Probabilistic Model Evaluation of Continuous Air Monitor Response Relative to Radiation Protection Goals

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Problem: Need for dose-based evaluation of CAM program (design phase – in place)

- Need to evaluate CAM program relative to radiation protection goals
- Need to evaluate CAM response in a holistic fashion
  - Instrument Factors
    - CAM alarm set point
    - Alarm response time
  - Dispersion Factors
    - Transport time (function of air exchange rate)
    - Placement (impacts dilution and transport time)
    - Closeness of worker and BZ clearance

Concept of Dose Control Level: The Radiation Protection Goal (RPG) for a worker

- Purpose of CAMs is to reduce or eliminate inhalation of radioactive material by alerting workers to high air concentrations
- Set a dose goal for the CAMs in a room.
  - You may want to control dose during a release to < 5 rem or 2000 DAC-hrs for most releases.
  - This goal is your RPG
  - Keep in mind, for Pu, this is a bit tricky because, in large releases, the worker might exceed the limit in the first breath. This possibility has to be accepted by managers, HP staff, and workers. The alternative is to require respiratory protection at all times.

Need to build mathematical exposure models that account for each of these factors

Inhalation dose (DAC-hr) dependent on:

Instrument Factors
- Alarm Time (AT)
- Alarm Sensitivity (DAC-Hr)

Non Instrument Factors
- Concentration in BZ [$C_{BZ}(t)$]
- Transport time to CAM (TT)
- Dilution between BZ and CAM
- location

Models Evaluated:

Steady-State
- Not time dependent
- Dilution is constant

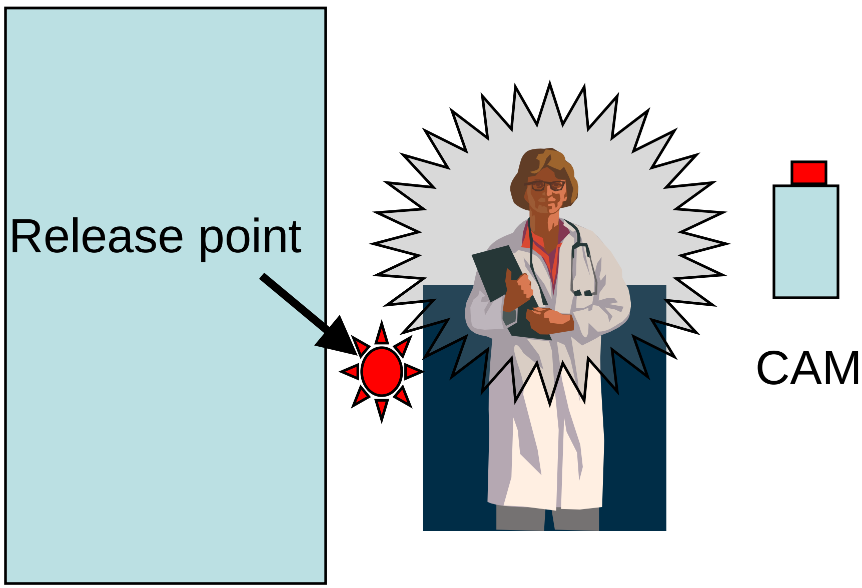
2-Component Mixing Model
- Time-dependent dispersion
- BZ, room volumes as compartments

Gradual Mixing Model
- Time-dependent dispersion
- Expanding hemisphere

Goal: Develop models that allow comparison of ability of CAM program to protect workers relative to goals through improved CAMs, ventilation, and placement

- Instrument Improvements
  - 24 DAC-hr versus 8 DAC-hr
  - 1 minute alarm versus 30 second alarm
- Ventilation Improvements
  - 7 ACH versus 15 ACH (transport velocity scales proportionally with ACH)
  - Removal rate constants k_1 and k_2 increase
- Placement Improvement
  - Transport times decrease (based on empirical data)

Exposure scenario: Release with nearby worker who accumulates dose until the first CAM Alarms



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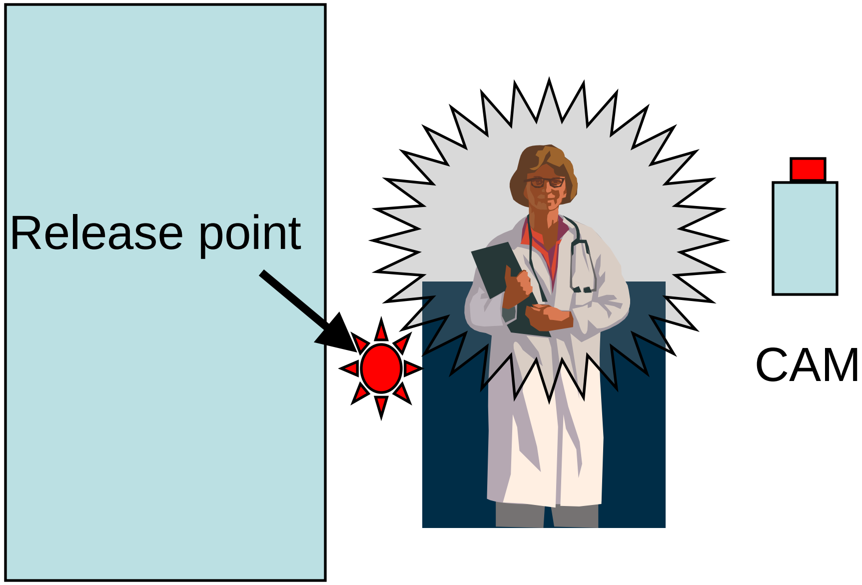
Details for each of the Mathematical Models



Start evaluation with Dose (D) calculations

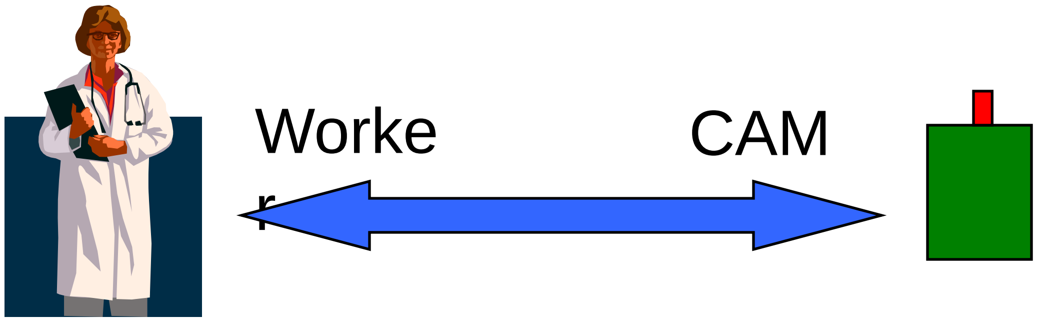
Calculation of Dose Relevant Exposure (DRE)

$$DRE = \frac{E(\frac{Bq}{m^3} \cdot hr)}{DAC} \quad \text{in units of DAC} - \text{hr}$$

Calculation of Committed Effective Dose Equivalent

$$D = DRE \cdot \left[\frac{50 mSv}{2000 DAC - hr} \right]$$

Concept: Develop mathematical model to predict relationship between CAM response and dose



$$E_w(t_E) = \int_0^{t_E} C_{BZ}(t)dt \Rightarrow E(t_E) = DF(t_E)\int_{t_{TT}}^{t_E} C_{CAM}(t)dt \Leftarrow E_{CAM}(t_E) = \int_{t_{TT}}^{t_E} C_{CAM}\,dt$$

$$\Downarrow$$

$$DF(t_E) = \frac{\int_0^{t_E} C(t)_{BZ}\,dt}{\int_{t_{TT}}^{t_E} C(t)_{CAM}\,dt}$$

Key link is dilution factor (DF)

Dilution Factor (DF) is Critical to Linking CAM response and worker dose: Two types of assumptions for models

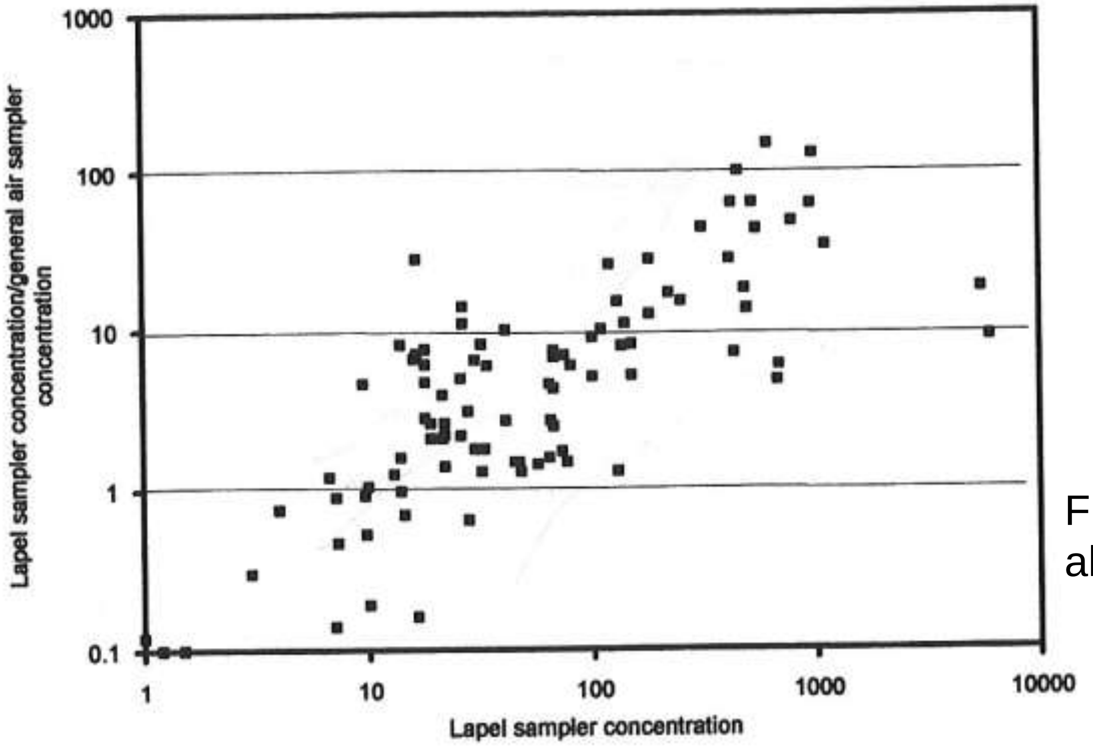
- Steady-State Assumption
  - The DF is a constant
  - Best for continuous releases where concentrations in the room reach equilibrium state
- Time-Dependent Assumption
  - The DF changes with time (from infinite to equilibrium value after a long period of time)
  - Best for acute releases and concentrations that rapidly change as the aerosol disperses into the room

Comparison for chronic release: Illustration of Steady-State Model [(DF_{SS}) is a constant]

$$E(t_E) = DF_{ss} \int_{t_{TT}}^{t_E} C_{CAM}(t)\,dt$$

Dilution Factors for Steady-State Model

$$\text{Dilution Factor} = \frac{\text{Mean BZ Concentration}}{\text{Mean CAM Concentration}}$$



From: Alvarez et al. HPJ,1994

Comparison for an acute release with time-dependent model [DF(t)]

Gradual Mixing Model[1]

[1]Jordan H, Gordon DJ, Whicker JJ, Wanningman DL. Predicting Worker Exposure from a Glovebox Leak LA-13833-MS; 2001

Mathematics of GMM

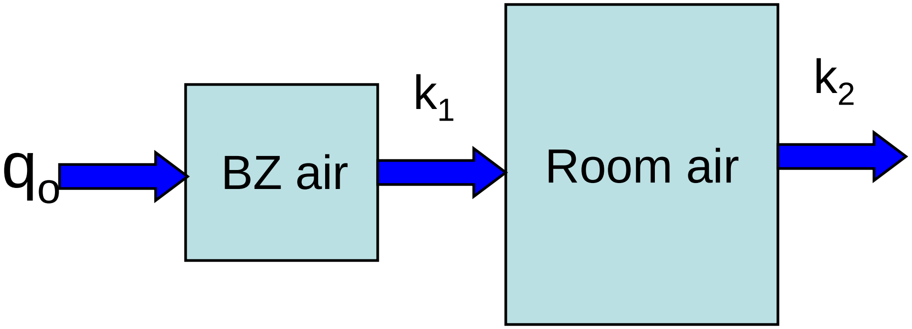
Calculation of DF_{GMM}

$$DF_{GMM}(t) = \frac{\dfrac{q_o}{V_{BZ}}}{\dfrac{q_o}{V_{CAM}}} = \frac{V_{CAM}}{V_{BZ}} = \frac{\frac{2}{3}\pi r_{CAM}^3}{\frac{2}{3}\pi r_{BZ}^3} = \frac{r_{CAM}^3}{r_{BZ}^3} = \frac{\left[v_{trans}\cdot(t_{TT})\right]^3}{r_{BZ}^3}$$

Calculation of DRE_{GMM}

$$DRE_{GMM}(t) = IC_{cam} \times DF_{GMM}(t)$$

Schematic of 2-Compartment Mixing Model (2-CMM)



Mathematics for 2-Compartment Mixing Model

Calculation of $DF_{2\text{-}CMM}$

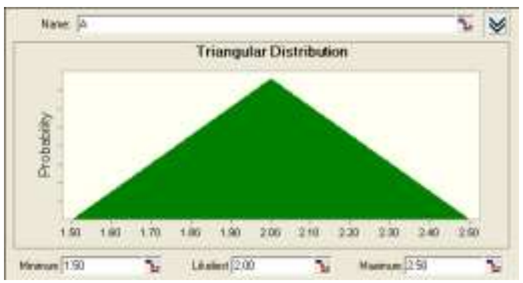
$$DF_{2-CMM}(t) = \frac{\dfrac{q_o}{V_{BZ}} \displaystyle\int_0^{t_E} e^{-k_1 t}\,dt}{\dfrac{q_o k_1}{V_{CAM}(k_2 - k_1)} \displaystyle\int_{t_{TT}}^{t_E} (e^{-k_1 t} - e^{-k_2 t})\,dt} = \frac{V_{CAM}(k_1 - k_2)}{V_{BZ} k_1^2} \left[\frac{1 - e^{-k_1 (t_{TT} + \Delta t_{TA})}}{\dfrac{e^{-k_2 t_{TT}} - e^{-k_2 (t_{TT} + \Delta t_{TA})}}{k_2} - \dfrac{e^{-k_1 t_{TT}} - e^{-k_1 (t_{TT} + \Delta t_{TA})}}{k_1}} \right]$$

Calculation of $DRE_{2\text{-}CMM}$

$$DRE_{2-CMM}(t) = IC_{cam} \times DF_{2-CMM}(t)$$

Model uncertainty and sensitivity analysis: Each factor in model has uncertainty, and which of the factors are the most important in each model: Crystal Ball Monte Carlo Analysis Tool

Example Model: A+B=C



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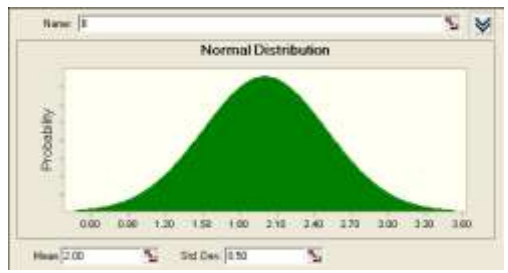

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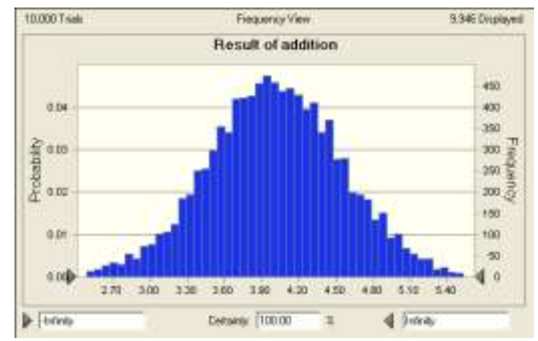


Evaluate sensitivity of the parameters

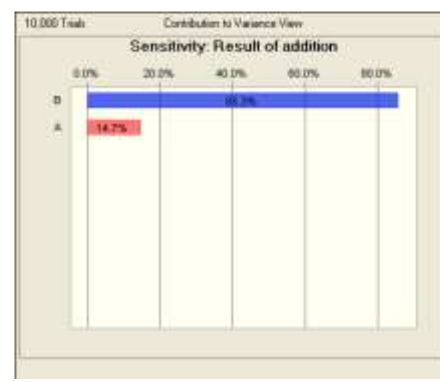


Table with settings for simulation runs

Parameter	Distribution type	Reference settings	Improved CAM only	Improved vent. and placement	Combined Improvements
Alarm level (DAC-hr)	Triangular	24	8	24	8
Time to alarm (min)	Triangular	1	0.5	1	0.5
Vent. ACH (hr^{-1})	Normal	7	7	15	15
Transport vel. ($cm\ s^{-1}$)	From ACH	7	7	15	15
Transport time (min)	Normal	0.8	0.8	0.4	0.4
K_1(min^{-1})	Normal	0.86	0.86	1.0	1.0
K_2 (min^{-1})	Triangular	0.12	0.12	0.25	0.25
Worker distance (m)	Triangular	0.75	0.75	0.75	0.75

General approach using Monte Carlo techniques

Model Selection

Steady-State

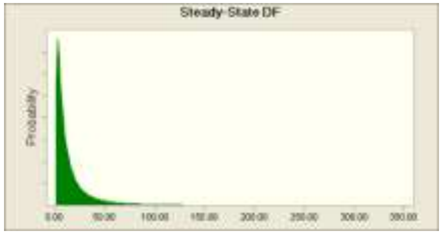
2-Compartment Mixing Model

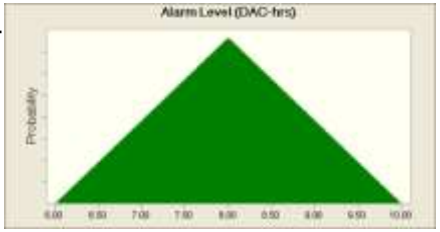
Gradual Mixing Model

Select New Set of Model Parameters Based on Probability Distribution

Initial Input Using Probabilitiey Distrbutions for Model Parameters

Examples





If N < 10,000 runs

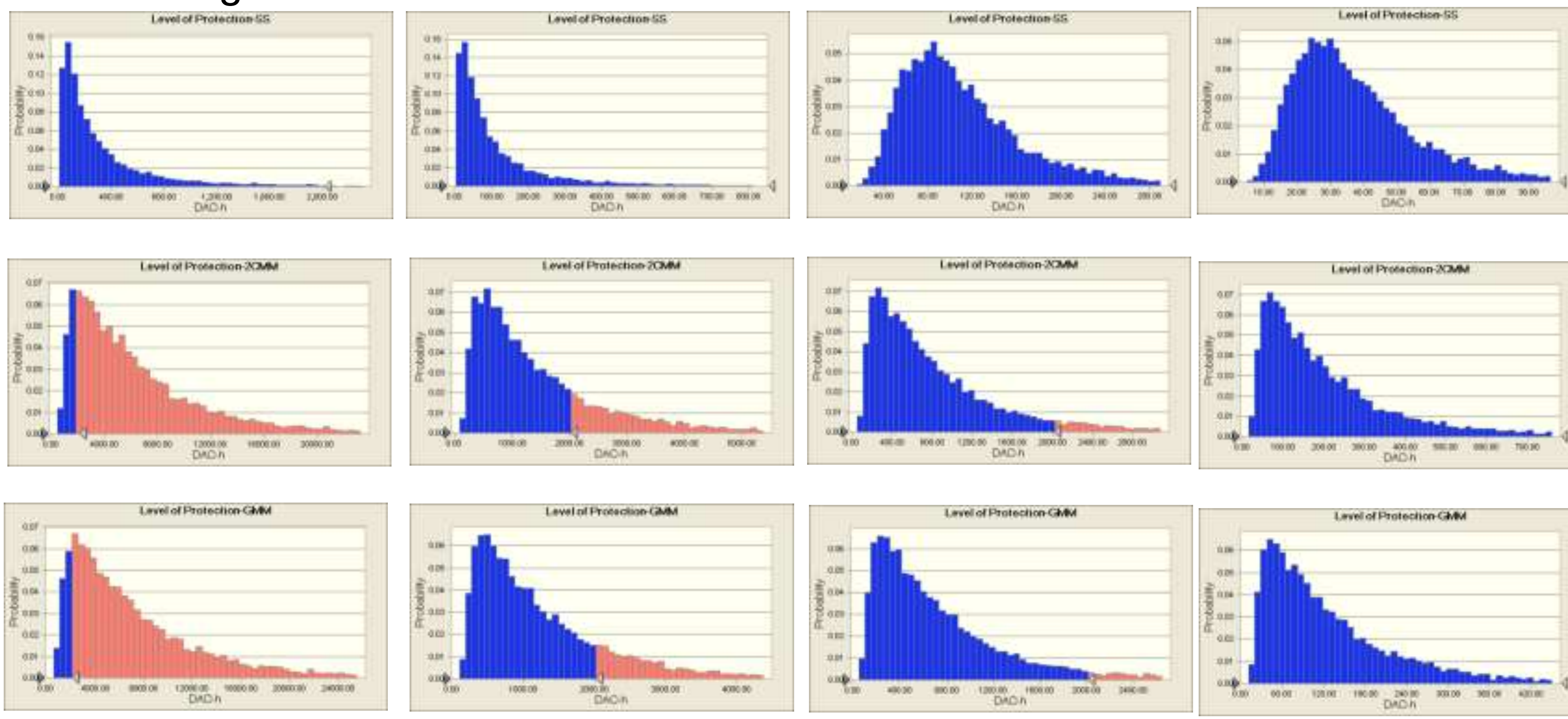
Calculate DRE and Accumulate Distribution of results from model run

If N = 10,000

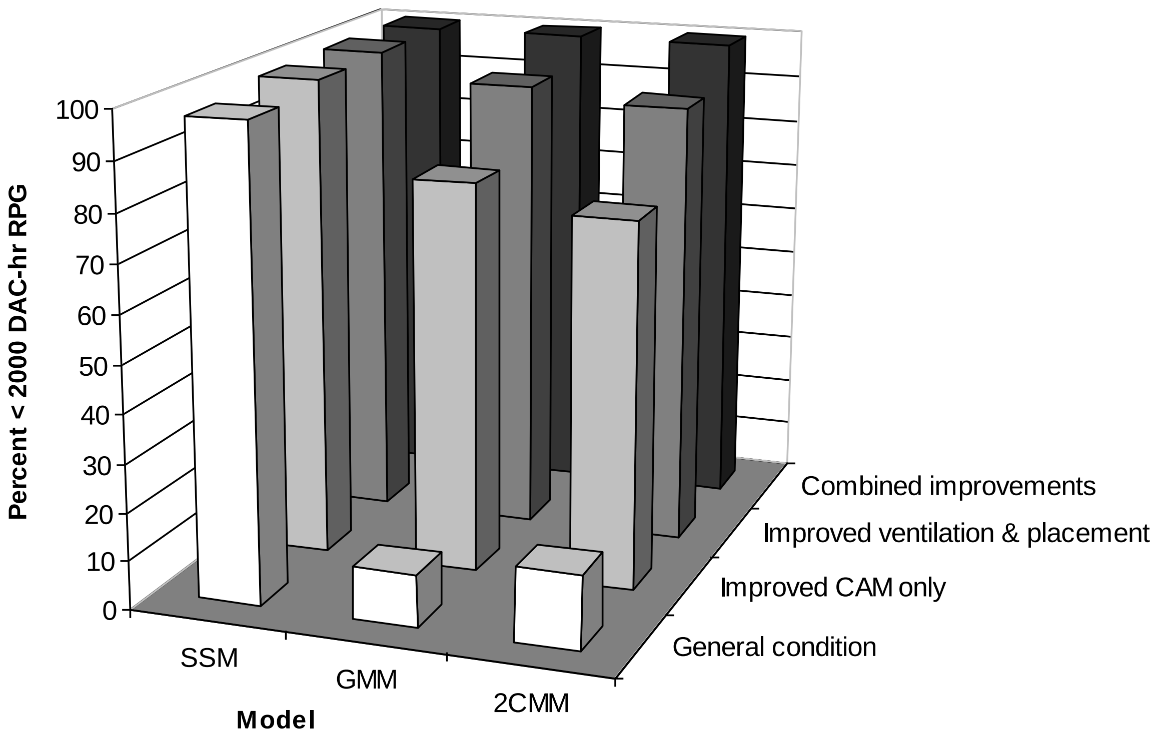
Report Results

Results: Distribution of percent of releases < RPG of 2000 DAC-hr (blue <2000DAC-hr, red >2000 DAC-hr)

	Reference settings	Improved CAM	Improved Vent. and Placement	Combined Improvements
SSM				
2-CMM				
GMM				

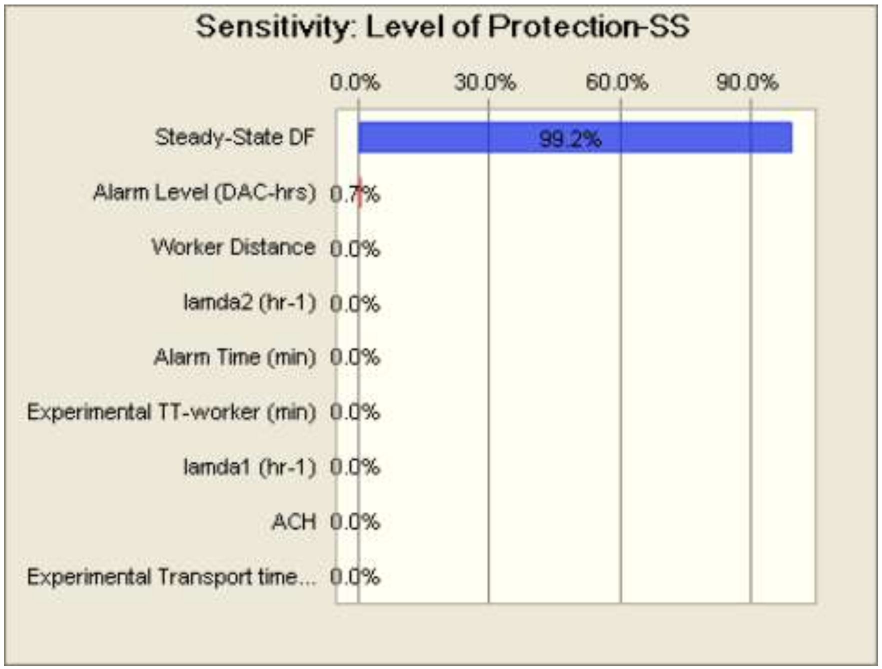


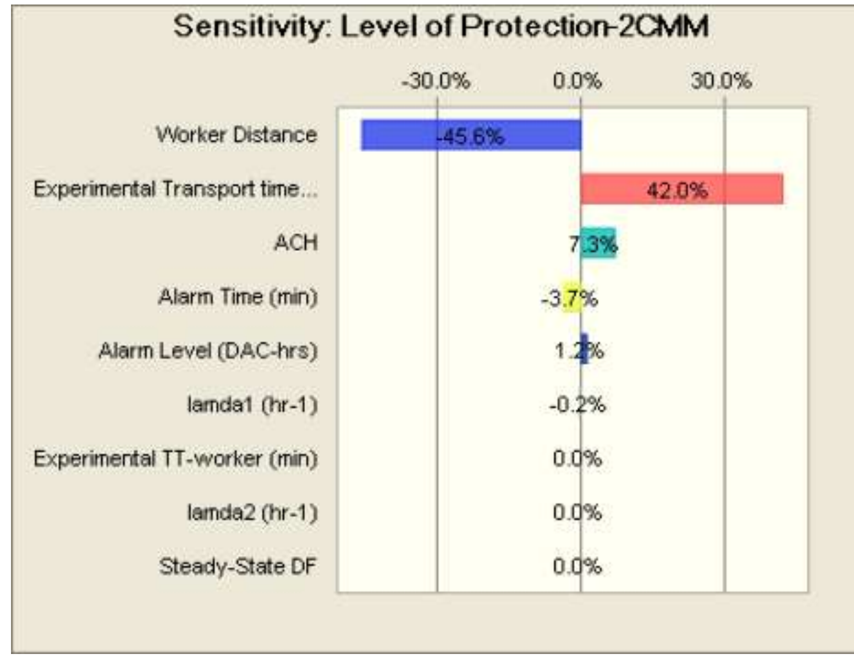
Results: Steady-State Dispersion Model



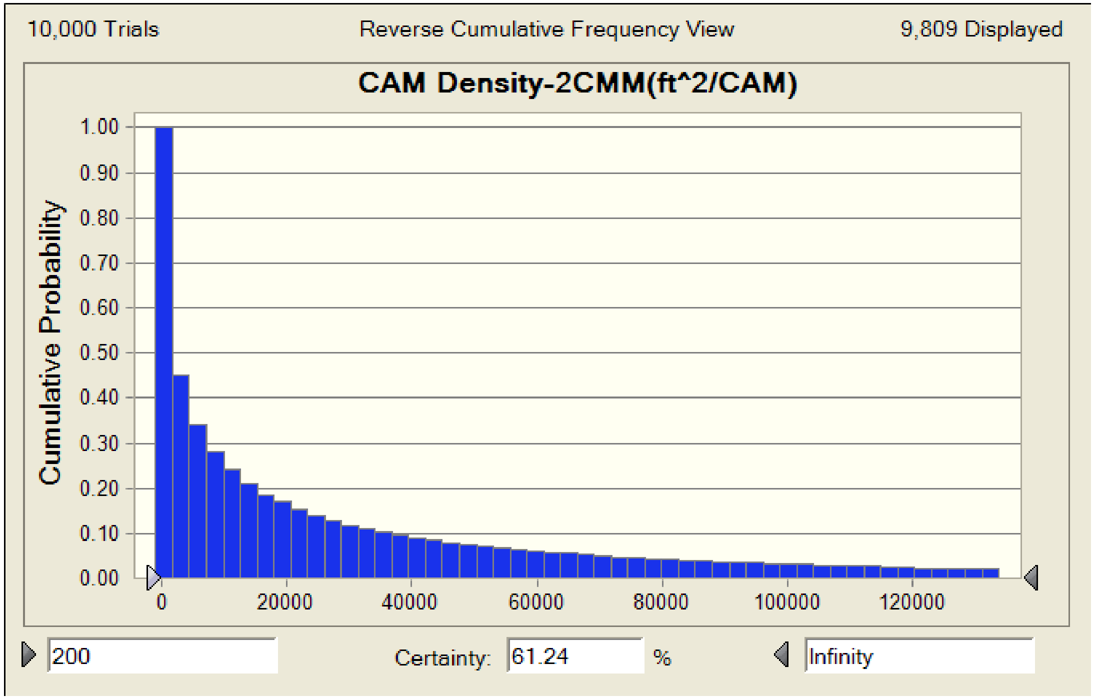
Typical results from sensitivity analysis- compare influence of variation in variables on final result

Reference Settings





Analysis of CAM density:Probability of being below RPG if density = 1 CAM/200 ft^2=61%



Conclusions

- Simple models were constructed for holistic evaluation of CAM performance relative to worker protection
- Monte Carlo simulations were run based on distributions of model parameters
- Workers are not always adequately protected, especially from larger, acute releases
- Results show the need for combined improvements in CAM instrument performance, ventilation, and CAM placement