ENVE 576
Indoor Air Pollution
Fall 2016

Week 13: November 15, 2016
IAQ in developing countries
Applications and standards

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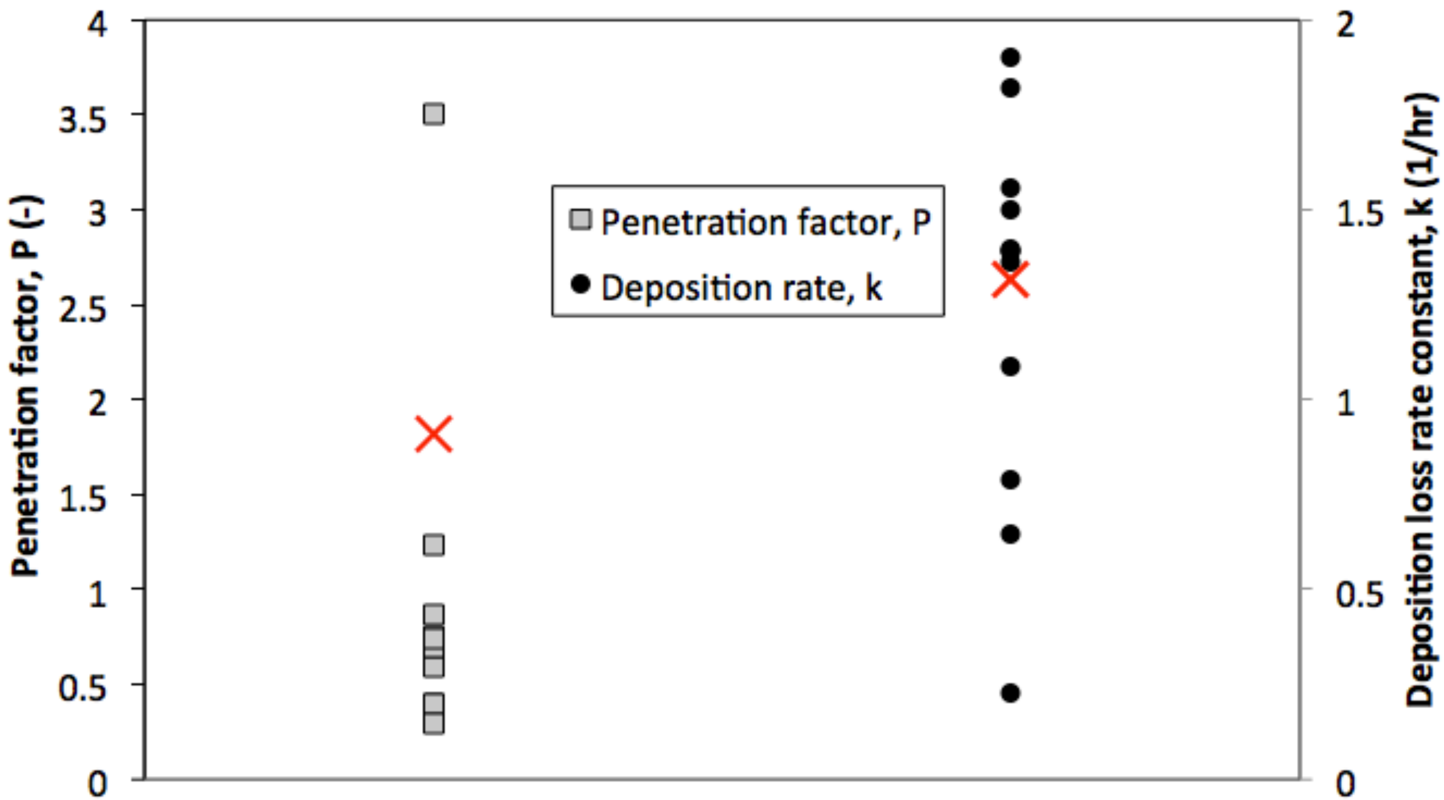
Take-home exam graded and returned

- Average = 267/300 (89%)
  - SD = 32/300 (11%)
  - Min = 184 (61%)
  - Max = 296 (99%)
- Problem 4:

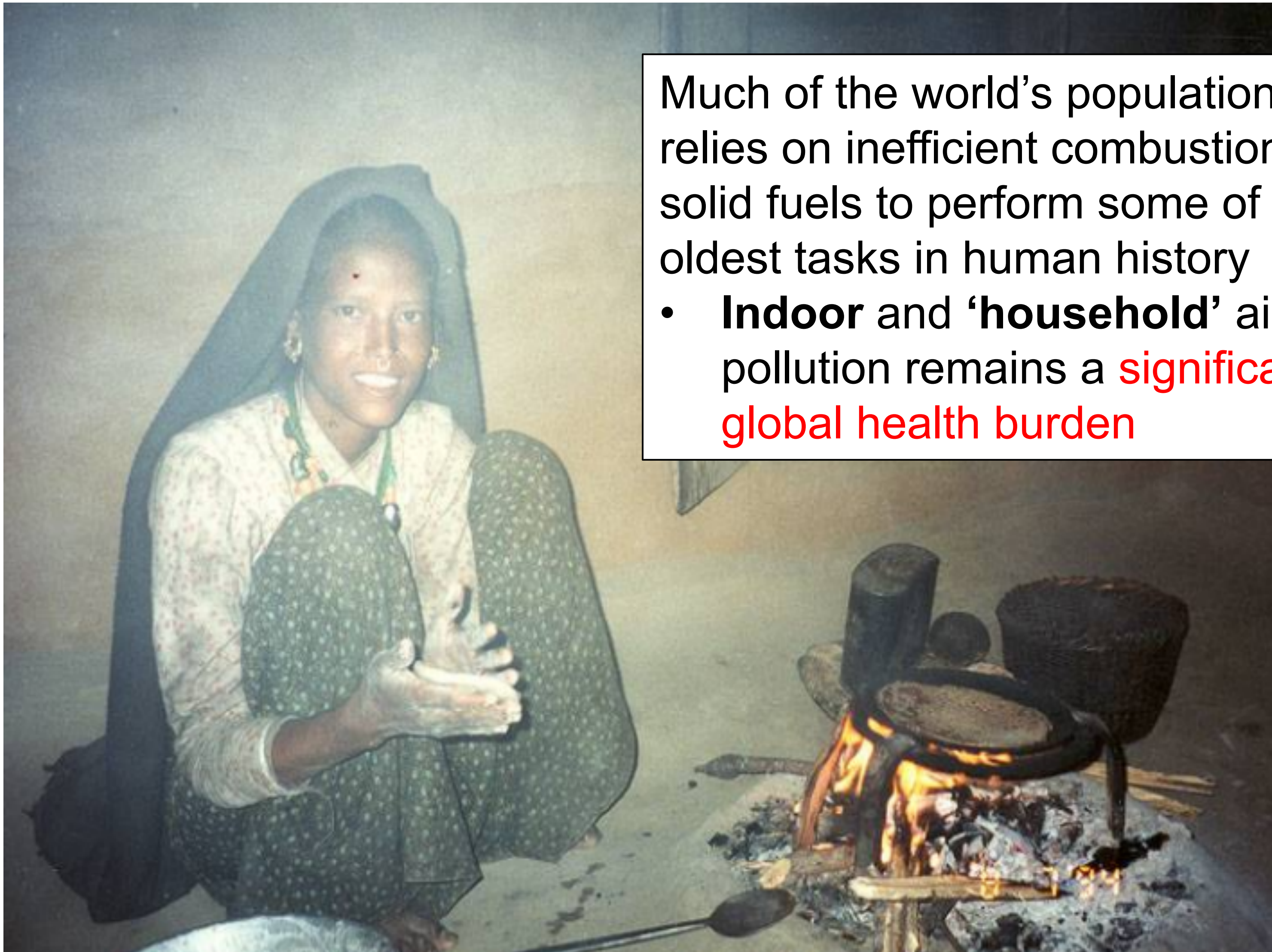
My estimates:
P = 0.91, k = 1.49/hr

Your mean (SD):
P = 0.91 (0.85)
k = 1.32 (0.52) 1/hr



INDOOR AIR POLLUTION IN DEVELOPING COUNTRIES

Indoor air pollution in developing regions of the world



Much of the world's population relies on inefficient combustion of solid fuels to perform some of the oldest tasks in human history

- **Indoor** and **'household'** air pollution remains a significant global health burden

Photo: Kirk Smith, UC-Berkeley

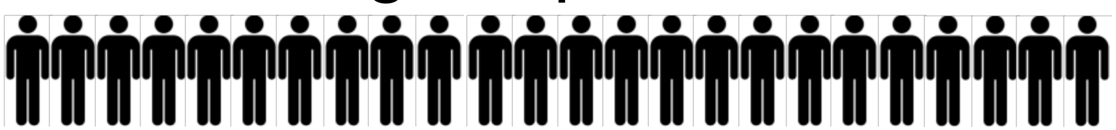
Biomass burning across the world

One-third of the world's population burns biomass for:

Cooking Heating Lighting

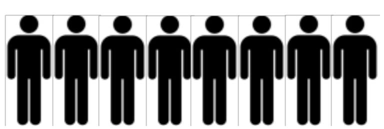
Fuels used include:

Wood, dung, crop residue

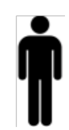


2.4 billion people

Coal



800 million people



= 100 million people

Fullerton et al., 2008 *Trans R Soc Trop Med Hyg*; Bruce et al., 2000 *WHO Bulletin*

Cooking and heating

- Poor ventilation (no flues or hoods)
- Low combustion efficiency
  - High levels of products of incomplete combustion

http://photos.state.gov/libraries/amgov/3234/Week_3/09222010_AP070911056524_300.jpg
http://images.angelpub.com/2010/37/5835/cookstove-2.jpg

Lighting

http://www.vleindia.com/images/thumb/1279793271_slide.jpg

- 1.6 billion people use fuel-based lighting after dark
  - Kerosene, diesel
- Indoor air pollution + substandard luminance + fire

Pollutants emitted from biomass burning

Particulate matter (UFPs, $PM_{2.5}$ and PM_{10})

Carbon monoxide (CO)

Nitrous oxides (NO_x)

Sulfur oxides (SO_x) (coal)

Metals (coal)

Hydrocarbons (HC; e.g. naphthalene)

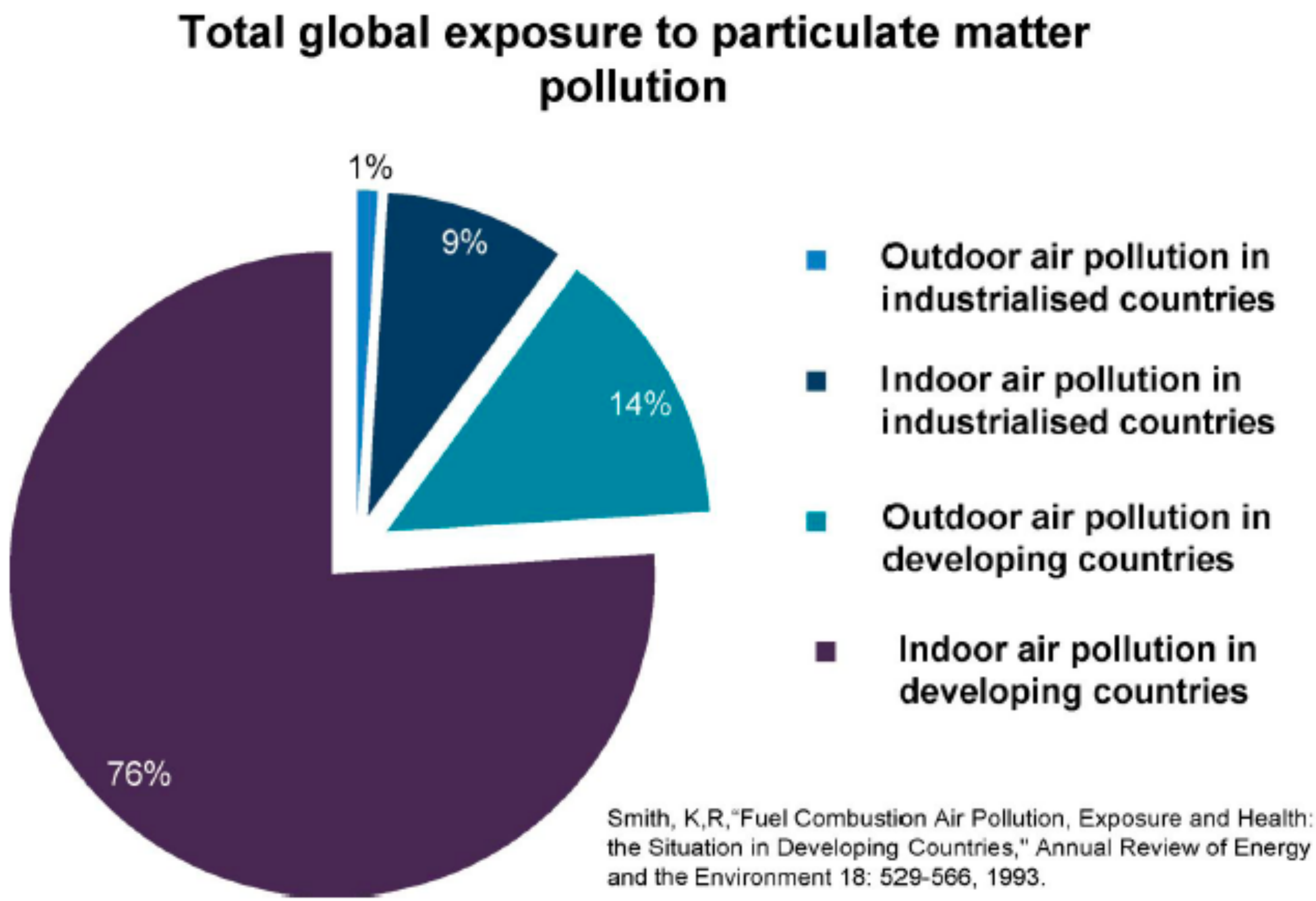
Polycyclic aromatic hydrocarbons (e.g. benzo[a]pyrene)

Oxygenated organics (e.g. formaldehyde) (wood)

Free radicals

Combustion efficiency is far less than 100%

Global exposure to particulate matter

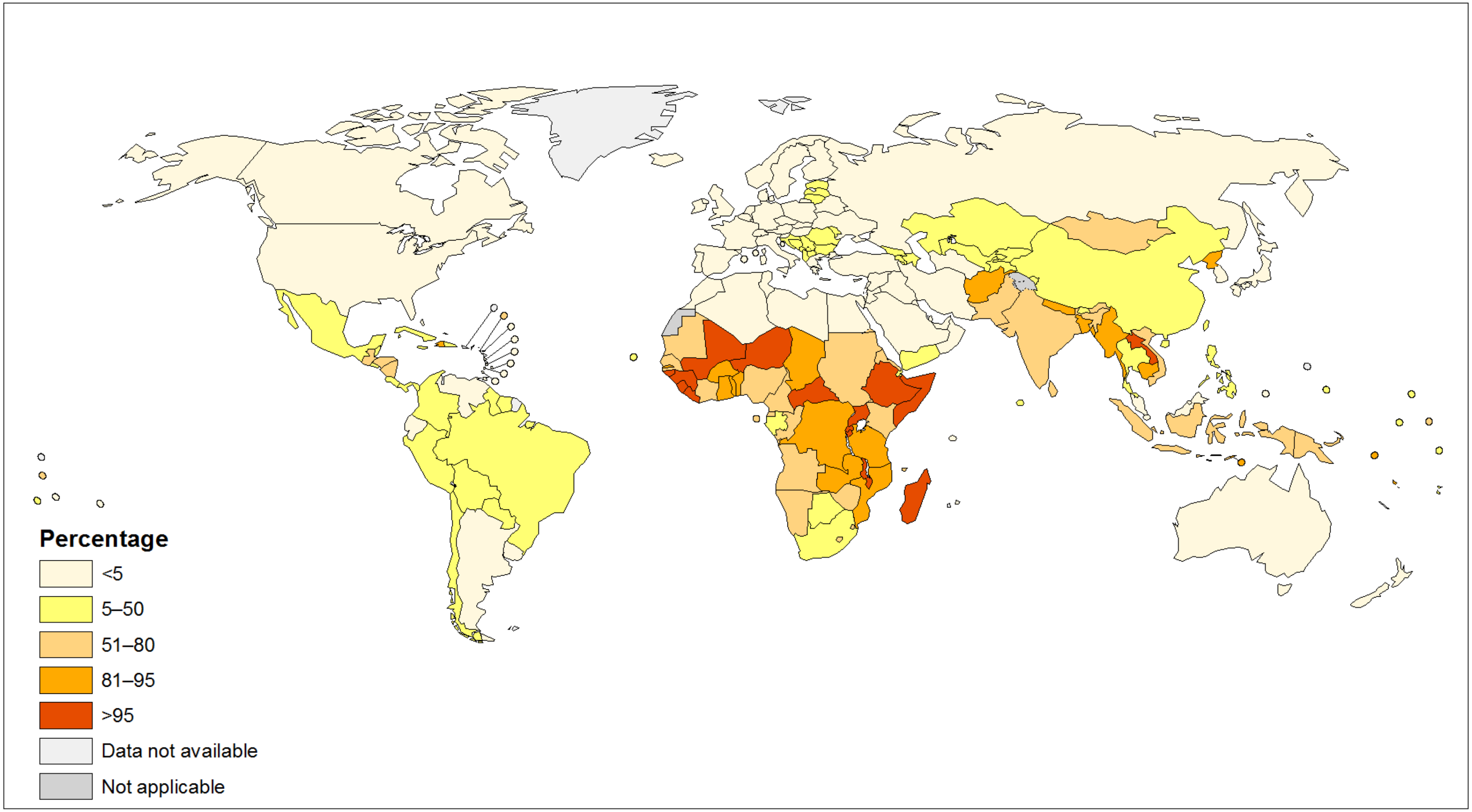


Fullerton et al., 2008 *Trans R Soc Trop Med Hyg*

GLOBAL HEALTH

and indoor air pollution

Population using solid fuels (%), 2010
Total



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Data Source: World Health Organization
Map Production: Public Health Information and Geographic Information Systems (GIS)
World Health Organization

World Health Organization

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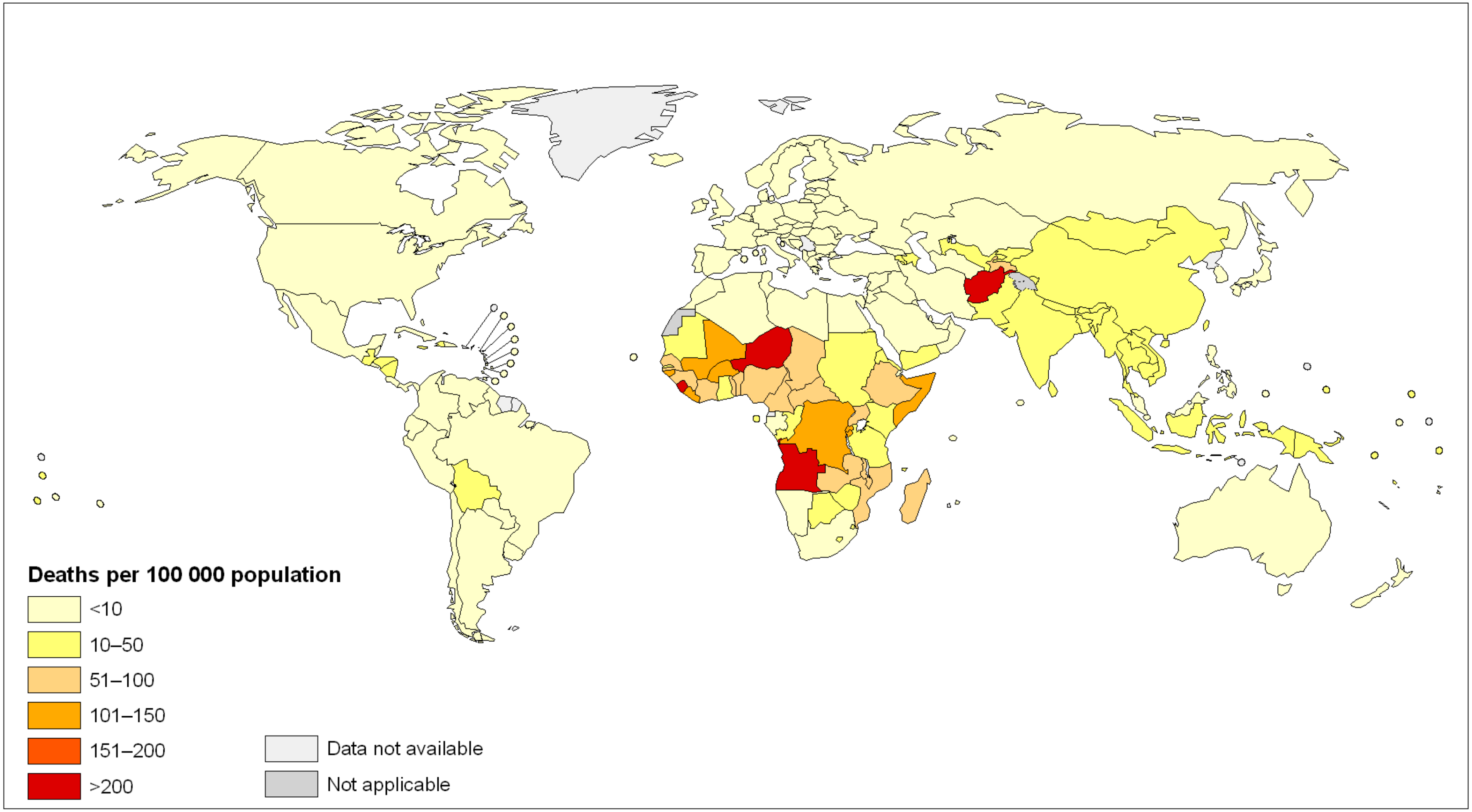
Deaths attributable to household air pollution, 2004



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World Health Organization

World Health Organization

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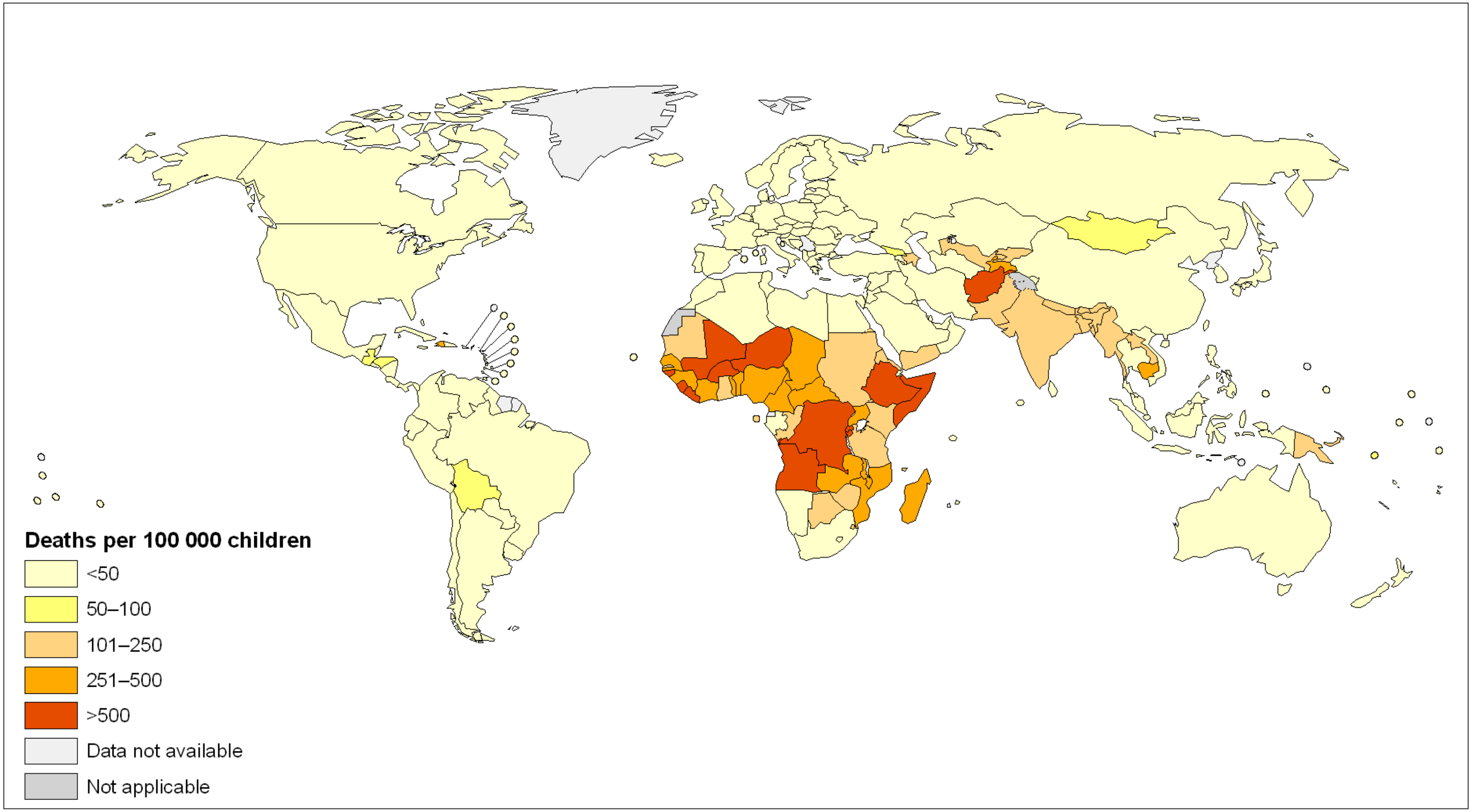
Deaths attributable to household air pollution in children aged under 5 years, 2004



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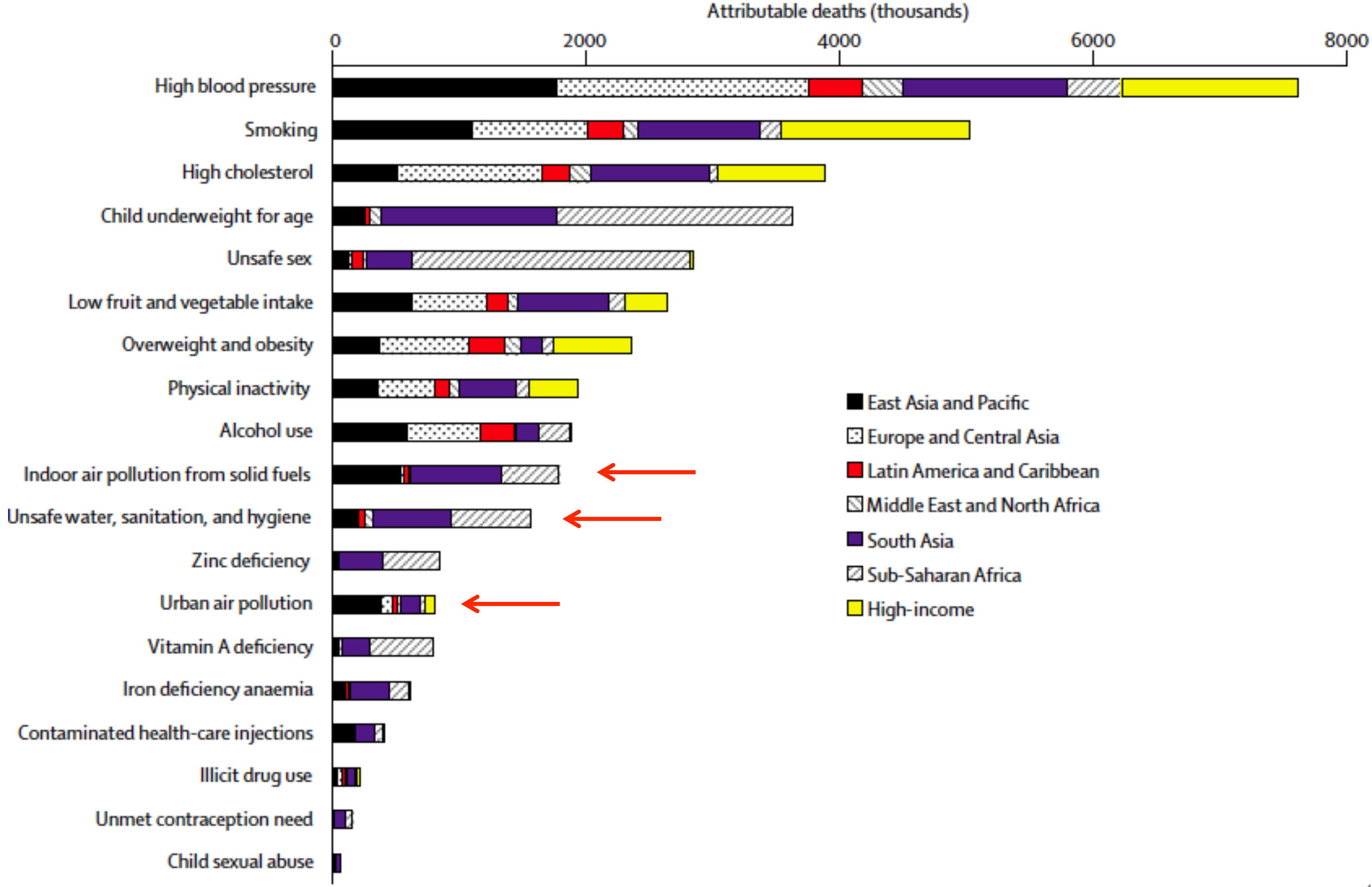
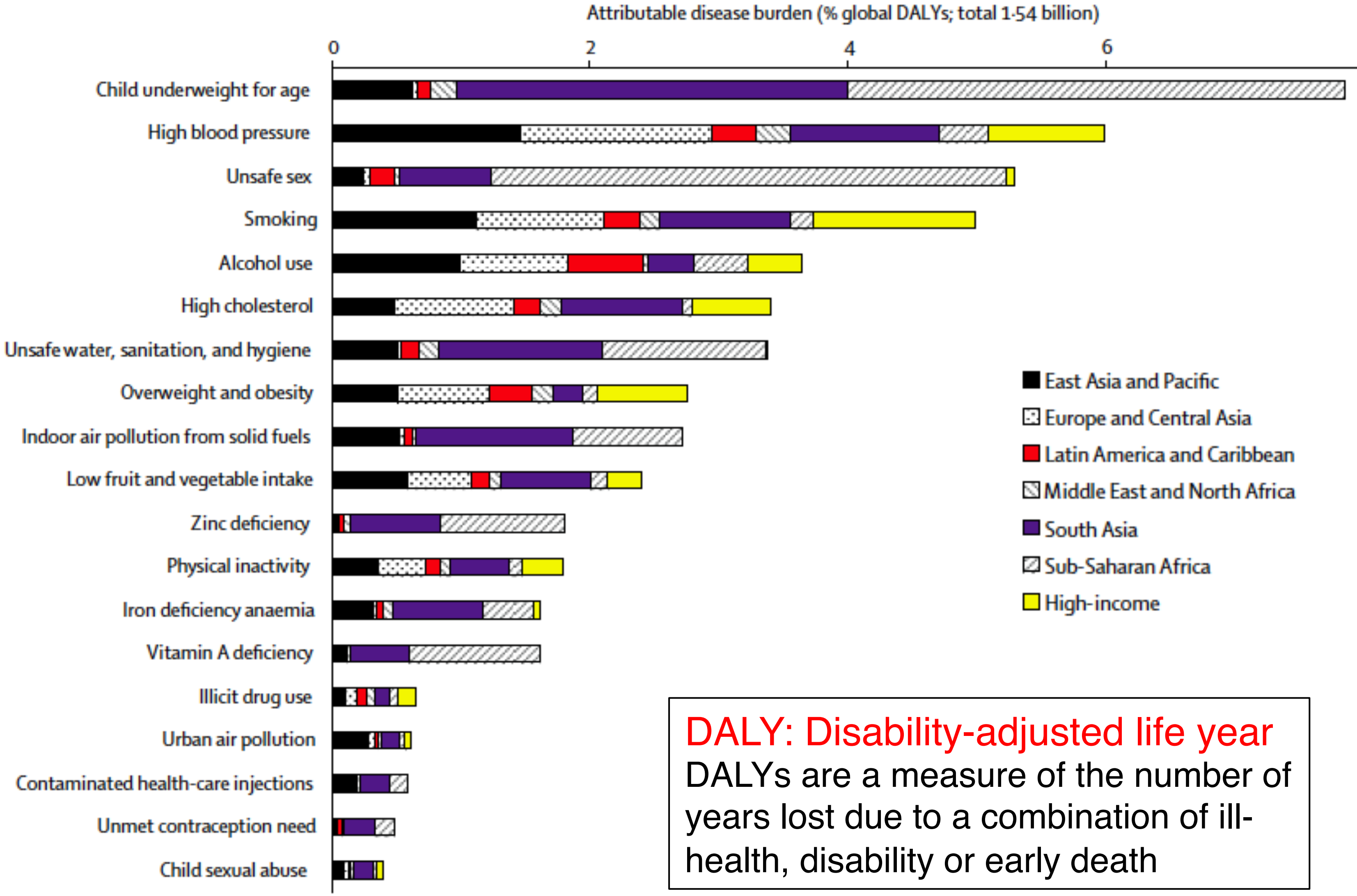
Global risk factors for mortality



Lopez et al., 2006 *The Lancet*

Global **disease burden**



DALY: Disability-adjusted life year
DALYs are a measure of the number of years lost due to a combination of ill-health, disability or early death

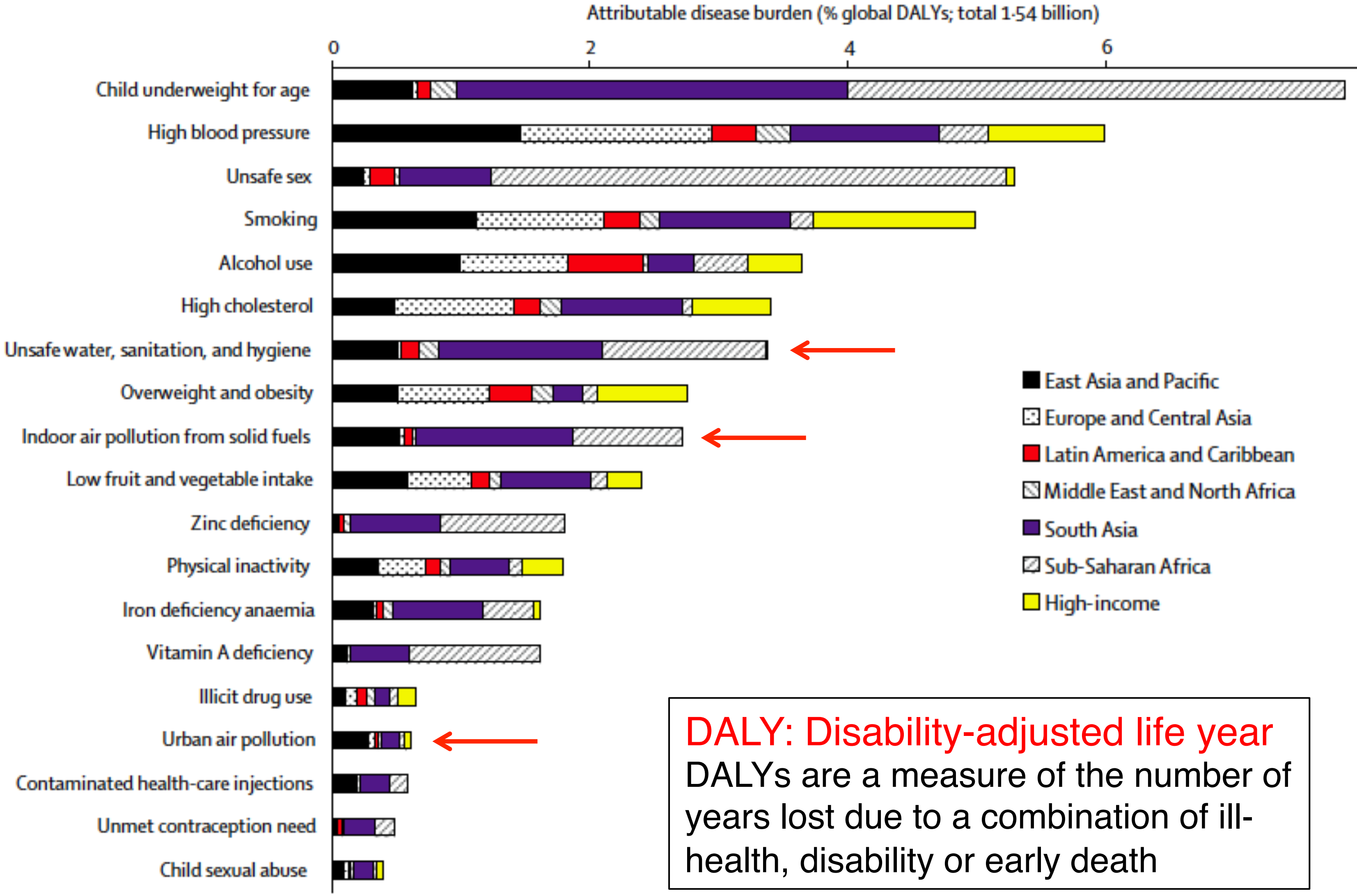
Lopez et al., 2006 *The Lancet*

DALY: Disability Adjusted Life Year

- Measure of overall disease burden
  - # of years lost due to illness, disability, or early death
  - Combines mortality and morbidity (existence of ill-health)
  - DALY = YLL + YLD
    - Years of Life Lost + Years Lived with Disability
  - 1 DALY = 1 year of healthy life lost
    - Relative to the longest avg life expectancy in the world
    - Japan, 82.6 years

  - Example: Cancer causes 25 DALYs per 1000 people
    - US population ~307 million → 7.7 million life years

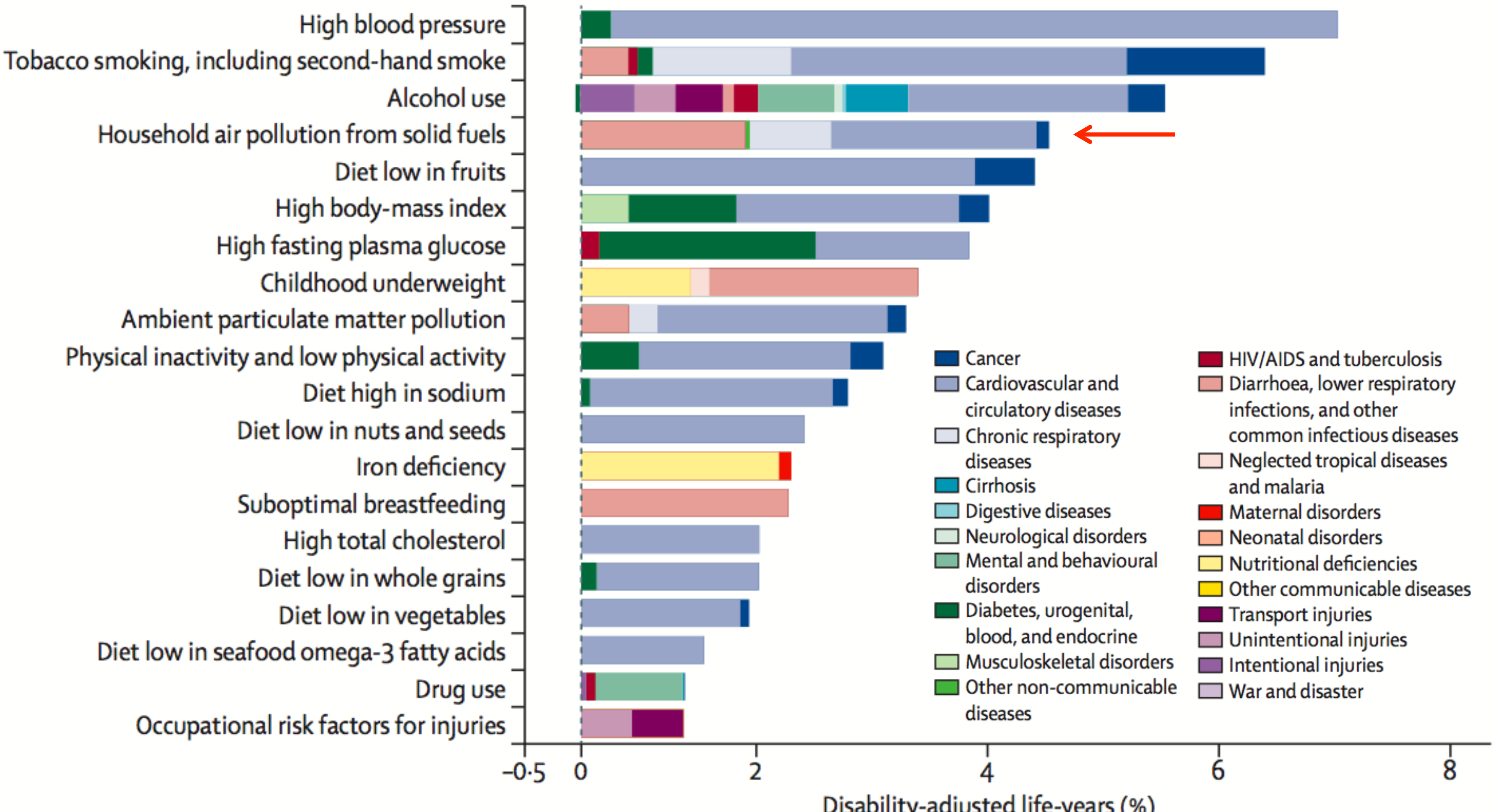
Global disease burden



DALY: Disability-adjusted life year
DALYs are a measure of the number of years lost due to a combination of ill-health, disability or early death

Lopez et al., 2006 *The Lancet*

Global disease burden: 2010 update



Women and young children are especially at risk!

Lim et al., 2013 *The Lancet*

Adverse health effects of biomass burning

Table 3 Respiratory diseases associated with solid fuel use

Health outcome	Meta-analysis RR (95%CI)[19]*
Strong evidence†	
Acute lower respiratory infection (ALRI) in children <5 years of age in developing countries	2.3 (1.9–2.7) 1.78 (1.45–2.18)[23]
Chronic obstructive pulmonary disease (COPD) in women >30 years of age, mainly homemakers residing in rural areas of developing countries	3.2 (2.3–4.8) 2.14 (1.78–2.58)[18]
Lung cancer (coal smoke exposure) in women >30 years of age	1.9 (1.1–3.5)
Moderate evidence‡	
COPD in men >30 years of age	1.8 (1.0–3.2)
Lung cancer (coal-smoke exposure) in men >30 years of age	1.5 (1.0–2.5)
Lung cancer (biomass smoke exposure) in women >30 years of age	1.5 (1.0–2.1)
Asthma in children aged 5–14 years	1.6 (1.0–2.5)
Asthma, >15 years of age	1.2 (1.0–1.5)
Tuberculosis, >15 years of age	1.5 (1.0–2.4)
Insufficient evidence§	
Upper airway cancer	
Low birth weight and perinatal mortality	
Cardiovascular diseases	

*Meta-analysis results from reference 19, unless otherwise stated.
†Strong evidence: Some 15–20 observational studies for each condition, from developing countries. Evidence is consistent (significantly elevated risk in most, although not in all, studies); the effects are sizable, plausible, and supported by evidence from outdoor air pollution and smoking.[19]
‡Small number of studies, not all consistent (especially for asthma, which may reflect variations in definitions and condition by age), but supported by studies of outdoor air pollution, smoking, and laboratory animals.[19]
§Insufficient for quantification based on available evidence.[19]
RR = relative risk; CI = confidence interval.

Perez-Padilla et al., 2010 *Int J Tuberculosis and Lung Disease*

Pollutant-specific adverse health effects

Table 2 Health-damaging pollutants as products of incomplete combustion of solid fuels[11,12,21]

Smoke phases	Characteristics	Mechanism and associated health effects
Particulate	Variety of particulates, different size and composition Respirable size, mean aerodynamic diameter <10 µm (PM_{10}) Fine particles <2.5 µm ($PM_{2.5}$) can be deposited in the lower respiratory tract Organic and inorganic (metals, for example) pollutants can be carried by particulate matter In some cases, carcinogenic pollutants are attached to the particle, for example, higher molecular weight (5-ring and more) polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene	Cause irritation and oxidative stress (additive to other compounds) producing lung and airway inflammation, hyperresponsiveness, and in long-term exposures airway remodeling and emphysema Reduced mucociliary clearance and macrophage response Carcinogenic
Gaseous	Carbon monoxide (CO)	Binds to hemoglobin interfering with transport of oxygen Headache, nausea, dizziness Low birth weight, increase in perinatal deaths. Feto-toxicant, has been associated with poor fetal growth
	Nitrogen oxides (NO_x)	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, longer-term exposure increases susceptibility to infections
	Sulfur dioxide (SO_2), mainly from coal	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, bronchoconstriction
	Hundreds of different hydrocarbons Aldehydes and ketones	Adverse effects are varied, including eye and upper and lower respiratory irritation, systemic effects
	Lower molecular weight (2–4 ring) PAHs	Carcinogenic
	Some of these are classified as carcinogenic: 1,3 butadiene; benzene; styrene, and formaldehyde	

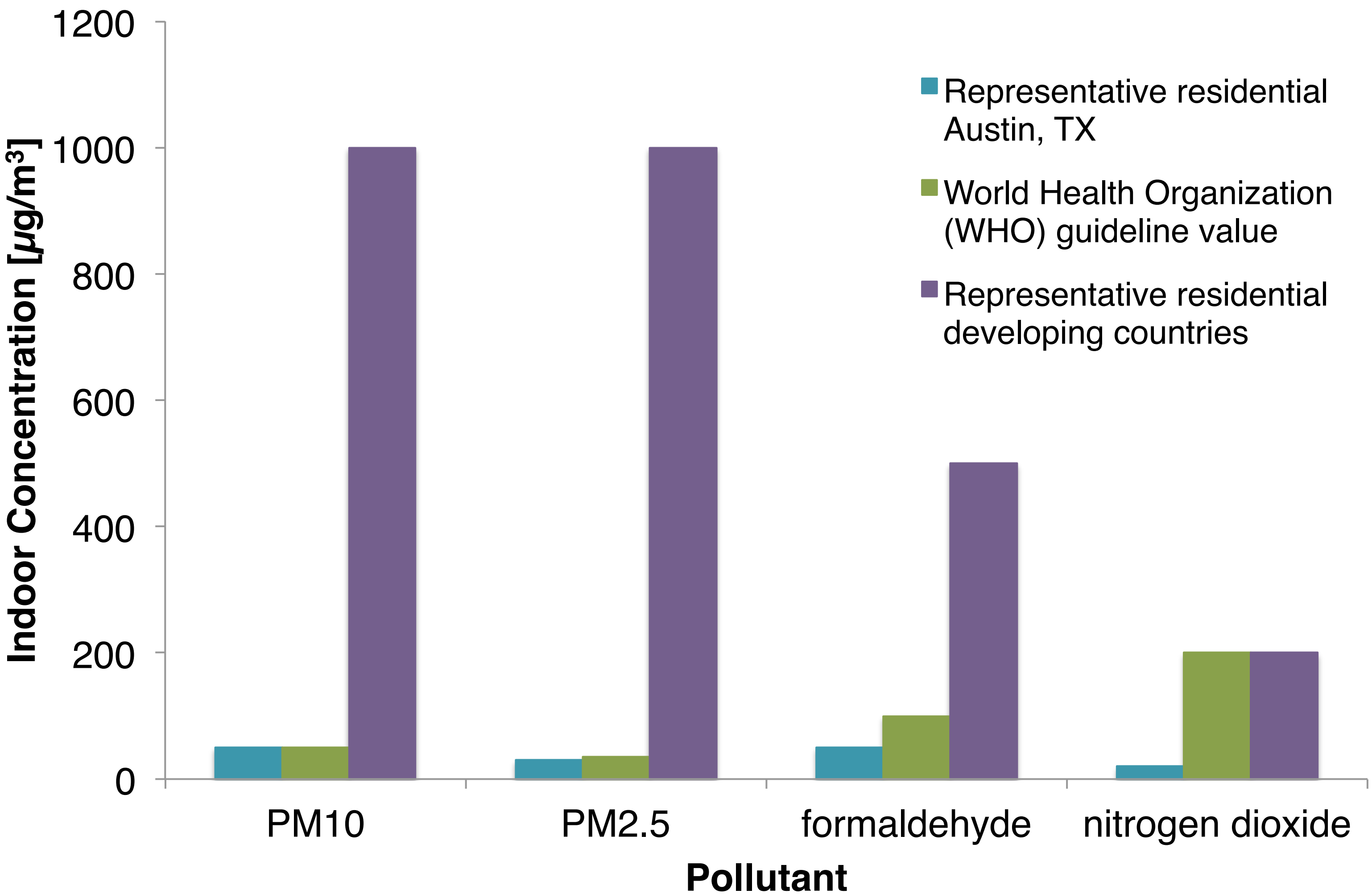
Others possible are arsenic and fluorine from coal combustion.

Perez-Padilla et al., 2010 *Int J Tuberculosis and Lung Disease*

QUANTIFYING EXPOSURES

Indoor and household air pollution

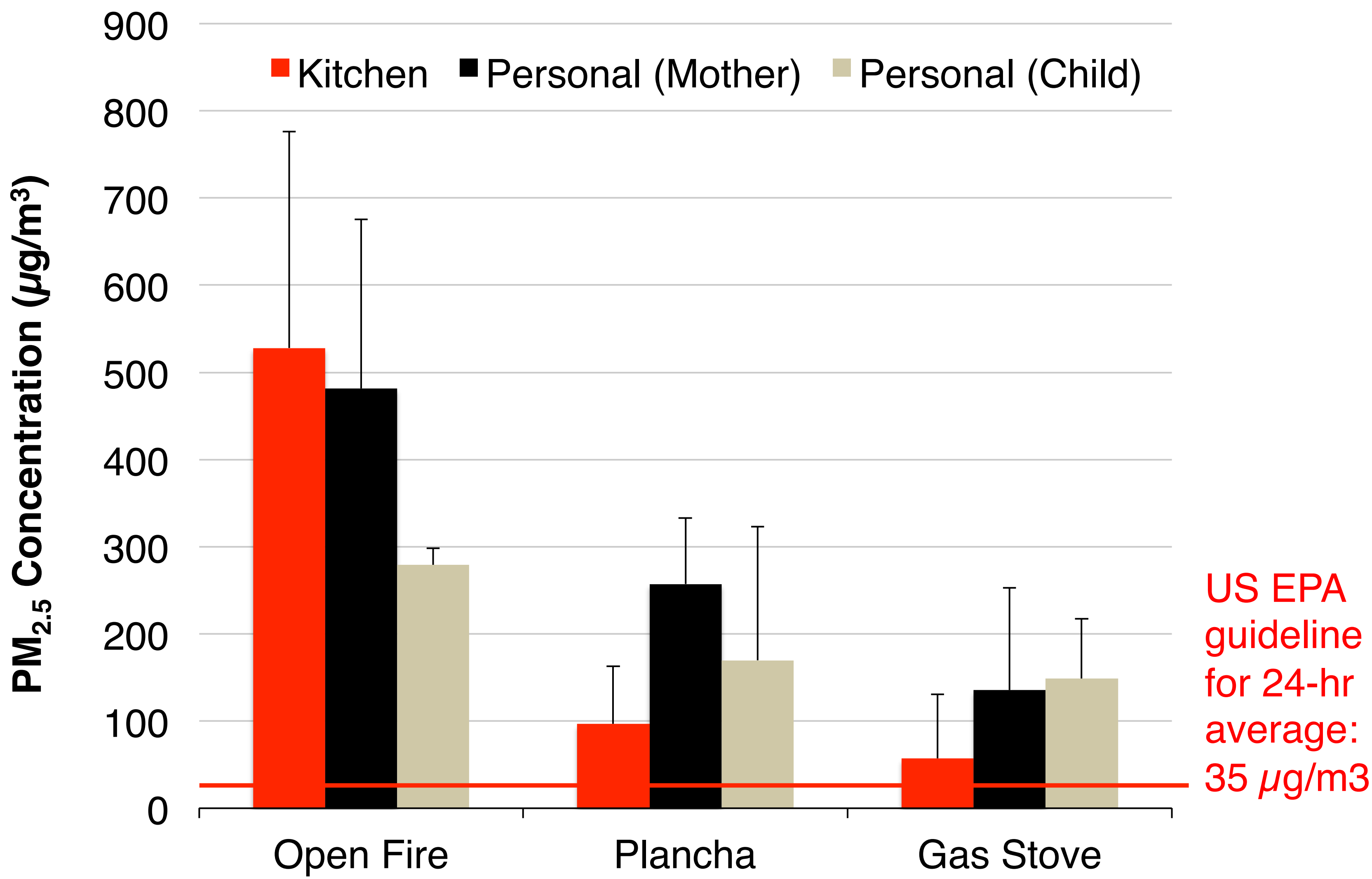
Representative pollutant concentrations



New and old stoves in Honduras: $PM_{2.5}$

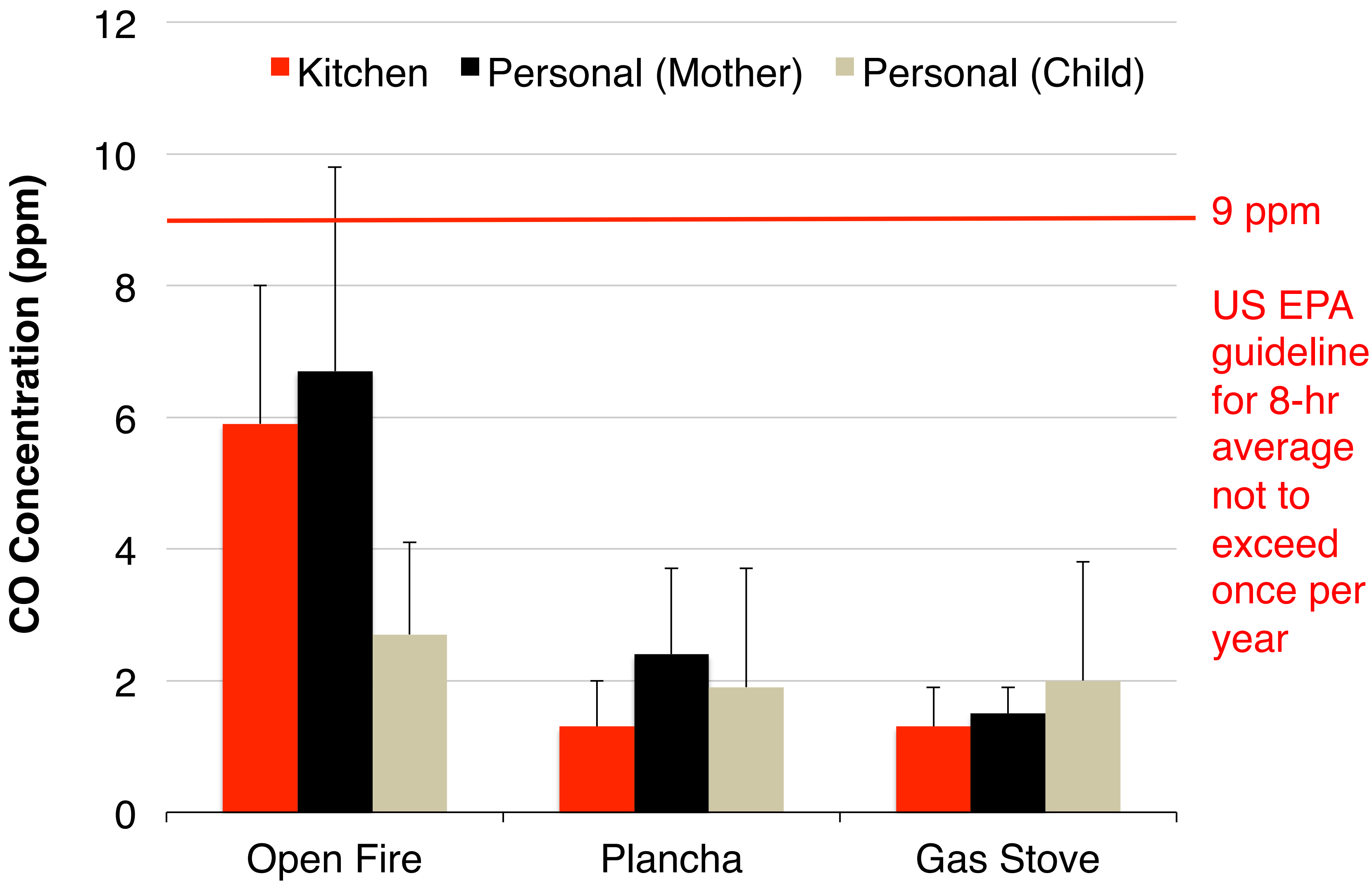
~30 homes each group

New and old stoves in Guatemala: $PM_{2.5}$



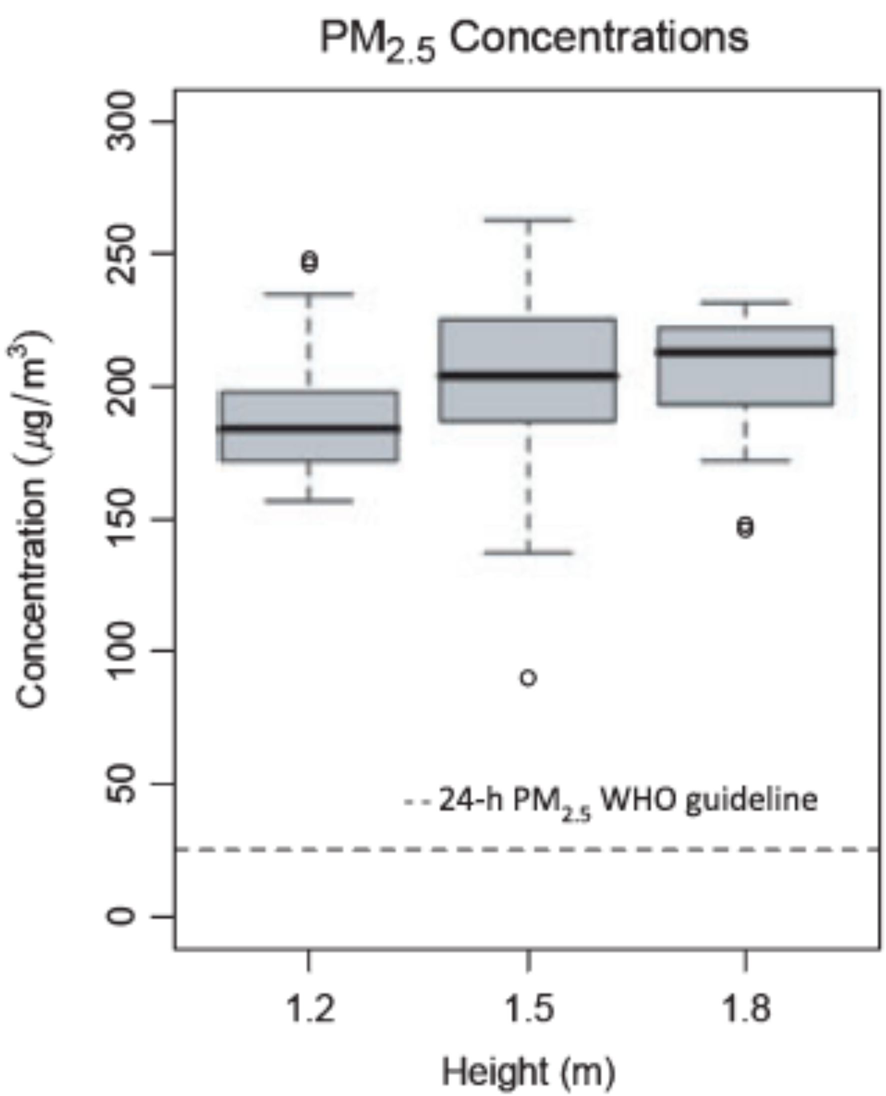
Naeher et al., 2000 *Indoor Air*

New and old stoves in Guatemala: CO



Naeher et al., 2000 *Indoor Air*

Kenya: Fuel-based lighting



Simple wick lamps

Test kiosk

Apple et al., 2010 *Indoor Air*

What pollutants do we measure?

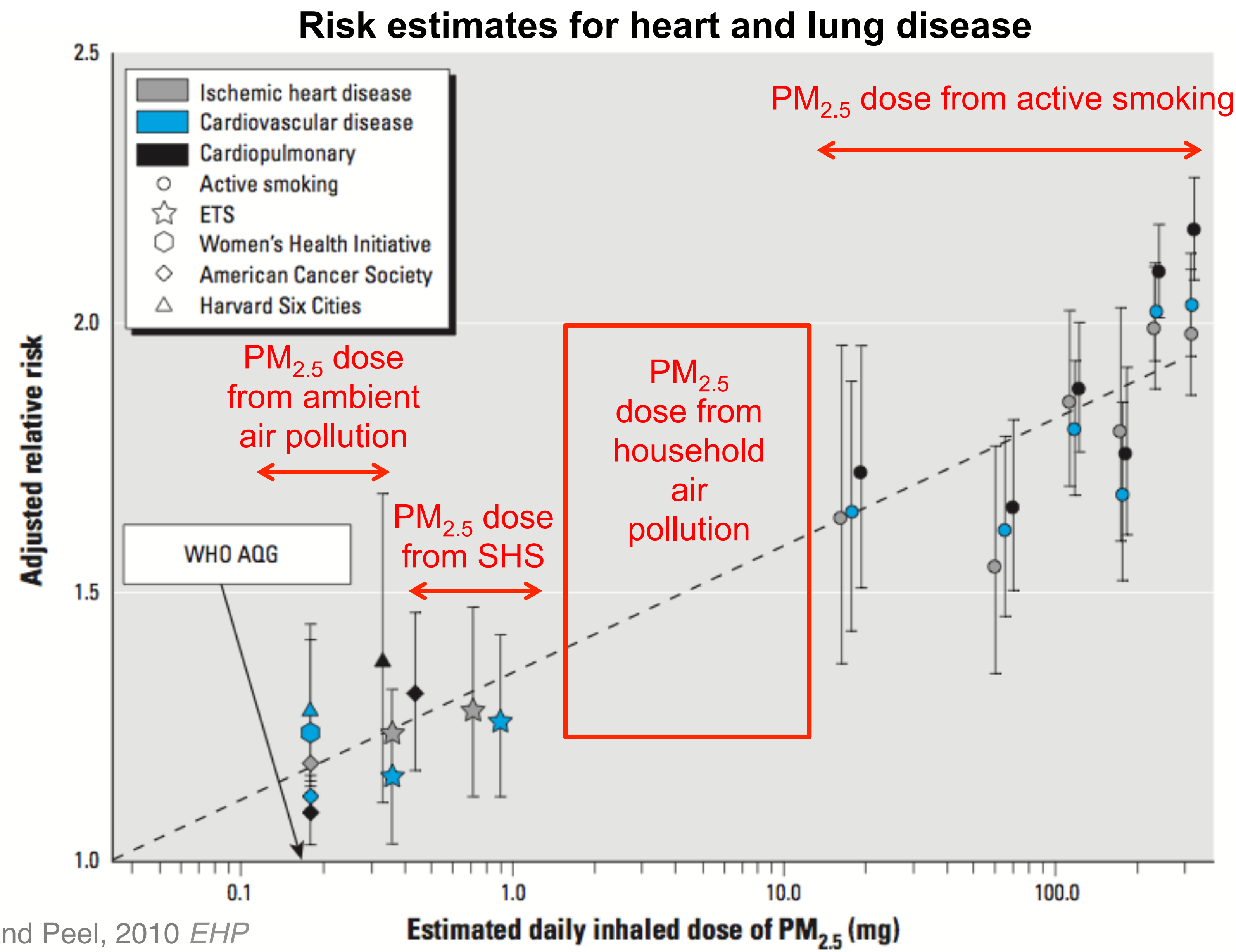
Carbon monoxide and PM

Why mostly only these two?

What are characteristics of desired equipment?

- inexpensive
- reliable
- field calibrated
- have continuous monitoring capacity
- have sufficient data storage

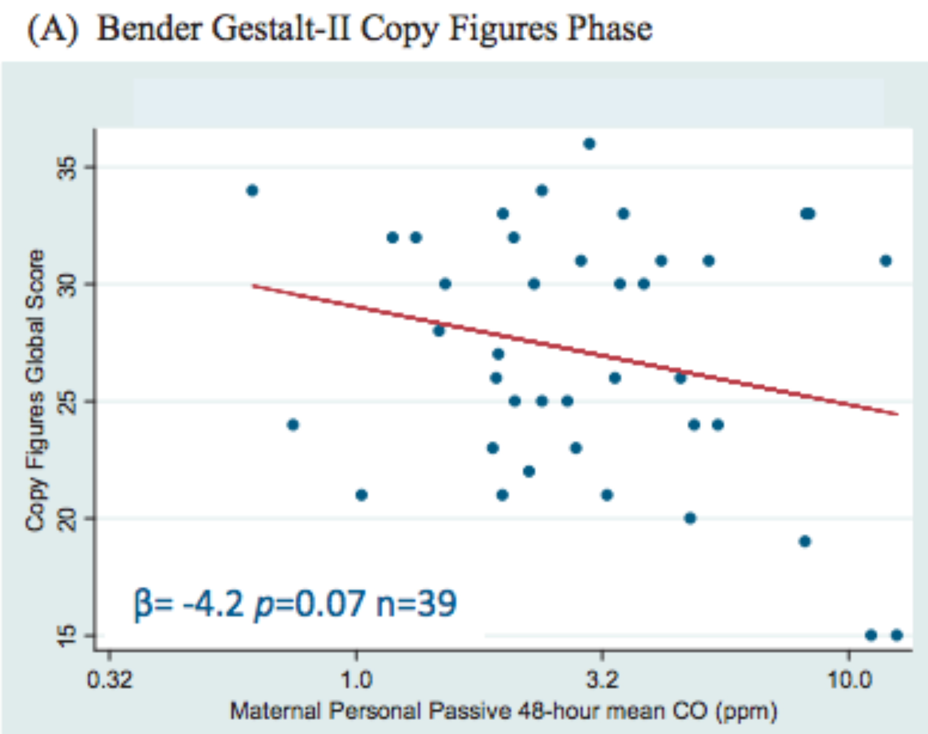
What do these exposures mean for health effects?

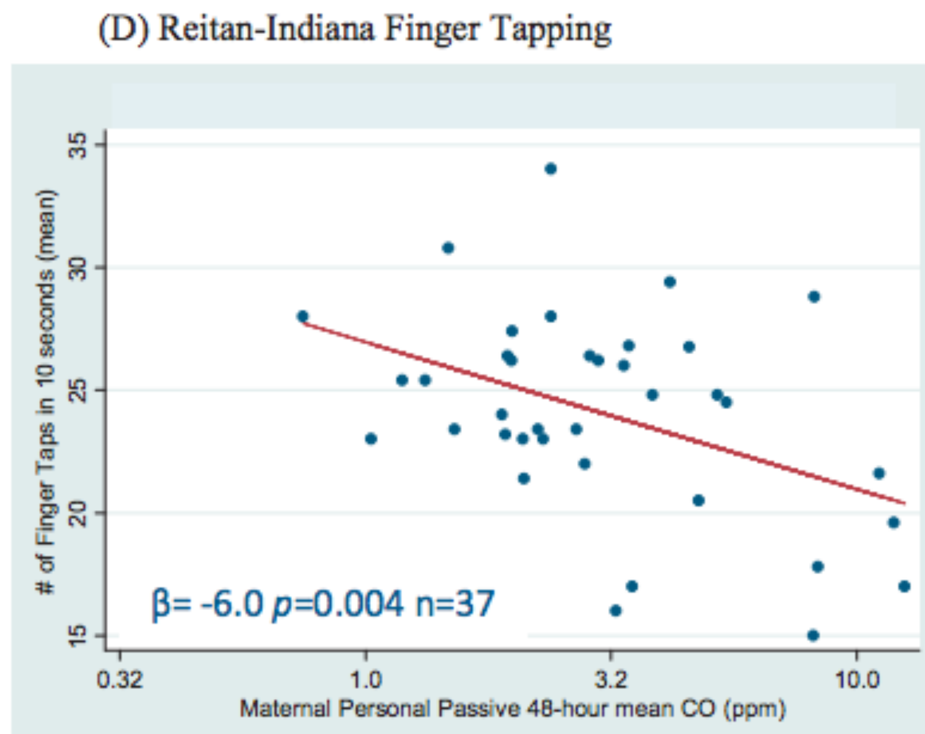


Smith and Peel, 2010 *EHP*

OTHER IMPACTS

Recent evidence of neurological effects





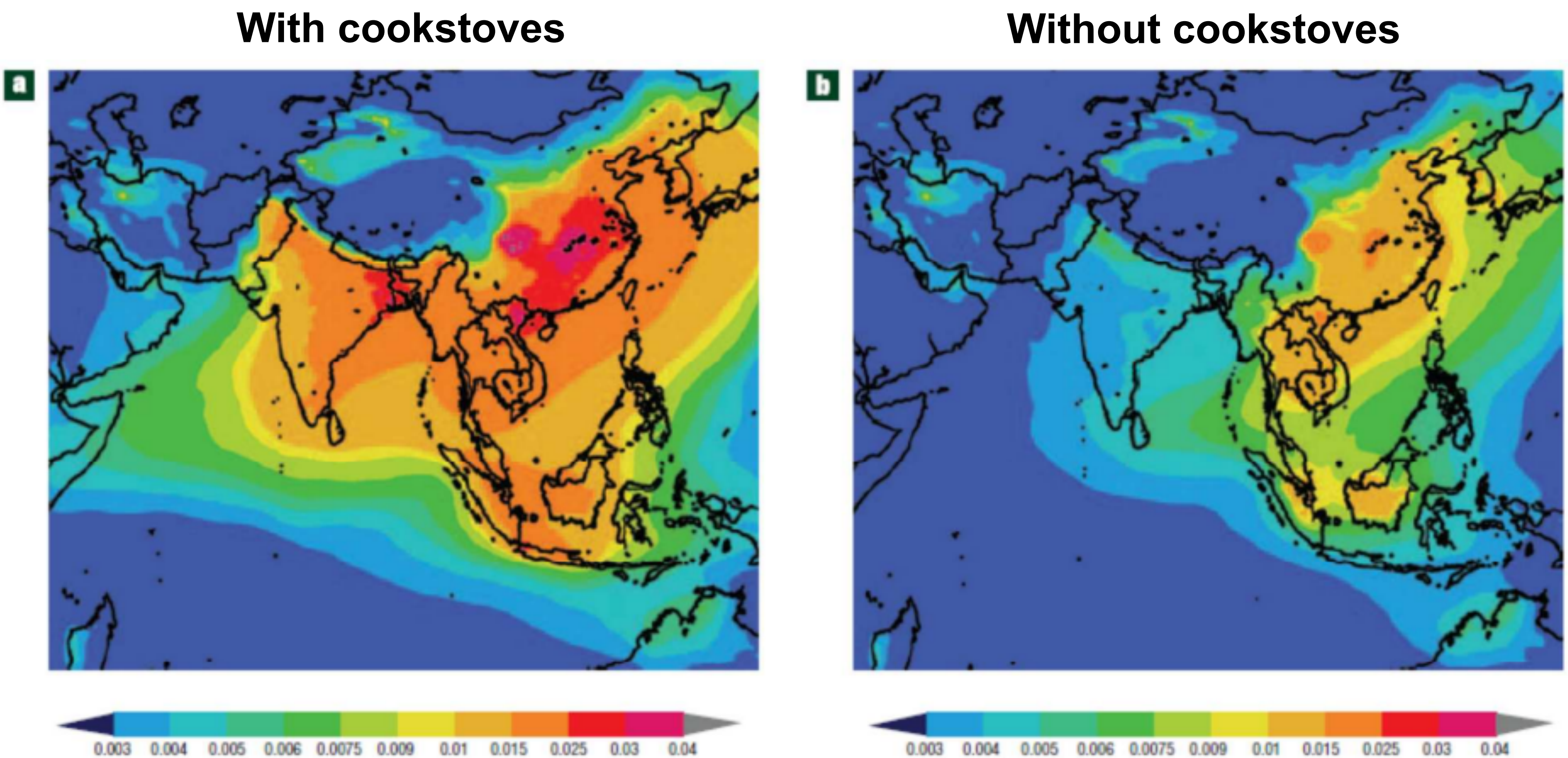
Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke

Linda Dix-Cooper [a], Brenda Eskenazi [b], Carolina Romero [c], John Balmes [a,d], Kirk R. Smith [a,*]

Dix-Cooper et al., 2012 *NeuroToxicology*

Climate impacts

- Black carbon (BC) with and without cookstove burning:



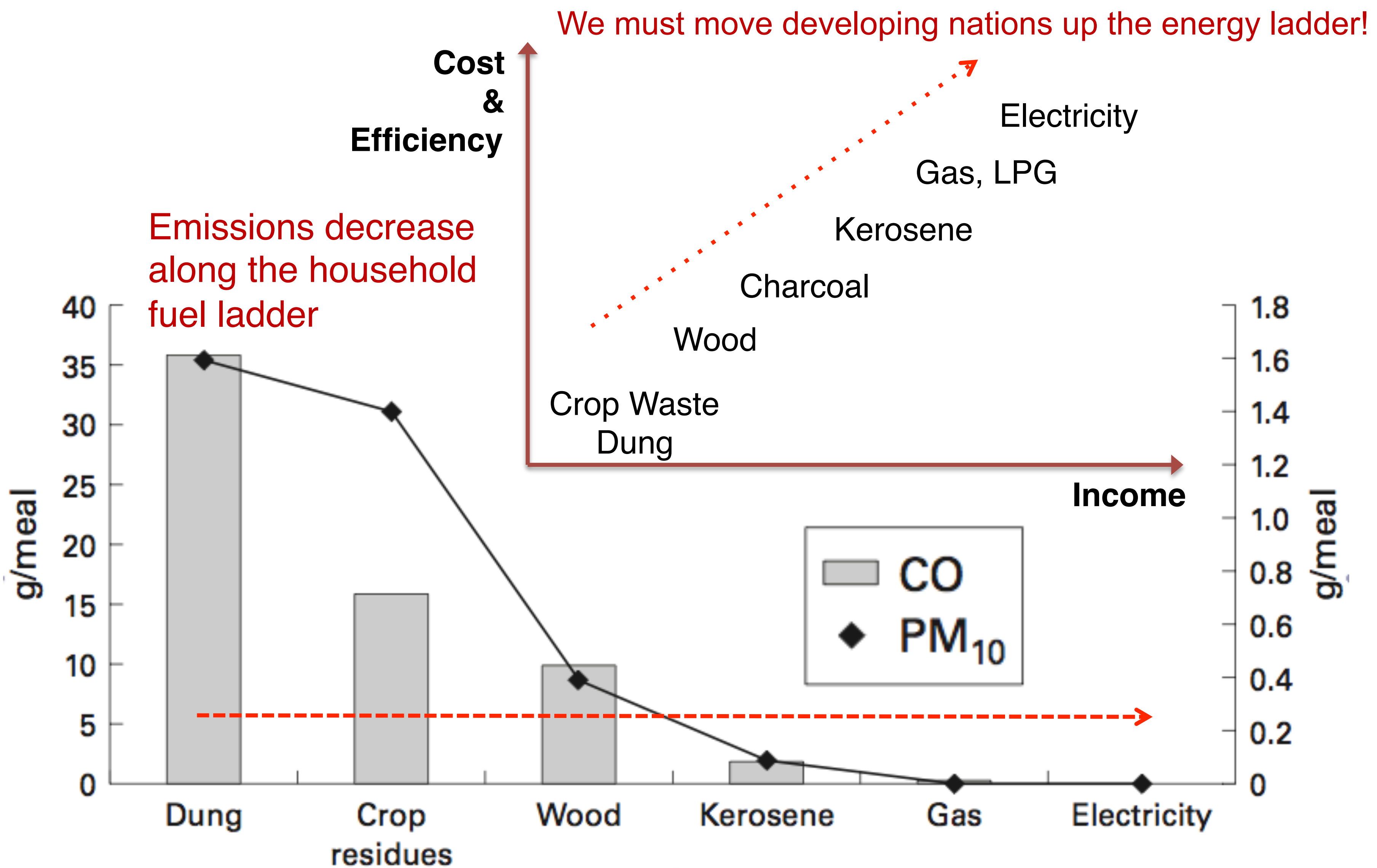
- BC is a contributor to global warming

Ramanathan and Carmichael, 2008 *Nature Geoscience*

INTERVENTIONS

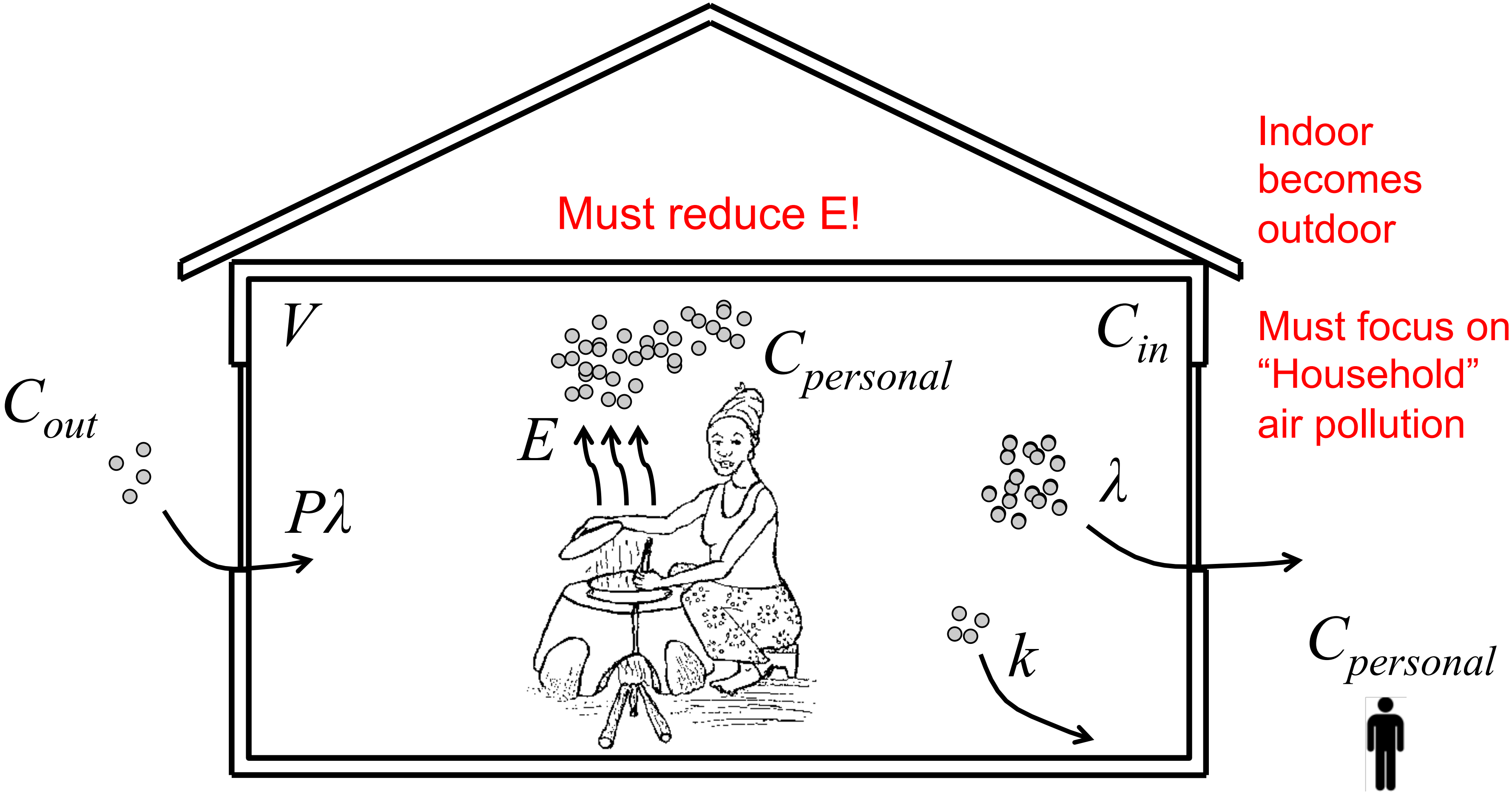
Clean cook stove campaigns

The energy ladder



Smith et al., 1999, US Environmental Protection Agency

Fundamental parameters driving exposures



C_{in} = Indoor concentration of pollutant C_{out} = Outdoor concentration of pollutant P = Penetration factor (-)
λ = Air exchange rate (hr^{-1}) k = Indoor loss rate (hr^{-1}) V = Volume of home (m^3) E = Emission rate (mg hr^{-1})

Cook stove emissions

$$Emission\ Rate, E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Emission Rate, E = mg pollutant per hour

Emission Factor = mg pollutant per kg of fuel

Energy Density = MJ per kg of fuel

Stove Power = MJ per hour

Efficiency = MJ delivered per MJ burned

Johnson et al. (2011) *Atmos Environ*

Calculating emission rates

$$Emission\ Rate,\ E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Typical values | Traditional Stove

- $EF_{PM2.5}$ = 5.2 g kg^{-1}
- Energy density of wood 18 MJ kg^{-1}
- Stove power = 4.9 kJ s^{-1}
  - Cooking energy needed = 11 MJ
  - Thermal efficiency = 14%
  - Cooking time = 4.5 hours

$$E = \frac{5.2\ g\ PM_{2.5}}{kg\ fuel} \times \frac{kg\ fuel}{18\ MJ} \times 4.9\frac{kJ}{s} \times \frac{3600\ s}{hr} \times \frac{MJ}{1000\ kJ} = 5\ \frac{g}{hr}$$

Johnson et al. (2011) *Atmos Environ*

Indoor concentrations

$$C_{ss} = P\cancel{C_{out}} + \frac{E/V}{\lambda + \cancel{k}} = \frac{E}{\lambda V}$$

- AER, λ = 25 hr^{-1}
- Kitchen volume, V = 30 m^3
- $E_{PM2.5}$ = 5 g hr^{-1}
- C_{ss} = 0.0067 g m^{-3} ≈ 7 mg m^{-3} ≈ 7000 μg m^{-3}
- WHO $PM_{2.5}$ standard = 35 μg m^{-3}
- 200 times higher

Johnson et al. (2011) *Atmos Environ*

Cookstoves: What has to change?

- Everything!

$$Emission\ Rate, E = \frac{Emission\ Factor}{Energy\ Density} \times Stove\ Power$$

$$Stove\ Power = \frac{Cooking\ Energy\ Needed}{Cooking\ Time \times \eta}$$

Stoves must get better
Fuels must get better

Can't just add a chimney

Cookstoves are major sources of outdoor pollution

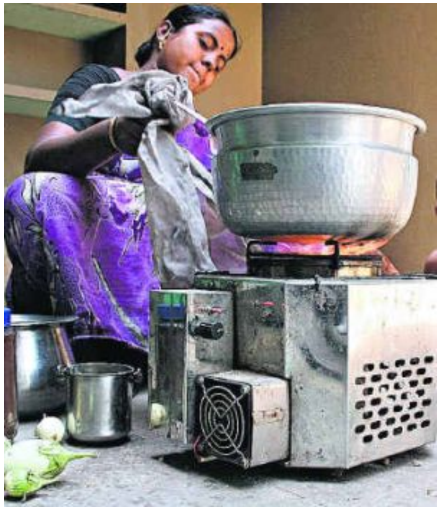
31-44% of primary $PM_{2.5}$ emissions in China
50-56% in India

Chafe et al., 2011 Indoor Air, Austin, TX

Enter: clean cook stoves

What is a clean cook stove?

1. Meets social, resource, income, and behavior needs
2. Improved performance relative to baseline conditions
   Pollutant emissions and energy efficiency
3. Scalable through markets or other mechanisms

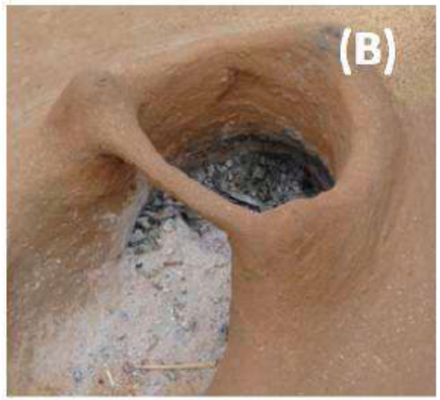




http://cleancookstoves.org/overview/what-is-a-clean-cookstove/

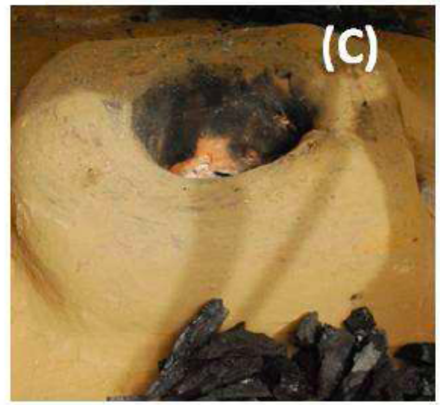
Example stoves

Traditional biomass *chulha*

Traditional coal *chulha*



Improved *chulha*



Kerosene

Biogas

Commercial biomass *bhati*

Commercial coal *bhati*

LPG stove

Sahu et al., 2011, ES&T

Example stoves

Fig. 1 – Stoves tested: A. Ecostove, B. VITA, C. UCODEA charcoal, D. WFP rocket, E. 3-stone fire, F. Philips, G. 6-brick rocket, H. Lakech charcoal, I. NLS, J. UCODEA rocket.

Jetter and Kariher, 2009 Biomass and Bioenergy

Ongoing research

- Emissions tests continue to be improved and conducted on more stoves
  - Often stark contrasts between laboratory and field test results
  - Some have turned to modeling efforts in stove design
- Exposure measurement studies continue to be conducted
  - Often coupled with health outcome studies
  - These take time, effort, and $$$ to do it right (i.e., randomized trials)
- The elephant in the room: cook stove adoption

Barriers to widespread adoption

- Previous reports have shown that stove implementation campaigns have been costly
  - And often result in poor adoption
- People often prefer their old inefficient stoves
  - Tradition or cooking preference
- People often use a mix of old and new stoves
  - "Stove stacking"
- People often alter their new stoves, diminishing effectiveness
- New stoves have had excessive costs
- Failures to integrate women in the stove design process

Social and behavioral aspects

- Stove adoption in El Fortin, Nicaragua
  - Problems with “culturally unfamiliar” stoves
  - Unfamiliar fuel types
- Surveyed 124 cooks in semi-rural Nicaragua
  - 1 year after introduction of improved cookstoves
- 48% still used their traditional open fire stoves
  - Often mixed
- Almost all preferred the new stove overall
- Many made adjustments to new stoves
  - Removing the plancha (griddle surface)
  - Leaving edges unsealed

Davis et al., Indoor Air 2011, Austin, TX

For more information

Indoor Air Pollution in Developing Countries: Research and Implementation Needs for Improvements in Global Public Health

Elliott T. Gall, MSE, Ellison M. Carter, MSE, C. Matt Earnest, MSE, and Brent Stephens, PhD

American Journal of PUBLIC HEALTH

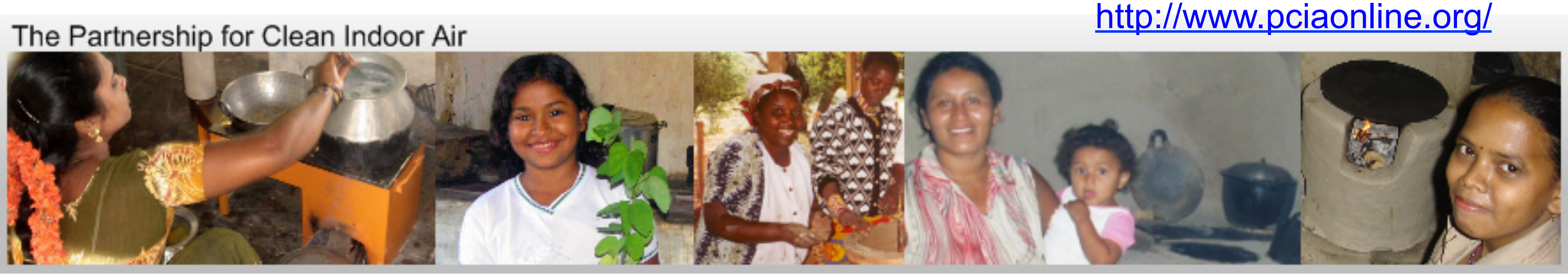
Barriers and research and implementation needs

- Costs of improved cook stove programs have been too high
  - Costs must come down
- Research and implementation agencies need to integrate
  - Lab testing, field testing, and implementation together
- Mixed successes with stove adoption
  - Wide array of researchers need to work to understand adoption
- Indoor (and household) concentrations are still too high after new stoves
  - Engineers need to continue to develop cleaner and more efficient stoves
- Health assessments remain limited to draw robust conclusions
  - Need to standardize measurements/metrics to conduct larger scale intervention studies
- Instrumentation is a significant barrier to exposure studies
  - Need to develop low-cost reliable sensors

GET INVOLVED

Partnership for Clean Indoor Air

http://www.pciaonline.org/



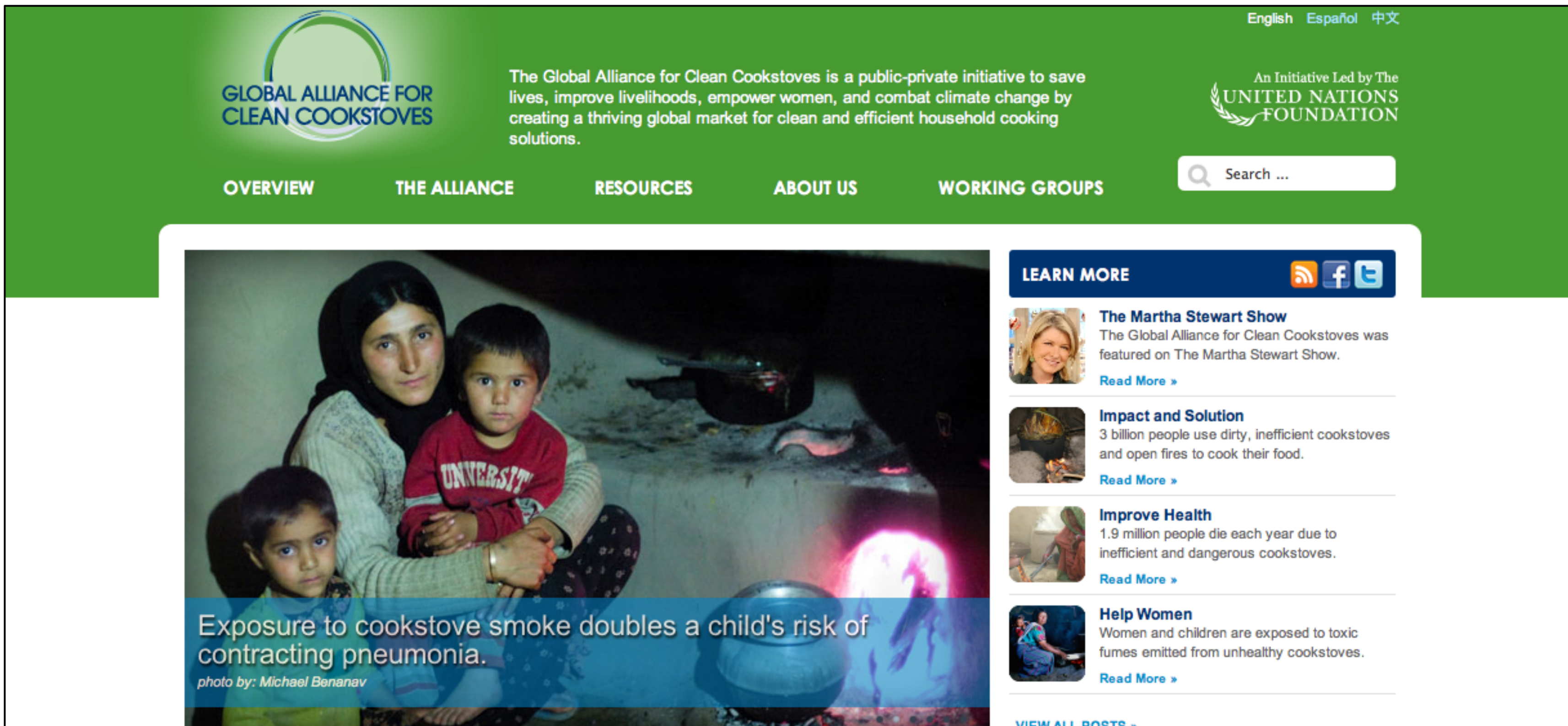
537 partner organizations contributing resources and expertise to reduce pollutant exposure from cooking and heating practices in households around the world.

Essential elements of effective, sustainable household energy and health programs:

1. Meeting the needs of local communities for clean, efficient, affordable and safe cooking and heating options
2. Improved cooking technologies, fuels and practices for reducing indoor air pollution
3. Developing commercial markets for clean and efficient technologies and fuels
4. Monitoring and evaluating the health, social, economic and environmental impact of household energy interventions

Global Alliance for Clean Cookstoves

The Global Alliance for Clean Cookstoves is a new public-private partnership to save lives, improve livelihoods, empower women, and combat climate change by creating a thriving global market for clean and efficient household cooking solutions. The Alliance's 100 by '20 goal calls for 100 million homes to adopt clean and efficient stoves and fuels by 2020.



http://cleancookstoves.org/

Resources for getting involved

- Some EWB resources
  - GA Tech: http://ewb-gt.org/?page_id=1568
  - Michigan Tech: http://ewb.students.mtu.edu/
- Some important academic groups in this field
  - Kirk Smith, UC-Berkeley: http://ehs.sph.berkeley.edu/krsmith/
  - Ashok Gadgil, LBL: http://cookstoves.lbl.gov/
  - Tami bond, UIUC: http://www.hiwater.org/
  - CSU Engines Lab: http://www.eecl.colostate.edu/research/household.php
  - Modi group, Columbia: http://modi.mech.columbia.edu/
  - Duke: http://sites.duke.edu/cookstove/
- Other important groups
  - Berkeley Air Monitoring Group: http://www.berkeleyair.com/
  - Trees, Water, People: http://www.treeswaterpeople.org/
  - Aprovecho: http://www.aprovecho.org
  - Bioenergylists: http://www.stoves.bioenergylists.org/

APPLICATIONS AND STANDARDS

Applications: Software

- I think we should all be aware of some of the software tools available for modeling air pollution in indoor environments

- You can always build well-mixed mass balance models in Excel or other programs (e.g., Matlab, Mathematica, Python, R, etc.)
  - Time-varying (dynamic) or steady state
  - Multi-compartments if necessary
  - Monte carlo for testing sensitivity to inputs

- Other commonly used tools include:
  - CONTAM
  - CFD

CONTAM

CONTAM

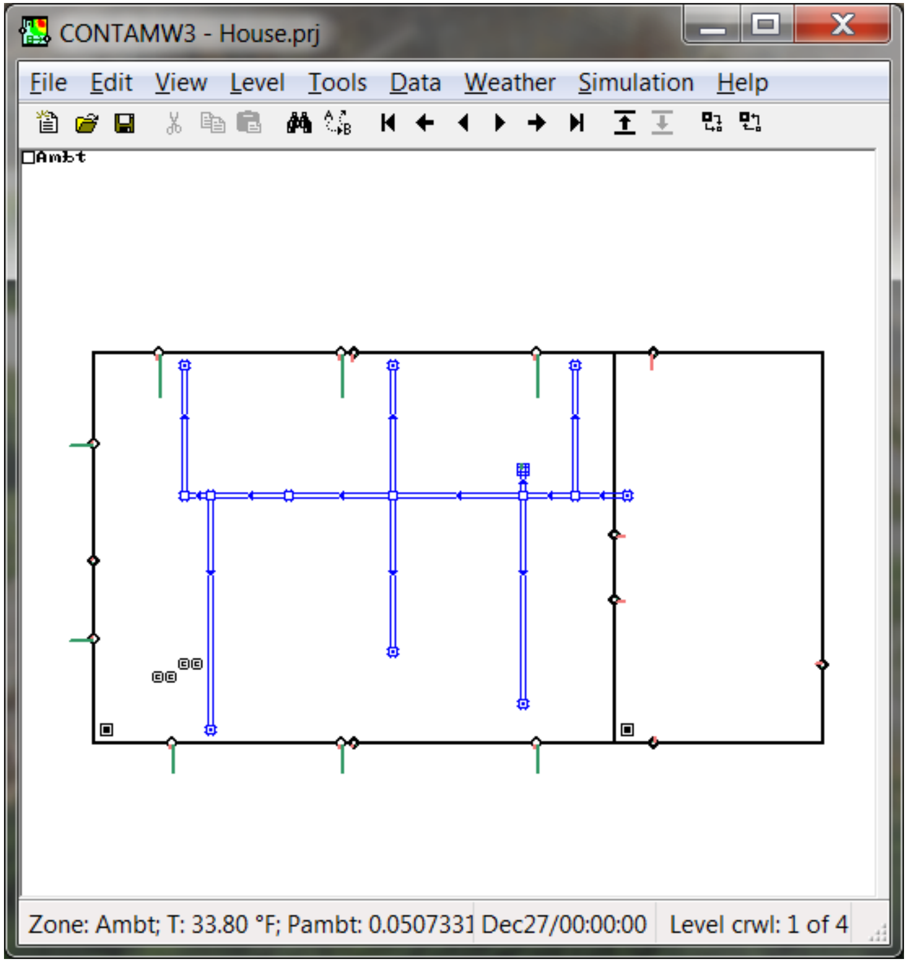
Multizone Airflow and Contaminant Transport Analysis Software

- Multi-zone airflow and contaminant transport analysis software
- Can be used to account for:
  - Airflows (infiltration, exfiltration, room-to-room airflows, wind-driven flow, stack effects)
  - Contaminant concentrations and mechanisms (dispersion indoors, transformation, adsorption, desorption, filtration, deposition, and others)
  - Personal exposures

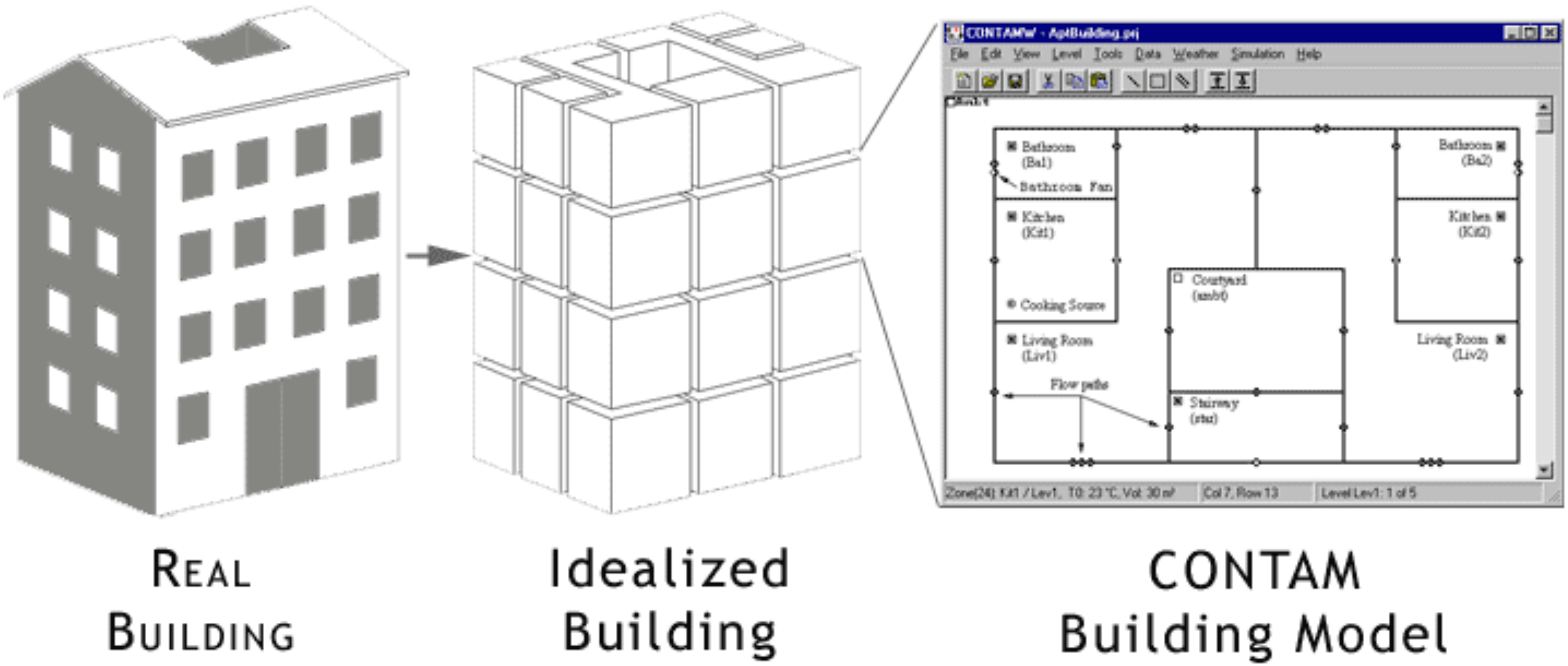
http://www.bfrl.nist.gov/IAQanalysis/CONTAM/

CONTAM

- You can build a building and set flow rates and boundary conditions everywhere
- It solves dynamic mass balances for you
- If you divide the building into different compartments, it gives you spatially-resolved concentrations



CONTAM


REAL
BUILDING
Idealized
Building
CONTAM
Building Model
CONTAMW - AptBuilding.prj
File Edit View Level Tools Data Weather Simulation Help
Bathroom
(Ba1)
Bathroom Fan
Kitchen
(Kit1)
Cooking Source
Living Room
(Liv1)
Flow paths
Courtyard
(ambt)
Stairway
(stai)
Bathroom
(Ba2)
Kitchen
(Kit2)
Living Room
(Liv2)
Col 7, Row 13
Level Lev1: 1 of 5

CONTAM outputs

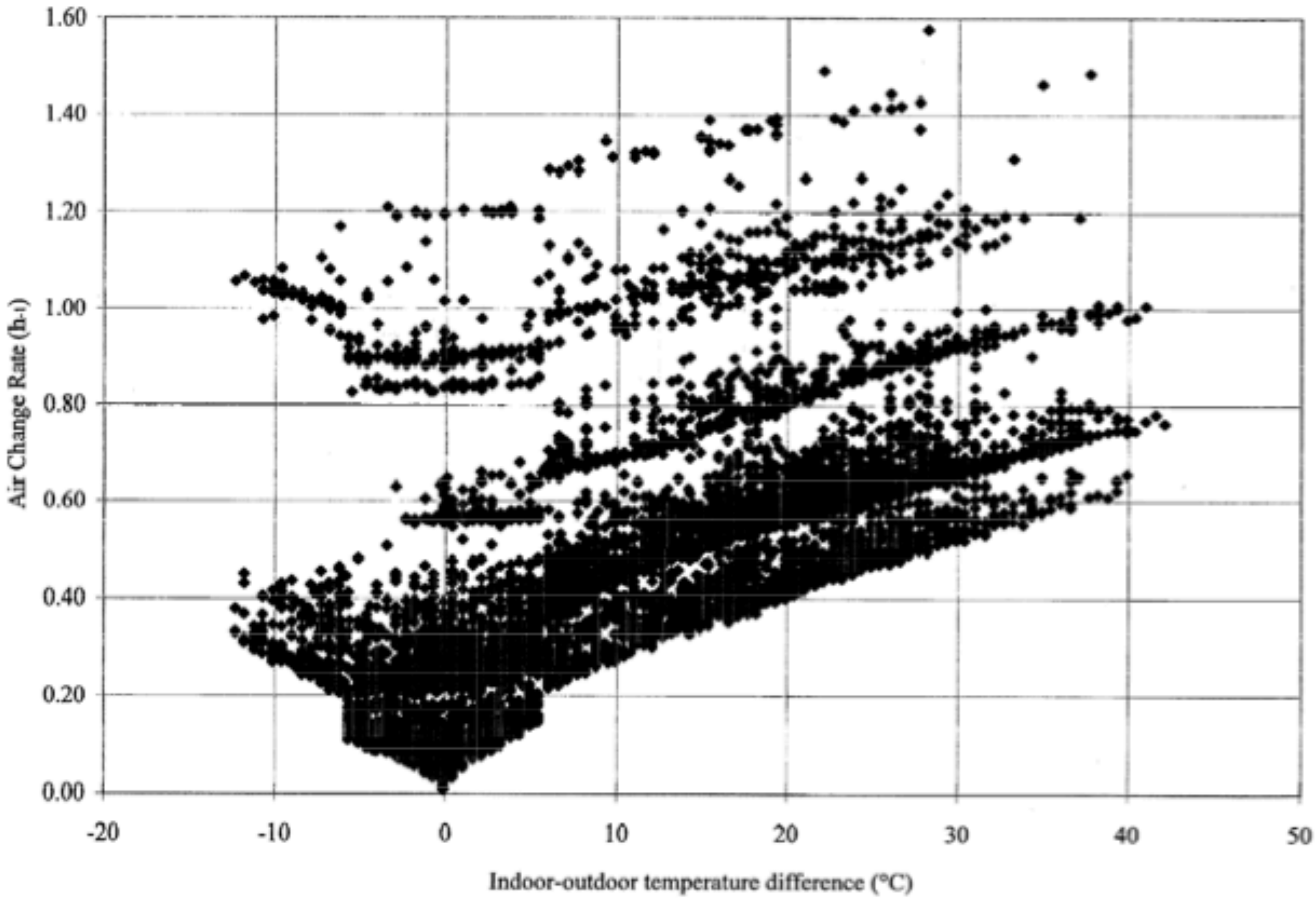


Figure 19 Hourly Air Change Rates for Albany: Whole House Exhaust Fan in KLA Zone Operated During Occupancy (Case #5B)

Persily and Martin **2000** A Modeling Study of Ventilation in Manufactured Houses National Institute of Standards and Technology. NIST Report

CONTAM outputs

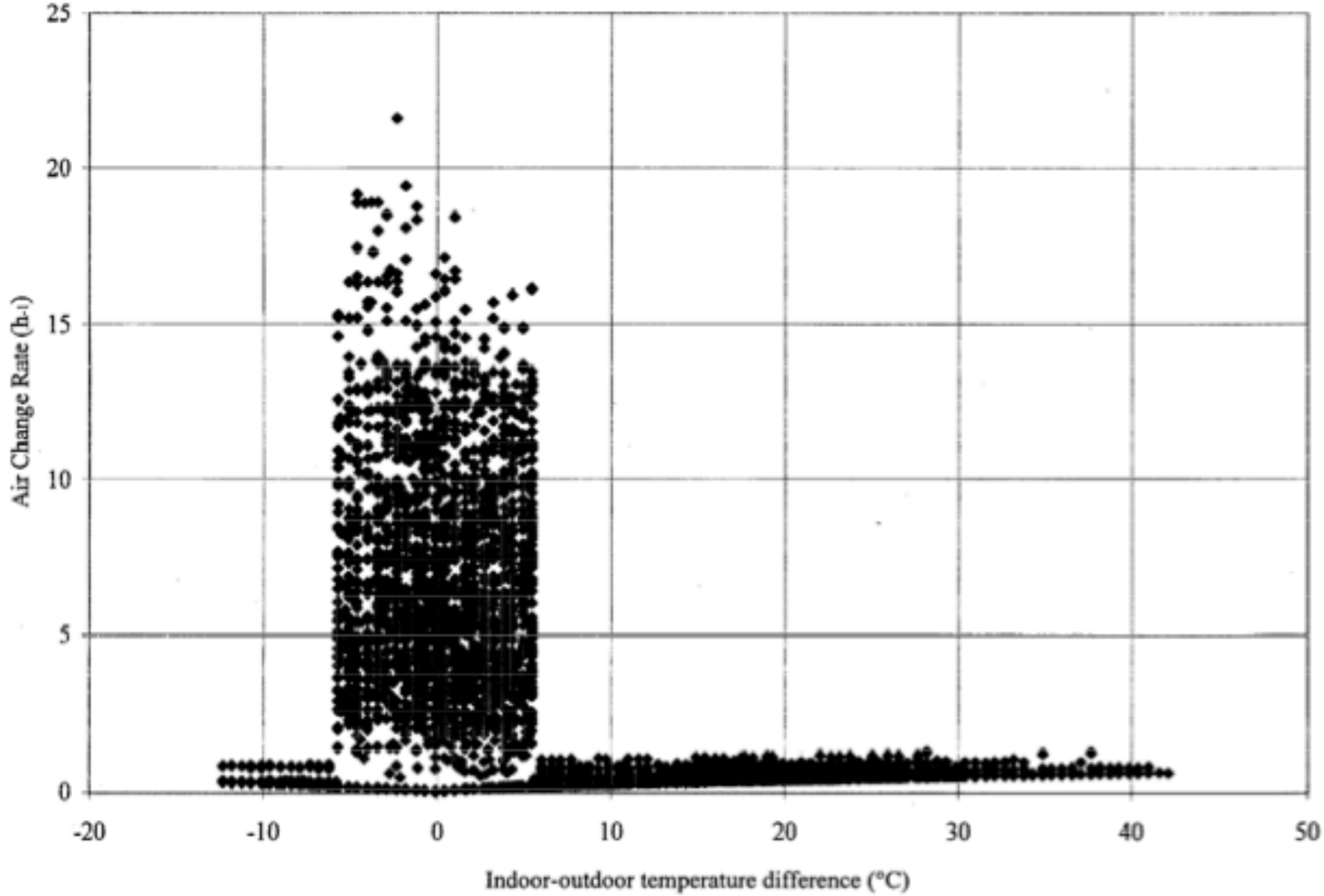
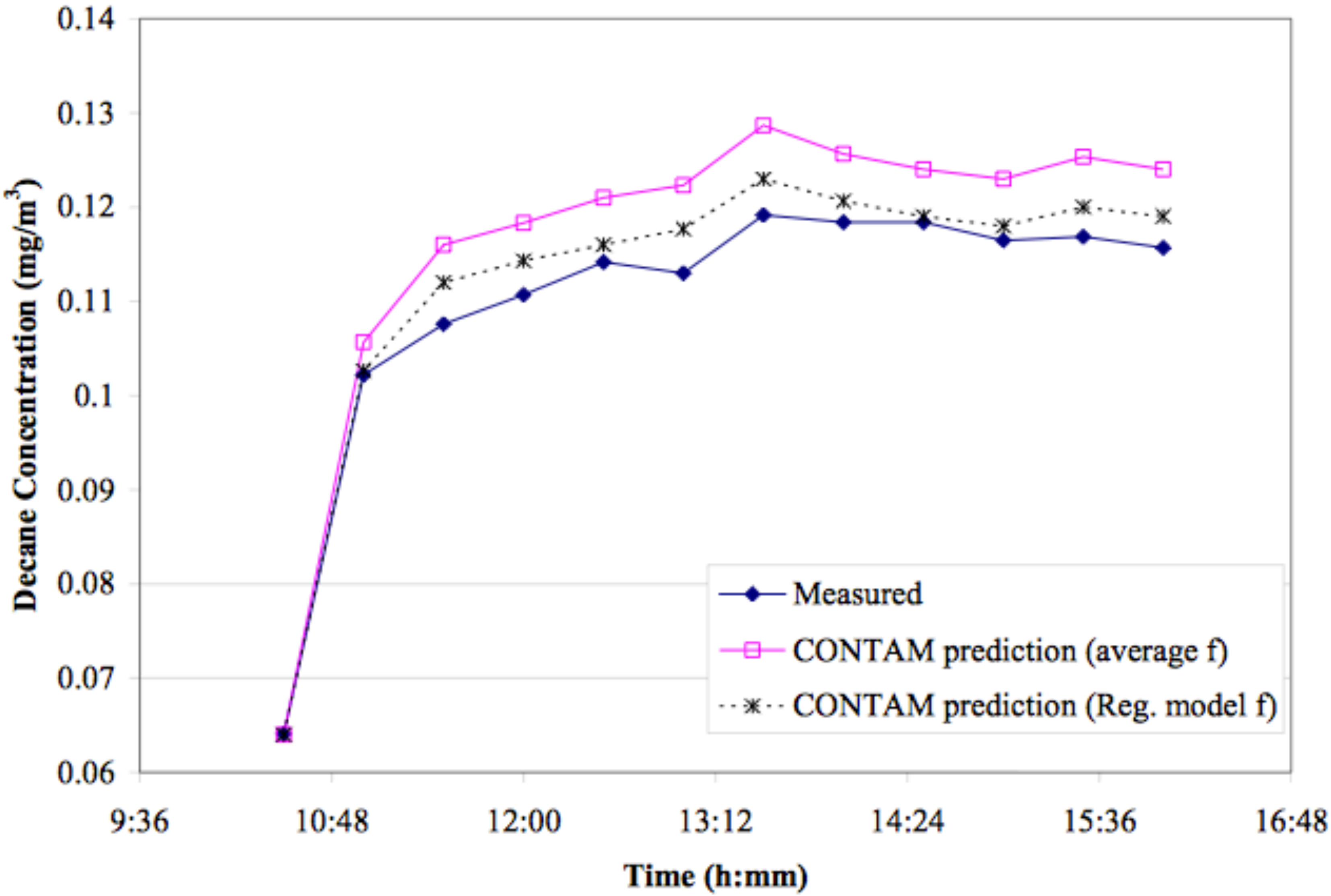


Figure 21 Hourly Air Change Rates for Albany: Window Operation

Persily and Martin **2000** A Modeling Study of Ventilation in Manufactured Houses National Institute of Standards and Technology. NIST Report

CONTAM outputs



Howard-Reed et al. **2005** Indoor Air 2005 Conference

2.2.2. Contaminant source

Two types of sources were used in the models: (1) a burst source of 500,000 particles with a diameter of 0.64 μm, intended to represent a tuberculosis-like particle and (2) a constant source of particles at 10 μg/min with a diameter of 10 μm, intended to represent squame cells. The burst source was chosen to be similar to tuberculosis because it represents a realistic contaminant problem in hospitals and falls within a size range (0.05–1 μm) corresponding to low removal efficiencies for many common particle filters [22]. The constant source was used to represent a steady release of squame particles from the surgical staff. The

2.3. Simulation design

A set of simulation scenarios was designed to examine how zonal contaminant concentrations and pressure differentials across important boundary flow paths are affected by:

- a constant flow differential between supply and return airflows, based on median values of flow differentials reported for AII rooms (including adjacent toilet rooms) and ORs in the survey [7]
- the state of the bathroom door (open or closed), assuming there is a constant exhaust flow in the toilet room
- an open door to the corridor
- an increase in the wall leakage area between pressurized zones
- the presence of an anteroom
- cascading pressure differences (i.e. OR > sterile core > outer corridor)

The following air cleaning systems are examined:

- MERV 15 filters in all rooms with supply points
- HEPA filters on the supply points
- UVGI systems
- Standalone HEPA filters
- A combination of lower air change rate (baseline value reduced by 2 h^{-1}) and in room filtration

Multizone modeling of strategies to reduce the spread of airborne infectious agents in healthcare facilities

Steven J. Emmerich [a], David Heinzerling [b], Jung-il Choi [c,*], Andrew K. Persily [a]

[a] Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA
[b] Center for the Built Environment, University of California at Berkeley, USA
[c] Department of Computational Science and Engineering, Yonsei University, Seoul, South Korea

Emmerich et al. **2013** *Building and Environment* 60:105-115

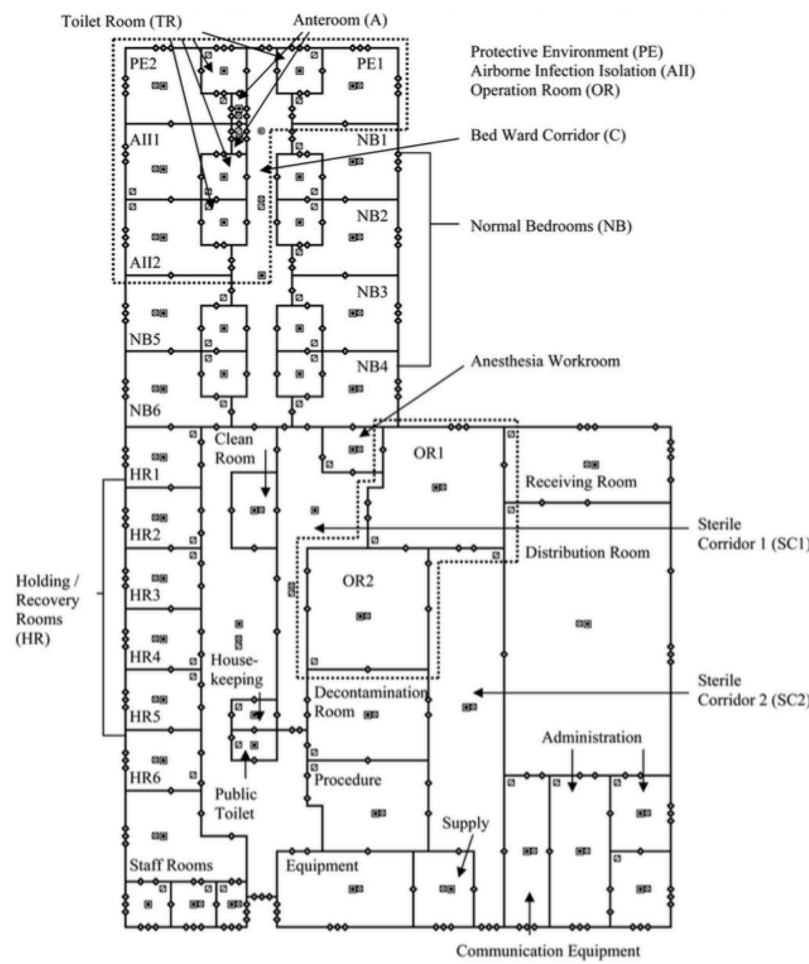


Fig. 1. Baseline CONTAM model–main floor.

Multizone modeling of strategies to reduce the spread of airborne infectious agents in healthcare facilities

Steven J. Emmerich [a], David Heinzerling [b], Jung-il Choi [c,*], Andrew K. Persily [a]
[a] Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA
[b] Center for the Built Environment, University of California at Berkeley, USA
[c] Department of Computational Science and Engineering, Yonsei University, Seoul, South Korea

Emmerich et al. **2013** *Building and Environment* 60:105-115

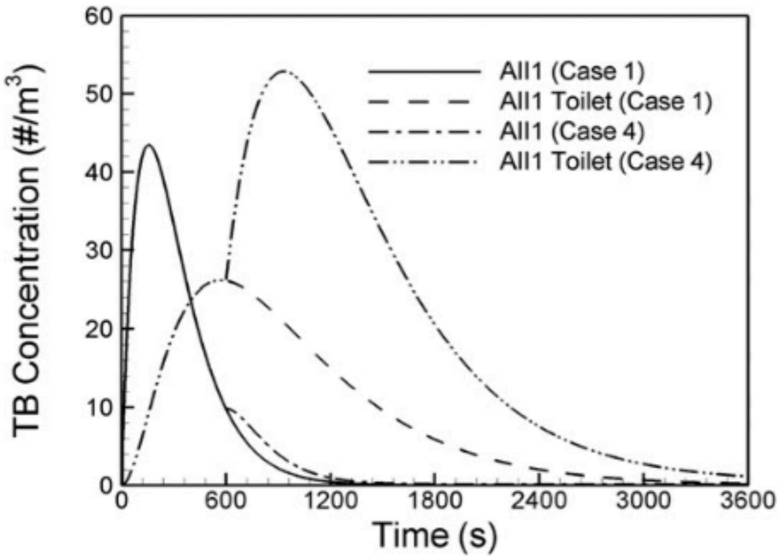


Fig. 4. The effect of door opening to corridor on TB concentration in AII suite 1: Cases 1 and 4 corresponds to the anteroom door to the corridor in AII suite 1 being closed (baseline model) and opened, respectively.

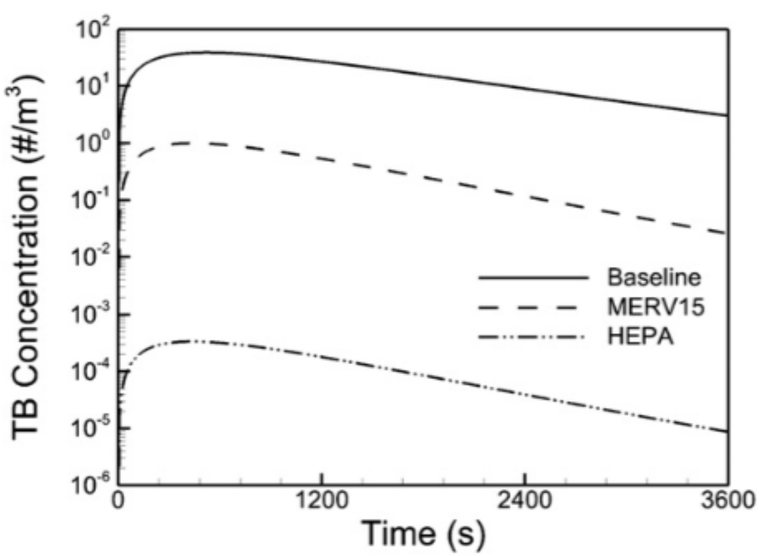


Fig. 6. The effect of air cleaning strategies on TB concentration in PE1.

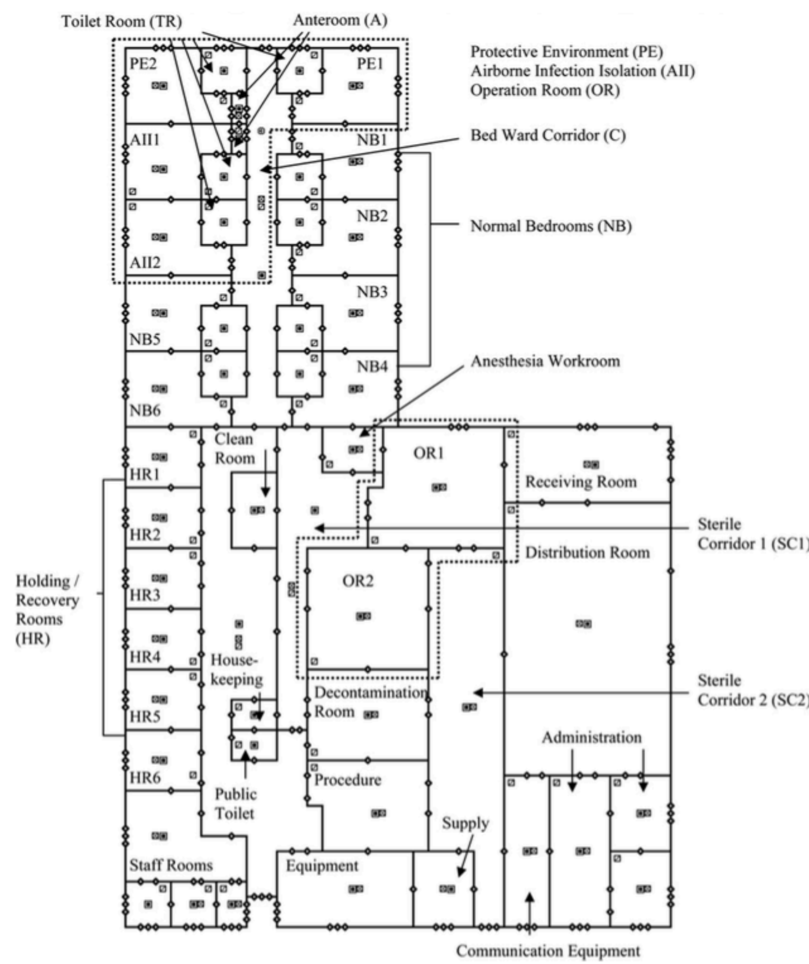
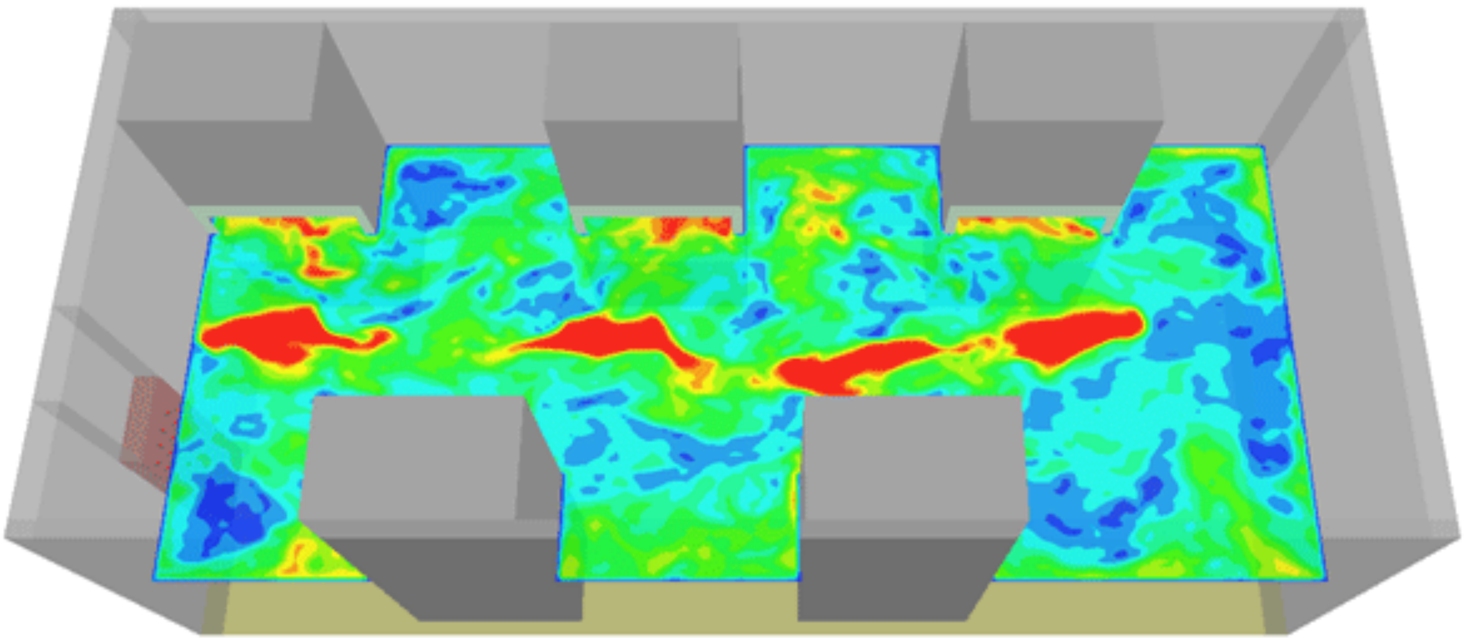


Fig. 1. Baseline CONTAM model–main floor.

Computational fluid dynamics: CFD

- If you want more highly resolved spatial detail, turn it computational fluid dynamics (CFD)



- CFD programs solve the Navier-Stokes equations for viscous, heat conducting fluids
  - Accounts for conservation of momentum, energy, and mass

CFD: Navier-Stokes Equations

Navier–Stokes Equations
3 – dimensional – unsteady

Glenn Research Center

Coordinates: (x,y,z)
Velocity Components: (u,v,w)

Time : t
Density: ρ
Total Energy: Et

Pressure: p
Stress: τ

Heat Flux: q
Reynolds Number: Re
Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right]$$

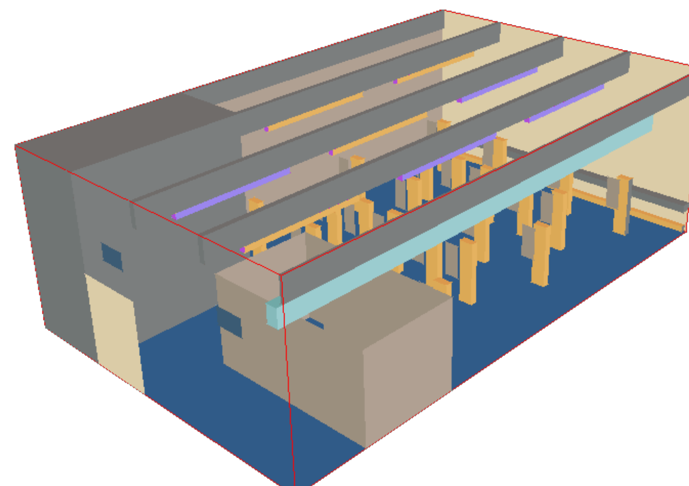
$$+ \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx} + v\,\tau_{xy} + w\,\tau_{xz}) + \frac{\partial}{\partial y}(u\,\tau_{xy} + v\,\tau_{yy} + w\,\tau_{yz}) + \frac{\partial}{\partial z}(u\,\tau_{xz} + v\,\tau_{yz} + w\,\tau_{zz})\right]$$

CFD simulations

- Involves discretizing an indoor space into a "mesh"
  - Thousands of small cells representing individual nodes
  - Develop a system of equations to solve Navier-Stokes
  - We use software for this (e.g., Fluent, AirPak, openFOAM, IES, others)

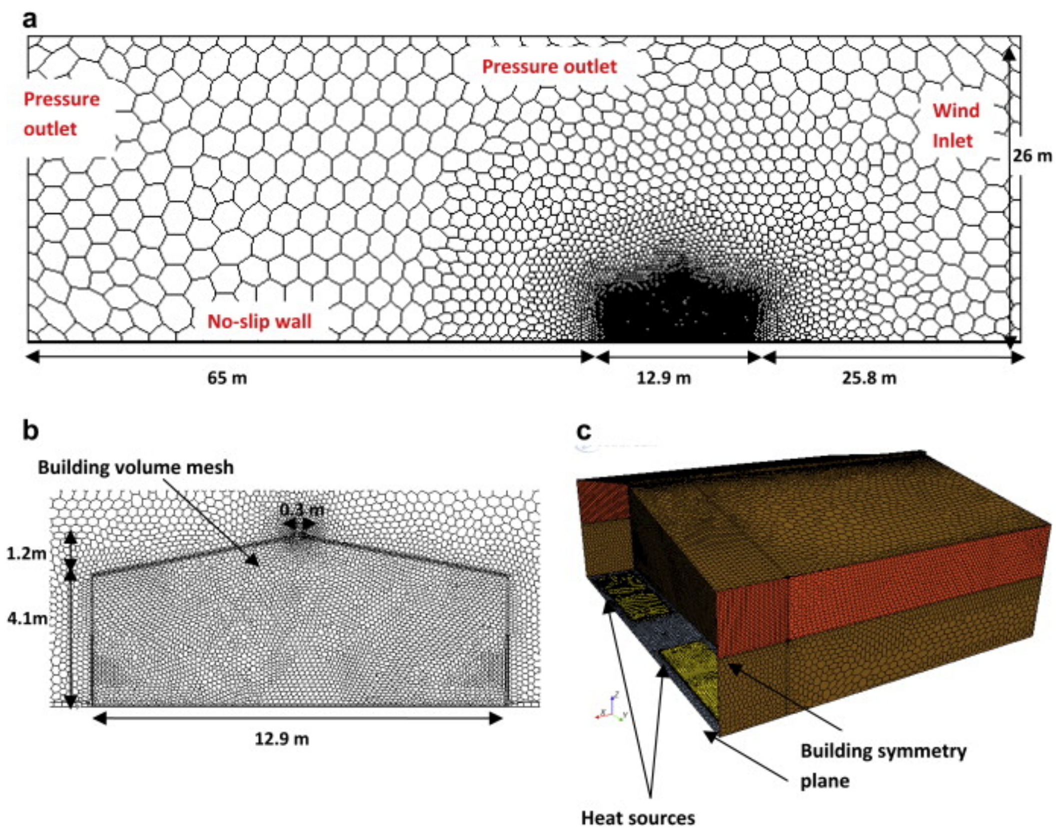
Take real geometry….

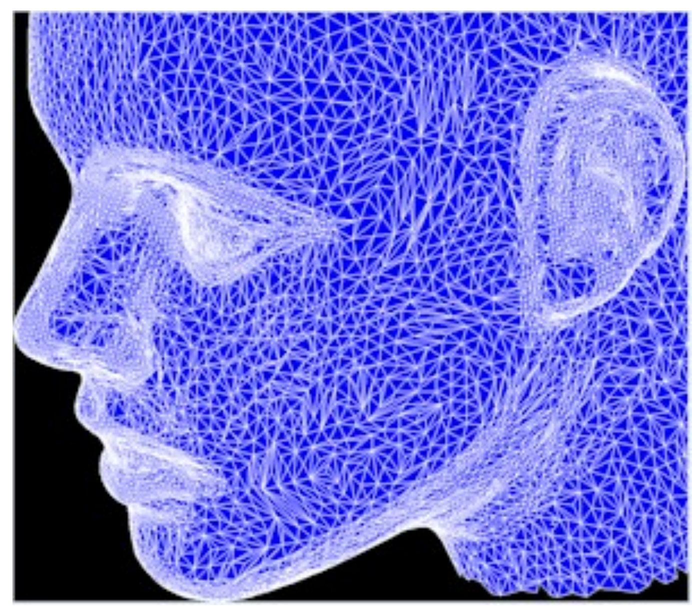
… and convert to model geometry



Images courtesy Atila Novoselac, UT-Austin

Defining a mesh

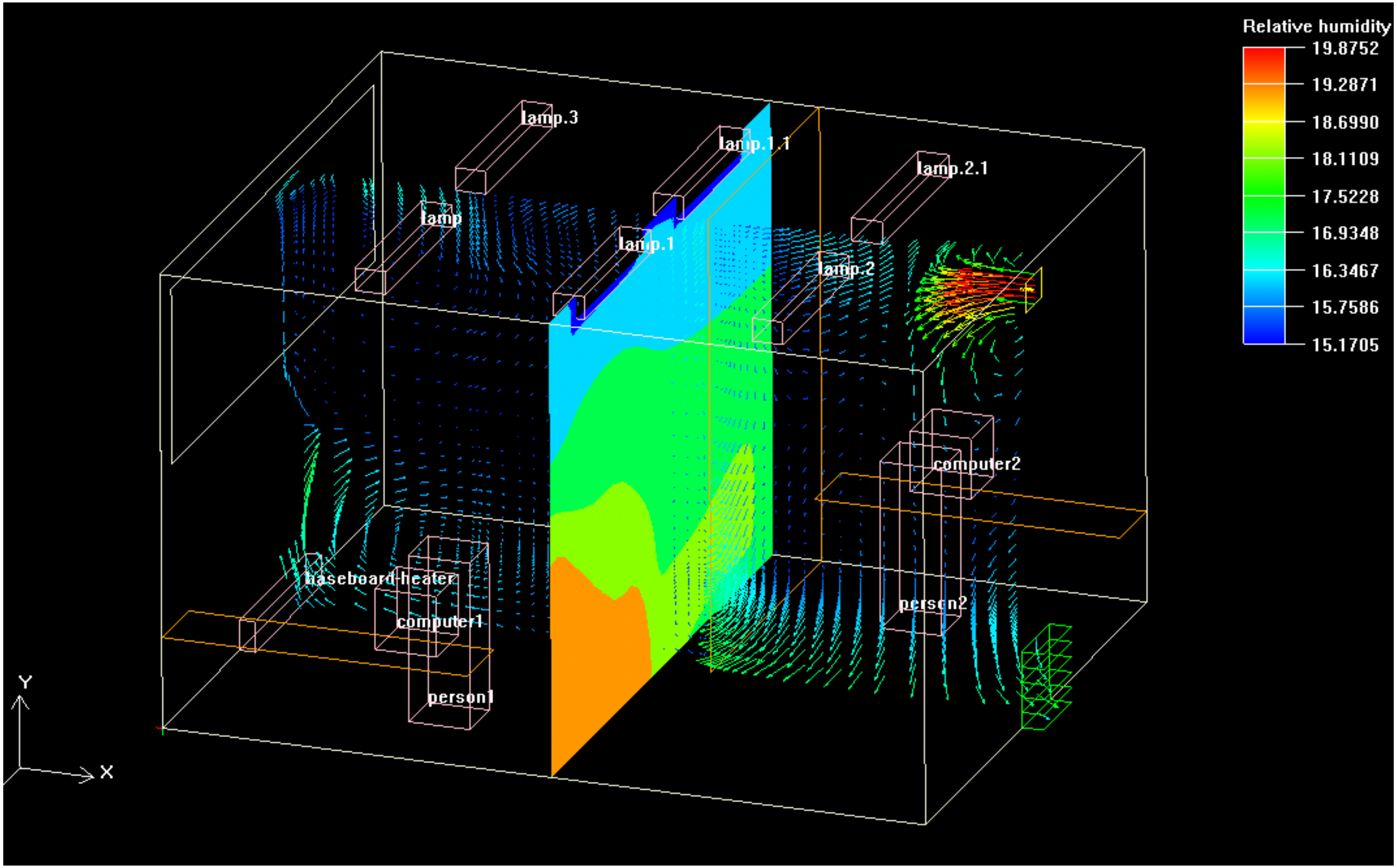




Peter V. Nielsen

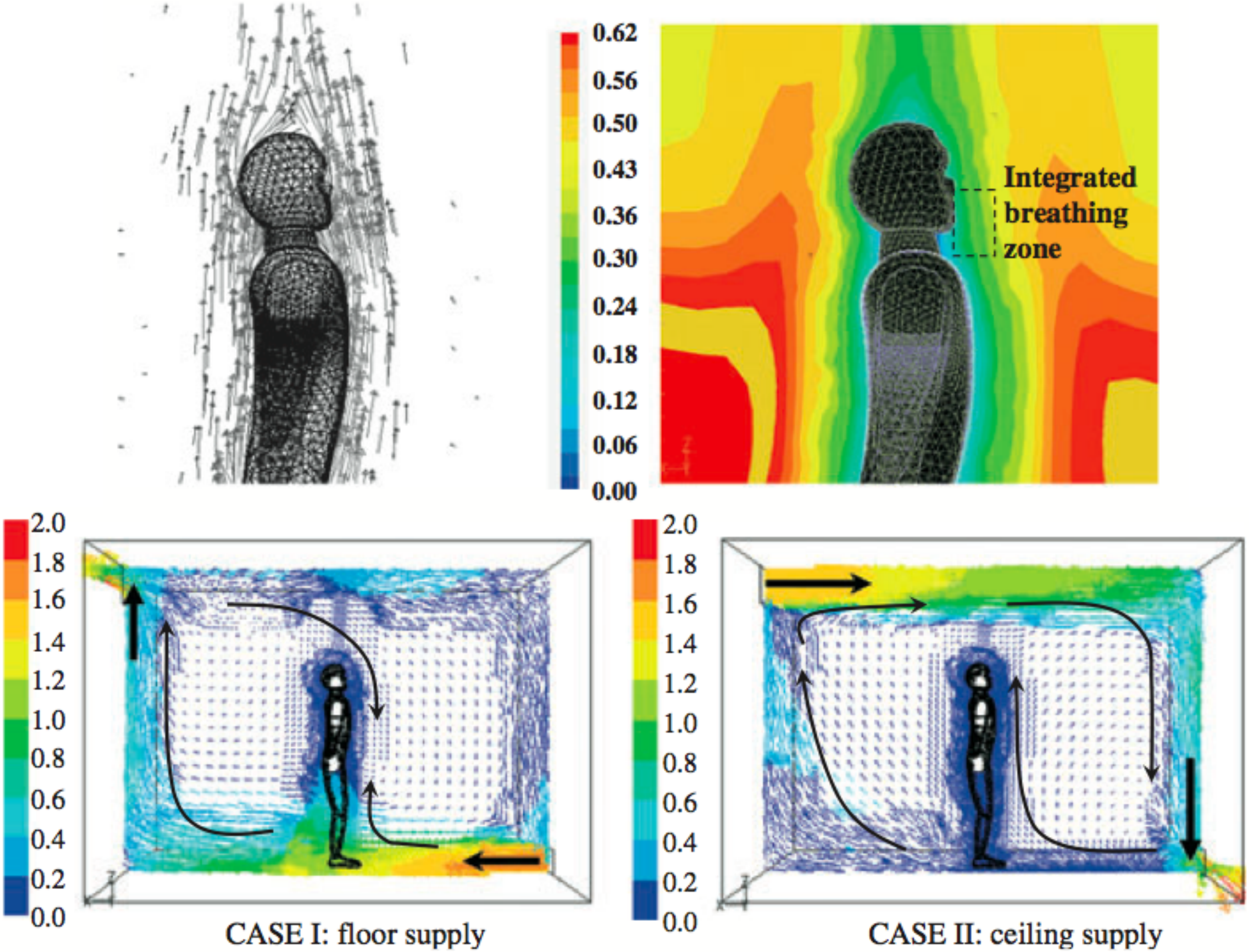
Images courtesy Atila Novoselac, UT-Austin

CFD outputs



Images courtesy Atila Novoselac, UT-Austin

CFD outputs



Rim et al. 2009 *Indoor Air*

CFD outputs

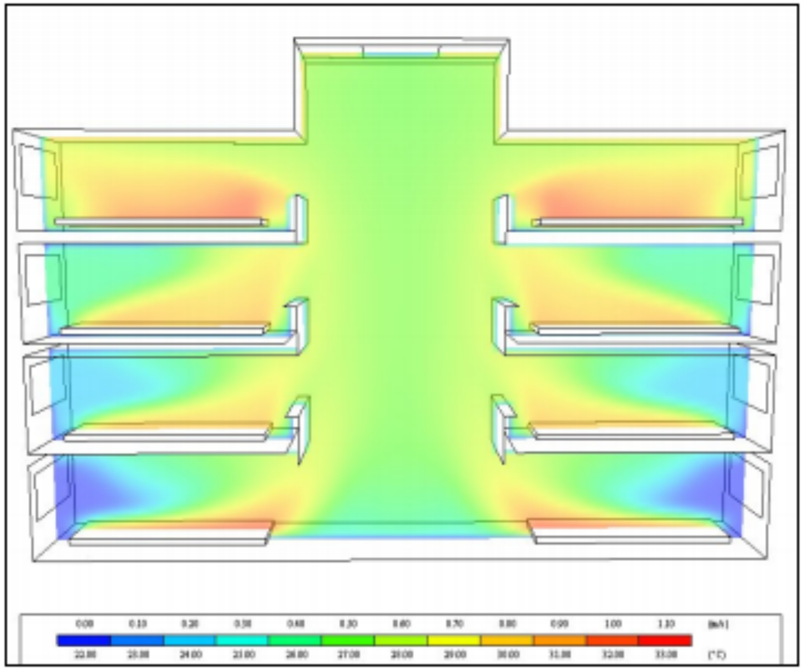


Figure 39: Temperature Contour Slice

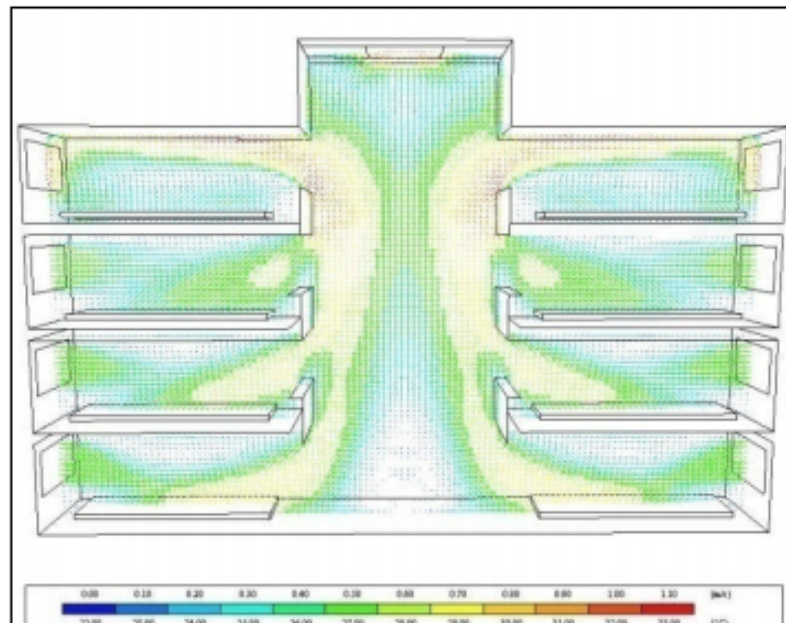


Figure 35: Velocity Vector Slice

CFD outputs

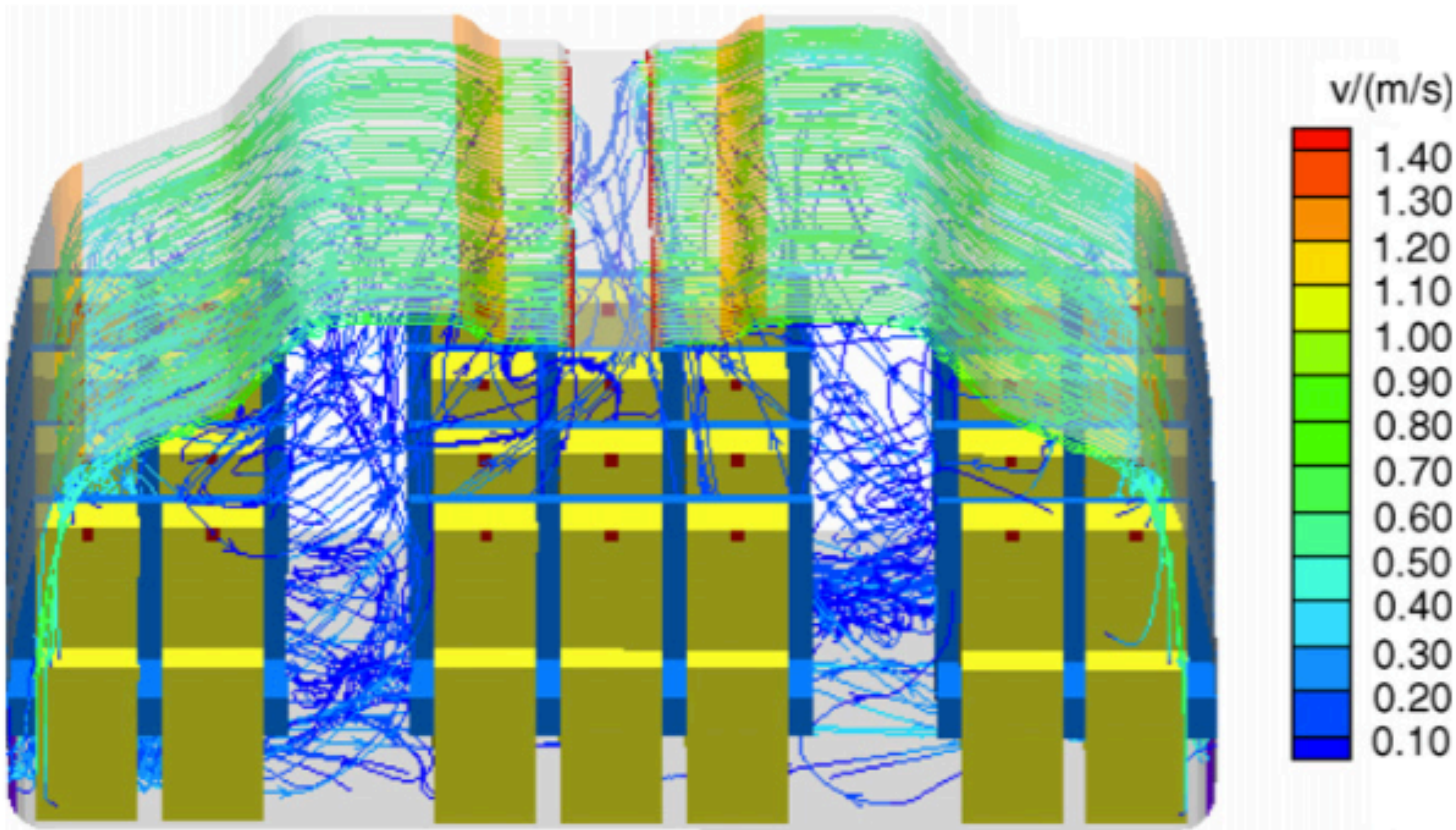


Fig. 7. Flow pathlines in the four-row cabin with the mixing air distribution.

Zhang and Chen 2007 *Building and Environment* 42:1675-1684

CFD outputs

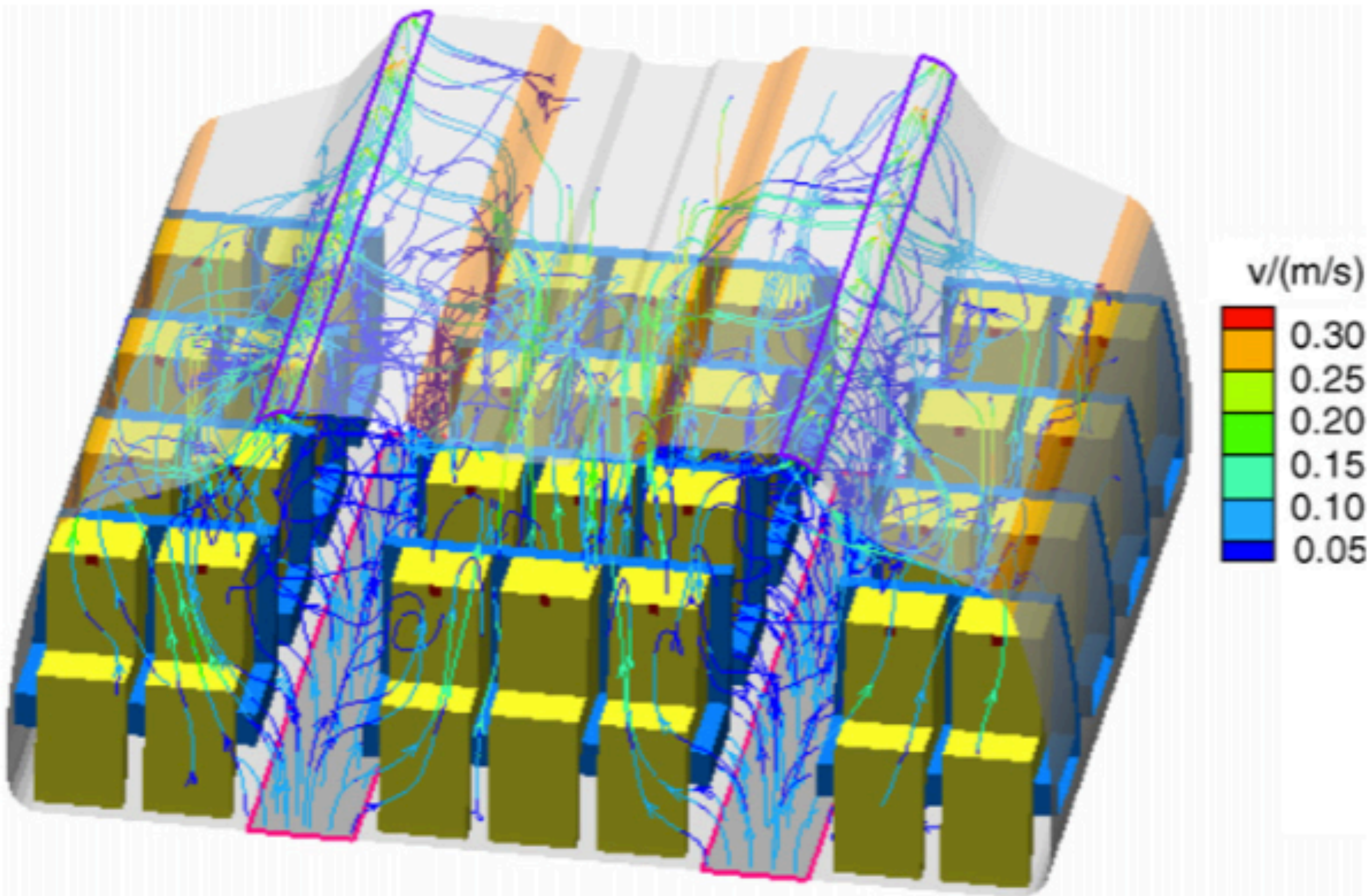
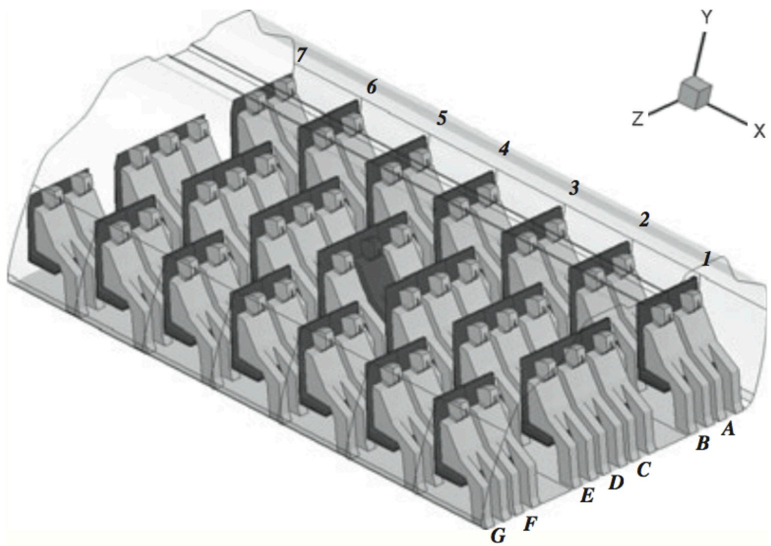
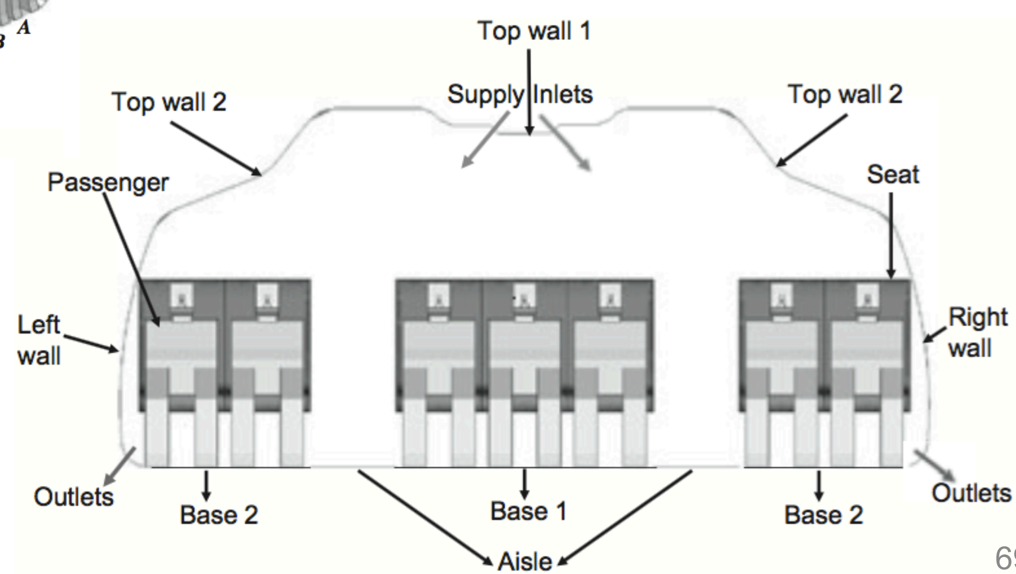


Fig. 8. Flow pathlines in the four-row cabin with the displacement air distribution.

Using CFD for research

Transport of expiratory droplets in an aircraft cabin



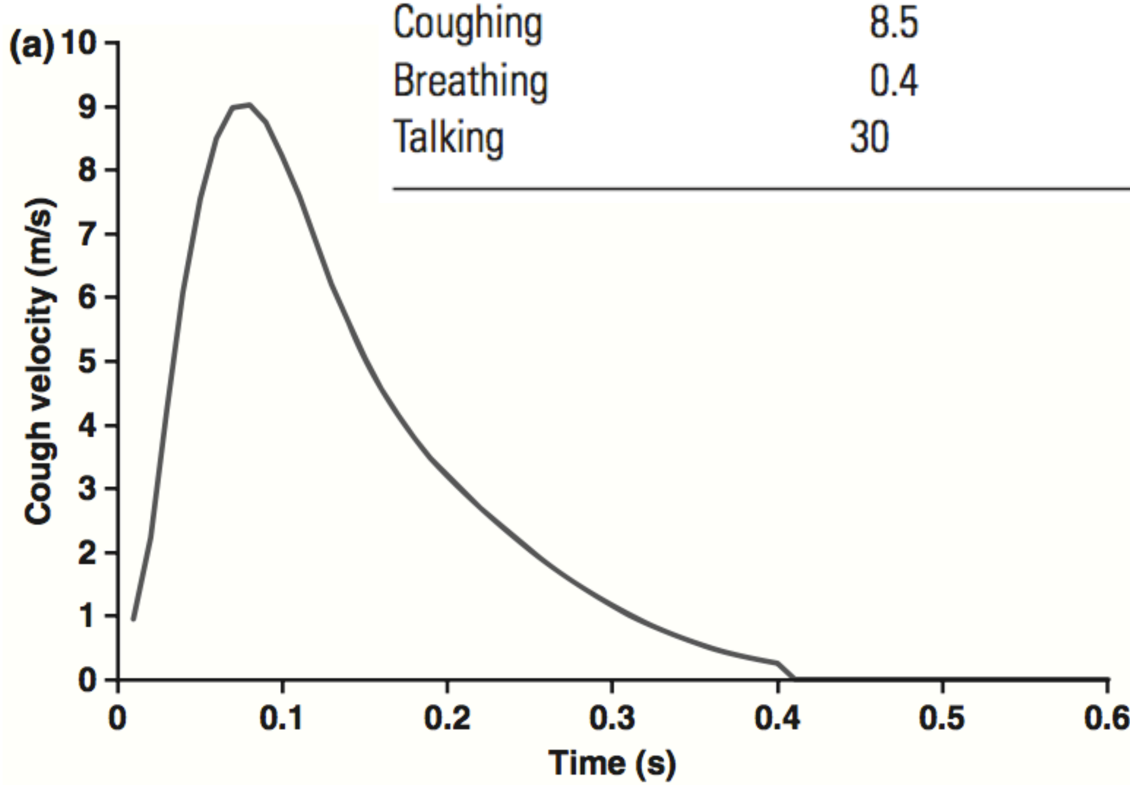


Gupta et al. 2011 *Indoor Air* 21:3-11

Using CFD for research

Transport of expiratory droplets in an aircraft cabin

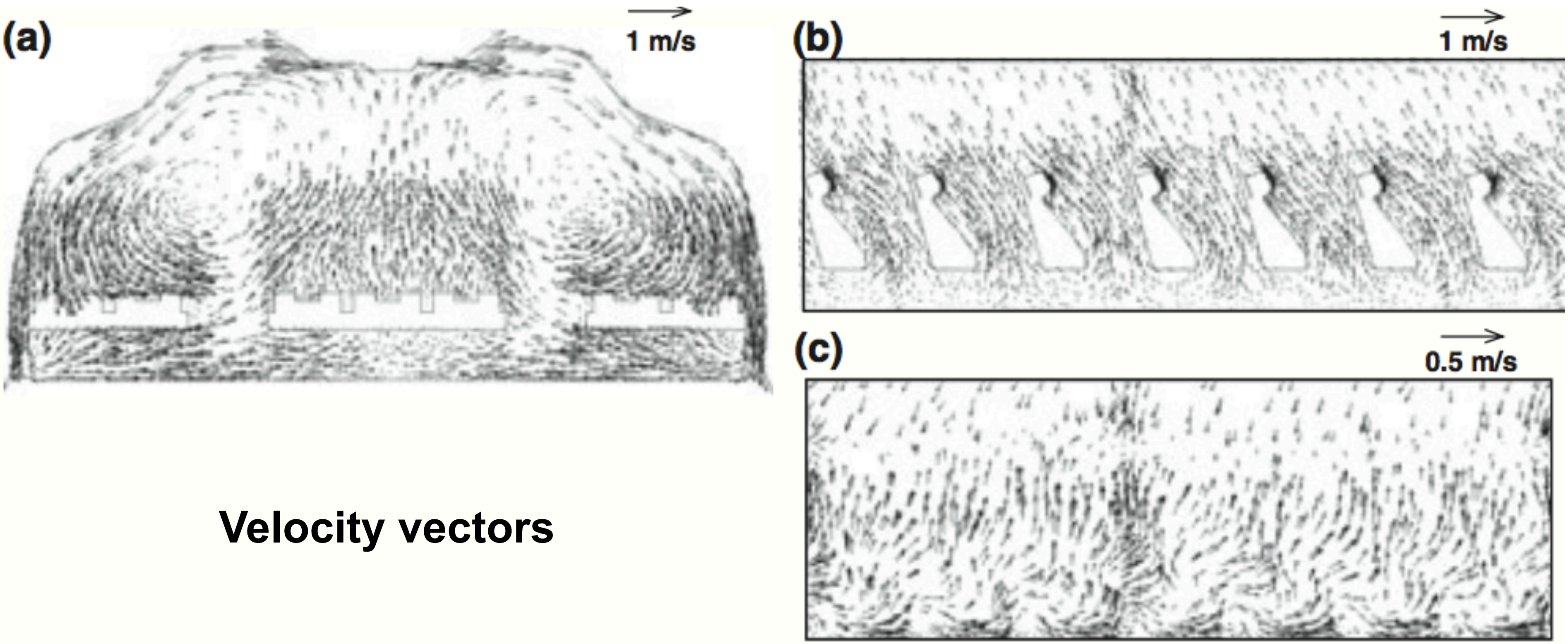
Exhalation	Droplet diameter (μm)	Number of droplets
Coughing	8.5	10^6 per cough
Breathing	0.4	525 per breath
Talking	30	2250 for 15 s of talk



Gupta et al. 2011 *Indoor Air* 21:3-11

Using CFD for research

Transport of expiratory droplets in an aircraft cabin



Velocity vectors

Gupta et al. 2011 *Indoor Air* 21:3-11

Using CFD for research

Transport of expiratory droplets in an aircraft cabin

Gupta et al. 2011 *Indoor Air* 21:3-11

Advantages and disadvantages of CFD

- Advantages
  - You can model complex phenomena in great detail
  - Easy to understand outputs

- Disadvantages
  - Time consuming and computationally intensive
  - Garbage in = garbage out
  - Solutions are limited merely to the specific environment and input conditions
    - It can be difficult to generalize results

- **At IIT, Professor Kevin Cassel teaches MMAE 517 CFD**

IAQ STANDARDS AND GUIDELINES

IAQ standards

- There are only a few indoor air quality standards in the US
- Primarily:
  - ASHRAE Standard 62.1
  - ASHRAE Standard 62.2
  - Well Building Standard
  - Various state and local governmental standards
    - Most just refer back to ASHRAE
  - For individual materials:
    - GREENGUARD certification for chemical emissions from building materials, finishes, and furnishings
    - GREENGUARD certification for chemical and particle emission from electronic equipment

- Secondarily (involves IAQ but not the entire focus):
  - USGBC's LEED for New Construction
  - USGBC's LEED for Homes

ASHRAE Standard 62.1-2010

ANSI/ASHRAE Standard 62.1-2010
(Supersedes ANSI/ASHRAE Standard 62.1-2007)
Includes ANSI/ASHRAE addenda listed in Appendix J

ASHRAE STANDARD

Ventilation for Acceptable Indoor Air Quality

1. PURPOSE

1.1 The purpose of this standard is to specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects.

1.2 This standard is intended for regulatory application to new buildings, additions to existing buildings, and those changes to existing buildings that are identified in the body of the standard.

1.3 This standard is intended to be used to guide the improvement of indoor air quality in existing buildings.

2. SCOPE

2.1 This standard applies to all spaces intended for human occupancy except those within single-family houses, multifamily structures of three stories or fewer above grade, vehicles, and aircraft.

2.2 This standard defines requirements for ventilation and air-cleaning system design, installation, commissioning, and operation and maintenance.

ASHRAE Standard 62.1-2010

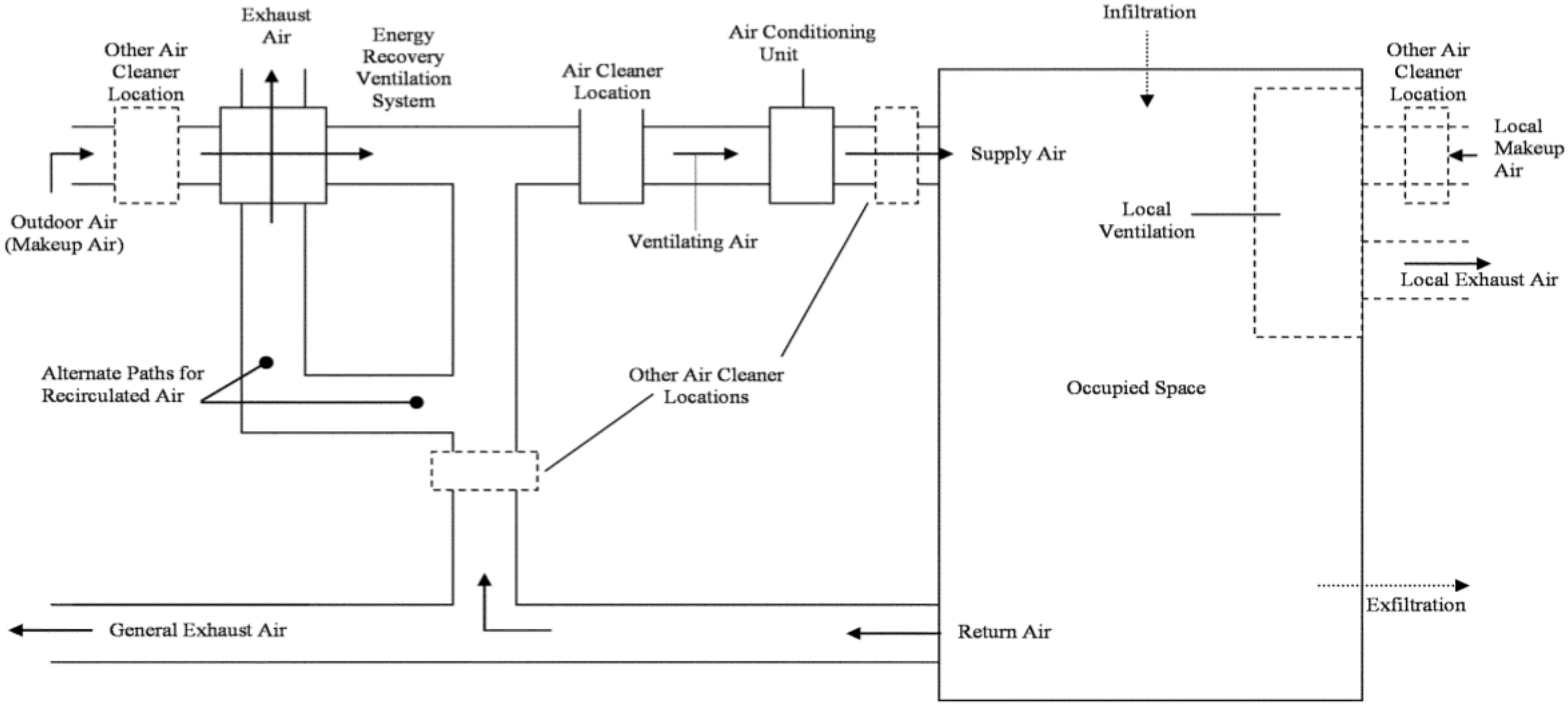


Figure 3.1 Ventilation system.

ASHRAE Standard 62.1-2010

TABLE 5-1 Air Intake Minimum Separation Distance

Object	Minimum Distance, ft (m)
Class 2 air exhaust/relief outlet (Note 1)	10 (3)
Class 3 air exhaust/relief outlet (Note 1)	15 (5)
Class 4 air exhaust/relief outlet (Note 2)	30 (10)
Plumbing vents terminating less than 3 ft (1 m) above the level of the outdoor air intake	10 (3)
Plumbing vents terminating at least 3 ft (1 m) above the level of the outdoor air intake	3 (1)
Vents, chimneys, and flues from combustion appliances and equipment (Note 3)	15 (5)
Garage entry, automobile loading area, or drive-in queue (Note 4)	15 (5)
Truck loading area or dock, bus parking/idling area (Note 4)	25 (7.5)
Driveway, street, or parking place (Note 4)	5 (1.5)
Thoroughfare with high traffic volume	25 (7.5)
Roof, landscaped grade, or other surface directly below intake (Notes 5 and 6)	1 (0.30)
Garbage storage/pick-up area, dumpsters	15 (5)
Cooling tower intake or basin	15 (5)
Cooling tower exhaust	25 (7.5)

ASHRAE Standard 62.1-2010

TABLE 5-2 Airstreams

Description	Air Class
Diazo printing equipment discharge	4
Commercial kitchen grease hoods	4
Commercial kitchen hoods other than grease	3
Laboratory hoods	4
Residential kitchen vented hoods	3
Hydraulic elevator machine room	2

- Class 1: Air with low contaminant concentration, low sensory-irritation intensity, and inoffensive odor.
- Class 2: Air with moderate contaminant concentration, mild sensory-irritation intensity, or mildly offensive odors. Class 2 air also includes air that is not necessarily harmful or objectionable but that is inappropriate for transfer or recirculation to spaces used for different purposes.
- Class 3: Air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.
- Class 4: Air with highly objectionable fumes or gases or with potentially dangerous particles, bioaerosols, or gases, at concentrations high enough to be considered harmful.

ASHRAE Standard 62.1-2010

Ventilation rate procedure

6.2.2.1 Breathing Zone Outdoor Airflow. The outdoor airflow required in the breathing zone of the occupiable space or spaces in a *ventilation zone*, i.e., the breathing zone outdoor airflow (V_{bz}), shall be no less than the value determined in accordance with Equation 6-1.

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \qquad (6\text{-}1)$$

where

A_z = zone floor area: the net occupiable floor area of the *ventilation zone* ft^2 (m^2)

P_z = zone population: the number of people in the *ventilation zone* during typical usage.

R_p = outdoor airflow rate required per person as determined from Table 6-1

Note: These values are based on adapted occupants.

R_a = outdoor airflow rate required per unit area as determined from Table 6-1

ASHRAE Standard 62.1-2010: VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft²	L/s·m²		#/1000 ft² or #/100 m²	cfm/person	L/s·person	
Correctional Facilities									
Cell	5	2.5	0.12	0.6		25	10	4.9	2
Dayroom	5	2.5	0.06	0.3		30	7	3.5	1
Guard stations	5	2.5	0.06	0.3		15	9	4.5	1
Booking/waiting	7.5	3.8	0.06	0.3		50	9	4.4	2
Educational Facilities									
Daycare (through age 4)	10	5	0.18	0.9		25	17	8.6	2
Daycare sickroom	10	5	0.18	0.9		25	17	8.6	3
Classrooms (ages 5–8)	10	5	0.12	0.6		25	15	7.4	1
Classrooms (age 9 plus)	10	5	0.12	0.6		35	13	6.7	1
Lecture classroom	7.5	3.8	0.06	0.3		65	8	4.3	1
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150	8	4.0	1
Art classroom	10	5	0.18	0.9		20	19	9.5	2
Science laboratories	10	5	0.18	0.9		25	17	8.6	2
University/college laboratories	10	5	0.18	0.9		25	17	8.6	2
Wood/metal shop	10	5	0.18	0.9		20	19	9.5	2
Computer lab	10	5	0.12	0.6		25	15	7.4	1

ASHRAE Standard 62.1-2010: VRP

TABLE 6-1 MINIMUM VENTILATION RATES IN BREATHING ZONE *(Continued)*
(This table is not valid in isolation; it must be used in conjunction with the accompanying notes.)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Notes	Default Values: Occupant Density (see Note 4)	Default Values: Combined Outdoor Air Rate (see Note 5)		Air Class
	cfm/person	L/s·person	cfm/ft^2	L/s·m^2		#/1000 ft^2 or #/100 m^2	cfm/person	L/s·person	
Office Buildings									
Breakrooms	5	2.5	0.12	0.6		50	7	3.5	1
Main entry lobbies	5	2.5	0.06	0.3		10	11	5.5	1
Occupiable storage rooms for dry materials	5	2.5	0.06	0.3		2	35	17.5	1
Office space	5	2.5	0.06	0.3		5	17	8.5	1
Reception areas	5	2.5	0.06	0.3		30	7	3.5	1
Telephone/data entry	5	2.5	0.06	0.3		60	6	3.0	1
Miscellaneous Spaces									
Bank vaults/safe deposit	5	2.5	0.06	0.3		5	17	8.5	2
Banks or bank lobbies	7.5	3.8	0.06	0.3		15	12	6.0	1
Computer (not printing)	5	2.5	0.06	0.3		4	20	10.0	1
General manufacturing (excludes heavy industrial and processes using chemicals)	10	5.0	0.18	0.9		7	36	18	3

ASHRAE Standard 62.1-2010: Required exhaust flows

TABLE 6-4 Minimum Exhaust Rates

Occupancy Category	Exhaust Rate, cfm/unit	Exhaust Rate, cfm/ft^2	Notes	Exhaust Rate, L/s·unit	Exhaust Rate, $L/s \cdot m^2$	Air Class
Arenas	–	0.50	B	–	–	1
Art classrooms	–	0.70		–	3.5	2
Auto repair rooms	–	1.50	A	–	7.5	2
Barber shops	–	0.50		–	2.5	2
Beauty and nail salons	–	0.60		–	3.0	2
Cells with toilet	–	1.00		–	5.0	2
Copy, printing rooms	–	0.50		–	2.5	2
Darkrooms	–	1.00		–	5.0	2
Educational science laboratories	–	1.00		–	5.0	2
Janitor closets, trash rooms, recycling	–	1.00		–	5.0	3
Kitchenettes	–	0.30		–	1.5	2
Kitchens—commercial	–	0.70		–	3.5	2
Locker/dressing rooms	–	0.25		–	1.25	2
Locker rooms	–	0.50		–	2.5	2
Paint spray booths	–	–	F	–	–	4
Parking garages	–	0.75	C	–	3.7	2
Pet shops (animal areas)	–	0.90		–	4.5	2
Refrigerating machinery rooms	–	–	F	–	–	3
Residential kitchens	50/100	–	G	25/50	–	2
Soiled laundry storage rooms	–	1.00	F	–	5.0	3
Storage rooms, chemical	–	1.50	F	–	7.5	4

ASHRAE Standard 62.2-2013 (actually showing 2007)

ANSI/ASHRAE Standard 62.2-2007
(Supersedes ANSI/ASHRAE Standard 62.2-2004)
Includes ANSI/ASHRAE addenda listed in Appendix C

ASHRAE STANDARD

Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings

1. PURPOSE

This standard defines the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality (IAQ) in low-rise residential buildings.

2. SCOPE

This standard applies to spaces intended for human occupancy within single-family houses and multifamily structures of three stories or fewer above grade, including manufactured and modular houses. This standard does not apply to transient housing such as hotels, motels, nursing homes, dormitories, or jails.

2.1 This standard considers chemical, physical, and biological contaminants that can affect air quality. Thermal comfort requirements are not included in this standard (see *ANSI/ASHRAE Standard 55-2004*, *Thermal Environmental Conditions for Human Occupancy*).

2.2 While acceptable indoor air quality is the goal of this standard, it will not necessarily be achieved even if all requirements are met

ASHRAE Standard 62.2-2010

4. WHOLE-BUILDING VENTILATION

4.1 Ventilation Rate. A mechanical exhaust system, supply system, or combination thereof shall be installed for each dwelling unit to provide whole-building ventilation with outdoor air each hour at no less than the rate specified in Tables 4.1a and 4.1b or, equivalently, Equations 4.1a and 4.1b, based on the floor area of the conditioned space and number of bedrooms.

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br} + 1) \quad (4.1a)$$

where

Q_{fan} = fan flow rate, cfm

A_{floor} = floor area, ft^2

N_{br} = number of bedrooms; not to be less than one

$$Q_{fan} = 0.05A_{floor} + 3.5(N_{br} + 1) \quad (4.1b)$$

where

Q_{fan} = fan flow rate, L/s

A_{floor} = floor area, m^2

N_{br} = number of bedrooms; not to be less than one

TABLE 4.1a (I-P)
Ventilation Air Requirements, cfm

Floor Area (ft^2)	Bedrooms				
	0–1	2–3	4–5	6–7	>7
<1500	30	45	60	75	90
1501–3000	45	60	75	90	105
3001–4500	60	75	90	105	120
4501–6000	75	90	105	120	135
6001–7500	90	105	120	135	150
>7500	105	120	135	150	165

TABLE 4.1b (SI)
Ventilation Air Requirements, L/s

Floor Area (m^2)	Bedrooms				
	0–1	2–3	4–5	6–7	>7
<139	14	21	28	35	42
139.1–279	21	28	35	42	50
279.1–418	28	35	42	50	57
418.1–557	35	42	50	57	64
557.1–697	42	50	57	64	71
>697	50	57	64	71	78

ASHRAE Standard 62.2-2010

Exceptions: Whole-building mechanical systems are not required provided that at least one of the following conditions is met:

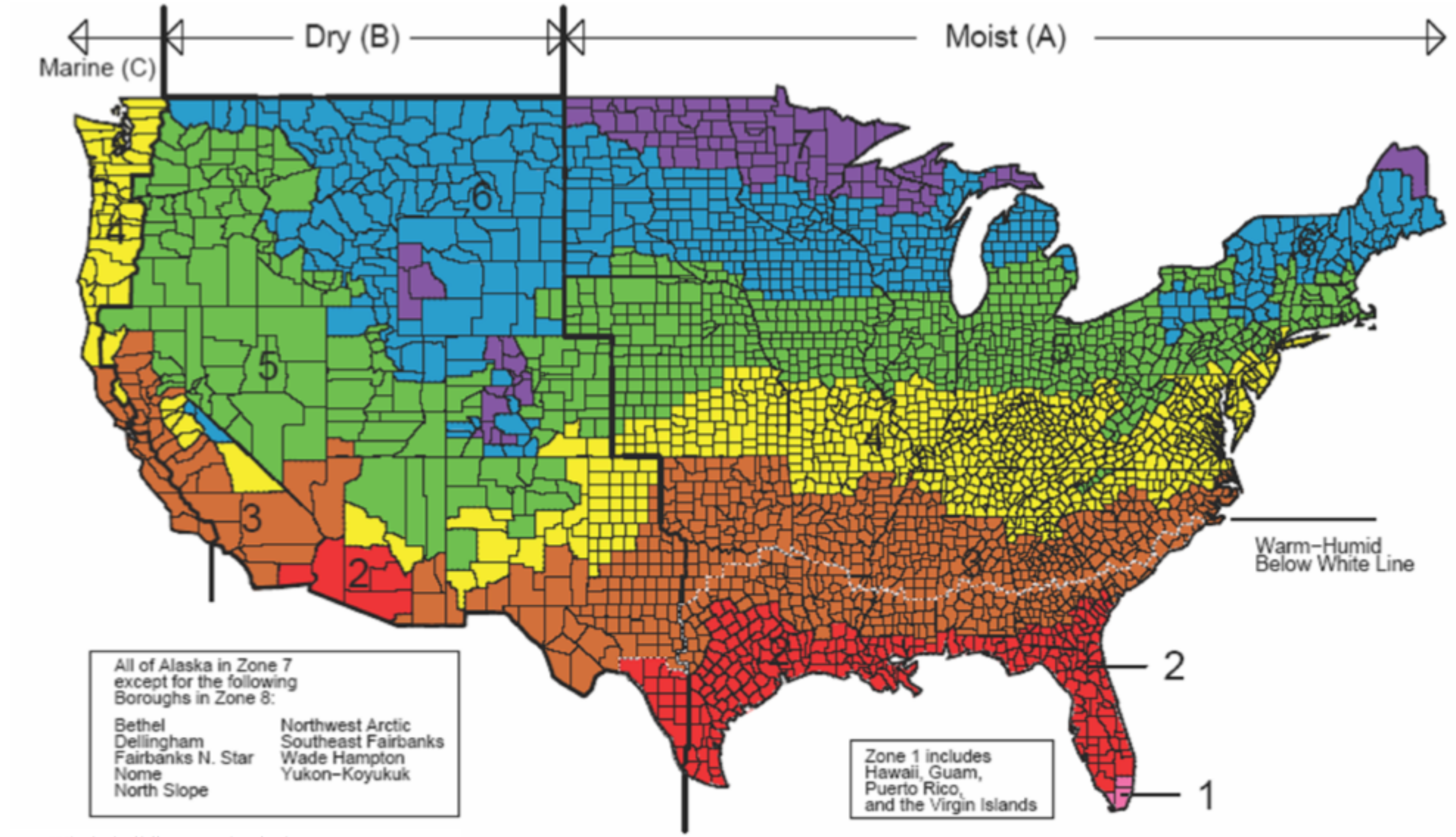
a. the building is in zone 3B or 3C of the IECC 2004 Climate Zone Map (see Figure 8.2),

b. the building has no mechanical cooling and is in zone 1 or 2 of the IECC 2004 Climate Zone Map (see Figure 8.2), or

c. the building is thermally conditioned for human occupancy for less than 876 hours per year,

and if the authority having jurisdiction determines that window operation is a locally permissible method of providing ventilation.

ASHRAE Standard 62.2-2010



Exceptions: Whole-building mechanical systems are not required provided that at least one of the following conditions is met:

a. the building is in zone 3B or 3C of the IECC 2004 Climate Zone Map (see Figure 8.2),

b. the building has no mechanical cooling and is in zone 1 or 2 of the IECC 2004 Climate Zone Map (see Figure 8.2), or

ASHRAE Standard 62.2-2010

4.4 Delivered Ventilation. The delivered ventilation rate shall be calculated as the larger of the total supply or total exhaust and shall be no less than specified in Section 4.1 during each hour of operation.

Exception: The effective ventilation rate of an intermittent system is the combination of its delivered capacity, its daily fractional on-time, and the ventilation effectiveness from Table 4.2.

$$Q_f = Q_r / (\varepsilon f) \qquad (4.2)$$

where

Q_f = fan flow rate

Q_r = ventilation air requirement (from Table 4.1a or 4.1b)

ε = ventilation effectiveness (from Table 4.2)

f = fractional on time

TABLE 4.2
Ventilation Effectiveness for Intermittent Fans

Daily Fractional On-Time, f	Ventilation Effectiveness, ε
$f \le 35\%$	0.33
$35\% \le f < 60\%$	0.50
$60\% \le f < 80\%$	0.75
$80\% \le f$	1.0

ASHRAE Standard 62.2-2010

5. LOCAL EXHAUST

5.1 Local Mechanical Exhaust. A local mechanical exhaust system shall be installed in each kitchen and bathroom. Each local ventilation system shall be either one of the following two:

1. an intermittent mechanical exhaust system meeting the requirements of Section 5.2 or
2. a continuous mechanical exhaust system meeting the requirements of Section 5.3.

Exception: *Alternative Ventilation.* Other design methods may be used to provide the required exhaust rates when approved by a licensed design professional.

TABLE 5.2
Continuous Local Ventilation Exhaust Airflow Rates

Application	Airflow	Notes
Kitchen	5 ach	Based on kitchen volume.
Bathroom	20 cfm (10 L/s)	

TABLE 5.1 Intermittent Local Ventilation Exhaust Airflow Rates

Application	Airflow	Notes
Kitchen	100 cfm (50 L/s)	Vented range hood (including appliance-range hood combinations) required if exhaust fan flow rate is less than 5 kitchen ach.
Bathroom	50 cfm (25 L/s)	

ASHRAE Standard 62.2-2010

6.5 Garages. When an occupiable space adjoins a garage, the design must prevent migration of contaminants to the adjoining occupiable space. Doors between garages and occupiable spaces shall be gasketed or made substantially airtight with weather stripping. HVAC systems that include air handlers or return ducts located in garages shall have total air leakage of no more than 6% of total fan flow when measured at 0.1 in. w.c. (25 Pa) using California Title 24[5] or equivalent.

6.3 Clothes Dryers. Clothes dryers shall be exhausted directly to the outdoors.

6.7 Minimum Filtration. Mechanical systems that supply air to an occupiable space through ductwork exceeding 10 ft (3 m) in length and through a thermal conditioning component, except evaporative coolers, shall be provided with a filter having a designated minimum efficiency of MERV 6 or better when tested in accordance with *ANSI/ASHRAE Standard 52.2, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.*[6] The system shall be designed such that all recirculated and mechanically supplied outdoor air is filtered before passing through the thermal conditioning components. The filter shall be located and installed in such a manner as to facilitate access and regular service by the owner. The filter shall be selected and sized to operate at a clean pressure drop no greater than 0.1 in. w.c. (25 Pa) unless the equipment is designed or selected to accommodate any additional pressure drop imposed by the filter selection (i.e., greater than 0.1 in. w.c. [25 Pa]).

Green building rating systems and IAQ/IEQ

LEED 2009 FOR NEW CONSTRUCTION AND MAJOR RENOVATIONS

System of 110 possible points;

- Site (26)
- Water (10)
- Energy and atmosphere (35)
- Materials and resources (14)
- Indoor environmental quality (15)
- Innovation in design (6)
- Regional priorities (4)

15/110 = 14% related to IEQ

LEED® for Homes Rating System

System of 136 possible points;

- Innovation and design (11)
- Location and linkages (10)
- Sustainable sites (22)
- Water efficiency (15)
- Energy and atmosphere (38)
- Materials and resources (16)
- Indoor environmental quality (21)
- Awareness and education (3)

21/136 = 15% related to IEQ

LEED-NC 2009: IEQ

Indoor Environmental Quality		15 Possible Points
☑ Prerequisite 1	Minimum Indoor Air Quality Performance	Required
☑ Prerequisite 2	Environmental Tobacco Smoke (ETS) Control	Required
☐ Credit 1	Outdoor Air Delivery Monitoring	1
☐ Credit 2	Increased Ventilation	1
☐ Credit 3.1	Construction Indoor Air Quality Management Plan—During Construction	1
☐ Credit 3.2	Construction Indoor Air Quality Management Plan—Before Occupancy	1
☐ Credit 4.1	Low-Emitting Materials—Adhesives and Sealants	1
☐ Credit 4.2	Low-Emitting Materials—Paints and Coatings	1
☐ Credit 4.3	Low-Emitting Materials—Flooring Systems	1
☐ Credit 4.4	Low-Emitting Materials—Composite Wood and Agrifiber Products	1
☐ Credit 5	Indoor Chemical and Pollutant Source Control	1
☐ Credit 6.1	Controllability of Systems—Lighting	1
☐ Credit 6.2	Controllability of Systems—Thermal Comfort	1
☐ Credit 7.1	Thermal Comfort—Design	1
☐ Credit 7.2	Thermal Comfort—Verification	1
☐ Credit 8.1	Daylight and Views—Daylight	1
☐ Credit 8.2	Daylight and Views—Views	1

LEED-NC 2009: IEQ

INDOOR ENVIRONMENTAL QUALITY

IEQ Prerequisite 1: Minimum Indoor Air Quality Performance

Required

Intent

To establish minimum indoor air quality (IAQ) performance to enhance indoor air quality in buildings, thus contributing to the comfort and well-being of the occupants.

Requirements

CASE 1. Mechanically Ventilated Spaces

Mechanical ventilation systems must be designed using the ventilation rate procedure as defined by ASHRAE 62.1-2007, or the applicable local code, whichever is more stringent.

OPTION 1. ASHRAE Standard 62.1-2007 or Non-U.S. Equivalent

Meet the minimum requirements of Sections 4 through 7 of ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality (with errata but without addenda). Projects outside the U.S. may use a local equivalent to Sections 4 through 7 of ASHRAE Standard 62.1-2007.

LEEDD-NC 2009: IEQ

IEQ Prerequisite 2: Environmental Tobacco Smoke (ETS) Control

Required

Intent

To prevent or minimize exposure of building occupants, indoor surfaces and ventilation air distribution systems to environmental tobacco smoke (ETS).

Requirements

OPTION 1

Prohibit smoking in the building.

Prohibit on-property smoking within 25 feet (8 meters) of entries, outdoor air intakes and operable windows. Provide signage to allow smoking in designated areas, prohibit smoking in designated areas or prohibit smoking on the entire property.

LEED-NC 2009: IEQ

IEQ Credit 1: Outdoor Air Delivery Monitoring

1 Point

Intent

To provide capacity for ventilation system monitoring to help promote occupant comfort and well-being.

Requirements

Install permanent monitoring systems to ensure that ventilation systems maintain design minimum requirements. Configure all monitoring equipment to generate an alarm when airflow values or carbon dioxide (CO_2) levels vary by 10% or more from the design values via either a building automation system alarm to the building operator or a visual or audible alert to the building occupants

AND

CASE 1. Mechanically Ventilated Spaces

Monitor CO_2 concentrations within all densely occupied spaces i.e., those with a design occupant density of 25 people or more per 1,000 square feet (95 square meters). CO_2 monitors must be between 3 and 6 feet (between 1 and 2 meters) above the floor.

Provide a direct outdoor airflow measurement device capable of measuring the minimum outdoor air intake flow with an accuracy of plus or minus 15% of the design minimum outdoor air rate, based on the value determined in IEQ Prerequisite 1: Minimum Indoor Air Quality Performance, for mechanical ventilation systems where 20% or more of the design supply airflow serves nondensely occupied spaces.

LEED-NC 2009: IEQ

IEQ Credit 2: Increased Ventilation

1 Point

Intent

To provide additional outdoor air ventilation to improve indoor air quality (IAQ) and promote occupant comfort, well-being and productivity.

Requirements

CASE 1. Mechanically Ventilated Spaces

OPTION 1. ASHRAE Standard 62.1-2007 or Non-U.S. Equivalent

Increase breathing zone outdoor air ventilation rates to all occupied spaces by at least 30% above the minimum rates required by ASHRAE Standard 62.1-2007 (with errata but without addenda[1]) as determined by IEQ Prerequisite 1: Minimum Indoor Air Quality Performance. Projects outside the U.S. may use a local equivalent to ASHRAE Standard 62.1-2007 if the same is used for IEQ Prerequisite 1: Minimum Indoor Air Quality Performance.

LEED-NC 2009: IEQ

IEQ Credit 3.1: Construction Indoor Air Quality Management Plan—During Construction

1 Point

Intent

To reduce indoor air quality (IAQ) problems resulting from construction or renovation and promote the comfort and well-being of construction workers and building occupants.

Requirements

Develop and implement an IAQ management plan for the construction and preoccupancy phases of the building as follows:

- During construction, meet or exceed the recommended control measures of the Sheet Metal and Air Conditioning National Contractors Association (SMACNA) IAQ Guidelines For Occupied Buildings Under Construction, 2nd Edition 2007, ANSI/SMACNA 008-2008 (Chapter 3).
- Protect stored on-site and installed absorptive materials from moisture damage.
- If permanently installed air handlers are used during construction, filtration media must be used at each return air grille that meets one of the following criteria below. Replace all filtration media immediately prior to occupancy.
  - Filtration media with a Minimum Efficiency Reporting Value (MERV) of 8 as determined by ASHRAE Standard 52.2-1999 (with errata but without addenda).
  - Filtration media is Class F5 or higher, as defined by CEN Standard EN 779-2002, Particulate air filters for general ventilation, Determination of the filtration performance.
  - Filtration media with a minimum dust spot efficiency of 30% or higher and greater than 90% arrestance on a particle size of 3–10 µg.

LEED-NC 2009: IEQ

IEQ Credit 3.2: Construction Indoor Air Quality Management Plan—Before Occupancy

1 Point

Intent

To reduce indoor air quality (IAQ) problems resulting from construction or renovation to promote the comfort and well-being of construction workers and building occupants.

Requirements

Develop an IAQ management plan and implement it after all finishes have been installed and the building has been completely cleaned before occupancy.

OPTION 1. Flush-Out[1]

PATH 1

After construction ends, prior to occupancy and with all interior finishes installed, install new filtration media and , perform a building flush-out by supplying a total air volume of 14,000 cubic feet of outdoor air per square foot (4,500 cubic meters of outdoor air per square meter) of floor area while maintaining an internal temperature of at least 60° F (15°C) and relative humidity no higher than 60%.

OPTION 2. Air Testing

Conduct baseline IAQ testing after construction ends and prior to occupancy using testing protocols consistent
with the EPA Co
listed in the tabl
requirements fr

Demonstrate that the contaminant maximum concentration levels listed below are not exceeded:

Contaminant	Maximum Concentration	EPA Compendium method	ISO method
Formaldehyde	27 parts per billion	IP-6	ISO 16000-3
Particulates (PM10)	50 micrograms per cubic meter	IP-10	ISO 7708
Total volatile organic compounds (TVOCs)	500 micrograms per cubic meter	IP-1	ISO 16000-6
4-Phenylcyclohexene (4-PCH)*	6.5 micrograms per cubic meter	IP-1	ISO 16000-6
Carbon monoxide (CO)	9 part per million and no greater than 2 parts per million above outdoor levels	IP-3	ISO 4224

* This test is only required if carpets and fabrics with styrene butadiene rubber (SBR) latex backing are installed as part of the base building systems.

LEED-NC 2009: IEQ

IEQ Credit 4.1: Low-Emitting Materials—Adhesives and Sealants

1 Point

Intent

To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.

Requirements

All adhesives and sealants used on the interior of the building (i.e., inside of the weatherproofing system and applied on-site) must comply with the following requirements as applicable to the project scope[1]:

- Adhesives, Sealants and Sealant Primers must comply with South Coast Air Quality Management District (SCAQMD) Rule #1168. Volatile organic compound (VOC) limits listed in the table below correspond to an effective date of July 1, 2005 and rule amendment date of January 7, 2005.

Architectural Applications	VOC Limit (g/L less water)	Specialty Applications	VOC Limit (g/L less water)
Indoor carpet adhesives	50	PVC welding	510
Carpet pad adhesives	50	CPVC welding	490
Wood flooring adhesives	100	ABS welding	325
Rubber floor adhesives	60	Plastic cement welding	250
Subfloor adhesives	50	Adhesive primer for plastic	550
Ceramic tile adhesives	65	Contact adhesive	80
VCT and asphalt adhesives	50	Special purpose contact adhesive	250
Drywall and panel adhesives	50	Structural wood member adhesive	140
Cove base adhesives	50	Sheet applied rubber lining operations	850
Multipurpose construction adhesives	70	Top and trim adhesive	250
Structural glazing adhesives	100		

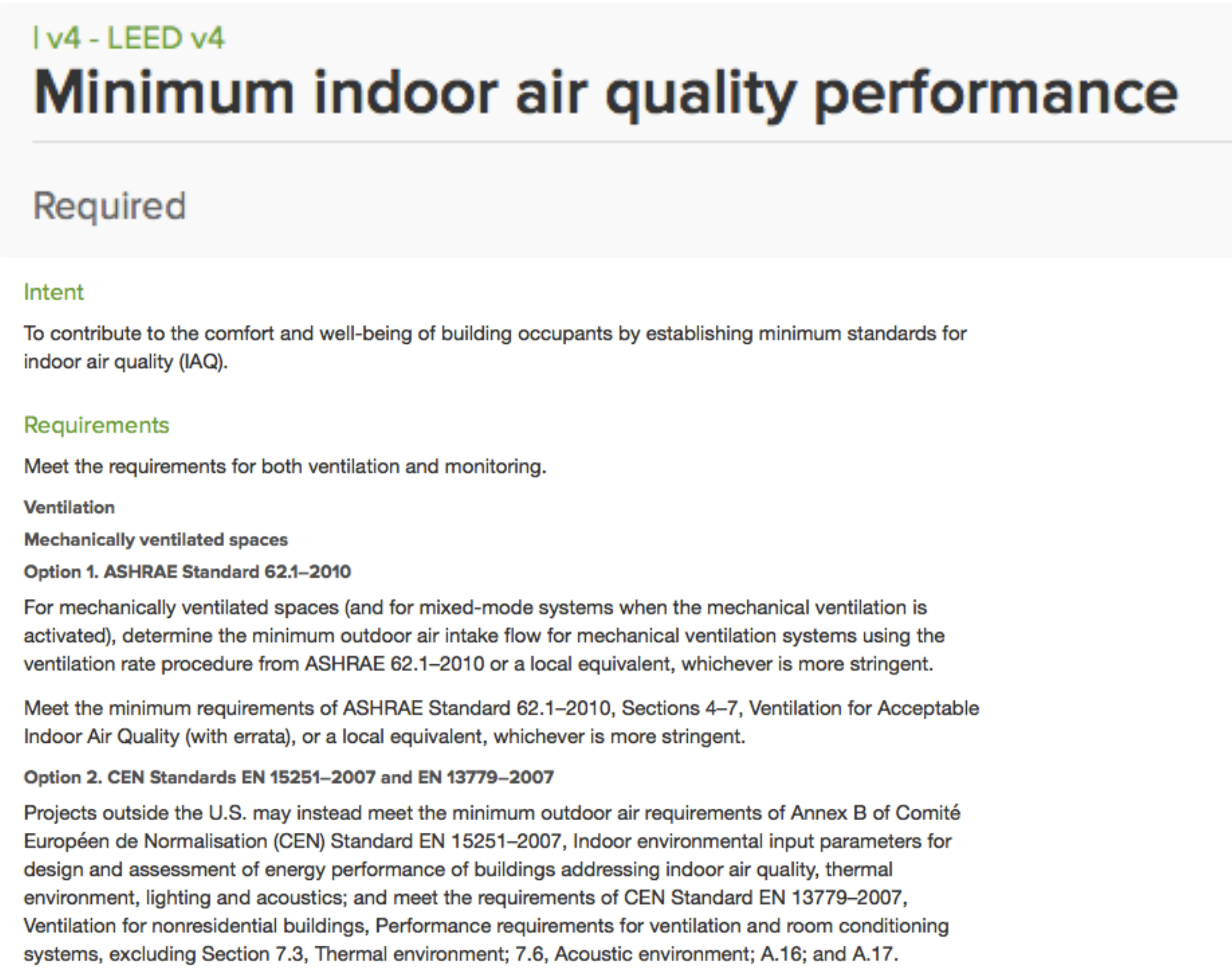
IEQ Credit 4.2: Low-Emitting Materials—Paints and Coatings

1 Point

IEQ Credit 4.3: Low-Emitting Materials—Flooring Systems

1 Point

LEED v4: IEQ



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LEED v4: IEQ

LEED BD+C: Schools | v4 - LEED v4

Indoor air quality assessment

Possible 2 points

Requirements

Select one of the following two options, to be implemented after construction ends and the building has been completely cleaned. All interior finishes, such as millwork, doors, paint, carpet, acoustic tiles, and movable furnishings (e.g., workstations, partitions), must be installed, and major VOC punch list items must be finished. The options cannot be combined.

Option 1. Flush-out (1 point)

Path 1. Before occupancy

Install new filtration media and perform a building flush-out by supplying a total air volume of 14,000 cubic feet of outdoor air per square foot (4 267 140 liters of outdoor air per square meter) of gross floor area while maintaining an internal temperature of at least 60°F (15°C) and no higher than 80°F (27°C) and relative humidity no higher than 60%.

OR

Path 2. During occupancy

If occupancy is desired before the flush-out is completed, the space may be occupied only after delivery of a minimum of 3,500 cubic feet of outdoor air per square foot (1 066 260 liters of outdoor air per square meter) of gross floor area while maintaining an internal temperature of at least 60°F (15°C) and no higher than 80°F (27°C) and relative humidity no higher than 60%.

Once the space is occupied, it must be ventilated at a minimum rate of 0.30 cubic foot per minute (cfm) per square foot of outdoor air (1.5 liters per second per square meter of outdoor air) or the design minimum outdoor air rate determined in EQ Prerequisite Minimum Indoor Air Quality Performance, whichever is greater. During each day of the flush-out period, ventilation must begin at least three hours before occupancy and continue during occupancy. These conditions must be maintained until a total of 14,000 cubic feet per square foot of outdoor air (4 270 liters of outdoor air per square meter) has been delivered to the space.

OR

Option 2. Air testing (2 points)

After construction ends and before occupancy, but under ventilation conditions typical for occupancy, conduct baseline IAQ testing using protocols consistent with the methods listed in Table 1 for all occupied

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LEED v4: IEQ

Contaminant			Maximum concentration	ASTM and U.S. EPA methods	ISO method
Particulates	**PM10** (for all buildings)		50 µg/m^3 Healthcare only: 20 µg/m^3	EPA Compendium Method IP-10	ISO 7708
	PM2.5 (for buildings in EPA nonattainment areas for PM2.5, or local equivalent)		15 µg/m^3		
Ozone (for buildings in EPA nonattainment areas for Ozone, or local equivalent)			0.075 ppm	ASTM D5149 - 02	ISO 13964
Carbon monoxide (CO)			9 ppm; no more than 2 ppm above outdoor levels	EPA Compendium Method IP-3	ISO 4224
Total volatile organic compounds (TVOCs)			500 µg/m^3 Healthcare only: 200 µg/m^3	EPA TO-1, TO-17, or EPA Compendium Method IP-1	ISO 16000-6
Formaldehyde			27 ppb Healthcare only: 16.3 ppb	ASTM D5197, EPA TO-11, or EPA Compendium Method IP-6	ISO 16000-3
Target volatile organic compounds*	1	Acetaldehyde	140 µg/m^3		
	2	Benzene	3 µg/m^3	ASTM D5197; EPA TO-1, TO-17, or EPA Compendium Method IP-1	ISO 16000-3, ISO 16000-6
	3	Carbon disulfide	800 µg/m^3		
	4	Carbon tetrachloride	40 µg/m^3		
	5	Chlorobenzene	1000 µg/m^3		
	6	Chloroform	300 µg/m^3		
	7	Dichlorobenzene (1,4-)	800µg/m^3		
	8	Dichloroethylene (1,1)	70 µg/m^3		
	9	Dimethylformamide (N,N-)	80 µg/m^3		
	10	Dioxane (1,4-)	3000 µg/m^3		
	11	Epichlorohydrin	3 µg/m^3		
	12	Ethylbenzene	2000 µg/m^3		

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LEED for Homes 2008: IEQ

Indoor Environmental Quality (EQ) (Minimum of 6 EQ Points Required)				OR		Y / Pts	No	Maybe
1. ENERGY STAR with IAP		1	ENERGY STAR with Indoor Air Package		13			
2. Combustion Venting		2.1	Basic Combustion Venting Measures	**EQ 1**	Prerequisite			
		2.2	Enhanced Combustion Venting Measures	**EQ 1**	2			
3. Moisture Control		3	Moisture Load Control	**EQ 1**	1			
4. Outdoor Air Ventilation	✍	4.1	Basic Outdoor Air Ventilation	**EQ 1**	Prerequisite			
		4.2	Enhanced Outdoor Air Ventilation		2			
		4.3	Third-Party Performance Testing	**EQ 1**	1			
5. Local Exhaust	✍	5.1	Basic Local Exhaust	**EQ 1**	Prerequisite			
		5.2	Enhanced Local Exhaust		1			
		5.3	Third-Party Performance Testing		1			
6. Distribution of Space Heating and Cooling	✍	6.1	Room-by-Room Load Calculations	**EQ 1**	Prerequisite			
		6.2	Return Air Flow / Room by Room Controls	**EQ 1**	1			
		6.3	Third-Party Performance Test / Multiple Zones	**EQ 1**	2			
7. Air Filtering		7.1	Good Filters	**EQ 1**	Prerequisite			
		7.2	Better Filters		1			
		7.3	Best Filters	**EQ 7.2**	2			
8. Contaminant Control	✍	8.1	Indoor Contaminant Control during Construction	**EQ 1**	1			
		8.2	Indoor Contaminant Control		2			
	✍	8.3	Preoccupancy Flush	**EQ 1**	1			
9. Radon Protection	✍	9.1	Radon-Resistant Construction in High-Risk Areas	**EQ 1**	Prerequisite			
	✍	9.2	Radon-Resistant Construction in Moderate-Risk Areas	**EQ 1**	1			
10. Garage Pollutant Protection		10.1	No HVAC in Garage	**EQ 1**	Prerequisite			
		10.2	Minimize Pollutants from Garage	**EQ 1**	2			
		10.3	Exhaust Fan in Garage	**EQ 1**	1			
		10.4	Detached Garage or No Garage	**EQ 1, 10.2, 10.3**	3			
				Sub-Total for EQ Category:	***21***		***0***	

LEED for Homes 2008: IEQ

EQ 2: Combustion Venting
Maximum points: 2

Intent

Minimize the leakage of combustion gases into the occupied space of the home.

Requirements

Prerequisites

2.1 Basic Combustion Venting Measures. Meet all the following requirements.

a) No unvented combustion appliances (e.g., decorative logs) are allowed.

b) A carbon monoxide (CO) monitor must be installed on each floor.

c) All fireplaces and woodstoves must have doors.

d) Space and water heating equipment that involves combustion must meet one of the following. Space heating systems in homes located in IECC-2007 climate zone 1 or 2 are exempt.

i. it must be designed and installed with closed combustion (i.e., sealed supply air and exhaust ducting);

ii. it must be designed and installed with power-vented exhaust; or

iii. it must be located in a detached utility building or open-air facility.

Credits

2.2 Enhanced Combustion Venting Measures (maximum 2 points). Install no fireplace or woodstove, or design and install a fireplace or woodstove according to the requirements in **Table 29**.

LEED for Homes 2008: IEQ

EQ 3: Moisture Control
Maximum points: 1

Intent

Control indoor moisture levels to provide comfort, reduce the risk of mold, and increase the durability of the home.

Requirements

Prerequisites

None.

Credits

3. **Moisture Load Control (1 point).** Install dehumidification equipment with sufficient latent capacity to maintain relative humidity at or below 60%. This must be achieved through one of the following:

   a) Additional dehumidification system(s).

   b) A central HVAC system equipped with additional controls to operate in dehumidification mode.

   Note: LEED for Homes does not encourage active dehumidification for all projects. Work with the HVAC contractor to determine whether this credit is appropriate and/or necessary.

LEED for Homes 2008: IEQ

EQ 4: Outdoor Air Ventilation
Maximum points: 3

Intent

Reduce occupant exposure to indoor pollutants by ventilating with outdoor air.

Requirements

Prerequisites

4.1 Basic Outdoor Air Ventilation. Design and install a whole building ventilation system that complies with ASHRAE Standard 62.2-2007. A summary of alternatives is provided below, but the HVAC contractor should review and follow the requirements of ASHRAE Standard 62.2-2007, Sections 4 and 7.

a) Mild climate exemption. A home built in a climate with fewer than than 4,500 infiltration degree-days[3] is exempt from this prerequisite.

b) Continuous ventilation. Meet the ventilation requirements in **Table 30** below.

c) Intermittent ventilation. Use Equation 4.2 of ASHRAE Standard 62.2-2007 to demonstrate adequate ventilation air flow.

d) Passive ventilation. Have a passive ventilation system approved and verified by a licensed HVAC engineer as providing ventilation equivalent to that achieved by continuous ventilation systems as described in **Table 30**.

Credits

4.2 Enhanced Outdoor Air Ventilation (2 points). Meet one of the following:

a) In mild climates (fewer than 4,500 infiltration degree-days), install a whole-building active ventilation system that complies with ASHRAE Standard 62.2-2007.

OR

b) Install a system that provides heat transfer between the incoming outdoor air stream and the exhaust air stream, such as a heat-recovery ventilator (HRV) or energy-recovery ventilator (ERV). The heat recovery system must be listed by a certified testing lab (e.g., UL, ETL).

4.3 Third-Party Performance Testing (1 point). Have a third-party test the flow rate of air brought into the home, and verify that the requirements of ASHRAE Standard 62.2-2007 are met. In exhaust-only ventilation systems, install exhaust ducts according to Table 7.1 of ASHRAE Standard 62.2-2007, and either test the flow rate out of the home or conduct air flow tests to ensure back-pressure of ≤ 0.20 inches w.c.

LEED for Homes 2008: IEQ

EQ 5: Local Exhaust
Maximum points: 2

Intent

Reduce moisture and exposure to indoor pollutants in kitchens and bathrooms.

Requirements

Prerequisites

5.1 Basic Local Exhaust. Meet all the following requirements:

a) Design and install local exhaust systems in all bathrooms (including half-baths) and the kitchen to meet the requirements of Section 5 of ASHRAE Standard 62.2-2007. Sample requirements that relate to minimum intermittent local exhaust flow rates are shown in **Table 31**, below.

b) Design and install the fans and ducts to meet the requirements of Section 7 of ASHRAE Standard 62.2-2007.

c) Exhaust air to the outdoors (i.e., exhaust to attics or interstitial spaces is not permitted).

d) Use ENERGY STAR labeled bathroom exhaust fans (except for exhaust fans serving multiple bathrooms).

Credits

5.2 Enhanced Local Exhaust (1 point). Use one of the following strategies in every bathroom to control the use of the local exhaust fan:

a) An occupancy sensor.

b) An automatic humidistat controller.

c) An automatic timer to operate the fan for a timed interval after occupant leaves the room.

d) A continuously operating exhaust fan.

5.3 Third-Party Performance Testing (1 point). Perform a third-party test of each exhaust air flow rate for compliance with the requirements in Section 5 of ASHRAE Standard 62.2-2007.

LEED for Homes 2008: IEQ

EQ 6: Distribution of Space Heating and Cooling
Maximum points: 3

Intent

Provide appropriate distribution of space heating and cooling in the home to improve thermal comfort and energy performance.

Requirements

A. Forced-Air Systems:

Prerequisites

6.1 Room-by-Room Load Calculations. Perform design calculations (using ACCA Manuals J and D, the ASHRAE Handbook of Fundamentals, or an equivalent computation procedure) and install ducts accordingly.

Credits

6.2 Return Air Flow (1 point). Ensure that every room (except baths, kitchens, closets, pantries, and laundry rooms) has adequate return air flow through the use of multiple returns, transfer grilles, or jump ducts. Meet one of the following requirements:

a) Size the opening to 1 square inch per cfm of supply (this area may include free area undercut below door).

b) Demonstrate that the pressure differential between closed rooms and adjacent spaces with return is no greater than 2.5 Pa (0.01 inch w.c.).

6.3 Third-Party Performance Test (2 points). Have the total supply air flow rates in each room tested using a flow hood with doors closed, or one of the other acceptable methods cited by the ACCA Quality Installation Specifications. Supply air flow rates must be within +/- 15% (or +/- 10 cfm) of calculated values from ACCA Manual J (as required by EA 6.1).

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EQ 7: Air Filtering
Maximum points: 2

Intent

Reduce particulate matter from the air supply system.

Requirements

A. Forced-Air Systems:

Prerequisites

7.1 **Good Filters.** Install air filters with a minimum efficiency reporting value (MERV) ≥ 8 and ensure that air handlers can maintain adequate pressure and air flow. Air filter housings must be airtight to prevent bypass or leakage.

Credits

7.2 **Better Filters (1 point).** Install air filters ≥ MERV 10 and ensure that air handlers can maintain adequate pressure and air flow. Air filter housings must be airtight to prevent bypass or leakage.

OR

7.3 **Best Filters (2 points).** Install air filters ≥ MERV 13 and ensure that air handlers can maintain adequate pressure and air flow. Air filter housings must be airtight to prevent bypass or leakage.

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EQ 8: Contaminant Control
Maximum points: 4

Intent

Reduce occupants' and construction workers' exposure to indoor airborne contaminants through source control and removal.

Requirements

Prerequisites

None.

Credits

8.1 Indoor Contaminant Control during Construction (1 point). Upon installation, seal all permanent ducts and vents to minimize contamination during construction. Remove any seals after all phases of construction are completed.

8.2 Indoor Contaminant Control (1 point each, maximum 2 points). Select from the following measures:

a) Design and install permanent walk-off mats at each entry that are at least 4 feet in length and allow accessibility for cleaning (e.g., grating with catch basin).

b) Design a shoe removal and storage space near the primary entryway, separated from living areas. This space may not have wall-to-wall carpeting, and it must be large enough to accommodate a bench and at least two pairs of shoes per bedroom.

c) Install a central vacuum system with exhaust to the outdoors. Ensure that the exhaust is not near any ventilation air intake.

8.3 Preoccupancy Flush (1 point). Flush the home with fresh air, according to the following guidelines:

a) Flush prior to occupancy but after all phases of construction are completed.

b) Flush the entire home, keeping all interior doors open.

c) Flush for 48 total hours; the hours may be nonconsecutive, if necessary.

d) Keep all windows open and run a fan (e.g., HVAC system fan) continuously or flush the home with all HVAC fans and exhaust fans operating continuously at the highest flow rate.

e) Use additional fans to circulate air within the home.

f) Replace or clean HVAC air filter afterward, as necessary.

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EQ 9: Radon Protection
Maximum points: 1

Intent

Reduce occupant exposure to radon gas and other soil gas contaminants.

Requirements

Prerequisites

9.1 Radon-Resistant Construction in High-Risk Areas. If the home is in EPA Radon Zone 1, design and build the home with radon-resistant construction techniques as prescribed by EPA, the International Residential Code, Washington State Ventilation and Indoor Air Quality Code, or some equivalent code or standard.

Credits

9.2 Radon-Resistant Construction in Moderate-Risk Areas (1 point). If the home is outside EPA Radon Zone 1, design and build the home with radon-resistant construction techniques as prescribed by EPA, the International Residential Code, Washington State Ventilation and Indoor Air Quality Code, or some equivalent code or standard.

Note: Radon-resistant construction does not guarantee that occupants will not be exposed to radon. The Surgeon General and EPA recommend that every home in the country be tested for radon. Information about radon testing is available at the EPA Web site, at www.epa.gov/radon/radontest.html.

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EQ 10: Garage Pollutant Protection
Maximum points: 3

Intent

Reduce occupant exposure to indoor pollutants originating from an adjacent garage.

Requirements

Prerequisites

10.1 No HVAC in Garage. Place all air-handling equipment and ductwork outside the fire-rated envelope of the garage.

Credits

10.2 Minimize Pollutants from Garage (2 points). Tightly seal shared surfaces between garage and conditioned spaces, including all of the following:

a) In conditioned spaces above the garage:

i) seal all penetrations;

ii) seal all connecting floor and ceiling joist bays; and

iii) paint walls and ceilings (carbon monoxide can penetrate unfinished drywall through diffusion).

b) In conditioned spaces next to the garage:

i) weather-strip all doors;

ii) place carbon monoxide detectors in adjacent rooms that share a door with the garage;

iii) seal all penetrations; and

iv) seal all cracks at the base of the walls.

AND/OR

10.3 Exhaust Fan in Garage (1 point). Install an exhaust fan in the garage that is rated for continuous operation and designed to be operated in one of the following ways. Nonducted exhaust fans must be 70 cfm or greater, and ducted exhaust fans must be 100 cfm or greater.

a) Fan must run continuously; or

b) Fan must be designed with an automatic timer control linked to an occupant sensor, light switch, garage door opening-closing mechanism, carbon monoxide sensor, or equivalent. The timer must be set to provide at least three air changes each time the fan is turned on.

OR

10.4 Detached Garage or No Garage (3 points).

Emissions standards

GREENGUARD
CERTIFICATION
FROM UL ENVIRONMENT

GREENGUARD Certification Program For Chemical Emissions For Building Materials, Finishes And Furnish

GREENGUARD Certification Program for Chemical and Particle Emissions for Electronic Equipment

GREENGUARD Certification Program for Chemical Emissions for Cleaners and Cleaning Maintenance System

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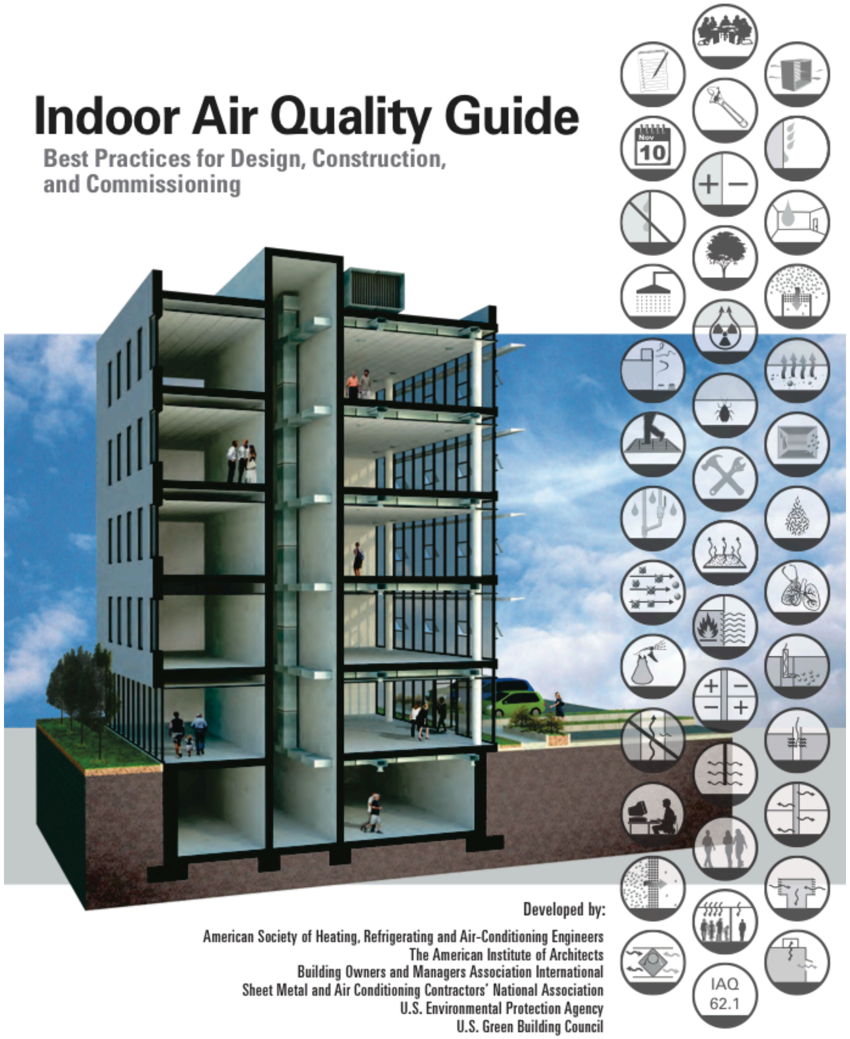

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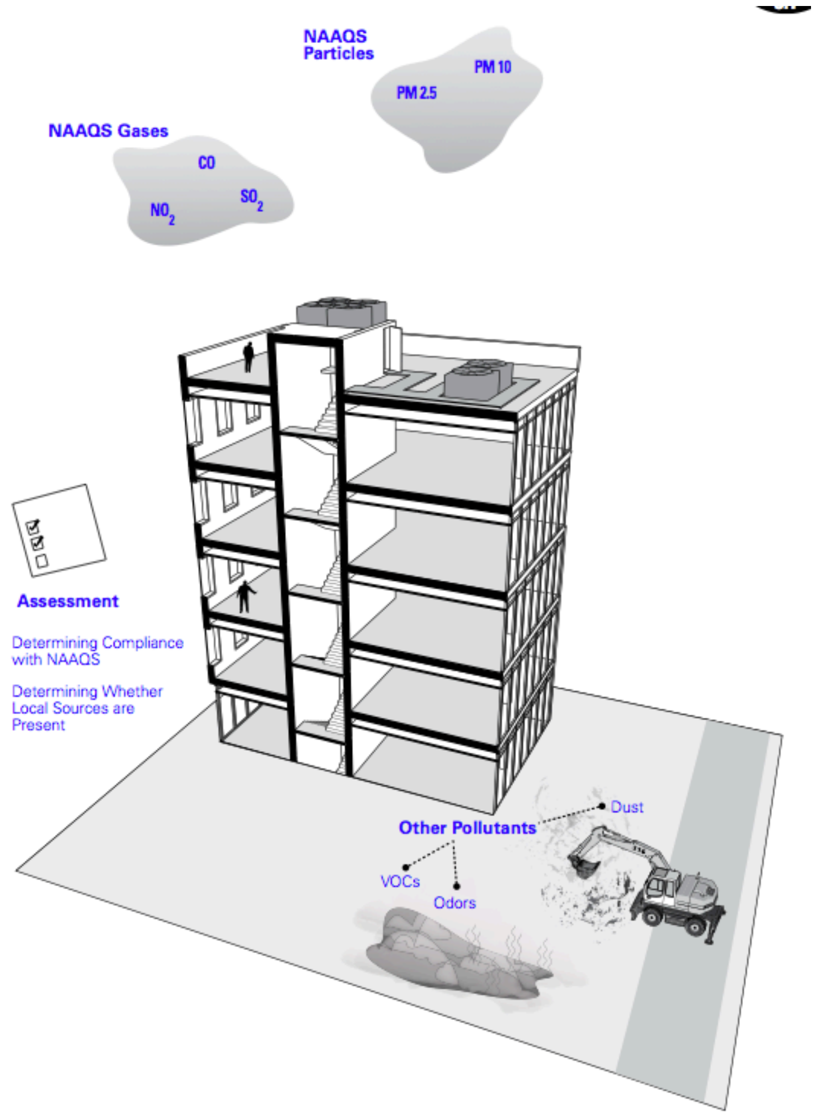

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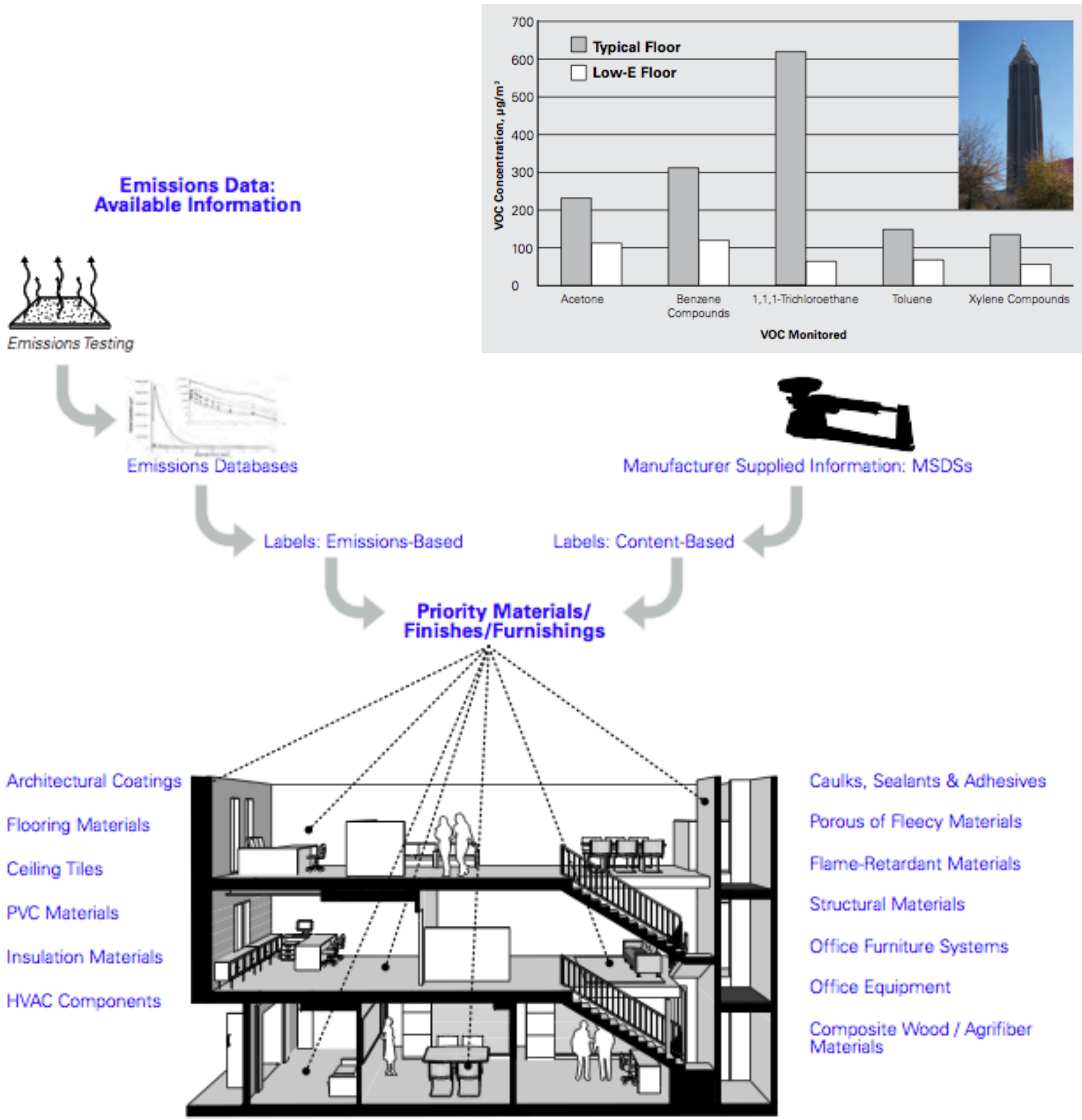

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The WELL Building Standard

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v1 with October 2016 addenda

- Delos Living LLC, with partnership from Mayo Clinic