Linking household energy use with indoor air quality

Michael A. Johnson, Kirk R. Smith, Rufus Edwards, Lidia Morawska, Mark Nicas, Ranyee Chiang

ETHOS Kirkland, 2015
Existing WHO Air Quality Guidelines (AQG)

- **Global update (ambient) 2005:**
  - PM$_{2.5}$ and PM$_{10}$
  - Chapter on IAP

- **Indoor AQG:**
  - Dampness and Mould: 2009
  - Selected pollutants: 2010
  - Household fuel combustion: this project

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Guideline/target</th>
<th>Exposure period</th>
<th>Level ($\mu$g/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ (2005)</td>
<td>Guideline</td>
<td>Annual average</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>IT-3</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>IT-2</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>IT-1</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Carbon monoxide (2010)</td>
<td>Guideline</td>
<td>8-hour</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Guideline</td>
<td>24-hour</td>
<td>7</td>
</tr>
</tbody>
</table>
Key questions for development of WHO IAQ Guidelines:

• What emission rates are required to meet WHO:
  • Annual average AQG and IT-1 for PM$_{2.5}$, and
  • 24-hr average AQG for CO?

• In light of the acknowledged challenges in securing rapid adoption and sustained use of very low emission household energy devices and fuels, particularly in low income settings, what approach should be taken during this transition?

• Should coal be used as a household fuel?

• Should kerosene be used as a household fuel?
Probabilistic Modeling for Populations

Use distributions of inputs variables in a Monte Carlo single zone model to predict distribution of concentrations you would expect to see in a population of users.

Key factors which impact indoor concentrations of air pollutants, and vary across any given population:
- Room size
- Ventilation
- Device emissions performance
- Device usage demands

\[
C_t = \frac{G f}{\alpha V} (1 - e^{-\alpha t}) + C_o (e^{-\alpha t})
\]

\(C_t\) = Concentration of pollutant at time \(t\) (mg m\(^{-3}\))
\(G\) = emission rate (mg min\(^{-1}\))
\(\alpha\) = first order loss rate (nominal air exchange rate) (min\(^{-1}\))
\(V\) = kitchen volume (m\(^3\))
\(t\) = time
\(C_o\) = concentration from preceding time unit (mg m\(^{-3}\))

Johnson et. al 2011
PM$_{2.5}$ emission rate performance and AQGs

- 10μg/m$^3$ PM$_{2.5}$ Final AQG
- 35μg/m$^3$ PM$_{2.5}$ Interim 1 AQG

Percentage of modeled kitchens meeting AQG's

PM$_{2.5}$ emissions rate (mg/min)

10μg/m$^3$ PM$_{2.5}$ performance and AQGs
WHO emission targets (PM$_{2.5}$)

<table>
<thead>
<tr>
<th>Particulate Matter 2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions Target</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td><strong>Unvented</strong></td>
</tr>
<tr>
<td>Initial</td>
</tr>
<tr>
<td>Final</td>
</tr>
<tr>
<td><strong>Vented</strong></td>
</tr>
<tr>
<td>Initial</td>
</tr>
<tr>
<td>Final</td>
</tr>
</tbody>
</table>

Provision for chimney stoves.

Included a model input distribution for fraction of emissions that enter room (1-50%) based on IAP reductions reported in literature.
PM$_{2.5}$ emission rate performance and AQGs

- Final AQG: 10 μg/m$^3$ PM$_{2.5}$
- Interim 1 AQG: 35 μg/m$^3$ PM$_{2.5}$

Current best performing open solid biomass stoves (e.g. gasifiers, forced draft)

Gas and liquid fuels

- 1.75 mg/min
- 0.23 mg/min

Percentage of modeled kitchens meeting AQG's

PM$_{2.5}$ emissions rate (mg/min)
Usage also fundamental to achieving benefits

How much clean stove use is used enough?

and

How much traditional stove displacement is displaced enough?

Tier X, Y, Z stove
Traditional stove use and PM$_{2.5}$ concentrations

- Takes very little traditional stove use to exceed WHO AQGs (~1 TSF use per week).
- Difficult to reach WHO AQGs if the traditional stove is not almost completely displaced.

Source: Johnson and Chiang, in review

ETHOS, Kirkland 2015
We want everyone to be here. Going from here to here still has meaningful benefits (RR 3→2). Difficult to rapidly transition here for many populations.

Source: Johnson and Chiang, in review.
Acknowledgements

Model interns: Laura Conway, Maneet Sandhar, and Lizi Feng

Feedback and assistance from Ajay Pillarisetti, David Pennise, Danna Charron, Bill Martin, Sumi Mehta, Nigel Bruce and the WHO GDG.

Contact Information
Michael Johnson
mjohnson@berkeleyair.com
+1.510.649.9355
www.berkeleyair.com
Tier 4
Tier 3
Tier 2
Tier 1

0 100 200 300 400 500 600 700 800

24 hour PM$_{2.5}$ concentration (μg/m$^3$)

Tier 4
Tier 3
Tier 2
Tier 1

Percent TSF displacement by new stove

WHO Annual Interim 1 Target

24 hour PM$_{2.5}$ concentration (μg/m$^3$)

Percent TSF displacement by new stove
Making the available clean

Making the clean available

Pollutant concentrations in room are a function of many factors, many of which change over time.
Pollutant concentrations in room are a function of many factors, many of which change over time.

Clear guidance on the source technologies is at the base of addressing indoor air quality.
Modeling Approaches

Single zone model
Room concentrations predicted from emissions, which mix perfectly and instantaneously throughout single volume.

Three-zone model
Predicted room concentrations split into defined zones (plume, ceiling, main room), with factors accounting for between zone mixing.

Computational Fluid Dynamic Model
Room concentrations estimated for thousands to billions of nodes based on flow, momentum, conservation of mass, etc.

Simple, requires less assumptions/inputs and computing power

Complex, requires more assumptions/inputs and computing power

C. L'Orange, M. Defoort, CSU
Modeling for emissions performance to meet WHO AQGs

What emissions rates from devices (stoves) would be required for X, Y, Z% of a population to achieve the WHO AQGs?

Run the Monte Carlo, single zone model using the distributional inputs, across several emission rates to relate the emission rates to levels of protection.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air exchange rate ($\alpha$)</td>
<td>hr$^{-1}$</td>
<td>20</td>
<td>5</td>
<td>45</td>
<td>7.5</td>
<td>(ARC, 2006; Bhangar, 2006; Brant et al., 2010; Johnson et al., 2011)</td>
</tr>
<tr>
<td>Kitchen volume (V)</td>
<td>m$^3$</td>
<td>30</td>
<td>5</td>
<td>100</td>
<td>15</td>
<td>(ARC, 2006; Bhangar, 2006; Brant et al., 2010; Johnson et al., 2011; Saksena et al., 2003)</td>
</tr>
<tr>
<td>Stove burn time</td>
<td>hr day$^{-1}$</td>
<td>4</td>
<td>0.75</td>
<td>8</td>
<td>2</td>
<td>(Bhangar, 2006; Brant et al., 2009; Raiyani et al., 1993; Smith et al., 1983)</td>
</tr>
</tbody>
</table>