COOKFIRES, CLIMATE, AND HEALTH:

THE UNFINISHED AGENDA OF INCOMPLETE COMBUSTION

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TERI University
Dehi, Sept 21, 2011
300-400 thousand years ago, hearths became a regular feature in human habitation

“On the earliest evidence for habitual use of fire”
Roebroeks and Villa, PNAS, 2011
Households using biomass or coal to cook

Comparative Risk Assessment (CRA) 2011- preliminary, Adair, et al.
The three major solid fuels
Biomass Cooking in History

• Today, ~43% use solid fuels, about 3 billion people

• Although the percentage is dropping, the absolute number is still rising.

• Perhaps 20 million people a year are added to the total each year.

• Indeed, there are more people using solid fuels today for cooking than the total world population in 1950

• Or any year previously
Woodsmoke is natural – how can it hurt you?

Or, since wood is mainly just carbon, hydrogen, and oxygen, doesn’t it just change to CO$_2$ and H$_2$O when it is combined with oxygen (burned)?

Reason: the combustion efficiency is far less than 100%
Energy flows in a well-operating traditional wood-fired Indian cooking stove

A Toxic Waste Factory!!

Typical biomass cookstoves convert 6-20% of the fuel carbon to toxic substances

Into Pot: 2.8 MJ (18%)
In PIC: 1.2 MJ (8%)
Waste Heat: 11.3 MJ (74%)

PIC = products of incomplete combustion = CO, HC, C, etc.

Source: Smith, et al., 2000
Toxic Pollutants in Biomass Fuel Smoke from Simple (poor) Combustion

- Small particles, CO, NO₂
- Hydrocarbons
  - 25+ saturated hydrocarbons such as *n-hexane*
  - 40+ unsaturated hydrocarbons such as *1,3 butadiene*
  - 28+ mono-aromatics such as *benzene & styrene*
  - 20+ polycyclic aromatics such as *benzo(α)pyrene*
- Oxygenated organics
  - 20+ aldehydes including *formaldehyde & acrolein*
  - 25+ alcohols and acids such as *methanol*
  - 33+ phenols such as *catechol & cresol*
  - Many quinones such as *hydroquinone*
  - Semi-quinone-type and other radicals
- Chlorinated organics such as *methylen chloride* and *dioxin*

Toxic Pollutants in Biomass Fuel Smoke from Simple (poor) Combustion

Organics known to be mutagens, immune system suppressants, severe irritants, inflammation agents, central nervous system depressants, cilia toxins, endocrine disrupters, or neurotoxins.

Several chemicals firmly established as human carcinogens.

Other toxic inorganic chemicals.

- 25+ alcohols and acids such as methanol
- 33+ phenols such as catechol & cresol
- Many quinones such as hydroquinone
- Semi-quinone-type and other radicals
  - Chlorinated organics such as methylene chloride and dioxin

Source: Naeher et al, J Inhal Tox, 2007
Health-Damaging Air Pollutants From Typical Woodfired Cookstove in India.

Typical Health-based Standards

Wood: 1.0 kg Per Hour in 15 ACH 40 m3 kitchen

Best single indicator

IARC Group 1 Carcinogens

- Carbon Monoxide: 150 mg/m³
  - Typical Indoor Concentrations: 10 mg/m³
- Particles: 3.3 mg/m³
  - Typical Indoor Concentrations: 0.1 mg/m³
- Benzene: 0.8 mg/m³
  - Typical Indoor Concentrations: 0.002 mg/m³
- 1,3-Butadiene: 0.15 mg/m³
  - Typical Indoor Concentrations: 0.0003 mg/m³
- Formaldehyde: 0.7 mg/m³
  - Typical Indoor Concentrations: 0.1 mg/m³
First person in human history to have her exposure measured doing the oldest task in human history

Emissions, yes, but what about exposures?

Kheda District, Gujarat, 1981
India in 2005

71% households use solid fuel for cooking

Venkataraman et al. 2010

Percent of households using biomass as their primary cooking fuel

* Indicates >1% Coal Use

*Includes coal use: J: 17%; WB: 13%; C: 2%; O: 2%
Estimated PM2.5 for solid fuel using households in India

- USEPA Standard: 15 mg/m3
- WHO Guideline: 10-35 mg/m3
- Preliminary result from CRA Balakrishnan et al.

~400 mg/m3 average

24 Hrs PM2.5 Concentration (mg/m3)
Three outcomes qualified with sufficient evidence to be included in the WHO CRA of 2004.
Global Burden of Disease from Top 10 Risk Factors
plus selected other risk factors

- Underweight
- Unsafe sex
- Blood pressure
- Tobacco
- Alcohol
- Unsafe water/sanitation
- Child cluster vaccination*
- Cholesterol
- Lack of Malaria control*
- Indoor smoke from solid fuels
- Overweight
- Occupational hazards (5 kinds)
- Road traffic accidents*
- Physical inactivity
- Lead (Pb) pollution
- Urban outdoor air pollution
- Climate change
- Chernobyl per month

Percent of All DALYs

- 1.6 million premature deaths/year
- 0.8 million premature deaths/year
- 0.12 million premature deaths/year
Indian Burden of Disease from Top 10 Risk Factors and Selected Other Risk Factors


Percent of All DALYs in 2000

- Underweight
- Unsafe water/sanitation
- Indoor smoke
- Unsafe sex
- Iron deficiency
- Tobacco
- Blood pressure
- Child cluster Vaccination
- Cholesterol
- Road traffic accidents
- Zn Deficiency
- Low fruit & veg
- Occupational (5 kinds)
- Lead (Pb)
- Climate change
- Urban outdoor air

420,000 premature deaths/year
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<tr>
<th>Code</th>
<th>Cause</th>
<th>Total</th>
<th>0-4</th>
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<th>30-44</th>
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Global Burden of Disease Database and Comparative Risk Assessment Being completely updated for late 2011 release.
Diseases for which we have epidemiological studies - 2010

ALRI/Pneumonia (meningitis)
Low birth weight
Stillbirth
Cognitive Impairment
Birth defects?
Asthma?

Chronic obstructive lung disease
Interstitial lung disease
Cancer (lung, NP, cervical, aero-digestive)
Blindness (cataracts, opacity)
Tuberculosis
Heart disease?
Burns, health and safety impacts of fuel gathering?

Blood pressure
ST-segment
Summary of Endpoints in New CRA for Household Air Pollution

• New estimates for diseases in previous CRA
  – Pneumonia in children
  – COPD in adults (male and female)
  – Lung cancer in adults (male and female)

• Diseases now included
  – Low birth weight
  – Cataracts
  – Heart disease

• Still unclear – not included
  – TB
  – Asthma
  – Other cancers
Story of Two Conferences

• Air pollution conference
  – High exposures to large vulnerable population
  – No more health effects work needed

• International health conference
  – Still doubt about causality
  – Need to know exact benefit to be expected

• Where are your randomized controlled trials?
History of an RCT

- ~1980: Early studies of health effects in Nepal and elsewhere
- 1981: First measurements of pollution levels in India
- 1984: International meeting to decide on needed research
  - Chose randomized control trial (RCT) of ALRI
- 1986-89: Unfunded proposals to do RCT in Nepal
- 1990: WHO establishes committee to find best sites
- 1990-1992: Criteria established and site visits made
- 1992: Highland Guatemala chosen
- 1991-1999: Pilot studies to establish data needed for proposal
- 1996-1999: Unfunded proposals
- 2001: NIEHS funding secured
- 2002-2005: Fieldwork completed
- 2011: Main results published – in press Sep
- 25+ years from deciding to conduct RCT to results!
First Randomized Trial
In Air Pollution History*

After a worldwide search, chose a site in
in the Guatemalan Highlands

* In normal populations
RESPIRE: (Randomized Exposure Study of Pollution Indoors and Respiratory Effects)

Highland Guatemala

Traditional 3-stone open fire

Chimney woodstove
Approximate Mean PM2.5 exposure in 100s of ug/m3
Preliminary MD-diagnosed Severe Pneumonia

Approximate Mean PM2.5 exposure in 100s of ug/m3
Preliminary

X-ray-confirmed Pneumonia

Approximate Mean PM2.5 exposure in 100s of ug/m³
Severe X-ray-confirmed Pneumonia

CXR Hypoxic ALRI Rate (per 100 Child-Yr)

Approximate Mean PM2.5 exposure in 100s of ug/m3

Preliminary
RESPIRE: Pneumonia Reductions with Exposure Reduction
Preliminary Results

<table>
<thead>
<tr>
<th>Exposure reduction</th>
<th>Overall MD-pneumonia</th>
<th>Severe (hypoxic) MD-pneumonia</th>
<th>CXR pneumonia</th>
<th>Severe (hypoxic) CXR pneumonia</th>
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</thead>
<tbody>
<tr>
<td>25%</td>
<td>0.92 (0.86, 0.99)</td>
<td>0.88 (0.80, 0.97)</td>
<td>0.84 (0.74, 0.96)</td>
<td>0.79 (0.69, 0.95)</td>
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<tr>
<td>50%</td>
<td>0.82 (0.70, 0.98)</td>
<td>0.73 (0.59, 0.92)</td>
<td>0.66 (0.49, 0.91)</td>
<td>0.56 (0.40, 0.88)</td>
</tr>
<tr>
<td>75%</td>
<td>0.67 (0.50, 0.96)</td>
<td>0.53 (0.35, 0.84)</td>
<td>0.44 (0.24, 0.83)</td>
<td>0.31 (0.16, 0.78)</td>
</tr>
<tr>
<td>90%</td>
<td>0.51 (0.31, 0.93)</td>
<td>0.35 (0.17, 0.76)</td>
<td>0.26 (0.09, 0.74)</td>
<td>0.15 (0.05, 0.67)</td>
</tr>
</tbody>
</table>

RESPIRE - Guatemala
Guatemala RCT: Kitchen Concentrations

Effect of Chimney Stove On Kitchen CO Levels

Factor of ~10 less

Smith, et al., 2010

285 48-h measurements

Smith, et al, 2010
Effect of Chimney Stove On Infant Exposures - 2x less

 smith, et al, 2010

1888 48-h measurements
Reasons that child personal exposures did not lower as much as kitchen levels:

--Time-activity: the kids do not spend their entire day in the kitchen

--Household (or “neighborhood”) pollution: a chimney does not reduce smoke, but just shifts it outside into the household environment, where the difference between intervention and control households was less

--Other burning around house not different
20-month average ground-level PM2.5 from satellite data

Large areas of rural India and China have high ambient air pollution – much from household fuel
Sources of Primary PM$_{2.5}$: India and China

Source: GAINS-China and GAINS-South Asia (2010)

IIASA, 2010
NASA INTEX_B Database
Percent PM$_{2.5}$ emissions from households

Chafe 2010 from NASA INTEX_B 2006
Global warming in 2005 due to all human emissions since 1750

- CO$_2$ is important for climate, but so are many other pollutants, including the ones circled that, unlike CO$_2$, also have significant health as well as climate impacts.

All of these are products of incomplete combustion, in some cases the only source.

IPCC, 2007
Global warming commitments of each of the gases as CO₂ equivalents

Wood: 1.0 kg
454 g Carbon

Plus PM2.5 and Black Carbon

CO₂ Carbon: 403 g

403 g

Methane Carbon: 3.8 g

86 g

Other GHG Carbon
Carbon Monoxide: 38 g
Hydrocarbons: 6.3 g

131 g
69 g

Nitrous Oxide
0.018 g

4.7 g

Zhang, et al., 2000
2+ million tons methane per year of 300 Mt total global human emissions comes from Indian stoves

*Includes coal use: J: 17%; WB: 13%; C: 2%; O: 2%
Controllable Global Warming from Black Carbon Emissions

Net of OC, Forcings from IPCC, 2007: 0.25 W/m²
Inventory from T Bond Database, V 7.1.1 Feb 2009

Transport 24%

Households 36%

Forest and Grassland 6%
Power 1%
Ships and Aircraft 2%
Ag Waste 4%

~One-third of net black carbon and carbon monoxide emissions globally come from household fuels

~One-sixth of ozone causing pollutants

~One-twentieth of methane
Household Fuels and Climate

- Climate impacts come from non-renewable wood, i.e., from net CO₂ emissions due to deforestation.
- Poor combustion also leads to other emissions such as the relatively well-understood GHGs – methane and nitrous oxide – which are “Kyoto” GHGs.
- In addition, a wide range of less well-understood short-lived GH-related emissions are emitted including:
  - CO and black carbon – warming agents
  - Ozone precursors – warming But also cooling agents such as sulfates and organic carbon particles
- There are also indirect climate impacts of these pollutants including:
  - Reducing carbon capture of forests by ozone damage
  - Darkening of snow/ice by black carbon
Heart Disease and Combustion Particle Doses

From “Mind the Gap,” Smith/Peel, 2010
Generalized Exposure-Response: Outdoor Air, SHS, and Smoking

IHD risks from combustion particles
Annual average PM2.5 in ug/m3

Smokers
Solid Fuel Zone
Secondhand Tobacco Smoke
Outdoor Air Pollution

CRA, 2011
Pneumonia from combustion particles
Annual average PM2.5 in µg/m³
Why M&E?

You don’t get what you expect,
but what you inspect
SMALL, SMART, FAST, & CHEAP
monitoring devices for household energy & health

STOVE USE MONITORS

Utilization

Time-of-use measuring devices allow more accurate estimations and objective definitions of usage patterns including cooking periods, meal times, and technology adoption rates.

Stove Use Monitors (SUMS) quantify utilization of cookstoves to improve estimates of personal exposure and environmental benefits related to household energy use. SUMS are based on commercially available, low-cost, small temperature loggers.

The stainless steel temperature sensors are the size of a coin and can record time, date, and temperature. Programming and downloading data can be easily performed in the field. They are easy to use, unobtrusive, waterproof and tamper-resistant. They come with algorithms and software to systematically assess stove use patterns.

Measurements of stove surface temperature can be used to test the effectiveness of behavioral interventions on stove use. Because they give precise, unbiased measures of a simple physical parameter, statistically reliable information is provided using smaller sample sizes than required for a household survey.

Device Software & Sample Output

Particles and Temp Sensor

Concentration

The ability to measure concentrations of small airborne particles is vital in understanding adverse health effects from combustion-derived air pollution. Available instrumentation to conduct such measurements is complex and expensive. Such devices are appropriate for developed countries and ambient air monitoring stations. However, their routine use in real-world household environments is expensive & cumbersome. Monitoring locations may also be remote, where security is questionable and electrical power not available, limiting the applicability of conventional instruments. In an effort to fulfill the needs for small, smart, fast, and cheap particle monitors that could be deployed easily in remote settings, a commercial smoke detector that uses optical scattering was identified and modified so that real-time signals could be logged continuously. This modified particle and temperature sensor is dubbed the UCB-PATS. Customized software handles data importing, graphing, and manipulation.

Time-Activity Monitoring

Location

Measurement of exposure to pollutants is vital to the field of environmental health. The significance of a hazard depends on the amount of time a person is in contact with it. For instance, high indoor air pollution levels have been found in many homes globally. The risk of respiratory disease depends on the amount of time people spend in the presence of this pollution.

Time-Activity Monitoring System (TAMS) detects the presence or absence of individuals in an enclosed space. The system consists of one to five small ultrasound emitting devices worn on an individual’s clothing. Each produces a distinct pattern that is emitted every few seconds. An ultrasound receiver is mounted on the wall of a room and detects the unique pattern from the device worn by an individual.

If the identifying signal pattern emitted from a particular locator is received a certain number of times during a minute, that locator, and presumably the person wearing it, is recorded as being present in the room. Field trials show good results, with a 93% accuracy rate as measured against direct observation.

For more information, google “Kirk R Smith” • To acquire devices, visit berkeleyair.com
The Time-Activity Monitoring System:
UCB-SUMS
Inter-instrument Comparison: 30 UCB-PATS UCB Particle and Temperature Monitoring System (custom PM monitor using smoke alarm technology)
How many hours should we measure to obtain good estimate of the long-term mean?

Kitchen PM$_{2.5}$ in household using open cookfire
Estimating Mother's Personal Kitchen PM2.5 Exposure Pattern by Combining Time-Activity Data (TAMS) with Continuous PM2.5 Kitchen Area Measurements (PATS)

Personal and Kitchen PM2.5 Concentrations

Cumulative Exposures

Mother's presence in the kitchen

Detailed Exposure Profiles
The Stove Use Monitoring System: UCB-SUMS
Patterns of Stove Use from Around the World
Captured with the UCB-SUMS

- Tamil Nadu, India (ROCKET stove, Fuel: Biomass)
- Shaanxi, China (SEMI-GASIFIER stove, Fuel: Corn cobs)
- Michoacan, Mexico (CHIMNEY stove, Fuel: Biomass)
- San Marcos, Guatemala (CHIMNEY Stove, Fuel: Biomass)

Graph showing SUMS Signal over the time of the day for different locations.
Objective Monitoring with the UCB-SUMS System

SUMS signal

Stove in use

Stove not in use
Transition from open fire to a chimney stove

- **Temperature**
- **Carbon monoxide (CO)**

---

**SUMs Temperature [°C]**

- 60
- 50
- 40
- 30
- 20
- 10
- 0

**CO [ppm]**

- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

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**First week of stove use**

- **Breakfast** 8:20
- **Lunch** 12:40
- **Dinner** 19:40
- **19:40**
Stove Use Monitors (SUMs) in Action

Ruiz et al., submitted
Percent of total Stove-days

Meals per day

Ruiz et al., submitted
Wireless Stove Use Monitors Being Field Tested in Mexico This Month - India next year
Principles by Which to Move Forward

- “Get rid of incomplete combustion” – bad for health, climate, ecosystems, agriculture and resource efficiency
- “You don’t get what you expect, but what you inspect” -- need to monitor in the field for both technical performance and usage
- “Not all stoves are equally bad” – need to target vulnerable populations
Stoves, a few principles.

• “Improved” has not meant clean. Need to combust cleanly, not just have good fuel efficiency or a chimney
  – Truly clean stove/fuel systems are very few in number today, and field experience even more scarce
  – All truly clean (“advanced”) stoves use blowers, but with TEG technology, there is no constraint imposed by lack of electrical supply

• “The poor cannot afford to pay” -- need to realign financing so that everyone pays, since all benefit – households, nations, globe
  – Poor will only pay for fuel savings, but many do not buy fuel and thus have little incentive
  – Cost of stoves that merely save fuel are much lower than those that are also clean -- thus sales will not bring health/climate benefits
Many thanks

Publications and presentations available at my website:  http://ehs.sph.berkeley.edu/krsmith/

Or just Google “Kirk R. Smith”