Effectiveness of Urban Shelter-In-Place (SIP): What factors affect effectiveness

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Outline

- Introduction
- Idealized models for analysis
- Metrics of effectiveness for community SIP
- Results from idealized models
- Conclusions

Background

- **Catastrophic outdoor toxic chemical releases**
  - Often sudden and unanticipated (~100 per year in the U.S. requiring community decisions and public responses)
  - For a dense large community, evacuation is often infeasible
- **Shelter-in-Place (SIP)**
  - Could be an effective temporary measure
  - Has been documented to have provided successful protection

Introduction

- **Many factors can affect SIP effectiveness**
  - Studies on SIP effectiveness for individual buildings exist
  - However, what about effectiveness of SIP for a whole community?
  - What is the relative importance of building air-exchange rates, toxic load exponent? Duration of release? Delays in starting and ending SIP?
  - How do these factors interact in influencing the effectiveness of SIP for a community?

Approach

- **Start with an idealized representation of the problem -- so as to remove event-specific particularities**
  - Some simplifications are made to abstract general conclusions

Models

Three Simple Models Interact to quantify Community-SIP:

- **An Outdoor Plume model**
- **A model to predict Indoor Concentrations**
- **A model to predict Health Effects**

Simplifications

- **The plume is modeled as Gaussian with constant steady wind**
- **Toxic chemical in the plume is idealized**
  - it is conserved, and does not sorb/desorb on indoor surfaces
- **Population density is uniform**
  - This provides predictions clear of complications from density variations
- **All community members respond promptly to SIP instructions**
  - all start SIP at t=0, and all end it together when told
- **Indoor Concentration are predicted with a well-mixed box-model**
- **Community houses have uniform air exchange rate**
  - We do explore different values of this parameter

Outdoor Plume Model

a variant of the Gaussian atmospheric diffusion model

$$C_{out}(x,y,z,t) = C_G(x,y,z)\cdot\frac{1}{2}\left[erf\left(\frac{x}{\sigma_x\sqrt{2}}\right) - erf\left(\frac{x-\overline{U}t}{\sigma_x\sqrt{2}}\right)\right] \quad \text{for} \quad t \le T_r$$

$$C_{out}(x,y,z,t) = C_G(x,y,z)\cdot\frac{1}{2}\left[erf\left(\frac{x-\overline{U}(t-T_r)}{\sigma_x\sqrt{2}}\right) - erf\left(\frac{x-\overline{U}t}{\sigma_x\sqrt{2}}\right)\right] \quad \text{for} \quad t \ge T_r$$

Outdoor Plume Model specifics

the Gaussian atmospheric diffusion model:

- Assumes a Steady wind speed and direction
- Uses dispersion coefficients based on curve fits to the standard Pasquill-Gifford data
- Employs a uniform grid (results checked for grid-independence)
- Uses a No-flux boundary at the ground and the mixing height using image-sources
- Assumes release at the ground level
- Predicts concentrations at a height of 2m above ground for the indoor model

Indoor Concentration Model

a well-mixed box model for indoor concentrations:

$$\frac{dC_{in}(x,y,t)}{dt} = \frac{Q}{V} \cdot \left[C_{out}(x,y,t) - C_{in}(x,y,t)\right]$$

- Sorption and desorption on indoor surfaces is ignored
- Similarly, filtration by the building envelope is ignored
- Mass balance is used to calculate indoor concentrations at each grid cell
- Indoor concentrations are updated at one minute intervals

Health Effects Model

a toxic-load model for health-effects:

$$\mathrm{TL}(t) = \int_0^t \left(C(t')\right)^m dt'$$

- For some chemicals, exposure to high concentrations for short duration is much worse than exposure to low concentrations for long durations. The effect is non-linear
- This behavior is incorporated into a toxic-load model (ten Berge 1986)
- We calculate the (time-dependent) toxic-load for each grid-point for both indoor and outdoor conditions
- When a present Toxic Load Limit ("TLL") is exceeded, corresponding adverse health effect is deemed to have taken place. We use the AEGL limits (NRC 2003) in our simulations

Community-SIP effectiveness

- Measuring community SIP effectiveness is complex
- Existing metrics in the literature relate to SIP protection from individual buildings
- Existing metrics for SIP effectiveness ignore the non-linear health-effects of many toxic chemicals
- We developed two new metrics relevant to this study: explained in the next slides

Summary of the two metrics

- Casualty Reduction Factor measures how many fewer casualties occur indoors (with SIP) versus outdoors (without SIP)

Causalty reduction factor = CRF

- However, in some releases, there are no casualties even outdoors.   SIP still improves the factor of safety in such cases. Safety Factor Multiplier measures the increase in the safety factor resulting from SIP

Safety Factor Multiplier = SFM

First Metric of Community-SIP: CRF

Casualty Reduction Factor (CRF)

$$CRF = 1 - \frac{\text{Population}\,(TL_{indoors} > TLL)}{\text{Population}\,(TL_{outdoors} > TLL)}$$

- **Equals the *fraction* of population that would avoid potential adverse health effect by sheltering indoors (compared to exposure outdoors)**

- **The numerator and denominator are the sizes of populations that would exceed the TTL if exposed to indoor and outdoor concentrations, respectively.**

More on CRF

$$\text{CRF} = 1 - \frac{\text{Population}\,(\text{TL}_{\text{indoors}} > \text{TLL})}{\text{Population}\,(\text{TL}_{\text{outdoors}} > \text{TLL})}$$

- Can vary from zero (no protection), to one (perfect protection)
- Can be evaluated as a function of time
- (For minor releases, CRF may be undefined because no one would be hurt outdoors, so the denominator is zero)

Safety Factor Multiplier (SFM)

- **Safety Factor** is the multiplier by which the exposed concentrations can be increased without exceeding the TTL, the limit for adverse health effects

$$\int_0^t \left(\mathrm{SF}\cdot C(t')\right)^m dt' = \mathrm{TLL}$$

$$\mathrm{SF} = \left(\frac{\mathrm{TLL}}{\mathrm{TL}(t)}\right)^{\frac{1}{m}}$$

From Safety Factor to SFM

- Sheltering indoors can increase the safety factor. This increase is captured in the **Safety Factor Multiplier**

$$SF_{in} = SFM \cdot SF_{out}$$

$$SFM = \left(\frac{TL_{out}}{TL_{in}} \right)^{\frac{1}{m}}$$

- SFM is evaluated for each location in the plume by comparing indoor and outdoor toxic loads

- A high SFM implies effective protection with SIP. An SFM close to 1 implies SIP is ineffective -- as bad as being exposed outdoors

More on SFM

$$SF_{in} = SFM \cdot SF_{out}$$

$$SFM = \left(\frac{TL_{out}}{TL_{in}} \right)^{\frac{1}{m}}$$

- In a given event, SFM will be the same for all buildings only if they all experience the same outdoor concentration profile, and have the same air exchange rate

- Neither of these conditions apply, so a distribution of SFM values will occur in a building stock in a community exposed to a toxic chemical plume

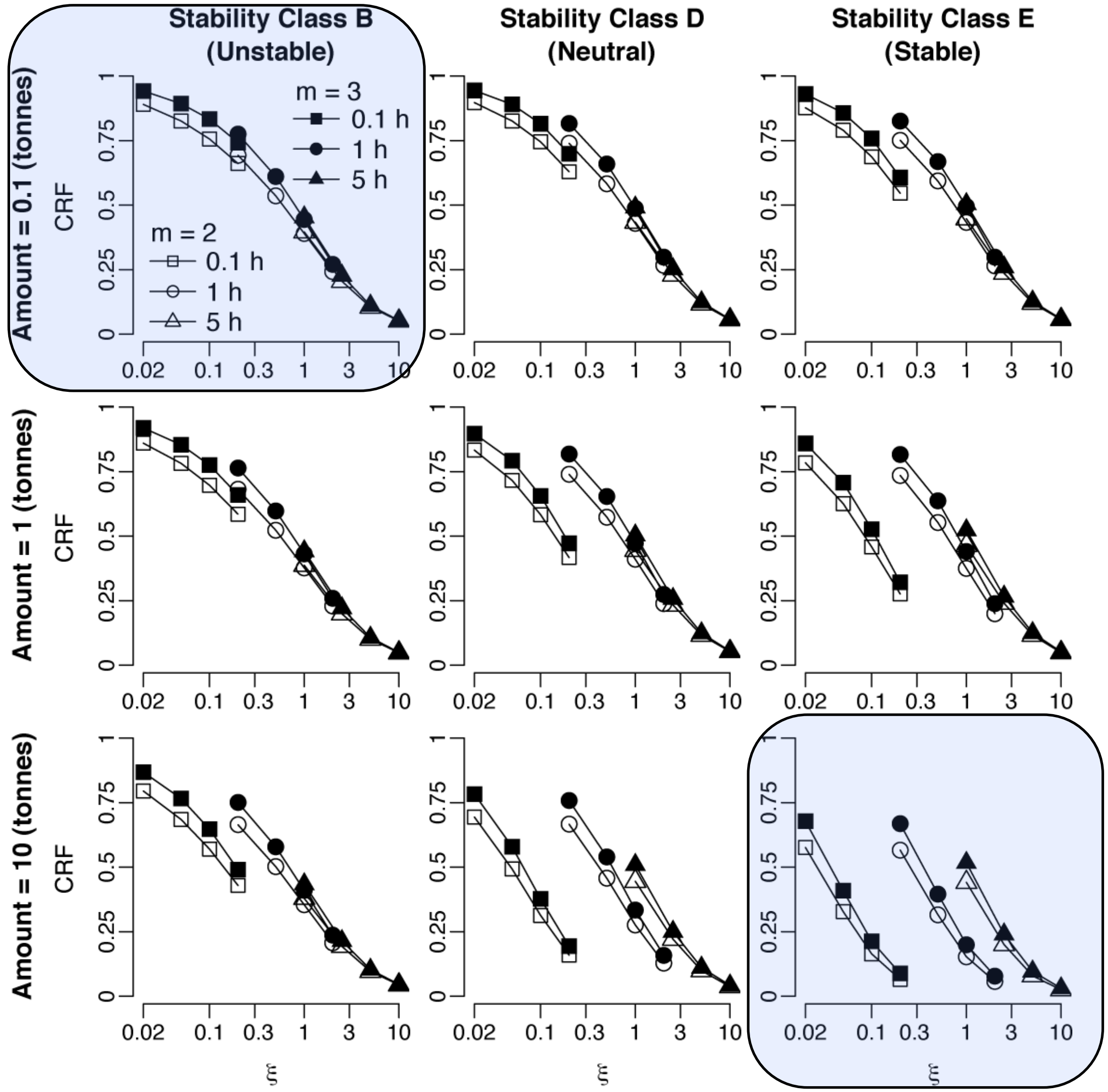
Specific Goals

Evaluate Community SIP effectiveness in terms of the two metrics (CRF and SFM) for a variety of parameter values for:

- **Release characteristics**
  - Release amounts (0.1, 1 and 10 tonnes)
  - Release duration (0.1, 1 and 5 hours)
  - Three stability classes: from B (moderately unstable), to E (moderately stable)
- **Chemical toxic load exponents**
  - Assume moderate toxicity: TLL set to 1 mg/m^-3 for 1 h (about six times less toxic than methyl isocyanate)
  - Three toxic load exponents, 1, 2 and 3
- **SIP strategy**
  - All homes have air exchange rates of 0.2, 0.5, 1, or 2 per hour (reflecting full anticipation or no anticipation and open windows)
  - SIP assumed to start immediately at start of release, at t=0
  - SIP termination explored for delays of 0.5, 1 and 3 h beyond departure of the plume

Results 1: effect of Release Duration on CRF

- **ξ, the product of air-exchange-rate and release-duration, strongly influences SIP effectiveness**
  - For m=2 and m=3, and small releases, low **ξ** leads to large CRF, I.e., high protection from SIP
  - However for m=1, for large releases, and stable atmospheric conditions (results not shown here), **ξ** does not have high explanatory power



Results 2: effect of Release Amount

- **Release-amount and release-duration interact in their effect on the CRF**

  - For releases of short duration, SIP effectiveness is highly sensitive to release amount. This is because small release will cause harm outdoors but not indoors, leading to high CRF. Also a very large release will cause harm indoors as well as outdoors in most places, leading to low CRF.

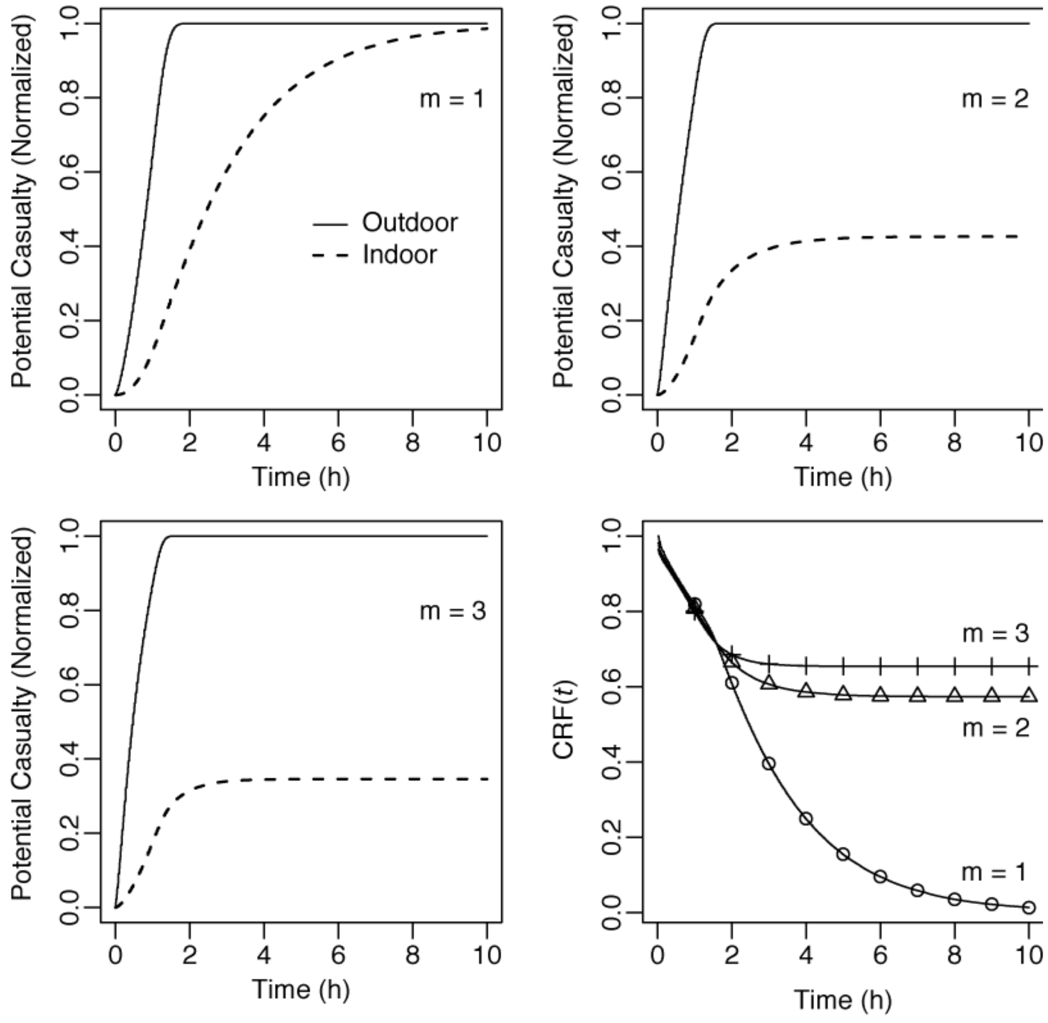
  - However, for releases of long duration, even a moderate release will eventually get indoors and cause harm. So, for long-duration releases, CRF is less sensitive to release-amount.

Results 3: effect of Toxic Load Exponent

Toxic Load Exponent, m, strongly influences SIP effectiveness

- For chemicals with m=1, CRF and SFM values will eventually approach zero and one, respectively, as SIP continues. I.e., SIP becomes ineffective.

- Higher toxic load exponent (e.g., m=3) lead to stronger and and more persistent benefits of SIP. This is because reduction in peak-concentration sharply reduces Toxic Load indoors compared to that outdoors



Results 4: delays in SIP termination: general

- For m=2 and m=3, delays in SIP termination cause very modest harm. This is because most of protection has already resulted from the lower peak-exposure indoors, during passage of the plume.

- For cases with m=1, long delays in SIP termination will make SIP ineffective, I.e., CRF will tend to 0, and SFM will tend to 1 as the delay becomes longer and longer

Results 5: delays in SIP termination for m=1

- **SIP termination effects for m=1**
  - In a high-air-exchange building, most of toxic load accumulates during the passage of the plume, and indoor concentrations decay rapidly afterwards. So, delays in SIP termination are less harmful
  - In a low-air-exchange building, less toxic load accumulates during passage of the plume, and indoor concentrations decay slowly. So, delays in SIP termination are more harmful.

Summary - 1

- **We introduced two new metrics (CRF and SFM) for assessing effectiveness of community-scale SIP**

- **Using relatively simple models, we explored the effectiveness of community-SIP as it is influenced by a number of parameters:**
    - Release scale, duration, and meteorology
    - Air exchange rates of shelters
    - Toxic load exponents of the airborne chemical
    - Delays in termination time for SIP

Summary - 2

Top three findings are:

- Product of release duration and air-exchange-rate influences SIP effectiveness substantially

- Toxic load exponent, m, determines if delays in terminating SIP might impact SIP effectiveness. Only for m=1 prompt termination is important.

- Variability in air-exchange-rate of shelters should be carefully considered in evaluating SIP as a strategy. There is large variability in air exchange rates in the U.S. building stock (a factor of 10 between the top 5% and bottom 5%).

Discussion

- More quantitative specific findings are available as LBNL report LBNL-61686, and are accepted for publication in an archival journal (*Atmospheric Environment*)

- More detailed analysis has been completed that incorporates sorption and desorption on indoor surfaces, uses realistic plume prediction with variable wind speed and direction, for a specific U.S. urban area. Impacts of delays in initiation of SIP are also presented in that analysis.

Questions?