International Journal for Service Learning in Engineering
Special Edition, pp. 151–169, Fall 2013
ISSN 1555-9033

Kitchen 2.0: Design Guidance for Healthier Cooking Environments

Mollie Ruth
Senior, Dept. of Civil and Environmental Engineering
Michigan Technological University
Houghton, MI 49931
mmruth@mtu.edu

Jarod Maggio
Doctoral Student, Dept. of Civil and Environmental Engineering
Michigan Technological University
Houghton, MI 49931
jcmaggio@mtu.edu

Kelli Whelan
Master's Student, Dept. of Civil and Environmental Engineering
Michigan Technological University
Houghton, MI 49931
kmwhelan@mtu.edu

Mark DeYoung,
Senior, Dept. of Mechanical Engineering Engineering Mechanics
Michigan Technological University
Houghton, MI 49931
mdyoung@mtu.edu

Jonathan May
Senior, School of Technology
Michigan Technological University
Houghton, MI 49931
jsmay@mtu.edu

Abram Peterson
Senior, Dept. of Civil and Environmental Engineering
Michigan Technological University
Houghton, MI 49931
abramp@mtu.edu

Kurt Paterson, PhD, PE
Head, Department of Engineering (Advisor)
James Madison University
Harrisonburg, VA 22807
paterskg@jmu.edu

***Abstract* – Among stove developers and implementers it has now become common knowledge that it is possible to reduce the amount of fuel, emissions, indoor air pollutants and greenhouse gases produced by traditional cookstoves through introducing improved cookstoves. However, improved cookstove effectiveness has not yet translated into an increase in the health and wellbeing of cookstove users. For this reason, the Kitchen2.0 team set out to investigate an alternative approach to solving the global health impacts of poor indoor air quality due to the use of biomass as cookstove fuel: ventilation. To better understand the role ventilation plays in kitchens with fires and cookstoves, a three-pronged approach was used, including global community surveys, a full-scale physical model, and a computational model. Field agents affiliated with Michigan Technological University helped complete surveys on cooking habits and structures worldwide. Physical testing was conducted in the Kitchen2.0 modular kitchen by running cooking tests with different kitchen structure configurations and stoves. The computational model was developed to simplify the testing of cooking scenarios. Ventilation was found to make a significant difference on the indoor air quality of the cooking environment, reducing carbon monoxide and very small particulate matter by about 50%. While improved cookstoves also improved air quality when paired with ventilation, they worsened air quality 10-30% when used without ventilation. The improved understanding of the impacts of ventilation could help community-based organizations improve indoor air quality, and the lives of billions worldwide.**

Index Terms – design, development, indoor air pollution, ventilation

BACKGROUND AND PROBLEM DEFINITION

Over three billion people rely on biomass (animal dung, crop residue, wood, and charcoal) as a primary household energy source (United Nations 2010.) Products of incomplete combustion from biomass create a high risk of emission exposure, both acute and chronic, for half of the world's population. Post-combustion compounds include carbonaceous particulate matter (PM), carbon monoxide (CO), and inorganic and polyaromatic aerosols (Desai et al. 2004.) Acute exposure can lead to eye, throat and lung irritation; chronic exposure has been linked to a range of debilitating respiratory diseases such as lower respiratory infections and chronic obstructive pulmonary disease. Other afflictions associated with biomass burning include asthma, cataracts, tuberculosis and lung cancer (Desai et al. 2004.) Children aged five years old and younger who live in biomass-using households are 2.3 times more likely to contract a severe lower respiratory infection (Mehta and Shahpar 2004.) The global health burden of combustion exposure is 2.7% (WHO 2013), claiming the lives of nearly 4 million people each year and debilitating millions more (Lozano et al. 2013.)

PURPOSE, PROJECT OBJECTIVES AND SCOPE

Currently, interventions are focused on reducing the quantity of emissions at the source by improving fuel combustion and heat transfer through the development and distribution of improved cookstoves, as well as increasing accessibility to higher quality fuels. While this is an environmentally responsible approach, the scope of these projects is limited. As of 2012 only 2.5 million improved cookstoves were disseminated from 590 public and private organizations, only affecting 0.5% of all biomass users (PCIA 2012.) Cost, limited distribution range, and low integration rates have hampered the success of both improved stoves and fuels (Ruiz-Mercado et al. 2011.)

Additionally, controlled laboratory protocols, often used to assess cookstove quality, poorly reflect typical cooking environments and thus may misrepresent actual dissemination outcomes (Roden et al. 2009.) Exposure to combustion emissions in poorly ventilated structures can be 100-fold higher than recommended limits (WHO 2013), and while previous studies have implied the benefits of ventilation (Ezzati 2000; Smith 1987), no study has systematically determined its effect using real-time monitoring. For this project, a systems analysis approach was used to assess indoor air quality (IAQ) in kitchens, shifting the focus from the source to the cooking environment.

This project focuses on better understanding the role of ventilation on IAQ. This was done through three primary initiatives: understanding the cooking practices and environments of people around the world; performing physical tests to determine the effect of ventilation in kitchens on IAQ; and developing and validating a computer model to rapidly simulate various cooking conditions.

METHODS

Surveys

Utilizing Michigan Technological University's (hereafter Michigan Tech) network of Peace Corps Masters International (PCMI), international senior design, and Pavlis Institute students, a deeper understanding was gained of local kitchen design, fuel usage, and cooking practices through semi-structured observation and surveys. Students were given two surveys to complete: 1) "Around the Town Observations" and 2) "In-Home Interviews and Observations." The first

provided general demographic information concerning the town's cooking habits (home/kitchen design, cooking practices, type of stove used, and fuel usage.) The second provided quantitative and more detailed information on individual family units on the same topics, as well as an opportunity to collect opinions and quotes from individuals. Interviewers were also encouraged to partake in participant observation and to take photographs relevant to the study. Community surveys were conducted over a three month period.

Physical testing

In over twenty different scenarios, the presence and transport of household air pollution (HAP) was monitored in a modular kitchen on Michigan Tech's campus following a modified Controlled Cooking Test (CCT) protocol for rice (PCIA 2012.) The easily adaptable modular kitchen allowed the team to test the effect of different ventilation scenarios on HAP levels in a controlled environment (Figure 1.) Control variables possible for the modular kitchen include removable wall panels, windows, doors, and roof material (metal or thatch.) The ventilation scenarios were informed by the global observations made by the team members and field contacts, and were based on common kitchen types. The modular kitchen was contained within a sealed tent equipped with blower door in order to control flow rate. Wind was simulated using several industrial fans. Environmental conditions on the exterior of the house (windspeed, temperature) were monitored using a meteorological station.

The presence and transport of two health-damaging cookstove emissions, CO and PM2.5 (particulate matter under 2.5 micrometers in diameter), were tracked during each trial at child standing/adult sitting height (36 in.) and adult standing height (60 in.) throughout the physical model home. CO was measured using a passive CO Data Logger (MicroDAQ) at a 10 second sample rate, and PM2.5 was measured with UCB-PATS 10 photoelectric monitors (UCB from Berkeley Air) at one sample per minute. An Aerodynamic Particle Sizer (APS) and TSI Dust-trak were co-located with a UCB device to ensure accuracy.

FIGURE 1

THE INTERIOR OF THE MODULAR TEST KITCHEN. THE STOVES WERE TYPICALLY LOCATED IN THE CORNER OF THE STRUCTURE UNLESS OTHERWISE SPECIFIED

FIGURE 2

THE EXTERIOR OF THE MODULAR TEST KITCHEN WITH THE FRAME OF THE ENCLOSING TENT ERECTED

Three stove types were used: the traditional three-stone fire and two leading improved stoves that have been widely accepted in HAP projects worldwide, StoveTec Greenfire and Envirofit G-3300. Both improved stoves use wood and biomass as their primary fuel and have been shown to reduce CO and PM2.5 emissions by more than half compared to the traditional three-stone fire in laboratory Water Boiling Tests (WBT) (Jetter et al. 2012.) The StoveTec measures 10.75”x11.75” and weighs roughly 18 lbs, and the Envirofit measures 11.3”x10.5” and weighs 11.4 lbs. Both improved stoves are manufactured modifications of the rocket stove. The three-stone fire is a widely-used cooking technique in which a fire is lit between three stones and a pot is placed on top of this tripod of stones.

Virtual computation

The use of the open source indoor air quality modeling software CONTAM with computational fluid dynamics (NIST 2012) was explored for simulating seven home and kitchen designs. For the theoretical methodology of coupling CONTAM with CFD software see Wang and Chen 2007. Various kitchen geometries were input into the model, along with window and door openings. Contamination sources (stove emissions) were input based on laboratory WBT emissions extrapolated from Jetter et al. 2012 for the three stone fire and the two improved stoves. Data from the modular kitchen physical CCT were used to calibrate the model and it was validated using unpublished field data collected in northern Tanzania by Maggio and Paterson.

RESULTS

Surveys

Out of the thirteen countries surveyed, sufficient data for interpretation were obtained from nine countries: Ghana, Guatemala, Kenya, Namibia, Panama, Philippines, Senegal, Tanzania, and Togo. Three key results from the surveys are covered in this paper. The first focuses on how regional and local variations in cooking habits differ and the implications for the importance of introducing development interventions (e.g. improved cookstoves and alternative fuels.) The second uses the information gained in order to indicate which communities would benefit the most from each type of intervention: improved cook stoves, education on drying fuel and better cooking techniques, or ventilation awareness. Finally, we were able to ascertain from the surveys certain new parameters for the laboratory tests that reflect real-world conditions. The outcomes (Table I) are generalities based on qualitative and subjective interpretations from a few communities in each country and should not be extrapolated to the entire country (although for simplicity the country's names are used to designate the location of the findings.)

The percent of indoor versus outdoor cooking was from in-person interviews and rounded to the nearest interval of five. Ventilation was evaluated based on how open structures were or if chimneys were used. Communities that had homes with few windows that were often closed scored a 1, while homes that had a mostly open separate structure or had well maintained chimneys scored a 5. Stove adoptability was estimated based on whether improved stoves were currently available in the villages or if people expressed interest in purchasing them. Villages with multiple stoves available at market and commonly found in people's homes scored a 5. On the other hand, interviews were done to see how likely people would be to purchase a stove in villages where none were currently found. Those that had little interest in purchasing an improved stove were scored a 1. Finally, fuel scarcity was determined based on personal accounts of how long it takes to collect fuel and fuel availability. A score of 5 was given if people had to travel less than a mile for fuel wood and spent less than 2 hours per week. A 1 was given for those that travelled more than 5 miles and spend more than 20 hours per week collecting fire fuel.

Surveys indicated the high variability in cooking environments globally, but also illustrated some interesting similarities. In Namibia, Senegal and Ghana for example, where the climates are generally dry, the majority of cooking is done outdoors or in three-sided enclosures. Also, the majority of people in these three countries collects wood as their primary cooking fuel, and indicates that fuel is scarce and requires long journeys to the forest. Therefore, for these countries we would recommend interventions that focus on improved cooking stoves designed to increase fuel efficiency over those that lower emissions. Additionally, ventilation and fuel drying is less important in these countries because people generally cook outside. In Tanzania and

Kenya, on the other hand, people mainly cook indoors with very little ventilation. Similarly, in Panama and Paraguay the majority of people cook in separate structures, but also with little ventilation. These countries should focus on interventions that reduce emission exposure whether through improved cookstoves, better fuel management, or better ventilation.

TABLE I

SUMMARY OF SURVEY FINDINGS FROM NINE COUNTRIES. SCALES OF (1-5) FOLLOW THE GENERAL TREND OF (1) BEING UNFAVORABLE AND (5) BEING FAVORABLE

Country	Indoor vs. Outdoor Cooking In/Out (%)	Ventilated Poorly - Well (1-5)	Stove Adoptability Unlikely - Likely (1-5)	Fuel Scarcity Scarce - Available (1-5)	Intervention Recommendations
Ghana	5/95	5	4	2	Improved stoves designed to increase fuel efficiency
Guatemala	95/5	2	2	5	Ventilation and education on drying fuel wood
Kenya	95/5	2	5	2	Factory made stoves combined with ventilation awareness
Namibia	25/75	5	2	3	Locally produced cookstoves
Panama	95/5	4	3	4	Improved stoves combined with education on fuel drying
Philippines	80/20	3	3	4	Improved charcoal stoves and improved charcoal production
Senegal	90/10	2	3	3	Improved stoves designed to decrease emissions
Tanzania	90/10	1	4	3	Factory made stoves combined with ventilation awareness
Togo	40/60	4	2	1	Improved stoves designed to increase fuel efficiency

In every community interviewed, except Kenyan communities, improved cook stoves had failed to gain widespread adoption even though development organizations had introduced various stove technologies. This may be due to the fact that Kenya was the only urban community surveyed or that charcoal was readily available in many parts of the country. The improved stoves that were in regular use were used either because of economic ability of a household to switch to alternative fuel (charcoal, kerosene, or liquefied petroleum gas), were used at a business (cantina, tea house, or school), or were a secondary stove to the wealthiest households (technology stacking.) However, even the wealthiest households usually had hired help, therefore the cooking was often done outside on an open fire, the improved stove seemed to be there as a status symbol and were rarely used. This information is not meant to discredit all stove intervention projects but provides a rationale for why new programs should understand previous history with stove projects and to investigate why they may have not succeeded.

In homes where most of the cooking is done indoors, in poorly ventilated homes, ventilation awareness campaigns should be integrated into any intervention project. While the surveys did not specifically gauge the extent to which families would be amenable to ventilation changes in their homes, one interviewee offered:

> "[I] recently moved [the] location of the fogon [stove] and now there are no more problems with smoke because it is leaving out of the corner it is closest to."
> --Interviewee A, Panama

This strategy, like most intervention technologies, is not likely to be the silver bullet solution. However, it does provide an additional technique for lowering emission exposure and improving health outcomes.

Additionally, the survey results greatly influenced the types of simulations run during the physical model CCTs. The physical model's configurations included three wall and half wall structures, which are common in West Africa, as testing scenarios. Tests were also conducted using two different roofing materials, because of a shift seen in East Africa from thatch roofing to corrugated metal, based on information garnered from the surveys.

Physical Model

Contaminant results are shown in Figure 3 as the percent change from the composite mean of a home scenario with closed ventilation scenario, a three-stone fire, and a metal roof. The mean was calculated using three trials over a complete cooking period plus approximately 30 minutes after extinguishing the fire (smoldering phase.) Even though most laboratory experiments exclude the smoldering phase, it was included in this study because of its significant impact on IAQ. Concentrations were limited to the average mean due to the variation in the data and the limited number of trials run per comparative scenario (2-5 trials/scenario.)

The following changes could be made to the test kitchen to create distinct physical scenarios:

- Ventilation: All windows and doors open, all windows and doors closed, partial ventilation (some windows and/or door open), partial walls (walls shortened to 2/3 original height, kitchen open to the outside on the top third of the structure below roof), removal of one wall (one wall open, three walls standing)
- Eaves: Open (default), sealed
- Roofing: Corrugated aluminum (default), thatch
- Fans: Low (combined air movement 9,600 CFM), high (combined air movement 12,000 CFM)
- Stove Type: traditional three stone fire, StoveTec with pot skirt (Improved Cookstove A), Envirofit (Improved Cookstove B)
- Stove location: in corner (default), near open door

The critical characteristic, as shown below for both CO and PM2.5 (Figure 3), is ventilation. As expected, the all-closed tests for all stoves proved the worst for both contaminants. However, the all-open tests were not necessarily better than cross ventilation tests (one window opened on either end of the house.) One might assume that more open windows would cause a proportional decrease in HAP, but as shown in the results of Improved Stove B, the cross ventilation scenario (two opposite windows open) with no fans (ambient ventilation only) had the greatest decrease in CO and PM2.5. This seemingly confounding result is easily explained by the computational model. When more windows are open in the CFD model, more eddies occur and circulate polluted air within the home rather than allowing it to be advected.

International Journal for Service Learning in Engineering
Special Edition, pp. 151–169, Fall 2013
ISSN 1555-9033

Ventilation can significantly reduce HAP levels in homes with indoor biomass cooking. For example, tests showed that thatched roofs enhance ventilation and further decrease indoor air pollutants compared to homes with metal roofs. Creating a cross ventilation scenario in a home with a metal roof reduces the concentration of CO and PM2.5 by 45 and 50%, respectively. Interestingly, introducing cross ventilation to a home with an existing three-stone fire strongly outperforms the introduction of an improved stove (if kept in a closed cooking environment); improved stoves were repeatedly found to create more pollution when operated in a closed home. Similar findings have been found where some households have an increase in pollutants after improved stoves are introduced in the field. For example, from an improved cookstove assessment in India, 30% of the households saw in increase in both CO and PM2.5 after improved cookstoves were introduced compared to their existing traditional cookstove (Dutta et al. 2007.)

Overall, these findings have serious implications when households climb the "technology ladder" and move from mud-to-concrete homes, thatch-to-metal roofs, and traditional-to-improved cookstoves, but continue to cook without ventilation. It is clear that cultural sensitivity to cooking practices, appropriate education on the cooking environment and technology introductions must be combined for successful development programs. As seen in Figure 3, the only scenarios that had worse pollution than the baseline three-stone fire tests with closed ventilation, were those conducted under the same conditions but with the improved stoves; all other scenarios shown below show improvement over the baseline tests.

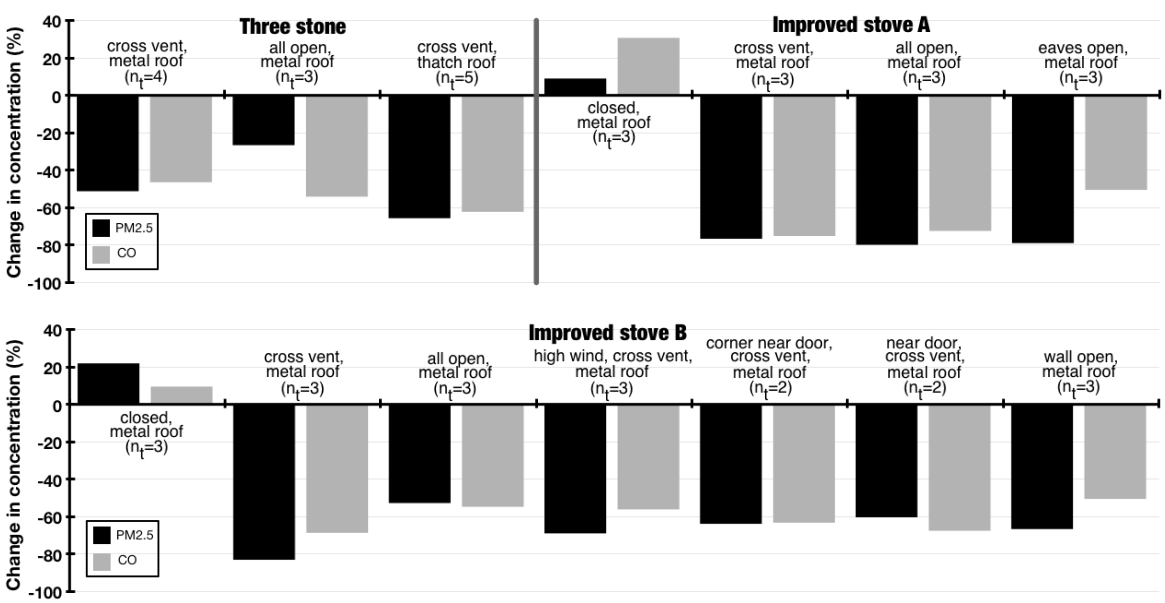

FIGURE 3

CHANGE IN AVERAGE AIR POLLUTANT CONCENTRATION (%) COMPARED TO THREE STONE, CLOSED, METAL ROOF EXPERIMENTS AVERAGE (N=3.)

Other findings from the Kitchen 2.0 physical model testing include:

- Thatched roofing reduced HAP in the home by 29.5% (PM2.5) and 29.4% (CO) on average; however this is not a recommended solution due to the health and socioeconomic problems associated with thatched roofing materials (e.g. insects, animals and status.)
- Average means do not reflect acute exposure levels observed during cooking periods. Instantaneous peak values up to 250 ppm and 15,000 $\mu g/m^3$ were recorded for CO and PM2.5, respectively.
- Highest concentrations were routinely experienced during igniting and extinguishing the stoves and were more prominent for PM2.5. The 30-minute period after extinguishing was included in the average mean results above to capture these emission elevations.
- The CCT was valuable for deeper understanding of HAP exposure, but contains an intrinsic amount of variation among trials compared to the traditional WBT. More repetitions are necessary for robust statistical analysis and confidence of data.
- Results from the Aerodynamic Particle Sizer (APS) show that over 99% (concentration by number) of the particles produced have a diameter of <0.5 µm, much smaller than the health-risk benchmark PM2.5. Further investigation is needed to quantify the concentration and characteristics of ultrafine particles produced through biomass combustion in field conditions and their implications on health risk. It is unclear whether these ultrafine particles are more likely to enter the bloodstream and cause infection, or if at some size particles become less of a threat, but it likely depends on the size, morphology, and composition of these ultrafine particles. Generally, smaller particles pose a greater risk, but how much of a risk is largely unknown.
- Results for particle morphology, important for interpreting health risk, and Elemental Carbon/Organic Carbon ratios, important for quantifying climate change, are still being analyzed, but general findings indicate that emissions produced during higher ignition temperatures and higher fuel-air ratios (as in the case with improved cookstoves) produce more compact carbon chains and higher EC/OC ratios. This could have significant implications on how particles from improved cookstoves affect health risk and climate forcing.

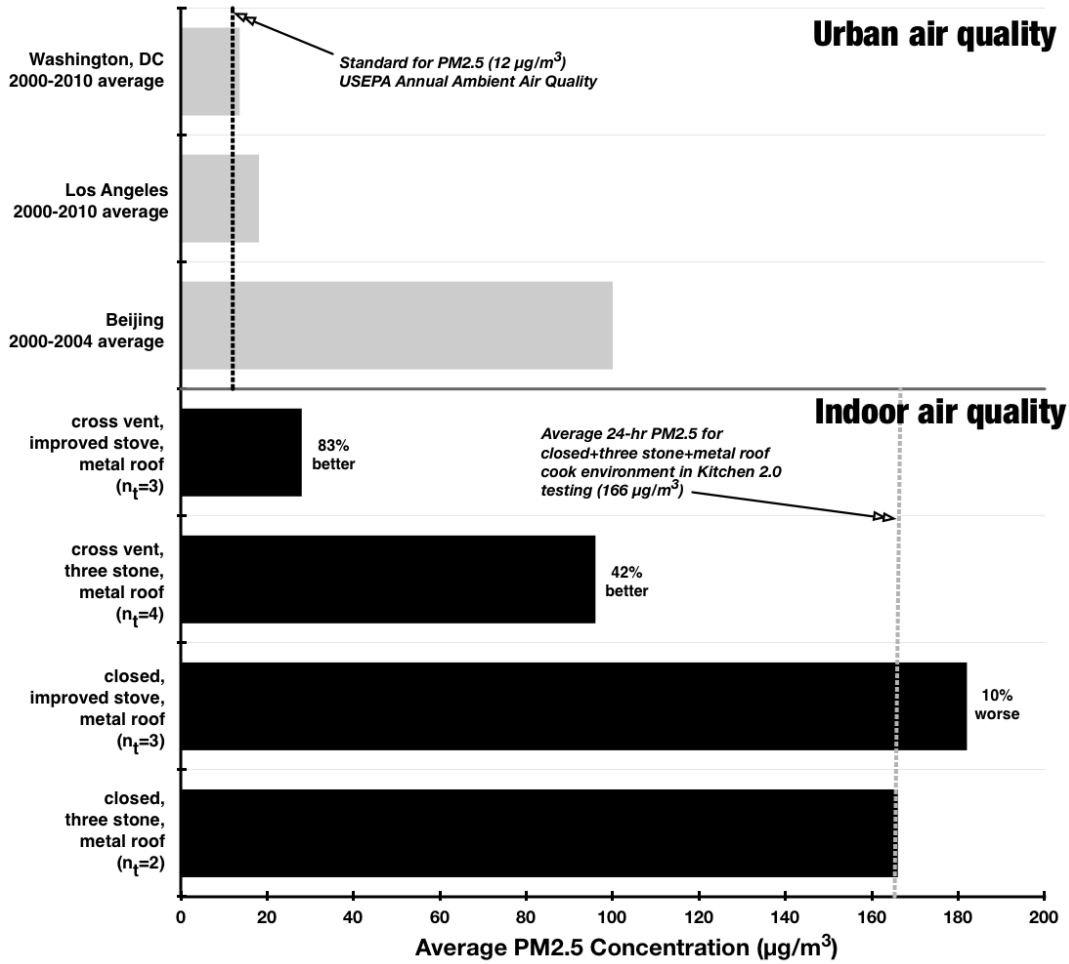

FIGURE 4

AVERAGE PM2.5 CONCENTRATION FOR DIFFERENT KITCHEN TESTS COMPARED TO OUTDOOR AIR QUALITY IN GLOBAL CITIES (YU 2006, USEPA 2013)

Figure 4 compares the average indoor PM2.5 concentration from selected kitchen tests with average annual outdoor PM2.5 concentrations from three cities. While there are not set guidelines for indoor PM2.5 concentrations, the USEPA annual ambient air quality standard for PM2.5 is 12 μg/m^3. While it is hard to directly compare annual outdoor averages to indoor averages over a cooking event, the comparison may help to put the numbers in context. It should be considered that the amount of time the average American spends outside in a day may be less than the amount of time women and children in many communities around the world spend inside while cooking.

Ventilation can drastically impact the health of those who use cookstoves. Dose estimates from the Kitchen2.0 physical model experiments were superimposed on Smith and Peel's 2010 comparison of estimated daily inhaled PM2.5 doses and adjusted relative risk. The four experimental scenarios compared reveal many cooking environments fall between the risks of active smoking and passive smoke exposure. When extrapolated to reflect the four million people dying worldwide from cookstove related diseases annually, it is estimated that nearly 50,000 additional people would die if improved cookstoves were introduced with no ventilation

International Journal for Service Learning in Engineering
Special Edition, pp. 151–169, Fall 2013
ISSN 1555-9033

training, while over 340,000 lives could be saved by implementing improved cookstoves in homes *combined with* ventilation changes.

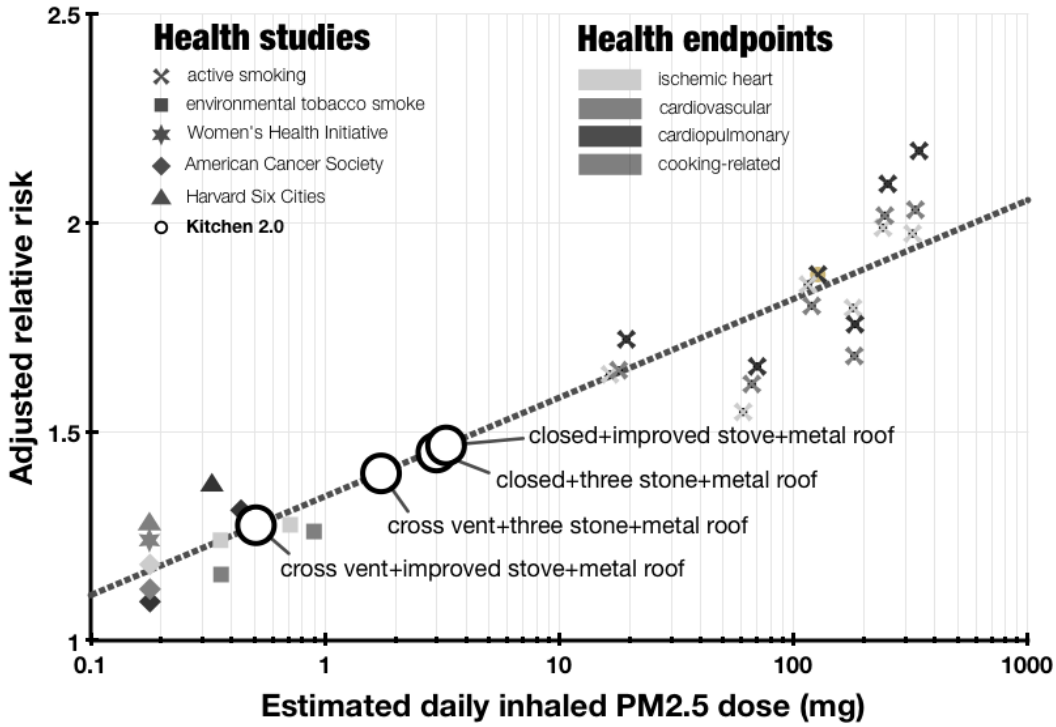

FIGURE 5

COOKING-RELATED DOSES COMPARED TO HEALTH RISK STUDIES, MODIFIED FROM SMITH AND PEEL 2010

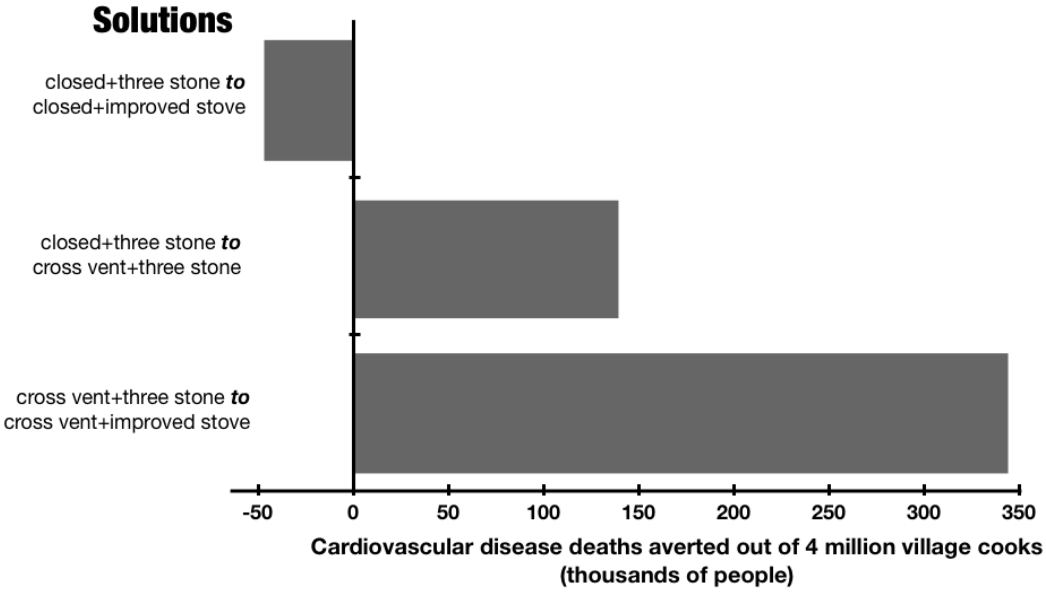

FIGURE 6

LIVES SAVED ANNUALLY BY COOKING ENVIRONMENT SOLUTIONS AS EXTRAPOLATED FROM SMITH AND PEEL 2010

Virtual Computation

Overall the model provided unique insight into airflow patterns and optimal ventilation schemes (Figure 7.) For a simple model ventilation layout, with one window open at each end of the test home, the model was able to accurately predict the average PM 2.5 concentration over three separate test runs to within 0.46%. For a more complex scenario with all possible windows and doors open, providing several possible infiltration and exfiltration points, the model error increased to 14.36%, still well within the range of statistical significance. The increase in error was due to the model poorly predicting concentration spikes due to igniting and extinguishing the fire, as well as other transient events (Figure 8.) However, the model is accurate enough in predicting average exposure over time, allowing the model to add value to future HAP intervention plans and assessments (Figure 9.) A more detailed analysis of the model is being prepared for a subsequent publication. The model is presented here to provide the reader with an understanding of the full scope of the Kitchen 2.0 project, an introduction to the model, preliminary findings and supportive evidence to the experimental and field datasets.

International Journal for Service Learning in Engineering
Special Edition, pp. 151–169, Fall 2013
ISSN 1555-9033

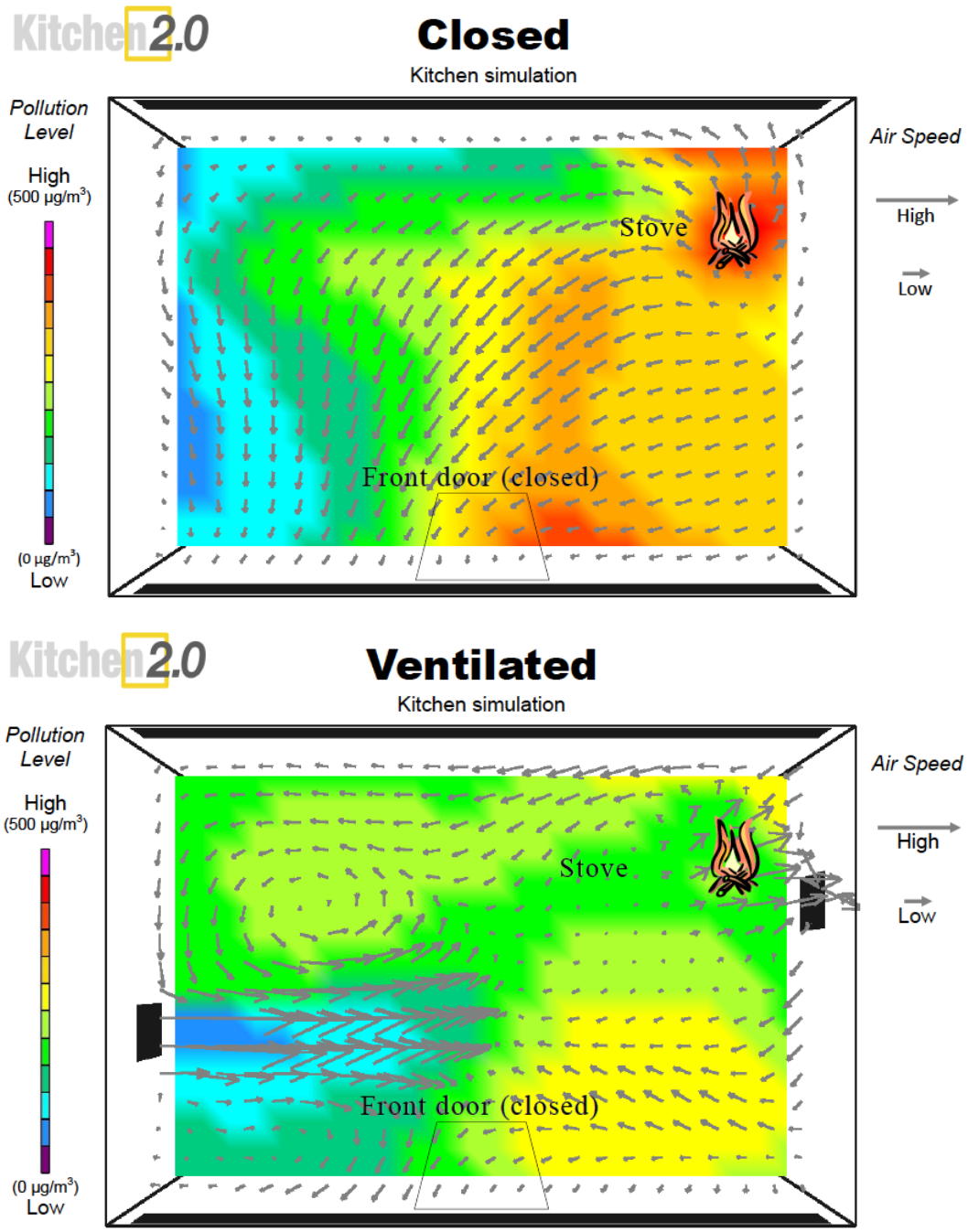

FIGURE 7
CONTAM SIMULATION RESULTS FOR CLOSED AND VENTILATED KITCHEN SCENARIOS AT 36" ABOVE THE GROUND

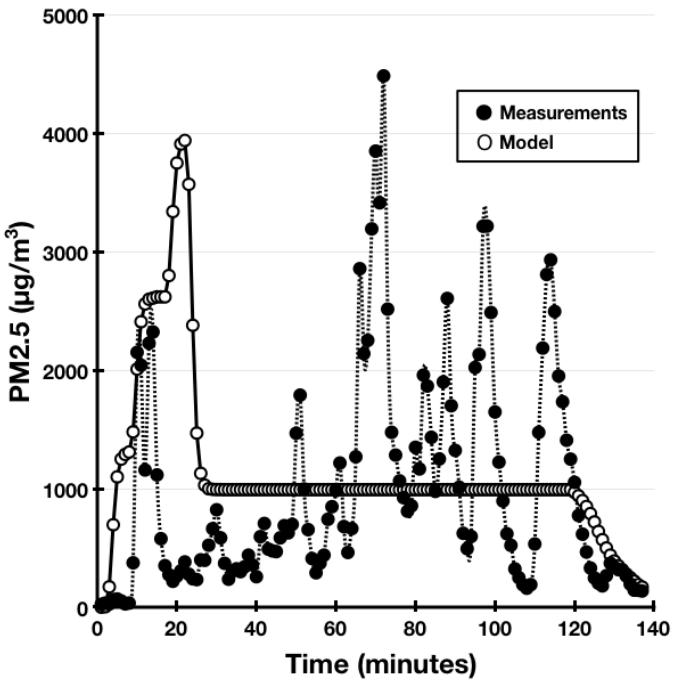

FIGURE 8

SIMULATION RESULTS FROM A ONE WINDOW OPEN, THREE STONE FIRE SIMULATION (BLACK) AGAINST FIELD RESULTS (WHITE) WHERE PM2.5 WAS MEASURED IN A HOME DURING RICE COOKING OVER A THREE-STONE FIRE IN TANZANIA BY MAGGIO AND PATERSON. THE SIMULATION OF AVERAGE PM2.5 CONCENTRATION IS UNDERESTIMATED BY 8.4% COMPARED TO FIELD TESTING. NOTICE THAT THE SPIKES IN THE FIELD OBSERVATIONS, DUE TO ADDING FUEL AND CHANGES IN WIND SPEED, ARE NOT REPLICATED IN THE COMPUTATIONAL MODEL.

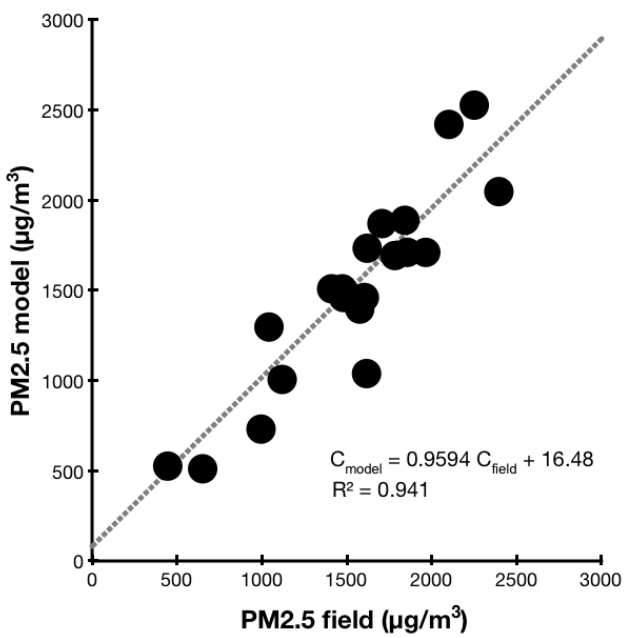

FIGURE 9

AVERAGE PM2.5 CONCENTRATIONS FROM COOKING EVENTS MEASURED IN THE FIELD COMPARED TO THE AVERAGE PREDICTED PM2.5 CONCENTRATION CALCULATED BY THE MODEL.

The model was validated using field data of rice cooking over a three-stone fire (Figure 9.) The simulation results of the field scenario, like the complex scenario, did not accurately follow the fluctuations in contaminants but was able to estimate the overall average concentration to within 8.4% (Figure 8.) It is likely that the model could accurately replicate constant source stoves, like charcoal stoves, but no field data were available for validation. Continued research should allow the model to be further refined and additional field data could provide a better sense of the robustness of the model.

DISCUSSION

As a result of the three initiatives of this project, design recommendations can be made. The best solution for improving IAQ in a home is to combine stove and fuel fixes with ventilation fixes. One of the most effective ways to increase ventilation is by providing cross ventilation, or openings on opposite sides of a structure to allow a direct path for airflow. In some cases, having too many openings may cause excessive turbulence, causing HAPs to be trapped inside the structure. However, almost any type of ventilation can decrease the concentration of HAPs in the cooking area compared to (often traditional) closed cooking spaces.

It should be emphasized that when improved stoves are used in non-ventilated environments, there is an *increase* in HAP concentration in the kitchen. These findings are contradictory to comparable studies done in a laboratory setting using the WBT, for example, Jetter et al. 2012. The following reasons help explain these differences in test results.

1. The WBT test is conducted under a hood where clean air is continually pulled into the stove while the contaminated emissions are removed and sampled from a vent above the hood. This is inherently different to the CCT where contaminants are allowed to accumulate inside of the home and are only removed through natural ventilation.
2. Lighting and extinguishing of the fires produce the most amount of emissions. Even though the improved stoves produced less emissions once lit they produce similar emissions during lighting, the initial production of PM2.5 and CO stayed in the home for the remainder of the test and were not removed as quickly during the closed ventilation tests.

Air inside the home, contaminated with products of incomplete combustion, is recycled back into the stoves altering the available oxygen. The fuel-air ratio is known to be important in combustion and may have been altered when the exhaust, with elevated amounts of CO, remain in the test area. Supporting data was found by looking at the CO/CO2 ratios of the tests (Table 2.) The CO/CO2 ratio results indicate that the amount of CO accumulated in the homes were slightly elevated for the closed improved stove tests compared with the three stove fire, which may explain why the overall contaminants were higher for these test scenarios. Another interesting point is the difference that is observed as we move from Closed – Cross – Open ventilation for the three stove types. There is not as much difference for the 3 stone fire's CO/CO2 ratios as there is for the improved cookstoves, meaning that the improved stoves may be more sensitive to changes in ventilation than the 3 stone fire.

TABLE 2
ANALYSIS OF CO/CO2 RATIOS MULTIPLIED BY 100 FOR ALL THREE STOVE TYPES UNDER THE THREE DIFFERENT VENTILATION SCENARIOS

	Closed Ventilation	Cross Ventilation	Open Ventilation
3 Stone Fire	3.93	3.35	2.91
Improved Stove A	4.08	2.48	2.05
Improved Stove B	4.02	2.33	2.30

Therefore organizations working to promote improved cookstoves need to make sure that they are being used with ventilation through careful selection of locations, education, and follow up. Alternatively, design considerations may need to be made that allows for larger openings in the stoves for oxygen to feed the fire and keep it burning efficiently when the stoves are used inside of poorly ventilated homes.

The information recorded and communicated from survey partners was inconsistent; this was identified as a challenge in project implementation. Possible ways to improve the overall project would be to better train our partners in qualitative research methods and disseminate the surveys through a more usable field system, while also providing an easier method for relaying the information in a more timely and structured manner. The next steps would be to partner with larger organizations like Peace Corps and Engineers Without Borders USA as well as create a Massive Open Online Course (MOOC) to better train the field agents. The MOOC pedagogy is based on the concept that the exchange of information through a vast network of invested individuals creates connections, collaborations, and an exchange of resources not possible on a local scale (Kop et al., 2011.) The course would cover the basics of IAQ where cookstoves are in use, engage students in the survey effort, discuss the effects of ventilation on IAQ, and introduce the CFD model as a tool for analyzing ventilation changes. The MOOC could also be used as an education tool for the general development community and the resulting survey data should be readily available to project designers and implementers.

The field results presented are primarily anecdotal and cannot be statistically representative of an entire country or even region. Therefore, more data are required to make more significant and reliable conclusions. The amount of variation found even within a region of a country validated the need for a fully customizable testing environment to better understand interventions and their global impacts. Overall the surveys provide intriguing insights into how communities interact with their cooking environment and should be used as a useful tool by IAQ projects in developing more user-specific and sustainable solutions.

The global surveys taken as part of this project and any surveys taken by other organizations in the future can help prioritize allocation of funds and efforts to maximize the impact that organizations can make on IAQ. The best places to focus on ventilation education are relatively warm regions where cooking currently takes place in closed structures. In regions with fuel shortages, increased stove efficiency and/or alternate fuel types should be explored (preferably in conjunction with ventilation, where applicable.) Assessing the differences between rural and urban communities is also worth consideration. In some urban areas, ventilating HAPs

out of the house may simply add to poor outdoor air quality. Moreover, projects in urban areas will have the added benefit of better distribution channels and motivated people to purchase improved cookstoves due to the high price and scarcity of fuels.

The CFD model is uniquely able to assist in the creative design process of cooking environment solutions because it can rapidly analyze many different ventilation and source scenarios. Development workers familiar with specific community needs can model realistic home geometries and cooking habits, and then test-run potential interventions, thereby saving time, resources, and community disruptions (or unintended negative impacts.) While the current CFD model is open source, it lacks ease-of-use. Future improvements to the model should involve providing a simplified version that is more accessible for less experienced users.

Kitchen 2.0 is a strategy for systematically and creatively applying ventilation techniques to improve IAQ. Kitchen 2.0 is a user-centered approach to improving the cooking environment because ultimately the time, talent, tools and motivation to improve IAQ must come from the households impacted. If introduced correctly, Kitchen 2.0 is a do-it-yourself solution, and could have a high degree of dissemination and uptake. This approach should provide longer lasting effects than the "charity drop" of stoves on a community, but may be harder to initiate. One possible barrier could be that the woman of the household has the motivation, but the man of the house may have the time, talent and tools, and decision-making power.

Social acceptability is arguably the most important consideration for considering IAQ projects. Where communities may be resistant to adopting improved stoves and/or fuel, ventilation may be more acceptable. People may be resistant to changing cooking habits, which would probably not be affected by kitchen structure. Where certain cooking practices are not adaptive to new stoves or fuels, ventilation strategies may be more successful. However it is also important to recognize that all possible ventilation solutions may not be appropriate in any given community. Creative ventilation designs and practices can be tested to develop local solutions that would be culturally acceptable such as:

- High vents where privacy is an issue
- Positioning stove outside or near a door (this is especially important to consider with improved stoves that are too heavy to be moved outside during ignition and extinguishing – when they produce the majority of emissions)
- Children go outside during ignition/extinguish phases

It may be noted that chimneys are potentially a good solution for poor IAQ but often times too expensive to install, inappropriate for certain climates, and ineffective if not properly maintained (Dutta 2007.) Kitchen 2.0 focuses on alternative ventilation practices for situations in which chimneys are not practical or have failed in the past.

In order to continue to gain understanding of IAQ and cooking environments around the world, the surveys created through Kitchen 2.0 need to be expanded to a larger base. Crowd-sourced platforms, such as allourideas.org, have been identified as a promising way of involving more communities and better sharing information gathered. They surveys may also need to be expanded to gauge social acceptability of various ventilation changes.

The initiatives undertaken in the Kitchen 2.0 project produced compelling results, but need further development, especially in the following areas: global survey database creation, CFD interface development, and dissemination of findings and IAQ strategies to communities. Results suggest that implementation of ventilation practices around the world could make a significant impact on respiratory health.

CONCLUSION

Current research on reducing HAP exposure has focused on alternative fuels and stove design, but this research indicates the significant value of ventilation in the cooking environment. A community survey was created to allow development designers to look at the big picture and focus efforts on strategies tailored to regional cooking practices. Physical testing revealed the importance of ventilation, especially when improved cookstoves are in use. Computational modeling offers a much easier approach to assessing potential structural and cooking changes within specific communities and homes in order to rapidly iterate designs. With more education and coordination among development groups over 340,000 lives could be saved annually by solving the problem of IAQ with a different perspective.

REFERENCES

Desai M.A., Mehta S., Smith K.R. Indoor smoke from solid fuels: Assessing the environmental burden of disease at national and local levels. Geneva, World Health Organization, 2004 (WHO Environmental Burden of Disease Series, No. 4.)

Dutta, K., Naumoff Shields, K., Edwards, R., Smith, K., Impact of improved biomass cookstoves on indoor air quality near Pune, India, *Energy for Sustainable Development*, Volume 11, Issue 2, June 2007, Pages 19-32. Available at: www.sciencedirect.com/science/article/pii/S097308260860397X [Accessed December 7, 2013].

Ezzati, Majid, Homayoun Saleh, and Daniel Kammen. "The Contributions of Emissions and Spatial Microenvironments to Exposure to Indoor Air Pollution from Biomass Combustion in Kenya," *Environmental Health Perspectives* 108 (2000): 833–839.

Jetter, James, Yongxin Zhao, Kirk Smith, Bernine Khan, Tiffany Yelverton, Peter DeCarlo, and Michael Hays. "Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards," *Environmental Science & Technology*, 46 (2012): 10827–10834.

Kop, Rita, Hélène Fournier, and John Sui Fai Mak. "A Pedagogy of Abundance or a Pedagogy to Support Human Beings? Participant Support on Massive Open Online Courses," *International Review of Research in Open and Distance Learning* 12 (2011): 74–93.

Lozano, R. et al., 2013. "Global and Regional Mortality from 235 Causes of Death for 20 Age Groups in 1990 and 2010: A Systematic Analysis for the Global Burden of Disease Study 2010," *The Lancet* 380 (2013): 2095–2128.

Mehta, Sumi and Cyrus Shahpar. "The Health Benefits of Interventions to Reduce Indoor Air Pollution from Solid Fuel Use: A Cost-Effectiveness Analysis," *Energy for Sustainable Development* 8 (2004): 53–59.

National Institute of Standards and Technology (NIST.) "NIST Multizone Modeling Website." Accessed March 11, 2013. http://www.bfrl.nist.gov/IAQanalysis/index.htm.

Partnership for Clean Indoor Air (PCIA.) "About PCIA." Accessed November 19, 2012. http://www.pciaonline.org/node/2.

Roden, Christopher, Tami Bond, Stuart Conway, Anibal Pinel, Nordica MacCarty and Dean Still. "Laboratory and Field Investigations of Particulate and Carbon Monoxide Emissions from Traditional and Improved Cookstoves," *Atmospheric Environment* 43 (2009): 1170-1181.

Ruiz-Mercado, Ilse, Omar Masera, Hilda Zamora and Kirk Smith, "Adoption and Sustained Use of Improved Cookstoves," *Energy Policy* 39 (2011): 7557–7566.

Smith, Kirk and Jennifer Peel, "Mind the Gap," *Environmental Health Perspectives* 118 (2010): 1643-1645.

Smith, Kirk, 1987. *Biofuels, Air pollution, and Health: A Global Review*, Plenum Press.

United Nations Statistics Division. "Millennium Development Goals Indicators: Population Using Solid Fuels." Accessed October 1, 2010 http://unstats.un.org/unsd/mdg/Series Detail.aspx?srid=712

U.S. Environmental Protection Agency (USEPA.) "Local Trends in Particulate Matter." Accessed April 11, 2013. http://www.epa.gov/airtrends/pm.html#pmloc.

Wang, L. and Chen, Q. 2007. "Theoretical and numerical studies of coupling multizone and CFD models for building air distribution simulations," Indoor Air, 17, 348-361.

World Health Organization (WHO.) "Indoor Air Pollution and Health." Accessed March 12, 2013. http://www.who.int/indoorair/en/.

Yu, Song, Yuanhang Zhang, Shaodong Xie, Limin Zeng, Mei Zheng, Lynn G. Salmon, Min Shao, and Sjaak Slanina, "Source Apportionment of PM2.5 in Beijing by Positive Matrix Factorization," *Atmospheric Environment* 40 (2006): 1526-1537.