ENVE 576
Indoor Air Pollution
Fall 2015

Week 12: November 10, 2015
IAQ measurement techniques
IAQ in developing countries

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Today's lecture

- Today:
  - Take-home exam due

1. IAQ measurement techniques
2. IAQ in developing countries

IAQ MEASUREMENT TECHNIQUES

Attribution: The majority of this material came from a 2012 graduate course at UT-Austin taught by Dr. Atila Novoselac, with help from Drs. Jeff Siegel, Neil Crain, and Richard Corsi

Motivation

- Throughout this course we've described a variety of indoor airborne pollutants
- Most can be categorized into:
  - Inorganic gases (e.g., O_3, CO, CO_2)
  - Organic gases (e.g., VOCs, aldehydes, SVOCs)
  - Particulate matter
    - Mass
    - Number
    - Biological
- But we haven't discussed how to measure all of these yet
  - Other than particulate matter last week

MEASURING INORGANIC GASES

CO, CO_2, and O_3

Techniques for measuring CO

- Electrochemical (common for hand held or home devices)
  - Two electrodes
  - Oxidize CO to CO_2 → generates electric current

- Biomimetic (gel cell)
  - Synthetic hemoglobin – darkens in presence of CO (color change)

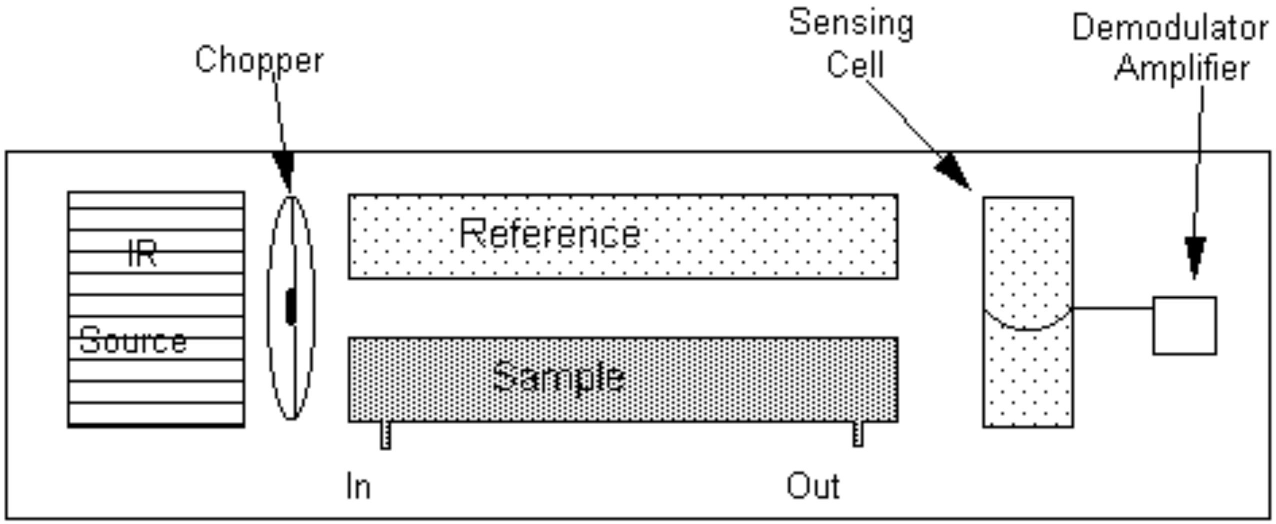
- Semiconductor (wires of tin dioxide / ceramic base)
  - CO reduces resistance
  - Works for high CO concentrations

- Non-Dispersive Infrared Detection (NDIR)
  - Relies on absorption band (similar for other instruments, e.g. CO_2)

Techniques for measuring CO_2

- Non-dispersive infrared (NDIR) → most common
- Electrochemical (reduce CO_2 → generate current)
- Photoacoustic (CO_2 absorbs light energy → measure pressure change)
  - Photoacoustic effect relates pressure change to CO_2 conc.
- Potentiometric (CO_2 into solution – changes pH)
- Gas chromatography w/ MS or TCD
  - High sensitivity
  - High cost

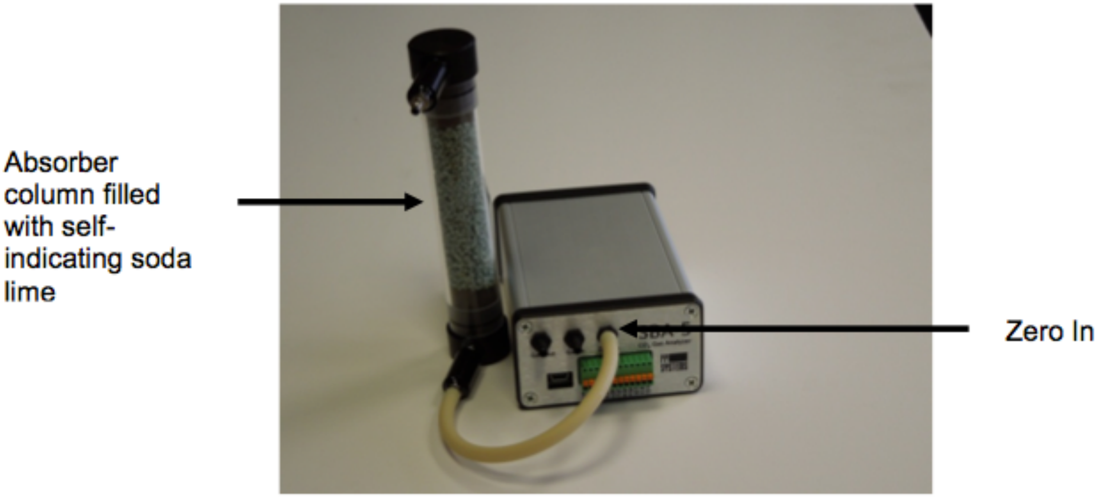
Non-dispersive infrared (NDIR)



- Measures the infrared light absorbed by CO_2 as it passes through a flow-through IR absorption cell
  - – CO_2 peak absorbance @ 4.3 μm (higher CO_2, higher absorption)
    - Possible interference from other species (H_2O, CO)
    - Interferences from other IR-absorbing gases are minimized by use of a highly wavelength-specific detector

Dealing with interference and NDIR

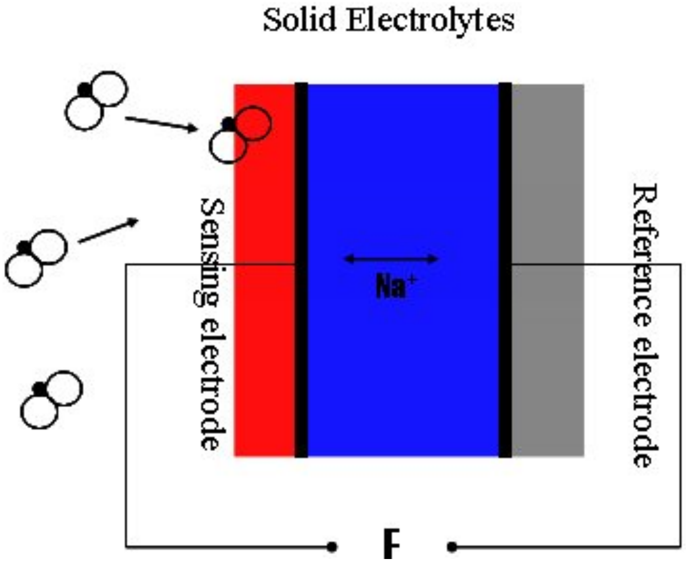
- PP Systems SBA-5 CO_2 analyzer
- IR beam at 4.26 µm (similar to light bulb)
- Positioned at one end of a tube with a sensor sensitive to photons at 4.26 µm at the other end
- The cell absorbs CO_2 and the sensor reading decreases
- New feature: auto-zero w/ soda lime



$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$ + heat

Electrochemical sensing

- CO_2 diffuses into the sensor through a porous membrane to the working electrode
  - Causes electrochemical reaction, oxidizes the target gas
- This reaction results in an electric current that passes through the external circuit



Ozone measurements: Diffusion badges

- Personal diffusion badges
  - Diffusion-based; chemical coating
  - The principle component of the coating is nitrite ion, which in the presence of ozone is oxidized to nitrate ion on the filter medium
    - $NO_2^- + O_3 \rightarrow NO_3^- + O_2$
  - After sample collection, the filters are extracted with ultrapure water and analyzed for nitrate ion by ion chromatography
  - Useful for inexpensive, long-term samples

Ozone measurements: UV absorbance

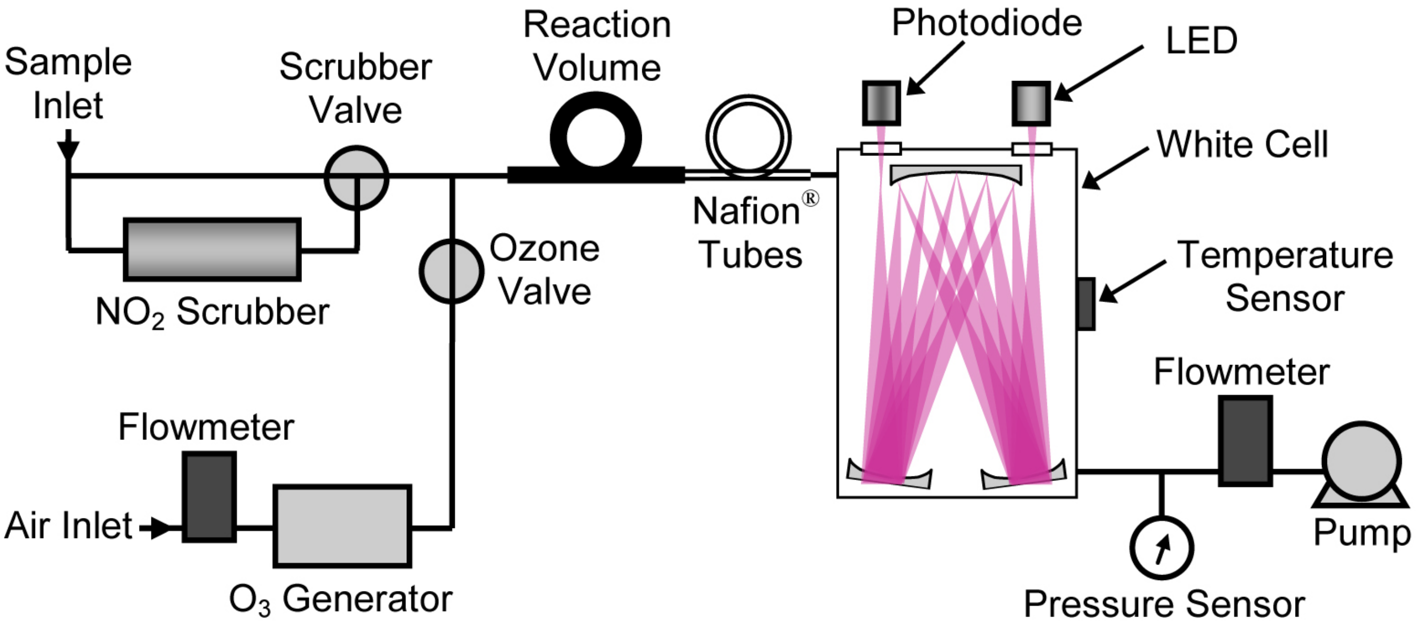
- Measure ozone by comparing transmission of light through a detection cell (ozone peak absorbance at 254 nm)
  - UV, not IR
- Light intensity measurements are made with ozone present and with ozone removed
  - Ozone measured using Beer-Lambert Law

$$T = \frac{I}{I_0} = e^{-\Sigma \ell} = e^{-\varepsilon \ell c}$$

NO_x measurements: UV

- UV example: 2B Technologies Model 405
- Measures $NO_x = NO + NO_2$
  - – NO_2 is measured using absorbance at 405 nm
  - – NO is measured by 100% conversion of NO with O_3
    - Measured by bypassing NO_2 scrubber and measuring light intensity with and without adding O_3 to convert NO to NO_2

$NO + O_3 \rightarrow NO_2 + O_2$



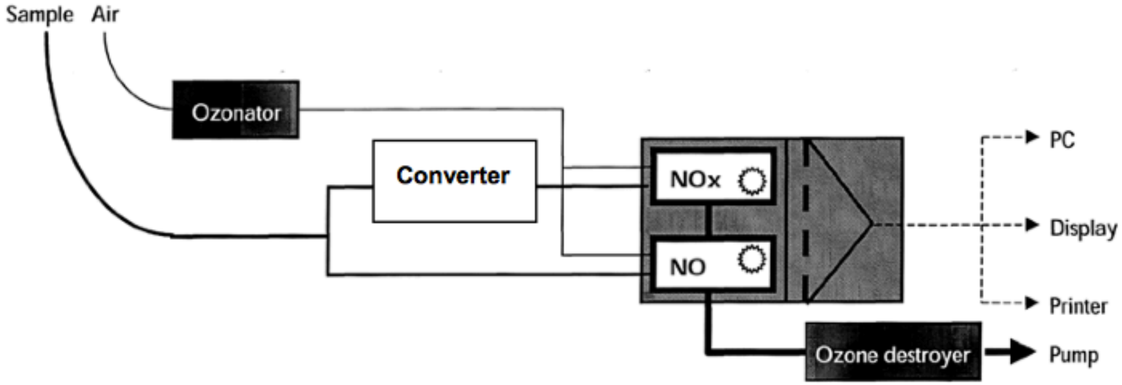
NO_x measurements: Chemiluminescence

- Reaction between NO and O_3 emits light
- Photons produced are detected by a photo multiplier tube
  - Output voltage is proportional to NO concentration

hv

$$NO + O_3 \text{ ==> } NO_2 + O_2$$

Nitrogen monoxide + Ozone ==> Nitrogen dioxide + Oxygen



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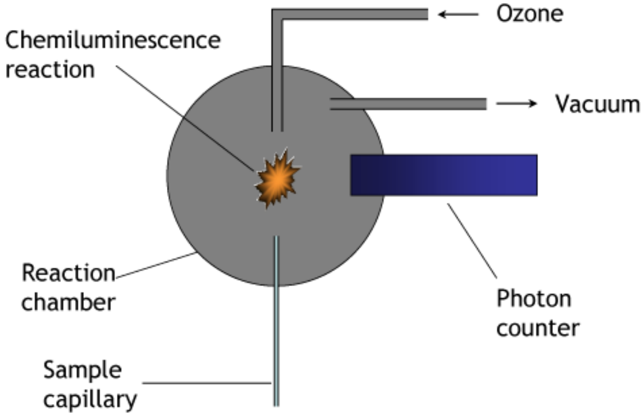


MEASURING ORGANIC GASES (VOC AND SVOC)

Sample Collection Methods

- Two methods:

1. Real-time measurement/analysis
   - Generally has a sensor (mostly FID, PID)
   - Some have separation (w/ GC) + sensor
   - Also: colorimetric tubes (general: MDL > 1 ppm)

2. Collect air sample for laboratory analysis
   - Whole-volume samplers (canisters, bags)
   - Concentration samplers (sorbents, SPME)
     - Either case: preservation and analysis in laboratory

Canister samples

- Whole volume
- Grab versus integrated
- EPA Methods TO-14/15
- Benefits:
  - Inert/impermeable
  - Lots of experience
  - Multiple analyses can be done
- Drawbacks
  - Bulky
  - Requires cleaning
  - Can get scratched
  - Sample stability (reactions)

1 – 15 L

400 mL

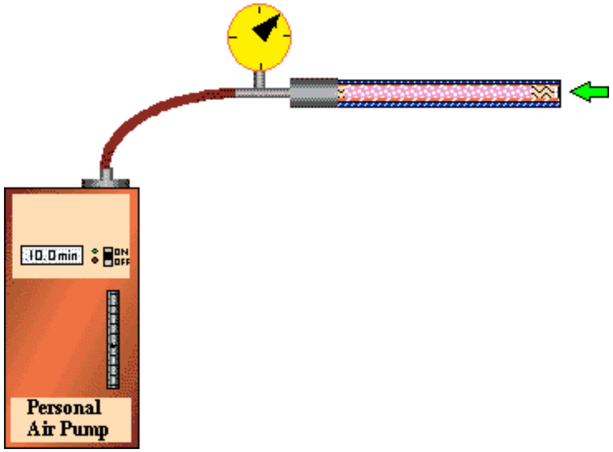
Tedlar bags

- Whole volume
- Tedlar = polyvinylfluoride
- Pump to collect (unlike canisters)
- Benefits:
  - Inert / impervious (like cans)
  - Repeat samples (like cans)
  - Lighter than cans
  - Lower initial cost than cans
- Disadvantages:
  - Not as reusable as cans
  - Susceptible to tearing
  - Requires cleaning
  - Stability with some compounds

0.5 – 100 L

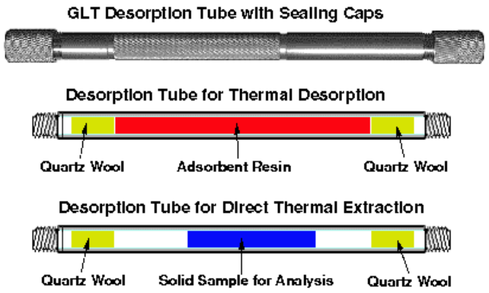
Sorbent sampling

- VOC adsorbs to solid adsorbent
- Passive sampling
  - Similar to ozone badge but w/out reaction
  - Integrated sample over 24 hours, etc.
  - Indoor, personal, outdoor
- Active Sampling
  - Pump air through a packed tube
  - Collect mass over known volume
  - C = m/V
  - Short-term vs. integrated
  - More control, but more difficult



Sorbent tubes

- EPA Method TO-17 = TD/GC/MS (important)
- Various sorbents can be used
  - TO-17 page 33
  - Need to match VOC types/ranges with sorbent
- Some issues
  - Method detection limit, precision, accuracy (pg. 28/29)
  - Sample preservation
  - Breakthrough volume
  - Artifact formation (especially via ozone)
  - Sorbent pre-conditioning / breakdown over time
- Use of multi-sorbent beds
- Focus on Tenax-TA

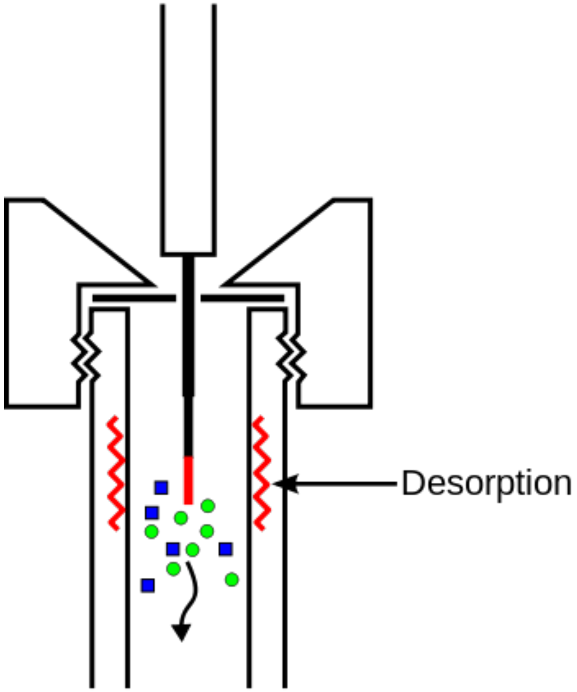


Sorbent: Tenax-TA

- 2,6-diphenylene oxide polymer resin (porous)
- Specific area = 35 m^2/g
- Pore size = 200 nm (average)
- Density = 0.25 g/cm^3
- Various mesh sizes (e.g., 60/80)
- Low affinity for water (good for high RH)
- Non-polar VOCs (T_b > 100 °C); polar (T_b > 150 °C)
  - lighter polar – Carbotrap and Carbopack-B common
- Artifacts w/ O_3: benzaldehyde, phenol, acetophenone

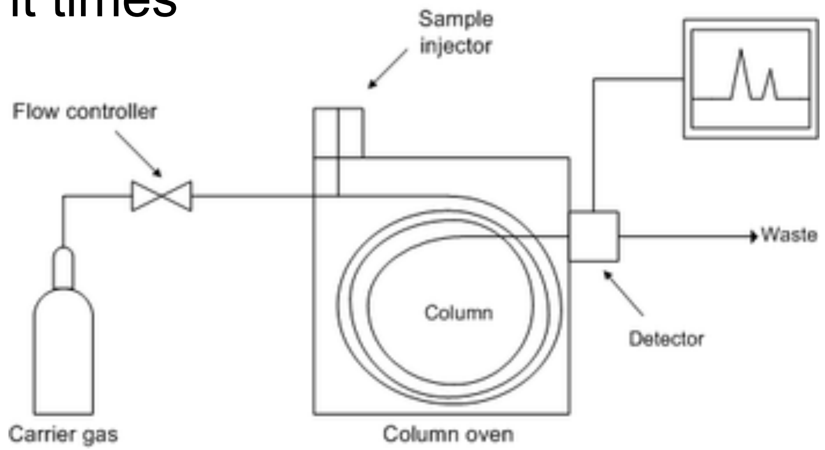
Solid-Phase Micro-Extraction (SPME)

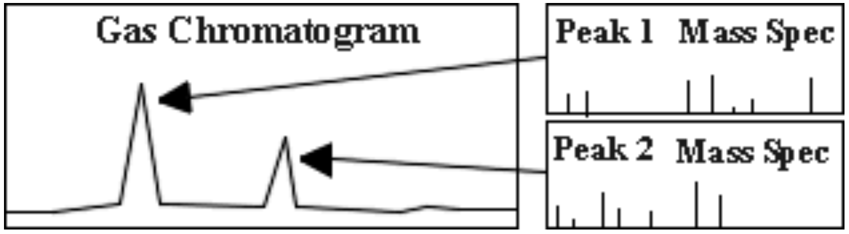
- Uses a fiber coated with an extracting phase:
  - PDMS / DVB / Carboxen
- Benefits
  - Highly concentrating for many indoor VOCs (ppt levels)
    - Can get VVOCs
  - Reusable
  - Relatively low cost
  - Small / light weight
  - Possible use in other media
  - Ease of injection to GC
- Drawbacks
  - Less experience / acceptability
  - Preservation issues
  - Difficulties w/ calibration



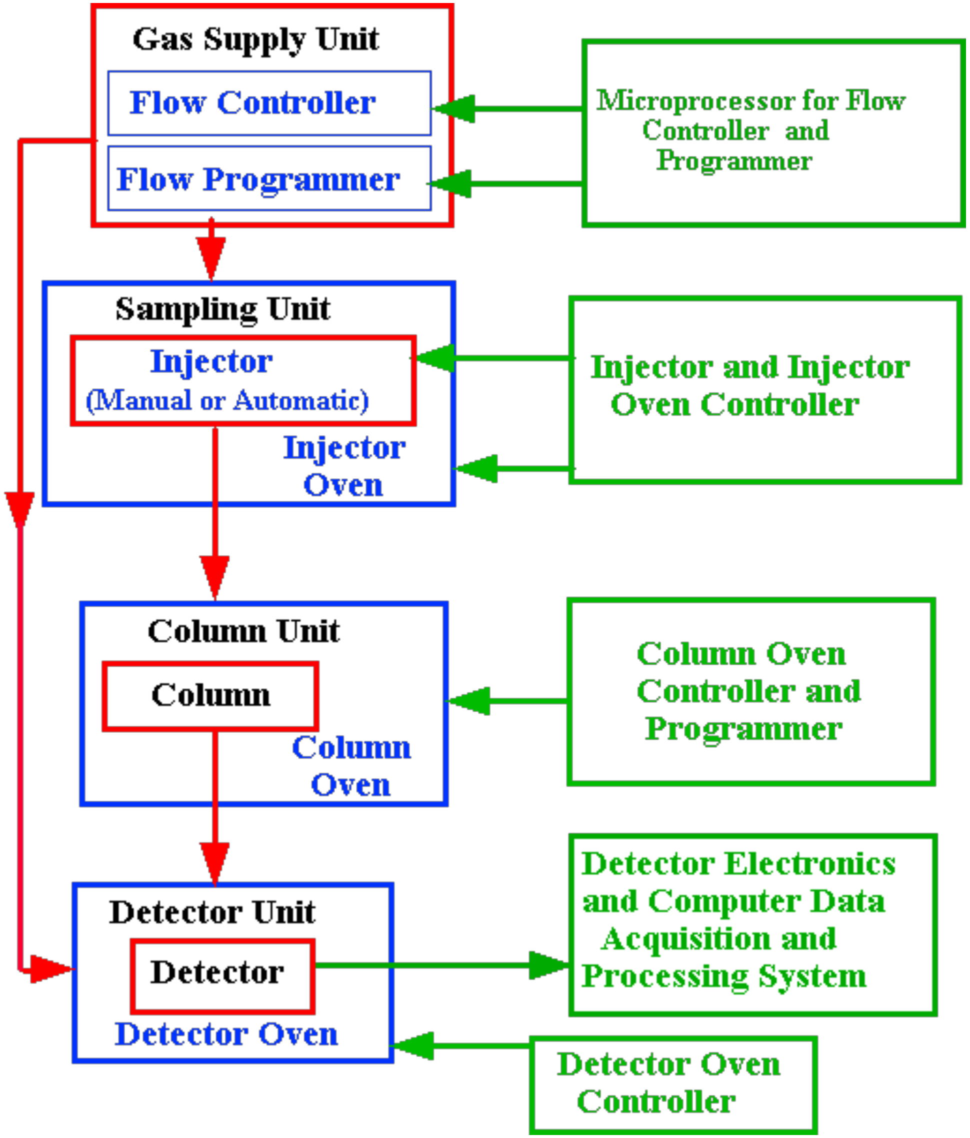
Gas Chromatography (GC)

- GC is used to separate compounds
  - Compounds are vaporized into an inert carrier gas through a capillary column
- Capillary column
  - Stationary microscopic layer of liquid or polymer on inert solid support inside a piece of glass or metal tubing
  - Causes compound to elute at different times
    - Retention time
- Thermal program of GC oven
- Temporal passage to a detector
  - Analyze "peaks"
  - Analyze molecular fragments (MS)





Gas Chromatography (GC)



Gas Supply Unit

Flow Controller

Flow Programmer

Microprocessor for Flow Controller and Programmer

Sampling Unit

Injector (Manual or Automatic)

Injector Oven

Injector and Injector Oven Controller

Column Unit

Column

Column Oven

Column Oven Controller and Programmer

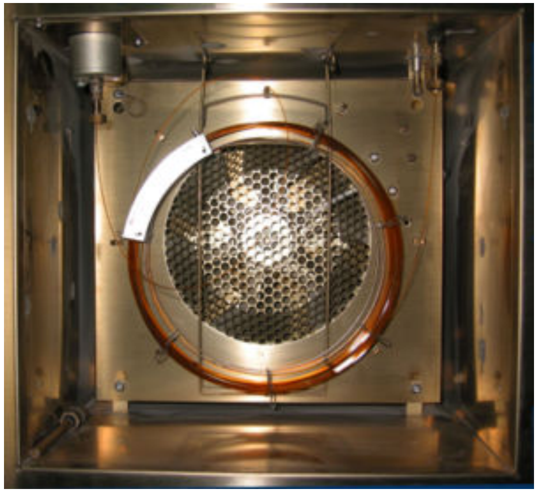
Detector Unit

Detector

Detector Oven

Detector Electronics and Computer Data Acquisition and Processing System

Detector Oven Controller



GC issues

- Type of injection?
- Need to cryo focus for low molecular weight volatiles?
- Type of column?
- Type of detector?
  - If MS, model of detection
- Temperature programs
- Instrument calibration / response

Detectors

- Flame ionization detector (FID)
- Photoionization detector (PID)
- Electron capture detector (ECD)

Non-specific or speciated (w/ GC)

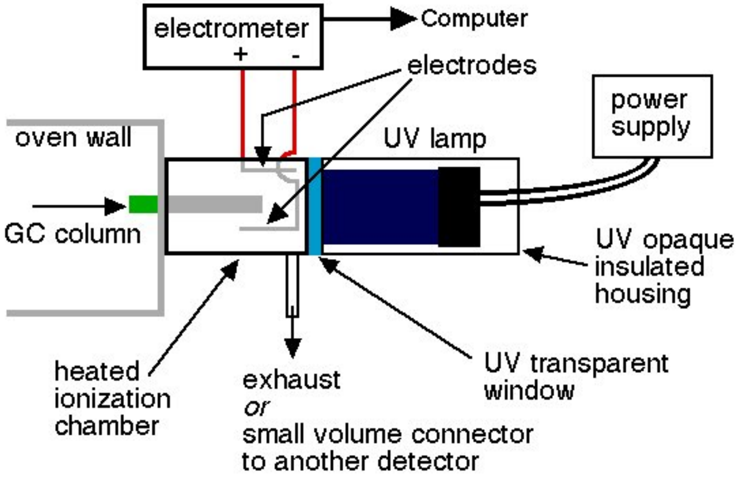
- Mass spectrometer (MS)

w/ speciated (w/ GC)

- These are primary detectors for VOCs in indoor air
- Specific uses vary considerably

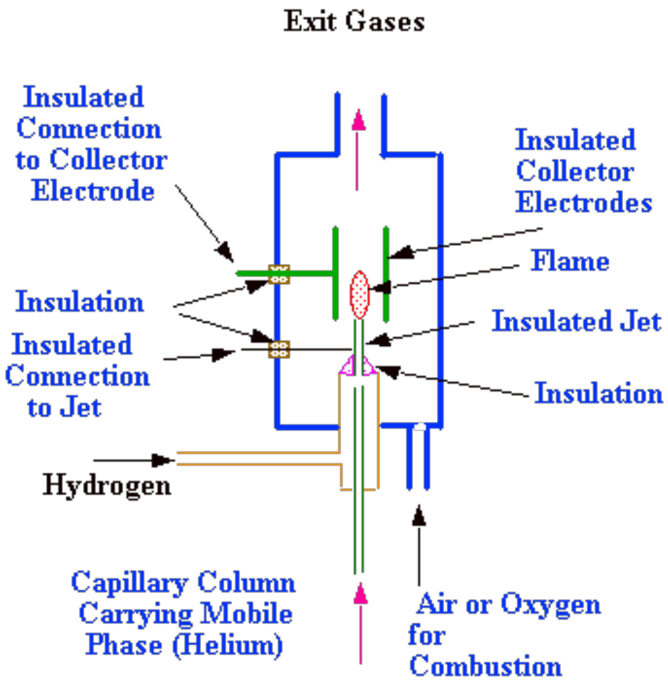
Photoionization Detectors (PID)

- UV light ionizes VOCs --- $R + h\nu \rightarrow R^{+} + e^{-}$
- Collected by electrodes = current
- VOCs with different ionization potential
- Benefits
  - Simple to use
  - Sample non-destructive (relatively)
- Drawbacks
  - No identification/speciation
  - Highly variable responses
  - Not all VOCs detected
  - Lamp burnout / contamination



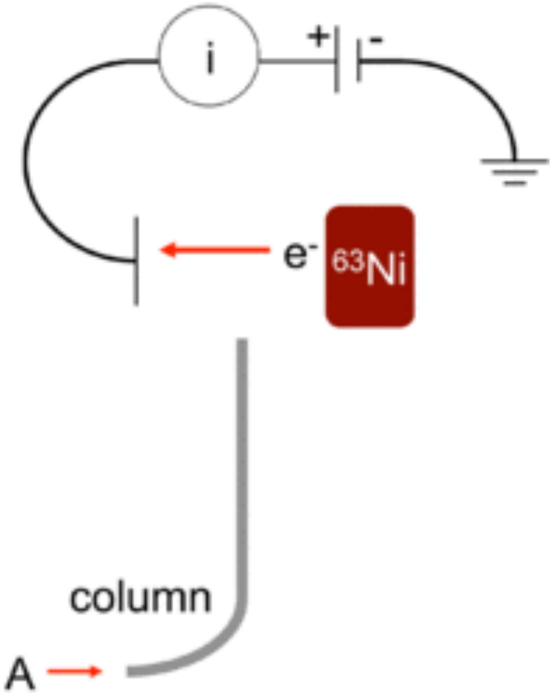
Flame Ionization Detectors (FID)

- Relatively simple system
- Hydrogen flame → ions formed
  - Ions migrate to plate, generate a current
  - Hydrocarbons have molar response proportional to the number of carbon atoms in their molecule
- Detection – typical to pg/s
- Benefits
  - Rugged, low cost, workhorse
  - Linear response over wide range
  - Insensitive to H_2O, CO_2, SO_2, CO, NO_x
- Drawbacks
  - No identification
  - Lower response if not simple HC
  - Destructive testing



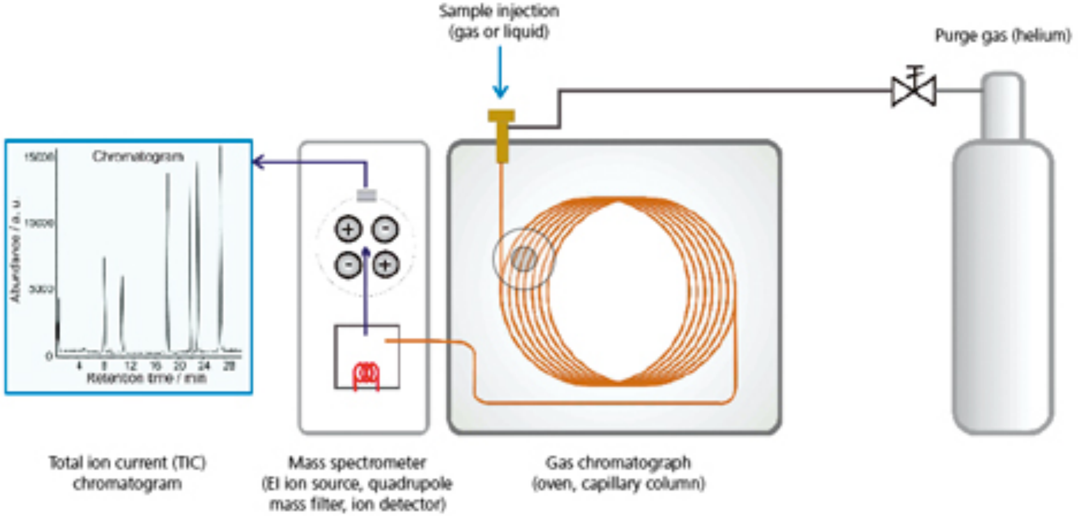
Electron Capture Detectors (ECD)

- Low energy Beta emitter = ^{63}Ni in make-up gas (Nitrogen)
- *e*- attracted to positively charged electrode (anode)
- Molecules in sample absorb e- and reduce current
  - effective: halogens (e.g., SF_6), nitrogen-containing compounds
- Benefits
  - 10-1000 times more sensitive than FID
  - femtogram/s ----- ppt levels
- Drawbacks
  - More limited linear range than FID
  - Radiological safety requirements
  - O_2 contamination issues
  - Response strong function of T, P, flow rate



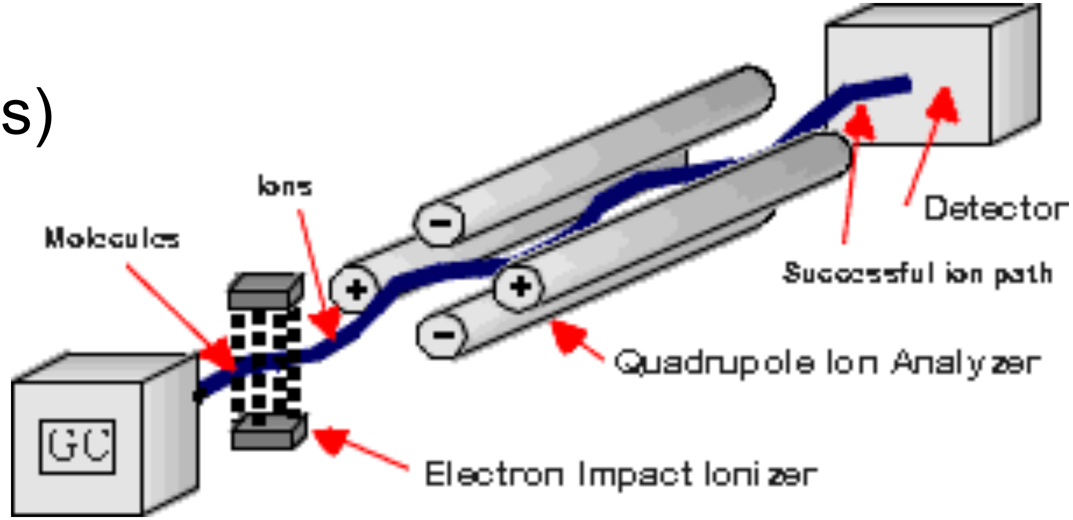
Mass Spectrometer (MS)

- Bombard molecules w/ intense electron source (ionization)
  - Generates positive ion fragments
- Ions accelerate to have same kinetic energy, then deflect in a magnetic field, where deflection is a function of molecular weight
- Use fragment fingerprint to identify molecule
- Quantify amount of fragments to determine mass
- Most common MS = quadrupole
- Benefits
  - “Gold standard”
  - Amount AND identific
- Drawbacks
  - Cost
  - Complexity
  - Maintenance

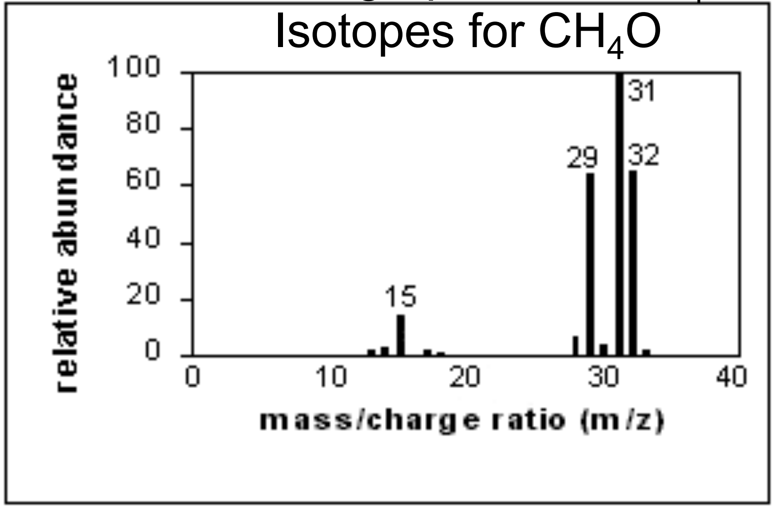


Quadrupole MS

- Electron source
- Four rods (electromagnets)
  - Applied Voltage
  - DC/AC components
  - Voltages = fn(time)
  - Affects trajectory
  - Selective M/Z to detector
  - m/z = mass-to-charge ratio
    - Ionization makes z = 1
- Cycles different M/Z
- Yields mass spectrum
- Always same for a molecule
- System in vacuum



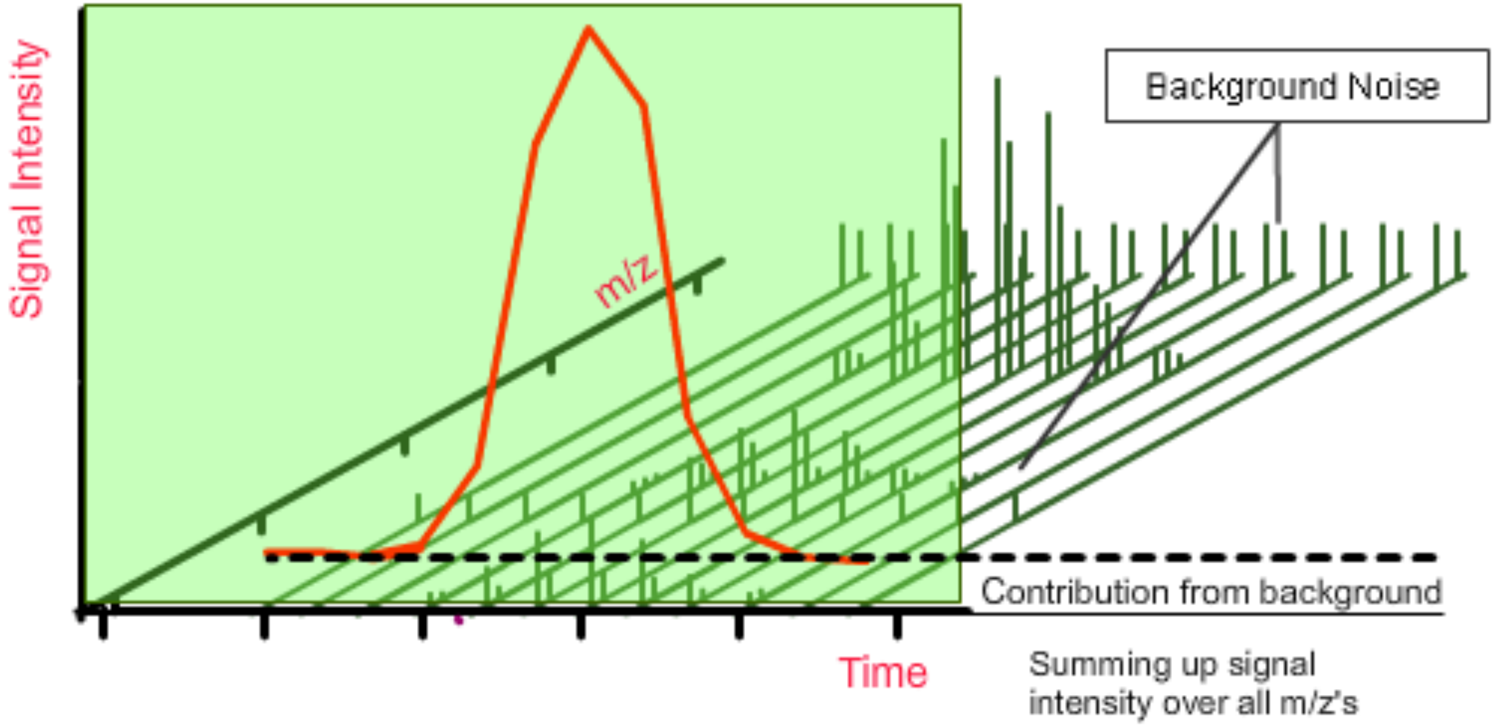
“Fingerprint” for CH_4O:


Isotopes for CH_4O

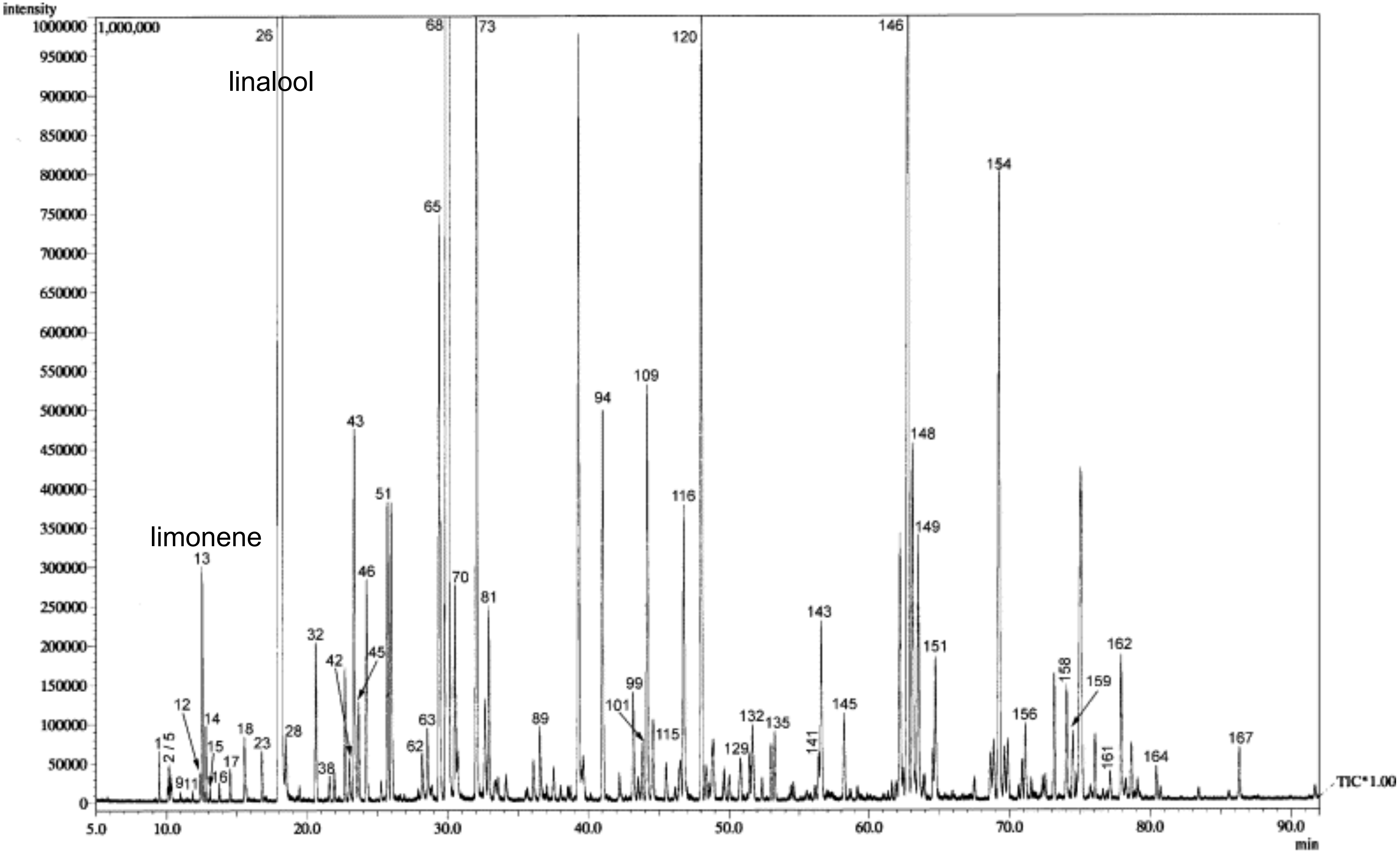
ions	m/z
$CH_3OH^{+\cdot}$	32
$H_2C{=}OH^+$	31
$HC{\equiv}O^+$	29
H_3C^+	15

Total Ion Chromatogram (TIC)

Sum up intensities of all mass spectral peaks belonging to the same scan



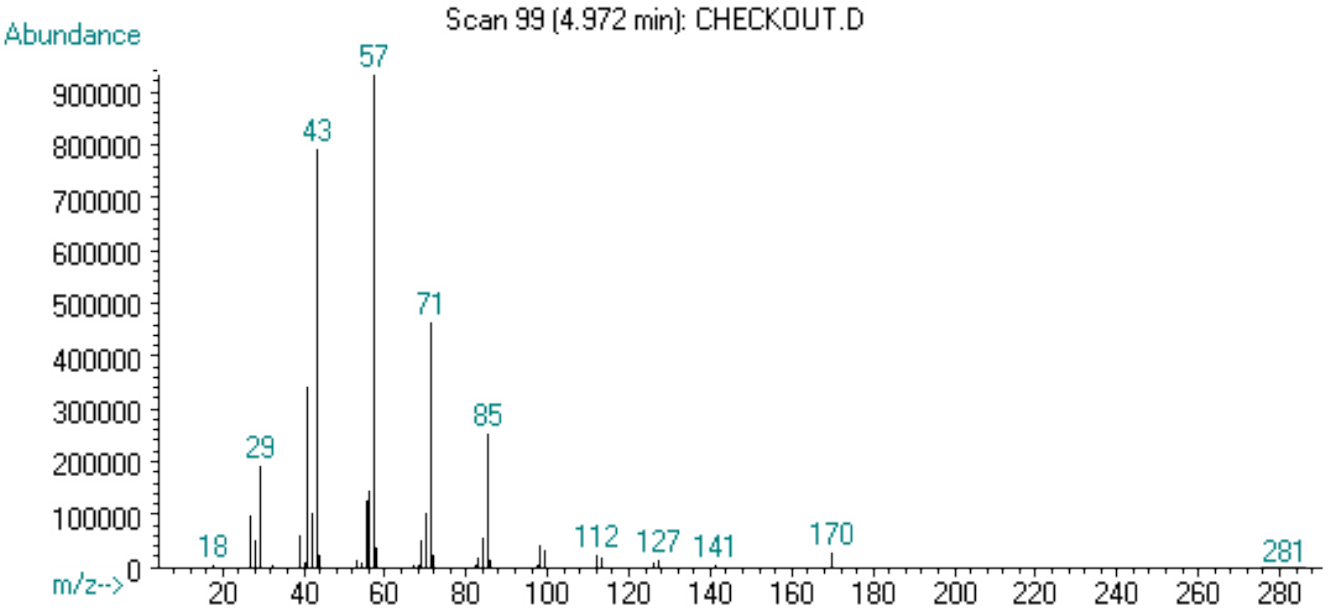
Total Ion Chromatogram (TIC)

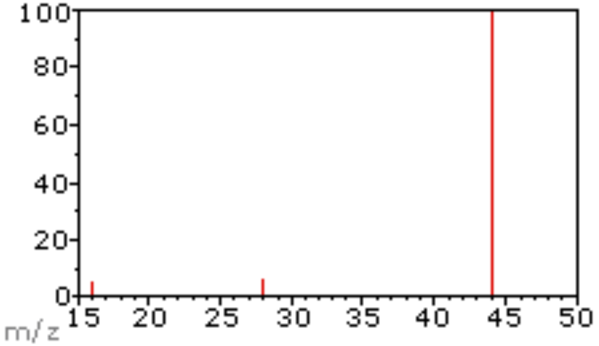


Mondello *et al., J. of Chromatography A*, 1067: 235-243 (2005)

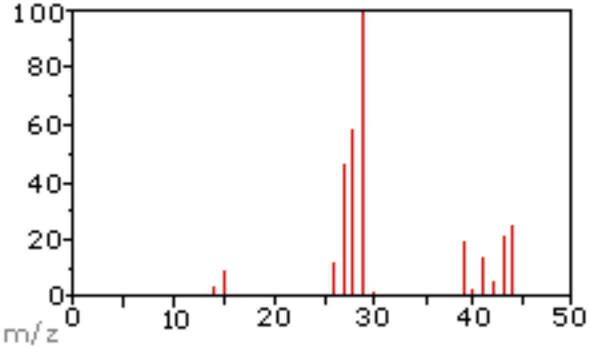
Mass spectrum

Example mass spectrum (fingerprint)

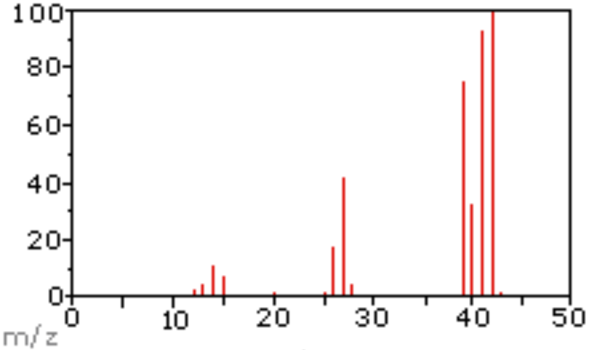




Carbon Dioxide

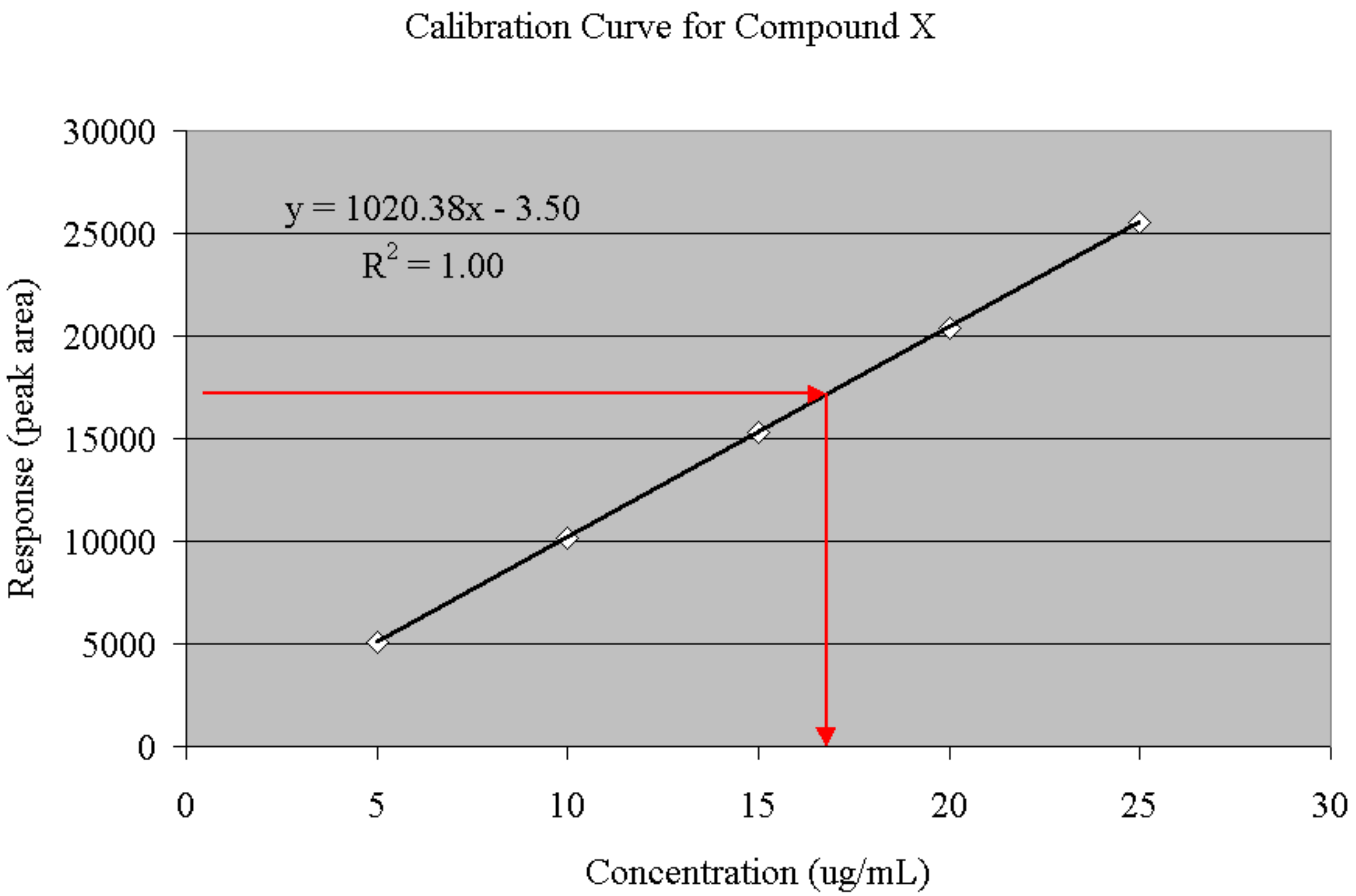


Propane



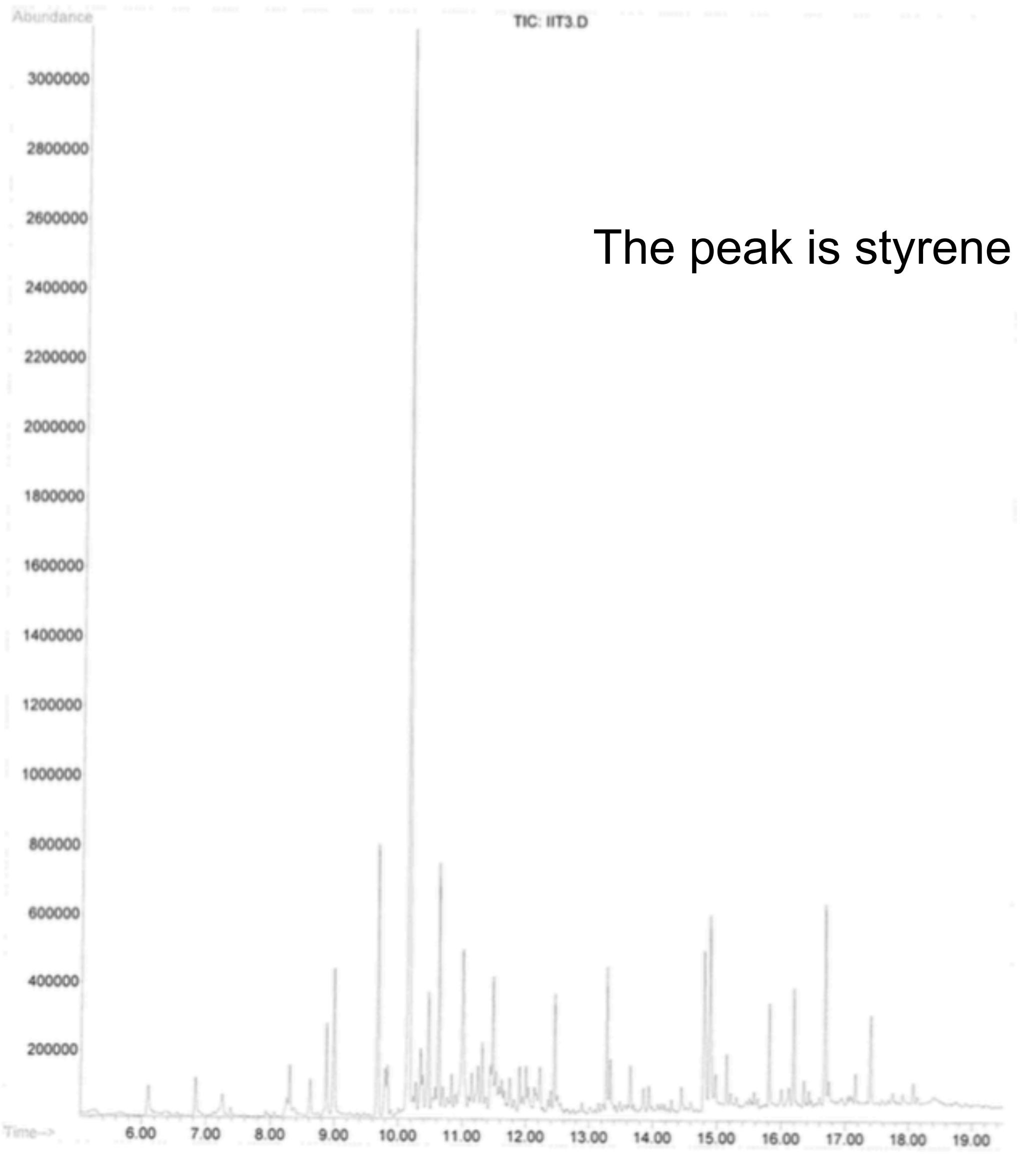
Cyclopropane

Calibration curves



$$\text{Response Factor} = \frac{\text{Peak Area}}{\text{Calibration Concentration}}$$

Real VOC data w/ library compound search



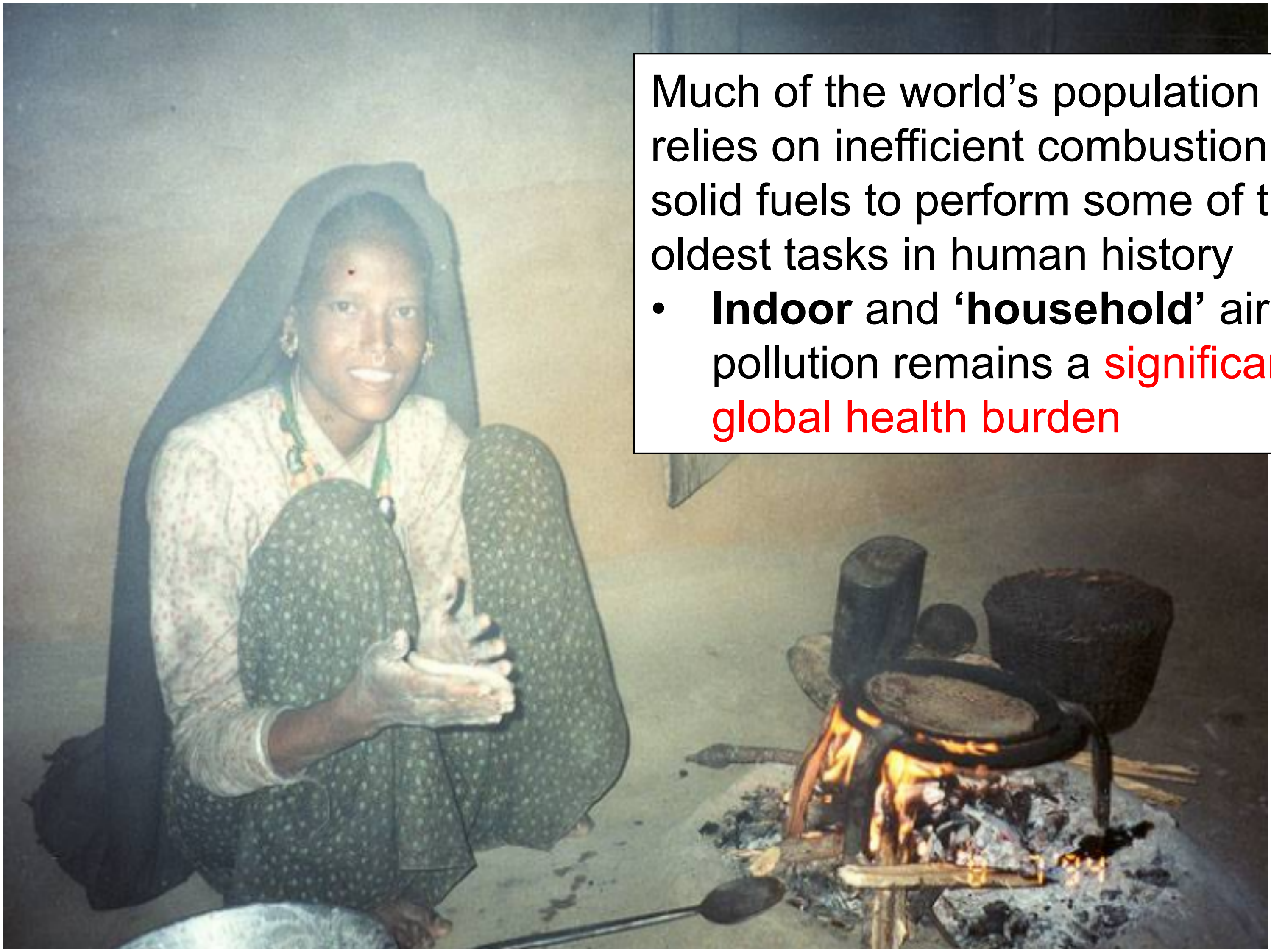
The peak is styrene

Summary of VOC measurements

- VOCs important in indoor environments
- Many types of VOCs
  - Different properties
  - Different effects
  - Different sample collection and analysis protocols
- Sampling and analysis protocols NOT TRIVIAL
  - Many types of collection methods
  - Many types of analysis detectors and methods
  - A lot of issues involved w/ sample/analysis decisions
  - A lot can go wrong (difficult business)
  - Cumbersome and costly, but very important

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

Indoor air pollution in developing countries

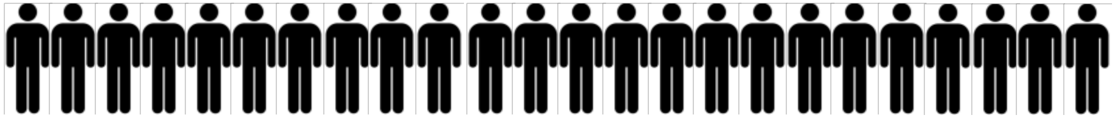
Biomass burning across the world

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

Cooking Heating Lighting

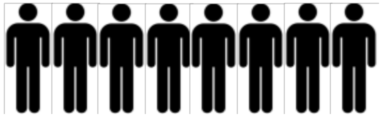
Fuels used include:

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)

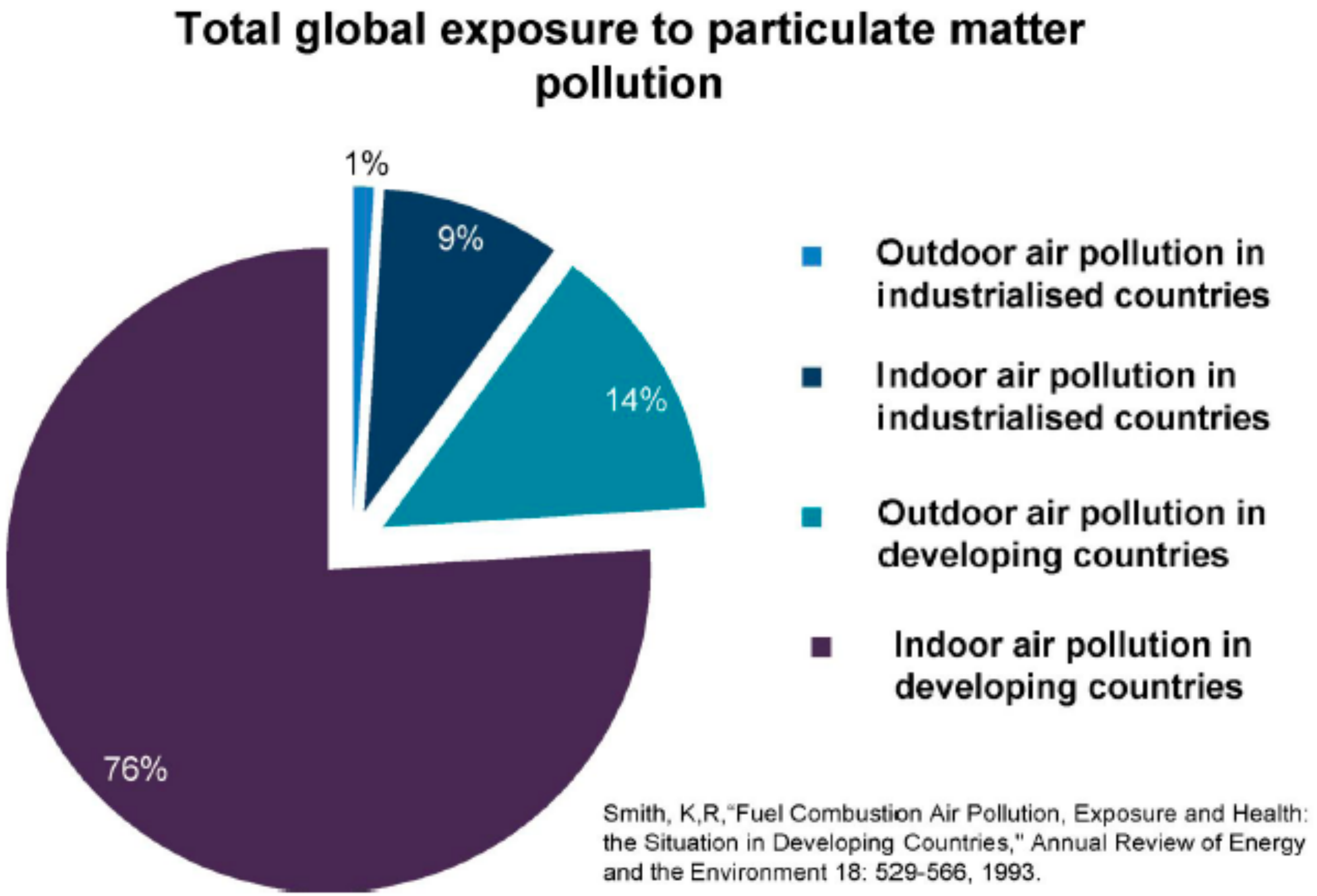
Polycyclic aromatic hydrocarbons (e.g. benzo[a]pyrene)

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

Free radicals

Combustion efficiency is far less than 100%

Global exposure to particulate matter



Total global exposure to particulate matter pollution

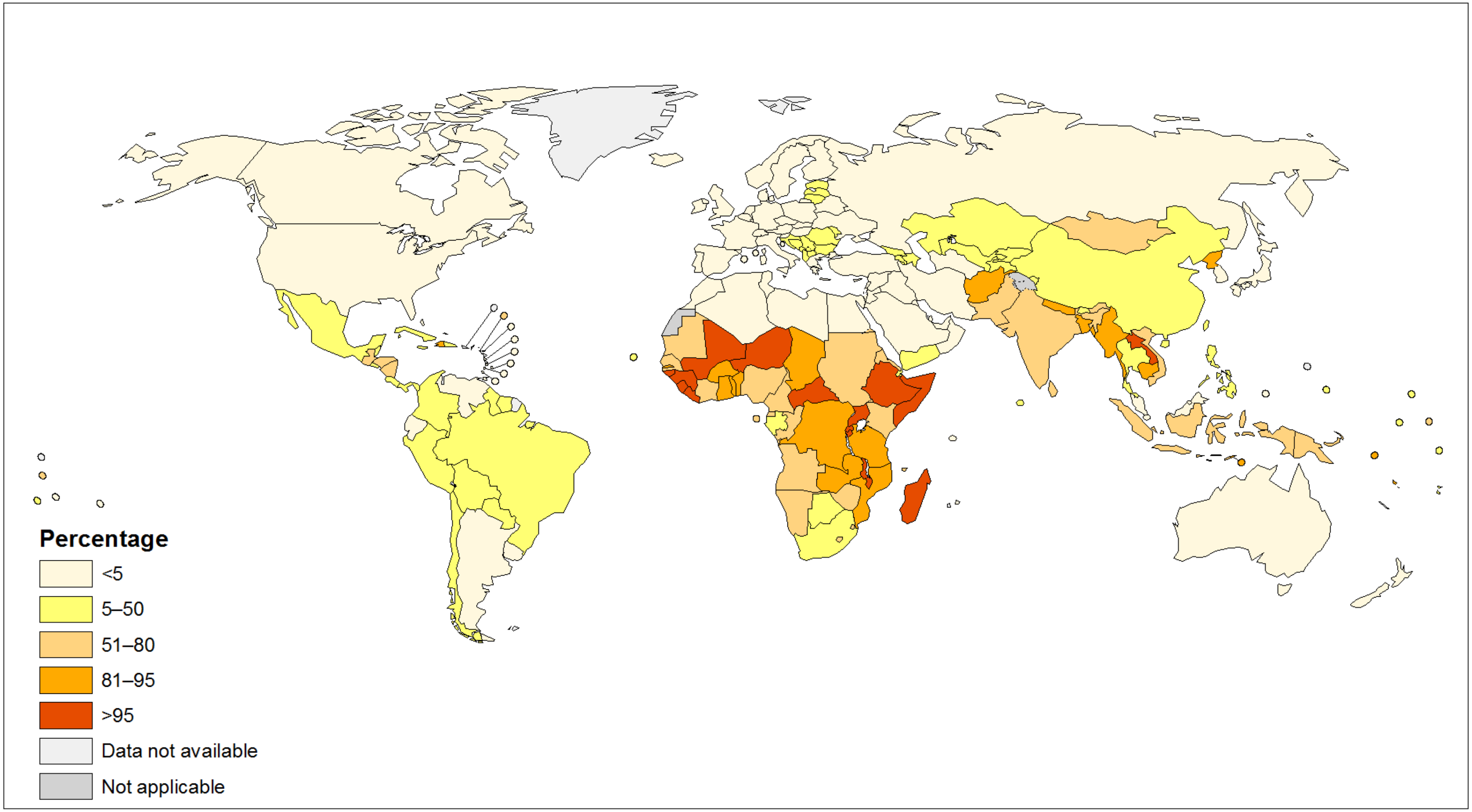
Smith, K,R,"Fuel Combustion Air Pollution, Exposure and Health: the Situation in Developing Countries," Annual Review of Energy and the Environment 18: 529-566, 1993.

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

GLOBAL HEALTH

and indoor air pollution

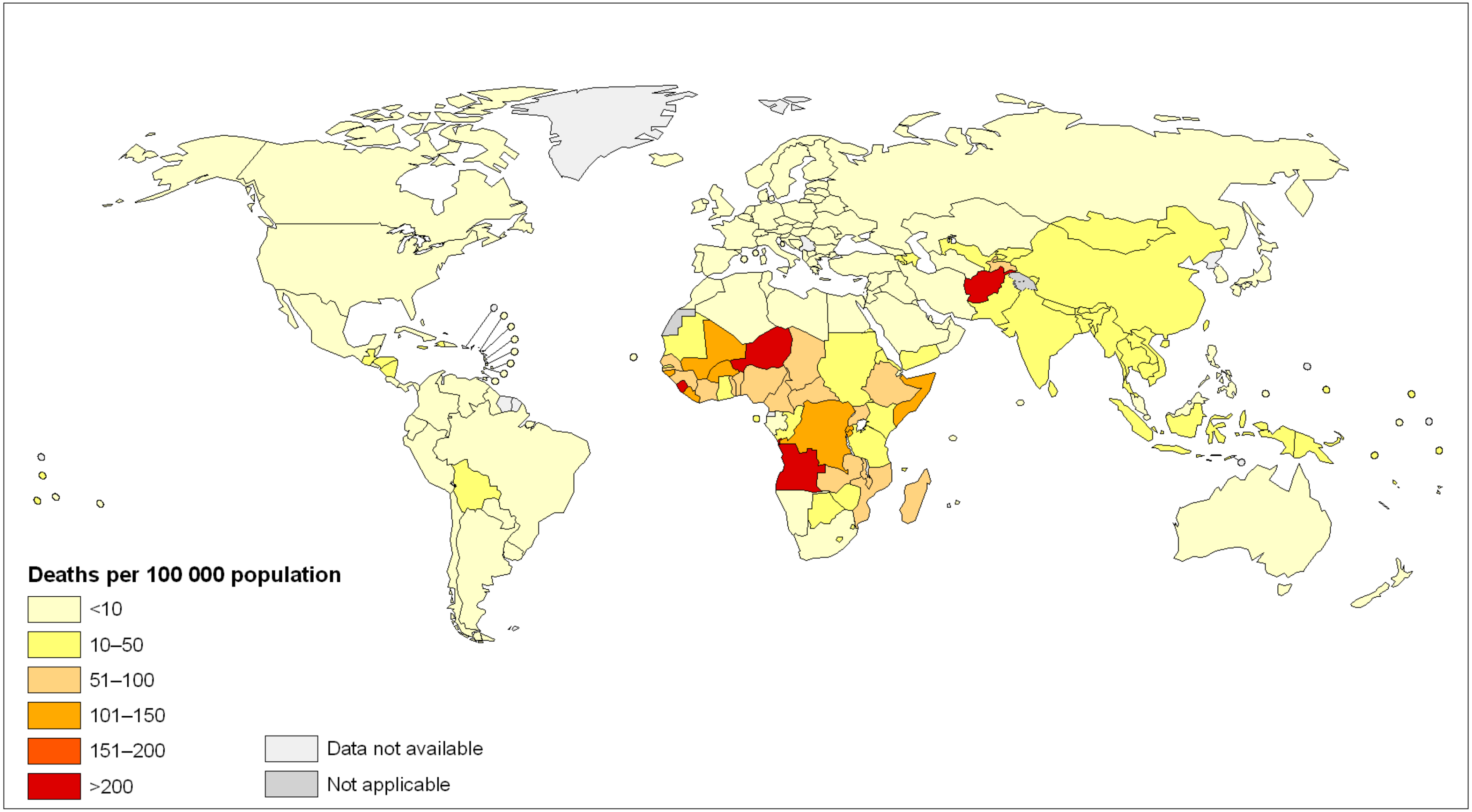
Population using solid fuels (%), 2010
Total



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

World Health
Organization

Deaths attributable to household air pollution, 2004



Data Source: World Health Organization
Map Production: Public Health Information
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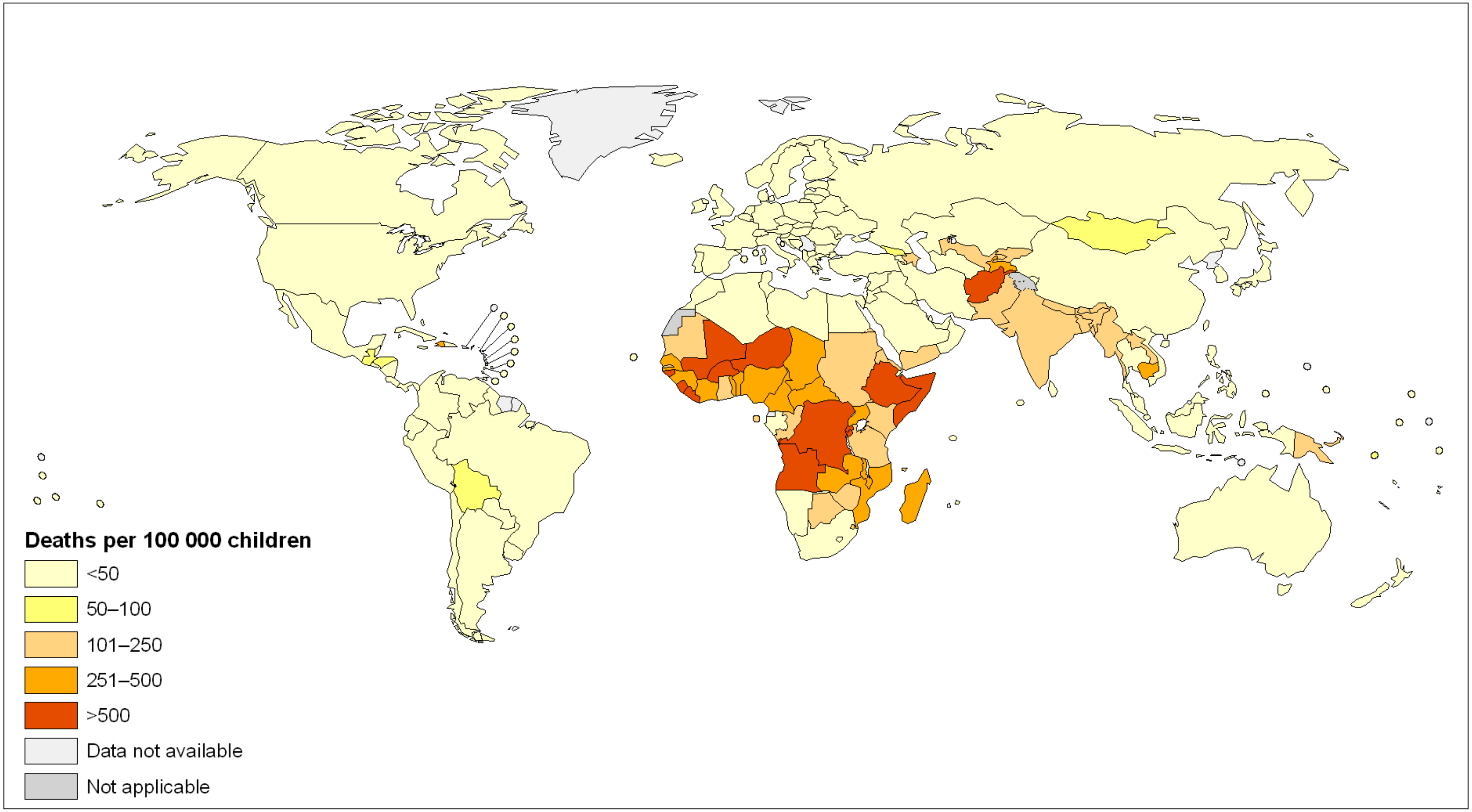
World Health Organization

World Health Organization

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



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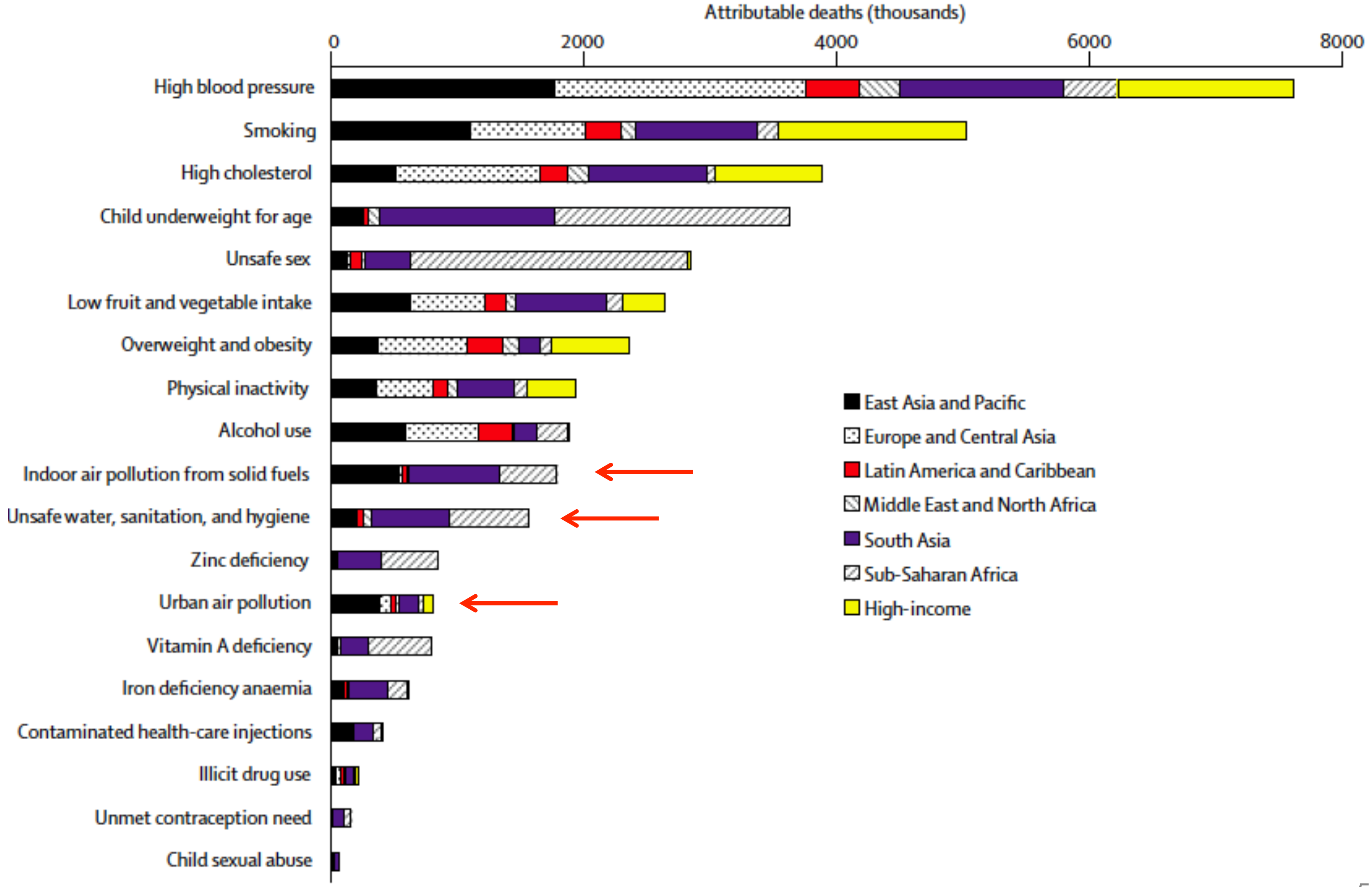
World Health Organization

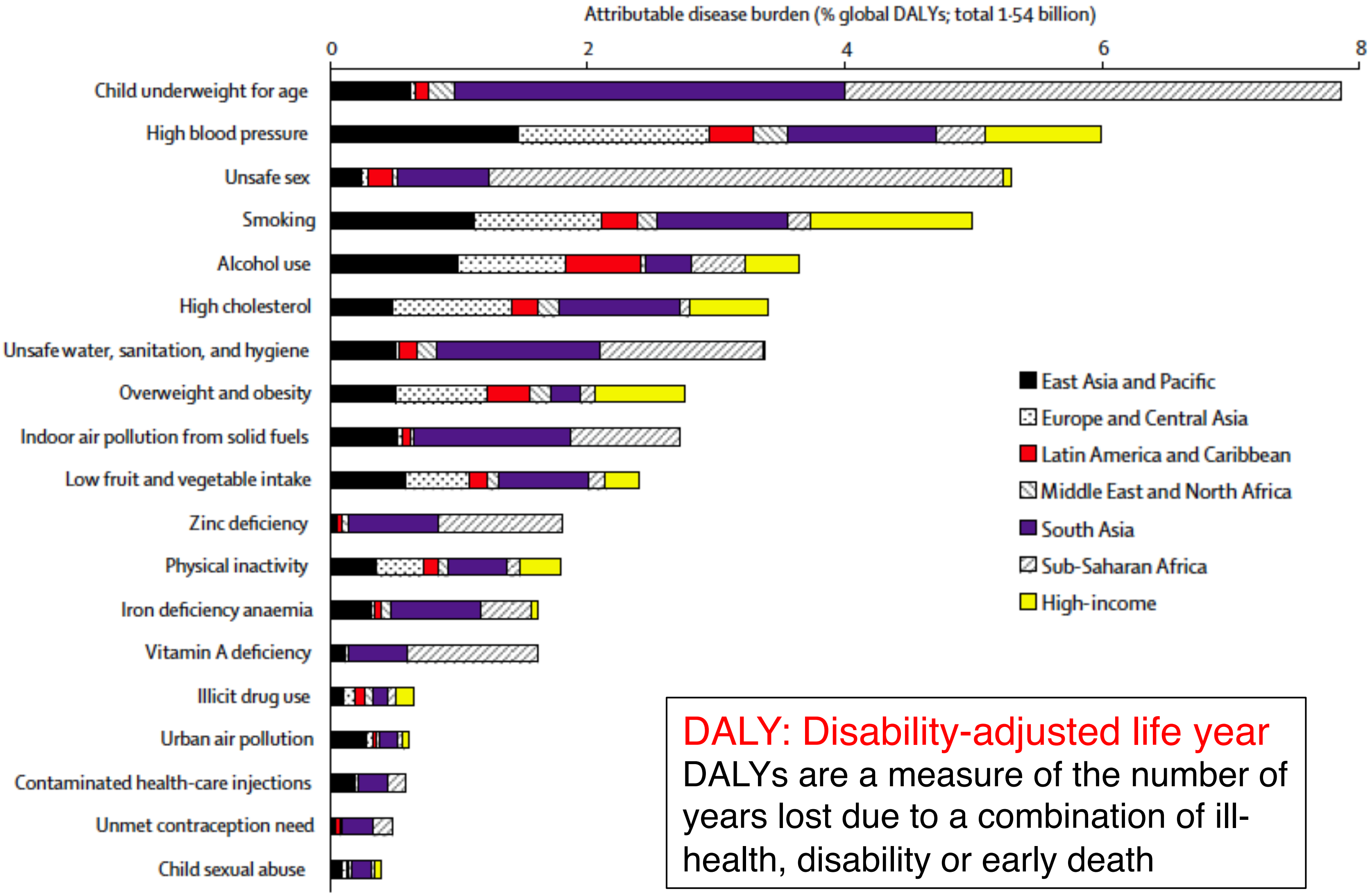
World Health Organization

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

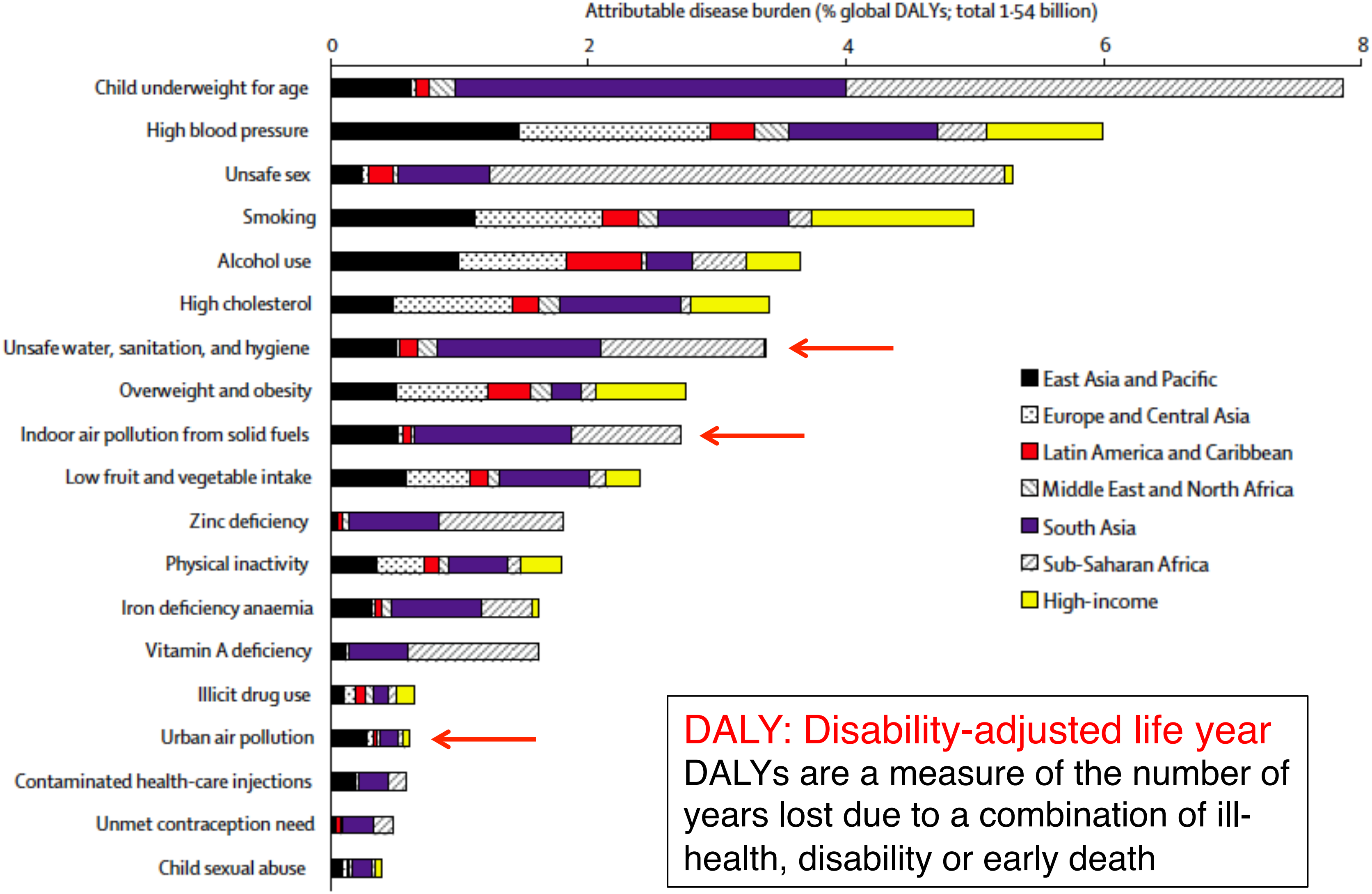
Lopez et al., 2006 *The Lancet*

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



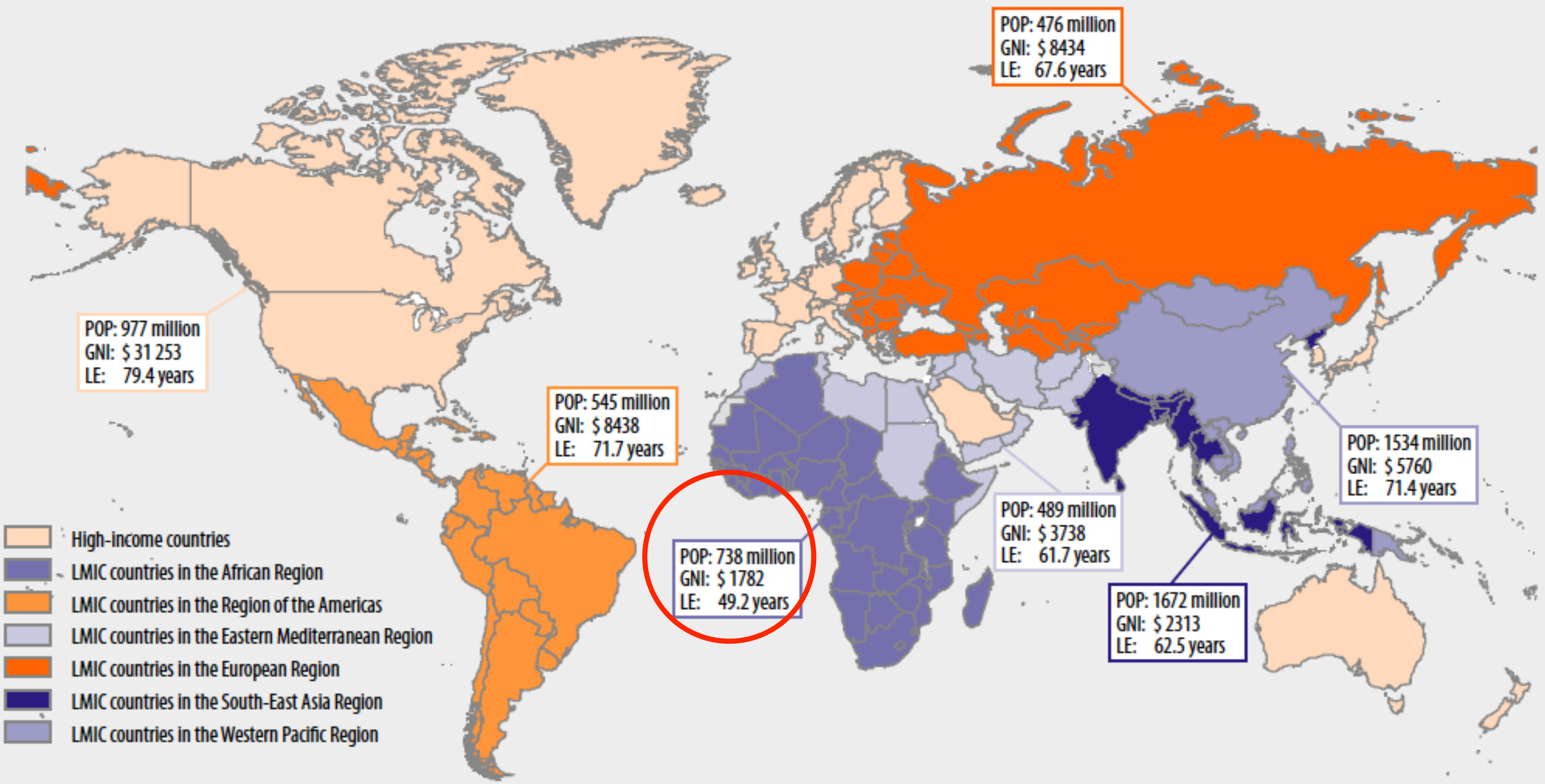
DALY: Disability-adjusted life year

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 life expectancy

Map 1: Low- and middle-income countries grouped by WHO region, 2004

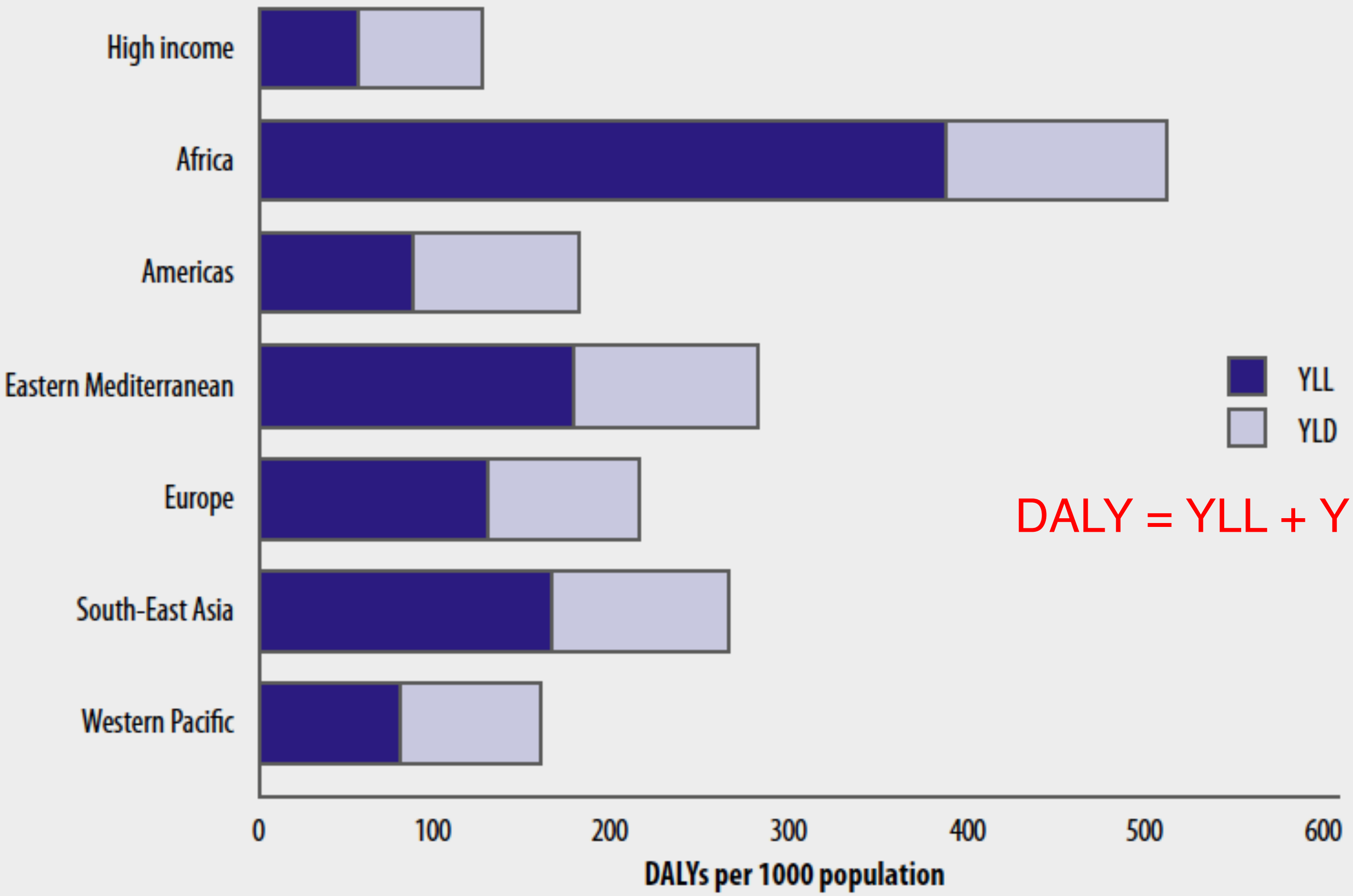


POP = population; **GNI** = gross national income per capita (international dollars); **LE** = life expectancy at birth;
LMIC = low- and middle-income countries

World Health Organization, The global burden of disease: 2004 update

Global DALYs

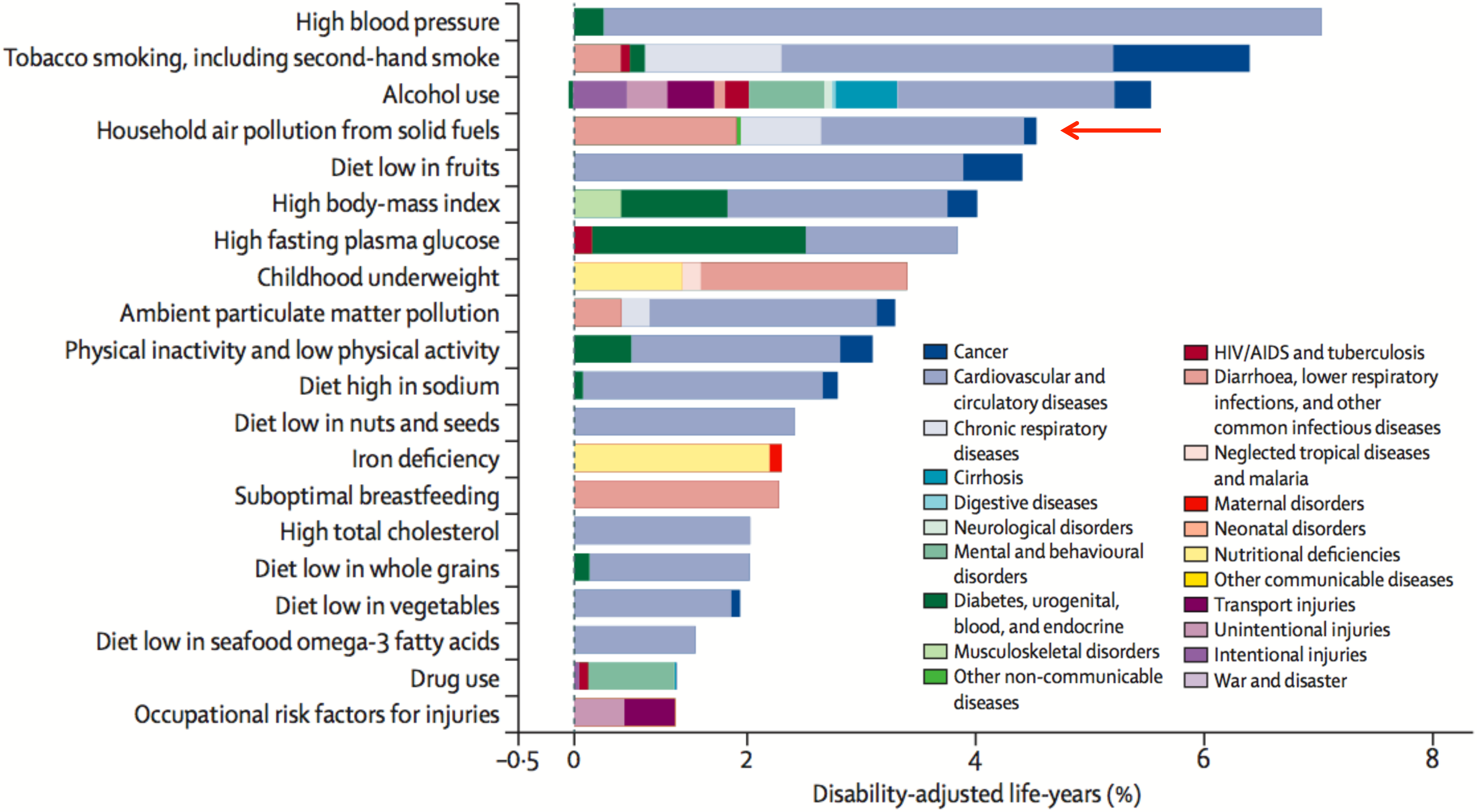
Figure 20 : YLL, YLD and DALYs by region, 2004



DALY = YLL + YLD

World Health Organization, The global burden of disease: 2004 update

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

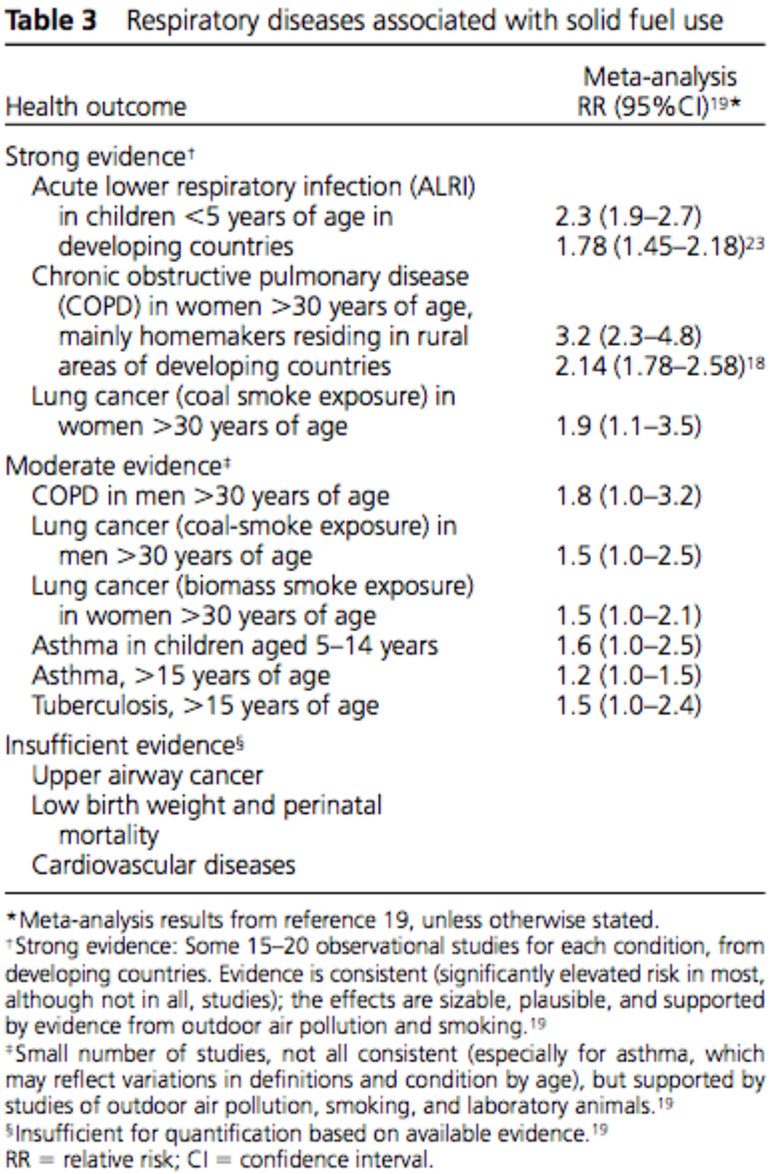


Table 3 Respiratory diseases associated with solid fuel use

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

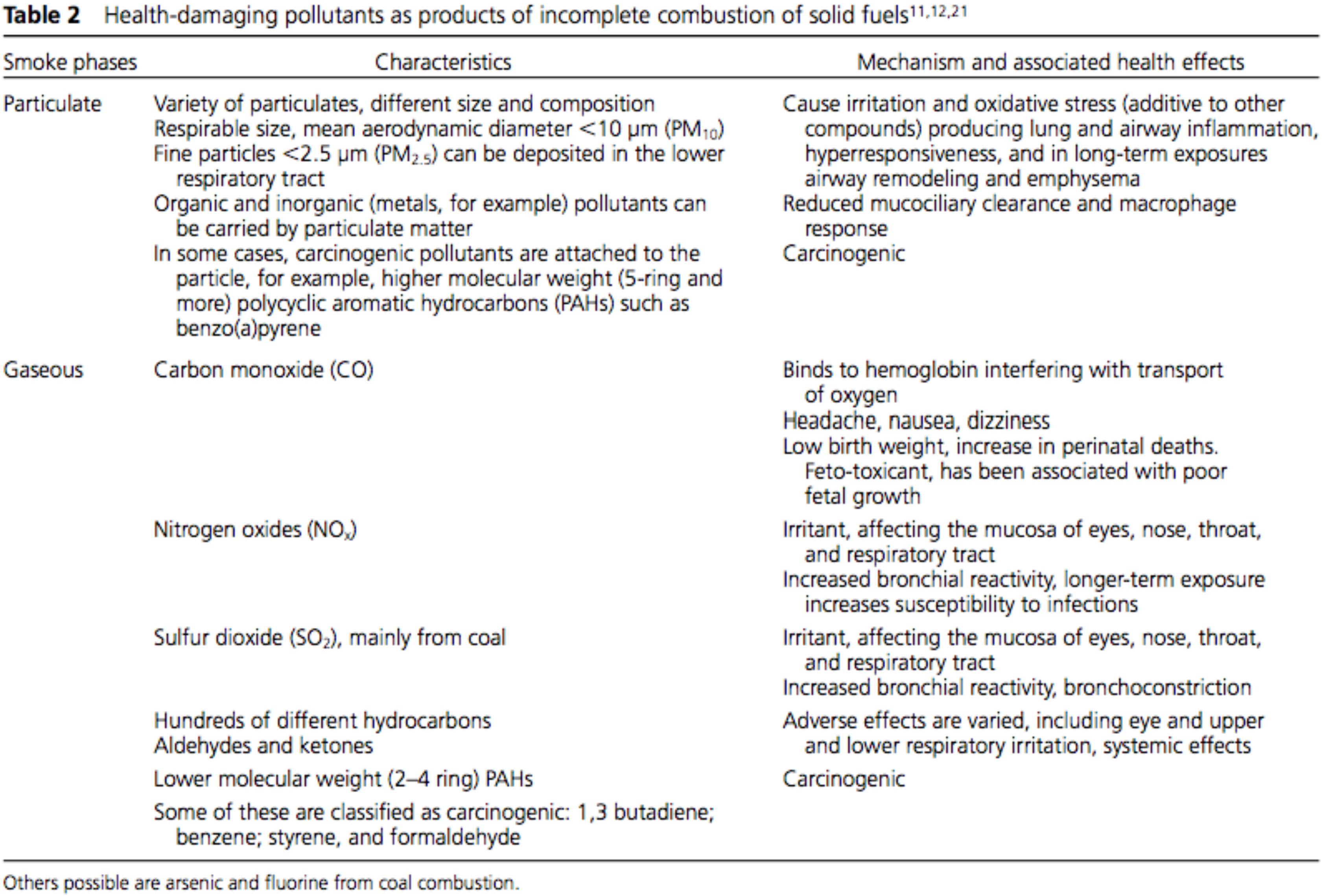


Table 2 Health-damaging pollutants as products of incomplete combustion of solid fuels[11,12,21]

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	

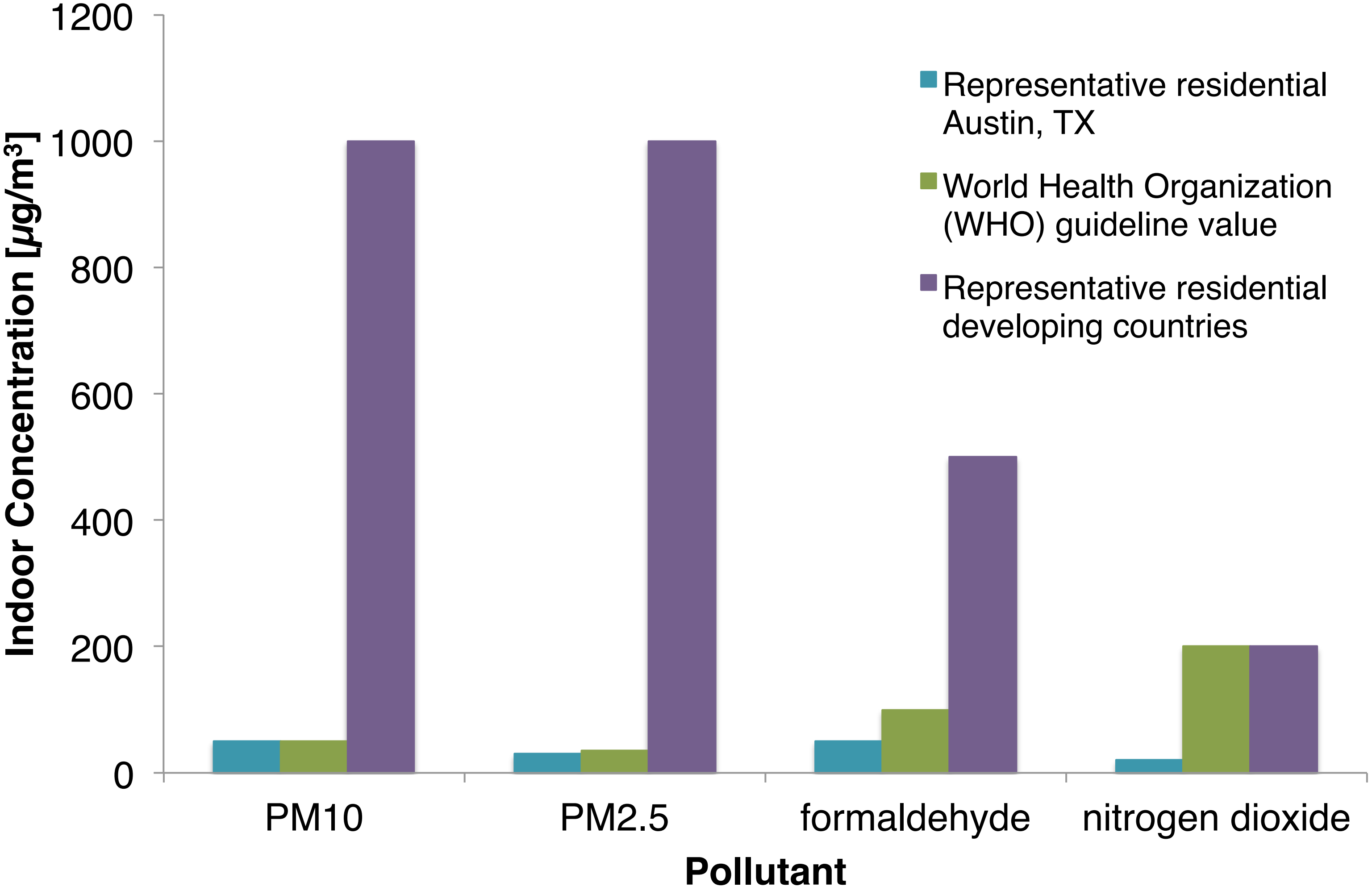
Others possible are arsenic and fluorine from coal combustion.

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

QUANTIFYING EXPOSURES

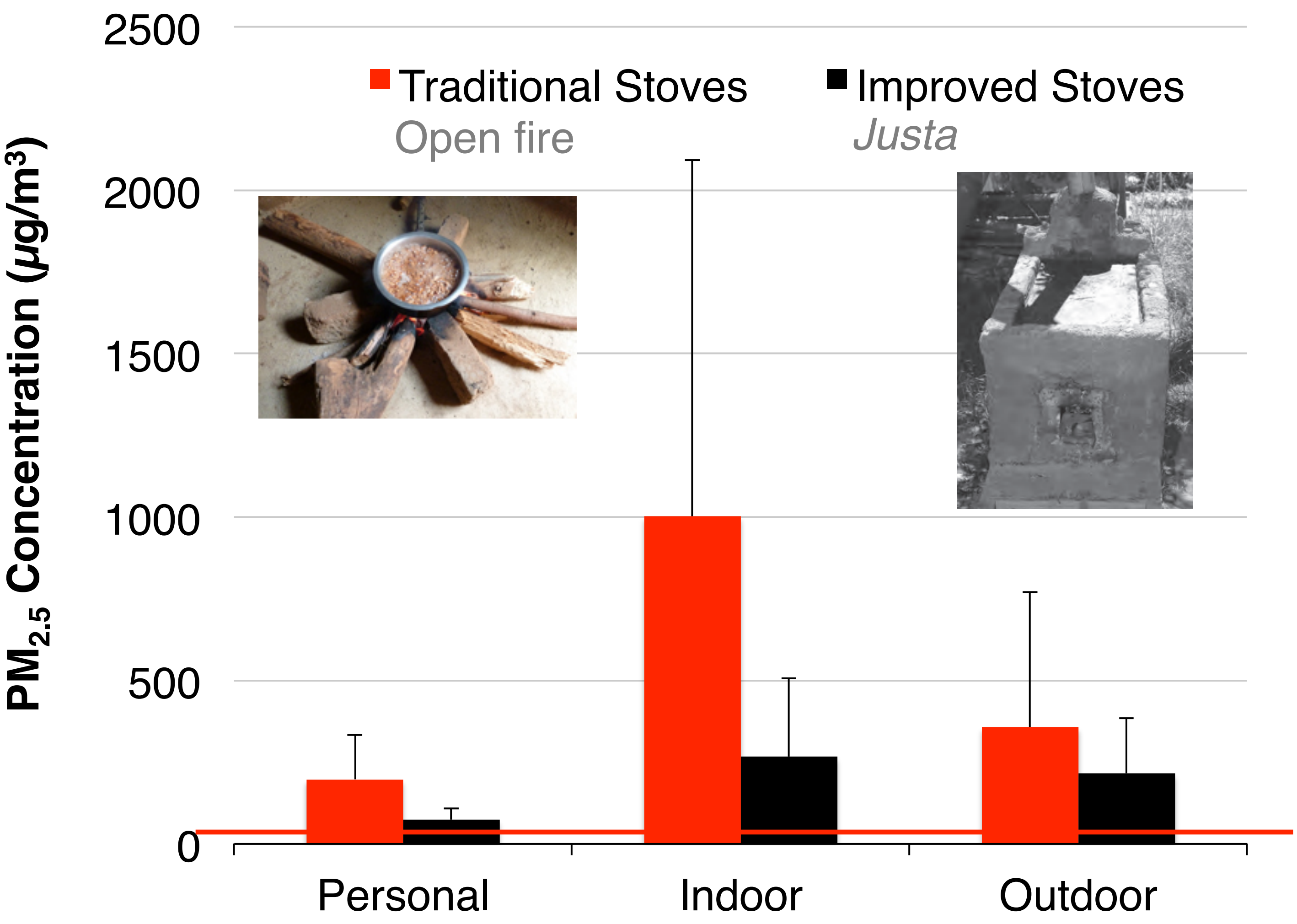
Indoor and household air pollution

Representative pollutant concentrations



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

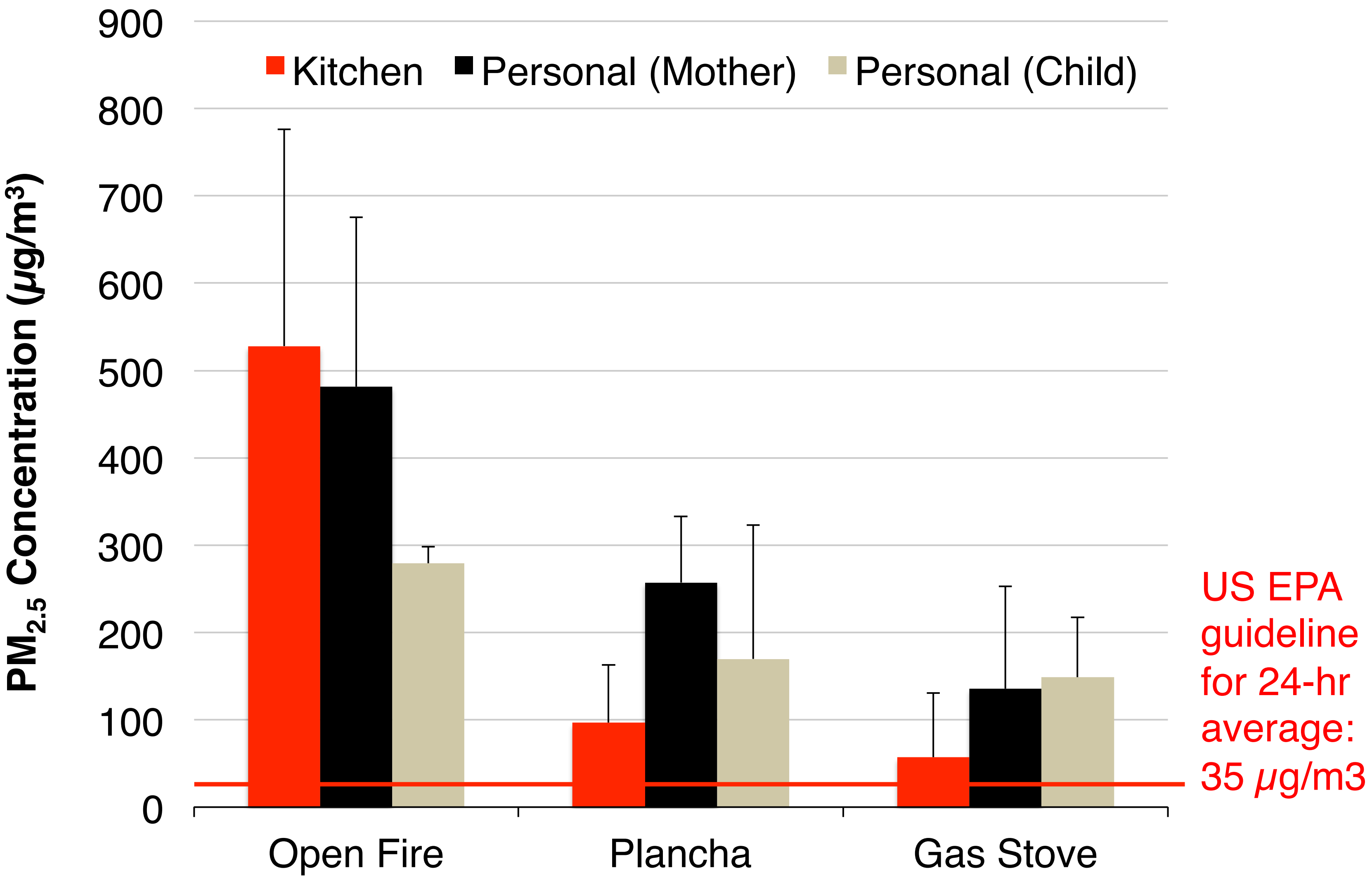
~30 homes each group



US EPA guideline for 24-hr average: 35 µg/m3

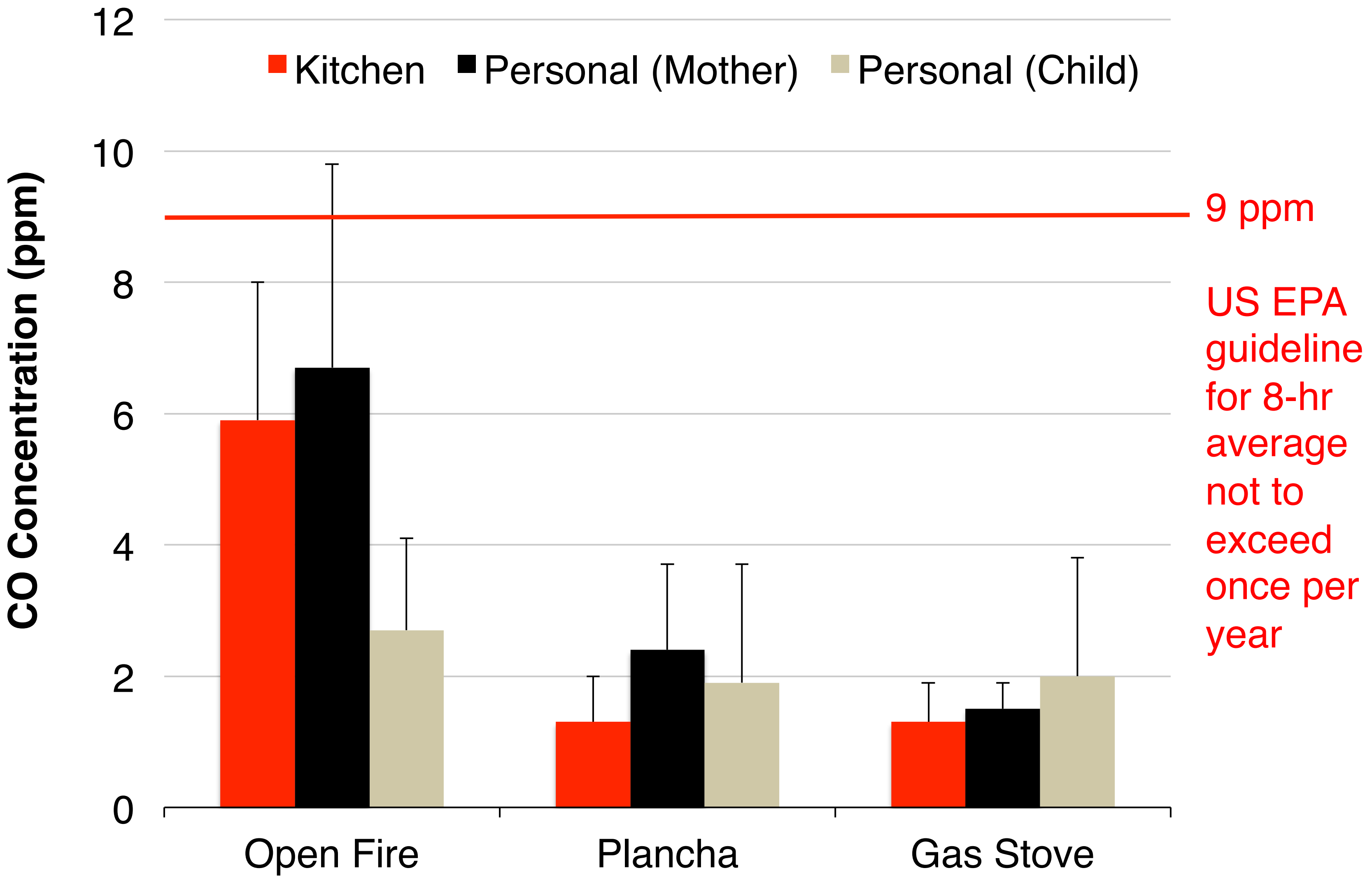
Clark et al., 2010 *Environmental Research*

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



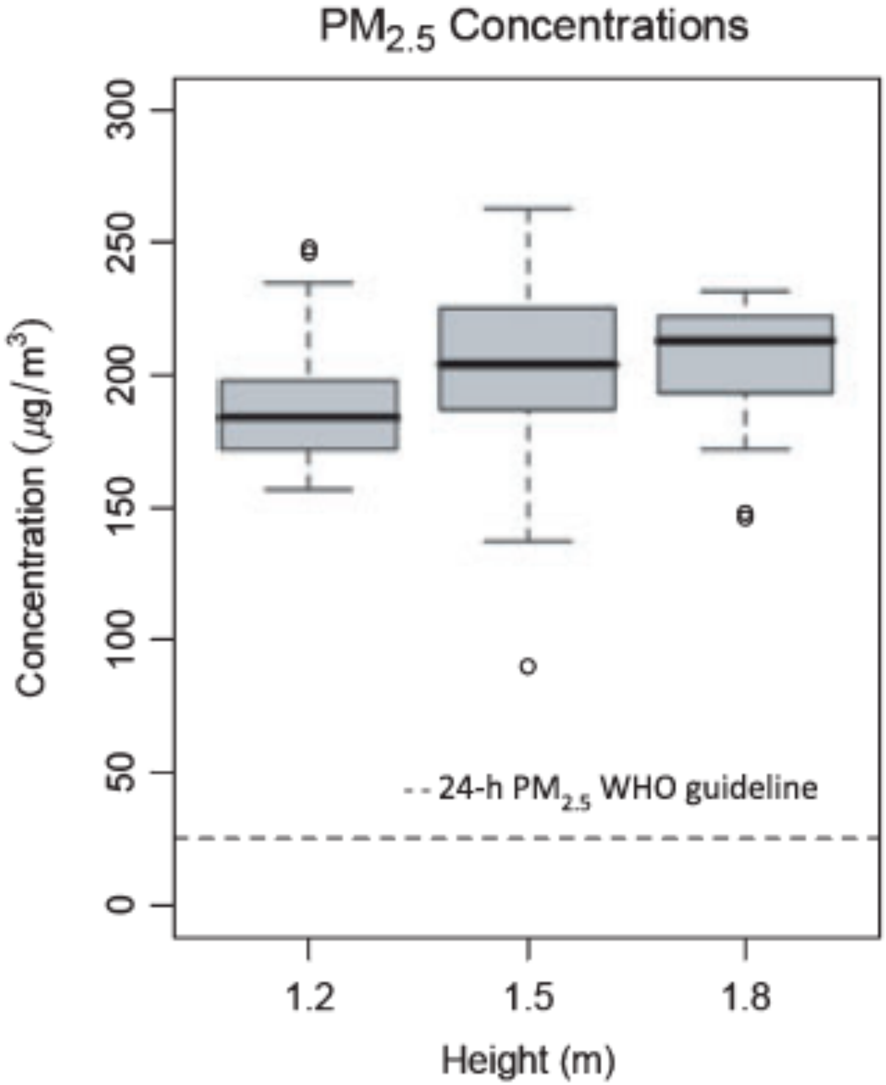
Naeher et al., 2000 *Indoor Air*

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

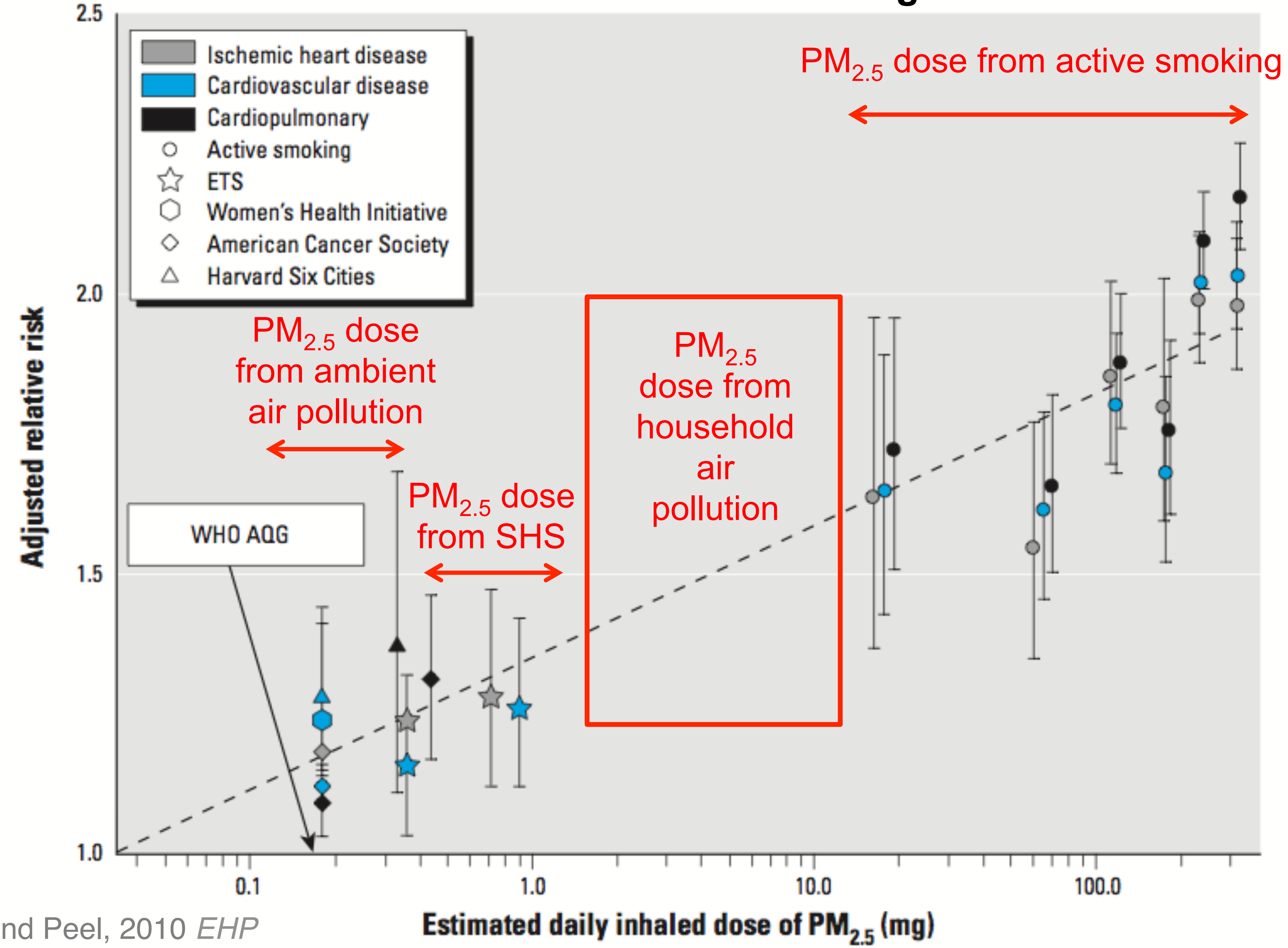
Why mostly only these two?

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?

Risk estimates for heart and lung disease

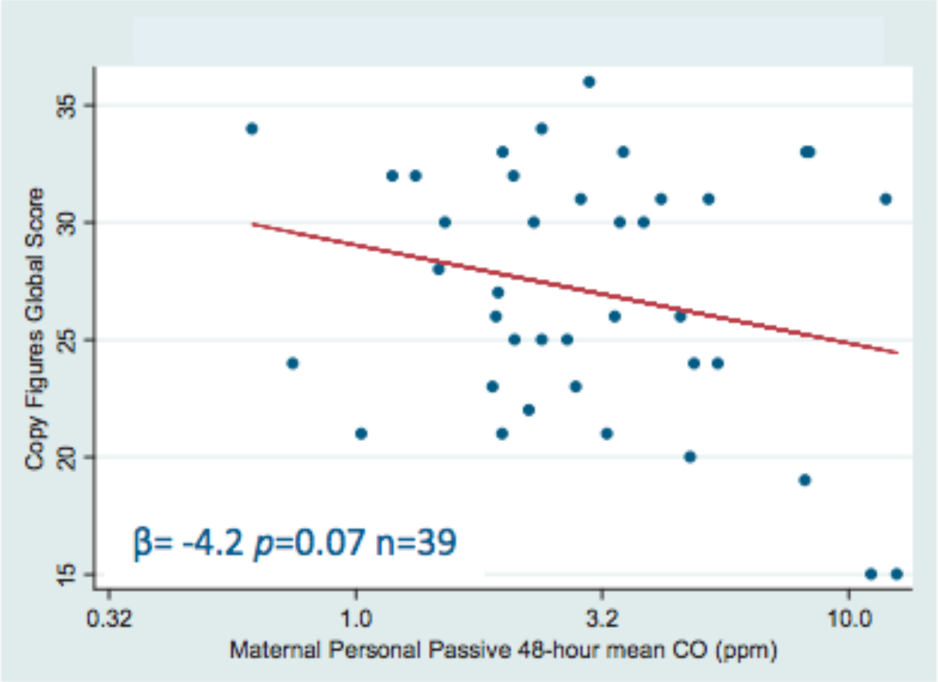


Smith and Peel, 2010 *EHP*

OTHER IMPACTS

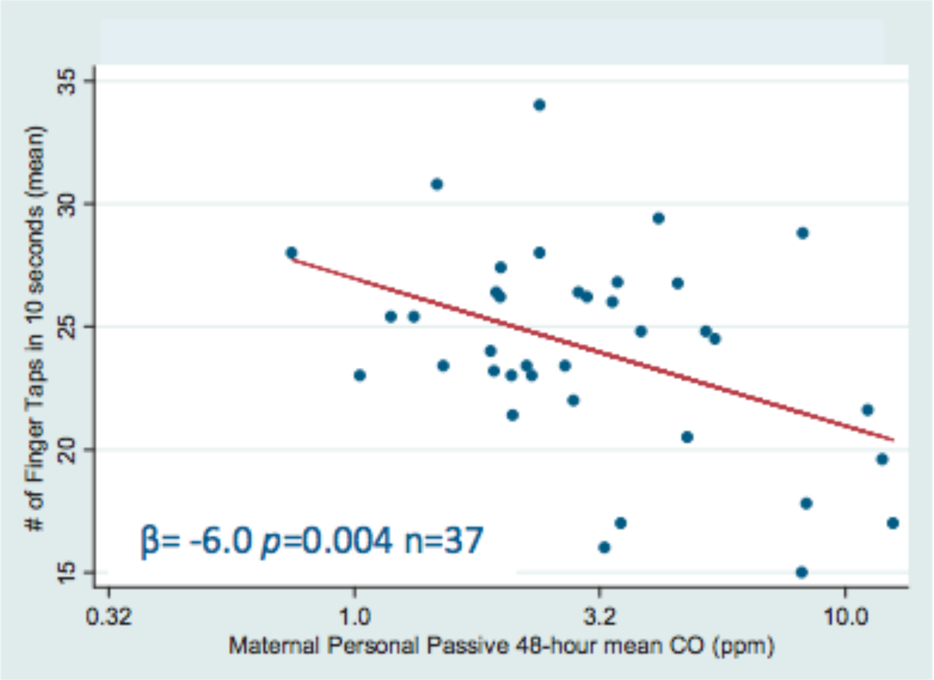
Recent evidence of neurological effects

(A) Bender Gestalt-II Copy Figures Phase



β= -4.2 *p*=0.07 n=39

(D) Reitan-Indiana Finger Tapping



β= -6.0 *p*=0.004 n=37

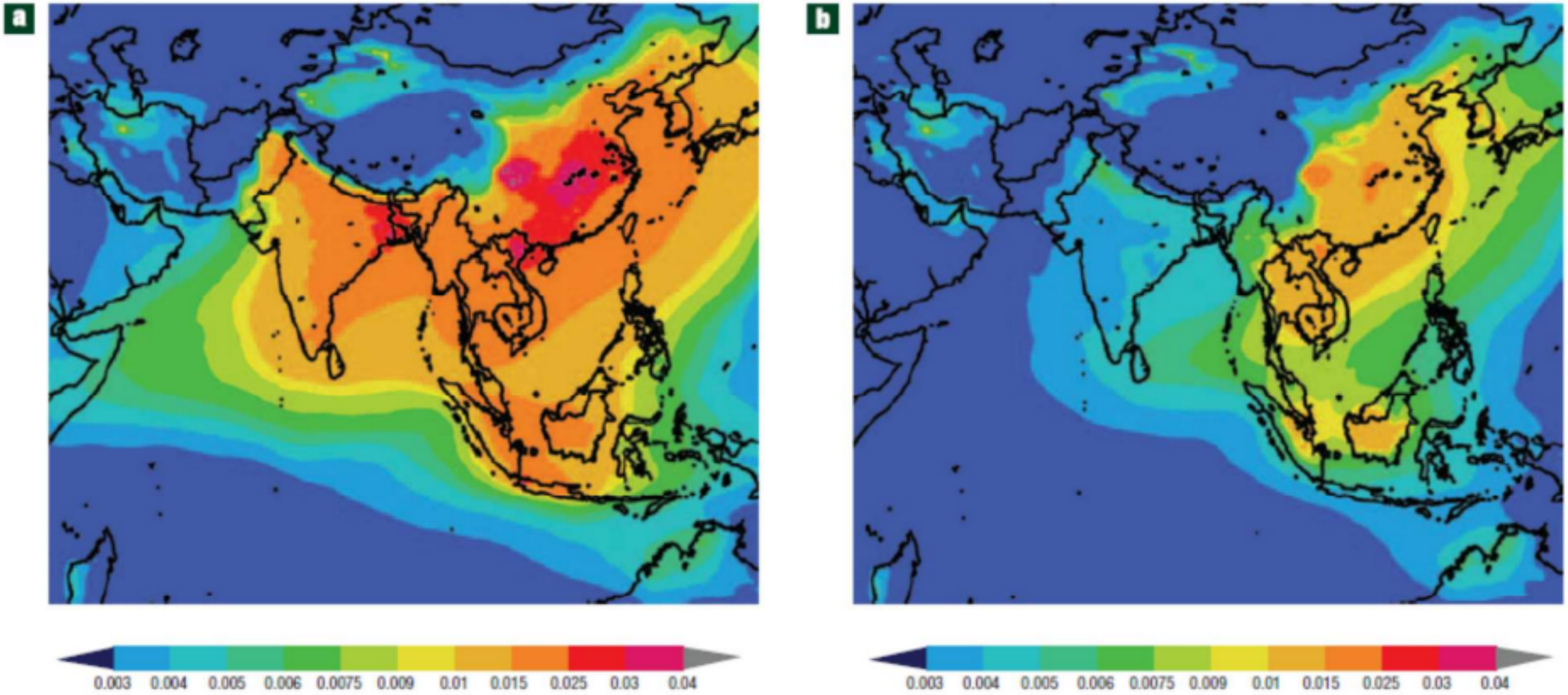
Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke

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:



With cookstoves **Without cookstoves**

- BC is a contributor to global warming

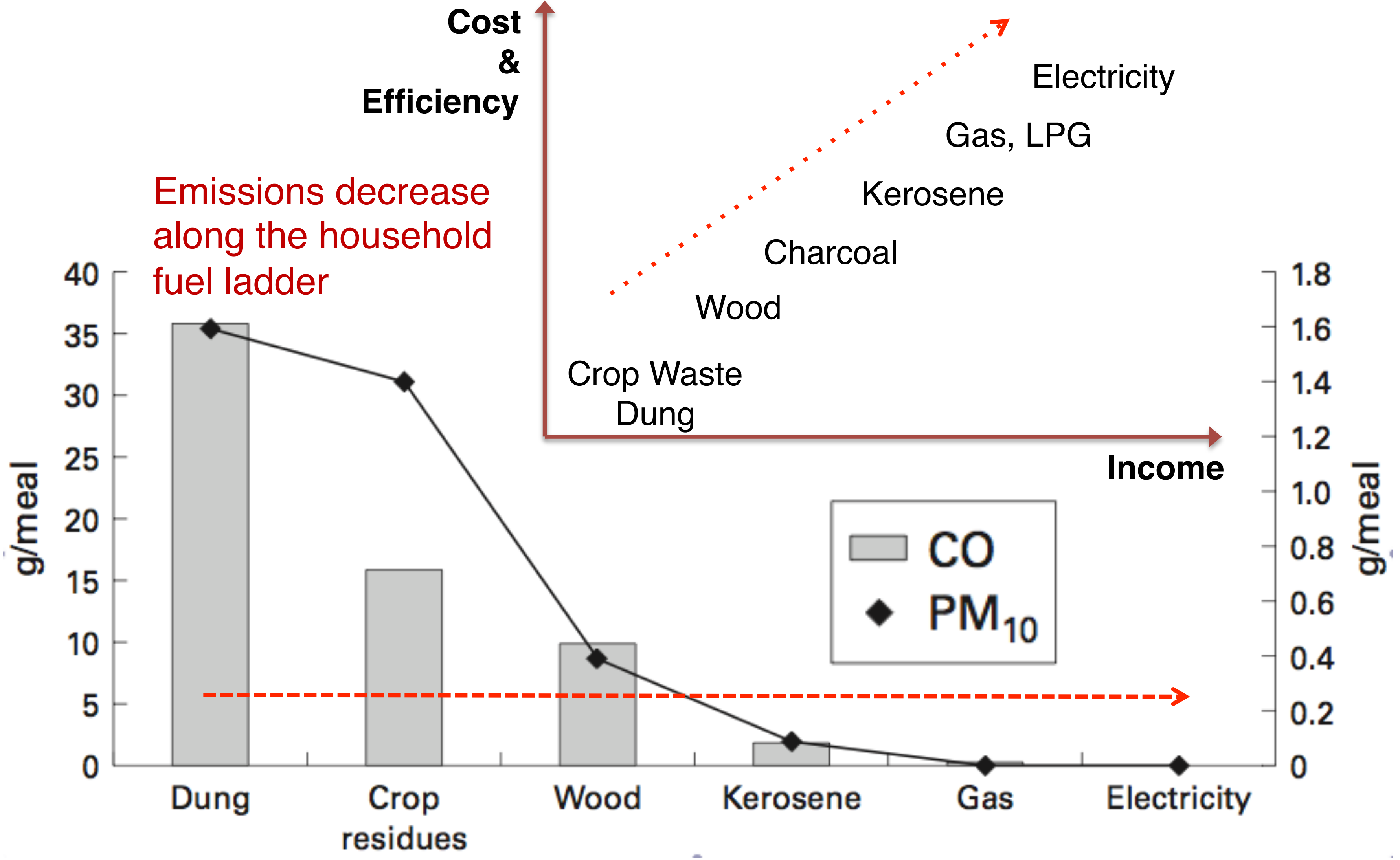
Ramanathan and Carmichael, 2008 *Nature Geoscience*

INTERVENTIONS

Clean cook stove campaigns

The energy ladder

We must move developing nations up the energy ladder!



Cost & Efficiency

Income

Dung

Crop Waste

Wood

Charcoal

Kerosene

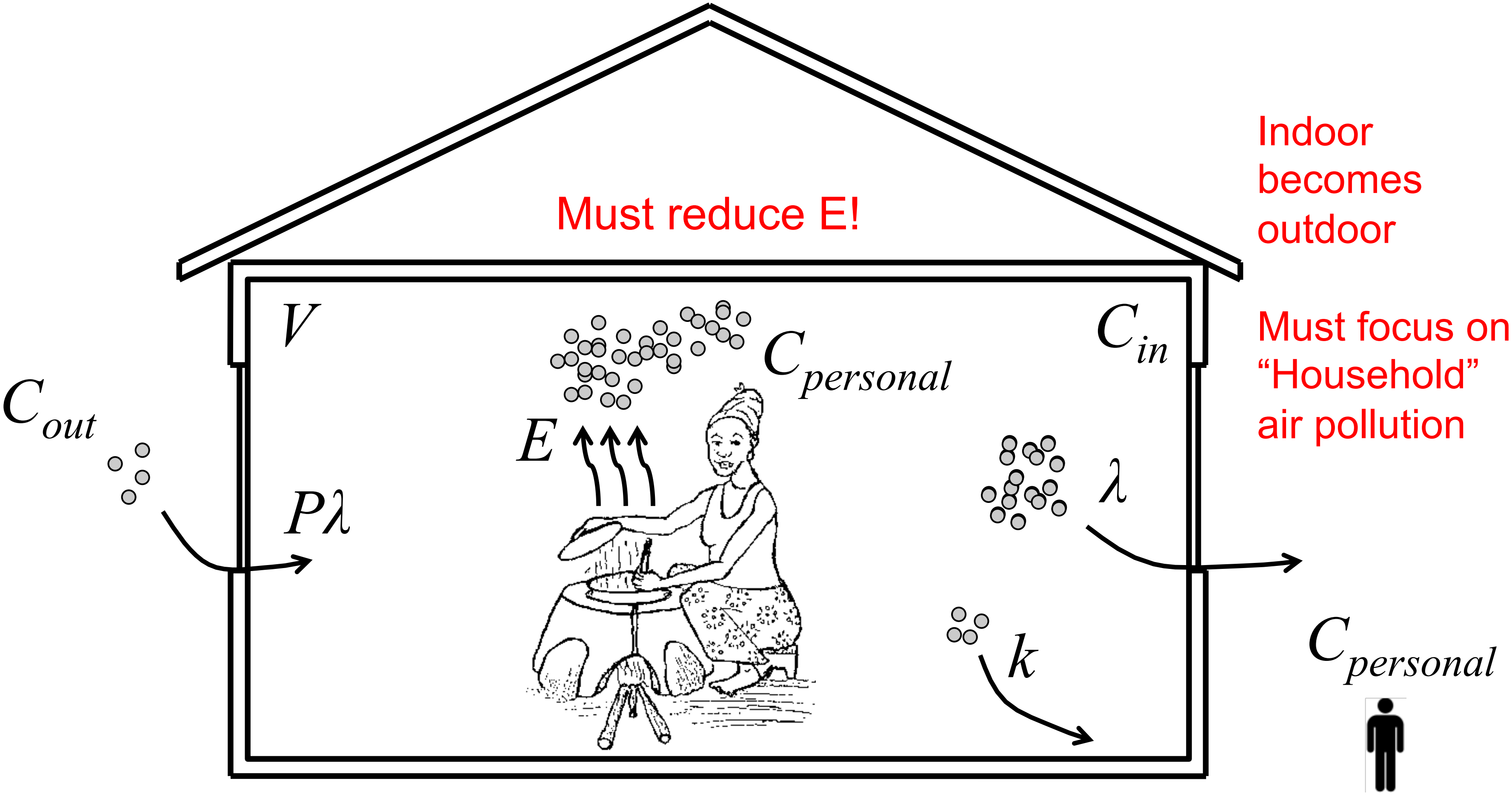
Gas, LPG

Electricity

Emissions decrease along the household fuel ladder

Smith et al., 1999, US Environmental Protection Agency

Fundamental parameters driving exposures



Indoor becomes outdoor

Must focus on “Household” air pollution

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!

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

$$\downarrow \quad \mathit{Stove\ Power} = \frac{\mathit{Cooking\ Energy\ Needed}}{\mathit{Cooking\ Time} \times \eta \quad \uparrow}$$

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

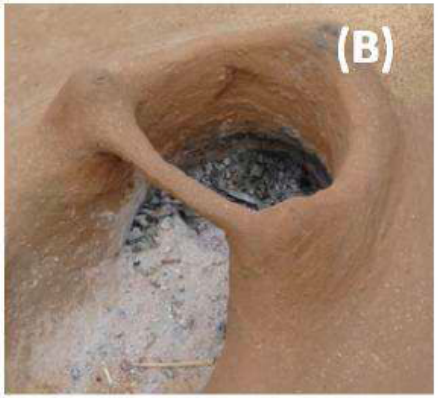
Source: SNV

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

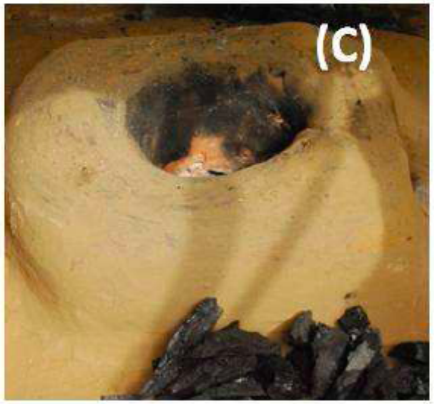
Example stoves

Traditional biomass *chulha*

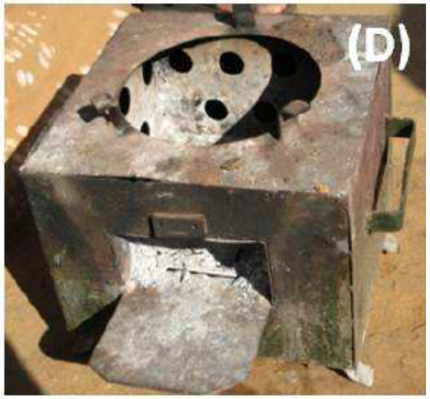
Traditional coal *chulha*



Improved *chulha*



Kerosene



Biogas

Commercial biomass *bhati*

Commercial coal *bhati*

LPG stove

Sahu et al., 2011, ES&T

Example stoves

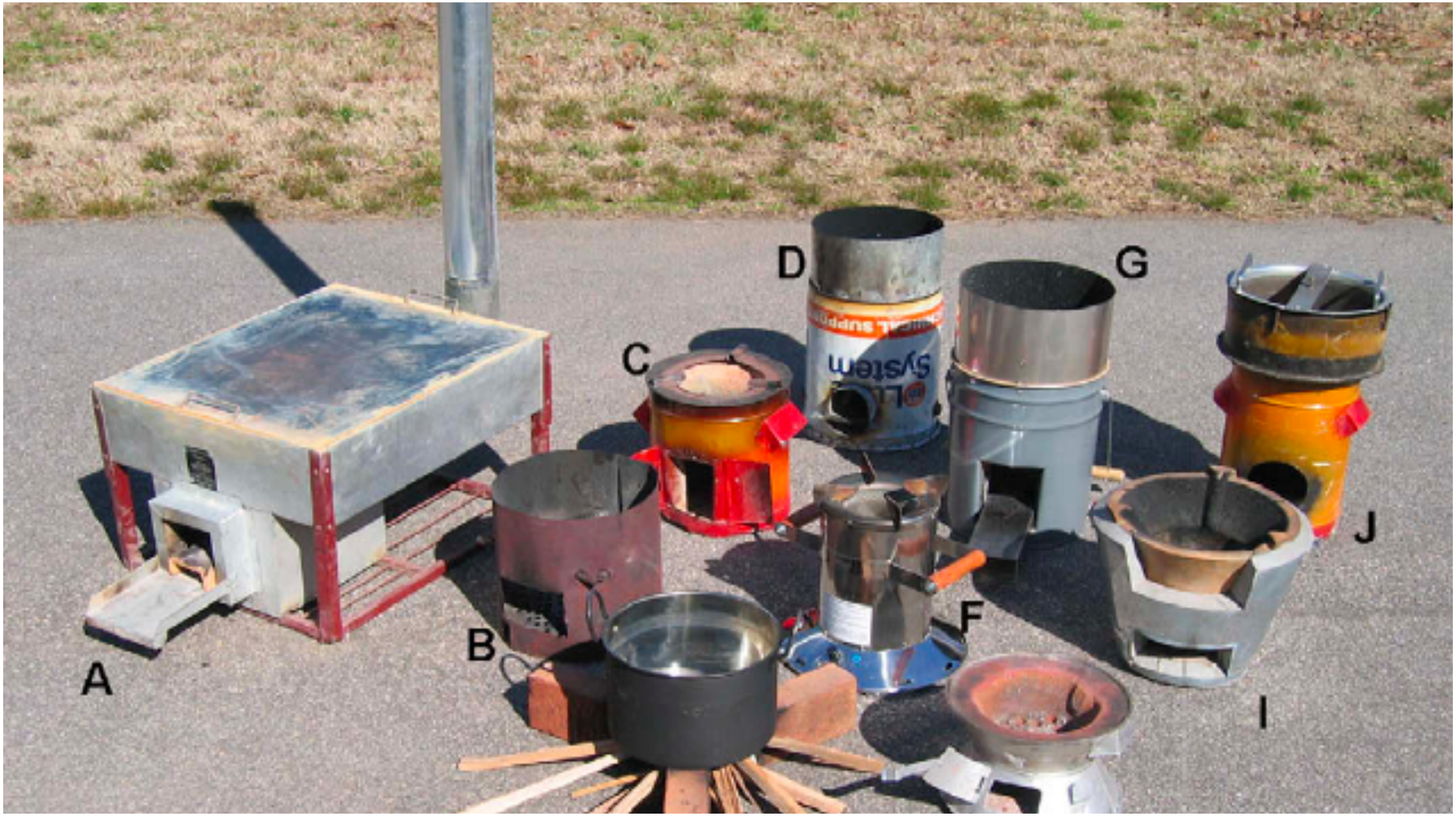


Fig. 1 – Stoves tested: A. Ecostove, B. VITA, C. UCODEA charcoal, D. WFP rocket, E. 3-stone fire, F. Philips, G. 6-brick rocket, H. Lakech charcoal, I. NLS, J. UCODEA rocket.

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

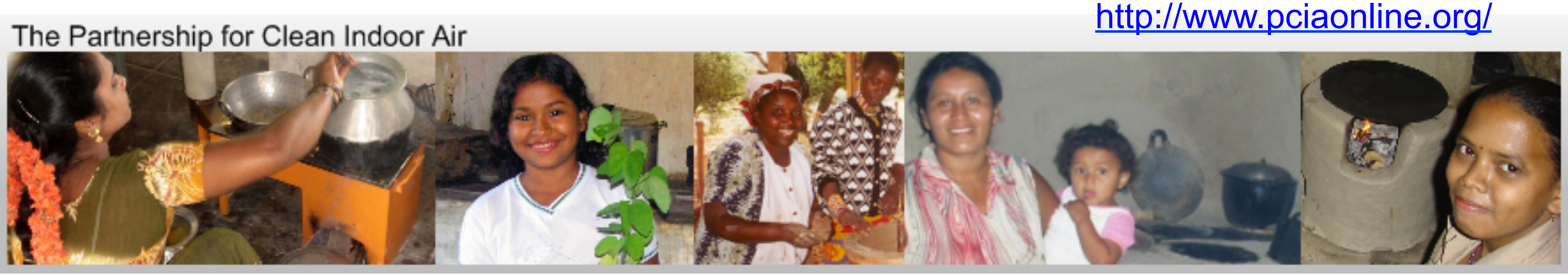
Barriers and research and implementation needs

- 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/



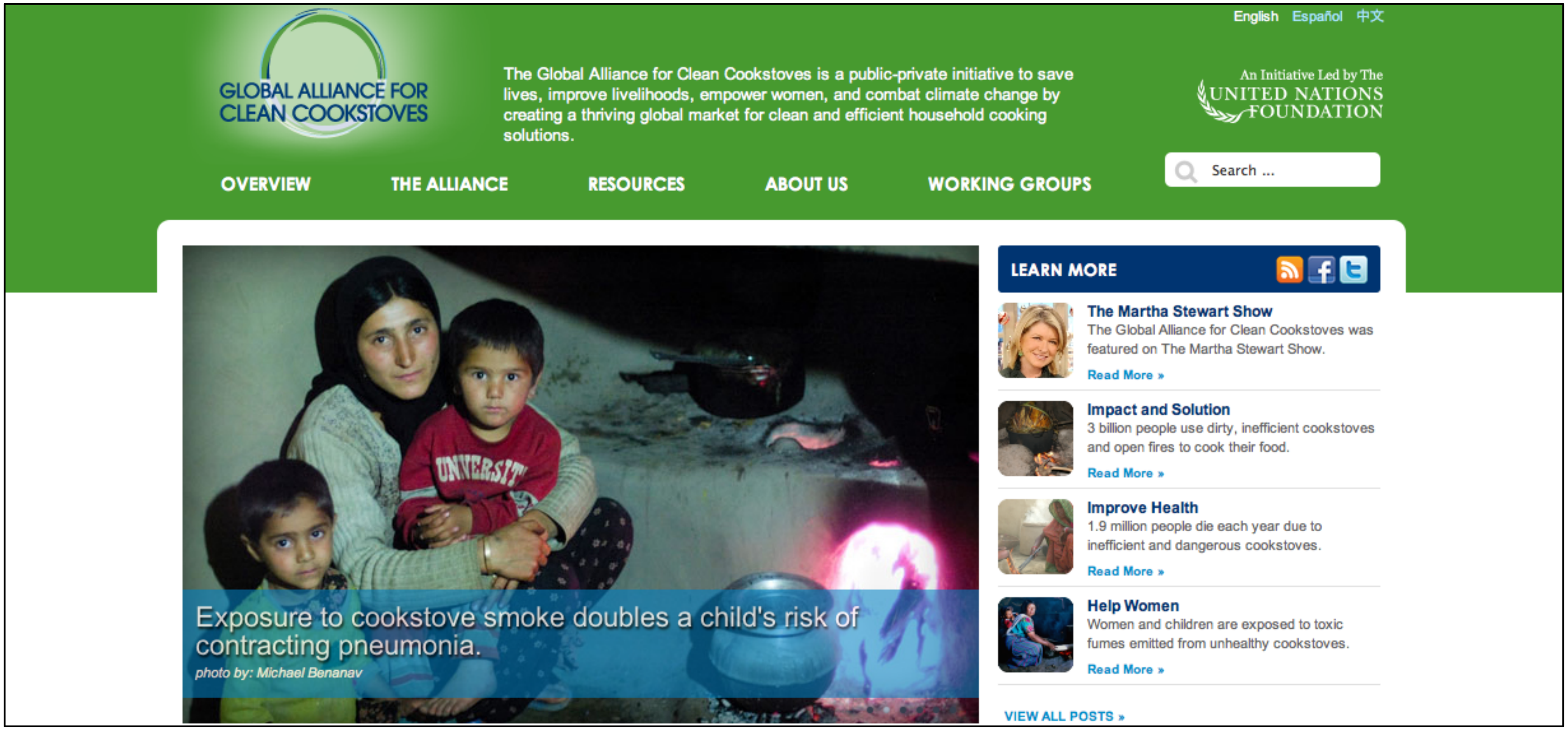
537 partner organizations contributing resources and expertise to reduce pollutant exposure from cooking and heating practices in households around the world.

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.



The Global Alliance for Clean Cookstoves is a public-private initiative to save lives, improve livelihoods, empower women, and combat climate change by creating a thriving global market for clean and efficient household cooking solutions.

Exposure to cookstove smoke doubles a child's risk of contracting pneumonia.

photo by: Michael Benanav

The Martha Stewart Show
The Global Alliance for Clean Cookstoves was featured on The Martha Stewart Show.
Read More »

Impact and Solution
3 billion people use dirty, inefficient cookstoves and open fires to cook their food.
Read More »

Improve Health
1.9 million people die each year due to inefficient and dangerous cookstoves.
Read More »

Help Women
Women and children are exposed to toxic fumes emitted from unhealthy cookstoves.
Read More »

VIEW ALL POSTS »

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/