Applications of Atmospheric Dispersion Modeling to On-Site Inspection

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Probabilistic Dispersion Modeling Can be Used to Improve Radionuclide Data Collection and Interpretation

- Issue: Commonly-used deterministic modeling
  - May not capture meteorological and source term uncertainties
  - Potentially leads to sampling plan / sensor placement that fails to detect plume

- Goal: Improve likelihood of atmospheric radionuclide detection through the use of high-resolution dispersion modeling

- Challenge: efficiently capturing complex time-dependent behavior of the atmosphere coupled to uncertainties in venting source term

- Requirements
  - Probabilistic estimates
  - Operational products that communicate key information to inform / optimize sensor sampling / placement

Example of plume variability (large variation in wind direction) due to frontal passage at Nevada location
Plumes Exhibit Complex Time-Dependent Behavior in Real-World Conditions

- "Gaussian" atmospheric plume for relatively homogeneous conditions
- Model results compared to concentration data from a tracer release at the Diablo Canyon nuclear power plant in California
- Animation of behavior of atmospheric plume produced by volcanic venting (Kilauea Volcano, HI)
Illustrative Example Selected to Highlight Key Phenomenology and Proposed Methodology

- U.S. community Weather Research and Forecast (WRF) Model
  - High-resolution modeling with nesting down to 1km grid spacing
  - Simulation period during the passage of an upper level trough / surface front during the period April 4-7, 2015

- Lagrangian dispersion model

- Example release scenario
  - Nevada National Security Site location U20az
  - Noble gas
  - Variable venting release rate (see figure)

Venting emission rate over 24 hours used in illustrative example
Meteorology Variability Can Result in Large Variations in Plume Direction and Spread

- High-resolution modeling needed to capture complexity of atmospheric flow and dispersion resulting from
  - Synoptic-scale forcing
  - Local weather effects induced by terrain, land-use, vegetation
  - Deposition / precipitation

- Variability especially evident in cases such as frontal / low pressure zone passage (shown in illustrative example)

Wind vectors (color coded by wind speed) at 10 m above ground level at Nevada National Security Site location showing features including flow around hills, canyon channeling, and downslope flow
Uncertainties in Release Term Characteristics Should Be Taken into Account (Example: Four Release Times)
Meteorological Ensembles Take into Account Initial/ Boundary Conditions and Model Physics Uncertainties

- Numerical weather prediction ensembles are an established technique that captures atmospheric variability and improves model fidelity.

- Current research is targeted at developing more robust efficient sampling techniques for ensemble generation.

Extension of Ensemble Approach Can Be Used to Construct Probability of Detection Product

- Combined meteorological and dispersion model ensemble simulations used to account for
  - Meteorological variability
  - Range of source terms (release)
  - Model uncertainties

- Likelihood of exceeding a specified air concentration/deposition threshold (or other detection criteria) is determined by calculating the probability of meeting the criteria at each location based on the ensemble of simulations.

Schematic showing plume and arbitrary 24-hour threshold concentration

Schematic illustrating areas exceeding threshold concentrations for multiple ensemble members (areas of overlap are regions of higher probability)
Example Probability of Exceeding Threshold (24-hour Integrated Air Concentration)

- Probability of exceeding threshold concentration determined from illustrative 21 member ensemble
- Higher degree of ensemble overlap leads to higher likelihood of detection (yellow-to-red)
- Small probability of exceeding threshold to west or southwest of release location
- Different release times / meteorology leads to different probabilistic behavior

*Probability of detection map during a period of high atmospheric forecast confidence (April 4th).*
Detection Strategies Based on Deterministic Modeling May Miss Plume Locations Captured by an Ensemble Approach

Deterministic (GEFS control run) and probabilistic (ensemble) modeling will produce detection maps resulting in different guidance on appropriate sampling locations / sensor placement locations (red dots). Deterministic modeling does not capture possibility of a northerly direction plume in illustrative example for April 7th.
Probability Maps Are Sensitive to Source Term Quantity and Specified Detection Threshold

Spatial coverage of 24-hour probability of detection maps is significantly reduced if the air concentration (threshold) detection limit is increased by a factor of 5.
Locations and density of samples
- Dependent on type and number of available sampling instruments
- Use of crosswind arcs for improved confidence
- Varying density of sensors in regions of higher/lower probability

Different placement strategies for post-facto (deposition) sampling vs. detection of on-going/future airborne releases

Larger numbers of sample locations and higher time-resolution data is required for extension to quantitative source estimation / reconstruction

Predicted dose rate areas

MEXT Dose rate measurement stations

NARAC simulation based on estimated release rate for Fukushima Dai-ichi release compared to Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) data for March 15, 1800 UTC*. Dose rate contours and data circles color coded to show levels: 120µGy h⁻¹ (red), 4µGy h⁻¹ (pink), 0.4µGy h⁻¹ (orange), 0.04µGy h⁻¹ (light orange) and 0.004µGy h⁻¹ (yellow).
Future Extensions of Probabilistic Approach

- Straightforward adaption to handle
  - Multiple atmospheric signatures (noble gas, particulate material)
  - Different locations (guided by seismic or other analyses)
  - Extended periods

- Computationally-efficient sampling and robust construction of meteorological and dispersion ensembles
  - Statistical methods to design ensembles to optimally sample sources of meteorological uncertainty – initial/boundary conditions and model physics options (e.g., Simpson et al., 2014*)
  - Methods for limiting or improving sampling of source term phase space (e.g., coupling to underground venting models)

\[
\text{Detection} = F_1(\text{Weather variability}, \text{Meteorological complexity}, \text{Dispersion and meteorological model physics}, \text{Resolution}) \times F_2(\text{Material Emission Rate}, \text{Release location}, \text{Physical / chemical properties (PSD)}, \text{Degradation/ reactivity}, \text{Dry/wet deposition}) \times F_3(\text{Sensor characteristics}, \text{Instrument threshold and sensitivity}, \text{Background}) \rightarrow \text{Probabilistic products}
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Many Current Emergency Response Dispersion Modeling Tools Can Be Adapted for OSI Applications

- Adaptation and extension of
  - Meteorological and dispersion modeling tools
  - Operational real-time capabilities and expertise

- High-resolution modeling
  - Weather forecasting
  - Realistic ground truth for exercises
  - Guidance for atmospheric radionuclide detection (sampling and sensor network placement)
  - Source reconstruction based on air/ground concentration data

- U.S. Department of Energy (DOE) operational capabilities (NARAC, IXP) and Web sites
  - Receive / share expert reachback analyses
  - Fully automated atmospheric dispersion and dose calculations
  - Accounts available as authorized by DOE

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*Sugiyama, G; Nasstrom, J; Pobanz, B; Foster, K; Simpson, M; Vogt, P; Aluzzi, F; Homann, S, 2012: Atmospheric Dispersion Modeling: Challenges of the Fukushima Daiichi Response, Health Physics, 102, p 493–508. doi: 10.1097/HP.0b013e31824c7bc9
Backup / Supplemental Slides
High-Resolution Dispersion Modeling Can be Used to Improve Radionuclide Data Collection and Interpretation

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*Example of plume variability (large variation in wind direction) due to frontal passage at Nevada location*
Example Result: Probability of Exceeding Threshold (24-hour Integrated Air Concentration)
Center provides tools and services to predict and map the probable spread of hazardous material into the atmosphere

Access to world-wide weather data and geographical information:

- Observed & forecast weather data
- Terrain & land surface
- Maps
- Population

National Atmospheric Release Advisory Center (NARAC):

- Computer systems for real-time 3-D plume simulations
- Un-interruptible, backup power
- 24x7 scientific analysis & technical support

Automated real-time 3-D plume model predictions for nuclear, radiological, chemical or biological releases available in minutes from national center using Internet/Web tools

Standalone simple plume modeling tools for end-user’s computer require no connection to LLNL
Source Terms Estimation and Refinement of Dispersion Simulations Were Based on Radiological Measurements

Initial Model Predictions
Guide Measurement Surveys

Measurement surveys and sensor data, e.g., DOE AMS, DOE, DoD, Japanese field data

Measurement Data transferred electronically to LLNL/NARAC

Updated predictions using measurement data

Software used to help select, filter and statistically compare measurements and predictions