Lawrence Berkeley National Laboratory
Lawrence Berkeley National Laboratory

Title
Factors affecting the concentration of outdoor particles indoors: Existing data and data needs

Permalink
https://escholarship.org/uc/item/2tg4m8s9

Authors
McKone, T.E.
Thatcher, T.L.
Fisk, W.J.
et al.

Publication Date
2002

eScholarship.org Powered by the California Digital Library
University of California

FACTORS AFFECTING THE CONCENTRATION OF OUTDOOR PARTICLES INDOORS: EXISTING DATA AND DATA NEEDS

T.E. McKone[1,2,*], T.L. Thatcher[1], W.J. Fisk[1], R.G. Sextro[1], M.D. Sohn[1], W.W. Delp[1], and W.J. Riley[3]

[1]Indoor Environment Dept., Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[2]School of Public Health, University of California, Berkeley, CA, USA
[3]Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

ABSTRACT
Accurate characterization of particle concentrations indoors is critical to exposure assessments. It is estimated that indoor particle concentrations depend strongly on outdoor concentrations. For health scientists, knowledge of the factors that control the relationship of indoor particle concentrations to outdoor levels is particularly important. In this paper, we identify and evaluate sources of data for those factors that affect the transport to and concentration of outdoor particles indoors. To achieve this goal, we (i) identify and assemble relevant information on how particle behavior during air leakage, HVAC operation, and particle filtration effects indoor particle concentration; (ii) review and evaluate the assembled information to distinguish data that are directly relevant to specific estimates of particle transport from those that are only indirectly useful; and (iii) provide a synthesis of the currently available information on building air-leakage parameters and their effect on indoor particle matter concentrations.

INDEX TERMS
Exposure assessment, indoor environment, mass-balance model, particles, air infiltration

INTRODUCTION
Because the US population is estimated to spend on average more than 80% of their time indoors, accurate characterization of particle concentrations indoors is critical to assessing total exposure to particles. In most cases, concentrations of ambient particles indoors depend primarily upon the quantity of particulate matter that penetrates through the building shell or is transported via the heating, ventilation, and air conditioning (HVAC) system. In addition, the concentration of particles indoors is affected by several other factors such as filtration, ventilation, deposition, re-emission, and indoor sources. To evaluate and model human exposures to particles requires information on these characteristics. We refer to such factors as Concentration-of-Outdoor-Particles-Indoors (COPI) factors. Most COPI factors vary from one type of building to another. Thus, COPI factors cannot be represented by a single value. Instead the variation in these factors needs to be explored and recorded. How this variation relates to building design and operation also needs to be evaluated. In this paper, we identify the COPI factors that are most needed for assessing human exposure to outdoor particles indoors and then compile and evaluate information sources for these COPI factors.

[*] Contact author email: temckone@lbl.gov

We consider four categories of COPI-factor information in our analysis. First is the nature of building shell leaks and what influence they have on airflow and particle transport indoors. Second is the role of HVAC systems in supplying air to the building interior, typically through filter media of varying types and filtration efficiency. Third is information obtained from experiments in which indoor/outdoor particle concentrations are measured and particularly whether there is ancillary information about the building and/or its leakage characteristics. Fourth is information from papers and reports in which particle penetration is estimated and discussed. We address these issues through three tasks that are summarized in the section below on methods.

METHODS

Considerable previous work has been expended to understand and measure building leakage and other airflow characteristics as they affect air infiltration and ventilation. However the connection between these airflow pathways and particle entry into buildings remains poorly understood. To address this issue, we examined a number of experiments and models to better characterize the transport of ambient particles from outdoor air to the indoor environment. We address these issues through three tasks—information retrieval, information evaluation, and information synthesis.

Task 1, Information Retrieval

We first identified relevant information, databases, etc. needed to assess how transport of particles from outdoor to indoor air is impacted by leaks, HVAC systems, particle mass-balance data, and penetration data. In the US, key sources of information for COPI factors include the US Department of Energy (DOE) Residential Energy Consumption Survey (RECS) (US DOE, 2000), the DOE Commercial Building Energy Consumption Survey (CBECS) (US DOE, 1997, 1998), the US Department of Commerce (1999) surveys of housing characteristics, and the US EPA Building Assessment Survey and Evaluation (BASE) study (US EPA, 1994). In addition to these surveys we had access to databases at LBNL and made use of summary data available in the literature.

Task 2, Information Evaluation

Once the relevant information was assembled, our next task was to review and evaluate this information to determine which resources provide relevant COPI factors. In this task, we used three criteria by which we evaluated the available information. First was the quantity of information available. For example, is the information derived from a large survey or from a few test houses? Second was the quality of the information. For example, the reliability of the methods used—direct measurement, modeling, replication, quality control, etc. Third was the representativeness of the available information. For example how well are the population of residential and commercial buildings represented, and were the samples stratified so as to properly capture variability by geographic region, season of the year, building age, etc. We used a review and evaluation of currently available information to identify data needs, current resources, and data gaps for COPI factors.

Task 3, Information Synthesis

Our third task provides a synthesis of the currently available information on COPI factors and their effect on particle concentration indoors. We used this effort to identify areas for which there are important gaps or weaknesses in the available information, particularly as it relates to linking air leakage, particle transport, and particle fate.

RESULTS

Based on the methods described above we have identified and ranked those relevant factors that affect the concentration of outdoor particulate matter indoors. The relevance of different factors in controlling the concentration of outdoor particles indoors is established in the context of an indoor/outdoor particle mass balance model. The concentration of outdoor particles in the indoor environment is a balance between the rates at which outdoor particles enter and leave the air within the building and the rates at which they are removed, transformed, and re-emitted in the indoor environment. In general, a mass balance equation representing the change in indoor concentration, C_i, within the volume, V, over time, t, can be written as follows:

$$\frac{dC_i V}{dt} = \text{[Entry of Outdoor Particle Mass]} - \text{[Exit of Indoor Particle Mass]}$$

$$- \text{[Mass Removal Indoors: deposition, filtration, transformation]} \quad (1)$$

$$+ \text{[Mass Re-emission Indoors: resuspension, transformation]}$$

In Figure 1, we illustrate the processes that affect the transport and concentration of indoor particles outdoors.

A Set of Relevant COPI Factors

Particle entry rates are influenced by the overall ventilation rate, the route of entry (e.g., through filters, cracks, windows), and particle penetration efficiencies. While considerable work has been expended on defining the factors affecting ventilation rates, there is still

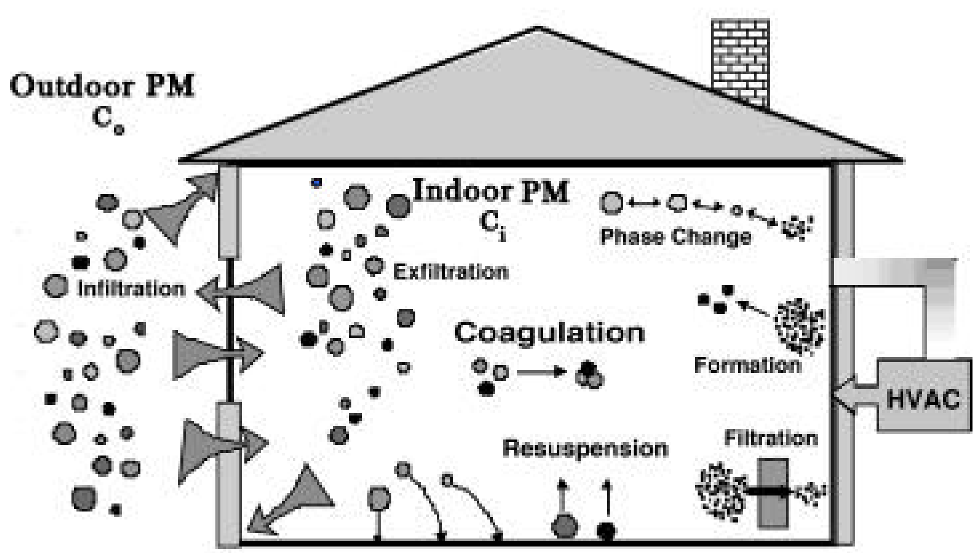

Figure 1. Transport and transformation mechanisms that define particulate matter concentrations in the indoor environment.

significant uncertainty concerning the route of entry in several areas, such as crack size distributions or infiltration rates in large commercial buildings. There is even more uncertainty in the area of particle penetration efficiency. Removal mechanisms and rates (e.g., deposition, filtration, and exfiltration) are probably the best understood of the mass balance components, with experimental data and well formulated theoretical models for at least some of the components. However, variability among buildings is very high and the causes for this variability are poorly understood. Chemical transformation in the indoor environment is only just beginning to be investigated and could prove to be an important loss factor for some particle types. It is also a potentially large confounding factor in that some transformations produce more particles or change the size distribution of particles.

The construction of a building and the operation of building HVAC and other systems will affect the overall ventilation rate, as well as the routes through which air enters a building. The following important building characteristics were identified for their effect on particle entry rates into buildings:

measured or predicted ventilation rates
window opening,
prevalence of mechanical ventilation
air leakage in ducts,
pathways for air and particle leakage into buildings,
particle penetration factors, and
stairwells and buoyancy induced flow.

Particle removal in buildings may be due to intentional removal mechanisms (such as filtration with the HVAC system) or inherent removal mechanisms (such as particle deposition to surfaces). We have identified the following factors for their significance in impacting loss and persistence of particles transported from outdoor air indoors:

filter efficiencies,
rates and times of air flow through filters,
particle removal by auxiliary air cleaners,
particle deposition rates in buildings, and
resuspension factors.

Evaluation of Available Data on COPI Factors

The DOE RECS is an ongoing survey of energy use in residential houses and goes back to 1978 (US DOE, 2000). It is a national statistical survey, sampling approximately 5,900 housing units in the 1997 survey alone. Surveys are based on either 30-minute personal interviews, telephone interviews, or mailed questionnaires. The resulting data describes energy use and many characteristics of the United States housing stock including the size of housing units, types of heating and cooling systems installed, and numbers of household members present. The survey is also a detailed source of information for quantifying the status and types of residential buildings geographically. The DOE, Energy Information Administration's CBECS is a periodic survey of energy use in commercial buildings. From this survey, DOE has issued two major reports, the first on energy consumption (US DOE, 1998) and the second on commercial building characteristics (US DOE, 1997). CBECS is a national statistical survey comparable to the RECS in its completeness and characterization of energy consumption in commercial buildings. Relevant information in the CBECS survey includes data on types, numbers, and sizes of buildings, HVAC system characteristics, and presence or absence of operable windows.

The US Department of Commerce (1999) also conducts surveys of housing characteristics using interviews. The 1997 survey of 56,000 housing units in 46 metropolitan areas collected data on single-family homes, apartments, and mobile homes. The most relevant data from this survey appear to be basic housing characteristics such as age, fuel use, heating and air conditioning equipment, and number of occupants. The EPA BASE study (US EPA, 1994) was carried out to obtain baseline information on indoor air quality, health symptom prevalence, and relevant building characteristics in US office buildings. One hundred office buildings were studied for the period 1996 to 1998. Relevant data from the BASE study include measured indoor and outdoor PM2.5 and PM10 concentrations, temperatures, and humidity levels; descriptions of the building envelope; descriptions of interior finish materials (which may affect particle deposition); a detailed description of the buildings' HVAC systems, including information of the types of particle filters (manufacturer, model, and usually an efficiency rating); and rated and measured air flow rates in HVAC systems. These data apply to a test space within each building, which is often smaller than the entire building. The BASE Study emphasizes large office buildings with mechanical ventilation and air conditioning.

Data Gaps and Data Needs for COPI Factors

Data quality, quantity, and representativeness were evaluated for key factors such as HVAC design and operation, infiltration and leakage area, deposition, penetration factors, and natural ventilation. We found that none of the critical factors affecting the indoor/outdoor particle relationship are yet well enough characterized to provide reliable inputs to exposure models. Particle deposition is an important factor affecting indoor particle concentrations in all types of buildings. However, deposition loss rates appear to be highly sensitive to indoor environmental conditions and particle characteristics, leading to significant variations in experimentally determined deposition rates. Another critical factor that is inadequately understood is the fraction of outdoor particles that remain in infiltrating air and enter the building interior, typically referred to as the penetration factor. Information of the efficiency of various types of filters is fairly high, both in quality and quantity. However, data on the types of filters used in residences, on time-average air flow rates in central forced-air residential heating and cooling systems, and on the use of auxiliary filtration systems are very sparse, leading to large uncertainties in particle filtration rates in residences. The extent to which windows are opened is another poorly understood factor that has a significant impact on indoor concentrations of outdoor particles. The available information on particle resuspension rates is extremely limited. There are still significant gaps in the assessment of factors such as infiltration rates into commercial buildings, the prevalence of local exhaust use in residential buildings, and the particle penetration data across a variety of buildings.

DISCUSSION

The concentration of outdoor particles in the indoor environment is a balance between several competing processes: particle entry, particle removal, and particle re-emission. Of these three processes, the least is known about particle re-emission. As a consequence re-emission rates introduce a high degree of uncertainty for predicted particle concentrations in occupied spaces.

In contrast to COPI factors that are needed to carry out mass balances on particles, the quantity and quality of data on basic building characteristics is quite high for both residential and commercial buildings. A more detailed presentation of the methods and results discussed in this paper is available in recent report by Thatcher et al. (2001) which is available from Lawrence Berkeley National Laboratory.

CONCLUSION AND IMPLICATIONS

Our review and evaluation affirms that understanding the processes affecting the concentration of outdoor particle indoors is essential for improving assessments of human exposure to particles of outdoor origin. This is particularly important for assessors who need to consider the spatial and temporal variation of indoor exposures to outdoor particles. Based on a detailed review and evaluation of data available and needed to link indoor concentration of particles to outdoor concentrations, we have determined that the most critical missing information includes the following:

- measured particle penetration factors,
- measured particle deposition rates in commercial and institutional buildings,
- infiltration rates in commercial buildings,
- the types of filters used in all buildings (except large offices),
- window opening behaviors, and
- rates of indoor resuspension of particles transferred indoors from outdoors.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Environmental Protection Agency (EPA) National Exposure Research Laboratory through Interagency Agreements DW-89938748 and DW-988-38190-01-0. Work was carried out at the Lawrence Berkeley National Laboratory (LBNL) through U.S. Department of Energy under Contract Grant No. DE-AC03-76SF00098.

REFERENCES

Thatcher TL, McKone TE, Fisk WJ, Sohn MD, Delp WW, Riley WJ, Sextro RG. 2001. Factors affecting the concentration of outdoor particles indoors (COPI): Identification of data needs and existing data, Lawrence Berkeley National Laboratory LBNL-49321.

US Department of Commerce, Bureau of the Census. 1999. American housing survey for the United States in 1999, H150/99, Washington DC: US Government Printing Office. http://www.census.gov/hhes/www/housing/ahs/99dtchrt/ahs99.html

US Department of Energy (US DOE). 1997. Energy Information Administration, Commercial building characteristics 1995, Washington DC: US Government Printing Office, http://www.eia.doe.gov/emeu/cbecs/contents.html

U.S. Department of Energy (US DOE). 1998. Energy Information Administration, Commercial buildings energy consumption and expenditures 1995, Washington DC: US Government Printing Office, http://www.eia.doe.gov/emeu/cbecs/contents.html

US Department of Energy (US DOE). 2000. Energy Information Administration, 1997 Residential energy consumption survey, housing characteristics. Washington DC: US Government Printing Office, http://www.eia.doe.gov/emeu/recs/recs97_hc/97tblh

US Environmental Protection Agency (US EPA). 1994. A standardized protocol for characterizing indoor air quality in large office buildings. Indoor Air Division, Office of Radiation and Indoor Air, Washington, DC.