Overview of Plume Modeling and Related Topics for Non-Model Users or New Model Users

Emergency Management Issues
Special Interest Group
Hazards Assessment Subcommittee
The Goals of the HASubC:

- Provide a forum to facilitate sharing HASubC research activities, findings, information, and good practices.
- Provide an infrastructure for the dissemination of detailed technical methodologies, information, and hazard assessment (HA) tools to reduce unnecessary duplication of HA effort and costs across the DOE complex.
- Monitor feedback to promote continuous improvement in emergency planning activities complex-wide.
Section 1: Introduction and Process Overview

General Information About Consequence Assessment
Model Uses

- Emergency Planning
  - Hazard zone determination
  - Preplanned protective actions

- Authorization Basis
  - Consequence Estimates determine need for varying levels of controls
Model Uses (continued)

- Environmental Regulatory Compliance
  - Required for permits and pollution estimates

- Emergency Response
  - Event specific protective actions
  - Response resource deployment
  - Cleanup and recovery effort planning
Consequences Calculation Answers

- Who will be affected.
- Who will be notified.
- Who will respond.
- Where and when consequences will occur.
- Where consequences will be above classification or protective action threshold.
Consequence Assessment Phases

- Source Term Estimation
  - How much stuff gets out and goes into the air?

- Dispersion Modeling
  - How does it move through the air and go wherever it’s going?
  - How does it disperse and become widespread and dilute?

- Dose Calculation
  - How does it affect people and things when it gets there?
Information Needed for Consequence Assessment

- At Minimum
  - Source Term
  - Meteorology
  - Receptor Locations
Which Phase is Most Important?

- The Source Term determination affects all of the other phases.
- Most discrepancies between modeler’s estimates happen in Source Term determination.
Section 2: Source Terms
How Much Stuff Gets Out
Source Term

Source Term = (MAR)(DR)(ARF)(RF)(LPF)

MAR = Material At Risk
DR = Damage Ratio
ARF = Airborne Release Fraction
RF = Respirable Fraction
LPF = Leak Path Factor
Factors Explained

- **MAR = Material At Risk**
  - How much material is available to be damaged?

- **DR = Damage Ratio**
  - What fraction of the material is damaged by the event?

- **ARF = Airborne Release Fraction**
  - Of the damaged material, how much can go into the air versus being damaged in-place?

- **RF = Respirable Fraction**
  - Of the airborne material, how much is finely divided enough to be inhaled?

- **LPF = Leak Path Factor**
  - Of the airborne material, how much is trapped inside the structure or remains of the structure and not released to the open environment?
Source Term Example

- Hypothetical warehouse
- Forklift carries two drums of finely-divided powdered hazardous material (500kg ea.).
- Turns corner too fast, one drum falls off.
- That drum breaks off the lid, spilling all contents.
Source Term Example

Source Term = (MAR)(DR)(ARF)(RF)(LPF)

MAR = 1000 kg
DR = one half (.5)
RF = 10% (0.1)
LPF = 10% (0.1)
ARF = 10% (0.1)

Source Term = (1000kg)(0.5)(0.1)(0.1)(0.1)
Source Term = 0.5kg

So, we model a release of 0.5 kg.
Some Models Help Determine Source Term

- HOTSPOT and EPIcode
  - Have default ARF and RF determination.
  - Have automatic release height calculation for fires and explosions.

- ALOHA
  - Evaporation rates for liquids.
  - Discharge rates for pipes and holes.
Often VERY Conservative

- Source Term has five factors that are multiplied
- Most modelers select a conservative value for each of the five
- The conservative nature of most consequence estimates compounds.
Section 4: Dispersion Modeling

How the Stuff Moves and Where it Goes After It Gets Out

- Source Term Estimation
- Transport & Dispersion Analysis
- Field Monitoring & Indicators
- Health Effects Estimates
- Integrate Modeling & Monitoring
- Consequence Estimate
- Communicate Results
Three Tiers of Methods

- **Elementary**
  - Tables of pre-calculated values
  - Very conservative, somewhat crude, relatively fast

- **Intermediate**
  - Simplified consequence calculations performed with current data
  - Usually PC-based

- **Advanced**
  - Advanced computerized methods
  - Capable of more realistically modeling atmospheric transport and dispersion when operated by a subject matter expert (still suffers from GIGO)
Model Sophistication Trade-Off

- Some Models use more sophisticated, flexible, detailed, or accurate input information.
- Produce more sophisticated, detailed, or accurate output products.
- However, they require more time, knowledge, skill, and training to use effectively.
Excellent Elementary Model

- Emergency Response Guidebook
- Green Pages are an Elementary Model

- Widely used and validated
- Based on ANL research

### TABLE OF INITIAL ISOLATION AND PROTECTIVE ACTION DISTANCES

<table>
<thead>
<tr>
<th>ID No.</th>
<th>NAME OF MATERIAL</th>
<th>SMALL SPILLS (from a sealed package or small leak from a large package)</th>
<th>LARGE SPILLS (from large leak or break in the package)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>Ammonia, anhydrous</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1002</td>
<td>Ammonia, anhydrous, liquefied</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1003</td>
<td>Ammonia, anhydrous, with more than 50% dilution</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1004</td>
<td>Anhydrous ammonia</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1005</td>
<td>Anhydrous ammonia, liquefied</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1006</td>
<td>Boron trifluoride</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1007</td>
<td>Boron trifluoride, compressed</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1008</td>
<td>Carbon monoxide</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1009</td>
<td>Carbon monoxide, compressed</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1010</td>
<td>Chlorine</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1011</td>
<td>Chlorine, compressed</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1012</td>
<td>Coal gas</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1013</td>
<td>Coal gas, compressed</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1014</td>
<td>Cyanogen</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1015</td>
<td>Cyanogen, liquefied</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1016</td>
<td>Cyanogen, gas</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1017</td>
<td>Ethylene oxide</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1018</td>
<td>Ethylene oxide with Nitrogen</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1019</td>
<td>Fluorine</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1020</td>
<td>Fluorine, compressed</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1021</td>
<td>Hydrogen bromide, anhydrous</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1022</td>
<td>Hydrogen bromide, anhydrous, with more than 50% dilution</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1023</td>
<td>Hydrogen chloride, anhydrous</td>
<td>30 m (100 ft)</td>
<td>60 m (200 ft)</td>
</tr>
<tr>
<td>1024</td>
<td>Hydrogen chloride, anhydrous, with more than 50% dilution</td>
<td>0.2 km (0.1 mi)</td>
<td>0.2 km (0.1 mi)</td>
</tr>
<tr>
<td>1025</td>
<td>AC (when used as a weapon)</td>
<td>60 m (200 ft)</td>
<td>460 m (1500 ft)</td>
</tr>
</tbody>
</table>

Widely used and validated

Based on ANL research
Model Types

- **Gaussian**
  - The basic model uses information from statistical studies of real releases to show trends of distribution

- **Dense Gas Model**
  - Model the way that heavier-than-air substances “hug the ground” – like molasses on a table top
Model Types (continued)

- La Grangian
  - Extremely advanced models - Complex thermodynamic and fluid dynamic model
  - More “predictive” and less “descriptive” than other model types
  - Example: NARAC

- Slab
  - Pretends the release moves as a sliding and growing disc or box
Gaussian Model Development

- Empirical Model
  - Experimenters released several materials at different times and under different conditions and took downwind measurements
  - They developed some formulae that approximated the overall patterns that the measurements showed
  - The formulae do not necessarily match the measurements from any one single release
Basic Gaussian Model

\[ C = \frac{QR}{\pi \sigma_y \sigma_z u} \]

- **C**: Airborne Concentration, g/m³
- **QR**: Rate of Release into air, g/sec
- **π**: Pi (3.141…), Unitless
- **σ_y**: Horizontal Dispersion Deviation, Unitless
- **σ_z**: Vertical Dispersion Deviation, Unitless
- **u**: Wind Speed, m/sec
What are those “σ” things?

- It’s the lower-case Greek letter sigma
- Statistically speaking, the Greek letter sigma stands for the degree of variation in a set of measurements
- “σₓ” - along-wind dispersion (variation) parameter
- “σᵧ” - cross-wind dispersion (variation) parameter
- “σz” - vertical-wind dispersion (variation) parameter
Some Models Consider More

- Deposition Velocity
  - Slow moving air can drop hazardous material
- Rain out
  - Falling precipitation can “wash” contaminant out of the air
- Particulates (dusts, mists, aerosols)
- Fire Model
- Jet releases and entrainment
- Heat exchange and buoyancy
Differing Levels of Complexity

Simple Model

Sophisticated Model
Model Limits

- How good are the models?
  - Provide Expected Average results ("projected dose")
  - Can’t Provide exact dose or deposition for any spot or time
  - Usually a factor of 3 is considered to be pretty good (x/3-3x range)

- Often described as a “hazard index to show relative risk” instead of predictor of actual consequence.
Model Limits (continued)

“... It is important for decision-makers to know that, even in the best of conditions, the model predictions can be expected to be accurate only within a factor of about two.”

-Steven Hanna
If a model estimated the height of a 5’10” (70-inch) man the same way, it might look like this (under the best of conditions).

- Accuracy factor of two.
- Over-estimates 70% of the time
Model Accuracy Illustration (continued)

It could be like this

- Accuracy factor of three.
- Over-estimates 70% of the time
How Are They Alike

All dispersion models are similar in that they calculate two basic characteristics of the emitted material –

- The speed and direction that the plume moves with the wind.
- The dispersion or lateral and vertical spread due to turbulence in the atmosphere.
Whenever possible, accidents are analyzed using the simplest applicable deterministic, phenomenological calculations (e.g. pressure estimates from a simple ideal gas law calculation, hand-calculated Gaussian plume dispersions).
§1.5.2 “In general, a site/facility should design and employ the simplest consequence assessment system (manual or computer-based) that will meet its goals for accurately characterizing transport and dispersion conditions in support of emergency response.”
Common Model Deficiencies

- Lack of accurate, up-to-date, and local meteorological information.
- The need and difficulty to clearly communicate the uncertainty in the model predictions.
In short, using a “fancy” model won’t always improve accuracy and might not be “better” than a simpler model.
Conditions of Release

- Elevation of Release
- Explosion Models (virtual release point)
- Wind Speed
- Stability Class (degree of mixing of the air)
- Receptor Height
- Deposition Velocity (how slow can the air move and still carry contaminants)
- Sample Time (for time-weighted averaging of exposure)
- Release Duration
Plume Rise Effect

Warm or hot plumes may rise like a hot air balloon before they spread.

An atmospheric temperature inversion may trap a rising plume lower to the ground.
Elevated Plume Effect

An elevated plume may skip the people closer to the source but affect people further away.
Plume Release Height Effect

A more elevated release dilutes more before getting to ground level
Virtual Release Point

- Virtual Release Point
- Actual Release Point

Wind Direction

Used for fires, explosions and “area releases”
Average Concentration

To the computer model, these may all be the same event.

Even though the events really are different, they may have the SAME AVERAGE CONCENTRATION.
Average Concentration (continued)

- Average concentration over time
  - Brief intense concentration – same as longer milder concentration.

- Average concentration in space
  - Patchy spotty release with intense portions – same average as a more evenly distributed plume.
Average Position Over Time

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- **Average Plume Position for 20-Seconds**
- **Average Plume Position for 20-Minutes**
Plume Centerline

These two plumes have the same centerline length and disperse the same along the centerlines.
Wind Direction

- Identifies plume trajectory and the downwind receptors.
- Has little or no effect on concentration of effluents (except when terrain effects are included in the modeling).
- Wind is from the direction reported.
Wind Speed

- Establishes plume arrival time at a particular receptor.
- Dilutes source material (i.e., inversely proportional).
- Determines transport times to establish radioactive decay and plume depletion.
Wind Speed Height

- Wind speeds increase higher from the ground.
- Important when you consider:
  - Where your measurement occurs.
  - Where your release happens.
Effect of Wind Speed

**Low Wind Speed**
- Wind Speed: 1 m/sec
- Emission Rate: 5 grams/sec
- 5 grams per meter of plume length

**High Wind Speed**
- Wind Speed: 5 m/sec
- Emission Rate: 5 grams/sec
- 1 gram per meter of plume length
Wind Speed and Deposition

- Fast moving air can carry relatively large or heavy particles.
- Particles fall out of slow or still air.
- The speed where the particles fall out is called “deposition velocity.”
- Some models consider deposition velocity and some don’t.
- Deposition velocity makes plumes shorter.
- Deposition velocity makes contamination more intense at close ranges.
Deposition

Large Particle Plume

Small Particle Plume

Neutral Buoyancy Gas Plume
Rain Out

- Falling precipitation (rain, snow, etc.)
- “Washes” the air
- Removes contaminant mechanically or chemically
- Causes contaminant to fall with the precipitation
Average Concentration
Sampling Time
(Time Weighted Average)

- Five, 10, 15, 30, and 60 minutes are common sampling times.
- Models base dose or exposure on a concentration averaged over the sampling time.
- For example, a 100 ppm plume that lasts for 2.5 minutes, averaged over 10 minutes is a 25 ppm exposure.
- The same plume averaged over 5 minutes is a 50 ppm exposure.
- Some (irritant) chemicals are not appropriate to average. Modelers should provide a peak exposure value for these.
Different Models Have Different Algorithms

- Puff Release (e.g., from an explosion)
- Steady State Release (e.g., from a leaking tank)
- Some models account for buoyant plume rise from fire
- Different versions of the same computer code can produce different estimates of results
Transport and Dispersion

- Release Height
- Wind Speed
- Atmospheric Stability
Dispersion

Source coordinates:
(0,0,H)

Receptor coordinates:
(x,y,z)
Crosswind Factor

Unstable Conditions yield more dispersion

Stable Conditions yield less dispersion and more concentration

\[ \sigma_1 < \sigma_2 \]
Gaussian Model

- A “similarity model”
  - Always assumes crosswind distribution has the same shape

- Empirical Model
  - Comes from statistical analysis of measured releases

- Often considered “The Basic Model”
Vertical Dispersion
Stability Class

- Stability class is a measure of how much the air mixes as it moves.
- There are six stability classes (some people say seven).
- The stability classes are called “A” through “F” (“G”).
- A is the least stable (most mixing).
- F (or G) is the most stable (least mixing).
Sunlight and Wind Speed

- Solar heating causes less stable atmospheres.
- Nighttime has more stable atmosphere than daytime (especially right before sunrise).
- E and F stability classes only happen at night.
- A, B, and C stability classes only happen in daytime.
- D stability class is “neutral” and can happen anytime.
- If the winds are over 6 m/s it’s almost always D.
Effect of Sun on Stability Class

Unstable

Neutral

Stable
## Stability Class Estimation Tool

<table>
<thead>
<tr>
<th>Surface Wind Speed (m/s)</th>
<th>Daytime Insolation</th>
<th>Nighttime Conditions</th>
<th>Anytime</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
<td>Slight</td>
</tr>
<tr>
<td>&lt;2</td>
<td>A</td>
<td>A-B</td>
<td>B</td>
</tr>
<tr>
<td>2-3</td>
<td>A-B</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>3-4</td>
<td>B</td>
<td>B-C</td>
<td>C</td>
</tr>
<tr>
<td>4-6</td>
<td>C</td>
<td>C-D</td>
<td>D</td>
</tr>
<tr>
<td>&gt;6</td>
<td>C</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>

- A: Extremely Unstable Conditions
- B: Moderately Unstable Conditions
- C: Slightly Unstable Conditions
- D: Neutral Conditions
- E: Slightly Stable Conditions
- F: Moderately Unstable Conditions
Stability Class Effect

Stable Condition: Plume Stays Concentrated

Unstable Condition: Plume Becomes Dilute
Stability Class Effect (continued)

More stable air causes plume to stay concentrated further downwind.
More Complex Stability Class Effects

- **Stable (Fanning)**
- **Neutral Below & Stable Above (Fumigating)**
- **Unstable (Looping)**
More Complex Stability Class Effects (continued)

Neutral (Coning)

Neutral Above & Stable Below (Lofting)
Stability Class Effect

More stable air causes plume to stay concentrated further downwind.

For elevated releases, a less stable condition may be more dangerous pushing the plume down toward the people.
Speed and Stability Class Effect

4.4 m/s @ D stab yields ERPG 2 for about 0.9 km

1.5 m/s @ E stab yields ERPG 2 for about 2.5 km
Puff Release
Model Limits

- Building wake effects and terrain steering
- Very low wind speeds
- Model validation conditions
  - Range (1000m < x < 10000m)
- Very stable conditions
Heavy or Dense Gas

• This Chlorine Gas release is spreading along the ground like spilled molasses on a table top.

• The HazMat Technicians are wading chest deep through the heavy material.
Dense Gas Versus Neutral Buoyancy

Neutral Buoyancy Plume is 350x50 yds at 10ppm

Heavy Gas Plume is 550x50 yds at 10ppm
Building Wake Effect

Buildings (and other objects) cause wake and cause the air to swirl downwind

Only extremely sophisticated models can (attempt to) calculate wake effects.

... May be more speculation than prediction
Building Wake Effect (continued)

Upwind Vortex

Wind Unaffected by structure

Recirculation Cavity

Downwashed Plume
Surface Roughness

Urban or Forest

Open Country
Commonly Analyzed Release Conditions

- Many Sites Use Generic Conditions
  - 1 m/s and F stability for worst-case
  - 4.5 m/s and D stability for average and most prevalent

- Some Sites May Chose Site-Specific Conditions (Pantex for example)
  - 95% - 1.5 m/s and E Stability
  - 50% - 6 m/s and D Stability
  - Mode – 4.4 m/s and D Stability
Section 4
Field Monitoring

Source Term Estimation

Transport & Dispersion Analysis

Health Effects Estimates

Integrate Modeling & Monitoring

Consequence Estimate

Communicate Results

Field Monitoring & Indicators

What is Actually Measured Down-Wind
FIELD MONITORING

- Helps to paint the real picture
- One measurement shows one spot at one time
- Limited by the instrument and the operator
- Can be fixed or portable instruments
- There’s no such thing as an “everything meter”
First and foremost, before sending personnel into harms way, ask yourself:

- Will they be able to gather useful information?
- Is the information worth the risks associated with sending them?
- Only the people going into the Hot Zone can say when they are ready to go in – don’t rush them . . . their lives are on the line.
Section 4
Dose Estimation

What Does the Stuff Do When It Gets There
Exposure Logic

Exposure

Severity
Mass/Time

Concentration
Mass/Volume

Breathing Rate
(Volume/Time)

Dose Conversion
Factor

Duration

Frequency
Number of Exposures

Period
Exposure/Time
Dose Conversion Factors

- Being exposed to or contaminated by radiological materials can have different effects
- There are different methods for accounting for the effects of exposure and contamination
- Methods are published by the International Council of Radiological Protection
Dose Conversion Continued

- “The Green Book” or “EPA 400” has the dose conversion factors used for emergency planning
- Radiological Dose based on Federal Guidance Report 11 (FGR11)
- When exposure (versus internal contamination) is less than 10% of the dose, it uses CEDE; otherwise, TEDE
Projected Dose

“It is important for emergency managers to realize that projected doses calculated in the context of using PAGs (Protective Action Guides) for decision making are not real doses to individuals, but are part of an emergency-response framework to reduce the complexities of decision making during an emergency.”

-Health Physics Society
Section 5
Consequence Assessment Challenges and Difficulties
How Long Will Met Conditions Last

For a plume to travel ten kilometers at 95th percentile weather conditions (1.5 m/s and E stability) would require unchanging (nighttime) weather for just under two hours.
Model Acceptance and Validation

- The Central Registry provides a library of DOE "Toolbox" Codes covering site:
  - Boundary accident dose consequences
  - Fire accident source terms
  - Leakpath factors
  - Chemical release/dispersion and consequence
  - Radiological dispersion and consequence
“Worst-Case” Modeling

- Generally . . . the set of conditions that keeps the concentration the highest for the longest distance downwind

- Usually:
  - Low wind speed and very stable atmosphere
  - Ground level release
  - Brief, intense release

- Useful as a point-of-reference and in very early event phases
“Worst-Case” Modeling (continued)

Long reaching plume that didn’t affect anything once it got there.

This plume diluted faster in unstable air but affected more.

Fast moving winds didn't give these people a chance to take protective action even though the plume diluted faster.
Jurisdiction Problems

- Which agency is responsible for applying plume models in an emergency.

- The lines are fuzzy and responsibilities not entirely clear.
Jurisdiction Problem Example

- Pantex Plant
- DOEHQ,
- NARAC
- Texas State Dept. of Health Services,
- Texas DEM, and
- City of Amarillo

All are likely to run simultaneous models with different platforms and different assumptions to end with different results.

This proved to be a problem in the 2003 TOPOFF Exercise.
Wise Practice

- Look at a variety of consequence estimates for the same event
- Use different tools and different assumptions
- See the range of consequence estimates
- Consider them all
- Don’t take any of them as “TRUTH”
Wise Practice (continued)

- Take field measurements and model results into consideration together
- Neither one gives the full picture
Take a Balanced Approach

- There are risks associated with both overestimating and underestimating consequence
- Consider the public reaction to Orson Welles’ “War of the Worlds”
Summary

Three Parts

- Source Term – (biggest impact)
- Transport and Dispersion
- Dose and Effect
Summary (continued)

- **Accuracy**
  - Factor of two or three in the transport and dispersion portion of the estimate
  - Communication of degree of accuracy is difficult but very necessary

- **Communication is the Key!**
  - Not just a footprint
  - Talk with the modeler or you won’t understand what you’re seeing