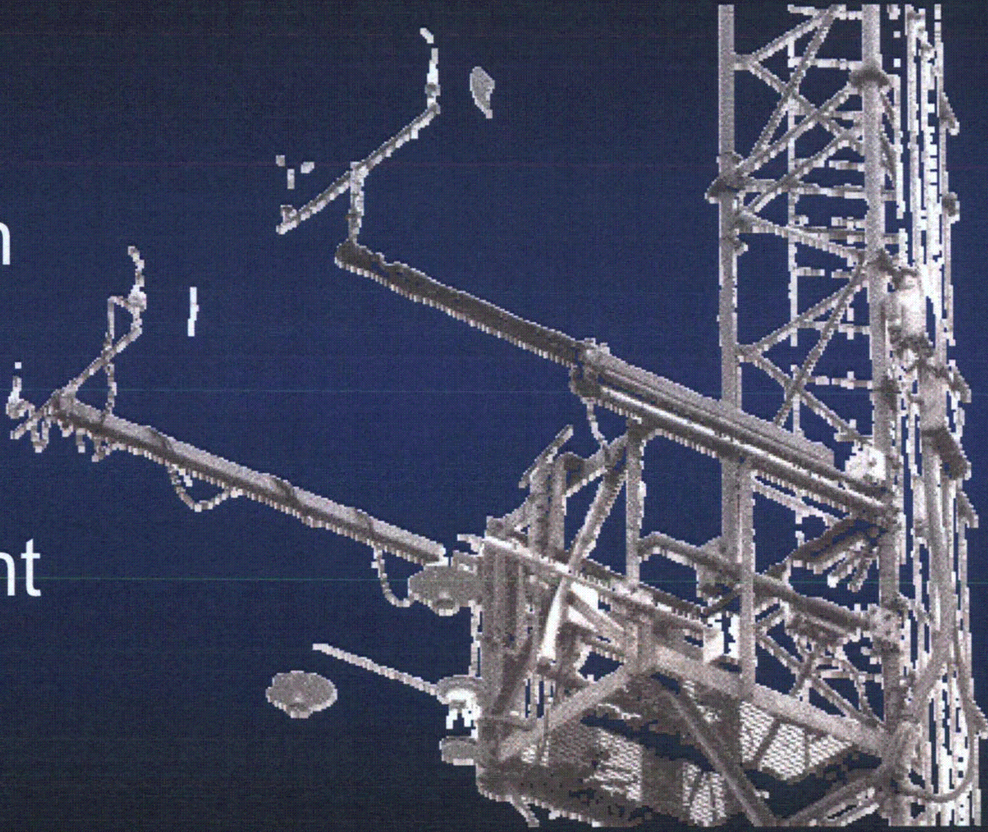


```
   SITE: [redacted]
  TITLE: TIME INTEGRATED W BODY   DOSE       UNIT: ONE
 PERIOD:   2 HOUR INTEGRATION          SCALE |-----------|
                                                1.00 MILES

MODEL: TIME INTEGRATED PARTICLE TRA
START DOSE INTEGRATION:05/02/95 19:0
END DOSE INTEGRATION: 05/02/95 20:1
MET SOURCE:                 15-MIN WORK
CALCULATION INTERVAL:              15 M
RELEASE OPT: DEFAULT RELEASES BY
                ACCIDENT TYPE
FIRST MET COND0S= 2MPH, WD=150DG, S
WIND CHANGES(1/4 HRS):  1

START OF RELEASE:          05/02/95 19:0
END OF RELEASE:            05/02/95 19:4
RELEASE RATE(CI/SEC):                5.6
RELEASE CHANGES:


CONTOUR     DOSE       LOCATION WHERE
 LEGEND     (REM)         1 REM   WB   PA
                       IS EXCEEDED

1  🟧       4.0E-01+     NOT EXCEEDED
2  🟪   7.0E-02-4.0E-01
3  🟥   1.0E-02-7.0E-02        ↓
4  ▨   2.0E-03-1.0E-02
5  🟪   4.0E-04-2.0E-03
6  🟦   7.0E-05-4.0E-04
7  ⬜   1.0E-05-7.0E-05
```

Screen capture from MIDAS^{tm} software by PLG, Inc.

Inputs to Dispersion Models

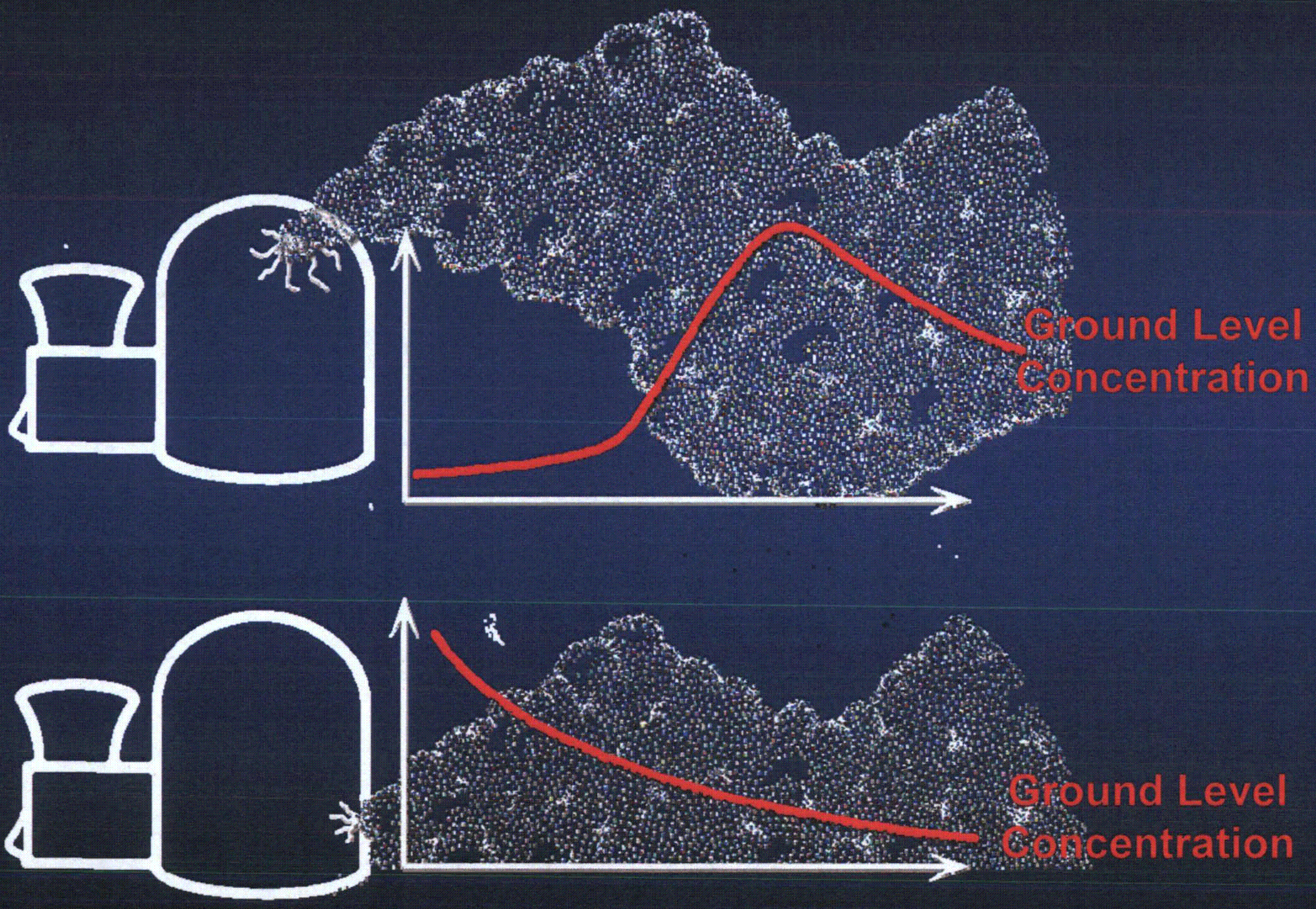
- Wind speed
- Wind direction
- Ambient temperature
- Release height
- Rainfall
- Stability class



Inputs to Dispersion Models

- A straight-line Gaussian model can generally be driven by a single set of meteorological data
  - Non-temporal; non spatial
- Wind field models can often be driven by multiple meteorological stations
  - Temporal and spatial
  - Improves modeling in complex terrain
- A wind field model driven by a single meteorological tower may not provide results any better than those from a straight-line Gaussian model
  - Highly dependent on surrounding terrain and meteorological regimes
- Additional meteorological towers may be necessary to adequately model sea breeze sites

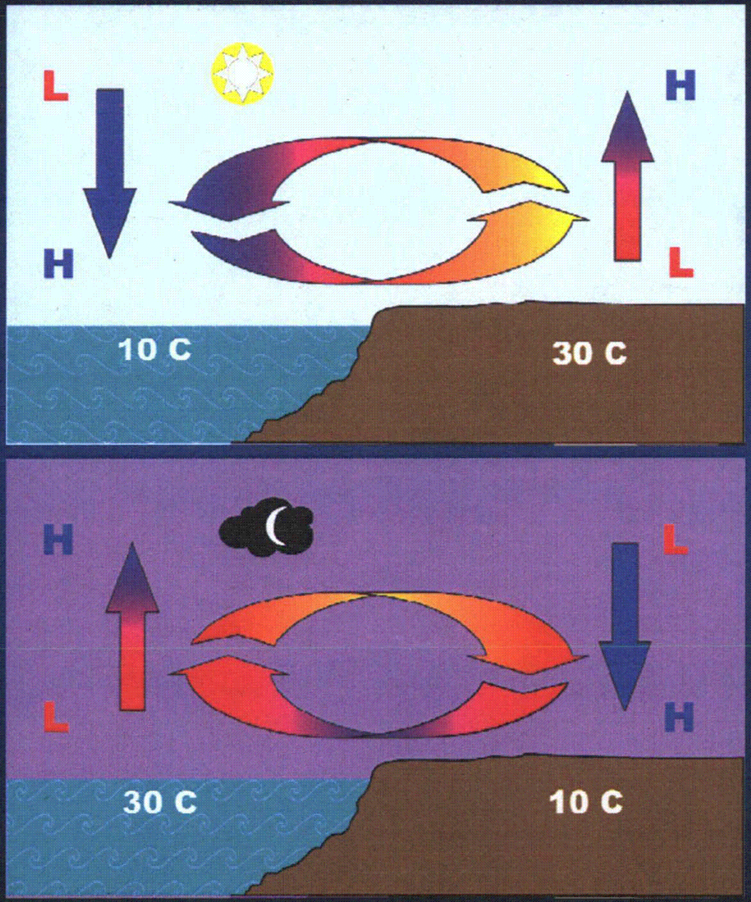
Elevated vs Ground Level Plumes



Terrain and Building Impacts on Diffusion Models

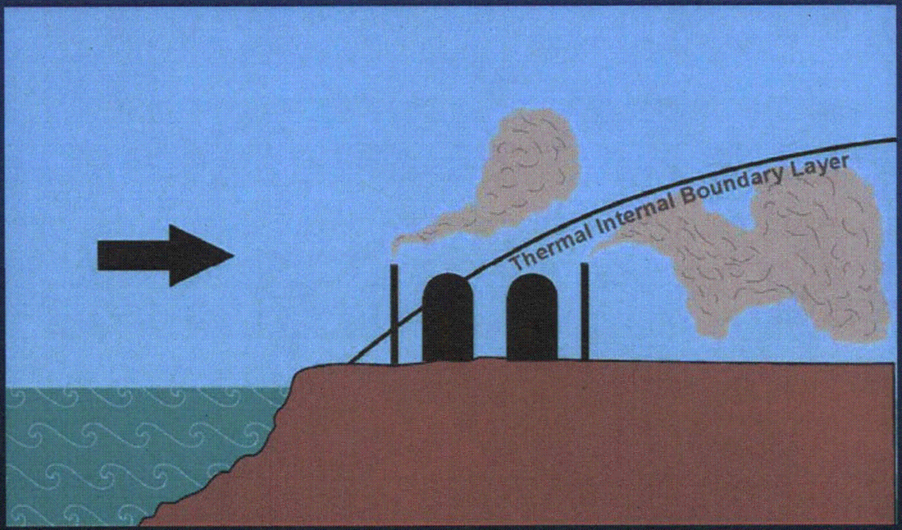
Transport and Diffusion at Coastal Sites

- Sea Breeze
  - Also applies to any other large body of water
  - Caused by differences in temperature of the air above water versus that above land after sunrise
  - If the regional wind flow is light, a circulation will be established between the two air masses
  - At night, the land cools faster, and a reverse circulation (weak) may occur

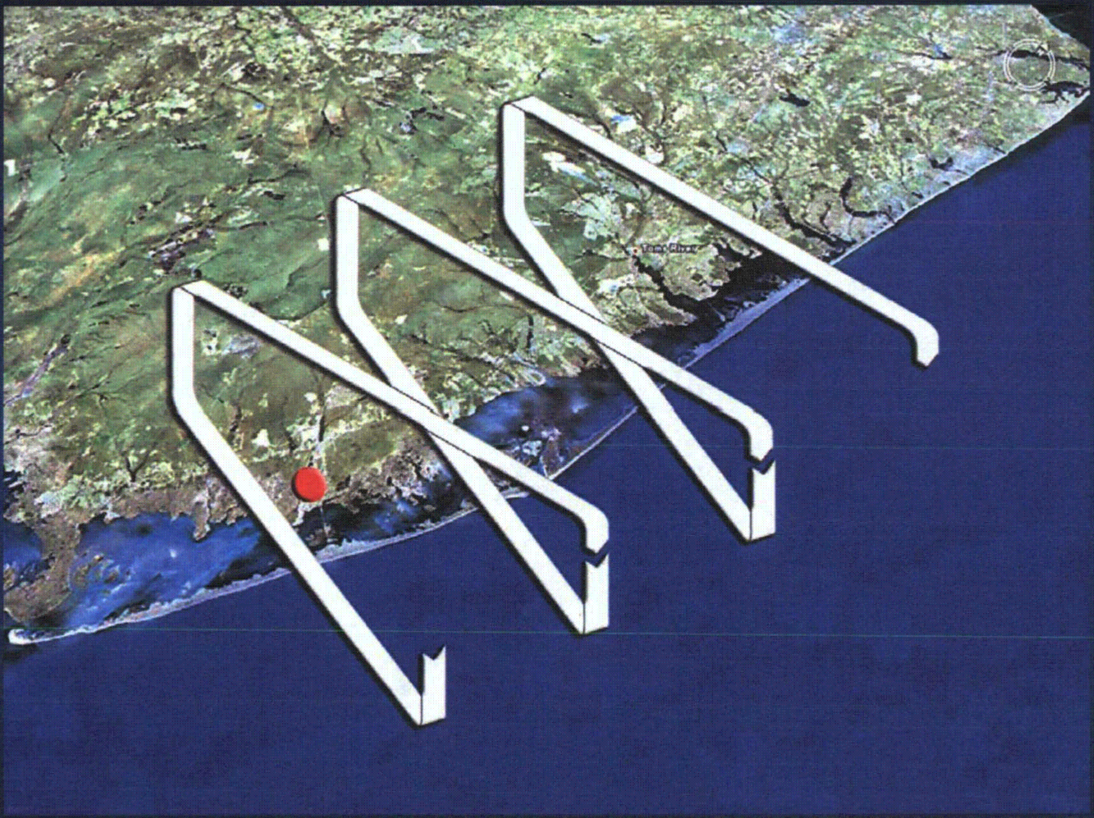


Impact of Sea Breeze

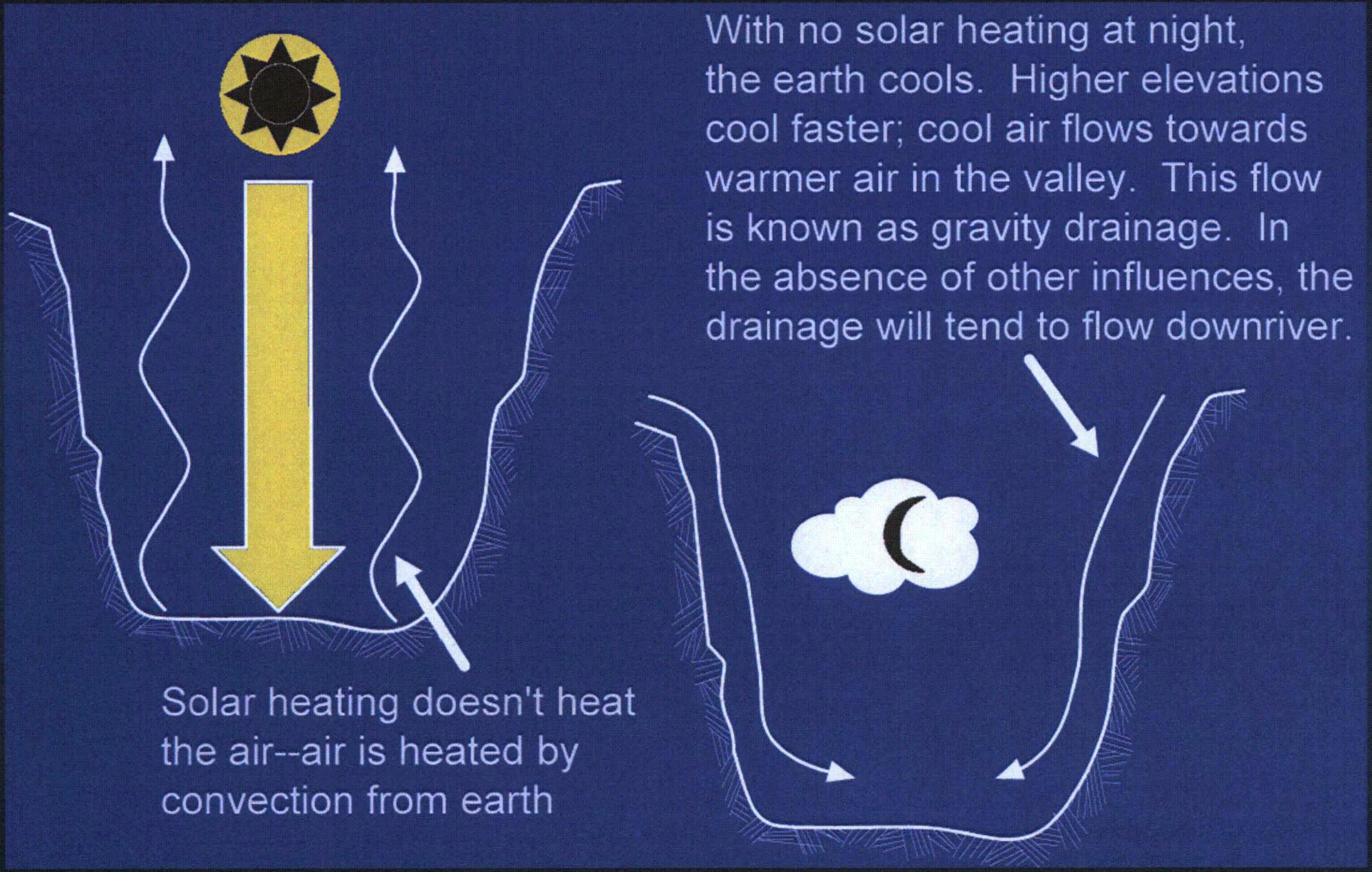
- The air over the water is cooler and is stable
- As the sea breeze forms, the stable air flows over the unstable air mass at the shore
- The boundary between the stable and unstable air is known as the thermal internal boundary layer (TIBL)
- Because the air below the TIBL is unstable, there is turbulence and mixing, drawing the plume to ground level
- As the day progresses, the TIBL layer moves inland



Impact of Sea Breeze



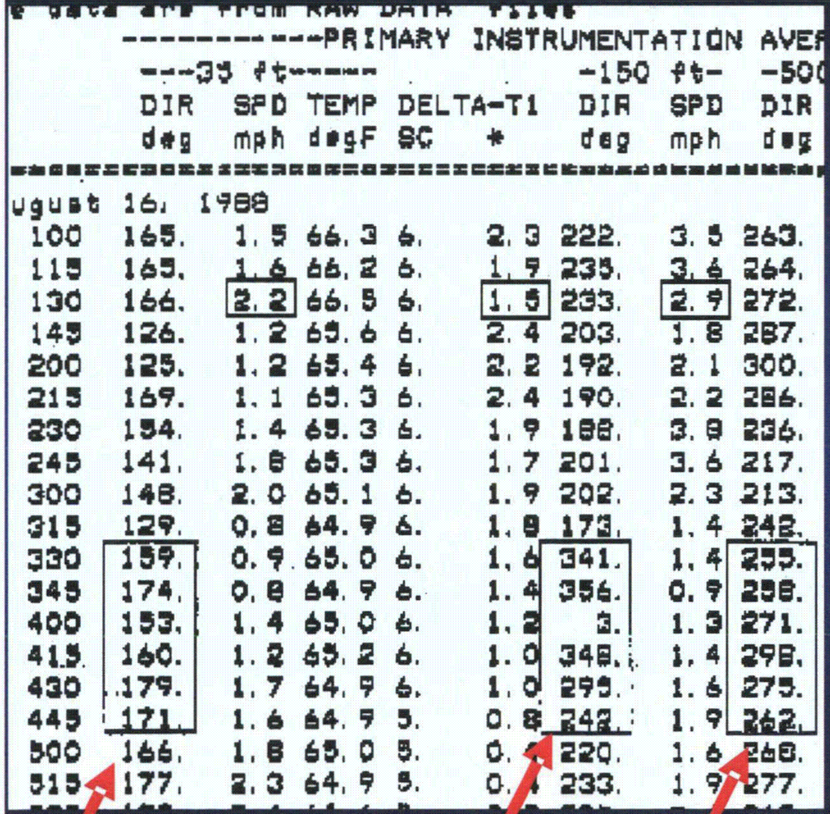
Transport and Diffusion at Valley Sites



With no solar heating at night, the earth cools. Higher elevations cool faster; cool air flows towards warmer air in the valley. This flow is known as gravity drainage. In the absence of other influences, the drainage will tend to flow downriver.

Solar heating doesn't heat the air--air is heated by convection from earth

Transport and Diffusion at Valley Sites

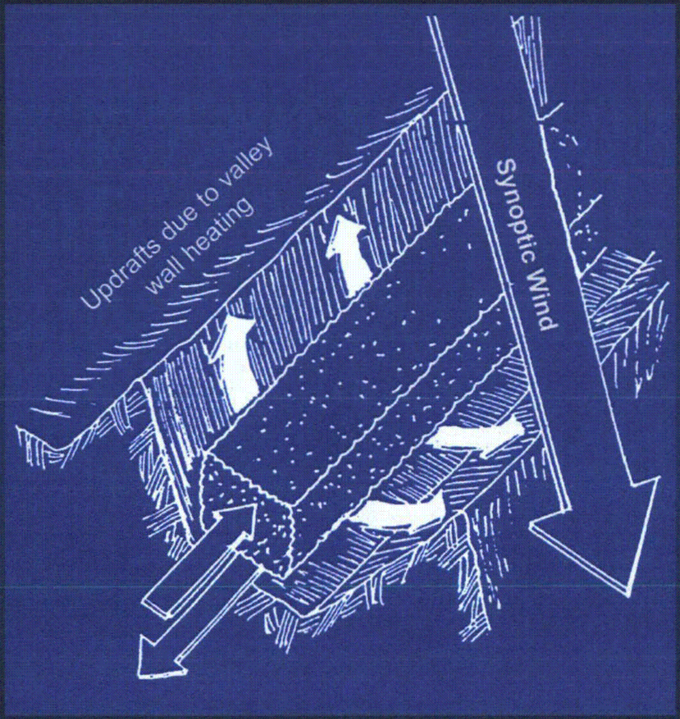


```
e data are from RAW DATA files
      ------------PRIMARY INSTRUMENTATION AVER
      ---35 ft------              -150 ft-  -500
      DIR   SPD TEMP DELTA-T1     DIR   SPD  DIR
      deg   mph degF SC     *     deg   mph  deg
===================================================
ugust 16, 1988
 100  165.  1.5 66.3 6.   2.3 222.   3.5 263.
 115  165.  1.6 66.2 6.   1.9 235.   3.6 264.
 130  166.  2.2 66.5 6.   1.5 233.   2.9 272.
 145  126.  1.2 65.6 6.   2.4 203.   1.8 287.
 200  125.  1.2 65.4 6.   2.2 192.   2.1 300.
 215  169.  1.1 65.3 6.   2.4 190.   2.2 286.
 230  154.  1.4 65.3 6.   1.9 188.   3.8 236.
 245  141.  1.8 65.3 6.   1.7 201.   3.6 217.
 300  148.  2.0 65.1 6.   1.9 202.   2.3 213.
 315  129.  0.8 64.9 6.   1.8 173.   1.4 242.
 330  159.  0.9 65.0 6.   1.6 341.   1.4 255.
 345  174.  0.8 64.9 6.   1.4 356.   0.9 258.
 400  153.  1.4 65.0 6.   1.2   3.   1.3 271.
 415  160.  1.2 65.2 6.   1.0 348.   1.4 298.
 430  179.  1.7 64.9 6.   1.0 295.   1.6 275.
 445  171.  1.6 64.9 5.   0.8 242.   1.9 262.
 500  166.  1.8 65.0 5.   0.[illegible] 220.   1.6 268.
 515  177.  2.3 64.9 5.   0.4 233.   1.9 277.
```

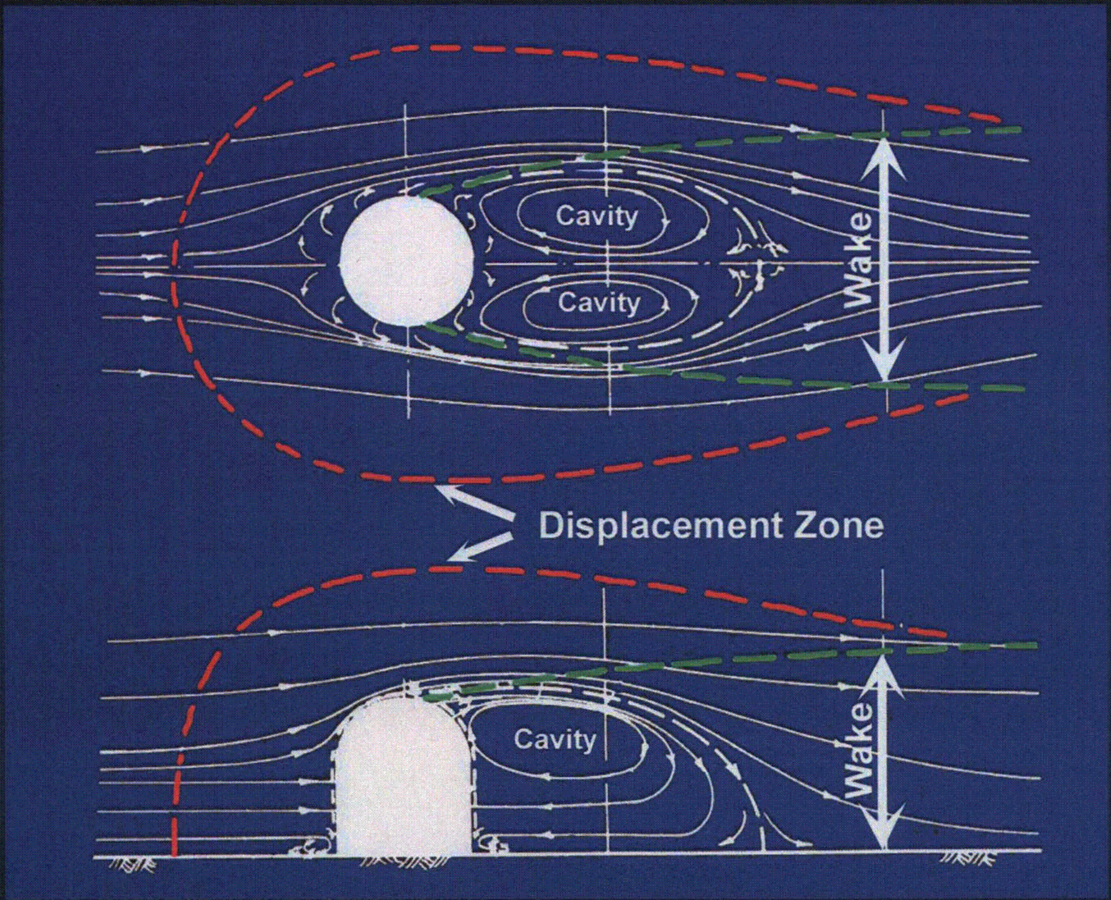
35 ft

150 ft

500 ft

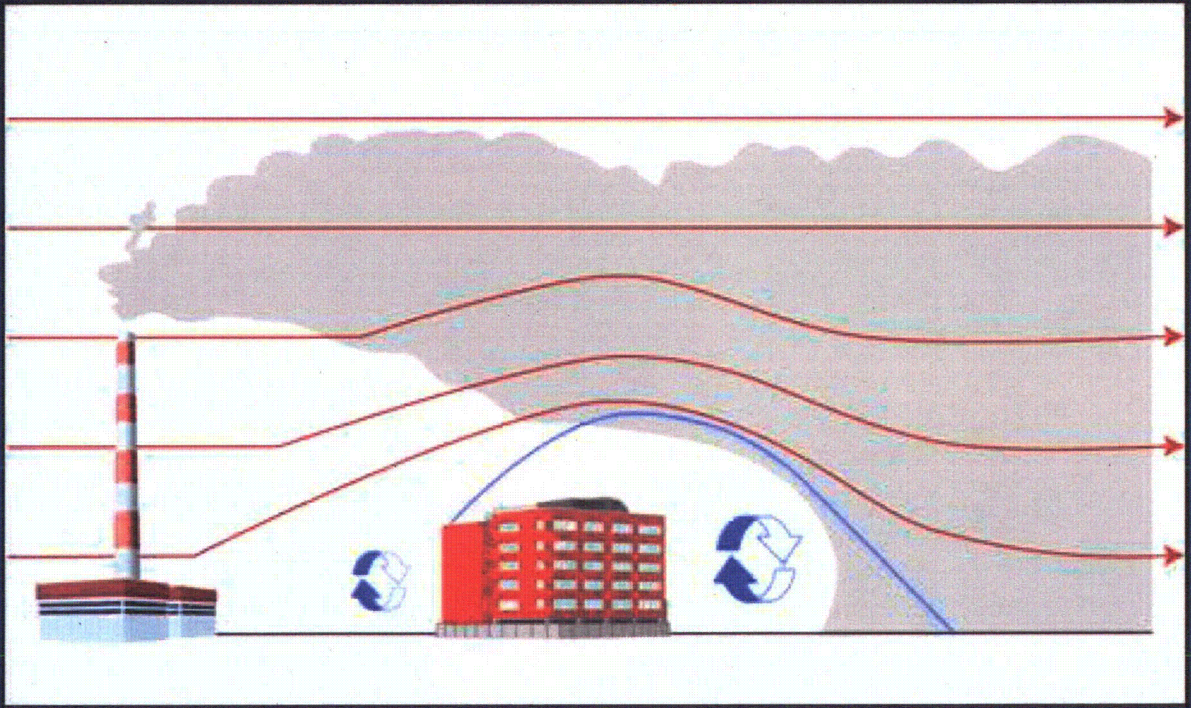


Building Wake



A sharp edged building would create more streamline distortion and turbulence than shown here

Building Wake



If the stack (plus plume rise) isn't high enough, the plume could be drawn into the building wake. Although mixing would occur, the plume would be at ground level sooner than projected