Regional Shelter Analysis:

Assessing the Protection US Buildings Provide Against Outdoor Particulate Hazards

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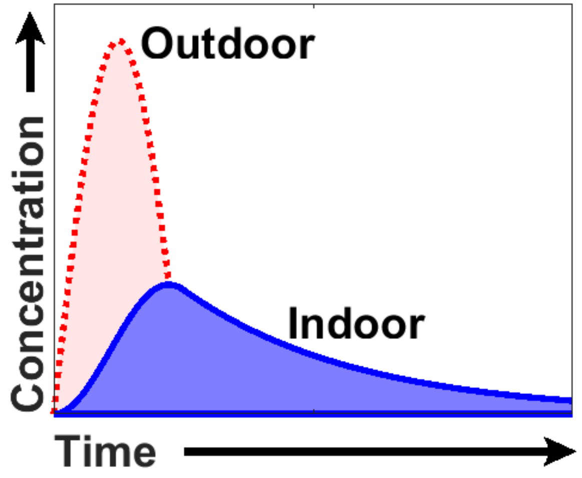
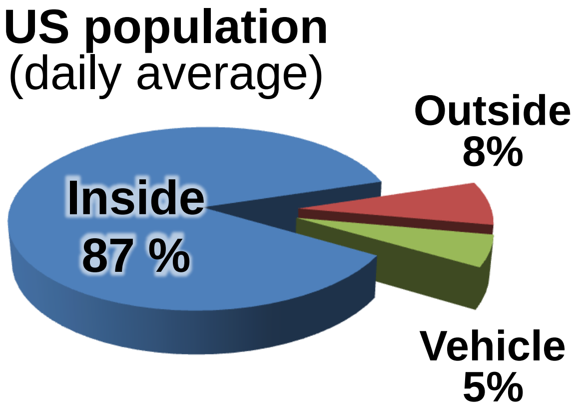
Motivation

- Buildings can protect their occupants from outdoor hazards (aspects have been studied for decades)
- On average, people are inside buildings and not outdoors
- Sheltering can be used as a protective action
- An integrated, all-hazards operational tool is needed to estimate the regional-scale benefits of being indoors (passive and active sheltering)





adapted from Klepis et al. JESEE 2001

Regional Shelter Analysis method overview - 1

- Our focus for this presentation is newly developed a *proof of concept*, inhalation protection capability suitable for assessing the protection US buildings provide their occupants against outdoor-origin particulate hazards

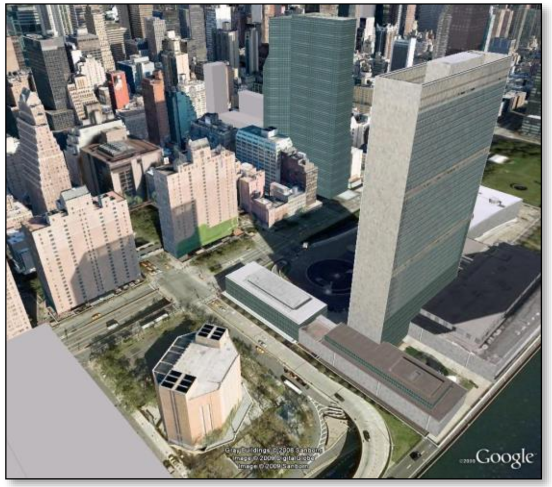
- The Regional Shelter Analysis assessment scale is determined by the analysis objectives (e.g., nation, state, region, city, local) and data availability
  - Our proof of concept capability utilizes data from FEMA databases covering all U.S. census tracts
  - The Regional Shelter Analysis methodology supports higher fidelity analyses when suitable input data is available

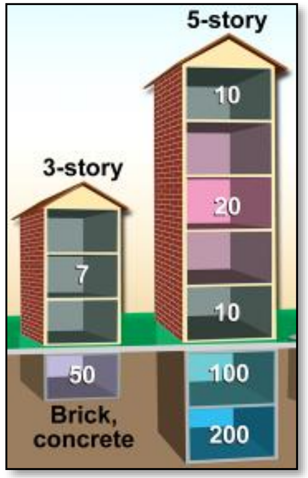
Regional Shelter Analysis method overview - 2

Within each region, determine the locations (buildings) where people are present

For each location determine (a) building protection and (b) occupancy (population)

Combine to calculate shelter quality





Regional Shelter Analysis summary

- Incorporates shelter quality into existing assessment methods
- Applicable to
  - Nuclear, radiological, chemical, and biological acute and chronic hazards (e.g., outdoor particle air pollution, wildfire smoke)
  - External radiation and **inhalation exposure (rad and non-rad) pathways**
  - Spatial scales ranging from individual buildings to census tracts to entire countries
  - Capable of using multiple data sources
- Elements being integrated into operational models
  - US Department of Energy, NARAC
  - US Department of Defense, HPAC

Illustrative fallout protection

Key physics considered

Airflow Considerations

Mechanical Air Exchange

Air movement through HVAC systems, furnaces, and ventilation (exhaust) fans

Infiltration/Exfiltration

Air movement through unintentional cracks through the building envelope (e.g., walls)

-- Natural Air Exchange is not considered --

Air movement through open windows and doors

Particle Removal Mechanisms

Losses within the heating and cooling system

Examples include loses within HVAC systems and furnaces

Deposition to indoor surfaces

Examples include losses to walls and furniture

Other Losses

Examples include radioactive decay

Overview of building protection modeling

- We use the single box model to estimate indoor concentrations
  - Captures the key physics of inhalation pathway building protection
  - Detailed models require often unavailable input data
- We derived analytical solutions for:
  - Buildings with filtered (or no) recirculation (e.g. homes)
  - Buildings with active HVAC systems
- For each building type of interest, we
  - Developed suite of input data through an in-depth literature review
  - Estimated the protection *distribution*

protection factor =

outdoor exposure / indoor exposure

$$= \frac{(\lambda_{out} + \lambda_{internal})}{\lambda_{in}}$$

λ_{out} = rate indoor particles exits the building

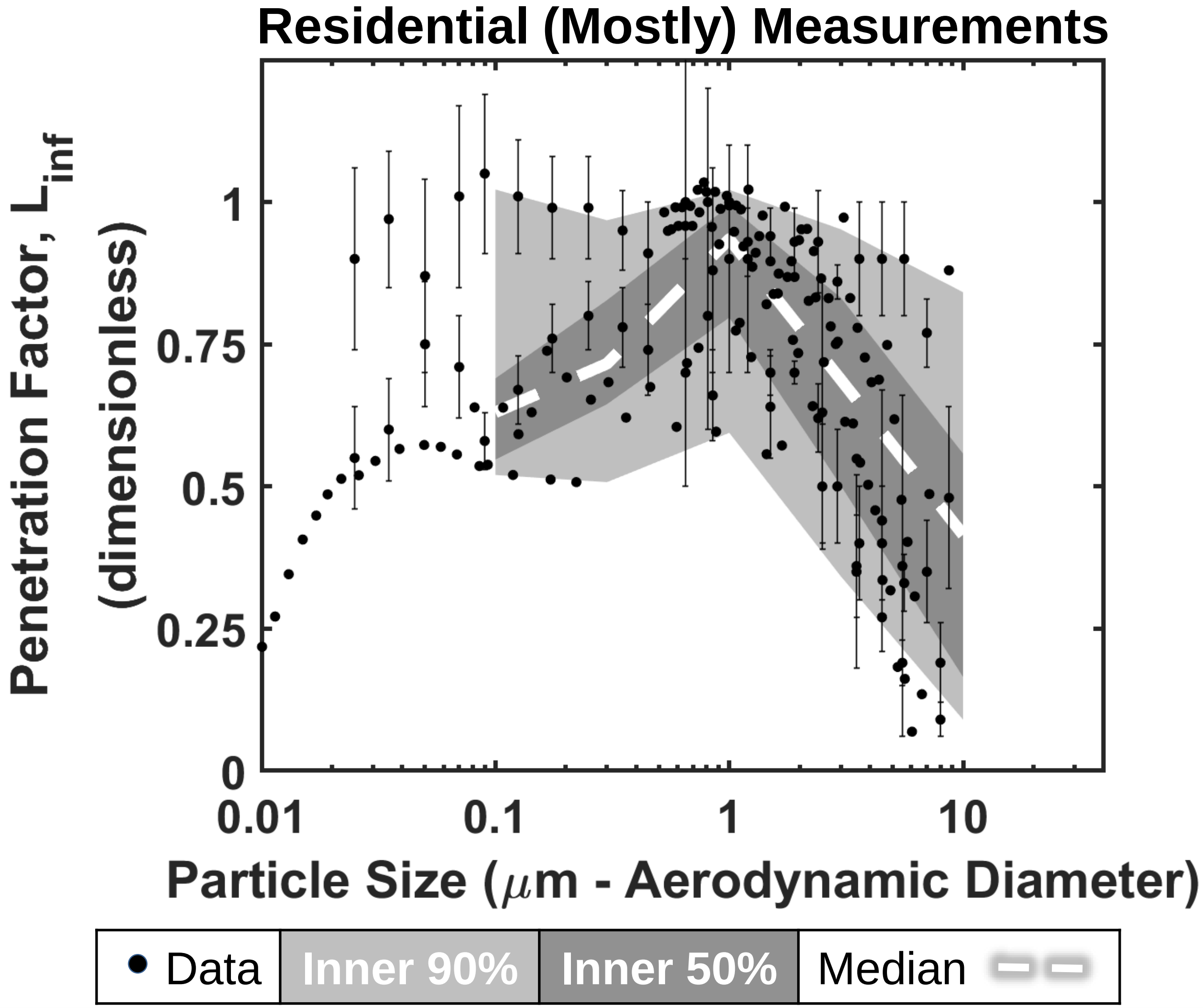
$\lambda_{internal}$ = rate indoor particles are lost within the building

λ_{in} = rate outdoor particles enter the building (includes losses)

Highlight on Indoor Losses

Penetration through building shell

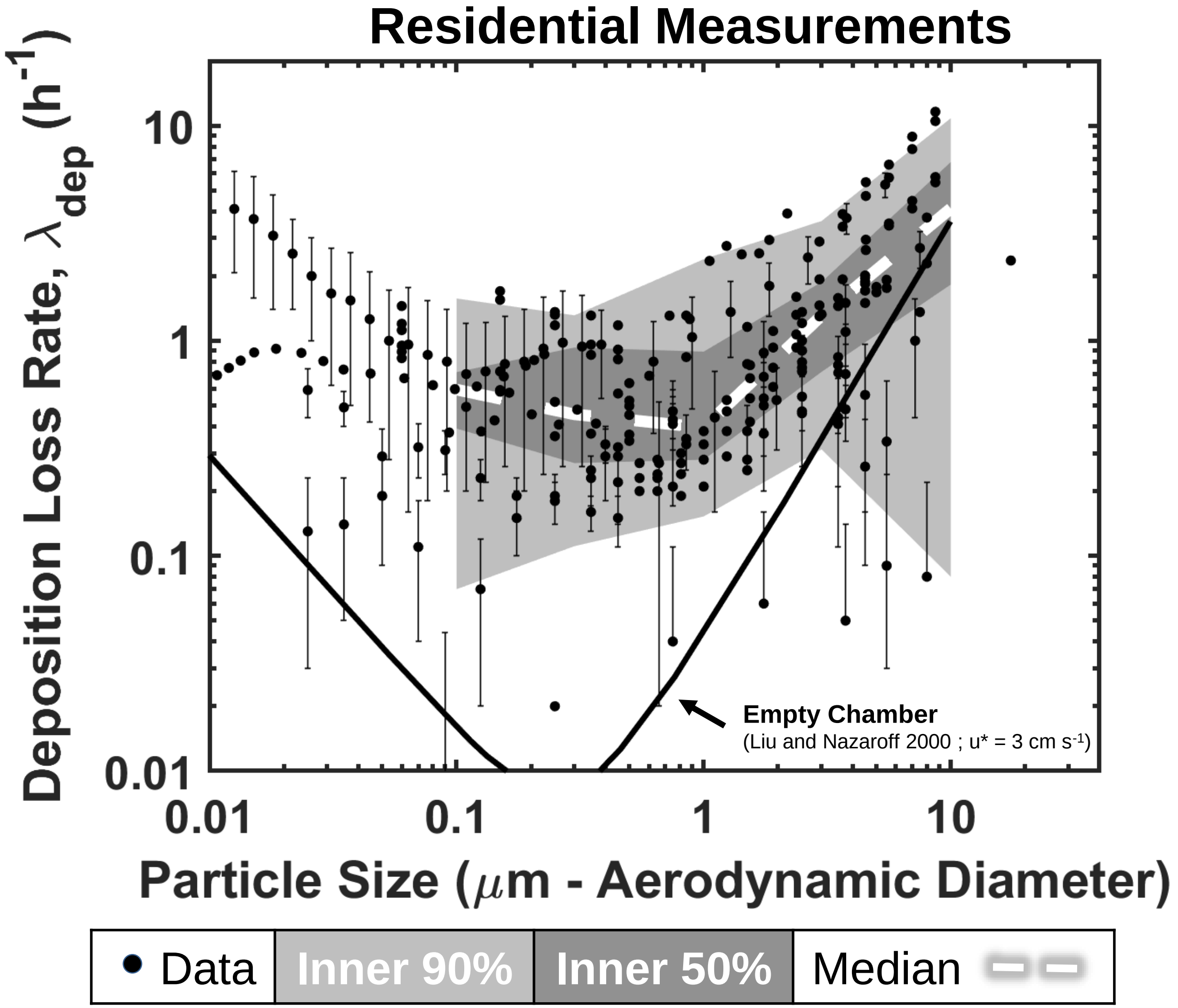
- Particles infiltrate through unplanning openings in building shell (e.g., cracks)
- We assembled *penetration* measurements from primary literature and inferred a distribution
- Most of the data correspond to residential structures
- We used these data for all building types



Highlight on Indoor Losses

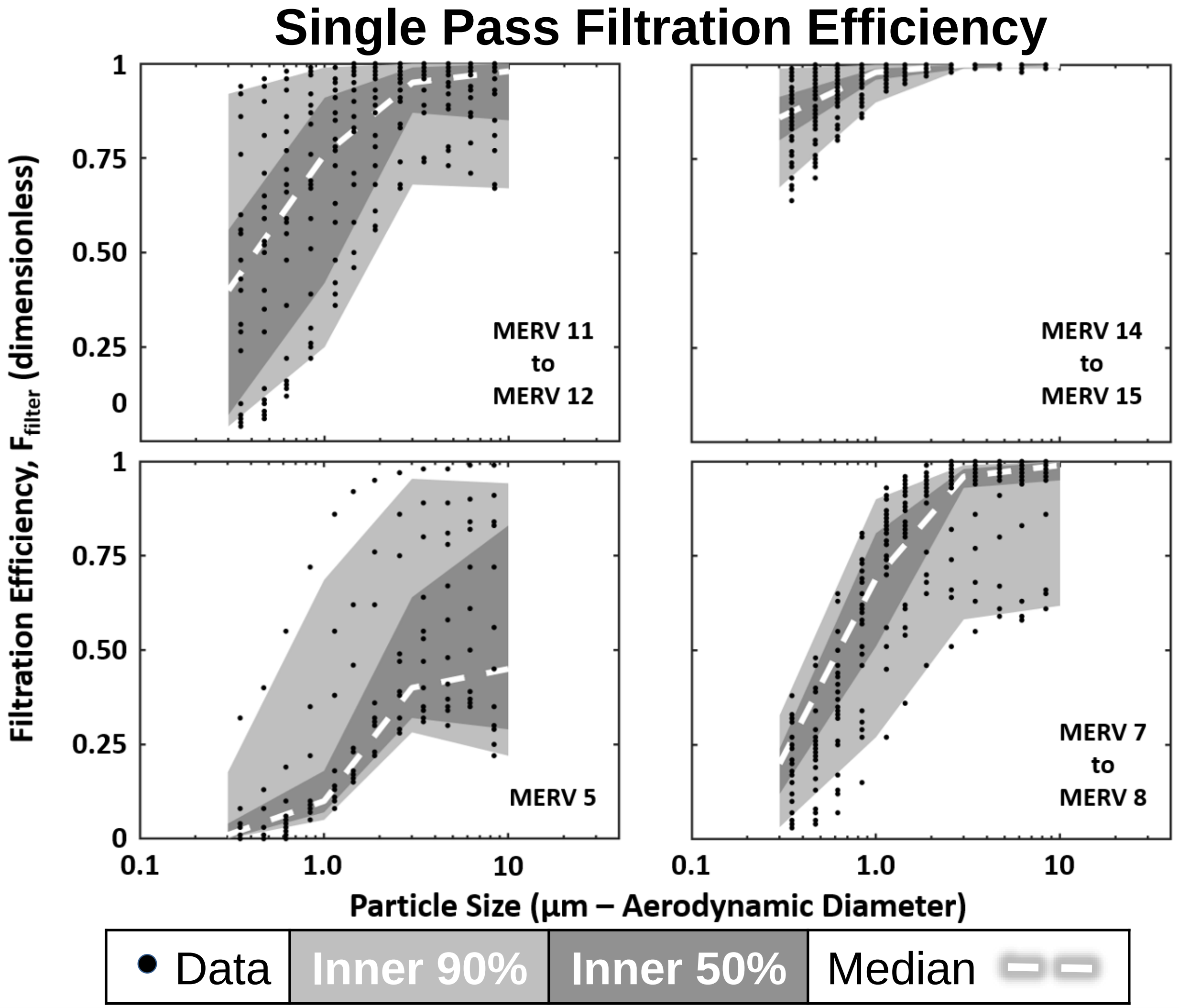
Deposition to indoor surfaces

- We assembled measurements of *residential deposition* in furnished rooms and inferred a distribution
- Wide range of conditions:
  - Airflow (turbulence)
  - Particle size
  - Particle source terms (e.g., cooking)
- Measured deposition (black dots) generally higher than empty chamber estimates (thick black line)
- Almost no data exist for other building types. We scale residential deposition by surface to volume ratio.



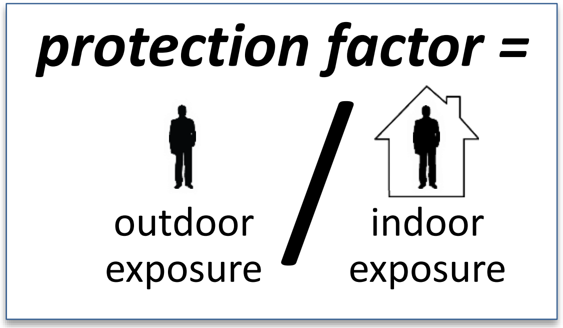
Highlight on Indoor Losses
HVAC filtration efficiency

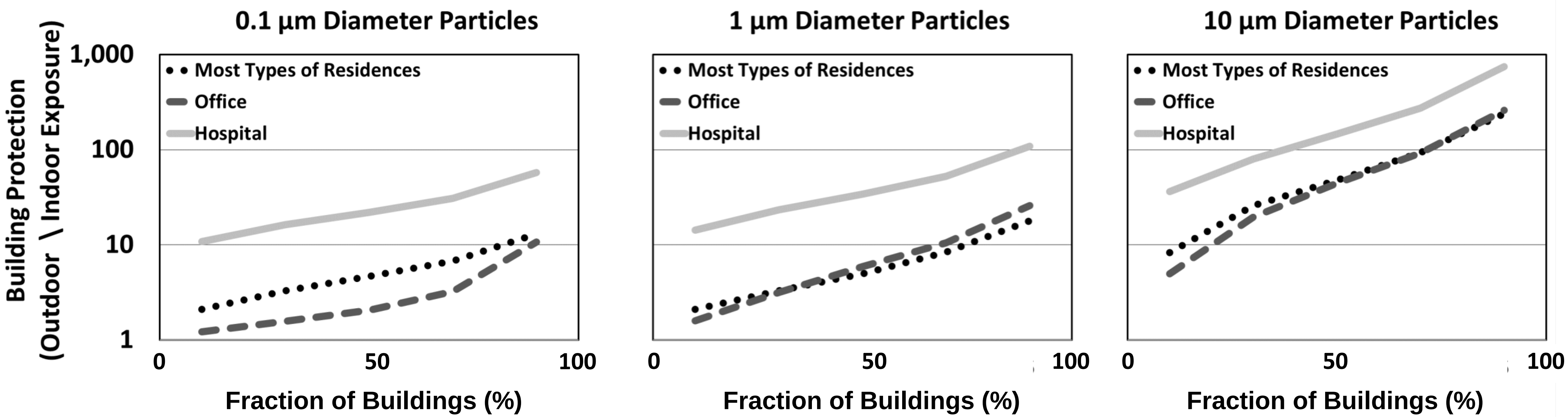
- HVAC and furnace filters remove particles
- Removal efficiency depends on
  - Filter type and quality (MERV rating)
  - Particle size
  - Filter loading (age)
- We assembled *single-pass filtration efficiency* measurements from primary literature and inferred a distribution
- We used these data for all building types (filter type/quality varies by building type)



Example result by building type

- Protection depends on particle size and building type
- Protection can vary over an order of magnitude for a given building type





Validating our results is challenging with current datasets

- No prior experimental study has characterized overall US building protection
- Prior authors have summarized historical building protection measurements

Residences*

	This study (1 µm)	Diapouli 2013 ($PM_{2.5}$)	Shi 2017 and Chen 2011 ($PM_{2.5}$)
Protection factor (outdoor / indoor)	5 (2.1 to 18)	1.4 (1.2 to 2.5)	n/a (1.25 to 3.3)

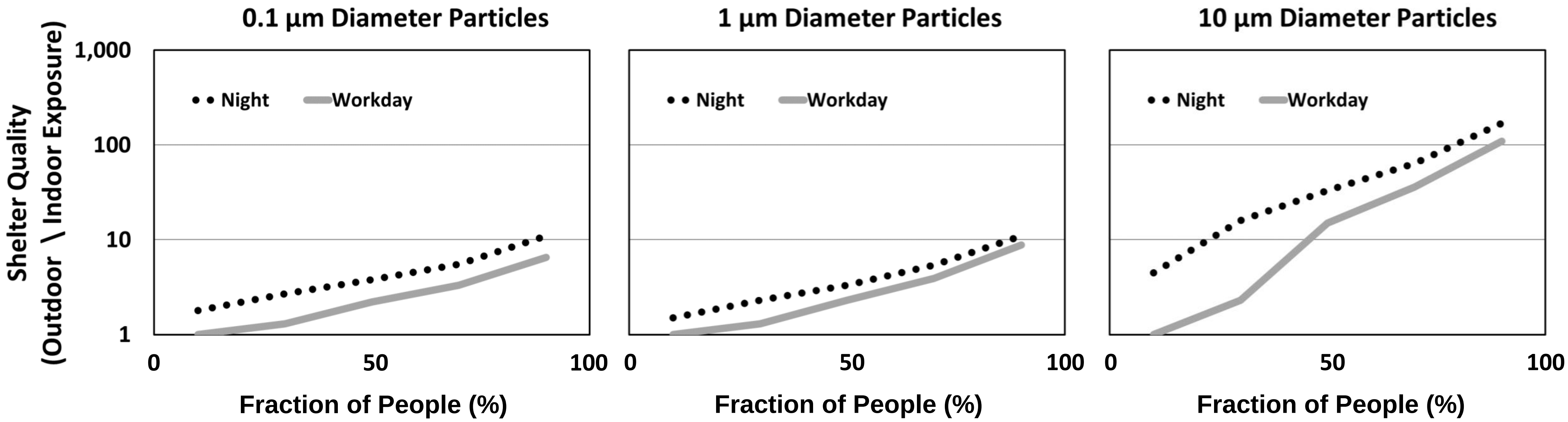
* Measured results correspond to deposition loss rates much lower than typically reported

Offices

	Particle size	This study	Chatoutsidou 2015 (1 week study)
Protection factor (outdoor / indoor)	**0.1 to 0.3 µm**	3.3 to 9.1	5.3 to 6.7
	1 to 3 µm	11 to 50	≥ 33

Example result
Median values for US Census Tracts

- Protection depends on particle size and time of day
- Protection varies within a census tract



Results summary

- We developed a “proof of principle” inhalation building protection capability for outdoor-origin particles

- US building protection varies strongly with particle size and building type

- For a given particle size and either (a) building type or (b) census tract, there is an order of magnitude variability in protection.

- The US Census tract shelter quality distributions are broadly similar during the night and workday.

- Most residential building types offer similar protection

Proposed future work…

Technical capability improvement

- Update and expand building models
- Enhance data on key input parameters, especially for non-residential buildings
- Expand particle size range to Ultra Fine Particles (UFP)
- Incorporate detailed information on buildings present in a particular region
- Assess building protection with active shelter measures
- Assess building protection associated with gaseous hazards
- Assess seasonal and regional variation in building protection
- Develop validation dataset

Thank you for your attention

For additional information,

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Key factors affecting indoor inhalation exposures to outdoor airborne hazards

- Loss of airborne material indoors
- Importance of peak concentration to hazard toxicity
- Rate at which outdoor and indoor air is exchanged
- Outdoor plume duration
- Time, after the outdoor plume has past, that individuals exit the building

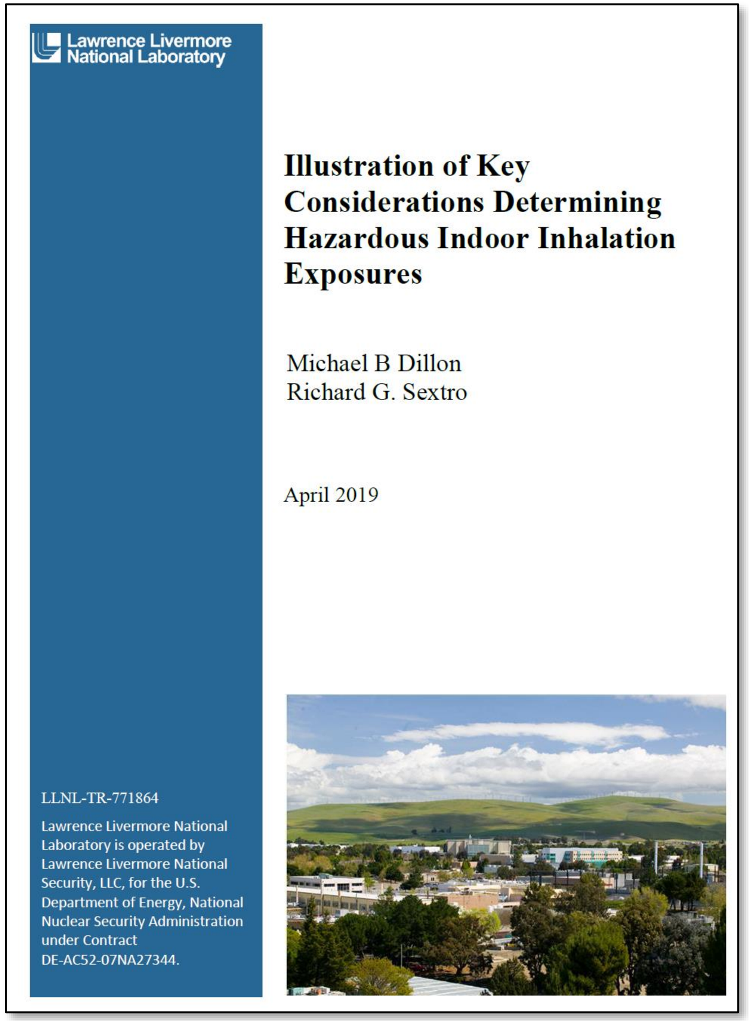
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Illustration of Key Considerations Determining Hazardous Indoor Inhalation Exposures

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